

BEAM LOSS MECHANISMS IN RELATIVISTIC HEAVY-ION COLLIDERS

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Doctoral Thesis
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Cover: Schematic drawing of the MAX IV synchrotron accelerator.

BEAM LOSS MECHANISMS IN RELATIVISTIC HEAVY-ION COLLIDERS

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ABSTRACT

The Large Hadron Collider (LHC), the largest particle accelerator ever built, is presently under commissioning at the European Organization for Nuclear Research (CERN). It will collide beams of protons, and later $^{208}\text{Pb}^{82+}$ ions, at ultrarelativistic energies. Because of its unprecedented energy, the operation of the LHC with heavy ions will present beam physics challenges not encountered in previous colliders. Beam loss processes that are harmless in the presently largest operational heavy-ion collider, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, risk to cause quenches of superconducting magnets in the LHC.

Interactions between colliding beams of ultrarelativistic heavy ions, or between beam ions and collimators, give rise to nuclear fragmentation. The resulting isotopes could have a charge-to-mass ratio different from the main beam and therefore follow dispersive orbits until they are lost. Depending on the machine conditions and the ion species, these losses could occur in localized spots, where the induced heating risks to quench the superconducting magnets.

In this thesis, I study first electromagnetic processes between $^{208}\text{Pb}^{82+}$ ions at the interaction points of the LHC through simulations. The beam-induced heat load from ions that have undergone bound free pair production (BFPP), which is the potentially most dangerous loss mechanism, is predicted to be 40% above the quench level although uncertainties are large. Measurements with $^{63}\text{Cu}^{29+}$ beams at RHIC show that localized losses from the collisions exist, although it is difficult to disentangle the losses from BFPP and electromagnetic dissociation (EMD).

Furthermore, residual ion fragments created in the collimation system of the LHC could induce quenches and I present the first measurements of such beam losses together with detailed simulations. The results reveal qualitative differences in loss behaviour between heavy ions and protons and serve both as an evaluation of the principles of ion collimation and as an experimental benchmark of the ICOSIM program.

Finally, simulations of the ion luminosity time evolution at RHIC and LHC

are presented and I show details of a physical model for collisions on a particle level. This model is combined with routines for intrabeam scattering and optical tracking, written by others, to a particle tracking code. The program gives a very good agreement with experimental data from RHIC over a wide range of physics stores with different conditions. The same code is then used to predict the luminosity time evolution in the LHC.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Large Hadron Collider (LHC) är världens största partikelaccelerator, som snart är redo att tas i bruk vid partikelfysiklaboratoriet CERN i Genève i Schweiz. Den kommer att kollidera ultrarelativistiska protoner och senare $^{208}\text{Pb}^{82+}$ joner. På grund av den höga energin i partikelstrålarna uppstår nya utmaningar vid driften av LHC som inte finns i andra existerande acceleratorer. Processer som gör att partiklar lämnar den tänkta strålbanan och i stället slår in i vacuumröret kan värma upp de supraledande magneterna i LHC så mycket att en så kallad quench uppstår, d.v.s. magneterna förlorar sin supraledande förmåga.

I denna avhandling diskuterar jag först olika sådana processer för joner. Processerna existerar även i Relativistic Heavy Ion Collider (RHIC), som ligger vid laboratoriet BNL utanför New York och är den största acceleratoren i drift för jonkollisioner, men där är de ofarliga.

Kolliderande joner kan plocka upp en elektron eller förlora en eller flera nukleoner genom elektromagnetiska reaktioner vid interaktionspunkterna. Dessa joner följer sedan dispersiva strålbånor tills de går förlorade. Jag presenterar simuleringsstudier av sådana joner som visar att den resulterande värmeutvecklingen kan förväntas ligga avsevärt över den högsta accepterade nivån. Felmarginalen är dock signifikant. Mätningar av dessa processer vid RHIC visar en tydlig korrelation mellan förluster och luminositeten, d.v.s. antalet reaktioner per träffyta, men de olika förlustprocesserna är svåra att särskilja.

Joner som fragmenterar i kollimatorerna i LHC kan av samma anledning orsaka en quench. Jag presenterar mätningar gjorda i Super Proton Synchrotron (SPS) vid CERN och jämför dem med simuleringar. Till sist presenterar jag en studie innehållande simuleringar av den dynamiska utvecklingen av luminositet och strålintensitet under driften av en accelerator för jonkollisioner och jämför med data från RHIC.

LIST OF PUBLICATIONS

This thesis is based on the following papers, which will be referred to by their Roman numerals in the text.

I Beam losses from ultra-peripheral nuclear collisions between $^{208}\text{Pb}^{82+}$ ions in the Large Hadron Collider and their alleviation
R. Bruce, D. Bocian, S. Gilardoni, and J.M. Jowett.
Phys. Rev. STAB **12**, 071002 (2009).

II Observations of Beam Losses Due to Bound-Free Pair Production in a Heavy-Ion Collider
R. Bruce, A. Drees, W. Fischer, S. Gilardoni, J.M. Jowett, S.R Klein, and S. Tepikian.
Phys. Rev. Lett. **99**, 144801 (2007).

III Measurements of heavy ion beam losses from collimation
R. Bruce, R.W. Assmann, G. Bellodi, C. Bracco, H.H. Braun, S. Gilardoni, E.B. Holzer, J.M. Jowett, S. Redaelli, and T. Weiler.
Phys. Rev. STAB **12**, 011001 (2009).

IV Time evolution of the luminosity of colliding heavy-ion beams in RHIC and LHC
R. Bruce, M. Blaskiewicz, W. Fischer, and J.M. Jowett.
(2009) *To be submitted to Phys. Rev. STAB*.

V Monitoring heavy-ion beam losses in the LHC
R. Bruce, G. Bellodi, H. Braun, S. Gilardoni, and J. M. Jowett.
pp MOPLS007 (2006) *Proceedings of EPAC 2006, Edinburgh, Scotland*.

VI Performance with lead ions of the LHC beam dump system
R. Bruce, B. Goddard, L. Jensen, T. Lefevre, and W. Weterings.
pp MOPAN068 (2008) *Proceedings of PAC07, Albuquerque, New Mexico, USA*.

VII Effects of ultraperipheral nuclear collisions in the LHC and their alleviation

R. Bruce, S. Gilardoni, and J.M. Jowett.

pp WEPP006 *Proceedings of EPAC08, Genoa, Italy.*

ABBREVIATIONS

BFPP	Bound free pair production
BLM	Beam loss monitor
BNL	Brookhaven National Laboratory
CERN	the European Organisation for Nuclear Research
EMD	Electromagnetic dissociation
EMD1	1-neutron electromagnetic dissociation
EMD2	2-neutron electromagnetic dissociation
IBS	Intrabeam scattering
IP	Interaction point
LHC	Large Hadron Collider—see Sec. 3.1
LSS	Long straight section
MCS	Multiple Coulomb scattering
MB	Main bend—the main dipole magnets in the LHC
ODE	Ordinary differential equation
QD	Defocussing quadrupole
QF	Focussing quadrupole
PD	PIN diode
RF	Radio frequency
RHIC	Relativistic Heavy Ion Collider—see Sec. 3.2
SPS	Super Proton Synchrotron—see Sec. 3.3
ZDC	Zero Degree Calorimeter—used to monitor the luminosity at RHIC

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INTRODUCTION

The primary goal of experiments in heavy-ion physics is to find and characterize new states of hadronic matter, such as the quark-gluon plasma. It is a state of extreme density and temperature, believed to have existed only fractions of a second after the Big Bang. Early studies were performed using fixed target experiments, and the highest energy was achieved at the Super Proton Synchrotron (SPS) at CERN [1] (the European Organisation for Nuclear Research). The first heavy-ion collider operating at a relativistic energy, and the only one which is operational at the time of writing, is the Relativistic Heavy Ion Collider (RHIC) [2] at Brookhaven National Laboratory. The colliding beams at RHIC have a centre-of-mass energy an order of magnitude higher than previous fixed target experiments. A detailed review of the history of the heavy-ion physics experiments can be found in Ref. [3].

A new relativistic heavy-ion collider, the Large Hadron Collider [4] (LHC), is presently under commissioning at CERN. The LHC is primarily designed as a proton-proton collider but it will also operate with heavy ions during shorter periods every year. Once operational, the LHC will reach centre-of-mass energies more than an order of magnitude higher than what is achievable in RHIC.

Apart from exciting new physics results, the continuous struggle to further raise the energy frontier leads to new challenges in the construction of the experimental facilities. Superconducting magnets are required to produce the strong magnetic fields necessary to steer the particle beams on their design orbit. In the LHC, the magnets are pushed close to their limit and even a small perturbation could lead to a quench (a departure from the superconducting state). At the same time, when the particle beams are more energetic than ever, this leads to very tight tolerances on beam losses, since the heating from lost particles might induce quenches. They have to be avoided by all means, because they cause costly downtime of the machine. A sophisticated collimation system is therefore needed to clean halo particles in a safe way.

During heavy-ion operation in the LHC, some beam loss mechanisms are considered to be particularly dangerous:

- Electromagnetic interactions between colliding ions, in particular bound free pair production, change their charge-to-mass ratio. This could lead to a loss of the affected particles in a localized spot.
- The collimation of ions is predicted to be less efficient than for protons, since ions hitting the primary collimators may fragment without being absorbed in the collimation region. The fragments have a different charge-to-mass ratio than the main beam and could be lost in well-defined locations.

This thesis deals with both types of losses and other closely connected problems. The first main task, which is treated in Chap. 6, is to quantify the operational impact of the electromagnetic interactions at the interaction points in the LHC. This is addressed through detailed simulation studies. An equally important task, treated in the same chapter, is to investigate possible ways to alleviate these beam losses. Furthermore, I present in Chap. 7 measurements of beam losses from electromagnetic interactions in the collisions in RHIC, where these losses do not impose a risk of quenches.

The ion beam losses must be surveyed by the beam loss monitor (BLM) system. An important problem, addressed in Chap. 8, is therefore to investigate if the present BLM system, optimized for proton operation, can be used to monitor ion losses. Furthermore, the ion beams have to be extracted and dumped in case of a quench. I investigate also the compatibility of different components in the LHC beam dump system with heavy ion beams.

The operational impact of ion losses in the LHC from collimation has been studied by others [5, 6]. However, an experimental validation of the physical models and the simulation tools is needed, which is another main task of this thesis. In Chapter 9, I present measurements done at the SPS using a prototype of an LHC collimator. Data were taken with different beam energies and angles of the collimator, and both with ions and protons. I compare the measurements with new simulations, which use different levels of detail in the modelling.

Finally, in Chap. 10 I discuss the time evolution of beam intensity and luminosity, which is defined as the reaction rate per cross section in a collider. Detailed simulations are benchmarked against data from RHIC, before the same simulation methods are applied to the LHC.

This thesis is organized as a coherent and self-contained essay in order to make it more accessible. Before describing the main studies, I give a general background with focus on aspects that are central for my work. First, in Chap. 2 an introduction to accelerator physics is given, followed in Chap. 3 by a short overview of the three accelerators treated in this thesis: the LHC, RHIC and SPS. After

that, in Chap. 4, I introduce different computer codes that were used. Finally in Chap. 5 I give an introduction to beam losses caused by ultraperipheral electromagnetic interactions between colliding beams and collimation-induced beam losses. Throughout the later chapters, which contain the main part of my work, I make references to the papers they are based on but the important results in the papers have been included in the chapters as well, with the goal that the reader should not be forced switch back and forth between the main chapters and the articles.

ACCELERATOR PHYSICS

This chapter introduces basic concepts in accelerator physics. Many comprehensive texts on accelerator physics exist. Sands [7] gives an introduction to the subject, although focused on electron storage rings, and Martini [8] gives a detailed account of transverse dynamics. Textbooks covering everything from introductory matters to advanced topics include the books by Wiedemann [9] and Lee [10].

After a description of synchrotrons, I give a brief overview of some central concepts in transverse and longitudinal beam dynamics as well as collisions. I do not aim at giving a complete summary of the subjects but rather to introduce concepts which are necessary for the understanding of later parts of the thesis. This chapter follows in large parts what can be found in the introductory texts [7–10], although I write the luminosity formulas in a slightly different way. Readers familiar with accelerator physics may omit this chapter.

2.1 Synchrotrons

Many types of devices constructed for particle acceleration exist but in this thesis I am concerned only with synchrotrons and give here an overview of their mode of operation. A summary of other types of accelerators can be found in Ref. [9].

A synchrotron is a circular accelerator where charged particles are rotating at a fixed orbit. Magnetic fields are used to keep them on their wanted trajectory and on every revolution they pass an accelerating longitudinal electric field provided by radio frequency (RF) cavities. As the particles gain energy, the magnetic fields are adjusted synchronously so that the orbit remains unchanged. The maximum achievable energy in a synchrotron is limited by the capacity of the

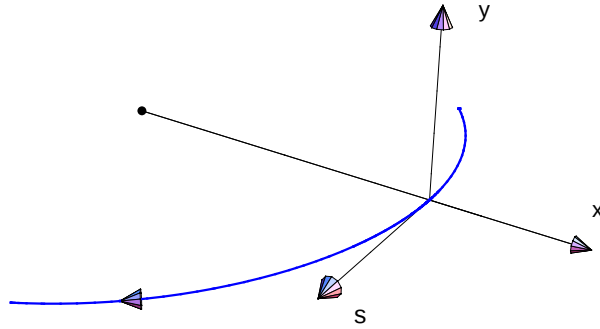


Figure 2.1: The curvilinear coordinate system used to describe the motion of a particle in an accelerator lattice. The s vector is always tangential to the design path, while x points towards the outside of the ring in the horizontal plane. In all accelerators described in this thesis the reference orbit is constrained to the $x - s$ plane.

bending fields and the radius of curvature of the ring and, in the case of particles with large energy losses from radiation, by the power of the RF system.

Synchrotrons include normally some straight sections, called insertions, which are placed between the arcs. The accelerating elements are usually placed in a straight section, as well as experiments in the case of LHC or RHIC. In these machines, there are two counter-rotating particle beams whose orbits cross at the experiments, where large detectors are used to study the collisional products. Machines where two beams collide are called colliders, and the positions where the beams collide are called interaction points (IPs).

The physics of the particle beam motion in an accelerator (accelerator physics) is treated in the following sections, while the particle physics of the collisions themselves is beyond the scope of this thesis.

2.2 Linear transverse dynamics

Particles propagating through an accelerator lattice (sequence of magnetic elements) are guided by different magnetic fields. To describe the motion of a particle under influence of these forces, a curvilinear coordinate system is used, defined in Fig. 2.1, which moves together with an ideal reference particle. This reference particle is exactly following the design path through the centres of all magnets. The s -coordinate measures the travelled distance along the design path and the coordinates (x, y) show the transverse deviation of a real particle from the design path at a certain s .

All magnetic fields are adapted for a certain reference momentum per charge. For heavy ions I write this reference momentum as $P_0 = A_0 p_0$, where A_0 is the mass number of the ion and p_0 the ideal momentum per nucleon. For ions with charge number Z_0 the total charge is $Z_0 e$, with e being the unit charge. The ratio between reference momentum and charge is called magnetic rigidity and obeys the relation

$$\frac{P_0}{Z_0 e} = B \rho_0, \quad (2.1)$$

where B is the magnetic field and ρ the bending radius. A real ion may have a slightly different momentum $Ap = Ap_0 + A\Delta p$, and certain physical processes could change its mass number by ΔA or charge number by ΔZ . Such an ion has a different magnetic rigidity

$$\frac{(A_0 + \Delta A)(p_0 + \Delta p)}{(Z_0 + \Delta Z)e} \approx B \rho_0 (1 + \delta), \quad (2.2)$$

where δ is the total fractional change in magnetic rigidity. Eq. (2.2) neglects increments of the mass excess but gives a very good approximation. Using Eq. (2.1), δ can be written as

$$\delta \approx \frac{Z_0(A_0 + \Delta A)}{A_0(Z_0 + \Delta Z)} (1 + \delta_p) - 1. \quad (2.3)$$

were $\delta_p = \Delta p/p_0$.

The motion of a particle around the reference orbit is determined by the Lorentz force and the exact equation of motion, expressed in the curvilinear system, is rather complex (see for instance Ref. [8]). However, a simpler equation can be obtained with some approximations. If the deviations (x, y, δ) from the ideal particle are small, the equation of motion can be expanded in these variables and here only linear terms are kept. Furthermore, the position along s in the lattice is used as independent variable instead of time so that I define $x' = dx/ds$.

The magnetic fields can be expanded using the multipole expansion [8, 11] and for the linear equations of motion only the two lowest order multipoles are kept. These are dipolar fields (constant vertical fields that are used to make the trajectory bend in the horizontal plane) and quadrupolar fields, which provide focussing. The quadrupolar fields are given by

$$\mathbf{B} = \begin{bmatrix} ky \\ kx \\ 0 \end{bmatrix}. \quad (2.4)$$

The Lorentz force on a charged particle from a quadrupole magnet is attractive towards the centre (focussing) in one plane and repulsive (defocussing) in the other, depending on the sign of the strength k .

With these simplifications, the motion of a particle is described by the Hill equation, which can be derived either from a Newtonian approach [8] or from

a Hamiltonian [10]:

$$\begin{aligned} x''(s) + \left(K_0(s) + \frac{1}{\rho_0^2(s)} \right) x(s) &= \frac{\delta}{\rho_0(s)} \\ y''(s) - K_0(s) y(s) &= 0 \end{aligned} \quad (2.5)$$

Here I have assumed no skew fields ($\partial B_x / \partial x = 0$) and that the ideal orbit lies in the $x - s$ plane. The normalized quadrupole gradient K_0 is defined as

$$K_0 = \frac{Z_0 e}{A_0 p_0} \left(\frac{\partial B_x}{\partial y} \right)_{x=y=0} = \frac{Z_0 e}{A_0 p_0} \left(\frac{\partial B_y}{\partial x} \right)_{x=y=0} = \frac{Z_0 e}{A_0 p_0} k, \quad (2.6)$$

where the equality follows from Maxwell's equations in vacuum.

Within a magnetic element, K_0 and ρ_0 are constant and the solution of Eq. (2.5) gives either a harmonic oscillation or an exponential function depending on the sign of K_0 . We note that there has to be different types of solutions in the horizontal and the vertical planes.

The general solution for x can be expressed by means of two linearly independent solutions $C_x(s), S_x(s)$ to the homogeneous problem, which are determined by the initial conditions $C_x(0) = 1, C'_x(0) = 0$ and $S_x(0) = 0, S'_x(0) = 1$, and a particular solution $\delta d_x(s)$ with $d_x(0) = d'_x(0) = 0$. These functions are (with $K = K_0 + 1/\rho_0^2$):

$$\begin{aligned} C_x(s) &= \frac{1}{2} \left(e^{i\sqrt{K}s} + e^{-i\sqrt{K}s} \right) \\ S_x(s) &= \frac{1}{2i\sqrt{K}} \left(e^{i\sqrt{K}s} - e^{-i\sqrt{K}s} \right) \\ d_x(s) &= \frac{1}{\rho_0 K} [1 - C_x(s)] \end{aligned} \quad (2.7)$$

A solution with arbitrary initial conditions can then be expressed as a linear superposition of C_x, S_x, d_x in form of a transfer matrix, propagating the initial conditions along s :

$$\begin{bmatrix} x(s) \\ x'(s) \\ \delta \end{bmatrix} = \begin{bmatrix} C_x(s) & S_x(s) & d_x(s) \\ C'_x(s) & S'_x(s) & d'_x(s) \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x(0) \\ x'(0) \\ \delta \end{bmatrix} \quad (2.8)$$

Here d_x gives the δ -dependence of the trajectory and is called dispersion. In this thesis I discuss only circular accelerators and, if Eq. (2.5) is solved in every element of the lattice, the coordinates of a particle can be propagated around the ring by means of matrix multiplications. An analogous solution exists for y .

A common simplification to Eq. (2.8) is done by assuming short magnets with high strengths. Writing the length of a given magnet as l , this assumption

gives $|\sqrt{K}l| \ll 1$ and $l \rightarrow 0$ while Kl remains constant if end-field effects are neglected. The transfer matrix can then be expanded in a power series. Keeping only first order terms in $\sqrt{K}l$, the matrix becomes particularly simple. As an example, the transformation of a quadrupole becomes

$$\begin{bmatrix} x(s) \\ x'(s) \\ \delta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -K_0 l & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x(0) \\ x'(0) \\ \delta \end{bmatrix}. \quad (2.9)$$

This is called the thin-lens approximation because of its similarity with the transformation of an optical lens with focal length $f = K_0 l$.

Eq. (2.5) can also be solved globally in the whole accelerator. Then $K_0(s), \rho_0(s)$ are piecewise constant functions with the same periodicity as the lattice. The general solution can be written as [8]

$$x(s) = \sqrt{2J_x \beta_x(s)} \cos[\mu_x(s) - \phi_x] + \delta D_x(s). \quad (2.10)$$

The betatron function $\beta_x(s)$ is periodic and positive and its square shows the variation of the beam envelope along s , while J_x is an integration constant representing the oscillation amplitude of a single particle. The distribution of J_x in an ensemble of particles is discussed in Sec. 2.4.

Furthermore, $\mu_x(s) = \int_0^s \beta_x^{-1}(\zeta) d\zeta$ is called the betatron phase and $D_x(s)$ is a particular solution to Hill's equation but with periodic boundary conditions. I call $D_x(s)$ the periodic dispersion and $d_x(s)$ the locally generated dispersion, that is, the dispersion generated in a certain part of the ring.

From Eq. (2.10), it can be seen that the particles perform pseudo-harmonic oscillations, called betatron oscillations. Their amplitude is modulated along s by $\sqrt{\beta_x}$ and the phase varies with $\mu_x(s)$. An example of trajectories $x(s)$ for a few different particles in an arc of the LHC, together with the envelope function $\sqrt{\beta_x}$, are shown in Fig. 2.2. For off-energy particles, the oscillation takes place around a different closed orbit, given by $D_x \delta$.

The fundamental solutions of the Hill equation can also be expressed in terms of β_x :

$$\begin{aligned} C_x(s) &= \sqrt{\frac{\beta_x(s)}{\beta_x(0)}} (\cos[\mu_x(s) - \mu_x(0)] - \alpha_x(0) \sin[\mu_x(s) - \mu_x(0)]) \\ S_x(s) &= \sqrt{\beta_x(s)\beta_x(0)} \sin[\mu_x(s) - \mu_x(0)] \end{aligned} \quad (2.11)$$

Here I have introduced $\alpha_x(s) = -\beta'_x(s)/2$ and I will refer to $(\beta_x, \alpha_x, \gamma_x, D_x)$, where $\gamma_x = (1 + \alpha_x^2)/\beta_x$, as the optical functions of an accelerator. Sometimes $(\beta_x, \alpha_x, \gamma_x)$ are called Twiss parameters. By inserting Eq. (2.11) in Eq. (2.8) one can construct the transfer matrix for an arbitrary distance in the ring or for a complete revolution. Transfer matrices for the optical functions themselves can also be constructed from the fundamental solutions.

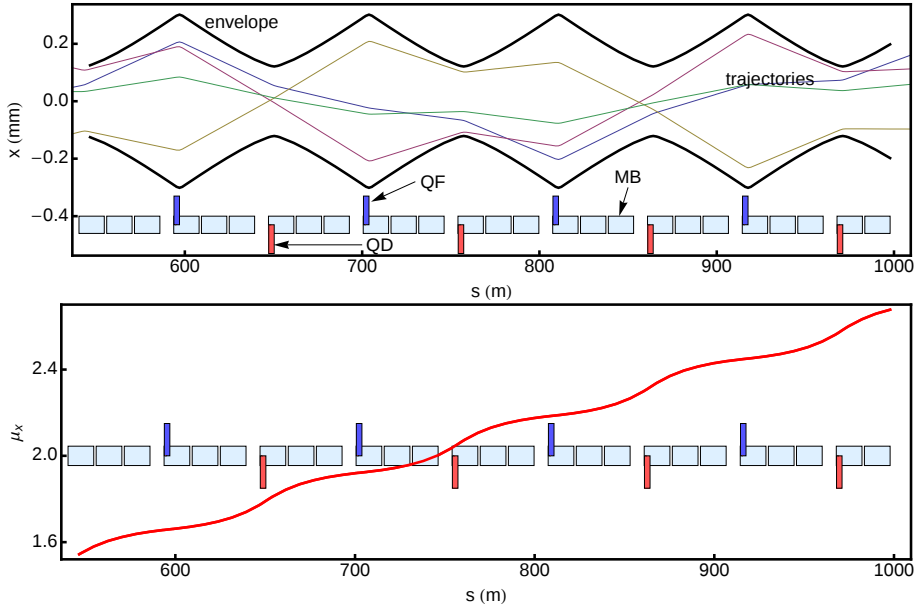


Figure 2.2: Up: An example of different orbits (thin lines) in a FODO lattice, consisting of a periodic series of focussing quadrupoles (QF, thin rectangles pointing upwards), defocussing quadrupoles (QD, thin rectangles, pointing downwards) and bending magnets (MB, grey rectangles). The thick black lines show the envelope function $\pm\sqrt{\epsilon_x\beta_x}$, where ϵ_x is the average of J_x over an ensemble of particles: $\epsilon_x = \langle J_x \rangle$. This is discussed more in Sec. 2.4. Down: the betatron phase μ_x of the same lattice.

All information about the linear focussing of a lattice can be obtained from β_x . A differential equation in β_x can be obtained by inserting Eq. (2.10) in Eq. (2.5):

$$\frac{1}{2}\beta_x\beta_x'' - \frac{1}{4}\beta_x'^2 + K(s)\beta_x^2 = 1 \quad (2.12)$$

However, Eq. (2.12) is analytically solvable only in special cases.

Analogous definitions exist for the vertical plane. However, since dispersion is generated by dipoles [see Eq. (2.7)], which in flat accelerators bend only in the $x-s$ plane, the vertical dispersion typically vanishes in rings.

In Fig. 2.2, one of the most common layouts of a lattice, called FODO, is shown. It consists of a series of focussing and defocussing quadrupoles with bending magnets or drifts in between. When focussing and defocussing quadrupoles are combined in pairs, their combined effect is a focussing in both planes if they have equal gradients (see for example Ref. [9] for details). A common design philosophy of accelerators is therefore to use a modular approach, where such a pair of quadrupoles, with bending dipole magnets between them, form a cell. The arcs of all rings discussed in this thesis (LHC, RHIC and SPS) are built

from many FODO cells. This periodic structure can clearly be seen in Fig. 2.2.

The number of betatron oscillations Q_x per machine turn is called tune and depends mainly on the quadrupoles. It is given by

$$Q_x = \frac{1}{2\pi} \oint \frac{ds}{\beta_x(s)}. \quad (2.13)$$

Normally accelerators are operated so that Q_x and Q_y are far from certain values called resonances. The simplest of them can be understood by considering the x -position of a particle at some fixed value s_0 over several consecutive turns. Since $\beta_x(s)$ is periodic, it is clear that the amplitude in Eq. (2.10) is constant $\sqrt{2J_x\beta_x(s_0)}$. The only variable changing is the phase μ_x , which increases by $2\pi Q_x$ on every turn. Therefore, the motion in x at s_0 is indistinguishable from a sampled harmonic oscillation. If Q_x were an integer, the motion in Eq. (2.10) would be periodic and $x(s_0)$ would have the same value on every revolution. In that case, any imperfections in the magnetic field around the ring act as perturbations, which are synchronous with the oscillation frequency. This will excite resonances, causing an increasing amplitude and unstable motion.

Therefore, integer values of Q_x have to be avoided. As it turns out [9] other resonances are excited by higher order multipole errors if the horizontal and vertical tunes satisfy

$$kQ_x + lQ_y = m, \quad (2.14)$$

where (k, l, m) are integers. Each resonance is connected with a certain order of a magnetic multipole. Normally the resonances at small values of (k, l, m) are the strongest and most dangerous ones. Eq. (2.14) describes a set of lines in the $Q_x - Q_y$ plane, which should be avoided and the tunes are normally chosen far from the lowest order resonances. This position in the plane is called working point.

The Hill equation (2.5) takes only linear magnetic fields into account, which are normally the dominating ones. However, higher-order multipoles are present in all real accelerators. Examples of sources of such non-linearities include imperfections in the magnet construction, effects at the ends of magnets or from non-linear elements put in the ring on purpose, in particular sextupole magnets. They are deployed for chromaticity correction. The spread in δ among the particles within the beam causes each particle to be focussed differently in the quadrupoles and therefore to have different values of Q_x . The ratio $\Delta Q_x/\delta$ is called chromaticity [9]. This is a second-order effect and therefore not present in Eq. (2.5). To properly account for non-linearities, one needs to include higher order terms in Eq. (2.5). If small, they can be treated as perturbations. A mathematical treatment of this can be found in literature [9, 10].

Misalignments of magnets create perturbations. In particular, if a quadrupole is misaligned in the horizontal or vertical plane, the design orbit enters the magnet off-centre where there is a non-zero magnetic field. Therefore, particles receive dipolar kicks. The superposition of many kicks from misalignments over

many turns result in a new equilibrium orbit [9] that no longer passes through the centres of all magnets.

The new equilibrium orbit can be (partly) corrected by orbit corrector magnets, which are short strong dipoles, giving all particles a kick. The correction is usually done on a global level around the whole ring. The passage of a particle through a corrector k can be represented by an addition of the kick angle ψ_k to x' . With a corrector located at s_0 , and with M being the transfer matrix from the corrector to some downstream position s_1 , the coordinates at s_1 are

$$\begin{bmatrix} x(s_1) \\ x'(s_1) \\ \delta \end{bmatrix} = M \begin{bmatrix} x(0) \\ x'(0) \\ \delta \end{bmatrix} + M \begin{bmatrix} 0 \\ \psi_k \\ 0 \end{bmatrix}. \quad (2.15)$$

This gives an addition to x of $M_{12}\psi_k$. If many correctors are present in the ring, then x at some arbitrary position s is the superposition of the unkicked trajectory x_0 and the sum over contributions from kicks located at different s_k . Using that the matrix element $M_{12} = S$ is given by Eqs. (2.11) and (2.8) we get:

$$x(s) = x_0(s) + \sum_k \Theta(s - s_k) \sqrt{\beta_x(s) \beta_x(s_k)} \sin[\mu_x(s) - \mu_x(s_k)] \psi_k. \quad (2.16)$$

Here Θ is the unit step function.

If the kicks are given by machine errors, like quadrupole misalignments, the exact same formulas can be applied, and the error terms are added to the sum. If the beam is left to circulate over many turns with the same kicks, a new equilibrium orbit may be calculated by a limiting procedure [9].

A particle with a large enough amplitude could hit the physical aperture $A_x(s)$ of the machine, in which case it is lost from the beam. One usually defines also a dynamic aperture of a machine, which is given by the smallest possible amplitude for which the oscillation remains stable. Outside the dynamic aperture, the motion becomes unstable because of non-linearities so that particles there are eventually lost.

2.3 Longitudinal dynamics

In synchrotrons, the acceleration is done on every turn by radio frequency (RF) cavities, which provide a high-frequency (normally MHz or GHz) electric field parallel to the direction of motion. The cavities are normally kept active also after the nominal energy is reached in order to provide a focussing in energy, since an ensemble of particles has a spread in δ . Particles with an energy smaller than the nominal one ($p < p_0$) are accelerated by the cavities, while particles with a higher energy ($p > p_0$) are decelerated in such a way that the accelerating

fields group particles in bunches, i.e. groups of particles travelling with a small spread in time and energy.

In some circumstances an average energy increase is needed also during constant-energy operation. Lighter particles, as well as highly energetic ones like heavy ions in the LHC, lose energy continuously through synchrotron radiation when their trajectories bend, as described in Ref. [7]. The RF cavities serve then to replenish this energy loss on every turn.

The RF cavities normally use a sinusoidal voltage $V(t)$ with a frequency $\omega_{RF} = h\omega_r$, which is a multiple h (called harmonic number) of the revolution frequency ω_r . The total change in δ of a particle during one turn is the difference between gain and loss, so

$$\dot{\delta} \approx \frac{ZeV(\tau) - U_{\text{loss}}(\delta)}{T_{r0}E_0}, \quad (2.17)$$

where dots designate time derivatives, T_{r0} is the revolution time, U_{loss} is the energy loss during one revolution and τ is the arrival time with respect to the ideal particle at the cavity. It is defined so that $\tau > 0$ for particles ahead.

The relation between an energy offset, represented by δ when assuming $\Delta Z = \Delta A = 0$, and path length during one revolution is given by the momentum compaction factor $\alpha_c = (\Delta L/L_0)/\delta$, where L_0 is the path length of the ideal particle [9]. The momentum compaction factor is the average of $D_x(s)/\rho_0(s)$ over the ring and is therefore an intrinsic property of the lattice.

During one revolution of time T_r , τ changes as $\Delta\tau = -\Delta T_r$, since τ is defined as positive for particles arriving at a cavity before the reference particle. With $T_r = L/(\beta_{\text{rel}}c)$ and $\beta_{\text{rel}} = v/c$ the relativistic factor as usual, we have therefore, using logarithmic derivation

$$\frac{\Delta\tau}{T_r} = -\frac{\Delta T_r}{T_r} \approx \frac{\Delta\beta_{\text{rel}}}{\beta_{\text{rel}}} - \frac{\Delta L}{L}. \quad (2.18)$$

Using standard relativistic formalism, and keeping only first order in δ , this can be rewritten as

$$\dot{\tau} \approx -\left(\alpha_c - \frac{1}{\gamma_{\text{rel}0}^2}\right)\delta, \quad (2.19)$$

where I write the usual relativistic factor for the ideal particle as $\gamma_{\text{rel}0}$.

From Eq. (2.19) it is clear that two regimes are possible. Defining $\gamma_t = \sqrt{\alpha_c^{-1}}$, we see that if $\gamma_{\text{rel}0} > \gamma_t$, a particle with higher momentum than the reference particle has a longer revolution time, while it is the opposite if $\gamma_{\text{rel}0} < \gamma_t$. At $\gamma_{\text{rel}0} = \gamma_t$ all particles have the same revolution time, regardless of energy. The energy $mc^2\gamma_t$ is usually referred to as the transition energy.

If we assume τ and δ small, we can expand $V(\tau) \approx U_0/(Ze) + \dot{V}_0\tau$ and $U_{\text{loss}}(\delta) \approx U_0 + U_1\delta$ around the ideal particle, where U_0 is the energy loss during one turn

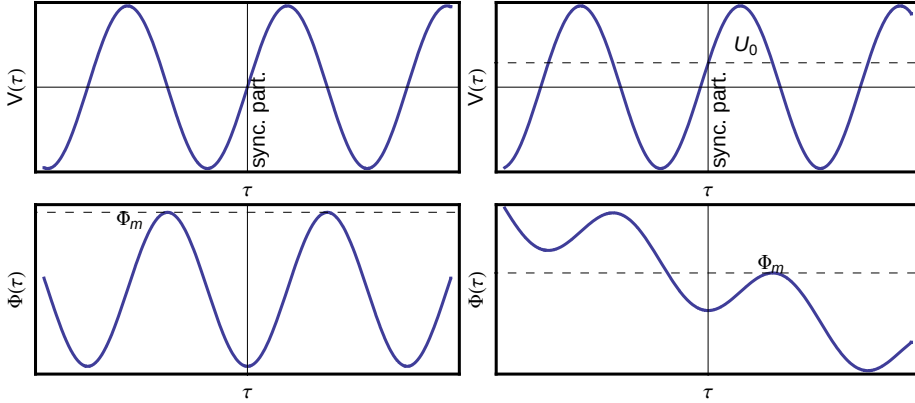


Figure 2.3: Example of a sinusoidal RF voltage (top) and the corresponding “potential energy” (bottom) defining the motion in the longitudinal plane. In the left plots, the energy loss per turn $U_0 = 0$, while $U_0 > 0$ at the right. U_0 is normally very small and has been exaggerated for better visibility. The maximum stable potential Φ_m is indicated, as well as the synchronous particle at $\tau = 0$. All plots show motion for $\gamma_{\text{rel}0} > \gamma_t$. Note that τ is defined as positive for particles ahead of the reference particle. Other sign conventions are sometimes found in literature.

that is replenished by the cavity. Combining Eqs. (2.17) and (2.19) gives a second order differential equation in τ :

$$\ddot{\tau} + \frac{U_1}{T_{r0}E_0}\dot{\tau} + \frac{(\alpha_c - \gamma_{\text{rel}0}^{-2})Ze\dot{V}_0}{T_{r0}E_0}\tau = 0 \quad (2.20)$$

Eq. (2.20) has the same form as the equation of motion for a damped harmonic oscillator. One can therefore picture the longitudinal motion as an oscillation in time and δ around the ideal particle. This is called synchrotron oscillation and its period is called synchrotron period T_S . If no damping force is present ($U_1 \approx 0$) the system is Hamiltonian.

For large oscillations in τ , the exact expression for the voltage has to be used, so the equation of motion is

$$\ddot{\tau} + \frac{U_1}{T_{r0}E_0}\dot{\tau} + \frac{\alpha_c - \gamma_{\text{rel}0}^{-2}}{T_{r0}E_0}(ZeV(\tau) - U_0) = 0. \quad (2.21)$$

The last term plays the role of a force field. Thus, one can construct a “potential energy”

$$\Phi(\tau) = \int_0^\tau \frac{\alpha_c - \gamma_{\text{rel}0}^{-2}}{T_{r0}E_0}(ZeV(t) - U_0) dt. \quad (2.22)$$

An example of Φ for a sinusoidal voltage, both with $U_0 = 0$ and $U_0 > 0$, is shown in Fig. 2.3. The motion can thus be pictured as the particle sliding on this potential surface. The potential wells are called RF buckets and define the

bunch structure of the beam. Every bucket can in principle contain a particle bunch, although this is rarely the case in real machines.

For small amplitudes, the motion is bounded as particles perform synchrotron oscillations back and forth inside the bucket. But a particle at a large enough amplitude passes the crest to the next bucket and the motion becomes unbounded. This eventually leads to a loss of the particle. The limit between stable and unstable motion, which can be represented by a contour in the $\delta - \tau$ phase space, is called separatrix.

In the case of negligible damping, $U_0 \approx U_1 \approx 0$, and only conservative forces act. In that case, the ideal particle arrives at $V(0) = 0$, as shown in Fig. 2.3.

2.4 Particle distribution in phase space

Within every bunch, there is a spread in the transverse coordinates (x, y) and in momentum deviation δ . Instead of keeping track of every particle in a bunch, which can be quite impractical because of the large populations (7×10^7 ions in the case of $^{208}\text{Pb}^{82+}$ in the LHC), the bunch can be described by a distribution function and the coordinates are considered as random variables.

For lepton beams an equilibrium distribution exists, resulting from the emission of synchrotron radiation (see Ref. [12] for details). For the ion beams in RHIC, synchrotron radiation is negligible, while in the LHC it is significant but the equilibrium would be reached after a very long time (if no collisions take place). Therefore, the distributions are highly dependent on the source and injectors, which are used to pre-accelerate the particles before injection in the larger rings. With the exception of the longitudinal distribution in RHIC, all distributions considered in this thesis are Gaussian.

In the horizontal plane the distributions, normalized to unity, are given by

$$\rho_x(x, x') = \frac{\beta_x}{2\pi\sigma_x^2} \exp\left(-\frac{x^2 + [\alpha_x x + \beta_x x']^2}{2\sigma_x^2}\right). \quad (2.23)$$

In the variables (J_x, ϕ_x) this corresponds to a uniform distribution in ϕ_x and an exponential distribution in J_x :

$$\rho_{J_x}(J_x, \phi_x) = \frac{\exp(-J_x/\epsilon_x)}{2\pi\epsilon_x} \quad (2.24)$$

Here $\epsilon_x = \langle J_x \rangle$ is the geometric beam emittance. The normalized emittance is defined as $\epsilon_N = \epsilon_x \beta_{\text{rel}0} \gamma_{\text{rel}0}$. It stays constant during the acceleration, since the RF cavities increase the longitudinal momentum only. Therefore, the angles x' become smaller and consequently the geometric emittance. Equivalent definitions exist in the vertical plane.

In the longitudinal plane, the distribution is given by

$$\rho_{\tau\delta}(\tau, \delta) = \frac{\exp\left(-\frac{\tau^2}{2\sigma_\tau^2} - \frac{\delta^2}{2\sigma_\delta^2}\right)}{2\pi\sigma_\tau\sigma_\delta}, \quad (2.25)$$

with $\sigma_\tau, \sigma_\delta$ being the standard deviations of the coordinates (τ, δ) .

Considering J_x and δ as independent random variables, and assuming a Gaussian distribution in δ , the standard deviation in x at a given position in the lattice is

$$\sigma_x(s) = \sqrt{\epsilon_x \beta_x(s) + \langle \delta^2 \rangle D_x^2(s)}. \quad (2.26)$$

A similar relation holds in y , although $D_y = 0$ in flat accelerators.

Several effects influence the distribution of circulating beams. Most important for the LHC and RHIC are intrabeam scattering (IBS), collisions and synchrotron radiation damping (only for LHC).

IBS occurs when particles are deviated through many small-angle elastic Coulomb scatterings on other particles in the same bunch. The overall result is a growth of all three beam dimensions. Two models, from Piwinski [13] and Bjorken-Mtingwa [14], are commonly used to describe this. Both models are assuming Gaussian distributions and, at high energy, the two models agree fairly well. An example of this is given in Paper IV. The emittance blowup caused by IBS is a function of all three bunch dimensions and the intensity. This is normally modelled by an instantaneous risetime $T_{\text{IBS},x}$, defined through

$$\frac{1}{T_{\text{IBS},x}} = \frac{\dot{\epsilon}_x}{\epsilon_x}. \quad (2.27)$$

Radiation damping occurs when charged particles emit synchrotron radiation as their trajectories are bent. The photons are emitted parallel to the direction of motion and, because of the oscillating trajectories, this direction is not necessarily parallel to s but has also transverse components. On the other hand, when the energy loss is replenished by the RF cavities, only the longitudinal momentum is increased. The combined effect results in shrinking beam dimensions, which counteracts IBS. One usually defines an instantaneous damping time T_{rad} to describe this analogous to Eq. (2.27) but with a negative sign. Details on how T_{rad} is calculated are given in Ref. [7].

Particles are removed through collisions and other unwanted loss mechanisms. This can be described through an instantaneous lifetime

$$\frac{1}{T_l} = -\frac{\dot{N}}{N} \quad (2.28)$$

for each loss process. As shown in Paper IV, the instantaneous lifetimes and rise-times can be combined into a system of ordinary differential equations (ODEs)

describing the coupled time evolution of the bunch intensity and beam dimensions. This has been done previously in Refs. [15–17].

Even though the distributions are changing in time, they remain approximately Gaussian under the influence of the processes discussed here. The distribution (2.23) is still approximately valid, but σ_x is growing in time.

2.5 Colliding bunches

When a flux of $\dot{n}$ particles per unit time hits a thin homogeneous target of thickness z and atomic density ρ , the number of reactions per time $\dot{N}$ is given by

$$\dot{N} = \dot{n} \sigma_i \rho z, \quad (2.29)$$

where σ_i is the interaction cross section for a given physical process. The instantaneous luminosity is defined as

$$\mathcal{L} = \dot{N} / \sigma \quad (2.30)$$

and it is a measure of how often interactions have the possibility to occur. $\mathcal{L}$ has the dimension $\text{m}^{-2}\text{s}^{-1}$. Integrated luminosity is the integral of $\mathcal{L}$ over a certain time. To have as much statistics as possible in an experiment, the integrated luminosity should be maximized. Therefore, a detailed understanding of the processes influencing the luminosity is important. Studies of the time evolution of the luminosity are presented in Paper IV.

In a collider, the incoming beam and the fixed target both have to be replaced by moving bunches. Derivations of the collider luminosity under various conditions are found in Refs. [18–22] and a summary is given in Ref. [23]. Here I derive formulas in a general way for Gaussian beams with unequal beam sizes.

To describe the motion of two colliding bunches, I use the coordinate systems defined in Fig. 2.4. The z_i -systems move with the bunches, while the s_i -systems have the origin fixed at the IP, where the beams cross at a small angle θ . This angle increases the offset between the beams outside the collision point in order to avoid parasitic collisions (since the beams share the same vacuum chamber over some distance around the IP, they could collide at unwanted places if the distance between the bunches is short enough).

The number of interactions per σ in a single crossing between two bunches is called the single collision luminosity, $\mathcal{L}_{sc}$. For bunches with normalized spatial densities ρ_i given in the z_i -systems, intensities N_i ($i = 1, 2$), both travelling with velocities v , $\mathcal{L}_{sc}$ is given by the overlap integral of the two bunches [23]

$$\begin{aligned} \mathcal{L}_{sc} = & N_1 N_2 2v \cos^2 \frac{\theta}{2} \times \\ & \iiint \rho_1(x_1, y, s - vt) \rho_2(x_2, y, s + vt) dx dy ds dt, \end{aligned} \quad (2.31)$$

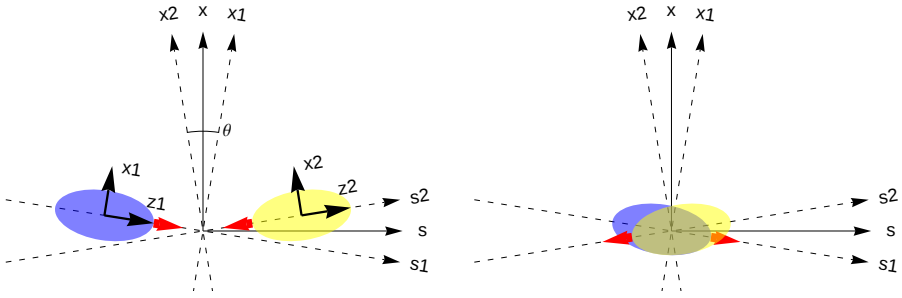


Figure 2.4: Schematic illustration of a collision between two bunches at an IP. The right image shows a later time. The directions of the movement are indicated by the thick arrows in the front of the bunches. The y -coordinates of all systems coincide. All distances are measured in the lab frame.

where t is the time coordinate. I have assumed all integrations to be carried out on the interval $[-\infty, \infty]$ and use this convention in the rest of this text, unless other limits are specified. The prefactor comes from the kinematics of the collision and is discussed in detail in Ref. [24].

When the bunches are well approximated by Gaussian distributions, the integral (2.31) can be solved or simplified. Eq. (2.23) can be integrated over x' to yield the transverse distribution. In the z_i -system moving with bunch i we thus write

$$\rho_i(x_i, y, z_i) = \frac{\exp\left(-\frac{x_i^2}{2\sigma_{xi}^2}\right)}{\sqrt{2\pi}\sigma_{xi}} \frac{\exp\left(-\frac{y_i^2}{2\sigma_{yi}^2}\right)}{\sqrt{2\pi}\sigma_{yi}} \frac{\exp\left(-\frac{z_i^2}{2\sigma_{zi}^2}\right)}{\sqrt{2\pi}\sigma_{zi}}. \quad (2.32)$$

Note that $z_1 = v\tau_1$.

To express the distributions in the fixed the $x-s$ system, I use the transformation [21]

$$\begin{aligned} x_i &= x \cos \psi_i + s \sin \psi_i \\ y_i &= y \\ s_i &= -x \sin \psi_i + s \cos \psi_i \end{aligned} \quad (2.33)$$

where $\psi_1 = \theta/2$ and $\psi_2 = -\theta/2$. Transforming the distributions (2.32) and inserting them in Eq. (2.31), the t , x , and y -coordinates can be integrated immediately to yield

$$\begin{aligned} \mathcal{L}_{sc} &= N_1 N_2 \cos \psi_1 \times \\ &\int \frac{\exp\left(-2s^2 \left[\frac{\cos^2 \psi_1}{\sigma_{z1}^2 + \sigma_{z2}^2} + \frac{\sin^2 \psi_1}{\sigma_{x1}^2 + \sigma_{x2}^2} \right]\right)}{\pi^{3/2} \sqrt{2(\sigma_{x1}^2 + \sigma_{x2}^2)(\sigma_{y1}^2 + \sigma_{y2}^2)(\sigma_{z1}^2 + \sigma_{z2}^2)}} ds \end{aligned} \quad (2.34)$$

Eq. (2.34) can not be integrated analytically in the general case, since the transverse beam sizes depend on s and can not be moved outside the integral [see Eq. (2.26)]. However, under different assumptions, further simplifications are possible.

Assuming that the IP is located in a drift section [$K(s) = 0$], and that β_u with $u = x, y$ has a minimum β_u^* at the IP, Eq. (2.12) can be solved to yield

$$\beta_u(s) = \beta_u^* \left(1 + \frac{s^2}{\beta_u^{*2}} \right), \quad (2.35)$$

Furthermore, I assume that $\beta_x^* = \beta_y^* \equiv \beta^*$, and that $D_x = 0$ in the vicinity of the IP, so that $\sigma_{ui} = \sigma_{ui}^* \sqrt{1 + s^2/\beta^*}$, where $\sigma_{ui}^* = \sqrt{\epsilon_{ui}\beta^*}$ is the transverse beam size at the IP. All these assumptions are valid for the IPs treated in this thesis in the LHC and RHIC. The single collision luminosity can then be written as

$$\mathcal{L}_{sc} = \frac{N_1 N_2}{2\pi\beta^* \sqrt{(\epsilon_{x1} + \epsilon_{x2})(\epsilon_{y1} + \epsilon_{y2})}} R_{\text{tot}}, \quad (2.36)$$

where R_{tot} is a total reduction factor coming from the crossing angle and the so-called hourglass effect. The hourglass effect, which is weak in the LHC but important in RHIC, is caused by the changing beam sizes along s . It is manifested when β_u changes significantly at the IP over the length of a bunch. In that case, particles in the front and end of a bunch encounter parts of the opposing bunch with a smaller transverse density. These particles have consequently a lower interaction probability.

The total reduction factor is given by

$$R_{\text{tot}} = \frac{\sqrt{2} \cos \psi_1}{\sqrt{\pi(\sigma_{z1}^2 + \sigma_{z2}^2)}} \int \frac{\exp \left(-2s^2 \left[\frac{\cos^2 \psi_1}{\sigma_{z1}^2 + \sigma_{z2}^2} + \frac{\sin^2 \psi_1}{\beta^*(1 + s^2/\beta^{*2})(\epsilon_{x1} + \epsilon_{x2})} \right] \right)}{(1 + s^2/\beta^{*2})} ds. \quad (2.37)$$

The integral in Eq. (2.37) is not analytically solvable in the general case, but I list R_{tot} for a few special cases of interest:

- Short bunches and no crossing angle—If $\sigma_{zi} \ll \beta^*$ and θ is small, we can approximate $s^2/\beta^{*2} \approx 0$, since the rest of the integrand vanishes at larger s where this term is significant. With $\psi_1 = 0$, the integration (2.37) yields

$$R_{\text{tot}} = 1. \quad (2.38)$$

- Finite crossing angle, but short bunches—Assuming again $s^2/\beta^{*2} \approx 0$, the integral in Eq. (2.37) can be solved to give [22]

$$R_{\text{tot}} = \frac{1}{\sqrt{1 + \frac{\sigma_{z1}^2 + \sigma_{z2}^2}{\sigma_{x1}^{*2} + \sigma_{x2}^{*2}} \tan^2 \frac{\theta}{2}}} \quad (2.39)$$

- No crossing angle, but long bunches—With $\psi_1 = 0$ the integration gives

$$R_{\text{tot}} = \frac{\sqrt{2\pi}\beta^* \exp\left(-\frac{2\beta^{*2}}{\sigma_{z1}^2 + \sigma_{z2}^2}\right) \operatorname{erfc}\left(\frac{\sqrt{2}\beta^*}{\sqrt{\sigma_{z1}^2 + \sigma_{z2}^2}}\right)}{\sqrt{\sigma_{z1}^2 + \sigma_{z2}^2}}. \quad (2.40)$$

This agrees with the hourglass factor for round beams derived in Ref. [19].

Finally, the luminosity $\mathcal{L}$ at an IP is the product of the number of interactions during a single bunch crossing and the bunch crossing frequency. For a collider with k_b bunches in each ring, circulating at a revolution frequency f_{rev} , the luminosity is

$$\mathcal{L} = \frac{N_1 N_2 k_b f_{\text{rev}}}{2\pi\beta^* \sqrt{(\epsilon_{x1} + \epsilon_{x2})(\epsilon_{y1} + \epsilon_{y2})}} R_{\text{tot}}. \quad (2.41)$$

HEAVY-ION ACCELERATORS

In this chapter I give an overview of the features of the different heavy-ion accelerators treated in this thesis: the Large Hadron Collider (LHC), the Relativistic Heavy Ion Collider (RHIC) and the Super Proton Synchrotron (SPS).

3.1 The Large Hadron Collider

The LHC project was discussed already in the 1980's but formally approved in 1994. The construction work began in 2001 in the tunnel where the Large Electron-Positron Collider (LEP) was previously located, at an average depth of 100 m underground. The tunnel is 26.7 km long and situated at the border between France and Switzerland. A view of a part of the LHC installed in the tunnel is shown in Fig. 3.1. The LHC is a synchrotron, primarily constructed to collide protons, but will during shorter periods each year collide heavy ions, starting with $^{208}\text{Pb}^{82+}$. Details of the design are found in the LHC design report [4]. The main parameters of the machine are listed in Table 3.1.

During the first ion runs, the nominal scheme (with parameters listed in Tab. 3.1) will not be used but instead a so-called early scheme with relaxed parameters. In the early scheme, β^* is increased by a factor two and the number of bunches is reduced to about 10%, while the bunch intensity is at the same level as in the nominal scheme. This allows studies of performance limitations under relaxed conditions. The filling time of the LHC is significantly reduced in the early scheme. It is important to note that the beam-loss induced performance limitations discussed in this thesis do not apply to the early scheme.

The beams pass a chain of injectors before they arrive in the LHC. In the case of ions, $^{208}\text{Pb}^{29+}$ are accelerated by a linear accelerator (Linac3) up to



Figure 3.1: Photo of a part of the LHC installed in the tunnel. White cryostats contain quadrupole magnets while blue cryostats house dipoles. The small blue cylinders attached to the magnets are beam loss monitors. The figure is taken from Ref. [1].

4.2 MeV/nucleon, before they are stripped to $^{208}\text{Pb}^{54+}$. They are then injected in the Low Energy Ion Ring (LEIR), accelerating them to 72 MeV/nucleon, and passed on to the Proton Synchrotron (PS), where the energy is increased to 5.9 GeV/nucleon. Afterwards, the ions are stripped to $^{208}\text{Pb}^{82+}$ before being injected in the Super Proton Synchrotron (SPS), where they are accelerated up to 177.4 GeV/nucleon. Finally they are injected in the LHC. Protons pass also through the PS and SPS, but they go through a different linear accelerator (Linac2) and through the PS Booster instead of the LEIR. Protons are injected at 450 GeV in the LHC.

In the LHC, the particles are slowly accelerated, while the magnetic fields are ramped up. At top energy (7 TeV for protons and 2.76 TeV/nucleon for $^{208}\text{Pb}^{82+}$ ions) the optics is changed in order to minimize β^* , and thereby the beam size at the IP. This is called squeezing. Once complete, the beams are put into collision. This is done by deactivating separation bumps around the IPs, which are active during the acceleration phase, where the two beams share the same vacuum chamber at the experiments without crossing each other.

At top energy, the beams are stored and left to circulate in the machine, while colliding at the IPs on every turn. Particles are continuously removed from the beams by the collisions and unwanted loss processes. When the event rate of the interactions of interest in the experiments is too low, due to the luminos-

Table 3.1: Design parameters for the LHC's proton and $^{208}\text{Pb}^{82+}$ beams in collision conditions [4]. The values of $\mathcal{L}$ and β^* refer to IP2 for $^{208}\text{Pb}^{82+}$ ions and IP1 and IP5 for protons (see Fig. 3.2).

Particle	p^+	$^{208}\text{Pb}^{82+}$
Energy/nucleon	7 TeV	2.759 TeV
γ_{rel0}	7461	2963.5
Max. dipole field	8.33 T	8.33 T
Revolution frequency	11.245 kHz	11.245 kHz
No. of bunches k_b	2808	592
Particles/bunch	1.15×10^{11}	7×10^7
Bunch spacing	25 ns	100 ns
Average collision rate	31.6 MHz	6.7 MHz
Transv. normalized emittance ϵ_N (1σ)	$3.75 \mu\text{m}$	$1.5 \mu\text{m}$
rms momentum spread $\langle \delta_p^2 \rangle^{1/2}$	1.13×10^{-4}	1.10×10^{-4}
Peak RF voltage	16 MV	16 MV
RF frequency	400 MHz	400 MHz
rms bunch length	7.55 cm	7.94 cm
Stored energy per beam	362 MJ	3.81 MJ
Design luminosity $\mathcal{L}$	$10^{34} \text{cm}^{-2}\text{s}^{-1}$	$10^{27} \text{cm}^{-2}\text{s}^{-1}$
horizontal and vertical β^*	0.55 m	0.5 m

ity decay, the remaining particles are dumped (with the beam dump system described below) and new particles are injected. One such operational cycle is called a store. Typical ion stores in the LHC are expected to be of the order of 10 h.

The general layout of the LHC is shown in Fig. 3.2. It consists of two concentric 27 km rings with counter-rotating beams. The rings are made of eight arcs, which consist of 23 FODO cells each, and eight insertions regions (identified as $\text{IR}j, j = 1..8$). Four IRs house utility insertions, while the other four contain colliding-beam experiments with interaction points numbered $\text{IP}j$. The IPs are the only places where the two beams overlap.

Two multi-purpose experiments, the CMS (Compact Muon Solenoid, at IP5) [25] and ATLAS (A Toroidal LHC ApparatuS, at IP1) [26], will further test the standard model of particle physics and its possible extensions. The LHCb [27] experiment at IP8 will study the physics of B-mesons in order to draw conclusions about the ratio of matter and antimatter in the universe and extensions to the standard model. The ALICE (A Large Ion Collider Experiment at IP2) [28] experiment, finally, will as main project study heavy ion collisions. The main goal of this project is to find and study quark-gluon plasma as discussed Chap. 1. Although ALICE is the main experiment for ions, CMS and ATLAS will also take ion collisions. A detailed account of the physics studied in the experiments is beyond the scope of this thesis.

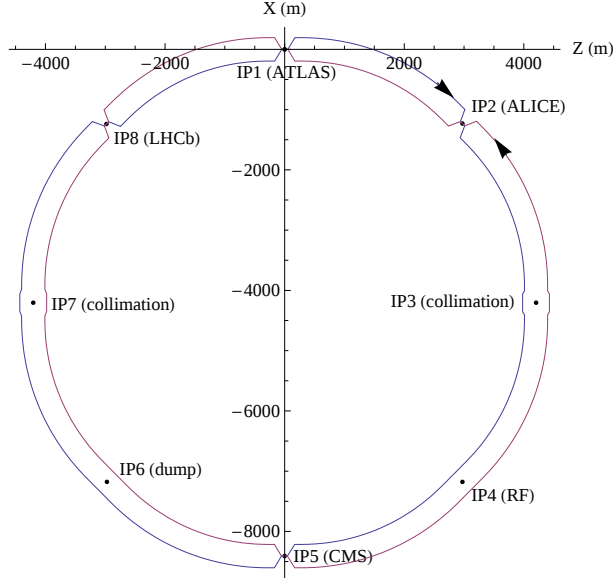


Figure 3.2: Schematic layout of the LHC (the separation of the two rings is exaggerated).

3.1.1 Optics

The LHC optics is based on 106.9 m long FODO cells in the arc, each containing six dipoles and two quadrupoles. The layout and optical functions of a cell are shown in Fig. 3.3.

At the experiments, the beam has to be as small as possible in order to maximize luminosity [see Eq. (2.41)]. Therefore, β^* is focussed down to very small values (down to 0.5 m for heavy ions in ALICE, 0.55 m for the other experiments) by inner triplet quadrupoles, and the dispersion is eliminated with dispersion suppressor regions using a missing dipole scheme, as described in Ref. [9]. The layout and optical functions after IP2 are shown in Fig. 3.3. The crossing angle varies between zero and $70 \mu\text{rad}$ for $^{208}\text{Pb}^{82+}$ ions in ALICE and is $285 \mu\text{rad}$ for protons and ions in ATLAS and CMS.

The optics design continues to evolve through various *versions*, usually corresponding to a given layout of the collider elements, with the latest one called V6.503.

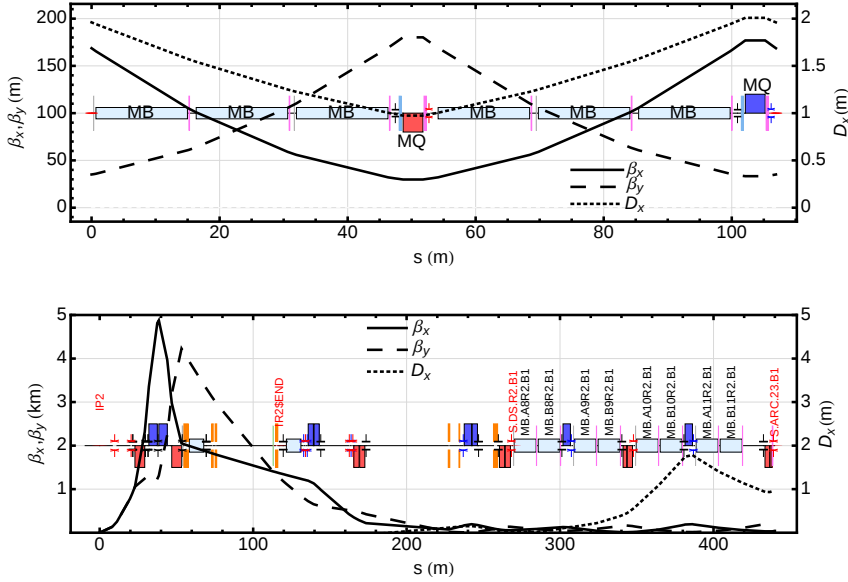


Figure 3.3: The layout of one cell in the regular arc of the LHC (up) and around IP2 where the ALICE experiment is situated (down) together with the optical functions. The names of main magnets (MB—main bend, and MQ—main quadrupole) are indicated, together with the coding indicating the position of the magnet in the ring in the lower plot.

3.1.2 Magnets

The LHC uses superconducting magnets and is based on a two-in-one magnet design with identical bending fields on the central orbits in the two rings. In order for the magnets to stay in their superconducting state, the coils have to be below a so-called critical surface in the space spanned by magnetic field, current, and temperature [29]. The phase diagram for NbTi (the material used in the superconducting cables in the LHC) is shown in Fig. 3.4. Some magnets are therefore cooled down to 1.9 K by liquid helium. Even a small disturbance (e.g. heating from beam losses or friction between cables) could bring the superconductors irreversibly over the critical surface in the phase diagram. The resulting departure from the superconducting state is called a quench. The induced Joule heating quenches also neighbouring volumes so that the quench propagates. The smallest temperature margin to quench is 1.6 K [30].

The magnet that I am mainly concerned with in this thesis is the main dipole, abbreviated as MB (main bend). The transverse cross section of it is shown in Fig. 3.5. The part closest to the beam is the beam screen, which is a racetrack-shaped chamber intended to protect the magnet from synchrotron radiation. Outside is the circular cold bore (labelled “beam pipe” in Fig. 3.5), which is

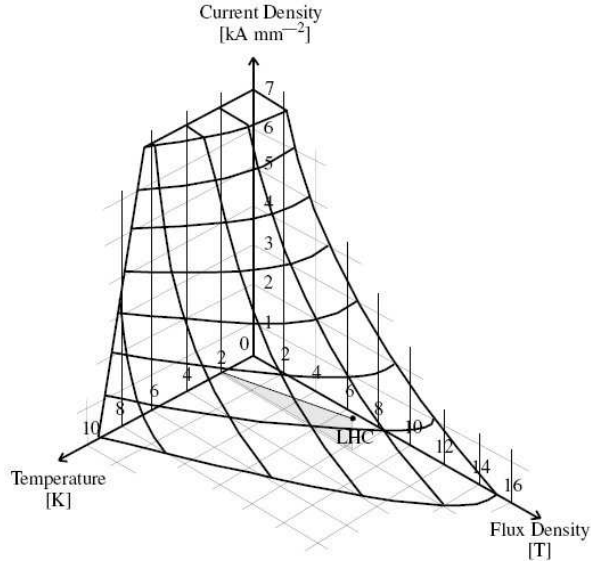


Figure 3.4: The critical surface of NbTi (the material used in the LHC superconductors). The material is superconducting when its working point is below the surface. A quench occurs if the magnetic field, the temperature or the current density is raised enough to pass the surface. The load line of the LHC is marked. The figure is taken from Ref. [31].

surrounded by the superconducting coil, consisting of an inner and an outer winding. The collar is a part of the coil support structure and is inserted in the iron yoke.

The Rutherford-type cables in the coil, shown in Fig. 3.6, consist of strands (28 and 36 in the inner and outer windings respectively), made of NbTi filaments, which are embedded in a copper matrix. Helium inside the cables occupies the space between the strands [32] but serves mainly to increase the heat capacity for protection against transient losses [33]. The cables are wrapped with three layers of polyimide electric insulation and a 0.5 mm-thick ground electric insulation is placed between the coil and the collar. The collar is built from 3 mm-thick austenitic steel plates with a 0.1 mm gap between them filled with helium in direct contact with the heat exchanger through the helium in the iron yoke.

A quench destroys the magnetic field of the affected magnet and therefore perturbs the orbit of the circulating beams. If, in the worst case, the full beam were to be perturbed enough to hit the aperture, it would cause physical damage to the affected element [34] due to the extreme stored energy (see Table 3.1). Therefore an advanced machine protection system is used (see Sec. 3.1.3), which detects quenches, extracts the beams from both rings within one turn, and dumps them onto absorber blocks. This beam dump system is located in IR6 (see Fig. 3.2) and more details are given in Sec. 3.1.3. The quench protec-

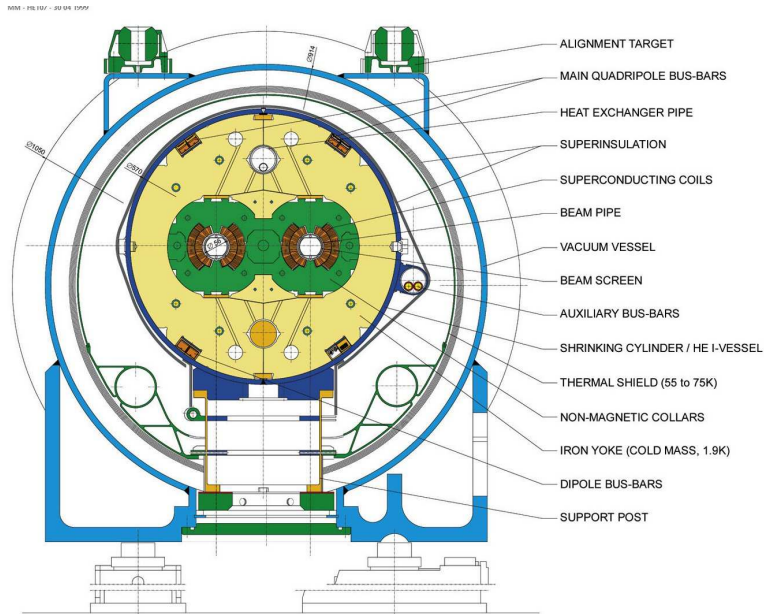


Figure 3.5: The cross section of an LHC main dipole magnet (MB type).

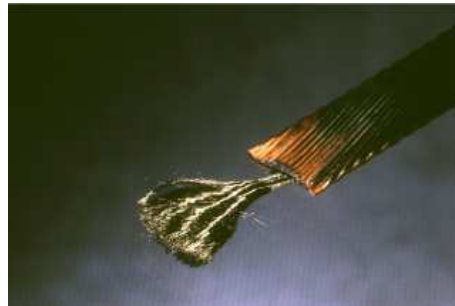
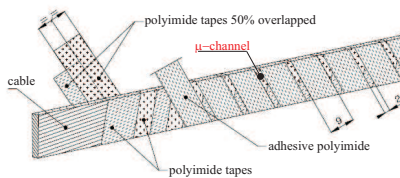


Figure 3.6: Close-up of a single cable where the current carrying strands, and the filaments composed of NbTi, are visible.

tion system will also fire heaters to quickly quench a number of magnets in a controlled way in order to dissipate the stored magnetic energy over a larger volume, since it otherwise might risk to damage the magnets.

Even if the magnets are protected from physical damage, quenches need to be avoided by all means during collider operation, since recovery involves the lengthy process of cooling the magnets down again, followed by refilling, ramping and squeezing of the beams. Downtime of the LHC is costly and must be minimized. Therefore, an important stage in the design of the LHC involves identifying possible causes of quenches and finding counter-measures.



Figure 3.7: An LHC-type secondary collimator jaw, similar to the one installed in the SPS which was used for the experiments in Paper III. The figure is taken from Ref. [36].

3.1.3 Machine protection

One important cause of quenches during normal operation is beam losses. Even a relatively small amount of losses ($7.8 \times 10^6 \text{p}^+ \text{m}^{-1} \text{s}^{-1}$ [35]) may lead to a quench. The LHC is much more sensitive to beam losses than other present machines because of the unprecedented stored beam energy (see Tab. 3.1). When operated with ions, the stored energy is one order of magnitude higher than at RHIC. Different kinds of beam loss mechanisms are discussed further in Chap. 5.

In order to protect the LHC magnets against beam losses, a very effective cleaning system is needed. A collimation system is installed in order to remove particles at high amplitudes in a safe way before they are lost. Particles with high betatron amplitudes are removed in IR7 and particles with large energy offsets are removed in IR3. The collimators are carbon fibre reinforced graphite jaws, with variable gap openings, which are designed to be the limiting aperture of the machine. A view of a collimator jaw is shown in Fig. 3.7

The collimation system deploys a two-stage mode of operation [37]. Particles at large amplitudes hit first a short primary collimator, which is the limiting aperture of the machine. There they interact with the material in such a way that they are either absorbed, scattered back into the beam, or scattered to an even larger amplitude through multiple Coulomb scattering (MCS). The latter particles form a secondary halo, which is intercepted and absorbed by the longer secondary collimators, possibly several turns later. The cleaning insertions do not contain superconducting magnets and are kept at room temperature. Further details on the LHC machine protection can be found in Ref. [38].

The collimation system, which has been optimized for proton operation, will also be used during ion operation. However, in spite of the much smaller stored energy in the ion beam than in the proton beam, the collimation is predicted to be much less efficient for ions. The reason is that ions may undergo nuclear fragmentation after the first impact on the primary collimator. This is discussed further in Sec. 5.2 and in Chap. 9.

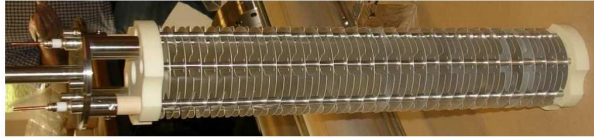


Figure 3.8: Interior part of an ionisation chamber used as a beam loss monitor in the LHC. Taken from Ref. [39].

If significant beam losses should anyway occur, it is necessary to rapidly detect them so that the beam can be extracted before a quench takes place. When a beam particle hits the aperture, it gives rise to a hadronic shower, which extends far beyond the impact point and creates a wide spectrum of low energy particles. These secondary particles are detected by a Beam Loss Monitoring (BLM) system [39, 40]. If the detected radiation exceeds a threshold level, a signal is given to the beam abort system.

The LHC BLMs are 50 cm long ionisation chambers filled with nitrogen, which are placed outside the cryostat, in locations where losses are likely to take place. In order to minimize the drift time of the ions and electrons produced through ionisation in the chamber, there is a stack of parallel aluminium plates inside the cylinder with alternating polarities and 5 mm spacing. A view of the interior part of an ionisation chamber is shown in Fig. 3.8, and BLMs installed in the tunnel are shown in Fig. 3.1.

As already discussed, the LHC BLM system has been primarily optimized for protons, but will also be used during ion operation. An important task is therefore to investigate how it works with ions. This is done in Chap. 6.

Once a signal is given for a beam dump, fast extraction kicker magnets deflect the beam to the septum magnets in IR6. These magnets guide the particles in the vertical plane out of the main ring into an extraction line. After passing a carbon-composite window, used as a vacuum barrier, it is finally dumped on an absorber block, located in a cavern some 650 m away. In order to dilute the heat load a set of dilution kickers in the extraction line sweep the train of bunches along a line, approximately 100 cm long (a figure illustrating the pattern is shown in Paper VI), on the absorber block. The beam dump system also contains beam intercepting devices designed to protect other LHC elements against badly extracted beams and a beam profile screen used to measure the impact position of the dumped beam.

3.2 The Relativistic Heavy Ion Collider

RHIC [41] is situated at the Brookhaven National Laboratory on Long Island outside New York, USA. It is the first large-scale machine ever capable of collid-

Table 3.2: Design parameters for $^{197}\text{Au}^{79+}$ and $^{63}\text{Cu}^{29+}$ beams in RHIC in collision conditions [41]. The design rms bunch length and $\langle\delta_p^2\rangle^{1/2}$ refer to an assumed Gaussian longitudinal bunch profile, but as shown in Paper IV, this approximation is not valid in RHIC. The values of $\mathcal{L}$ and β^* refer to the PHENIX and STAR interaction points.

Particle	$^{63}\text{Cu}^{29+}$	$^{197}\text{Au}^{79+}$
Energy/nucleon	100 GeV	100 GeV
γ_{rel0}	106.4	107.4
Revolution frequency	78.9 kHz	78.9 kHz
No. of bunches k_b	37	103–111
Particles/bunch	4.5×10^9	1×10^9
Transv. normalized emittance (1σ)	$3.3 \mu\text{m}$	$3.1 \mu\text{m}$
rms momentum spread $\langle\delta_p^2\rangle^{1/2}$	6.4×10^{-4}	8.25×10^{-4}
RF harmonic numbers	—	2520,360
RF voltage, $h = 2520$	—	3.0 MV
RF frequency, $h = 360$	—	0.3 MV
Stored energy per beam	0.19 MJ	0.35 MJ
Peak luminosity $\mathcal{L}$	$2 \times 10^{28} \text{cm}^{-2} \text{s}^{-1}$	$3 \times 10^{27} \text{cm}^{-2} \text{s}^{-1}$
horizontal and vertical β^*	0.9 m	0.8 m

ing ultra-relativistic heavy ions. Earlier heavy ion experiments were performed using fixed target experiments (e.g. SPS at CERN and AGS at BNL). It became operational in year in 2000, after 10 years of development and construction.

RHIC consists of two six-fold symmetric storage rings, called the Blue and the Yellow ring, which are located at ground level. The rings have a circumference of 3.8 km. The arcs consist of 11 FODO cells each. Two ion beams are circulating in opposite directions in the two rings and can be brought into collision at six interaction points around the ring. At four of these points experiments called STAR [42], PHENIX [43], PHOBOS [44] and BRAHMS [45] have been built. The other two interaction points are for the moment not being used for particle experiments.

RHIC has collided a variety of ions from polarized protons to $^{197}\text{Au}^{79+}$ at a maximum energy of 100 GeV/nucleon for ions during various periods, called runs. Paper II presents data from Run-5 with $^{63}\text{Cu}^{29+}$ beams and Paper IV is based on data from Run-7 with $^{197}\text{Au}^{79+}$ beams. The main beam parameters for these two runs are presented in Table 3.2 and more information on the running conditions can be found in Refs. [46, 47].

Before particles are injected in RHIC, they are pre-accelerated by a linac and the Alternating Gradient Synchrotron (AGS). The AGS was used for heavy ion fixed target experiments before the construction of RHIC.

The two rings in RHIC use separate magnets and are not contained within the

same cryostat, as opposed to the two-in-one design used in the LHC. Therefore, the magnetic guide fields in the RHIC rings can be adjusted independently, which means that collisions between different ion types with the same energy per nucleon are easily achievable. In the LHC this is more complicated [48].

The LHC increases the available energy in ion collisions by about a factor 27 compared to RHIC. However, the lower energy in RHIC has the advantage that it makes the machine less sensitive to quenches caused by beam losses. Each lost particle deposits correspondingly less energy at the same time as the required magnetic fields are lower (3.458 T in the main dipoles), which increases the temperature margin. The main magnets are superconducting and operate at 4.6 K. RHIC has also a collimation system to clean particles at high amplitudes and BLMs to survey beam losses [41].

Another difference with respect to the LHC is the double RF system in RHIC. The first RF system with a harmonic number $h = 360$ is used to accelerate the particles up to top energy, where another more powerful storage RF system with $h = 2520$ is turned on to operate in parallel with the first one. The purpose of the storage RF is to create shorter RF buckets, since larger longitudinal beam sizes would imply a larger R_{tot} and therefore lower luminosity. In order for the longer bunches to fit in the $h = 2520$ buckets, the bunches are rotated in the longitudinal phase space as shown in Ref. [49].

3.3 The Super Proton Synchrotron

The SPS at CERN has a 6.9 km circumference and was commissioned in 1976. The SPS has been used to accelerate a variety of particles: protons, antiprotons, electrons and positrons (when serving as injector for LEP) and heavy ions. In the early 1980's it was used as a proton-antiproton collider. Now it serves as the last injector for the LHC but is also providing beams for numerous fixed-target experiments using both heavy ions and protons. A schematic view of the SPS is shown in Fig. 3.9.

The SPS is based on a six-fold symmetry with six arcs and long straight sections (LSS). It has only one vacuum pipe and uses normal-conducting magnets. As in the LHC, beam losses are detected with a BLM system. The SPS BLMs are 18 cm long ionisation chambers filled with N_2 gas at 1.1 bar and contain parallel aluminium plates. They are mounted close to lattice quadrupoles where losses could be expected. In total, 216 BLMs are mounted around the ring.

The SPS has also been used as test stand to develop and validate different system of the LHC, and in particular for collimation. A prototype of an LHC collimator has been mounted in LSS5 and was used for the experiments described in Paper III.

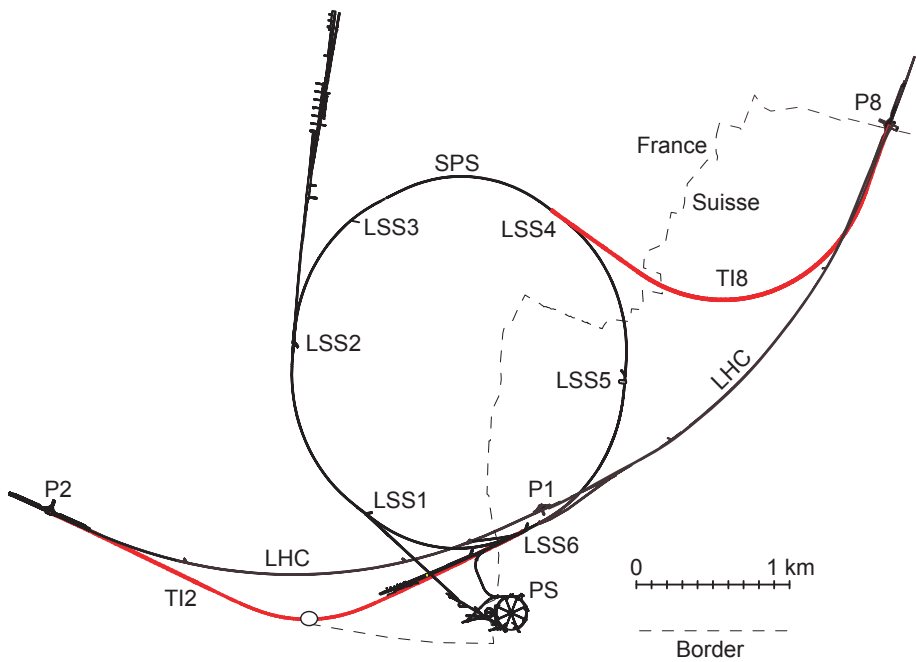


Figure 3.9: A schematic view of the SPS ring from the top. Also the LHC is indicated, as well as the PS and the border between France and Switzerland.

COMPUTER CODES

Several computer programs have been used for the work presented in this thesis. In this chapter, I give an overview of their features.

4.1 FLUKA

All papers included in this thesis except Paper IV contain results based on simulations of the showers of lost beam particles hitting magnets. These simulations were performed using the FLUKA program [50, 51], which is a Monte Carlo code for particle interaction and transport through a user-defined 3D geometry.

The first version of FLUKA was developed as long ago as in 1962 at CERN. This version handled only high energy proton beams and was used to design shieldings of high energy proton accelerators. Since then, the code has been continuously modified and improved in order to handle new particles, energy ranges and interactions. The physics has evolved over the years and FLUKA has been updated to include better and more accurate models. The name FLUKA was invented in 1970 and is short for "Fluktuierende Kaskade" in German. At that point, FLUKA was used to study calorimeter fluctuations.

The present version of FLUKA (2008.3) has little or no remnants of earlier versions. It is now maintained, developed and distributed by an official collaboration between CERN and INFN¹ Milan, but also other institutes and universities, for instance NASA² and SLAC³, are contributing. At present, FLUKA is used for a wide range of applications. Some examples are spacecraft radiation protection, particle detectors, radiation cancer therapy, nuclear waste management

¹Instituto Nazionale di Fisica Nucleare

²National Aeronautics and Space Administration

³Stanford Linear Accelerator Centre

and beam-machine interactions in accelerators at CERN and SLAC. A detailed description of the history of FLUKA can be found in chapter 23 in the FLUKA online manual [52].

FLUKA is based on five major modules, which are fully integrated with each other, that handle different interactions and particles: Hadrons, muons, electrons and photons, low-energy neutrons, and heavy ions. The code is based on nuclear models, except the low-energy neutron module, which handles neutrons with an energy below 20 MeV. This module uses instead a tabulated cross section library. A detailed description of the modules and the physical models they are based on is however beyond the scope of this thesis but can be found in the FLUKA manual and other online material [52].

In the default mode, FLUKA tracks every particle created in every interaction. This execution mode, which is called analogue, is very slow in terms of computational speed, especially at higher projectile energies. Therefore, different biasing techniques are used to speed up the simulation. Biasing was used in most simulations described in this thesis, with the exception of calculation of cross-sections and the passage of particles through a collimator.

Examples of biasing methods include ways of increasing statistics in important parts of the geometry, by splitting every particle into several with lower statistical weight, and down-sampling statistics in unimportant parts by “killing” particles and increasing the weight of the remaining ones. One can also down-sample statistics for certain particle types, in particular electrons and photons, which are very numerous. Both these methods do not change the physics of the problem, only the convergence rate. There are also methods that do change the physics. Cut-offs in energy of the transported particles can be introduced but have to be used with great care. In Paper III, FLUKA was used to simulate the fragmentation of ions hitting a collimator. For this simulation, the quantity of interest is only the outgoing fragments. Therefore, biasing was used in that simulation so that no other secondary particles were tracked.

During a simulation, FLUKA can record many different quantities specified by the user. In this thesis, FLUKA is used to score energy deposition resulting from the hadronic and electromagnetic showers induced when lost beam particles hit different materials. To do this, the user defines a spatial grid, called binning, and FLUKA averages the energy deposition over each of the bins. Choosing the appropriate size of the binning is very important for the correctness of the conclusions drawn from the simulation result. Too large a binning may average out peaks, while if the mesh is too small, the result becomes noisy and an increasing amount of statistics is needed for convergence. Typically a good size of the binning is smaller than the dimensions of any significant changes in the energy deposition.

In Papers I, II, and III, simulation chains of tracking linked together with FLUKA are used. The by far largest uncertainty on the final result of these simulations comes from FLUKA. The reason is that many physical models interact through

repeated particle transports and interactions in the FLUKA simulation. Therefore, estimating an overall systematic error is very hard. Previous comparisons with experimental data are the most reliable guide to the error bars.

FLUKA uses a module called DPMJET III [53] to simulate heavy ion interactions. It has been successfully benchmarked at energies of 100–200 GeV/nucleon [53, 54]. However, no experimental data exist at LHC energies.

4.2 MAD-X

The first version of the program MAD [55] (Methodical Accelerator Design) was developed at CERN in 1983. It is a tool for designing the optics of accelerators, storage rings and transport lines. The current version, which has been used throughout this thesis, is called MAD-X. A beginners guide can be found in Ref. [56], while a detailed description of the physics of the core module, which has not changed since the previous version MAD-8, can be found on the website [55].

MAD-X is a command-line driven program with a text-based interface. It uses a special language in which the user writes an input file. From this file, MAD-X reads definitions of magnetic elements and their sequence as well as the tasks that should be carried out. The sequence is used to calculate a closed orbit and the optical functions discussed in Sec. 2.2. Additional tasks are for example that it can propagate given values of particle coordinates (tracking) or optical functions through a lattice.

MAD-X has also a matching module, which can be used to find magnetic strengths that will produce desired values of the optical functions at given positions under certain constraints. MAD-X can also handle and correct possible machine imperfections and it can be used for both circular and linear accelerators. Other modules in MAD-X can calculate changes in emittance caused by IBS, synchrotron radiation and quantum excitation.

In MAD-X some routines for creating postscript files with plots of output data exist.

4.3 Madtomma

The first version of the language used in the MAD-X input file was developed in the early 1980s, and although many updates have been made since then, the interface is essentially the same. With large and complex accelerators, like the LHC or RHIC, the input files can be long and hard to overview. Furthermore, the results computed by MAD-X are typically part of some larger calculation,

where parts of it are performed using other software. Therefore, the creation of input and analysis of the output is more practical if the MAD-X program is integrated in a wider environment.

For this purpose, Madtomma [57] (MAD to Mathematica) has been under development by J.M. Jowett and collaborators since the early 1990s. It is a collection of packages, which integrates MAD-X in the Mathematica [58] environment. Madtomma provides a high-level meta-language that enables the user to create input files, run them in MAD-X and post-process the results inside Mathematica. Special packages have been created that contain short commands for manipulating the LHC optics.

Another advantage with Madtomma is that the user can create functions that automatically generate input files for a large number of cases of interests, analyze the results and return only certain relevant output. Furthermore, through Mathematica a wide range of visualisation functions are available that enhance the graphical representation of the MAD-X output.

All possible MAD-X commands are not covered by the high-level constructs, but Madtomma supports also input of low-level MAD-X commands and the execution of external input files, which can be combined with the high-level language.

All simulations using MAD-X presented in this thesis were performed within the Madtomma framework.

4.4 ICOSIM

To study the LHC ion collimation inefficiency, described in Sec. 5.2, a program called ICOSIM (for Ion COLLimation SIMulation) has been developed [5]. ICOSIM combines tracking of particles through the accelerator lattice with a Monte Carlo simulation of the particle-matter interaction of beam particles impacting on a collimator.

ICOSIM reads output files from MAD-X, which contain the optical functions and mechanical aperture. This makes it straightforward to simulate any machine for which such a representation exists. The program creates an initial beam distribution that is tracked in the variables $(x, x', y, y', \delta, A, Z)$ through the lattice. The number of particles in the distribution is not constant, since interactions in the collimators may split particles into several smaller fragments with different values of A, Z and particles hitting the physical aperture are removed from the tracking. Synchrotron oscillations are neglected, because typical timescales are long (the synchrotron period is $T_S \approx 500$ turns for the LHC and $T_S \approx 440$ turns for the SPS) compared to the time between a first interaction of an ion with a collimator and the final loss (1-10 turns for most particles, 100 turns in rare cases).

Particles are tracked up to the first collimator impact using the linear matrix formalism described in Sec. 2.2. Transfer matrices between collimators are used and a small artificial emittance blowup is introduced on every turn, which accounts for diffusion caused by effects that need not be specified. The linear tracking is typically done for 10^5 turns and serves to generate impact coordinates on the collimator.

From the first collimator impact, element by element tracking is used in ICOSIM and chromatic effects at leading order, as well as sextupoles in thin kick approximation, are included. Higher order multipoles are neglected, since particles are typically lost in less than 100 turns, which is not enough to see a significant effect of small non-linearities. At the end of each element, a check is performed to determine which particles are outside the aperture. The impact momenta and coordinates on the vacuum chamber are estimated by a linear interpolation inside the magnetic element.

ICOSIM has a simple built-in Monte-Carlo program to simulate the collimator interaction, which includes multiple scattering using a Gaussian approximation [see Ref. [59] or Eq. (5.8)], ionization through the Bethe-Bloch formula [59], nuclear fragmentation and electromagnetic dissociation. The last two processes are simulated by sampling from tabulated cross sections, created by FLUKA, for all possible fragments and fragmentation channels. Only the heaviest fragment created in each interaction is tracked. In the LHC, only these fragments are important to follow, since ions with $|\delta| > 0.05$ are already lost in the warm collimation insertion.

BEAM-LOSS MECHANISMS

A number of physical processes exist that make beam particles leave their trajectory and hit the machine aperture. One example is resonances or unstable motion caused by unavoidable field errors and higher order multipoles, as discussed in Sec. 2.2. Particles inside the dynamic aperture may also diffuse out from the core of the beam and in to the unstable region, e.g. through IBS. An overview of many such processes is given in Ref. [60]. Beam losses could also be irregular, that is, occur due to unforeseen, accidental beam conditions during a shorter time period, e.g. machine failures or operational errors.

This thesis concentrates on a few types of beam-loss mechanisms which are important in relativistic heavy-ion colliders. These include losses from ultraperipheral electromagnetic interactions and collimation. I discuss these processes in more detail in the following sections.

5.1 Ultraperipheral electromagnetic interactions

When two fully stripped ions collide at an IP, a variety of processes leading to fragmentation and particle production can occur. Hadronic nuclear interactions, which are usually the main object of study of the experiments, occur only when the impact parameter b , defined as the distance between the centres of the two colliding particles, is smaller than about twice the nuclear radius R . Ultraperipheral collisions are those in which two colliding ions pass close to each other with $b > 2R$. In such events, the intense Lorentz-contracted electromagnetic fields of the nuclei can be represented as pulses of virtual photons in the equivalent photon picture of Fermi, Weizsäcker and Williams [11]. These extremely energetic photons collide and cause electromagnetic interactions that are particularly strong in heavy-ion collisions because the density of virtual photons around the nuclei is proportional to Z^2 . Reviews of this field can be found

in Refs. [61–64]. In comparison with the cross-section for inelastic hadronic interactions, $\sigma_h \approx 8$ b, the rates of ultraperipheral interactions are very large. From the point of view of collider operation, the most important electromagnetic processes are the sub-classes of these interactions which remove ions from the beam, namely bound-free pair production (BFPP) and electromagnetic dissociation (EMD) [65].

In BFPP, the virtual photons surrounding relativistic ions collide and produce an e^+e^- pair where, in contrast to the much more frequent free pair production, the electron is created in an atomic shell of one of the ions. Schematically, the reaction between two bare nuclei with atomic numbers Z_1, Z_2 can be written as

$$Z_1 + Z_2 \longrightarrow (Z_1 + e^-)_{1s_{1/2}, \dots} + Z_2 + e^+. \quad (5.1)$$

In EMD one nucleus absorbs a photon and undergoes a transition into an excited state, typically by excitation of the giant dipole resonance. When this decays, it emits one or several nucleons. The most common processes are the emission of one or two neutrons. For the case of $^{208}\text{Pb}^{82+}$ ions, the 1-neutron reaction (called EMD1 hereafter) can be written as

$$^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \longrightarrow ^{208}\text{Pb}^{82+} + ^{207}\text{Pb}^{82+} + n. \quad (5.2)$$

5.1.1 Cross sections

Before discussing the operational impact of BFPP and EMD, I give a brief summary of their interaction cross sections. The details of how the cross sections are calculated is however beyond the scope of this thesis.

In the case of BFPP, the partial cross section for electron capture to a low-lying atomic state i on nucleus 1 takes the approximate form [66]

$$\sigma_i \approx Z_1^5 Z_2^2 (A_i \log \gamma_{\text{cm}} + B_i), \quad (5.3)$$

where γ_{cm} is the Lorentz boost of the ions in the centre-of-mass frame and A_i, B_i depend only weakly on Z for the atomic s -states. The total cross section for BFPP to *one* of the colliding ions is then

$$\sigma_{\text{BFPP}} = \sum_i \sigma_i \quad (5.4)$$

where the sum is over all atomic shells. Some numerical values of σ_{BFPP} at RHIC and LHC, calculated in Ref. [66], are given in Table 5.1.1.

However, the BFPP cross section for collisions of 100 GeV/nucleon $^{63}\text{Cu}^{29+}$, which was used in Paper II, was not calculated in Ref. [66]. A simple estimate was made through an interpolation of the data given in Fig. 7 of Ref. [66], which shows σ_i/Z^7 as a function of Z (the colliding particles are of the same

Table 5.1: Cross sections for BFPP, EMD1 and EMD2 in the LHC and RHIC. The event rates were calculated using the nominal luminosity in Tab. 3.1 and δ is defined by Eq. (2.3). The BFPP cross sections are taken directly where possible from Ref. [66], or estimated by fitting sums of contributions of the form (5.3), to the information in Ref. [66]. The EMD cross sections were simulated with FLUKA. For the values available in Ref. [67], the agreement is good.

	LHC Pb-Pb 2759 GeV/nucleon	RHIC Au-Au 100 GeV/nucleon	RHIC Cu-Cu 100 GeV/nucleon
Bound free pair production			
σ_{BFPP} (b)	281	114	0.2
Rate (kHz)	281	342	4
δ (%)	1.2	1.3	3.6
1-neutron electromagnetic dissociation			
σ_{EMD1} (b)	96	45	1.2
Rate (kHz)	96	135	24
δ (%)	-0.48	-0.51	-1.6
2-neutron electromagnetic dissociation			
σ_{EMD2} (b)	29	17	0.22
Rate (kHz)	29	51	4.4
δ (%)	-0.96	-1.0	-3.2
Electromagnetic dissociation, all channels			
σ_{EMD} (b)	226	99	3.9
Rate (Hz)	226	297	78

ion species) for different atomic shells i and a given $\gamma_{\text{cm}} = 3400$. The desired cross section can thus be obtained by summing the interpolated terms σ_i for $Z = 29$ over the states as in Eq. (5.4) and scaling to get the correct γ_{cm} according to Eq. (5.3):

$$\sigma_{\text{BFPP}} = 29^7 \times \frac{\log \gamma_{\text{cm}}}{\log 3400} \times \sum_i s_i. \quad (5.5)$$

A value of 0.2 b is found using $\gamma_{\text{cm}} = 106.4$ for the $^{63}\text{Cu}^{29+}$ beam. Here an approximation has been done, since also B_i in Eq. (5.3) is rescaled by $\log 106.7 / \log 3400 \approx 0.57$. This error is however small, since it is clear from Ref. [66] that $|A_i|$ and $|B_i|$ have the same order of magnitude, although $|A_i| > |B_i|$, with $A_i > 0$ and $B_i < 0$. This means that $|A_i| \times \log \gamma_{\text{cm}} \gg |B_i|$ and that Eq. (5.5) slightly overestimates σ_{BFPP} for $^{63}\text{Cu}^{29+}$ operation in RHIC. Applied to other tabulated values in Ref. [66], the same method produces an agreement within 10%. It should also be mentioned that recent calculations using the equivalent photon method of Weizsäcker and Williams, published after Paper II, give $\sigma_{\text{BFPP}} = 0.198$ b [68] for $^{63}\text{Cu}^{29+}$ collisions in RHIC.

The cross sections for EMD were calculated with FLUKA, by simulating a large number of events through direct calls to the event generator (i.e. by simulating a fixed target experiment without constructing a full geometry). The resulting cross sections for EMD1 and the 2-neutron process, called EMD2 hereafter, are

shown in Table 5.1.1. These results are consistent with results from others [67].

Thus, the total cross section for particle loss by electromagnetic processes in the LHC is around 507 b, compared to the 8 b for nuclear inelastic interactions.

5.1.2 Operational considerations

Both BFPP and EMD change the magnetic rigidity of at least one of the colliding nuclei, which can be seen from Eq. (2.3). During the interactions, the transverse momentum recoil is very small, so the modified ions emerge at a small angle to the main beam. In EMD, the recoil changes δ_p , while this is negligible for BFPP. However, ions from both processes follow dispersive orbits according to their δ and may be lost at the first point in the ring where the horizontal aperture A_x and dispersion d_x generated locally since the IP satisfy

$$d_x \delta \gtrsim A_x. \quad (5.6)$$

The beam losses caused by these processes contribute significantly to the decay of intensity and luminosity in an ion collider [65, 69]. This has been evaluated for the LHC [4, 15], where ions could collide at three IPs: ATLAS, ALICE, and CMS. Because of the large cross sections, BFPP and EMD are the dominant limit on usable luminosity lifetime for the LHC experiments, which is clear from the results of Paper IV.

Eq. (5.6) is given for a reference particle starting at the IP with $x = x' = 0$. All other particles perform betatron oscillation around it. At the impact position they form a spot on the vacuum chamber, centred around the reference particle, whose size depends on the emittances and the optical functions (β_x, β_y, d_x). The smaller the spot, the more concentrated is the induced heating.

The rate of removal of particles from the beam at the IPs is given by Eq. (2.30). With values of $\mathcal{L}$ and energy E per ion in Tab. 3.1, and σ_{BFPP} from Table 5.1.1, the total power in the BFPP beam in the LHC is $\mathcal{L}\sigma_{\text{BFPP}}E \approx 25.8 \text{ W}$. If the location of the losses happens to be in a superconducting magnet [15, 70, 71], this power could be high enough to cause a quench. The assessment of the risk of quenches and possible performance limitations in the LHC due to this effect is the main topic of Paper I.

In RHIC, there is however no risk of quenches from BFPP. Apart from the much lower energy, the particles converted from $^{197}\text{Au}^{79+}$ beams remain within the acceptance of the ring. During $^{63}\text{Cu}^{29+}$ operation in RHIC, BFPP does give rise to localized losses but because of the lower cross section and energy the total power is only 0.004 W. Instead, the $^{63}\text{Cu}^{29+}$ run provided an opportunity measure BFPP between colliding beams as explained in Chap. 7 and Paper II. Earlier measurements of BFPP have been carried out in fixed target experiments [72–74].

Although EMD does not pose any risk of quenches at RHIC, mutual EMD between ions of the colliding beams has also been measured at RHIC [75] and is routinely used to monitor the luminosity [76, 77]. The residual neutrons are then detected using a Zero Degree Calorimeter (ZDC).

5.2 Beam losses from collimation

Another type of ion-specific beam losses results from the ion-matter interaction in collimators. To explain the problem, I give first a brief overview of the collimation in the LHC. Details on the LHC collimation for protons can be found in Refs. [4, 78–80].

As discussed in Sec. 3.1.3, the LHC collimation system consists of primary and secondary collimators. Both are made of graphite jaws. High-amplitude protons hitting the primary collimator scatter back into the beam or onto the secondary collimators. The condition on the angular kick $\delta x'$ given by the primary collimator for a particle to be intercepted by the secondary collimator is [37]

$$\delta x' > \sqrt{\frac{(M_2^2 - M_1^2)\epsilon_x}{\beta_x(s_p)}}. \quad (5.7)$$

Here s_p is the s -coordinate at the primary collimator and M_1, M_2 are the transverse positions of the primary and secondary collimators, given in the number of σ_x [as defined in Eq. (2.26)] from the centre of the vacuum chamber.

This collimation scheme has been designed for protons but will be used also during heavy-ion runs. The physics of the particle-matter interactions of heavy ions is however qualitatively different from protons, since ions undergo nuclear fragmentation and EMD. The inefficiency of the LHC ion collimation can be understood by comparing the length of material that an ion would need to traverse in order to hit the secondary collimator with the interaction length of nuclear fragmentation processes. Taking standard LHC $^{208}\text{Pb}^{82+}$ parameters in Eq. (5.7) ($M_1 = 6$, $M_2 = 7$, $\epsilon_N = 1.5 \mu\text{m}$, $\gamma_{\text{rel}0} = 2963.5$, $\beta_x(s_p) \approx 135 \text{ m}$), we see that the angular kick that a $^{208}\text{Pb}^{82+}$ ion would need to receive in the primary collimator in order to hit the secondary collimators is approximately $7 \mu\text{rad}$. To have this rms angle of the ion distribution exiting a collimator, the required length of the jaw would be 2 m if we use the Gaussian approximation of the Moliere formula [59] to calculate the rms MCS angle θ_0 :

$$\theta_0 = \frac{13.6 \text{ MeV}}{vp} Z_0 \sqrt{\frac{z}{z_0}} \left[1 + 0.038 \ln \left(\frac{z}{z_0} \right) \right] \quad (5.8)$$

Here z is the distance traversed in the material and z_0 the radiation length, defined as mean distance over which a high-energy charged particle loses all but $1/e$ of its energy through bremsstrahlung.

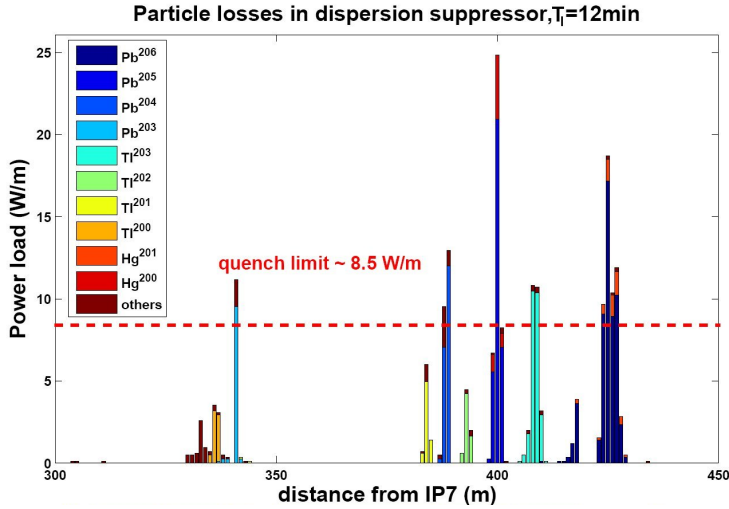


Figure 5.1: Heat deposition in the LHC dispersion suppressor during $^{208}\text{Pb}^{82+}$ operation at collision energy as simulated by ICOSIM for an assumed beam lifetime of 12 min. Courtesy of G. Bellodi.

The length of the primary collimators is only 60 cm, and typical trajectories inside them much shorter, while the interaction lengths for nuclear inelastic interactions and EMD are around 2.5 cm and 19 cm respectively [5]. Since the transverse recoil of the heavy fragments is very small, it is clear that the heavy ions that are not absorbed in the primary collimator are likely to be fragmented without having obtained a sufficiently large angle to reach the secondary collimators.

The created fragments (e.g. ^{207}Pb , ^{203}Tl and others) have a different magnetic rigidity from the main beam [see Eq. (2.3)]. Just as the particles affected by BFPP or EMD, these ions follow the locally generated dispersion function d_x from the collimator and may be lost downstream in the machine where the horizontal aperture A_x satisfies Eq. (5.6). Because of the different δ of the created ion species, they are lost at different localized spots, making the machine act as a spectrometer. Some impact locations could be outside the warm collimation insertion, meaning a potential risk of quenching superconducting magnets.

Studies of the LHC ion collimation inefficiency with ICOSIM (described in Sec. 4.4) have been carried out by others [5, 6]. The output of ICOSIM is a lossmap containing the relative importance of different loss locations, which has to be converted into deposited power in the superconducting magnets. An example of such a simulated lossmap is shown in Fig. 5.1. As a worst-case scenario a beam lifetime of $T_l \approx 12$ minutes has been assumed as normalization, which is the minimum lifetime that the collimation system has to accept [5]. It is clear that in this situation the heat load is much above what can be tolerated (the lowest heat load at which a quench could occur is indicated by a horizontal

line in Fig. 5.1). During normal conditions, with beam lifetimes of the order of a few hours, the heating power has to be scaled down accordingly.

To verify the fundamental assumptions on ion collimation and assess the predictive power of the ICOSIM simulations, an experimental benchmark using a working machine is necessary. In Paper III, I present results from an experiment performed at the SPS, where a prototype collimator was deliberately moved into a circulating $^{208}\text{Pb}^{82+}$ beam to provoke losses. I compare the measurements with lossmaps produced with standard version of ICOSIM and with an updated version in which I link ICOSIM to FLUKA for a more detailed treatment of the ion-matter interactions in the collimator.

BFPP AND EMD IN THE LHC

In this chapter, a three-step simulation approach is used to study the risk of quenches caused by BFPP and EMD in the LHC. Single $^{208}\text{Pb}^{81+}$ ions are tracked from the IP, where they were converted, up to the loss position where they hit the aperture. The impact coordinates are then fed into FLUKA 2008.3, where a 3D model of the affected magnet has been implemented. FLUKA is used to simulate the resulting power load in a spatial grid in the magnet. The heat distribution is in turn passed on to a thermal network simulation. This last step, which was done by D. Bocian, simulates the full heat flow inside the magnet and returns a temperature map as output. Predictions of whether the magnet will quench are then based on a comparison of the expected temperature with known quench characteristics of the magnet. I discuss also different methods to alleviate the losses, in particular through closed orbit bumps.

The full study is presented in Papers I and VII. This chapter gives a summary with focus on my part of the work. Earlier tracking studies were performed in Ref. [15], using an integration of the equations of motion in the magnet and a previous version of the LHC optics. In this thesis I study V6.503 and use a faster method, which is needed in order to track the large ensembles of particles that are necessary for sufficient statistics in the later steps in the simulation chain.

6.1 Optical tracking

The condition for loss of nuclei modified by BFPP or EMD is given by Eq. (5.6) and depends thus on the beam optics, the aperture and the ion species. The δ_{BFPP} of ions affected by BFPP in the LHC is given in Tables 5.1.1. For EMD1 ($\Delta A = -1$) and EMD2 ($\Delta A = -2$) also the average momentum deviation per nucleon caused by the recoil has to be included. This has been estimated with

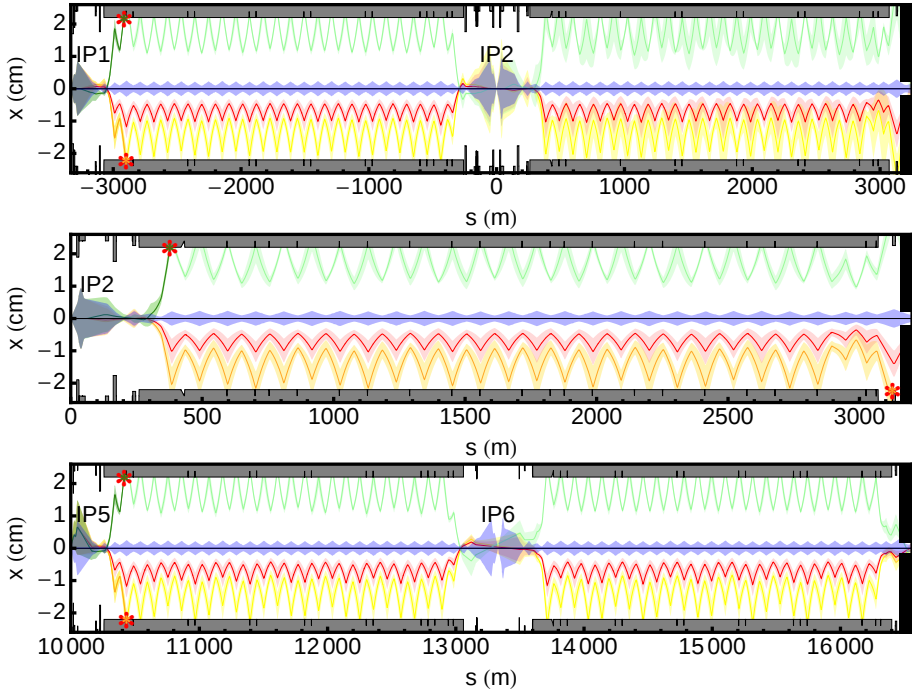


Figure 6.1: The simulated horizontal 6σ envelopes of the nominal $^{208}\text{Pb}^{82+}$ beam (blue), the $^{208}\text{Pb}^{81+}$ BFPP beam (green), the $^{207}\text{Pb}^{82+}$ EMD1 beam (red) and the $^{206}\text{Pb}^{82+}$ EMD2 beam (yellow) coming out of IP1 (top), IP2 (middle) and IP5 (bottom) in the LHC, with the machine aperture superimposed. The envelopes are plotted in a lighter colour after the impact (indicated by a red star) of the central orbit on the aperture. The horizontal scales have $s = 0$ at each IP in turn and the closest horizontal collimators are represented as black boxes at 6σ to the right. The length of the collimators is not to scale for the sake of readability.

FLUKA and the total average δ are given by $\delta_{\text{EMD1}} = -0.0049$ and $\delta_{\text{EMD2}} = -0.0097$ using Eq. (2.3).

Since the momentum acceptance of the LHC arcs is $|\delta| < 0.006$ [4], BFPP and EMD2 will cause localized losses in the LHC while EMD1 will not. An illustration of the envelopes of the beams with BFPP, EMD1 and EMD2 ions, calculated with MAD-X, is shown in Fig. 6.1.

I describe first the tracking of ions affected by BFPP, since that is the most dangerous process. An ion that enters the IP with $x = x' = \delta = 0$, and acquires an extra electron through BFPP, exits with $\delta = \delta_{\text{BFPP}}$ and follows a dispersive trajectory approximately given by $x_B \approx \delta_{\text{BFPP}} d_x$. To increase the accuracy x_B is calculated with MAD-X.

Any other BFPP ion performs betatron oscillations around it and has also a dispersive contribution from the momentum deviation δ_p inside the bunch. For highest accuracy the optical functions are computed with MAD-X for the ions with $\delta = \delta_{\text{BFPP}}$. These optical functions are denoted by a tilde. With $s = 0$ at the IP, the position x and angle x' of a $^{208}\text{Pb}^{81+}$ ion at some downstream position s_1 is, in analogy to Eq. (2.8):

$$\begin{bmatrix} x(s_1) \\ x'(s_1) \\ \delta_p \end{bmatrix} = \begin{bmatrix} x_B(s_1) \\ x'_B(s_1) \\ 0 \end{bmatrix} + \begin{bmatrix} \tilde{C}_x(s_1) & \tilde{S}_x(s_1) & \tilde{d}_x(s_1) \\ \tilde{C}'_x(s_1) & \tilde{S}'_x(s_1) & \tilde{d}'_x(s_1) \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x(0) \\ x'(0) \\ \delta_p \end{bmatrix} \quad (6.1)$$

The functions $\tilde{C}_x$ and $\tilde{S}_x$ are completely analogous to Eq. (2.11), but they are evaluated with initial conditions taken from the periodic on-momentum solution at the IP ($\tilde{\beta}_x(0) = \beta_x(0)$ and $\tilde{\mu}_x(0) = \mu_x(0)$). For the off-momentum dispersion function $\tilde{d}_x$, the initial condition is $\tilde{d}_x(0) = 0$.

The δ_p of the BFPP particles has a Gaussian distribution with a standard deviation given in Table 3.1. The initial $x(0)$ and $x'(0)$ are also normally distributed but we must take into account that the distribution of these collision points is *not* that of the incoming bunches, which is given by Eq. (2.32). By integrating over the distributions of the two bunches, in analogy with Eq. (2.31), it can be shown (see Paper I for details) that the transverse distribution of the BFPP particles is given by

$$\lambda(x, x') = \frac{\beta_x}{\sqrt{2\pi}\sigma_x^2} \exp\left(-\frac{2x^2 + (\alpha_x x + \beta_x x')^2}{2\sigma_x^2}\right), \quad (6.2)$$

with a standard deviation in x a factor $\sqrt{2}$ smaller than the incoming bunch. The vertical coordinates y and y' are treated analogously.

The size of the BFPP beam changes as it travels through the accelerator lattice. Using Eq. (6.1) to propagate the beam distribution in Eq. (6.2) the standard deviation of the BFPP particles at some downstream position s_1 can be shown to be

$$\sigma_\lambda(s_1) = \sqrt{\frac{1 + \sin^2[\tilde{\mu}_x(s_1) - \tilde{\mu}_x(0)]}{2} \tilde{\beta}_x(s_1)\epsilon + \tilde{d}_x^2(s_1)\langle\delta_p^2\rangle}, \quad (6.3)$$

This can be compared to the main beam, with $\sigma_x(s_1) = \sqrt{\beta_x(s_1)\epsilon + D_x^2(s_1)\langle\delta_p^2\rangle}$, where D_x is the periodic on-momentum dispersion. Differences come both from the fact that the BFPP beam envelope is oscillating with $\tilde{\mu}_x$ and the chromatic variation of the optical functions.

The impact point of the BFPP losses can be directly deduced from Fig. 6.1 and a fast tracking of single particles is implemented from the IP to the beginning of the element where losses occur using Eq. (6.1). Inside this element an analytical algorithm is used to find the impact coordinates and momenta.

At IP2 in the LHC, the BFPP beam is lost near the end of a superconducting dipole magnet in the dispersion suppressor. Tracking gives normally distributed

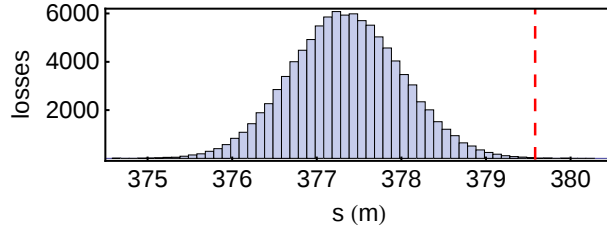


Figure 6.2: The longitudinal distribution of the impact positions of lost $^{208}\text{Pb}^{81+}$ ions from BFPP after IP2 in the LHC, as simulated by tracking 10^5 particles. The dashed vertical line indicates the end of a superconducting dipole magnet.

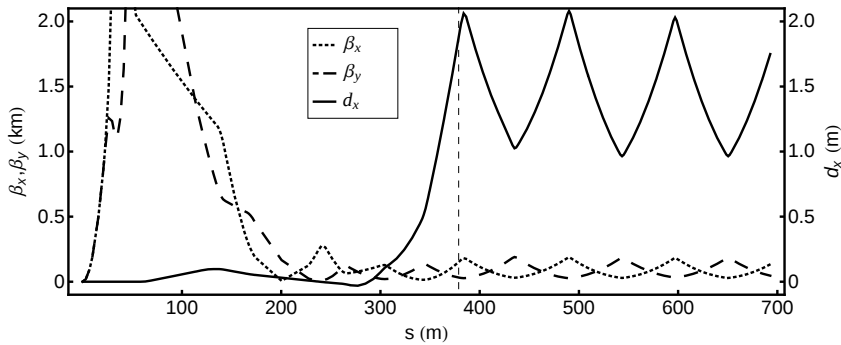


Figure 6.3: The horizontal and vertical β -functions downstream of IP2 shown together with the locally generated dispersion d_x . The dashed vertical line indicates the central loss position of the BFPP particles, close to the first maximum of the dispersion.

losses along s , shown in Fig. 6.2, with a mean of $s = 377.35$ m from IP2 and a standard deviation of 65 cm. In the case of IP1 or IP5 the loss positions are around 418 m downstream of each IP, also in superconducting dipole magnets, with projected rms spot sizes of 58 cm and 74 cm respectively. The situation around the three IPs is therefore comparable, and I focus on IP2 hereafter.

Fig. 6.3 shows β_x , β_y and d_x downstream of IP2. The dashed vertical line, close to the first maximum of d_x , indicates the impact point of the BFPP ions.

In a real machine, the impact points of BFPP ions vary as a function of imperfections such as magnet misalignments, field errors, and the imperfect aperture. Using a geometric aperture interpolated from measurements [81, 82] causes small distortions of the longitudinal loss distribution, since the aperture imperfections introduce small displacements of the impact points of single particles. Furthermore, I have simulated imperfect corrections resulting in a residual closed orbit caused by measured magnet misalignments [81, 82]. The average

longitudinal position of the BFPP impact point near IP2 varied by up to 2 m in these optics. A negative horizontal closed orbit, x_c , in the BFPP impact zone causes BFPP ions to be lost further downstream and losses may appear in the corrector magnet and beam position monitor (BPM) attached to the next main quadrupole. Such losses could make the BPM unusable. Unrealistic orbits $x_c \lesssim -2$ mm at the impact point cause some BFPP ions to miss the aperture completely at the first maximum of the dispersion function and continue instead to the second (see Fig. 6.1), where they hit another main dipole magnet.

6.2 Shower simulation

The coordinates of the BFPP particles impacting on the vacuum chamber are used as starting conditions for a FLUKA simulation of the hadronic and electromagnetic showers induced in the dipole magnet. A 3D model of a main dipole has been implemented [83] as shown in Fig. 6.4.

The FLUKA model of the magnet contains some simplifications. The matrix of superconducting NbTi filaments and copper inside the coil was modeled as a homogeneous body with weight fractions of the materials corresponding to the real coil, and the curvature of the magnet was neglected (although it was included in the tracking up to the impact on the beam screen). Furthermore, the magnetic field was included inside the yoke but omitted outside, where it cannot affect the results of the magnet quench evaluation. These approximations introduce negligible errors when compared to the overall error in the FLUKA simulation, which could be as large as a factor 2–3.

Several binnings were used to score the energy deposition and some 10^4 particles were sufficient to keep the statistical error below 2%. Fig. 6.5 shows the power density in the inner layer of the superconducting coil and Fig. 6.6 presents the energy deposition along the length of the cable at the hottest azimuth in the radial bin in the coil closest to the impact for the different binnings. In both figures, energy deposition is converted to power density P at the design luminosity of Table 3.1 using

$$P(r, \phi, z) = \mathcal{L} \sigma_{\text{BFPP}} W(r, \phi, z), \quad (6.4)$$

where W is the average, over many possible showers, of the energy deposition per unit volume in the superconductor or other material per lost $^{208}\text{Pb}^{81+}$ ion, as simulated by FLUKA.

6.3 Results

The heat distribution from FLUKA was used to estimate the resulting temperature profile through a thermal network simulation. The FLUKA output was

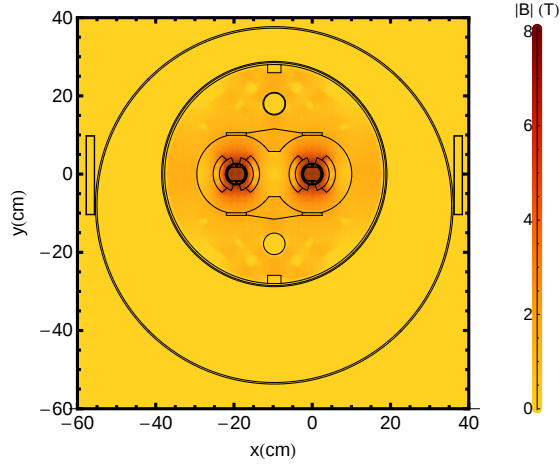


Figure 6.4: The transverse cross section of the FLUKA model of the LHC main dipole magnet with the magnetic field superimposed. A drawing of the real magnet is shown in Fig. 3.5. The rectangular boxes on the outside of the magnet in the FLUKA model represent beam loss monitors as discussed in Chap. 8.

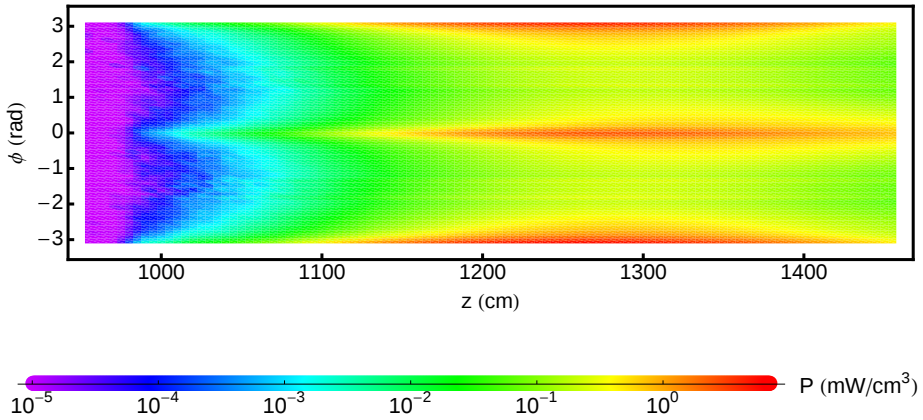


Figure 6.5: The heating power from beam losses caused by BFPP in the inner layer of the coil of an LHC main dipole as simulated with FLUKA. The power density was averaged over the width of a cable and is shown as a function of azimuthal angle ϕ and longitudinal coordinate z , with $z = 0$ in the beginning of the magnet. The beam loss is centred around $z = 1206$ cm and $\phi \approx -3.11$ rad.

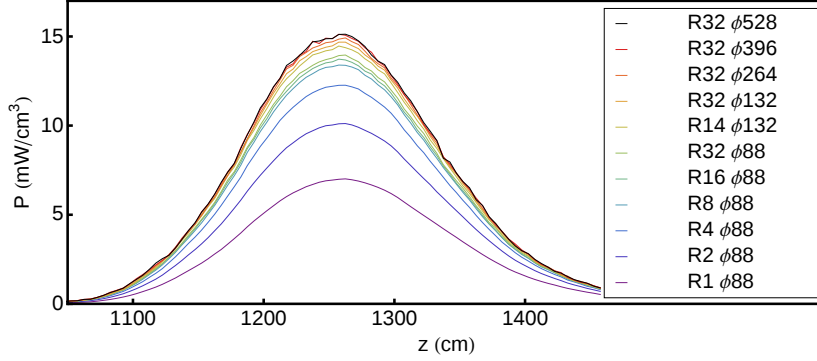


Figure 6.6: The linear power density along z caused by BFPP in the inner layer of the coil of the dipole magnet for varying radial and azimuthal binnings, where $Ri \phi j$ stands for i radial bins and j azimuthal bins. In all cases, a longitudinal cell size of $\Delta z = 5$ cm was used. The hottest bin was selected for each mesh.

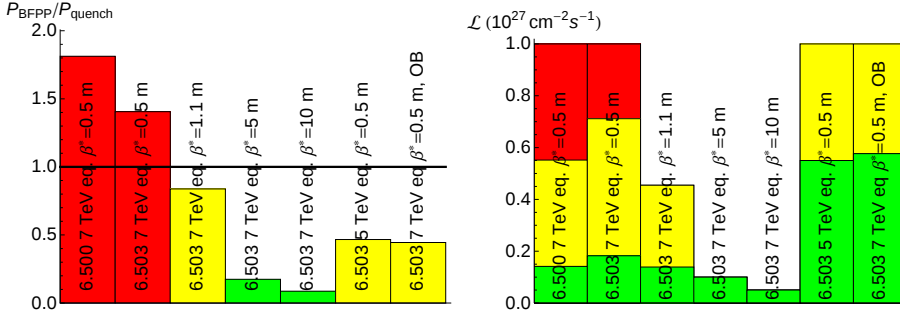


Figure 6.7: The expected heating power from losses caused by BFPP at IP2 normalized by the heating power that causes a quench (left) and expected quench behaviour at different luminosities (right) for various energies (labelled with the proton-equivalent energy), versions and configurations of the LHC optics. The colours are a semi-quantitative indication of how dangerous the losses are expected to be: Red bars mean that the simulated heat load is above the quench limit (note that operation may still be possible due to simulation errors), yellow that the heat load is below the quench limit but quenches cannot be excluded due to simulation uncertainties, while green bars can be considered as safe. The height of the bars indicate design luminosity. The assumed value in the 5 TeV configuration might be too optimistic for reasons of aperture, in particular for the final focusing triplets.

interpolated to estimate the heat load in every strand in the coil at the azimuth with the highest energy deposition. With this input, the network simulation was performed by D. Bocian. Details are given in Paper I. The result shows that under nominal conditions, the heating caused by BFPP is expected to be 40% above the quench level.

As the commissioning and operation of the LHC progresses, Pb-Pb collisions will occur in a variety of configurations [4, 84] with varying beam energy, intensity, and other parameters such as β^* . First ion collisions will likely take place at an energy of 1.97 TeV/nucleon (the same magnetic rigidity as a 5 TeV proton beam) rather than the nominal energy of Table 3.1 where magnetic fields and excitation currents are lower, meaning that more heat can be absorbed before a quench takes place. On top of that, both the luminosity and the energy deposited per lost BFPP ion will be lower. The risk of BFPP-induced quenches decreases if collisions were to occur at an even lower energy and is negligible for the early ion scheme, discussed in Sec. 3.1.

The simulation chain was repeated for several relevant cases and the resulting quench performance is shown in Fig. 6.7. It was not necessary to repeat the network simulation for all cases because of the similarity of the heat deposition profiles. The combined simulation error, estimated to a factor 3.9 in worst case, is indicated in the figure. The right part of Fig. 6.7 shows expected luminosity limitations, where it is assumed that the spatial heat load distribution in a certain distribution stays constant when the luminosity varies. This is strictly true only when the luminosity is changed through a decrease in bunch population or number of bunches.

6.4 Losses from EMD in the LHC

Ions affected by EMD1 stay within the momentum acceptance of the LHC ring and are cleaned by the collimation system (see Fig. 6.1). However, EMD2 does create localized losses, similar to BFPP. For EMD2 ions, δ_p is the sum of two random variables: The natural momentum deviation in the bunch with standard deviation given in Table 3.1 and the recoil caused by EMD, which was simulated with FLUKA. The resulting distribution is approximately Gaussian with mean -1.25×10^{-4} and standard deviation 2.9×10^{-4} .

I used the formalism showed in Sec. 6.1 to track EMD2 particles from IP2. Detailed loss maps are shown in Paper I. Around half of the losses pose no risk of quenches, while the other half is lost on an aperture limitation in a drift 70 cm in front of an orbit corrector magnet, where the heat load is highly concentrated.

The quench limit of the corrector depends on its current and therefore on the closed orbit and the global orbit correction scheme. No network model to eval-

uate the quench level of the corrector exists, so FLUKA and network model simulations were not carried out. Assuming its quench limit to be similar to the dipole's, there is a risk of quenching because of the small spot size.

However, it is possible to exclude this magnet from the global orbit correction at the price of possible residual orbit distortions. Therefore losses from EMD2 are less serious than from BFPP, since a dipole is necessary for machine operation. During the first ion runs at 1.97 TeV/nucleon, the corrector is much less likely to quench than at top energy, for the reasons explained in Sec. 6.3.

6.5 Alleviation of losses

In the LHC, quenches caused by lost BFPP and EMD2 ions are likely to occur and methods to avoid them have to be found. Several methods using specialized hardware are possible, the most promising one being the installation of extra collimators around each IP where the dispersion starts to rise in the cold part of the machine [4, 85]. This could be a very efficient solution but requires extra hardware as well as displacing some magnets to make room in the tunnel. For the first heavy-ion runs, methods to mitigate the effects of BFPP and EMD2 using existing hardware will be needed. The only free parameter is then the optics, since lowering the luminosity should be left as a last resort.

The optics can be changed in such a way that the dangerous losses are more spread out or move to another location. This might be achieved by manipulating the quadrupoles between the IP and the impact point to increase $\tilde{\beta}_x$ or $\tilde{d}_x$ to make the beam size larger. However, requirements on the tune [86], matching conditions on the periodic β_x and D_x at the ends of the dispersion suppressors, and constraints on magnet strengths limit the scope of this approach. A gain in spot size of at best 20% was achieved using this method.

Another alleviation method could be to move the impacts to more favourable positions. A close-up of the first 700 m after IP2 in Fig. 6.1 is shown in Fig. 6.8. The dispersive trajectories oscillate with d_x , and the BFPP particles are lost very close to its first maximum, called s_1 . The EMD2 beam continues further downstream. The BFPP envelope in Fig. 6.8 is wider at the second maximum s_2 of d_x , thanks to the larger value of $\tilde{\beta}_x$, so a loss there would be more diluted. Thus a localized closed orbit bump around s_1 is proposed to displace x_B towards the centre of the beam pipe so that the BFPP particles can escape to s_2 .

The bump moves the envelope of the EMD2 ions towards the outside of the beam pipe at s_1 provoking losses there. On balance this is beneficial because the aperture is constant in the neighbourhood of s_1 , so the losses are spread out much more than at the downstream loss point. This new loss position for the EMD2 ions is the same as for BFPP ions with a flat orbit but since the EMD2 ion flux is almost a factor 10 lower than for BFPP, the heating at this position

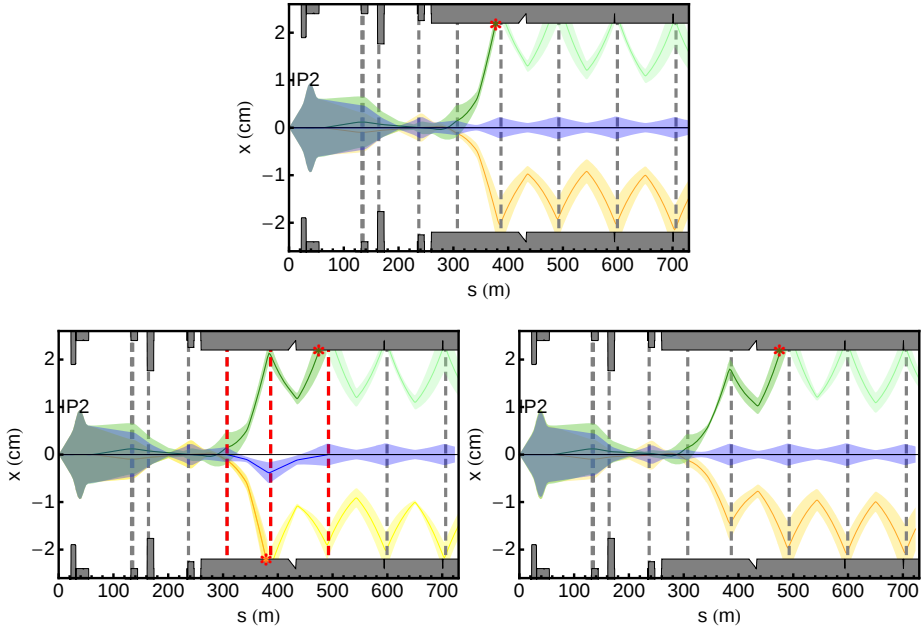


Figure 6.8: Horizontal physical aperture and 6σ envelopes after IP2: with the usual flat orbit (up), with an orbit bump (down left), and with decreased dispersion (down right). The beams are the main circulating $^{208}\text{Pb}^{82+}$ beam (blue), the $^{208}\text{Pb}^{81+}$ BFPP beam (green), and the $^{206}\text{Pb}^{82+}$ EMD2 (yellow). The vertical dashed lines show the locations of horizontal corrector magnets and those indicated in red are active (in this case, correctors called “MCBC” and “MCB”).

is kept low enough to avoid quenching the dipole.

The off-momentum orbit can be displaced by orbit correctors attached to the main quadrupoles in the LHC. The orbit bump amplitude required was calculated using Eq. (2.16), demanding that 95% of the BFPP beam, with the beam size given by Eq. (6.3), stays inside the aperture at s_1 . The resulting beam envelope with the bump active is shown in Fig. 6.8.

The orbit of the circulating beam is displaced by up to 3.8 mm in this configuration, which still provides sufficient aperture margin. The three correctors making the bump would operate at between 9% and 26% of their maximum strength, leaving a comfortable margin for their function in the global orbit correction.

The simulation chain of tracking, FLUKA, and network model was repeated with the orbit bump included. The maximum heat load at the new impact position, in another superconducting dipole magnet, is about a factor 3.5 less than without the bump. The expected heat distribution at s_2 with the orbit bump activated is predicted to be a factor 2.25 below the quench limit, still not

completely safe.

Because of the machine imperfections the bump amplitude will have to be fine-tuned around the theoretical value to compensate the local closed-orbit and misalignments of the beam pipe. The BLMs placed around each loss location (as discussed in Chap. 8) will be an essential tool to monitor how the BFPP losses move from the first to the second maximum of the dispersion. The bump has to be introduced at a lower luminosity, since the magnets could otherwise quench while it is being tuned.

If moving the losses to another location with a larger spot size was insufficient, one could spread out the losses with several orbit bumps, which allow fractions of the BFPP beam past each maximum of d_x . The losses can be spread over n dispersion maxima by $n - 1$ orbit bumps using $n + 1$ correctors in such a way that, ideally, a fraction $1/n$ is lost at each impact point, decreasing the maximum heating power in a single element by $1/n$. In Paper I, I give formulas for calculating the required bump amplitudes by integrations in the phase space at the IP. An example for $n = 3$ is shown in Paper VII, neglecting the dispersion in the bunch and using the older version 6.500 of the LHC optics, but still useful to illustrate the method.

Since BLMs have to be used when the bumps are tuned, the precision of the achieved loss distribution is however limited. Furthermore, at IP1 and IP5, the required disturbance of the nominal orbit is too large to be tolerated.

Another method to move losses to s_2 is to tune the quadrupoles after IP2 in order to decrease the dispersion at s_1 . I used MAD-X to rematch IP2 with all constraints mentioned in Ref. [86]. The change in phase over IR2 can be compensated in IR4, keeping the overall tune within limits. One solution is shown in Fig. 6.8. The expected heating power is higher than with the orbit bump, although below the quench level. Quenches cannot be excluded with this method either.

BEAM LOSS MEASUREMENTS IN RHIC

In this chapter, based on Paper II, I describe beam loss measurements from RHIC. The measurements were carried out to detect losses from BFPP and first I give a summary of this. In addition, I discuss recent findings, which show that other beam loss mechanisms could have been responsible for a part of the measured signal.

During normal $^{197}\text{Au}^{79+}$ operation in RHIC, δ_{BFPP} is so small (see Table 5.1.1) that ions affected by BFPP remain inside the momentum acceptance $\delta_{\text{max}} \approx 0.018$ of the ring. Instead an opportunity arose to measure beam losses from BFPP during $^{63}\text{Cu}^{29+}$ operation, where δ_{BFPP} was large enough to create localized losses that could be detected directly. Beam parameters are given in Table 3.2. The cross section of BFPP between the colliding 100 GeV/nucleon $^{63}\text{Cu}^{29+}$ beams is estimated in Sec. 5.1.1 at 0.2 b. The much lower energy and cross section than in the LHC show that there is no risk of quenches.

An array of PIN diodes (PDs) was placed downstream of the PHENIX IP in the Yellow ring in order to detect the losses, and the measurements were compared with a two-step simulation of BFPP losses consisting of tracking and FLUKA. I have recently realized that BFPP is not the only collisional loss process that cause localized losses in the vicinity of the PDs. Ions that have undergone EMD2 are lost very close to the BFPP impact location but on the other side of the beam pipe. Furthermore, hadronic interactions create other isotopes with a similar δ although with lower cross sections. Therefore, the measured signal is now believed to be a superposition of these loss types.

I describe the simulations done in Paper II in Section 7.1 and the measurements in Sec. 7.2. The new findings regarding additional loss sources are discussed in Sec. 7.3.

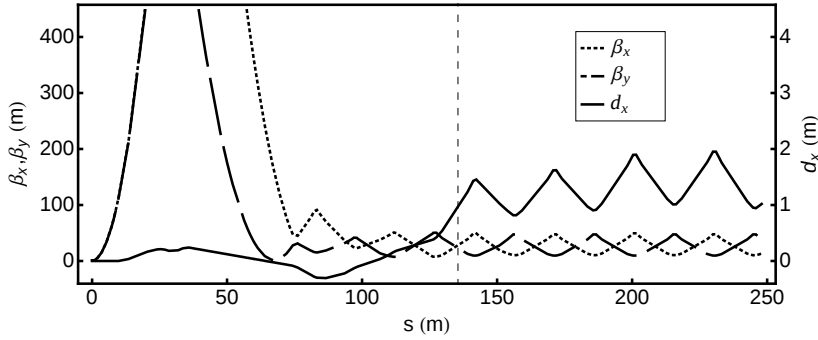


Figure 7.1: The horizontal and vertical β -functions downstream of the PHENIX IP (located at $s = 0$) shown together with the locally generated dispersion d_x . The dashed vertical line indicates the central loss position of the BFPP particles, close to the first maximum of the dispersion.

7.1 Simulations

Tracking of $^{63}\text{Cu}^{28+}$ ions affected by BFPP from the PHENIX IP was performed using MAD-X. The optical functions downstream of PHENIX are shown in Fig. 7.1 and Fig. 7.2 shows the simulated envelopes of the nominal $^{63}\text{Cu}^{29+}$ beam together with the $^{63}\text{Cu}^{28+}$ beam created by BFPP. The tracking shows that the BFPP beam hits the aperture within a 9.7 m long dipole magnet starting at $s = 129.6$ m from the IP, followed by a 2.12 m drift space and a quadrupole magnet. Including a final step of analytic orbit calculation inside the dipole, an impact at $s_i \approx 135.5$ m was predicted with an angle of incidence of $\langle x'(s_i) \rangle \approx 2.7$ mrad. This prediction of the impact point in the ideal lattice was used to determine the placement of the extra BLMs.

An attempt to reconstruct the horizontal orbit from BPM measurements was unsuccessful since only a limited amount of data was available for a short part of the ring. Therefore, the possible spread of the impact point was estimated by calculating the propagated uncertainty using Eq. (2.16). A possible error on the horizontal quadrupole misalignments of 1 mm was assumed, corresponding to the 95 % confidence interval and the fact that the magnets could have moved between the measurements of the misalignments and when the beam loss measurements were done. The absolute error on the BPM data was taken to be 0.5 mm, reflecting the limited data and possible non-reproducibility. Combining these errors, and taking into account that the BFPP impact point is displaced due to the misalignment of the vacuum envelope, gives an rms error of 2 m. Thus the expected impact point is 135.5 ± 2 m.

FLUKA version 2006.3 was used to simulate the shower of the lost $^{63}\text{Cu}^{28+}$ ions. A 3D model (see Fig. 7.3) of the impact region geometry was implemented,

including the PDs and the dipole magnetic field. The impact coordinates and momenta given by the tracking were used as starting conditions. Both placements of the PDs (described in Sec. 7.2) were simulated and the results are shown together with the measurements in Sec. 7.2.

Typically, the length of the simulated shower was 2–2.5 m and the maximum PD signal was expected about 2.5 m downstream of the impact point. When the shower is contained within the dipole, moving the impact point along s only translates the shower. If the impact point is moved closer towards the end of the magnet or the angle of incidence decreased, more of the shower particles emerge into the void before the quadrupole and the profile changes qualitatively. A second peak in energy deposition appears at the entrance of the quadrupole and eventually exceeds the first one. This qualitative behaviour of the shower can be expected also with possible additional loss mechanisms discussed in Sec. 7.3.

Since the PDs measure losses by counting the number of minimum-ionizing particles (MIPs) that pass their active area, FLUKA was set up to count the number of MIPs entering the diodes in the simulation. A detection efficiency of 30% was assumed and 0.3 MeV/c was assumed as the lowest momentum for electrons causing a count in a PD [87]. Since the PDs are much more sensitive to particles entering through the side orthogonal to the cryostat, only these particles were counted.

The time resolution of the PDs can go up to 40 MHz. This is not enough to separate different shower particles from the same primary $^{63}\text{Cu}^{28+}$ ion or even to separate different ions within the same particle bunch. Therefore, for each bunch there cannot be more than one count on each diode, so the maximum count rate is the bunch frequency of 2.9 MHz. But the estimated production rate of BFPP ions is 4 kHz (see Tab. 5.1.1), meaning that there will be, on average, 1.4×10^{-3} BFPP ions per bunch. Thus it is very unlikely that two BFPP ions will come from the same bunch, so every one will be counted. Furthermore, the FLUKA simulations show that there are around 0.01 MIPs reaching a PD per lost ion. Hence no two secondaries arrive simultaneously at a PD and every MIP entering a PD causes a count. This justifies that all MIPs are counted in the simulation. Even if other possible loss mechanisms are taken into account, the total rate is still so much lower than the bunch frequency that all MIPs cause a count.

Both configurations of PDs, discussed in Sec. 7.2 were simulated.

7.2 Experimental results

Since the BFPP beam was not visible to the existing detectors, an array of new beam loss monitors in the form of PDs of the type Hamamatsu S3590 were

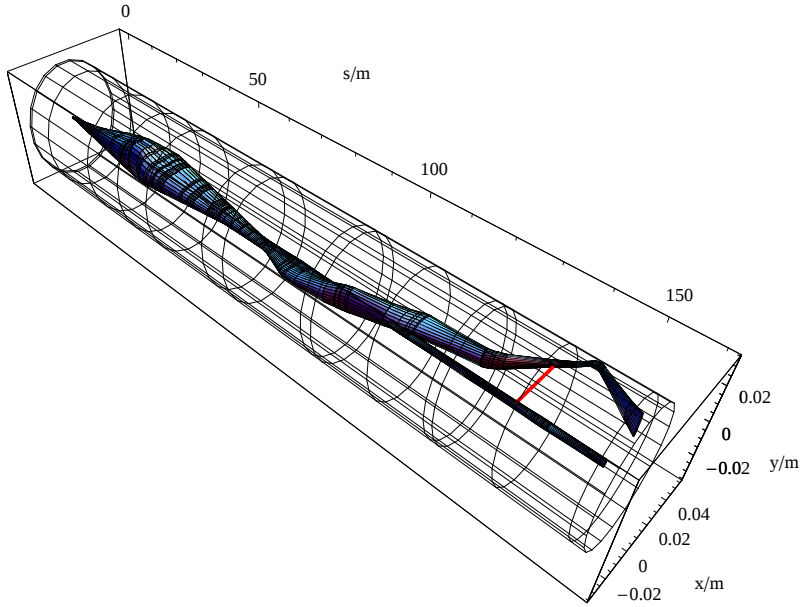


Figure 7.2: The 1σ envelopes of the BFPP beam and the nominal beam emerging from the PHENIX IP. The wire frame shows the size of the vacuum pipe in the arc and the impact point is indicated by the perpendicular line.

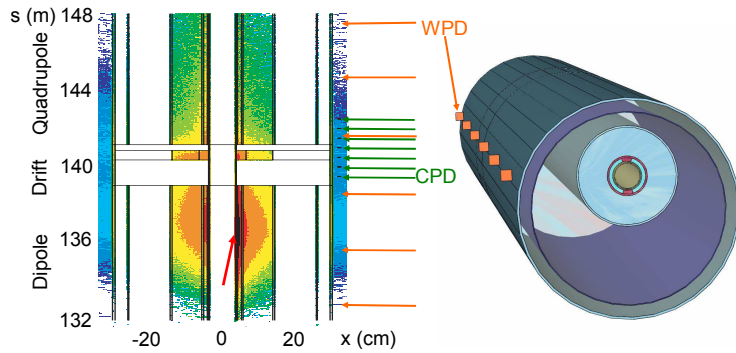


Figure 7.3: Left: The energy deposition from a typical shower from BFPP losses shown in a thin slice in the $x-s$ -plane through the geometry. The red arrow indicates the impact point and the green and orange arrows show the positions of the PDs in the CPD and WPD. Right: The 3D model of the geometry as implemented in FLUKA around the impact point. The orange squares show the PDs in the WPD.



Figure 7.4: A PIN diode mounted on the outside of the cryostat, downstream of the PHENIX IP in the yellow ring at RHIC. Courtesy of J.M. Jowett.

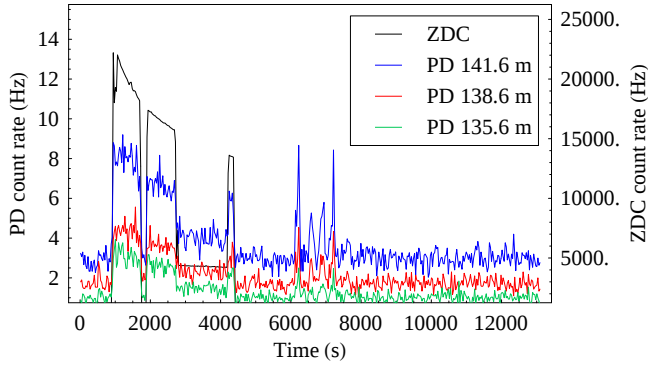


Figure 7.5: Count rates measured on the Zero Degree Calorimeter (ZDC) luminosity monitors (black, right scale) and the three PDs with the highest signal (colours, left scale) during a store with the WPD. The data was binned in 30 second intervals. A clear correlation between the luminosity and the PD count rates can be seen.

mounted on the outside of the magnet cryostat downstream of the IP of the PHENIX experiment in the yellow ring, around the predicted impact of the BFPP losses. An example of the installation is shown in Fig. 7.4. The PDs have a time resolution of 25 ns and the counts were read out every second. The PDs have an active area of 1 cm², sensitive to the passage of MIPs. They were initially positioned in a wide configuration (WPD), 3 m apart, and later moved closer together (CPD), 0.5 m apart, around an observed count-rate maximum at 141.6 m.

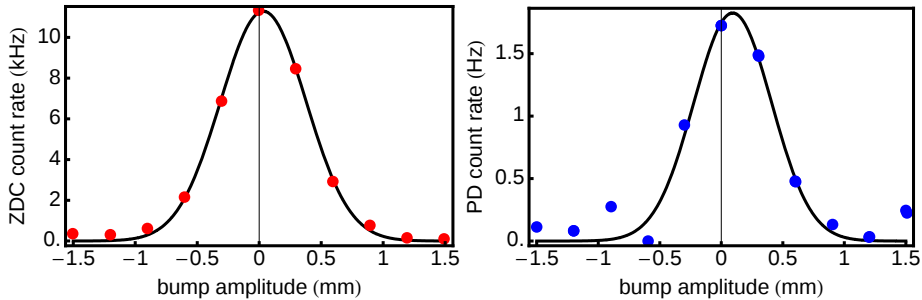


Figure 7.6: The ZDC count rate (proportional to luminosity, left) and background-subtracted PD count rate (right) vs. relative orbit displacement between beams in a van der Meer scan. A Gaussian fit of the form $A \exp(-\frac{(x-x_0)^2}{\sigma_x^2})$ is shown together with the data. The two fits had $\sigma_x = 0.49$ mm and 0.44 mm and $\chi^2/DOF = 0.23$ and 0.20 , assuming a measurement error of 500 Hz on the ZDC signal and 0.3 Hz on the PD.

Data were collected from the PDs during 14 stores in RHIC with $^{63}\text{Cu}^{29+}$ ions. A set of recorded signals is shown in Fig. 7.5, together with the ZDC count rate (which is directly proportional to the luminosity). The PD signals show a good temporal correlation with luminosity and are very localized along s , close to the predicted impact position. The correlation coefficient between the highest PD signal and the ZDC varied between 0.7 and 0.98 , depending on the time binning. Therefore it is very unlikely that some other source than the collisions could cause the signals.

The correlation is even clearer in van der Meer scans, in which the beam orbits are scanned transversely across each other and the luminosity variation is recorded as in Ref. [88]. Fig. 7.6 shows the ZDC rate and the signal of one of the PDs as a function of the orbit bump amplitude.

Since the data were taken parasitically during normal colliding-beam operation, the PD signals were often polluted by other losses, e.g. from collimation. Therefore the cleanest data sets were picked out and the averaged count rate with background subtracted, normalized to luminosity, was calculated for each PD. The background noise level was calculated for each PD as the average signal without luminosity.

Fig. 7.7 shows the measured and simulated signals from BFPP losses along s . The magnitudes of the count rates (1 – 20 Hz) agree well with simulations of BFPP losses. The maximum count rate is however found at different PDs in the simulation and measurement, and the measured spot is wider than the simulated one. As discussed in Sec. 7.3, the agreement in spotsize and location of the maximum is likely to improve when other possible loss processes are taken into account, while the discrepancy in magnitude can be expected to increase.

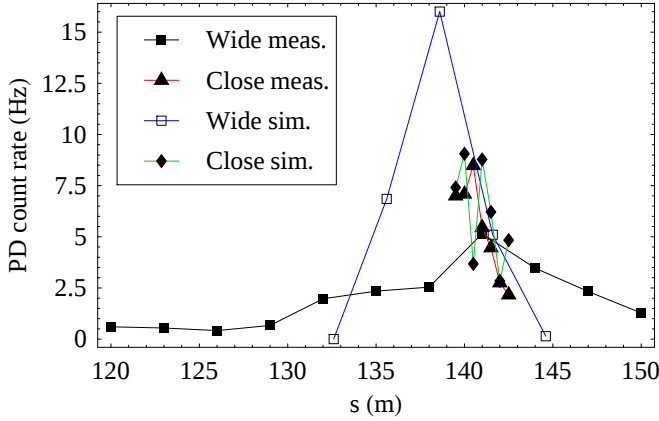


Figure 7.7: The PD signals from both configurations together with simulation results, averaged over the fills and normalized to a typical average luminosity of $9.1 \times 10^{27} \text{cm}^{-2} \text{s}^{-1}$. Because of the large uncertainty in the FLUKA simulation, the simulation gives only the order of magnitude to expect in the measurement.

Several sources contribute to the overall error. The FLUKA simulation has an approximate uncertainty of a factor 3 when considering secondary shower particles far from the core. Moreover, the PD signals themselves have error bars—apart from the statistical error a small relative change in the counting efficiency between the PDs could change the result.

7.3 Other loss processes

It has recently been discovered that additional loss mechanisms, correlated with the collisions, could have been responsible for a part of the measured signal. The δ caused by the most frequent electromagnetic processes at the IP is shown in Tab. 5.1.1. Since Z is close to $A/2$ for Cu, the $|\delta|$ of a one-electron $^{63}\text{Cu}^{28+}$ ion is similar to that of a $^{61}\text{Cu}^{29+}$ ion. None of the two species can pass the first peak of d_x after the IP, so provided that they reach it, they are lost close to each other but on opposite sides of the vacuum pipe. The cross section for EMD2 is estimated with FLUKA to 0.22 b (see Tab. 5.1.1). Losses from EMD1 on the other hand stay within the aperture at the first maximum of the dispersion.

New tracking has been performed with $^{63}\text{Cu}^{28+}$ from BFPP and $^{61}\text{Cu}^{29+}$ from EMD2. As in the LHC, the kicks in δ_p from the EMD process are taken into account and simulated with FLUKA. The result is shown in Fig. 7.8. The additional energy spread causes an enlargement of the impact spot along s . Even though the other losses hit the opposite side of the vacuum pipe, the resulting showers are so large that there is a flux of secondary particles on both sides of the magnet. This is clear from Fig. 7.3.

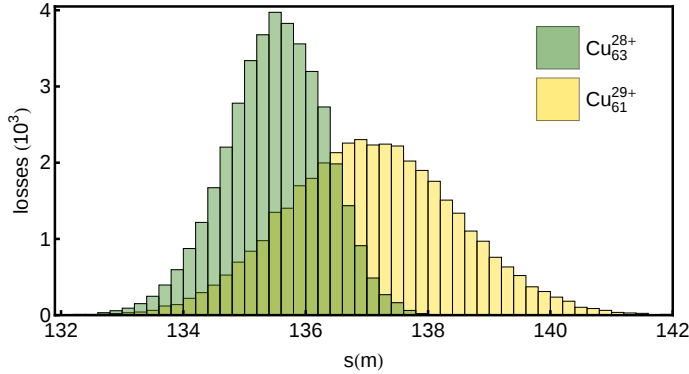


Figure 7.8: Loss maps created by optical tracking in a perfect lattice of $^{63}\text{Cu}^{28+}$, created through BFPP, and $^{61}\text{Cu}^{29+}$, created through EMD2. A cross section of 0.22 b, given by a FLUKA simulation, was assumed for the EMD2 process. In the initial simulation study in Paper II, only the $^{63}\text{Cu}^{28+}$ losses were taken into account.

The distance between the loss spots may facilitate the disentangling of the contributions from the different isotopes. In the ideal lattice there is a 1.6 m difference between the BFPP and EMD2 impact points. Furthermore, since BFPP has a positive δ , a distortion of the closed orbit towards the outside of the ring would move the BFPP losses upstream, while the EMD2 losses with negative δ would be displaced downstream. If this were the case during the measurements, it could explain that the measured PD signals in the wide configuration show a large and diluted loss spot along z , which is wider than what could be expected from BFPP or EMD2 alone.

Furthermore, the relative importance of the hadronic cross section compared with the electromagnetic is much higher for $^{63}\text{Cu}^{29+}$ beams than for $^{208}\text{Pb}^{82+}$ or $^{197}\text{Au}^{79+}$ and a variety of fragments are created through both types of interactions at the IP. Even though BFPP, EMD1, and EMD2 dominate, other isotopes with a similar δ need also to be considered in a complete analysis. For these losses, just as for EMD2, an additional spreading of the loss spots compared to BFPP occurs due to the momentum kick in the decay. In total, less than half of the collisional losses in the vicinity of the PDs is estimated to originate from BFPP. It should be noted that the FLUKA calculation of hadronic cross sections for the creation of single isotopes involve large uncertainties.

Taking the other processes into account in the FLUKA simulation is likely to improve the agreement of the shape of the loss pattern by increasing the spread of the impact along s . Furthermore, the EMD2 losses can be expected to move the maximum signal downstream, in agreement with measurements. It is interesting to note that at the same time, the discrepancy in magnitude of the PD signals is likely to increase.

To study the additional loss sources quantitatively, further tracking and FLUKA simulations are needed, as well as precise estimates of the cross sections for creation of the relevant isotopes. This is planned as future work.

LHC BLMs AND BEAM DUMP

In this chapter I discuss further machine protection issues in the LHC. Both the BLMs and beam dump are vital parts of the machine protection system, primarily designed for proton operation. However, they will be used also during the ion runs, and it is therefore important to verify that they will function properly with ions.

This chapter contains parts of Papers I, V and VI.

8.1 Beam loss monitors

The BLM system in the LHC is introduced in Sec 3.1.3 and more information can be found in the chapter 13 in the LHC design report [4] and in Refs. [39, 40].

The amount of energy deposition in the gas volume of a BLM outside the cryostat, far from the initial lost particles, corresponds to a certain heating of the superconductors. If a BLM signal is too high, the beam is automatically dumped. For protons, the ratio between BLM signal and heating, as well as suitable BLM locations, has been determined through simulations [89, 90]. However, this ratio could well be different depending on the type of particle lost and the showers it gives rise to. Therefore, there are two important problems related to the monitoring of ion beam losses: The BLM thresholds signals for $^{208}\text{Pb}^{82+}$ ions should be evaluated (this is done in Sec. 8.1.1), and it should be verified that the placement of BLMs provides adequate coverage of the $^{208}\text{Pb}^{82+}$ loss patterns (this is discussed in Sec 8.1.2).

8.1.1 Threshold signals for $^{208}\text{Pb}^{82+}$ ions

To investigate the first problem, I simulated the development of the showers generated by particle losses, both from $^{208}\text{Pb}^{82+}$ ions and protons, in an LHC dipole magnet with FLUKA; the geometry was as described in Sec. 6.2 and Fig. 6.4. The BLMs are schematically modeled as thin rectangular iron boxes filled with nitrogen, placed outside the MB cryostat. This simplification is consistent with simulations done for protons [39].

A generic beam loss of protons or $^{208}\text{Pb}^{82+}$ ions was represented by a pencil beam (all particles have the same momentum and hit in the same position) at nominal LHC energy (see Table 3.1) impinging on the inside of the vacuum chamber, 1 cm from the entrance of the magnet in the horizontal plane, with an incident angle of 0.5 mrad.

During the simulation, the energy deposition was scored in the beam screen, in the superconducting coil (using the mesh described in Sec. 6.2) and in the BLMs. The BLM signal was assumed to be proportional to the energy deposition in its gas volume. The resulting energy deposition profiles along the hottest superconducting cable in the MB coil and in the closest BLM are shown in Fig. 8.1. In order to facilitate the comparison, the curves for ions have been scaled with charge.

As can be seen in Fig. 8.1, the ratio between the heat deposited in the coils and the energy deposition in the BLMs is similar for $^{208}\text{Pb}^{82+}$ ions and protons at the same energy per nucleon, while 7 TeV protons have a slightly lower ratio between BLM signal and heating of the coil than 2.76 TeV/nucleon $^{208}\text{Pb}^{82+}$ ions. Because of this similarity it is concluded that the same thresholds of the BLM signals, at which a beam dump is triggered, can generally be used for $^{208}\text{Pb}^{82+}$ ions and protons in the LHC.

This similarity, which might seem counter-intuitive at first, comes from the fact that the particles causing ionization of the gas in the BLMs are not the $^{208}\text{Pb}^{82+}$ ions and protons lost directly from the beam, but instead low-energy secondary particles, mainly electrons, created in the hadronic shower. This shower is very similar for heavy ions and protons [91], even though the ions have a much shorter nuclear interaction length (0.8 cm for 2.76 TeV/nucleon $^{208}\text{Pb}^{82+}$ and 25 cm for 7 TeV protons on a Cu target according to FLUKA simulations). When an ion traverses a target, the nucleus splits up into smaller fragments through EMD and nuclear interactions in several steps. Once totally fragmented it gives rise to a similar shower profile as independent nucleons.

The secondary shower particles make new interactions. Some of them, mainly π^0 mesons, decay in further electromagnetic showers, driven by bremsstrahlung and pair production [92]. A larger and larger fraction of the total energy is therefore carried by the leptons and photons and the final energy deposition is predominantly electromagnetic. At the shower maximum, a huge number of low

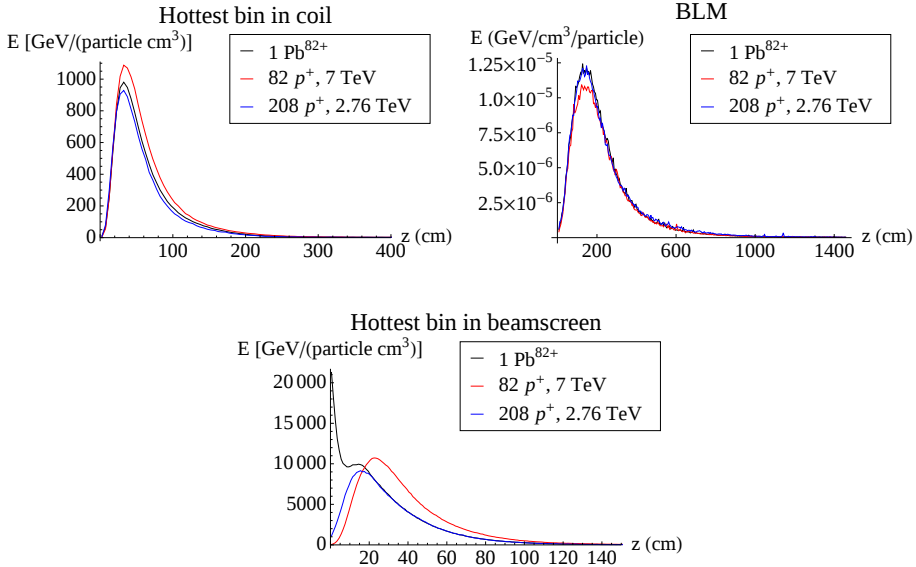


Figure 8.1: The energy deposition in the hottest wire in the coil (left), in the N_2 gas inside the ionization chamber (right) and in the beam screen (down) for Pb ions and protons. The three cases are scaled to equivalent total energy of incoming particles.

energy particles are simultaneously depositing energy whose total far exceeds the direct energy deposition from the first few interactions. This peak for ions is very similar to the one created by independent nucleons.

A significant difference in energy deposition between $^{208}\text{Pb}^{82+}$ ions and protons is visible only in the beginning of the shower, close to the central core. Here the difference in ionization energy loss, given approximately by the well-known Z_0^2 dependence in the Bethe-Bloch formula [59], is clearly visible and the ions cause a much higher energy deposition. Thanks to the small impact angle, this effect is only visible in the beam screen, as shown in Fig. 8.1.

8.1.2 BLM positions

BLMs for protons are mounted on all quadrupoles in the arcs and dispersion suppressors [39], where losses could be expected because of the maxima of the $\beta_{x,y}$ -functions. However, as discussed in Chap. 5, certain beam loss mechanisms exist that are unique for ions.

The optical studies described in Sec. 6.1 were used to determine suitable positions for BLMs to monitor losses from BFPP and EMD2. For BFPP, large

parts of the predicted loss regions were not covered by original scheme and extra monitors have therefore been proposed and installed. Because of the uncertainty of the impact position, discussed in Sec. 6.1, and the fact that the loss peaks are narrow and localized, a tight coverage with BLMs is needed. Based on the energy deposition profile in the BLM gas (see Fig. 8.1) a 1.5 m spacing between chambers has been assumed for both beams to ensure full detection and localization of losses.

The original tracking simulations discussed in Paper V that were used to determine the s -values of the extra BLMs were based on an older version of the LHC optics. In the latest version 6.503, some primary loss positions have changed by several metres. This lies however within the estimated possible movements of the losses so all locations are still covered.

No extra BLMs are needed for losses from EMD2, since the loss locations are already covered by the default scheme.

8.2 The LHC beamdump with $^{208}\text{Pb}^{82+}$ ions

Because of the different shower characteristics of heavy ions and protons, explained in Sec. 8.1.1, one might fear that the many beam intercepting devices in the beam extraction system could receive a higher peak energy deposition from ions than from protons. To examine if this risks to cause material damage, simulations of a $^{208}\text{Pb}^{82+}$ bunch hitting these devices were performed with FLUKA 2006.3. Both nominal operation and different failure scenarios were considered.

It turns out, however, that the heat load is actually lower during ion operation than with protons. The reasons are that even though each ion gives rise to approximately a 82^2 times higher peak energy deposition than a proton, the total number of ions in the beam is much smaller (see Table 3.1). Furthermore, since the bunch spacing is 4 times larger, when the ion bunches are diluted the overlap between different ion bunches is negligible, while there is a significant overlap for protons. These factors cause an overall reduction in the peak heat load during ion runs, so that the beam dump system should work just as safely with $^{208}\text{Pb}^{82+}$ ions as with protons.

BEAM LOSSES FROM ION COLLIMATION IN THE SPS

In this chapter I present measurements and simulations of ion beam losses from collimation. The measurements serve both as a test of the theoretical assumptions on the principles of ion collimation and as an experimental benchmark of the ICOSIM program (described in Sec. 4.4). The experiments were performed in the SPS, where a prototype of an LHC collimator was deliberately moved into the ion beam in order to provoke losses. The resulting signals from the BLMs downstream of the collimator were recorded and compared to simulations. To simulate the particle-matter interaction in the collimator, I used both the built-in Monte Carlo of ICOSIM, and FLUKA, which I have linked to ICOSIM. Finally I compare the results with proton loss patterns. This chapter is based on Paper III.

9.1 Experimental setup

A prototype of a secondary LHC collimator has been installed in the SPS [93]. It consists of a pair of 1 m long graphite jaws, one on each side of the aperture, which can be moved independently to intercept the beam in the horizontal plane. The optical functions in the vicinity of the installation are shown in Fig. 9.1 and the horizontal aperture in Fig. 9.2.

Moving the collimator into the beam creates losses, which are recorded by the 216 BLMs placed around the ring (see Sec. 3.3). Since the SPS uses normal-conducting magnets, there is no risk of quenches. Losses are read out and integrated over every machine cycle (18 s in the case of ions). Figs. 9.1 and 9.2 show the s -values of the four BLMs (called BL520, BL521, BL522 and BL523) immediately downstream of the collimator. BL520 and BL522 are mounted

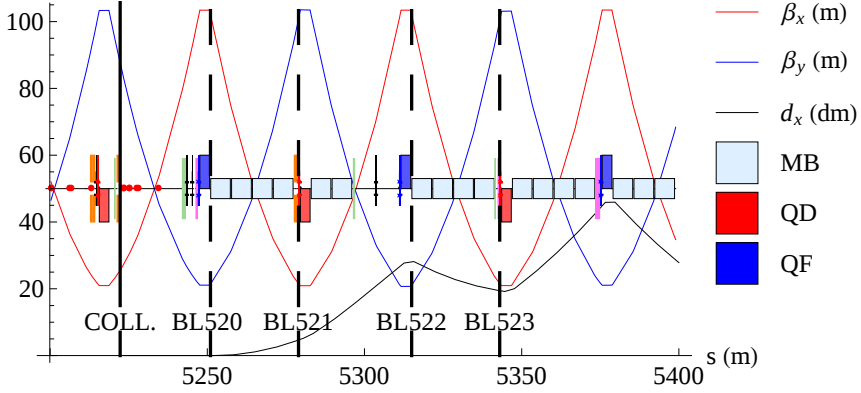


Figure 9.1: The β -functions of the SPS downstream of the collimator and the locally generated dispersion d_x from the collimator. The magnetic elements are also shown (MB=main bend, QF=focussing quadrupole, QD=defocussing quadrupole). The BLMs and the collimator are indicated by vertical lines.

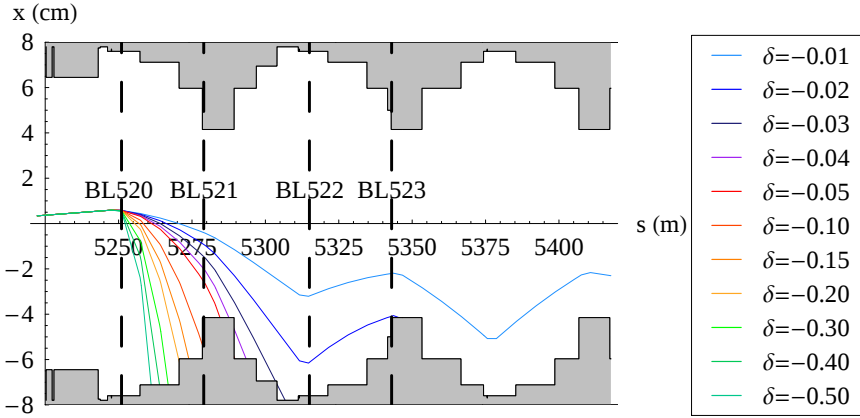


Figure 9.2: Dispersive horizontal orbits of fragmented ions produced in one of the collimator jaws, shown together with the horizontal aperture. The collimator is located at $s = 5222$ m at the left edge. The vertical dashed lines indicate the locations of the four BLMs closest downstream. A large fraction of the total losses occur at the aperture limitation at $s = 5277$ m.

in the vertical plane below the beamline, while BL521 and BL523 are in the horizontal plane on the inside of the ring.

Beam loss data were collected during $^{208}\text{Pb}^{82+}$ dedicated ion runs in late 2007 where the collimator was moved into a circulating 106.4 GeV/nucleon beam. Data were also collected with a 5.9 GeV/nucleon beam that was injected when

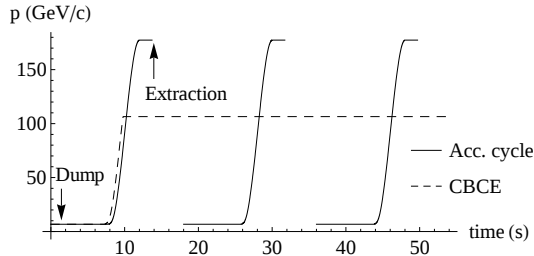


Figure 9.3: The $^{208}\text{Pb}^{82+}$ momentum per nucleon during three cycles of the SPS in the case of acceleration and a circulating beam at constant energy (CBCE). In the acceleration cycle, the dumping of the beam during the collimation measurements is indicated, as well as the extraction momentum.

the collimator was in a position to intercept a part of the beam already on the first turn. The momentum during the magnetic cycle of the SPS in both cases is shown in Fig. 9.3. In the case of the low energy beam injected on the collimator, the data were collected during the first second of the cycle. Before the magnets started to ramp, the beam was dumped. The jaws were either kept parallel to the beam or with a 2 mrad angle. The transverse normalized rms emittance was approximately $1\ \mu\text{m}$ and the injected intensity around 6×10^7 ions, corresponding to one bunch.

From the BLM signals, the detector background, consisting of noise and other beam losses that are not caused by the collimator movement, had to be subtracted. As background data I used the loss map from the machine cycle before the collimator movement as was done in Ref. [93].

I present also a comparison with 270 GeV proton loss data from measurements done by others [60]. The normalized emittances were $\epsilon_x \approx 2.7\ \mu\text{m}$, $\epsilon_y \approx 4\ \mu\text{m}$ and the intensity $N \approx 10^{12}$.

The circulating beam current was measured by a Beam Current Transformer (BCT). These measurements were used later to normalize the BLM signals by the number of lost particles. For the 5.9 GeV/nucleon beam, the normalization of the losses by the BCT could not be performed, since the injected intensity varied between different cycles and significant losses occurred already during the first turn, upon impact on the collimator, before measurements of the beam current were available.

9.2 Simulations

The combined dynamics of the circulating beam and the particle-matter interaction in the collimator was simulated with ICOSIM (see Sec. 5.2 for a description).

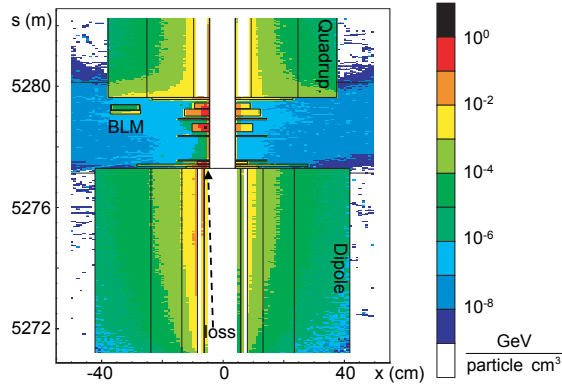


Figure 9.4: The geometry as implemented in FLUKA around the monitor BL521 with the simulated energy deposition from a typical loss superimposed. The loss is indicated by the dashed arrow.

Apart from the built-in Monte Carlo of ICOSIM, which I call FLUKA *XS* because the tabulated cross sections were calculated by FLUKA, I have created another version of the code, called FLUKA *full*, which is instead linked with FLUKA at runtime. On every turn, ICOSIM feeds FLUKA with the coordinates of ions impacting on the collimator. FLUKA then simulates the passage of the ions through the collimator geometry, using a 3D model of the jaws, and surviving fragments are returned to ICOSIM for further tracking. The FLUKA *full* method is more detailed and sophisticated but significantly slower in terms of computation time.

The lossmap from ICOSIM is used as starting conditions for a new set of FLUKA simulations of the magnets in which the losses occur. Such simulations are done at all four BLMs shown in Fig. 9.2, which are mounted close to the main loss peak in both simulations and measurements. An example of the simulated shower is shown in Fig. 9.4. In the FLUKA simulations, the energy deposition in the gas volume of each BLM, per ion lost in that part of the ring, is recorded. For comparison with the measured signal, the energy deposition was normalized by the total number of losses in the simulation around the whole ring.

9.3 Results

Fig. 9.5 shows the simulated and measured BLM signals around the maximum at 106.4 GeV/nucleon, normalized to 10^{10} lost particles and averaged over several machine cycles. Results for both straight and tilted jaws for both simulation methods are shown. The pattern from the measurements is very similar to the simulation and is a consequence of the dispersive orbits of ion fragments with different values of δ starting at the collimator jaws, as shown in Fig. 9.2.

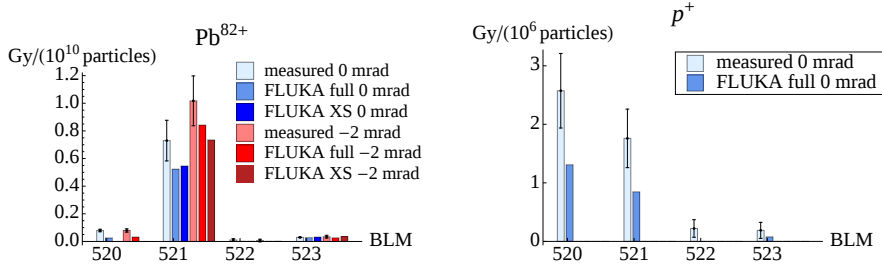


Figure 9.5: Average loss map for 106.4 GeV/nucleon $^{208}\text{Pb}^{82+}$ ions (left) and 270 GeV protons (right) with parallel jaws (blue bars) and jaws tilted by 2 mrad (red bars). The measurements are compared with simulations using both methods of simulating the particle-matter interaction in the collimator, as described in text. The standard deviation between different measurements is indicated.

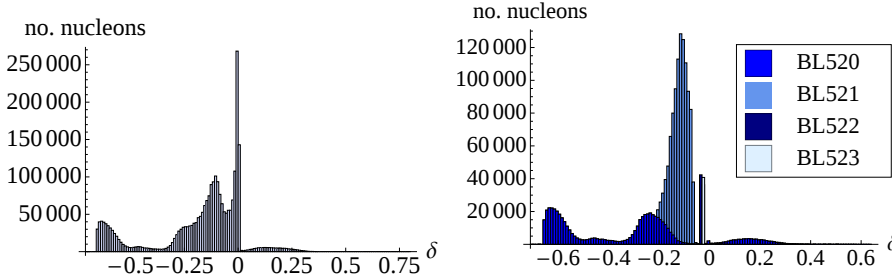


Figure 9.6: The simulated distribution of δ calculated according to Eq. (2.3), using the FLUKA *full* method, of all high energy nuclei except $^{208}\text{Pb}^{82+}$ coming out of the collimator (left) and of the ions lost within a 15 m interval upstream of each BLM (right) at 106.4 GeV/nucleon with parallel jaws. The height of the bars show the number of nucleons belonging to ions having δ within a certain interval.

Fragments satisfying $-0.2 < \delta < -0.08$ are lost near the aperture limitation at $s = 5277$ m, close to BL521. Fig. 9.6, showing the spectrum of δ of all ions exiting the collimator, demonstrates that this corresponds to a large fraction of the fragments, so that this monitor is expected to show a high signal.

At BL523, only fragments with a magnetic rigidity much closer to the original $^{208}\text{Pb}^{82+}$ ion are lost ($\delta \approx -0.02$). This is close to what can be expected in the cold regions of the LHC. In the vicinity of BL520, however, the losses are not only dispersive, since light fragments with large vertical betatron angles are also lost there. Fig. 9.7 shows the mass spectrum of the particles lost close to each BLM.

The magnitudes of the simulated signals agree well with measurements, al-

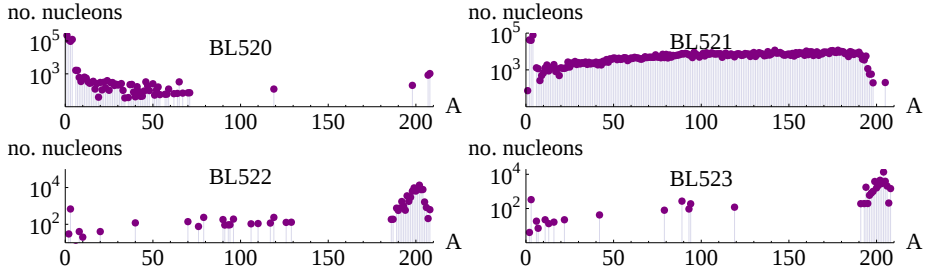


Figure 9.7: The A distribution of ion fragments lost within 15 m upstream of each BLM at 106.4 GeV/nucleon and parallel collimator jaws as simulated with FLUKA *full*. The heights of the bars show the number of nucleons from ions having a certain A .

though they are lower. The discrepancies are however well within estimated error margins, which are dominated by the systematic error of the shower simulation.

The simulated ratio between the losses at BL521 and BL523 shows an excellent agreement with measurements, while the expected relative loss at BL520 is lower. This could be due to the fact that BL520 is located only 30 m downstream of the collimator, meaning that it might see traces of shower particles from the collimator that are not properly taken into account in the simulation.

When the jaws are tilted, the average distance travelled in the collimator decreases and fewer particles are absorbed. Therefore, the BLM signals are higher, which is well reproduced by the simulations.

Both simulation methods are in good agreement with data, except at BL520, where FLUKA *XS* does not show any losses. The reason is that only heavy fragments are tracked, as explained in Sec. 5.2, while the losses close to BL520 are dominated by lighter fragments. This simulation method is suitable only when lighter ions can be neglected.

The loss maps at 5.9 GeV/nucleon are shown in Paper III. At this energy, the δ of the fragments exiting the collimator is caused not only by the fragmentation but also by ionization energy losses that change δ_p . Therefore, the spectrum of δ changes significantly. There is a good agreement between simulations and data also at this energy.

Fig. 9.5 shows also the measured and simulated proton loss maps at 270 GeV. The ratio between the higher peaks agree well with measurements, although the simulation underestimates the signals, and it is clear that there is a significant qualitative difference between proton and ion loss patterns: the maximum signal for protons was found at BL520, while in the ion runs it was found on BL521. This can be understood from the fact that the δ of the protons is much lower,

which means that large betatron angles caused by multiple scattering are the main loss mechanism instead of dispersion. This difference is a striking parallel to the expected behaviour in the LHC, and the ability of the simulations to quantitatively predict it in the SPS provides a very valuable benchmark.

TIME EVOLUTION OF THE ION LUMINOSITY

In this chapter, which summarizes Paper IV, studies of the time evolution of the luminosity and bunch intensities in heavy ion colliders are presented. During the design and operation of a collider, an important task is to maximize the integrated luminosity for the physics experiments. To do that, a detailed understanding of the underlying dynamics is necessary.

Data, collected by others in a large number of stores at RHIC during Run-7, are presented in Paper IV and not discussed in detail here. A stochastic cooling system is installed in the Yellow beam in RHIC [94]. This system uses a feedback loop to reduce the longitudinal diffusion of particles out from the central core of the beam. Here I consider only the stores where this system was not in use in order to make a comparison with the LHC.

The measurements are used to benchmark a multi-particle tracking simulation, taking into account collisions, IBS, radiation damping, betatron motion and synchrotron motion. The code, described in Sec. 10.1, is based on a Fortran program initially developed for stochastic cooling [94–96]. For the purpose of simulating colliding beams, the code has been revised and updated. The structure of the code has been changed in several ways but I focus on the new physics that has been included. The most important addition is a new routine for modelling collisions on a particle level. I show a derivation of the collision probability for a single particle, averaged over betatron phase, as a function of its coordinates and the local density of the opposing bunch.

I compare the simulation with the data from RHIC in Sec. 10.2 and then, in Sec. 10.3, I use it to make predictions for the LHC. The results for the LHC are compared with another simulation method, in which a system of ordinary differential equations describing the emittances and bunch populations is solved

numerically. This method is faster but has the disadvantage of assuming Gaussian bunch distributions. Similar simulations have been done in Ref. [15].

10.1 Tracking simulation

The tracking simulation follows two bunches containing a number of macro particles, meaning that each particle in the simulation represents a large number of particles in the real machine. In the simulations presented here, 5×10^4 particles were used to represent a bunch of 10^9 particles in RHIC or 7×10^7 particles in the LHC. The 6D coordinates of the particles are updated on a turn-by-turn basis as a function of the physical processes acting on them. The following processes are taken into account:

- Synchrotron and betatron motion: All coordinates are updated deterministically on every turn, as functions of the machine tune, chromaticity and RF voltage. Particles outside the acceptance of the RF bucket are removed. Linear betatron coupling is taken into account in thin-lens approximation. A detailed description can be found in Ref. [95].
- Collisions: collision probabilities are sampled as a function of the local density of the opposing beam. This is described in Sec. 10.1.1.
- IBS: As described in Sec. 10.1.2, the longitudinal bunch profile in RHIC is not Gaussian. Commonly used IBS models (from Piwinski [13] and Bjorken-Mtingwa [14]) make this assumption so a more detailed model is needed. The tracking code uses a model, developed by M. Blaskiewicz [95], where first the global growth rates are calculated using the Piwinski model in the smooth lattice approximation as if the bunch were Gaussian. Then, for each particle, individual growth rates are computed by modulating the global growth rates by the local particle density. Each particle is then given a random kick. Details can be found in Ref. [95].
- Radiation damping and quantum excitation: Damping is important in the LHC, while it is negligible in RHIC. In the code, a simple model developed in Ref. [97] is used. All particles receive a deterministic amplitude decay and a random excitation, which is calculated by imposing that a given equilibrium beam size, supplied by the user in the input, should be a stationary distribution.

Other processes are neglected. A detailed treatment of beam-gas scattering has been done elsewhere for RHIC [98, 99] and for the LHC [100, 101]. In both cases, beam-gas scattering is negligible compared to the effects of collisions and IBS.

The strength of the processes are scaled up where appropriate to account for the smaller number of macro particles and by an additional factor, set by the

user, that makes each simulation turn represent many machine turns. Typically one turn in the simulations presented here corresponds to 2×10^4 turns in the real machine. Each physical process corresponds to a subroutine in the program that is executed once per simulation turn.

10.1.1 Collisions in tracking simulations

On every simulation turn a collision between the two bunches is simulated. The program loops through all particles and calculates for each of them a collision probability P_1 as a function of its coordinates and the distribution of the opposing bunch. A random number is then sampled to determine if an interaction takes place, in which case the particle is removed. The rest of this section is devoted to the calculation of P_1 .

I start from the overlap integral in Eq. (2.31), which gives the total number of interactions during a single bunch crossing for arbitrary distributions with coordinates defined in Fig. 2.4. First, it will be assumed that the crossing angle $2\theta = 0$, so that the respective axes of all systems are parallel. P_1 is then given by the number of expected interactions if bunch 1 contains only one particle. The one-particle density ρ_{p1} can be modeled by using the Dirac δ -function (which I write as δ_D to avoid confusion with the deviation in magnetic rigidity). Since a negligible transverse magnetic field is assumed at the IP (the experiments are usually installed in such a way that this is fulfilled), a particle in bunch 1 with spatial coordinates (x_1, y_1, z_1) in the bunch and transverse angles (x'_1, y'_1) follows approximately a straight line so

$$\rho_{p1}(x, y, s - vt) = \delta_D(s - vt - z_1) \delta_D(x - [x_1 + x'_1 s]) \delta_D(y - [y_1 + y'_1 s]). \quad (10.1)$$

In the most general collision routine in the tracking code, the density ρ_2 of the opposing bunch is determined by sorting the particles in discrete bins along the directions (x, y, z_2) . It is assumed that the transverse distributions at $s = \tau = 0$ are independent, and that the longitudinal density ρ_{2z} does not depend on x or y . The transverse binnings are performed at $s = \tau = 0$, but these distributions change along s with $\beta_{xy}(s)$, which is assumed to be equal in both planes in the proximity of the IP. At a given s , close to the IP, the bunch is wider by a factor $\kappa(s)$, defined as

$$\kappa(s) = \sqrt{\frac{\beta_{xy}(s)}{\beta^*}} = \sqrt{1 + \frac{s^2}{\beta^{*2}}}, \quad (10.2)$$

where Eq. (2.35) has been used for simplification.

Inserting ρ_{p1} in Eq. (2.31), multiplying by the interaction cross section σ , and integrating, gives P_1 for a particle with given coordinates $(x_1, x'_1, y_1, y'_1, z_1)$:

$$P_1 = 2\sigma N_2 \int \frac{\rho_{2x}^*\left(\frac{x_1+x'_1 s}{\kappa(s)}\right)}{\kappa(s)} \frac{\rho_{2y}^*\left(\frac{y_1+y'_1 s}{\kappa(s)}\right)}{\kappa(s)} \rho_{2z}(2s - z_1) ds. \quad (10.3)$$

where $\rho_{2x}^*(x), \rho_{2y}^*(y)$ are the transverse densities at the IP. In the code, the integral in Eq. (10.3) is replaced by a sum over all bins that a specific particle passes through.

This method is very slow in terms of computing time, and a faster code is obtained by assuming Gaussian distributions in x and y , which is generally a very good approximation (in RHIC, the longitudinal distribution is however non-Gaussian as explained in Sec. 10.1.2). Furthermore, since every simulation turn corresponds to a large number of machine turns, where the betatron phase ϕ_u ($u = x, y$) has a uniform distribution on the interval $[0, 2\pi]$, P_1 is averaged over ϕ_u . The resulting collision probability, derived in Appendix A of Paper IV, is a function of z_1 and the J_u only:

$$P_1 = \sigma N_2 \frac{\exp\left(-\frac{J_x}{2\epsilon_{2x}} - \frac{J_y}{2\epsilon_{2y}}\right) I_0\left(\frac{J_x}{2\epsilon_{2x}}\right) I_0\left(\frac{J_y}{2\epsilon_{2y}}\right)}{2\pi\beta^* \sqrt{\epsilon_{2x}\epsilon_{2y}}} R \quad (10.4)$$

Here I_0 is a modified Bessel function and R is a reduction factor to the luminosity. The tracking code can use several different expressions for R , with the most general one being a function of z_1 and therefore different for every particle. Significant gains in execution speed are obtained (without loss in accuracy for the cases considered here) by using the same R for all particles.

This makes a generalization to the case of non-zero crossing angle straightforward. A global luminosity reduction factor R_{tot} can be derived in analogy with Eq. (2.37) for arbitrary longitudinal profiles:

$$R_{\text{tot}} = \int \exp\left(-\frac{2\beta^* \sin^2 \theta}{(\epsilon_{1x} + \epsilon_{2x}) \left(1 + \frac{2\beta^{*2} [1 + \cos(2\theta)]}{(z_1 + z_2)^2}\right)}\right) \times \frac{\rho_{z1}(z_1) \rho_{z2}(z_2)}{1 + \frac{(z_1 + z_2)^2}{4\beta^{*2} \cos^2 \theta}} dz_1 dz_2. \quad (10.5)$$

The integration in Eq. (10.5) is replaced by a sum over discrete bins in the code. When the longitudinal distributions are Gaussian, R_{tot} simplifies to Eq. (2.37), which in turn give the standard reduction factors for the hourglass effect and the crossing angle. If the distribution of J_x is given by Eq. (2.24), $\mathcal{L}_{sc}$ can be calculated as

$$\mathcal{L}_{sc} = N_1 \int \rho_{1Jx}(J_x) \rho_{1Jy}(J_y) \frac{P_1(J_x, J_y)}{\sigma} dJ_x dJ_y. \quad (10.6)$$

Solving the integral yields Eq. (2.36).

When collisions occur at several IPs, P_1 is summed up over all of them (only the factor R_h/β^* varies). Furthermore, P_1 has to be scaled to account for the smaller number of macro particles and the shorter time scale in the simulation.

In order to compute P_1 , the total interaction cross section is needed. By summing the cross sections for BFPP and EMD in Table 5.1.1 with a 7 b hadronic cross section [76], it is estimated at 223 b.

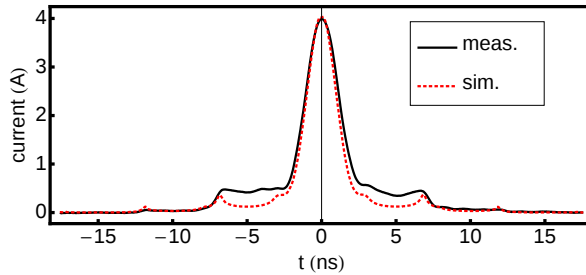


Figure 10.1: Example of a measured bunch profile in RHIC after the ramp when collisions are turned on, shown together with the simulated profile used as starting conditions in the simulations. It was generated by letting an initially Gaussian bunch circle in the machine under the influence of IBS.

10.1.2 Starting distribution

The starting distribution of the particles in the tracking is important for the agreement between measurement and simulation. In the transverse plane, the beams are well approximated by Gaussian distributions, both in RHIC and LHC, and the initial coordinates are generated by the code from the starting emittances. The transverse beam sizes in RHIC were not measured but inferred from the observed starting bunch populations and luminosity using Eq. (2.41). Equal starting emittances in the horizontal and vertical planes were assumed, as well as equal transverse beam sizes in the two bunches. Despite not being justified by measurements, this reduces the dimensionality of the problem to a tractable level. There is, in any case, insufficient data to attempt a fit to the small variations in size of individual bunches. I have found that, if different beam sizes are used in the simulation, the luminosity remains approximately unchanged while the bunch currents show small variations.

In the longitudinal plane, the distribution is expected to be Gaussian in the LHC but not in RHIC. An example of the bunch current measured at RHIC when the beams were put into collision is shown in Fig. 10.1, together with the starting profile used in the simulations. This profile is the result of the dynamics of the double RF system used in RHIC. The starting distribution was generated by tracking a bunch under the influence of IBS. Details are given in Paper IV.

Since IBS is very strong in RHIC, particles are continuously diffusing out of the RF bucket. This loss process is called debunching. This effect is somewhat similar to Touschek scattering, with the difference that in the standard formulas for Touschek effect [102] all scattering events leading to a loss are assumed to occur with large momentum transfers between particles in the centre of the bucket. The debunching losses are however diffusive in nature and most scattering events leading to a loss take place between particles very close to the separatrix. According to tracking simulations, more particles are lost because of debunching than collisions in RHIC.

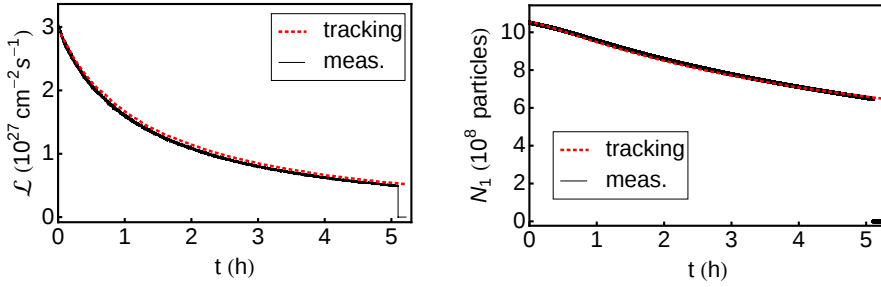


Figure 10.2: The luminosity (left) and bunch intensity from one of the beams (right) from measurements for store 8908 in RHIC, shown together with the result from tracking simulations. The average ratio ξ between a simulated and measured quantity is 1.05 for $\mathcal{L}$ and 0.99 for N_1

10.2 Comparison between simulations and measurements in RHIC

As an example of the detailed time evolution in a store, we show in Fig. 10.2 the measured and simulated luminosity and bunch populations for store 8908. The agreement with the simulation is very good.

For more statistics, 139 stores with varying bunch populations and luminosity from RHIC Run-7 were simulated. To measure the goodness of the tracking simulation, a benchmark parameter ξ is defined as the average ratio between a simulated and measured quantity U over the first three hours:

$$\xi = \frac{1}{3 \text{ h}} \int_{t=0\text{h}}^{t=3\text{h}} \frac{U_{\text{sim}}(t)}{U_{\text{fit}}(t)} dt \quad (10.7)$$

Here U is one of the quantities $\mathcal{L}, N_1, N_2$. Histograms of ξ for 139 stores are shown in Fig. 10.3. An overall good agreement is found. For the bunch populations, ξ is distributed around 1 with a standard deviation of only 3%. The measured luminosity was on average overestimated by around 11%. Possible sources of the discrepancies include the use of the same longitudinal starting profile in all stores, variations in β_{xy}^* between stores, the cross section for mutual electromagnetic dissociation (used to convert the measured luminosity) and the neglect of dynamic aperture.

10.3 Predictions for the LHC

In the LHC, there are important differences with respect to RHIC. A single RF system is used and bunches are expected to have a Gaussian distribution in the longitudinal plane. Simulations of bunches circulating at the injection plateau,

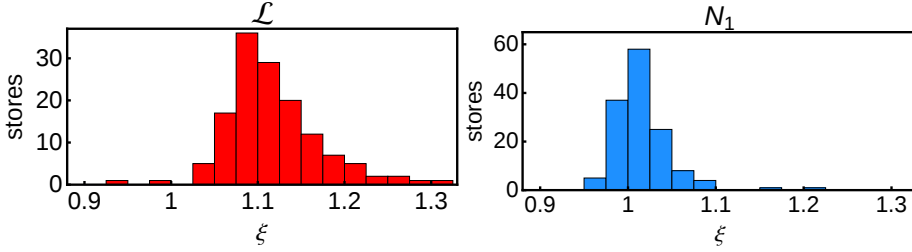


Figure 10.3: Comparison of tracking simulation and measurement of luminosity (left), and bunch intensity of one of the beams (right) for 139 stores in RHIC without stochastic cooling. The parameter ξ is defined by Eq. (10.7).

at a constant energy without colliding while the LHC is filled, are shown in Paper IV. Some losses from debunching are expected.

Simulations of the time evolution of $^{208}\text{Pb}^{82+}$ beams at the collision energy of 2.76 TeV/nucleon, using a different simulation method based on ODEs, were done in Ref. [15]. Here these simulations are repeated, including also the luminosity reduction factor, and compared with tracking for 1–3 active IPs. The ODE method is briefly described for completeness.

Instead of following single particles, the rms emittances and intensities are used to describe the bunches, and their time evolution is computed by solving numerically a system of coupled ODEs (similar to Refs. [16, 17, 103]). In total there are six dynamical variables: $\epsilon_{xyi}, \epsilon_{li}, N_i$, where ϵ_{li} is the longitudinal emittance. The time evolution of the system is given by [15]:

$$\begin{aligned} \frac{d\epsilon_{xyi}}{dt} &= \frac{\epsilon_{xyi}}{T_{\text{IBS},xy}(N_i, \epsilon_{xyi}, \epsilon_{li})} - \frac{\epsilon_{xyi}}{T_{\text{rad},xy}} \\ \frac{d\epsilon_{li}}{dt} &= \frac{\epsilon_{li}}{T_{\text{IBS},l}(N_i, \epsilon_{xyi}, \epsilon_{li})} - \frac{\epsilon_{xyi}}{T_{\text{rad},z}} \\ \frac{dN_i}{dt} &= - \frac{\sigma N_1 N_2 f_{\text{rev}} n_{\text{IP}} R_{\text{tot}}}{2\pi\beta^*(\epsilon_{xy1} + \epsilon_{xy2})} \end{aligned} \quad (10.8)$$

Here $T_{\text{IBS},xy}, T_{\text{IBS},l}$ are the instantaneous IBS rise times, and n_{IP} the number of IPs with collisions. Beam-gas scattering is neglected as its influence on the dynamics is negligible as discussed in Sec. 10.1. By adding additional terms to the equations the method can easily be expanded to account for other effects leading to particle loss or emittance growth.

To solve the system numerically, Mathematica [58] is used. With precalculated and interpolated values of $T_{\text{IBS},l}$ and $T_{\text{IBS},xy}$, as explained below, the gain in execution speed when simulating the time evolution in a store is more than a factor 1000 compared with the tracking. A 10 h store takes on the order of a second to solve on a normal desktop computer. A disadvantage of the ODE method is that Gaussian bunches are assumed, so it is not suitable for

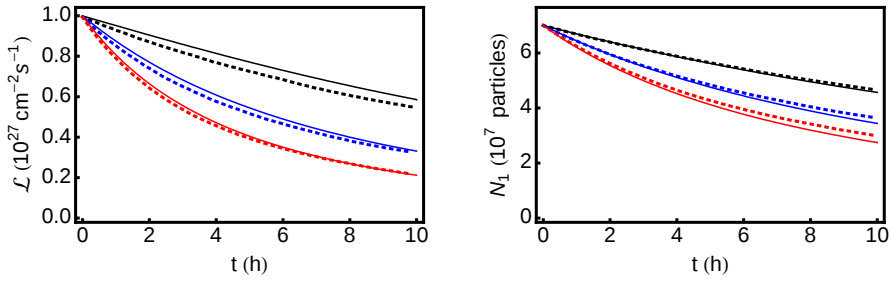


Figure 10.4: The simulated time evolution in the LHC of the luminosity (left) and bunch intensity (right) during a 10 h store at top energy with colliding beams. Results are shown from the tracking method (dotted lines) and the ODE method (solid lines) for the cases of one (black lines), two (blue lines) or three (red lines) active IPs taking collisions.

simulations of RHIC. Furthermore, a term would need to be added to describe debunching.

The IBS rise times are calculated with MAD-X, where a generalized version of the Bjorken-Mtingwa model is used [14, 104, 105]. The evaluation of $T_{\text{IBS},l}$ and $T_{\text{IBS},xy}$ is done offline on a grid of points and interpolated at runtime. Details are shown in Paper IV. This is the key step that allows a fast interactive analysis of many cases of interest. Since round beams are assumed, $T_{\text{IBS},xy}^{-1} = (T_{\text{IBS},x}^{-1} + T_{\text{IBS},y}^{-1})/2$. The calculated rise times from MAD-X agree within about 20% with the Piwinski model used in the tracking.

Results of simulations with both methods are shown in Fig. 10.4. At collision energy the dynamics in the LHC changes significantly, since radiation damping becomes important and compensates the emittance blowup from IBS. As particles are removed from the beams through collisions, IBS becomes weaker while damping stays constant. Therefore, the emittance shrinks during the store. The agreement between the simulation methods is good except for the emittance, which is shrinking significantly faster with the ODE method. Losses from debunching are negligible in the LHC. Beam losses are expected to be dominated by collisions, since debunching is negligible. Some of the discrepancies can be accounted for by the difference in IBS model.

CONCLUSIONS

In relativistic heavy-ion colliders, several beam-loss mechanisms exist, which are absent in other types of machines. I have discussed processes which modify the charge or the mass of beam ions, so that they follow dispersive trajectories. Depending on the machine parameters and the magnetic rigidity of the fragment, these particles may be lost in localized spots.

Through ultraperipheral electromagnetic interactions at the IPs, ions may acquire an extra electron through bound free pair production (BFPP) or lose one or several nucleons through electromagnetic dissociation (EMD). In RHIC these losses do not pose any other problems than a decay of the intensity and luminosity, while in the LHC they could contain enough power to cause quenches.

I have presented studies of BFPP between colliding $^{208}\text{Pb}^{82+}$ ions in the LHC, using optical tracking, a FLUKA simulation of the induced shower and a thermal network simulation (done by others). At nominal parameters, the estimated heat load in the LHC was found to be 40% above the quench level, although uncertainties are significant. Losses from EMD are less serious but may also, under certain conditions, lead to quenches. Beam loss measurements at RHIC show a clear correlation between the luminosity and the signals around the predicted BFPP impact point, although it is difficult to disentangle it from other processes causing losses.

Furthermore, an analysis of some parts of the machine protection system in the LHC has been presented. In particular the BLMs and beam dump system. The study shows that these components will function as desired during the LHC heavy ion runs.

Ions that have undergone nuclear fragmentation in LHC's collimation system, designed for protons, is another source of ion-specific beam losses. Fragments of different rigidity are lost in different localized spots, making the machine act as a spectrometer. Tracking studies have been performed by others but in this

thesis I have shown the first experimental evidence for these losses, using an LHC prototype collimator installed in the SPS. Qualitative differences in the loss pattern between ions and protons were found, which were well reproduced by simulations. The data are consistent with the expectation that protons scattered in the collimator are lost because of large scattering angles, while ions are lost due to nuclear fragmentation. Quantitatively, a simulation chain of tracking and FLUKA gave an agreement with measurements within 30% for the strongest BLM signal.

I have also presented studies of the time evolution of the luminosity and beam intensities during stores in RHIC and LHC. The beam losses from ultraperipheral electromagnetic interactions at the IP are responsible for a large part of the total decay in both machines. Another beam loss mechanism, which is very important in RHIC, is the diffusion of particles out of the RF bucket under the influence of intrabeam scattering. In the LHC, this effect is almost non-existent since radiation damping is strong enough to counteract IBS.

Detailed tracking simulations that account for these losses is in good agreement with data from a large set of stores in RHIC. In the LHC, the tracking simulations were compared with a faster method, based on ODEs, which assumes Gaussian distributions. An overall good agreement was found and both simulation methods predict that the transverse emittance at top energy will shrink during a store because of radiation damping. For runs at lower energy, this conclusion could change.

The LHC increases the available energy in heavy-ion collisions by more than a magnitude and the studies in this thesis form a foundation for understanding some of the operational challenges that must be overcome in order to achieve nominal performance.

COMMENTS ON THE PAPERS

I Beam losses from ultra-peripheral nuclear collisions between $^{208}\text{Pb}^{82+}$ ions in the Large Hadron Collider and their alleviation

I have done the simulation work in this paper except the thermal network model simulations. I have also developed the idea of alleviation by orbit bumps discussed in Section IV. The paper is written by me with some contributions from co-authors.

II Observations of Beam Losses Due to Bound-Free Pair Production in a Heavy-Ion Collider

My work for this paper consists of simulations, including optical tracking, sensitivity analysis and Monte-Carlo simulations of the particle-matter interaction, and some data analysis. The paper is written mainly by me.

III Measurements of heavy ion beam losses from collimation

For this paper, I have done all simulation work (including modifying the ICOSIM program for use with the SPS, implementing an interface between ICOSIM and FLUKA, and various improvements and bug-fixes in the code). I participated in the planning and performance of the measurements and I have done all data analysis. I have also written the text.

IV Time evolution of the luminosity of colliding heavy-ion beams in RHIC and LHC

In this paper, I have done the modelling and implementation of the collisions between two bunches, with some advice from co-authors, and joined this with the IBS routine written by M. Blaskiewicz to a new simulation code. With this code, I have done all tracking simulations in the paper. The ODE simulations were initially done by J.M. Jowett but have been repeated and modified by me for comparison with the tracking code. The text is written mainly by me.

V Monitoring heavy-ion beam losses in the LHC

This paper contains older estimates from 2006 of the impact of Bound free pair production in the LHC. Since then the LHC optics has changed and updated results are shown in Paper I. My part of the work was the evaluation of the beam dump thresholds for $^{208}\text{Pb}^{82+}$ ions and the layout of the BLM system monitoring BFPP and Electromagnetic Dissociation, including all simulations leading to the final result. The paper is written by me except the section on extra BLMs for collimation.

VI Performance with lead ions of the LHC beam dump system

My part of this paper consisted of FLUKA simulations of the impact of a $^{208}\text{Pb}^{82+}$ ion bunch on different devices in the LHC beam dump extraction line. I have written the paper except the section describing the beam imaging screen.

VII Effects of ultraperipheral nuclear collisions in the LHC and their alleviation

This paper contains details on the alleviation of BFPP in the LHC with orbit bumps. An intermediate version of the LHC optics was used. Results with the latest version at the time of writing (6.503) are presented in Paper I. I have done all the simulations as well as the derivation of formulas for the required orbit bump amplitudes. I have also written the paper. Note the error on p. 3: the cross section for EMD1 should be 96 barn.

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PAPERS

Beam losses from ultra-peripheral nuclear collisions between $^{208}\text{Pb}^{82+}$ ions in the Large Hadron Collider and their alleviation

R. Bruce, D. Bocian, S. Gilardoni, and J.M. Jowett.

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Beam losses from ultraperipheral nuclear collisions between $^{208}\text{Pb}^{82+}$ ions in the Large Hadron Collider and their alleviation

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Electromagnetic interactions between colliding heavy ions at the Large Hadron Collider (LHC) at CERN will give rise to localized beam losses that may quench superconducting magnets, apart from contributing significantly to the luminosity decay. To quantify their impact on the operation of the collider, we have used a three-step simulation approach, which consists of optical tracking, a Monte Carlo shower simulation, and a thermal network model of the heat flow inside a magnet. We present simulation results for the case of $^{208}\text{Pb}^{82+}$ ion operation in the LHC, with focus on the ALICE interaction region, and show that the expected heat load during nominal $^{208}\text{Pb}^{82+}$ operation is 40% above the quench level. This limits the maximum achievable luminosity. Furthermore, we discuss methods of monitoring the losses and possible ways to alleviate their effect.

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I. INTRODUCTION

The Large Hadron Collider (LHC) is presently being commissioned at CERN [1]. Its main beam parameters are given in Table I. In its first phase of operation it will collide protons but later also heavy nuclei, starting with $^{208}\text{Pb}^{82+}$ at center-of-mass energies up to 1.15 PeV [2]. This will open up a new energy regime in experimental nuclear physics, extending the study of the hadronic matter (“quark-gluon plasma”) that existed in the early universe about 10^{-6} s after the big bang [3]. At the same time, colliding heavy-ion beams at this unprecedented energy will present beam physics challenges not encountered in previous colliders.

When two fully stripped ions collide at an interaction point (IP), a variety of processes leading to fragmentation and particle production can occur. Hadronic nuclear interactions, which are usually the main object of study of the experiments, occur only when the impact parameter b is smaller than about twice the nuclear radius R . *Ultraperipheral collisions* are those in which two colliding ions pass close to each other with $b > 2R$. In such events, the intense Lorentz-contracted fields of the nuclei can be represented as pulses of virtual photons in the equivalent photon picture of Fermi, Weizsäcker, and Williams [4]. These extremely energetic photons collide and cause electromagnetic interactions that are particularly strong in heavy-ion collisions because the density of virtual photons around the nuclei is proportional to Z^2 . Reviews of this field can be found in Refs. [5–8]. In comparison with the cross section for inelastic hadronic interactions, $\sigma_h \approx 8$ b,

the rates of ultraperipheral interactions are enormous: for example, the cross section for e^+e^- pair production given by the Racah formula [9] is of order 2×10^5 b. From the point of view of collider operation, the most important electromagnetic processes are the subclasses of these interactions which remove ions from the beam, namely, bound-free pair production (BFPP) and electromagnetic dissociation (EMD) [10].

In BFPP, the virtual photons surrounding relativistic ions collide and produce an e^+e^- pair where, in contrast to the much more frequent free pair production, the electron is created in an atomic shell of one of the ions. Schematically, the reaction between two bare nuclei with atomic numbers Z_1, Z_2 can be written as

$$Z_1 + Z_2 \rightarrow (Z_1 + e^-)_{1s1/2,\dots} + Z_2 + e^+. \quad (1)$$

In EMD one nucleus absorbs a photon and undergoes a transition into an excited state, typically by excitation of the giant dipole resonance. When this decays, it emits one

TABLE I. Design parameters for the LHC’s proton and $^{208}\text{Pb}^{82+}$ beams in collision conditions [1]. The values of $\mathcal{L}$ and β^* refer to IP2 for $^{208}\text{Pb}^{82+}$ ions and IP1 and IP5 for protons (see Fig. 1).

Particle	p	$^{208}\text{Pb}^{82+}$
Energy/nucleon	7 TeV	2.759 TeV
Number of bunches k_b	2808	592
Particles/bunch	1.15×10^{11}	7×10^7
Transverse normalized emittance (1σ)	$3.75 \mu\text{m}$	$1.5 \mu\text{m}$
RMS momentum spread $\langle \delta_p^2 \rangle^{1/2}$	1.13×10^{-4}	1.10×10^{-4}
Stored energy per beam	362 MJ	3.81 MJ
Design luminosity $\mathcal{L}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	$10^{27} \text{ cm}^{-2} \text{ s}^{-1}$
Horizontal and vertical β^*	0.55 m	0.5 m

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or several nucleons. Because of the nuclear Coulomb barrier, the most common processes are the emission of one or two neutrons. For the case of $^{208}\text{Pb}^{82+}$ ions, the one-neutron reaction (called EMD1 hereafter) can be written as



Both BFPP and EMD change the magnetic rigidity of at least one of the colliding nuclei [as usual, magnetic rigidity is defined as a particle's momentum p per unit charge Ze , or $p/Ze = (B\rho)$, where ρ is the bending radius in a magnetic field B]. If the charge of an ion changes by $e\Delta Z$, and the number of nucleons by ΔA , the resulting rigidity can be written as $(B\rho)(1 + \delta)$, where the fractional deviation δ from the main beam with atomic number Z_0 and mass number A_0 is given to a very good approximation (neglecting increments of the mass excess) by

$$\delta \approx \frac{Z_0(A_0 + \Delta A)}{A_0(Z_0 + \Delta Z)}(1 + \delta_p) - 1. \quad (3)$$

Here $\delta_p = \Delta p/p_0$ is the fractional momentum deviation per nucleon with respect to an ion circulating on the central orbit of the storage ring.

During the interactions, the transverse momentum recoil is very small, so the modified ions emerge at a small angle to the main beam. In EMD, the recoil changes δ_p (see Sec. VII), while this is negligible for BFPP. However, ions from both processes follow dispersive orbits according to their magnetic rigidity and may be lost at the first point in the ring where the horizontal aperture A_x and dispersion d generated locally since the IP satisfy

$$d\delta \geq A_x. \quad (4)$$

The beam losses caused by these processes contribute significantly to the decay of intensity and luminosity in an ion collider [10,11]. This has been evaluated for the LHC [1,12], where ions might collide at three IPs: the ATLAS experiment at IP1, ALICE at IP2, and CMS at IP5.

The general layout of the LHC is shown in Fig. 1. It consists of two concentric 27 km rings with counterrotating beams. Each ring is made of eight long straight sections matched to eight regular arcs through dispersion suppressor regions. The two rings overlap in four of the eight long straight sections housing colliding-beam experiments. The optics design continues to evolve through various *versions*, usually corresponding to a given layout of the collider elements, with the latest one called V6.503. The LHC uses superconducting magnets with the two apertures within the same cryostat, where some are cooled down to 1.9 K by liquid helium. Further details of the LHC optics and layout can be found in Ref. [1].

The rate of removal of particles from the beam at the IPs is directly proportional to the interaction cross section, which in the case of BFPP takes the approximate form [13]

$$\sigma_{\text{BFPP}} \approx Z_1^2 Z_2^2 \sum_i (A_i \log \gamma_{\text{cm}} + B_i), \quad (5)$$

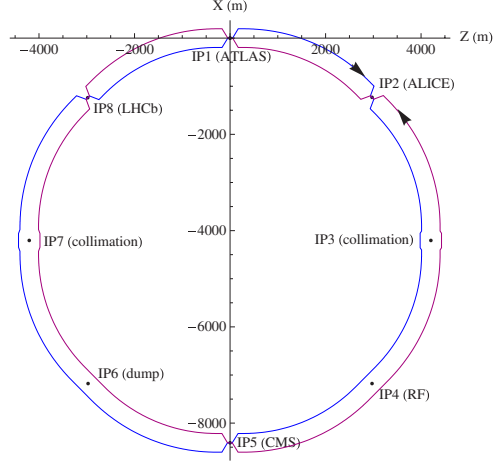


FIG. 1. (Color) The schematic layout of the LHC (the separation of the two rings is exaggerated).

where the electron is captured by nucleus 1 and the sum is taken over atomic shells i . Here γ_{cm} is the relativistic factor of the ions in the center-of-mass frame, and A_i, B_i depend only weakly on Z . For 2.76 TeV/nucleon $^{208}\text{Pb}^{82+}$ collisions in the LHC, the total cross section for electron capture to *one* of the nuclei is [13]

$$\sigma_{\text{BFPP}} \approx 281 \text{ b}. \quad (6)$$

Using Table I and Eq. (6), the BFPP event rate is $\mathcal{L}\sigma_{\text{BFPP}} \approx 281 \text{ kHz}$ ($\mathcal{L}$ is the collider luminosity).

Predictions of the cross sections for BFPP have varied substantially over the years but have converged on values close to those found using the plane-wave Born approximation of Ref. [13]; as these authors point out, it was shown earlier [14], that higher order Coulomb corrections may reduce the values by a few percent. We estimate the uncertainty in the BFPP cross section to about 20% [13].

The corresponding cross section for EMD1 was calculated with the Monte Carlo program FLUKA [15–17], by simulating a large number of the events through direct calls to the event generator:

$$\sigma_{\text{EMD1}} \approx 96 \text{ b}. \quad (7)$$

This relies on a recent improved implementation of EMD effects which has been benchmarked against the RELDIS code [18] (e.g., in this case RELDIS gives 104 b [1]). FLUKA was also used to estimate the cross section for two-neutron EMD (called EMD2) to

$$\sigma_{\text{EMD2}} \approx 29 \text{ b}, \quad (8)$$

while the total EMD cross section, including all decay channels, is

$$\sigma_{\text{EMD}} \approx 226 \text{ b.} \quad (9)$$

Thus, the total cross section for particle loss by electromagnetic processes is around 507 b, compared to the 8 b for nuclear inelastic interactions, and is the dominant limit on usable luminosity lifetime for the experiments.

Furthermore, if Eq. (4) is satisfied somewhere, then the lost particles hit the vacuum chamber in a well-defined location which may lie in a superconducting magnetic element [12,19,20]. With the energy E per ion in Table I, the total power in the BFPP beam is $\mathcal{L}\sigma_{\text{BFPP}}E \approx 25.8 \text{ W}$. This induced heating may raise the temperature enough to bring the superconducting cable irreversibly over the critical surface in its phase diagram, the space spanned by magnetic field, current, and temperature. The resulting departure from the superconducting state is called a quench. The induced joule heating also quenches neighboring volumes so that the quench propagates. In case of a quench in the LHC, the beam will be dumped within one machine turn and the quench protection system will fire heaters to quickly quench a number of magnets and dissipate the stored magnetic energy over a larger volume, avoiding damage to the magnets. Nevertheless, quenches have to be avoided by all means during collider operation since recovery involves the lengthy process of cooling the magnets down again, followed by refilling, ramping, and “squeezing” of the beams. Downtime of the LHC is costly.

BFPP has been measured in fixed target experiments [21–23]. The first measurement in a collider [24] occurred during 100 GeV/nucleon $^{63}\text{Cu}^{29+}$ operation of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, where the detected induced showers agreed within a factor 2 with FLUKA simulations and the location of the losses was predicted within 2 m. Although neither BFPP nor EMD pose any risk of quenches at RHIC, mutual EMD between ions of the colliding beams has also been measured at RHIC [25] and is routinely used to monitor the luminosity [26,27].

The risk of inducing quenches means that it is vital to study, quantify, and possibly alleviate the impact of BFPP and EMD in the LHC, in order to ensure safe operation uninterrupted by lengthy quench-recovery procedures.

To study the loss processes, we use a three-step simulation method, consisting of optical tracking of the ions with modified rigidity, a Monte Carlo simulation of the hadronic and electromagnetic shower created as the ions fragment following their initial impact on the vacuum envelope, and a thermal network simulation of the heat flow inside the surrounding cryomagnet. To illustrate the method we apply it to BFPP in the ALICE experiment at IP2 of the LHC, with brief comparisons with the other IPs in Secs. II, III, IV, V, and VI. In Sec. VII we treat losses from EMD and in Sec. VIII we describe a system of beam-loss monitors (BLMs) to survey the losses. Finally, in Sec. IX, we discuss possible methods of alleviation.

II. OPTICAL TRACKING

The condition for loss of nuclei modified by BFPP or EMD in a localized spot, given by Eq. (4), depends thus on the beam optics, the aperture, and the ion species. For $^{208}\text{Pb}^{82+}$ ions in the LHC, the δ caused by BFPP is $\delta_{\text{BFPP}} = 0.012$ [using $\Delta Z = -1$ in Eq. (3)]. For EMD1 ($\Delta A = -1$) and EMD2 ($\Delta A = -2$) we include also the average momentum deviation per nucleon caused by the recoil, which we estimated with FLUKA to $\langle \delta_p \rangle \approx -7.4 \times 10^{-5}$ for EMD1 and $\langle \delta_p \rangle \approx -1.25 \times 10^{-4}$ for EMD2. This results in $\delta_{\text{EMD1}} = -0.0049$ and $\delta_{\text{EMD2}} = -0.0097$ from Eq. (4).

Since the momentum acceptance of the LHC arcs is $|\delta| < 0.006$ [1], BFPP and EMD2 will cause localized losses in the LHC while EMD1 will not.

To illustrate the losses from BFPP and EMD, we used the program MAD-X [28] to compute the off-momentum optical functions. The computation was done for both beams using V6.503 of the LHC optics. Figure 2 shows the resulting beam envelopes for beam 1 (circulating clockwise when viewed from the top) for the nominal beam and the secondary beams of ions created by BFPP or EMD at each of the experimental IPs.

Even if ion species other than $^{208}\text{Pb}^{82+}$ were used, particles affected by BFPP would still be lost, since Eq. (3) and $|\delta| < 0.006$ requires $Z_0 \geq 168$. The power drops rapidly with Z^7 according to Eq. (5). In comparison, the corresponding condition at RHIC is $Z_0 \geq 58$ so that the measurements in Ref. [24] were only possible with $^{63}\text{Cu}^{29+}$ beams and not the more usual $^{197}\text{Au}^{79+}$.

Ions created by EMD1 are lost if $A_0 \leq 166$, meaning that this might be a source of localized losses during future collisions between lighter ions. However, for lighter ions, the cross section is significantly lower [18].

Since BFPP is the most dangerous process in the LHC, we focus on it here and treat EMD in Sec. VII.

A $^{208}\text{Pb}^{82+}$ ion, in the center of the bunch and following the ideal trajectory through the center of all magnets, enters the IP with $\delta = 0$. If it acquires an extra electron through BFPP, it exits with $\delta = \delta_{\text{BFPP}}$. Downstream of the IP it follows a dispersive trajectory x_B , which together with the linear optics is calculated exactly with MAD-X rather than using the linear approximation $x_B \approx d\delta$.

To write the orbit of any other $^{208}\text{Pb}^{81+}$ ion, we use subscript i to denote that the function A should be evaluated at $s = s_i$ and express derivatives with respect to s as $dA/ds = A'$. Furthermore, we use a tilde to represent chromatic optical functions for the BFPP particles (e.g. at $s = s_i$ the usual envelope function is β_i for the nominal $^{208}\text{Pb}^{82+}$ beam and $\tilde{\beta}_i$ for the $^{208}\text{Pb}^{81+}$ beam). Unless stated otherwise, all optical functions refer to the horizontal plane.

With $s = s_0$ at the IP, we write the position x_1 and angle x'_1 of a $^{208}\text{Pb}^{81+}$ ion at some downstream position s_1 as

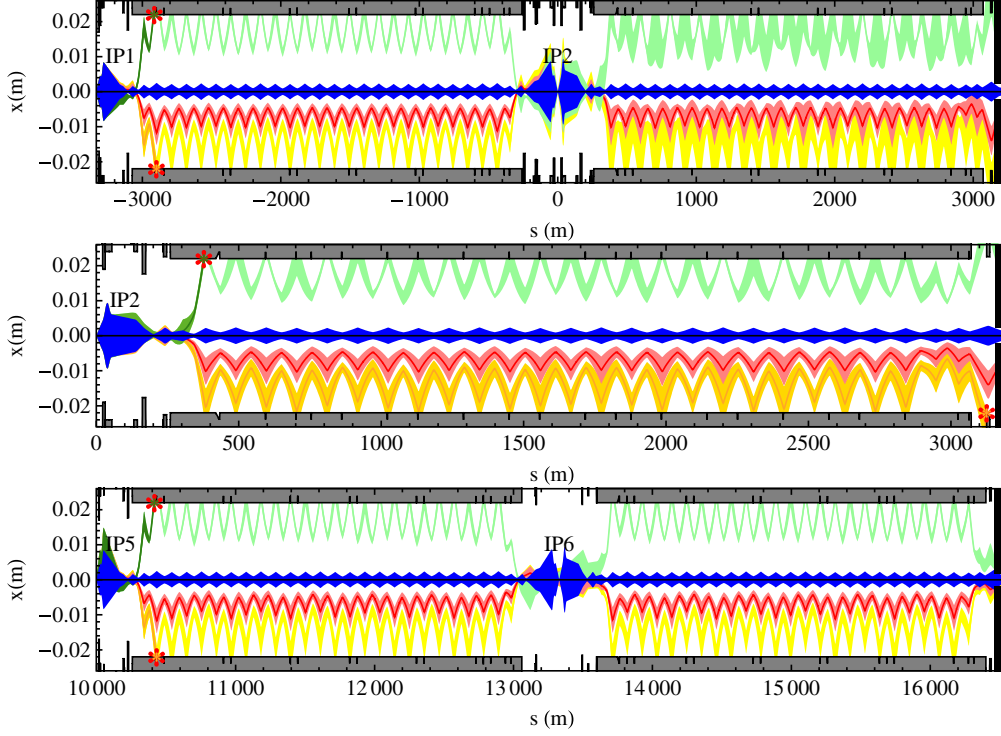


FIG. 2. (Color) The simulated horizontal 6σ envelopes of the nominal $^{208}\text{Pb}^{82+}$ beam (blue), the $^{208}\text{Pb}^{81+}$ BFPP beam (green), the $^{207}\text{Pb}^{82+}$ EMD1 beam (red), and the $^{206}\text{Pb}^{82+}$ EMD2 beam (yellow) coming out of IP1 (top), IP2 (middle), and IP5 (bottom) in the LHC, with the machine aperture superimposed. The envelopes are plotted in a lighter color after the impact (indicated by a red star) of the central orbit on the aperture. The horizontal scales have $s = 0$ at each IP in turn and the closest horizontal collimators are represented as black boxes at 6σ to the right. The length of the collimators is not to scale for the sake of readability.

$$\begin{bmatrix} x_1 \\ x'_1 \\ \delta_p \end{bmatrix} = \begin{bmatrix} x_{B,1} \\ x'_{B,1} \\ 0 \end{bmatrix} + \begin{bmatrix} \tilde{C}_1 & \tilde{S}_1 & \tilde{d}_1 \\ \tilde{C}'_1 & \tilde{S}'_1 & \tilde{d}'_1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \\ \delta_p \end{bmatrix} \quad (10)$$

using a standard representation of the transfer matrix in terms of the optical functions. The trajectory of a BFPP ion is thus the superposition of the central dispersive trajectory x_B caused by the electron capture, a betatron oscillation around it, and a dispersive contribution from the momentum deviation within the bunch.

The functions $\tilde{C}_1$ and $\tilde{S}_1$ are given by

$$\begin{aligned} \tilde{C}_1 &= \sqrt{\frac{\tilde{\beta}_1}{\beta_0}} [\cos(\tilde{\mu}_1 - \tilde{\mu}_0) + \tilde{\alpha}_0 \sin(\tilde{\mu}_1 - \tilde{\mu}_0)] \\ \tilde{S}_1 &= \sqrt{\beta_1 \beta_0} \sin(\tilde{\mu}_1 - \tilde{\mu}_0), \end{aligned} \quad (11)$$

where $\tilde{\mu}$ is the off-momentum betatron phase and $\tilde{\alpha} = -\tilde{\beta}'/2$. They are evaluated with initial conditions taken from the periodic on-momentum solution at the IP ($\tilde{\beta}_0 = \beta_0$ and $\tilde{\mu}_0 = \mu_0$). For the off-momentum dispersion function $\tilde{d}$, the initial condition is $\tilde{d}_0 = 0$.

Since the betatron amplitudes and δ_p are small, and there are essentially no nonlinear elements in this part of the ring, the linear approach in Eq. (10) is accurate as long as the central dispersive trajectory x_B is calculated without approximation.

The δ_p of the BFPP particles has a Gaussian distribution with a standard deviation given in Table I. The initial x_0 and x'_0 are also normally distributed but we must take into account that the distribution of these collision points is *not* that of the incoming bunches. Assuming zero periodic dispersion and head-on collision between identical Gaussian bunches at an IP, the horizontal phase space

distribution of each bunch is

$$f_{\beta}(x_0, x'_0) = \frac{N_b \beta_0}{2\pi\sigma_0^2} \exp\left(-\frac{x_0^2 + (\alpha_0 x_0 + \beta_0 x'_0)^2}{2\sigma_0^2}\right), \quad (12)$$

where N_b is the number of particles per bunch, $\sigma_0 = \sqrt{\beta_0 \epsilon}$, and ϵ is the horizontal geometric emittance. The luminosity density λ in phase space, which corresponds to the distribution of the BFPP ions, is then calculated by integrating over the two colliding bunches, where we denote the coordinates in the opposing bunch at the IP by u and impose $u_0 = x_0$ as a condition for a collision to take place:

$$\begin{aligned} \lambda(x_0, x'_0) &= \frac{\int f_{\beta}(x_0, x'_0) f_{\beta}(x_0, u'_0) du'_0}{\int f_{\beta}(x_0, x'_0) f_{\beta}(x_0, u'_0) dx'_0 du'_0 dx_0} \\ &= \frac{\beta_0}{\sqrt{2\pi}\sigma_0^2} e^{-[2x_0^2 + (\alpha_0 x_0 + \beta_0 x'_0)^2]/(2\sigma_0^2)}. \end{aligned} \quad (13)$$

This is again a Gaussian distribution, but with a smaller standard deviation

$$\sigma_{\lambda,0} = \left(\int x_0^2 \lambda(x_0, x'_0) dx'_0 dx_0\right)^{1/2} = \frac{\sigma_0}{\sqrt{2}}. \quad (14)$$

Similarly, the standard deviation of the angular distribution of the BFPP ions is

$$\sigma_{p,0} = \sqrt{\frac{\epsilon}{\beta_0} \frac{2 + \alpha_0^2}{2}}, \quad (15)$$

which reduces to the familiar expression $\sqrt{\epsilon/\beta_0}$ if $\alpha_0 = 0$ (as holds at all IPs in the LHC). We see that the distribution of collision points in space is narrower than the bunch distribution by a factor $\sqrt{2}$, while the angular distribution is similar to that of the initial bunch. The vertical coordinates y and y' are treated analogously.

The size of the BFPP beam changes as it propagates through the accelerator lattice. Using Eq. (10) to propagate

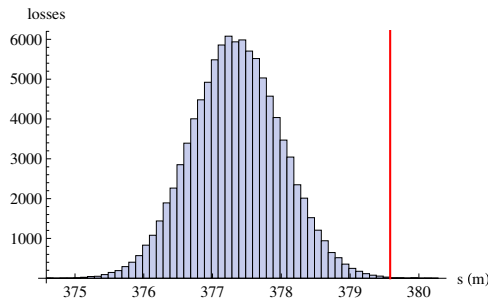


FIG. 3. (Color) The longitudinal distribution of the impact positions of lost $^{208}\text{Pb}^{81+}$ ions from BFPP after IP2 in the LHC, as simulated by tracking 10^5 particles. The red line indicates the end of a superconducting dipole magnet.

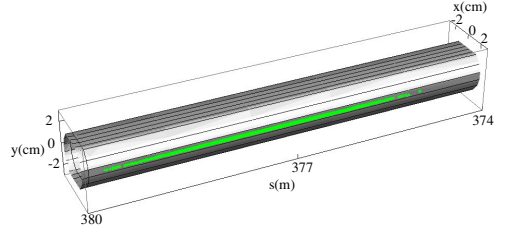


FIG. 4. (Color) The distribution of the impact positions of lost $^{208}\text{Pb}^{81+}$ ions from BFPP after IP2 in the LHC, as simulated by tracking 10^4 particles, shown together with the beam screen.

the beam distribution in Eq. (13) the standard deviation of the BFPP particles at s_1 can be shown to be

$$\sigma_{\lambda,1} = \sqrt{\frac{1 + \sin^2(\bar{\mu}_1 - \bar{\mu}_0)}{2} \bar{\beta}_1 \epsilon + \bar{d}_1^2 \langle \delta_p^2 \rangle}. \quad (16)$$

This can be compared to the main beam, with $\sigma_1 = \sqrt{\beta_1 \epsilon + D_1^2 \langle \delta_p^2 \rangle}$, where D_1 is the periodic on-momentum dispersion. Differences come both from the fact that the BFPP beam envelope is oscillating with $\bar{\mu}$, rather like a mismatched beam at injection, and the chromatic variation of the optical functions.

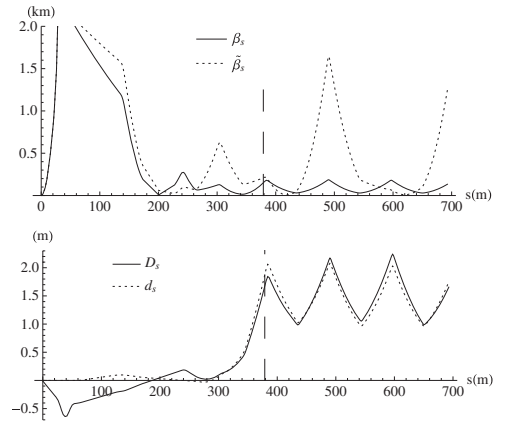


FIG. 5. The on-momentum horizontal β function downstream of IP2 compared with the off-momentum $\bar{\beta}$, calculated as described in the text (top), and the periodic dispersion function D shown together with the locally generated dispersion d (bottom). The dashed vertical line indicates the central loss position of the BFPP particles, close to the first maximum of the dispersion.

We can deduce the impact point of the BFPP losses directly from Fig. 2. Once this is known, we implement a fast tracking of single particles from the IP to the beginning of the element where losses occur using Eq. (10). Inside this element an analytical algorithm is used to find the impact coordinates and momenta.

At IP2 in the LHC, the BFPP beam converted from the clockwise-circulating beam 1 is lost near the end of a superconducting dipole magnet in the dispersion suppressor (known as “MB” type). Tracking gives normally distributed losses along s , shown in Figs. 3 and 4, with a mean of $s = 377.35$ m from IP2 and a standard deviation of 65 cm. In the case of IP1 or IP5 the loss positions are around 418 m downstream of each IP, also in superconducting dipole magnets, with projected rms spot sizes of 58 and 74 cm, respectively. The situation around the three IPs is therefore comparable, and we focus on IP2 in the remainder of this paper, except where otherwise indicated.

In Fig. 5 we show the on- and off-momentum β functions downstream of IP2. Around the impact point we have $\beta_1 \gg \tilde{\beta}_1$ meaning that the BFPP beam is much smaller than the nominal beam. This effect concentrates the heat load in a smaller volume of the magnet.

III. SHOWER SIMULATION

The next step to determine the risk of quenches from the BFPP beam losses is to estimate the energy deposition they give rise to. Defining the origin of cylindrical coordinates (r, ϕ, z) at the center of the beam pipe at a magnet entrance, the heating power density P is

$$P(r, \phi, z) = \mathcal{L} \sigma_{\text{BFPP}} W(r, \phi, z), \quad (17)$$

where W is the average, over many possible showers, of the energy deposition per unit volume in the superconductor or other material per lost $^{208}\text{Pb}^{81+}$ ion.

The quantity W , which has the unit $\text{J}/(\text{cm}^3 \text{ ion})$, depends on the distribution in space and momentum of the ions lost on the beam pipe, and the cross sections for the many interactions that occur as the shower develops in the material structure of the magnet. We estimate W through simulations with FLUKA, where a 3D model of a main dipole has been implemented [29] as shown in Fig. 6.

The lost particles first hit the beam screen, which is a racetrack-shaped chamber intended to protect the magnet from synchrotron radiation. Outside is the circular cold bore (labeled “beam pipe” in Fig. 6), which is surrounded by the superconducting coil, consisting of an inner and an outer winding. The collar is a part of the coil support structure and is inserted in the iron yoke. All these parts are heated by the hadronic and electromagnetic showers.

The FLUKA model of the magnet contains some simplifications: (i) The matrix of superconducting NbTi filaments and copper inside the coil was modeled as a homogeneous body with weight fractions of the materials corresponding to the real coil. (ii) The curvature of the magnet was

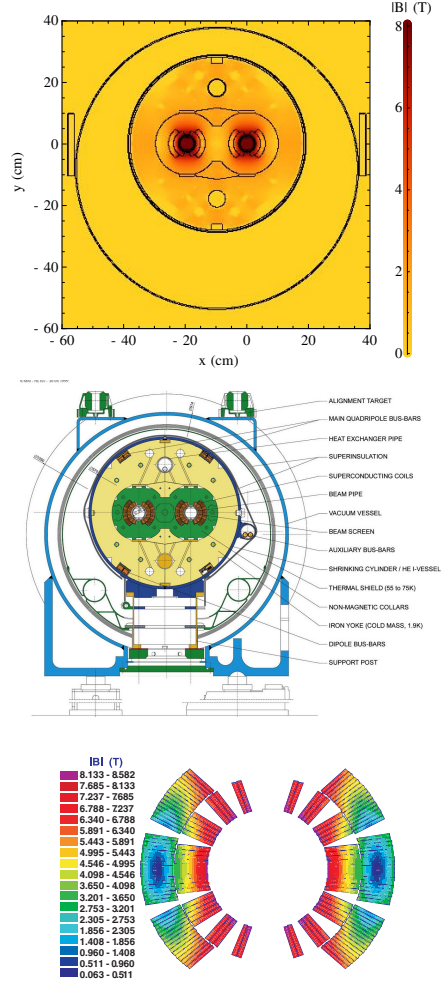


FIG. 6. (Color) The transverse cross section of the FLUKA model with the magnetic field superimposed (top), a technical drawing [1] (bottom) of an LHC main dipole (middle) and the magnetic field in the superconducting cables (bottom). The rectangular boxes on the outside of the magnet in the FLUKA model represent beam-loss monitors as discussed in Sec. VIII.

neglected (although it was included in the tracking up to the impact on the beam screen). The cold mass is 15.2 m long and has a sagitta of 9.18 mm [1]. Simplified FLUKA simulations, representing the magnet as a solid block (either rectangular or with a 9.18 mm sagitta), shows that the introduced error is around 3%–4%, which is negligible compared to the overall simulation error. (iii) The magnetic

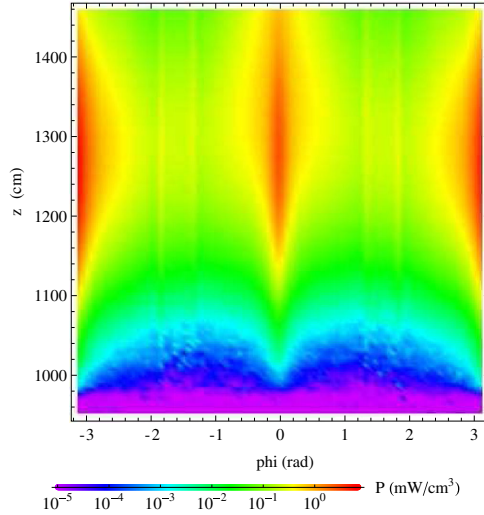


FIG. 7. (Color) The heating power from beam losses caused by BFPP in the inner layer of the coil of an LHC main dipole as simulated with FLUKA. The power density was averaged over the width of the cable and is shown as a function of azimuthal angle ϕ and longitudinal coordinate z , with $z = 0$ in the beginning of the magnet. The beam loss is centered around $z = 1206$ cm and $\phi \approx -3.11$ rad.

field was included inside the yoke but omitted outside, where it cannot affect the results of the magnet quench evaluation. (iv) Parts of the magnet far away from the coil are not necessary to include for the purpose of estimating the energy deposition in the coils; however, they are

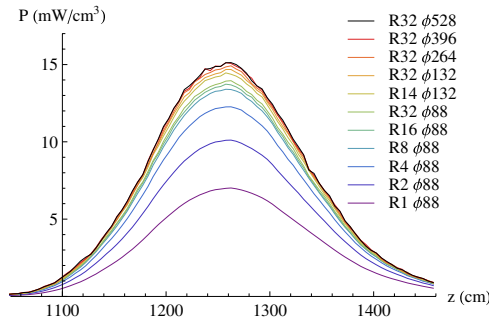


FIG. 8. (Color) The linear power density along z caused by BFPP in the inner layer of the coil of the dipole magnet for varying radial and azimuthal binnings, where $Ri\phi j$ stands for i radial bins and j azimuthal bins. In all cases, we used a longitudinal cell size of $\Delta z = 5$ cm. The hottest bin was selected for each mesh.

needed for later simulations of the beam-loss monitors (BLMs) described in Sec. VIII.

The coordinates and momenta of the particles impinging on the inside of the beam screen, generated by the tracking described in Sec. II, were fed as initial conditions to the FLUKA simulation. Some 10^4 particles were sufficient to keep the statistical error below 2% when the energy deposition in each cell of several spatial cylindrical grids was recorded.

Figure 7 shows the power density in the inner layer of the superconducting coil and Fig. 8 presents the energy deposition along the length of the cable at the hottest azimuth in the radial bin in the coil closest to the impact for different meshes. In both figures, energy deposition is converted to power density at the design luminosity of Table I with Eq. (17). The maximum power density in the coil is $P \approx 15.5$ mW/cm³ using LHC optics V6.503, and does not change if the cell sizes $r\Delta r\Delta z\Delta\phi$ are reduced.

We estimate that the FLUKA simulation has a systematic error margin of a factor 2–3, taking into account the uncertainties from the surface effects in the grazing incidence, the transverse momentum distribution, and the showering and cross sections at LHC energy. This error is consistent with Refs. [24,30].

IV. THERMAL NETWORK SIMULATION

The heat load distribution in the coil can be used to estimate the resulting temperature profile. Since the flux of lost $^{208}\text{Pb}^{81+}$ ions changes only on the scale of tens of minutes, a steady state situation is considered, with a continuous deposition and evacuation of heat from the coil. We discuss fluctuations of the heat load in the end of this section.

To better understand the heat flow, we describe briefly the coil geometry. The Rutherford-type cables in the coil (see Fig. 9) consist of strands (28 and 36 in the inner and outer windings, respectively), made of NbTi filaments, which are embedded in a copper matrix. Helium inside the cables occupies the space between the strands [31] but serves mainly to increase the heat capacity for protection against transient losses [32]. The cables are wrapped with three layers of polyimide electric insulation and a 0.5 mm-thick ground electric insulation is placed between the coil and the collar, which has been identified from measurements as a heat reservoir [33]. The collar is built from 3 mm-thick austenitic steel plates with a 0.1 mm gap between them filled with helium in direct contact with the heat exchanger through the helium in the iron yoke. The heat flow in steady state, schematically shown in Fig. 10, is mainly limited by the heat conduction of the electric insulation of the cables and the size of the helium channels in the magnet.

There are several estimates of the quench limit, that is the smallest power density that could cause a quench.

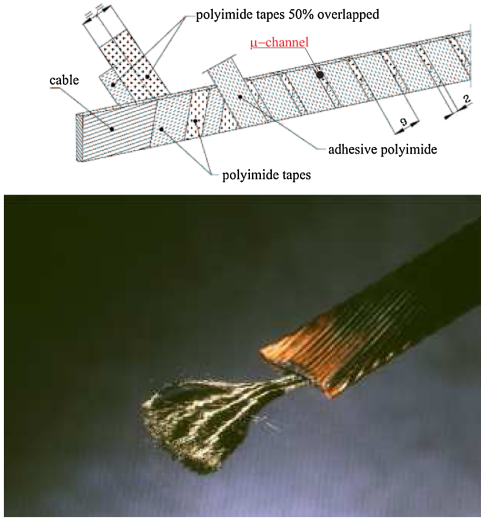


FIG. 9. (Color) Close-up of a single cable where the current carrying strands, and the filaments composed of NbTi, are visible.

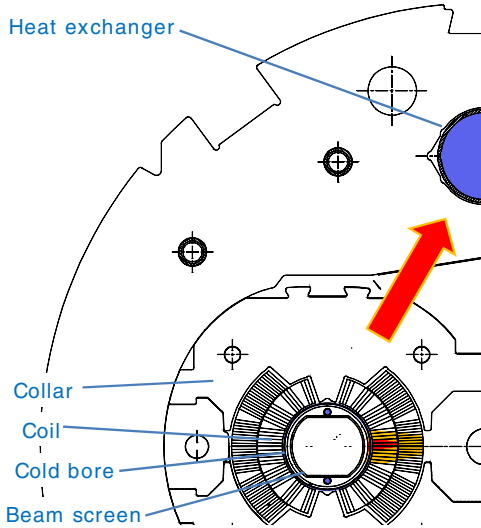


FIG. 10. (Color) Cross section of a part of an MB magnet where the red arrow schematically indicates the heat flow from the coil to the heat exchanger.

In Refs. [1,34] it is estimated as 5 mW/cm^3 and 4.5 mW/cm^3 . The maximum simulated BFPP power is more than a factor 3 higher. These estimates are based on experiments [35,36] where a homogeneous heat deposition in a cable sample is assumed. In the case of BFPP however, the energy deposition is nonuniform and distributed over the entire MB coil.

References [37,38] describe a more detailed method of heat-flow modeling in the coil, based on a thermal equivalent of an electrical network. This *network model* can be used to simulate the steady state heat flow caused by a given input heat source, e.g., a beam loss. It can then be inferred from the temperature map whether the magnet quenches or not. Since the network model simulations in Refs. [37,38] show that the quench limit is highly dependent on the heat load distribution and the coil structure, a new network model simulation, directly using the heat deposition map simulated with FLUKA, should be the most accurate assessment of the risk of quenches due to the BFPP beam losses.

The network model takes as input a mesh of thermal elements, which was created from technical drawings of the magnet. It describes accurately the radial structure of the magnet from cold bore to collar, i.e., the cold bore, cold bore insulation, the helium channel around the cold bore and the coil, with the strands as the smallest thermal unit. It implements the thermal paths of the heat flowing from the cables through the insulation to the collar (Fig. 10). Furthermore, superfluid, normal fluid, and gaseous helium phases are taken into account, as well as both heat con-

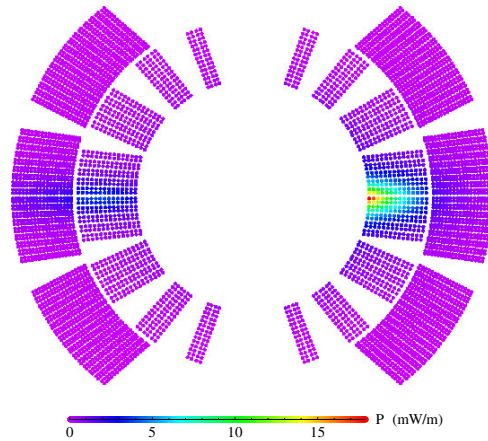


FIG. 11. (Color) The power deposition in each strand of the superconducting coil in the 5 cm-longitudinal cell where it assumes its maximum value, as interpolated from the result of the FLUKA simulation.

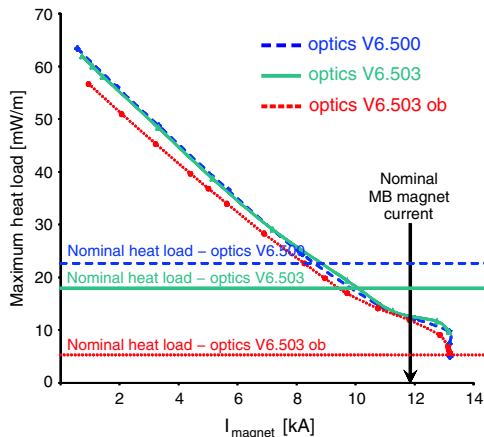


FIG. 12. (Color) Maximum allowed heat load in a single strand versus current of the MB dipole magnet for three different spatial heat load distributions caused by BFPP in different versions of the LHC optics: V6.500, V6.503 (current), and V6.503 ob (with an orbit bump as discussed in Sec. IX). The horizontal lines show the heat loads expected at design luminosity as calculated by FLUKA. The required current for 2.76 TeV/nucleon $^{208}\text{Pb}^{82+}$ operation is indicated by a vertical black arrow. At the arrow, the tolerated power is smaller than the expected for V6.500 and V6.503, meaning that quenches can be expected during nominal operation.

duction and convection, and nucleate boiling of normal fluid helium [38].

Other required simulation input includes the heat conductivity of the materials in the coil (calculated with the CRYODATA software [39]), the temperature margin distribution in the coil, computed with the ROXIE program [40], and the power deposition in each strand. Since they are not arranged in a regular polar mesh, the binning used in the FLUKA simulation cannot be made to correspond exactly to the strand positions. The power in the strands is therefore obtained through a two-dimensional linear interpolation of the FLUKA output (shown in Fig. 11) using the cell dimensions $\Delta z = 5$ cm, $\Delta\phi = 2\pi/132$ rad, and $\Delta r \approx 1.1$ mm (corresponding to 14 radial bins).

In the course of the network model simulation, the input distribution in the magnet is varied by scaling each value of the heat load map in Fig. 11 up or down by a global scaling factor in order to determine the quench limit. The result of this simulation is presented in Fig. 12, which shows the maximum allowed input power load in a single strand before a quench occurs as a function of the magnet current for three different power load distributions caused by BFPP losses in different LHC optics versions. (This is somewhat artificial since changing the magnet current would normally amount to a change in beam energy and loss distri-

bution but the abstraction illuminates the physics of the magnet, considered as a “target”). Figure 12 shows possible working points of the magnet for a given heat source distribution, and the margin to quench at nominal beam energy can be read out directly. Here we discuss LHC optics V6.503 and leave the others for later sections. The expected heat loads are indicated by a horizontal lines.

The function shown in Fig. 12 drops steeply for large currents, when the current itself is the limiting factor for quenching. In this regime, the energy is efficiently transported away by the superfluid helium. This is not the case for smaller currents since, when higher temperatures are tolerated, the helium loses its superfluidity. When not all of the energy can be transported away, the heating becomes the limiting factor for quenching and the function is approximately linear.

As can be seen from Fig. 12, quenches are likely to occur at nominal operation and the luminosity for case V6.503 has to be decreased by 30% to go below the quench limit. Since the loss conditions are very similar at IP1 and IP5, quenches can also be expected there at comparable levels.

When averaging the power from BFPP losses over the width of the cable, the simulated quench limits for these loss distributions are 5–6 mW/cm³ depending on optics version. This is in good numerical agreement with Refs. [1,34], although we have assumed a higher temperature margin and lower magnetic field. Therefore, for the same temperature margin, our modeling of the magnet is more pessimistic for the BFPP heat distribution.

All presented simulations assume steady state, where the heat load is constant in time. However, the real distribution of the losses in time shows statistical fluctuations. The number of BFPP particles created in a single-bunch crossing can be approximated by a Poisson distribution. At nominal luminosity the expectation value is $\mathcal{L}\sigma_{\text{BFPP}}/(k_b f_{\text{rev}}) = 0.043$ events per crossing, where $\mathcal{L}$ and k_b are given in Table I, σ_{BFPP} by Eq. (6), and $f_{\text{rev}} = 11.1$ kHz is the revolution frequency. The sum of BFPP particles created in several crossings has also a Poisson distribution, which can be approximated by a normal distribution for a large number of particles.

To estimate if statistical fluctuations could cause quenches, we assume operation at 95% of the quench level (which might be overly optimistic) and calculate the probability of an increase in the number of BFPP particles large enough to induce a quench. The network model simulations show that the temperature margin at this average heat load is 0.3 K. We consider three time scales as in Ref. [32].

$t \lesssim 10$ μs .—During this time, corresponding to 65 bunch crossings, 1.9 BFPP events are expected on average, and the heat deposited in the superconducting cable is not yet transferred to the helium inside the cable. The capability of withstanding a quench is thus given by the cable enthalpy reserve corresponding to a 0.3 K increase, which is calculated to 0.48 mJ/cm³. If the BFPP particles are pessimistically assumed to be lost at the same s value, this

corresponds to an increase in the number of BFPP events during a $10\ \mu\text{s}$ interval by more than a factor 1000. The probability of this occurring during one month of $^{208}\text{Pb}^{82+}$ operation at full luminosity (which is overly optimistic) is practically zero.

$10\ \mu\text{s} \leq t \leq 0.1\ \text{s}$.—The heat is transferred to the helium inside the cable but not out through the insulation. The enthalpy reserve is $11.7\ \text{mJ}/\text{cm}^3$, corresponding to an increase in the number of BFPP events by a factor 8 during $0.1\ \text{s}$. The probability of this occurring during one month of $^{208}\text{Pb}^{82+}$ operation is again vanishingly small.

$t \geq 0.1\ \text{s}$.—Heat is transferred out through the cable insulation to the heat exchanger and we consider the steady state quench limit given by the network model. During $0.1\ \text{s}$ there is on average 19 068 BFPP events, while 20 071 are required for a quench. The expected number of such fluctuations during one month is 4.8×10^{-6} .

The very small probability of a statistical fluctuation causing a quench justifies our steady state approach.

A successful benchmark of the network model [38] used a special heating device inserted into a cold magnet to produce a known heat load. Measurement and simulation agreed within 30% for the current where a quench occurs in the relevant range of heating the power. We take this a guide to the uncertainty of the network model simulation.

V. SENSITIVITY ANALYSIS

In reality, the impact points of BFPP ions vary as a function of imperfections such as magnet misalignments, field errors, and the imperfect aperture. Taking into account the real geometric aperture interpolated from measurements [41,42], the longitudinal loss distribution changes slightly, but FLUKA simulations show that the increase of peak heat load in the coils is negligible.

We also studied the variations of the loss pattern caused by optical imperfections. Imperfect corrections resulting in a residual closed orbit caused by measured magnet misalignments [41,42] were simulated and BFPP ions tracked in the resulting optics. The average longitudinal position of the impact point near IP2 varied by up to 2 m. A negative horizontal closed orbit, x_c , in the BFPP impact zone causes BFPP ions to be lost further downstream and losses may appear in the corrector magnet and beam position monitor (BPM) attached to the next main quadrupole. Such losses could make the BPM unusable. Unrealistic orbits $x_c \leq -2\ \text{mm}$ at the impact point cause some BFPP ions to miss the aperture completely at the first maximum of the dispersion function and continue instead to the second (see Fig. 2), where they hit another main dipole magnet. This is discussed further in Sec. IX.

To illustrate the sensitivity of the whole simulation chain with respect to optical distortions, we compared with V6.500, an earlier version of the LHC optics, with a 7% smaller β at the impact point after IP2. However, in the off-

momentum optics, $\tilde{\beta}$ is a factor 2 smaller, reducing the longitudinal spot size to $\sigma_{\text{A},1} \approx 49\ \text{cm}$. The resulting maximum allowed power as a function of current is shown in Fig. 12. This is very similar to V6.503, but the expected heating during nominal operation is about 25% higher due to the smaller spot size.

The error sources in all simulation steps give rise to a large uncertainty of approximately a factor 3.9 on the final quench limit in the worst case. The real error is however expected to be much smaller than that. Our practical conclusion is that the heat load from BFPP beam losses are likely to be above the quench limit and therefore limit the luminosity of Pb-Pb collisions in the LHC.

VI. COMPARISON OF OPERATING CONFIGURATIONS

As the commissioning and operation of the LHC progresses, Pb-Pb collisions will occur in a variety of configurations [1,2] with varying beam energy, intensity, and other parameters such as the optical function β^* at the interaction point [note that $\beta^* = \beta_0$ defined in Eq. (4)]. First ion collisions will likely take place at an energy of 1.97 TeV/nucleon (the same magnetic rigidity as a 5 TeV proton beam) rather than the nominal energy of Table I where magnetic fields and excitation currents are lower, meaning that more heat can be absorbed before a quench takes place (see Fig. 12). On top of that, both the luminosity and the energy deposited per lost BFPP ion will be lower.

We repeated the tracking and FLUKA simulation for this case, assuming $\beta_0 = 0.5\ \text{m}$ at IP2 (which is overoptimistic for reasons of aperture but a useful comparison). The resulting distribution of the heat deposition is very similar to the nominal case apart from a global scaling factor of 0.63. Thus there is no need to redo the thermal network simulation—the maximum tolerated heat load can be read out directly from the curve 6.503 in Fig. 12, at the appropriate current of 8.46 kA. The error introduced by omitting the last simulation step is less than 10% if we use as a benchmark V6.500, for which the full simulation chain was carried out. This gives an expected heat load with a 1.97 TeV/nucleon $^{208}\text{Pb}^{82+}$ beam at 46% of the quench level, which means that quenches are unlikely to take place but still within the simulation uncertainty.

We have performed similar tracking and FLUKA simulations for various values of β_0 that may be used for collisions. Increasing β_0 reduces the luminosity ($\mathcal{L} \propto \beta_0^{-1}$) and the event rate for BFPP [see Eq. (17)]. Furthermore, in each optics version $\tilde{\beta}$ and $\tilde{d}$ at the impact point after IP2 are slightly different, thus causing variations in the loss distributions. The heating in the magnet scales therefore only approximately as $P(x, y, z) \propto \beta_0^{-1}$.

The results of the quench performance for BFPP at IP2 for all optics versions are summarized in Fig. 13. The bottom part shows expected luminosity limitations, where

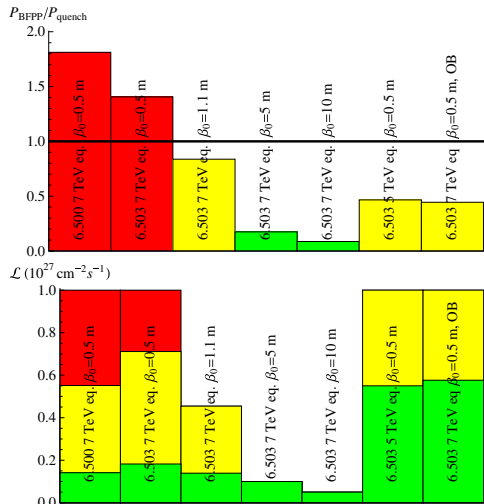


FIG. 13. (Color) The expected heating power from losses caused by BFPP at IP2 normalized by the heating power that causes a quench (top) and expected quench behavior at different luminosities (bottom) for various energies (labeled with the proton-equivalent energy), versions and configurations of the LHC optics. The colors are a semiquantitative indication of how dangerous the losses are expected to be: Red bars mean that the simulated heat load is above the quench limit (note that operation may still be possible due to simulation errors), yellow that the heat load is below the quench limit but quenches cannot be excluded due to simulation uncertainties, while green bars can be considered as safe. The height of the bars indicates design luminosity. The assumed value in the 5 TeV configuration might be too optimistic for reasons of aperture, in particular for the final focusing triplets.

we have assumed that the spatial heat load distribution in a certain distribution stays constant when the luminosity varies. This is strictly true only when the luminosity is changed through a decrease in bunch population or number of bunches.

In Fig. 13 we also show the result for the nominal optics but with an orbit bump introduced to reduce the maximum energy deposition. This is discussed in detail in Sec. IX.

No heavy-ion collisions are planned to take place at injection energy.

VII. LOSSES FROM EMD IN THE LHC

Since the ions affected by EMD1 stay within the momentum acceptance of the LHC ring, they are intercepted by the momentum collimation system (see Fig. 2).

For EMD2 ions, we consider δ_p as the sum of two random variables: The natural momentum deviation in the bunch with standard deviation $\sigma \approx 1.1 \times 10^{-4}$ [1]

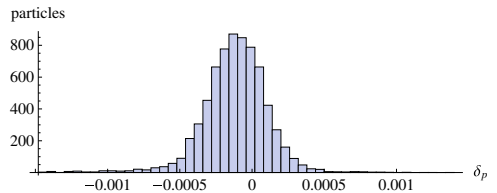


FIG. 14. (Color) The distribution of δ_p caused by EMD2 as simulated by FLUKA. The distribution has $\langle \delta_p \rangle \approx -1.25 \times 10^{-4}$ and $\sqrt{\langle (\delta_p - \langle \delta_p \rangle)^2 \rangle} \approx 2.6 \times 10^{-4}$.

and the recoil caused by EMD, which was simulated with FLUKA (see Fig. 14). The resulting distribution is approximately Gaussian with mean $\mu = -1.25 \times 10^{-4}$ and standard deviation $\sigma = 2.9 \times 10^{-4}$.

We used Eq. (10), with x_B replaced by the central EMD2 trajectory, to track particles from IP2 with this δ_p distribution and a phase space distribution given by Eq. (13). The resulting loss map is shown in Fig. 15. Around half of the losses are distributed over several locations, where there is no risk of quenches due to the small intensity and the wide spot sizes, while the other half is lost at $s \approx 3125$ m towards the end of a drift, 70 cm in front of an orbit corrector magnet, called MCBC. Since the losses occur at a place where the aperture is steeply decreasing, they are distributed over a very small longitudinal distance with a standard deviation of 2.9 cm. Therefore, the heat density per particle is correspondingly higher than in the case of BFPP. In Fig. 16 we show a close-up of the impact of the 6- σ envelope of the EMD2 beam from IP2.

The quench limit of the corrector is not well known. It is a function of the current and magnetic field, which are highly dependent on the closed orbit and the global orbit correction scheme. Furthermore, no network model of the corrector exists, so detailed simulations with FLUKA and the network model were not carried out. Assuming its

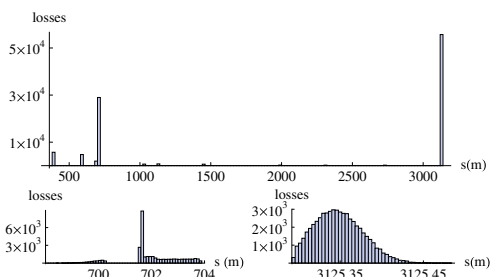


FIG. 15. (Color) The distribution of $^{206}\text{Pb}^{82+}$ losses after IP2. The two bottom plots show zooms on the largest peaks on the upper plot. Only the loss at $s \approx 3125$ m risks to induce quenches, because of the small projected spot size.

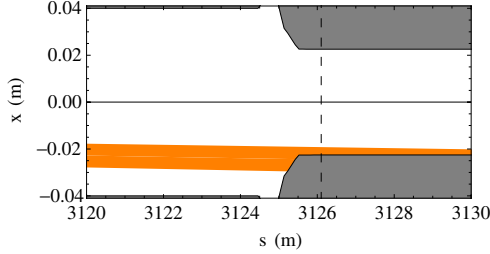


FIG. 16. (Color) The impact of the 6σ envelope of the $^{206}\text{Pb}^{82+}$ ions created by EMD2 at IP2 at an aperture restriction. The projected longitudinal rms spot size on the beam screen is only 2.9 cm. The loss takes place in a drift section and the beginning of next magnet, a corrector, is indicated by a dashed vertical line.

quench limit to be similar to the dipole's, we conclude that there is a risk of quenching from the small spot size. Since the beam is automatically dumped if the corrector quenches, this cannot be allowed to happen.

However, it is possible to exclude this magnet from the global orbit correction. This means that it will not be operating during heavy-ion runs, excluding quenches at the price of possible orbit distortions. Therefore losses from EMD2 are less serious than from BFPP, since a dipole is necessary for machine operation. During the first ion runs at 1.97 TeV/nucleon, the corrector is much less likely to quench than at top energy, for the reasons explained in Sec. VI.

Further losses from EMD2 take place 433.7 m downstream of IP1 and IP5, in a drift section only 30 cm in front of a main quadrupole. In this case the projected rms beam sizes of the impinging ions are 30 cm for both IP1 and IP5. In spite of this small size, the risk of quenches is small for several reasons. The quench limit of a quadrupole is around 40% higher than that of a dipole [38] and the cross for EMD2 section is about 10 times smaller than for BFPP. Furthermore, during the measurements described in Ref. [38], it was found that the tolerable heat load is approximately 50% higher in the ends of the magnet, where the magnetic field is lower and the cooling more efficient. However, to quantitatively determine the margin to quench, network model simulations should be carried out.

VIII. MONITORING LOSSES

Since beam losses caused by BFPP or EMD might induce quenches, it is vital to survey these losses while beams are colliding and to make sure that the beam is extracted quickly to a dump before a quench can occur. The LHC's beam-loss monitor (BLM) system has been designed to detect losses around the ring during proton operation [43,44]. The LHC BLMs are 50 cm long ionization chambers filled with nitrogen that detect secondary



FIG. 17. (Color) Interior part of an ionization chamber used as a beam-loss monitor in the LHC. Taken from Ref. [43].

charged shower particles outside the magnet cryostat. In order to minimize the drift time of the ions and electrons set free in the chamber, there is a stack of parallel aluminum plates inside the cylinder with alternating polarities and 5 mm spacing. A view of the interior part of an ionization chamber is shown in Fig. 17.

The locations of the BLMs and the thresholds for triggering the beam dump system have been determined for protons through simulations [45,46]. The BLM threshold signal should correspond to a certain level of power deposition in the coil and the ratio of these two quantities could well be different depending on the type of particle lost and the showers it gives rise to. Accordingly, there are two important problems related to the monitoring of ion beam losses from the collisions: (i) to determine the BLM threshold signals for Pb ion losses; (ii) to verify that the placement of BLMs provides adequate coverage of the loss patterns.

To investigate the first problem, we simulated the development of the showers generated by particle losses, both from $^{208}\text{Pb}^{82+}$ ions and protons, in an LHC dipole magnet with FLUKA; the geometry was as described in Sec. III and Fig. 6. The BLMs are schematically modeled as thin rectangular iron boxes filled with nitrogen, placed outside the MB cryostat. This simplification is consistent with simulations done for protons [43] and can be considered reasonable since we are primarily interested in the ratio between heat deposition from heavy-ion and proton losses rather than the absolute signal from the BLM.

For each particle species, a generic beam loss was represented by a "pencil" beam: a monoenergetic beam of particles, all hitting the vacuum chamber at the same point (in the horizontal plane, 1 cm from the entrance of the magnet) at the same angle of incidence (0.5 mrad). An arbitrary loss can be modeled as a superposition of pencil beams. Simulations were done with $^{208}\text{Pb}^{82+}$ ions and protons at 2.76 TeV/nucleon and with protons at 7 TeV.

During the simulation, the energy deposition was scored in the beam screen, in the superconducting coil (using the mesh described in Sec. III) and in the BLMs. Since the BLM signal is proportional to the ionization energy loss in its gas volume and ionization is the dominant energy loss process for the low-energy charged secondaries that emerge outside the cryostat, this is a fair approximation. The resulting energy deposition profiles along the hottest superconducting cable in the MB coil and in the closest BLM are shown in Fig. 18. The ratio between the heat

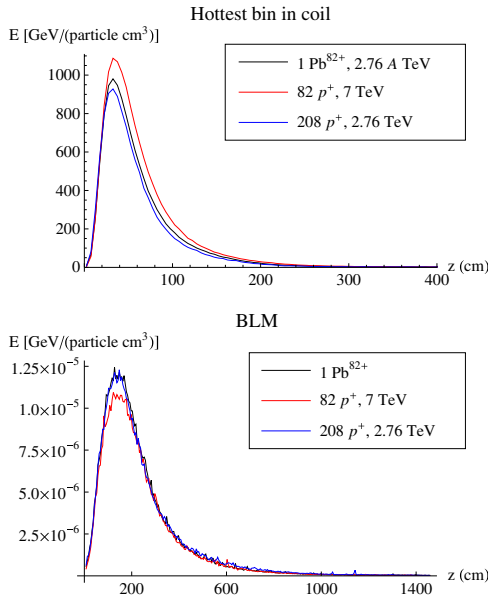


FIG. 18. (Color) The energy deposition in the hottest wire in the coil and in the N_2 gas inside the ionization chamber for Pb ions and protons. The three cases are scaled to equivalent total energy of incoming particles.

deposited in the coils and the energy deposition in the BLMs is similar for $^{208}\text{Pb}^{82+}$ ions and protons at the same energy per nucleon, while 7 TeV protons have an even lower ratio between BLM signal and heating of the coil than 2.76 TeV/nucleon $^{208}\text{Pb}^{82+}$ ions.

This similarity comes from the fact that the particles causing ionization of the gas in the BLMs are not the $^{208}\text{Pb}^{82+}$ ions and protons lost directly from the beam, but instead low-energy secondary particles, mainly electrons, created in the hadronic shower. The energy deposition resulting from the hadronic shower is very similar for heavy ions and protons [47], even though the nuclear interaction lengths are very different (0.8 cm for 2.76 TeV/nucleon $^{208}\text{Pb}^{82+}$ and 25 cm for 7 TeV protons on a Cu target according to FLUKA simulations). This comes from the fact that, when an ion traverses a target, the nucleus splits up into smaller fragments through electromagnetic dissociation and nuclear interactions in several steps. Once totally fragmented it gives rise to a similar shower profile as independent nucleons. The energy deposition from the first few interactions is far exceeded by deposition by the low-energy secondary particles created later in the shower.

If the energy per nucleon increases, so do the cross sections, and more energy is deposited closer to the impact.

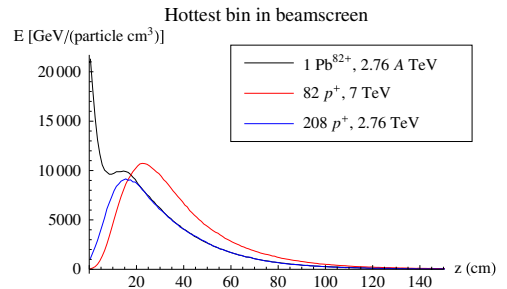


FIG. 19. (Color) The energy deposition for the $^{208}\text{Pb}^{82+}$ ions and protons at LHC energy in the beam screen, as a function of the longitudinal coordinate in the magnet, averaged over 0.1×0.1 mm² transversally and 10 mm longitudinally.

This explains why 82 protons at 7 TeV have a somewhat higher energy deposition in the coil than the 208 protons at 2.76 TeV.

The only location where a significant difference in energy deposition between $^{208}\text{Pb}^{82+}$ ions and protons can be seen is in the beginning of the shower, close to the central core. Here the difference in ionization energy loss, given approximately by the well-known Z_0^2 dependence in the Bethe-Bloch formula [48], is clearly visible and the ions cause a much higher energy deposition. Thanks to the small impact angle, this effect is only visible in the beam screen, as shown in Fig. 19.

Based on the similar ratio between energy deposition in the coil and in the BLMs outside the cryostat, we conclude that we can use the same beam dump thresholds for $^{208}\text{Pb}^{82+}$ ions and protons in the LHC. This result applies to all mechanisms for ion beam losses in the LHC, not only those discussed in this paper.

Suitable positions for BLMs were determined from the optical studies illustrated in Fig. 2. Studies were performed both for the nominal parameters and a configuration known as the “early ion scheme” optics (which has a higher $\beta^* = 1.0$ m, see Chap. 21 in Ref. [1]) and for the two beams circulating in opposite directions.

Because of the uncertainty of the impact position, described in Sec. V, and the fact that the loss peaks are narrow and localized, the LHC’s machine protection system needs a very tight coverage with BLMs. Based on the energy deposition profile in the BLM gas (see Fig. 18) a 1.5 m spacing between chambers has been assumed for both beams to ensure full detection and localization of losses.

The BLMs foreseen for proton operation are mounted on all quadrupoles in the arcs and dispersion suppressors [43]. Extra chambers for monitoring ion losses from BFPP have been requested in all loss locations that are not already covered. Since a fraction of the losses might escape the first loss location and instead hit the aperture close to the

second peak of the dispersion, this position will also be monitored.

No extra BLMs are needed for losses from EMD2, since the loss locations are already covered by the default scheme.

IX. ALLEVIATION OF LOSSES

Ideally, the optics and aperture of a heavy-ion collider would be such that the transformed ions stay within the acceptance of the ring and are cleaned by the collimators. But this may conflict with other design constraints like the overwhelming cost advantage of keeping the aperture small. In the case of the LHC, quenches caused by lost BFPP and EMD2 ions are likely and methods to avoid them have to be found. Several methods using specialized hardware are possible, the most promising one being the installation of extra collimators around each IP where the dispersion starts to rise in the cold part of the machine [1,49]. This could be a very efficient solution but requires extra hardware to be installed, as well as displacing some magnets to make room in the tunnel and cannot be done before the first heavy-ion physics runs.

For these runs at least, other methods to mitigate the effects of BFPP and EMD2 using existing hardware will be needed. We cannot influence the quench limit of the dipole magnet, nor σ_{BFPP} , which leaves only $\mathcal{L}$ and W as the free parameters [see Eq. (17)]. It has been suggested that, for certain conditions on the filling time of the LHC, a higher integrated luminosity may be reached if the peak luminosity is reduced [50] by varying β^* during a fill as a function of the remaining intensity. However, this only pays off if the single-bunch intensity can be raised. Otherwise the only remaining option is to reduce W by varying the distribution of the impacting losses.

This might be achieved by manipulating the quadrupoles between the IP and the impact point to increase $\tilde{\beta}$ or $\tilde{d}$, spreading out the spot of heat deposition. However, strict requirements on the betatron phase advance around the LHC [51], matching conditions on the periodic β and dispersion functions at the ends of the dispersion suppressors and constraints on magnet strengths limit the scope of this approach. A gain in spot size of at best 20% was achieved using this method.

Another alleviation method might be to adjust the orbit or optics to move the impacts to more favorable positions. The horizontal orbit of the particles affected by BFPP and EMD2 emerging from IP2 in a perfect lattice, as calculated by MAD-X, is shown in the top part of Fig. 20 together with the main circulating beam. This is a close-up of the first 700 m in Fig. 2. The dispersive trajectories oscillate with d , and the BFPP particles are lost very close to its first maximum, which we call s_1 , while the EMD2 beam continues further downstream.

The green BFPP envelope in Fig. 20 is significantly wider at the second maximum s_2 of d , thanks to the larger

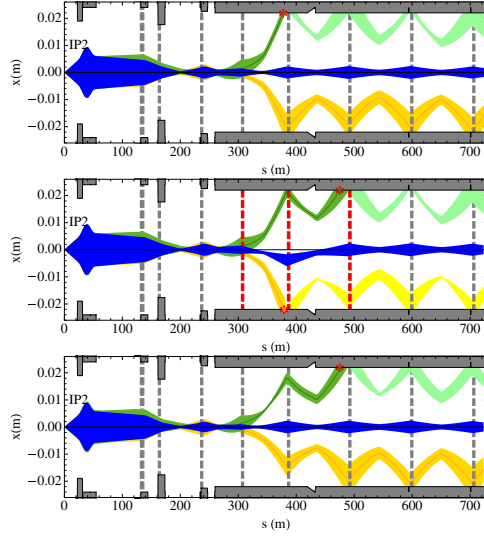


FIG. 20. (Color) Horizontal physical aperture and 6σ envelopes after IP2: with the usual flat orbit (top), with an orbit bump (middle), and with decreased dispersion (bottom). The beams are the main circulating $^{208}\text{Pb}^{82+}$ beam (blue), the $^{208}\text{Pb}^{81+}$ BFPP beam (green), and the $^{206}\text{Pb}^{82+}$ EMD2 (yellow). The vertical dashed lines show the locations of horizontal corrector magnets and those indicated in red are active (in this case, correctors called “MCBC” and “MCB”).

value of $\tilde{\beta}$ (see Fig. 5). A localized closed-orbit bump introduced around s_1 displaces x_B towards the center of the beam pipe and allows some of these particles to escape downstream to s_2 . There, the lost ions are diluted over a larger volume decreasing the maximum power deposition.

At the same time, the envelope of the EMD2 ions moves towards the outside of the beam pipe at s_1 provoking losses there. On balance this is beneficial because the aperture is constant in the neighborhood of s_1 , so the losses are spread out much more than at the later loss point shown in Fig. 16. This new loss position for the EMD2 ions is the same as for BFPP ions with a flat orbit but since the EMD2 ion flux is almost a factor 10 lower than for BFPP, the heating at this position is kept low enough to avoid quenching the dipole (see Fig. 12).

The off-momentum orbit can be displaced by orbit correctors attached to the main quadrupoles in the LHC. The orbit bump amplitude required was calculated to keep 95% of the BFPP beam, with the beam size given by Eq. (16), inside the aperture at s_1 . The resulting beam envelope with the bump active is shown in Fig. 20.

The orbit of the circulating beam is displaced by up to 3.8 mm in this configuration but it is clear that the 6σ envelope is still far from the aperture. Apertures in the

LHC are conventionally characterized using a quantity n_1 , defined as the maximum acceptable primary collimator opening, in units of beam σ that still provides a protection of the mechanical aperture against losses from the secondary beam halo [1]; the complete definition incorporates a variety of tolerances that we shall not enumerate here. The bump reduces n_1 for the circulating beam, from 30 to 21. This still provides sufficient aperture margin. The three corrector magnets used to make the bump would operate at between 9% and 26% of their maximum strength, leaving a comfortable margin for their function in the global orbit correction. The β beating due to the bump is around 0.3%, which is acceptably small [1].

We have repeated the simulation chain of tracking, FLUKA, and network model for the BFPP ions with the orbit bump included. The spot size at the new impact position, in another superconducting dipole magnet, is 220 cm and the maximum heat load from FLUKA is 4.5 mW/cm³, about a factor 3.5 less than without the bump. The result of network model simulation is included in Fig. 12. The expected heat distribution at s_2 with the orbit bump activated (indicated by a horizontal line) is predicted to be a factor 2.25 below the quench limit, still not completely safe.

Operationally, the bump amplitude will have to be fine-tuned around the theoretical value to compensate the local closed orbit and misalignments of the beam pipe. The BLMs placed around each loss location (as described in Sec. VIII) will be an essential tool to monitor how the BFPP losses move from the first to the second maximum of the dispersion.

The orbit bump will be set up at low luminosity, in order to avoid potential quenches, by means of a van der Meer scan [52], in which the beam orbits are scanned *vertically* across each other at the IP. One could also imagine tuning the bump using a higher value of β^* at the IP. However, this is less reliable since the optical functions between the IP and the impact point will change with β^* . Another option is to introduce the bump at lower beam intensity in an earlier fill and rely on reproducibility.

From the point of view of machine protection, we must consider the possibility that one of the three correctors used in the bump might quench, leaving the bump open and possibly causing damage. Two of them (of type MCBC) are directly connected to the beam abort system which would dump the beam immediately. In case of a quench of the third corrector (of type MCB), no automatic beam dump occurs. The resulting global orbit distortion will, if it is small enough, be corrected by the orbit feedback system, in which case the BFPP beam may quench a magnet. If the distortion is too large, the resulting beam losses will trigger a beam abort via the BLMs (and possibly also the beam position monitors). In all cases, the quench protection system should protect the magnets from physical damage.

If moving the losses to another location with a larger spot size was insufficient, one might spread out the losses

with several orbit bumps, which allow fractions of the BFPP beam past each maximum of d . By tuning the orbit bumps the losses can be spread over n dispersion maxima by $n - 1$ orbit bumps using $n + 1$ correctors in such a way that, ideally, a fraction $1/n$ is lost at each impact point. This decreases the maximum heating power in a single element by $1/n$ and can bring it below the quench limit if n is made large enough. However, since BLMs have to be used when the bumps are tuned, the precision of the achieved loss distribution is limited.

To determine the required bump amplitudes Δ_i at each impact location s_i , we consider the initial phase space at the IP. The particles lost at a location with horizontal aperture A_i satisfy (for $i \in [1, n - 1]$)

$$x_i - \Delta_i > A_i, \quad (18)$$

where x_i is given by Eq. (10) as a function of the initial conditions at the IP. These inequalities define regions R_i in the initial phase space, which vary with Δ_i . The fraction F_i of particles lost at s_i is the integral distribution function over the phase space area outside the aperture limitation (18) and not outside any previous aperture limitation:

$$F_i = \int_{R_i \cap (R_1^c \cup R_2^c \cup \dots \cup R_{i-1}^c)} \lambda(x_0, x_0') f_{\delta_p}(\delta_p) dx_0 dx_0' d\delta_p, \quad (19)$$

where R^c denotes the complement of region R and f_{δ_p} is the assumed Gaussian distribution function of δ_p .

The Δ_i can then be determined by requiring

$$F_i = 1/n, \quad \forall i \quad (20)$$

and solving Eqs. (19) recursively, starting at $i = 1$, which can be solved analytically to yield

$$\Delta_1 = \sqrt{2} \sigma_{\lambda,1} \text{erf}^{-1} \left(\frac{n-2}{n} \right) + x_{B,1} - A_1. \quad (21)$$

Here $\sigma_{\lambda,1}$ is given by Eq. (16). Numerical integration and solution has to be used for higher values of i .

The method of one or several orbit bumps only works as long as the displacement of the closed orbit is kept within acceptable limits and the corrector magnets do not operate too close to their maximum strength. This is not the case at IP1 and IP5, where the required bump amplitude for BFPP particles to avoid the first maximum of d is 8–9 mm. The method will not work there unless other changes are made to the optics.

Instead of an orbit bump, another method to move losses to s_2 would be to tune the quadrupoles after IP2 in order to decrease the dispersion at s_1 . MAD-X was used to rematch IP2 with all constraints mentioned in Ref. [51] and beam envelopes for one solution are shown in the third plot of Fig. 20. The longitudinal size of the spot at s_2 is 179 cm, meaning a higher heating power than with the orbit bump. So quenches cannot be excluded with this method either.

The required change in phase advance in the insertion is $0.05 \times 2\pi$, which can be compensated in the insertion in

IP4 containing the rf system [51] to keep the overall tune in the machine constant. This method has the advantage of not displacing the circulating beam but does not reduce the far-downstream losses from EMD2. Given the numerous other constraints on the LHC optics, it is difficult to envisage applying this method at IP1, IP2, and IP5 simultaneously.

X. CONCLUSIONS

Electromagnetic interactions, such as bound-free pair production and electromagnetic dissociation in ultraperipheral nuclear collisions at the LHC, modify the charge and mass of beam ions. These particles follow dispersive orbits until they are lost in locations determined by the machine optics, aperture, and the magnetic rigidity of the ions. When sufficiently localized they can heat superconducting magnetic elements enough to make them quench.

We have presented the first fully integrated simulation chain of beam tracking, shower simulation, and a thermal network model to evaluate the heat flow and quench behavior of the superconducting coils immersed in superfluid liquid helium. This simulation has been applied to the most critical loss mechanism, BFPP, occurring in the three heavy-ion collision points in the LHC. Heat deposition caused by $^{208}\text{Pb}^{81+}$ ions in main dipoles downstream from IP1, IP2, and IP5 is expected to be 40% above the quench limit, while $^{207}\text{Pb}^{82+}$ from EMD1 stay within the acceptance of the arc and are cleaned by the collimation system. Furthermore, depending on its excitation level, there is some risk from quenches of a corrector magnet downstream of IP2 by $^{206}\text{Pb}^{82+}$ ions created through EMD2.

To avoid quenches, an efficient beam-loss monitor system to detect these losses is needed. Shower simulations of the relations between the signals in the loss monitors and the energy deposition in superconducting coils have been carried out for $^{208}\text{Pb}^{82+}$ and proton beams. These demonstrate that, thanks to nuclear fragmentation, the beam abort system can be set to trigger at the same signal level for both beams. Additional monitors have been installed in critical locations for heavy-ion losses in the LHC.

Finally, we have investigated methods to alleviate the losses caused by BFPP and EMD2. We can move them to different locations in the machine, where the losses are spread out over a larger distance, lowering the energy deposition to around 45% of the quench limit. Approaches using orbit correctors to create a local orbit bump or quadrupole tuning to decrease the dispersion have been illustrated. These methods have the advantage of not requiring new hardware in the LHC but are not easily applied to all interaction points and do not provide sufficient safety margins against quenches. An efficient solution is likely to require new hardware such as additional collimators or masks in the dispersion suppressor sections.

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Observations of Beam Losses Due to Bound-Free Pair Production in a Heavy-Ion Collider

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Observations of Beam Losses Due to Bound-Free Pair Production in a Heavy-Ion Collider

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We report the first observations of beam losses due to bound-free pair production at the interaction point of a heavy-ion collider. This process is expected to be a major luminosity limit for the CERN Large Hadron Collider when it operates with $^{208}\text{Pb}^{82+}$ ions because the localized energy deposition by the lost ions may quench superconducting magnet coils. Measurements were performed at the BNL Relativistic Heavy Ion Collider (RHIC) during operation with 100 GeV/nucleon $^{63}\text{Cu}^{29+}$ ions. At RHIC, the rate, energy and magnetic field are low enough so that magnet quenching is not an issue. The hadronic showers produced when the single-electron ions struck the RHIC beam pipe were observed using an array of photodiodes. The measurement confirms the order of magnitude of the theoretical cross section previously calculated by others.

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When fully-stripped heavy ions of atomic numbers Z_1 , Z_2 are brought into collision at the interaction point (IP) of a collider, a number of electromagnetic interactions are induced by the intense fields generated by the coherent action of all the $Z_{1,2}$ charges in either nucleus (for a review, see Ref. [1]). Some of these “ultraperipheral” interactions have much higher cross sections than the hadronic nuclear interactions that are the main object of study. Among them, the bound-free pair production (BFPP), sometimes known as electron capture from pair production, occurs when the virtual photon exchanged by the ions converts into a pair, and the electron is created in an atomic shell of one of the ions:

$$Z_1 + Z_2 \xrightarrow{\gamma} (Z_1 + e^-)_{1s_{1/2}, \dots} + Z_2 + e^+. \quad (1)$$

The resulting one-electron atoms have a slightly larger magnetic rigidity than the original bare nucleus. (Magnetic rigidity is defined as $p/(Qe) = B\rho$ for a particle with momentum p and charge Qe that would have bending radius ρ in a magnetic field B). Since the transverse recoil is very small, this “secondary beam” will emerge at a very small angle to the main beam. However, it will be bent and focused less by the guiding magnetic elements and may be lost somewhere in the collider ring.

It has long been known that this process, together with electromagnetic dissociation of the nuclei, could be a major contribution to the intensity and luminosity decay of ion colliders [2,3]. It was realized more recently [4,5] that, in certain conditions, the BFPP beam will be lost in a well-defined spot, initiating hadronic showers in the vacuum envelope of the beam. The resulting localized heat deposition could induce quenches of superconducting

magnets. Detailed calculations have been given elsewhere for 2.76 TeV/nucleon $^{208}\text{Pb}^{82+}$ operation of the LHC at CERN [5–8]. The consequent luminosity limit is expected to occur at a level close to the design performance. It is therefore vital to test our quantitative understanding of the features of the BFPP process in order to ensure safe operation of the LHC, uninterrupted by lengthy quench-recovery procedures. BFPP has been measured in fixed target experiments [9–11] at lower energy but not, until now, in a collider. An opportunity arose during $^{63}\text{Cu}^{29+}$ operation of RHIC at Brookhaven National Laboratory.

The flux of ions in the secondary BFPP beam emerging from the interaction point is the product of the collider luminosity and the BFPP cross section. The partial cross section for electron capture for a given low-lying atomic bound state i on nucleus 1 has the approximate form [12]

$$\sigma_i \approx Z_1^5 Z_2^2 (A_i \log \gamma_{\text{cm}} + B_i) \quad (2)$$

where γ_{cm} is the Lorentz boost of the ions in the center-of-mass frame and A_i , B_i depend only weakly on Z . The total cross section for BFPP to one of the colliding ions is then

$$\sigma_{\text{BFPP}} = \sum_i \sigma_i \quad (3)$$

where the sum is over all atomic shells. Some numerical values from [12] are given in Table I. The cross section for collisions of 100 GeV/nucleon $^{63}\text{Cu}^{29+}$ was not calculated in Ref. [12] but we have estimated it as 0.2 b by interpolation of the data given in Fig. 7 of Ref. [12], scaled with Z and $\log \gamma_{\text{cm}}$ according to Eq. (2). Applied to other tabulated values in Ref. [12], this method produces an agreement within 10%.

TABLE I. BFPP cross sections, typical peak luminosity, BFPP rates and relative changes in magnetic rigidity at RHIC and LHC. Values are taken directly where possible, or estimated by fitting sums of contributions of the form (2), to the information in Ref. [12]. $\delta = 1/(Z - 1)$ is the fractional deviation of the magnetic rigidity.

	σ_{BFPP} (barn)	$L/10^{27}$ (cm ⁻² s ⁻¹)	BFPP rate (kHz)	δ (%)
LHC Pb-Pb 2759 GeV/nucleon	281	1	281	1.2
RHIC Au-Au 100 GeV/nucleon	114	3	342	1.3
RHIC Cu-Cu 100 GeV/nucleon	0.2	20	4	3.6
RHIC Cu-Cu 31 GeV/nucleon	0.08	1	0.08	3.6

The impact point of the lost ions is predicted by tracking the orbit of the BFPP beam in the collider optics until it intersects the physical aperture (vacuum pipe) of the beam line. To lowest order in the uncorrelated betatron amplitudes, a , b , and relative magnetic rigidity deviation from the central value, δ , the horizontal displacement from the central orbit, at a distance s from the IP is

$$x(s) = a\sqrt{2\beta(s)}\cos[\mu(s)] + b\sqrt{2\beta(s)}\sin[\mu(s)] + d_x(s)\delta. \quad (4)$$

Averaging over all ions gives the transverse emittance of the beam: $\langle a^2 + b^2 \rangle = \epsilon$; $\beta(s)$ is the usual “Twiss function” determined by the focusing properties of the accelerator, $\mu(s) = \int_0^s \beta(u)^{-1} du$ is the betatron phase and $d_x(s)$ is the locally generated dispersion ($d_x(0) = d'_x(0) = 0$) that encodes the spectrometer effect of the bending magnets.

An ion following the central trajectory (i.e., in the middle of the bunch) in the BFPP beam enters the IP with $a = b = \delta = 0$ and emerges, still with $a = b = 0$, but $\delta = 1/(Z - 1)$. This ion will hit the beam pipe at the first location where the horizontal aperture A_x satisfies $A_x(s) = d_x(s)/(Z - 1)$. In the arc, $A_x = 3.455$ cm.

During $^{197}\text{Au}^{79+}$ operation at RHIC, δ is not large enough for this to occur ($x_{\text{max}} \approx 2.5$ cm). However, during $^{63}\text{Cu}^{29+}$ runs [13], the larger δ (Table I) meant that the ions should be lost in a well-defined location where they can be detected directly. Thanks to the small cross section, there was no risk of quenching any superconducting materials. Since the BFPP beam was not visible to the existing detectors, beam loss monitors in the form of p - i - n diodes (PDs) of the type Hamamatsu S3590 were mounted on the outside of the magnet cryostat downstream of the IP of the PHENIX experiment. The PDs have a time resolution of 25 ns and the counts were read out every second. They were initially positioned in a wide configuration (WPD), 3 m apart (see Fig. 1), and later moved closer together (CPD), 0.5 m apart, around an observed count-rate maximum at 141.6 m.

A linear interpolation of $d_x(s)$ between magnet ends, based on the design model of the collider, identified the elements within which the BFPP beam was lost: a 9.7 m long dipole magnet starting at $s = 129.6$ m, followed by a 2.12 m drift space and a quadrupole magnet, shown in Fig. 1. More precise tracking, including chromatic effects (δ dependences), and a final step of analytic orbit calcula-

tion inside the dipole, predicted an impact at $s_i \approx 135.5$ m with an angle of incidence of $\langle x'(s_i) \rangle \approx 2.7$ mrad. Tracking an assumed Gaussian distribution of the amplitudes a and b in Eq. (4) gives the distribution of impact momenta in the spot around this point. Figure 2 shows the main $^{63}\text{Cu}^{29+}$ beam together with the $^{63}\text{Cu}^{28+}$ BFPP beam propagating from the IP.

To the extent that the RHIC hardware differs from the design model, the impact point may be shifted. The global distortion of the central orbit by misalignments of the magnets is partially corrected by localized corrector magnets. A least-squares fit was made to orbit data from beam position monitors (BPMs) and measured misalignments (of order 1–2 mm) of the quadrupole magnets in the form

$$x(s) = x_\beta(s) + \sum_j \Theta(s - s_j) \times \sqrt{\beta(s)\beta(s_j)} \sin[\mu(s) - \mu(s_j)] \theta_j. \quad (5)$$

Here $\Theta(s)$ is the unit step function, x_β the first two terms in Eq. (4) and θ_j are the angular kicks from misalignments and correctors at locations s_j . Unfortunately not enough data were available to make a satisfactory fit. Instead, the possible spread of the impact point was estimated by calculating the propagated error using Eq. (5). A possible error on the horizontal quadrupole misalignments of 1 mm was assumed, corresponding to the 95% confidence inter-

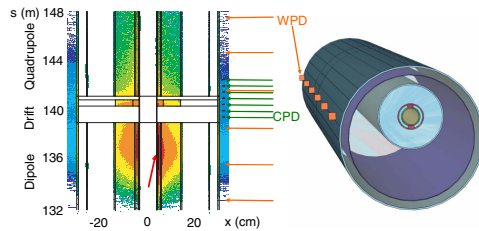


FIG. 1 (color online). Left: The energy deposition from a typical shower shown in a thin slice in the x - s plane through the geometry. The arrow (red online) near the center of the figure indicates the impact point and the arrows along the right side (green and orange online) show the positions of the PDs in the CPD and WPD. Right: The 3D model of the geometry as implemented in FLUKA around the impact point. The squares (orange online) show the PDs in the WPD.

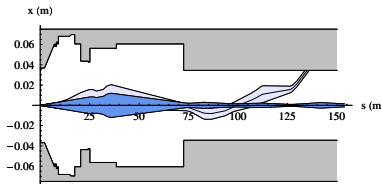


FIG. 2 (color online). The horizontal projection of the 1σ envelope of the BFPP beam and the nominal beam emerging from the PHENIX IP. The BFPP beam hits the inside of the vacuum chamber at 135.5 m.

val of the measurement and the fact that the magnets may have moved between early 2005 when the BFPP measurement was done and late 2006 when the misalignments were measured. The absolute error on the BPM data was taken to be 0.5 mm, reflecting the limited data and possible non-reproducibility. Combining these errors gives an impact point of 135.5 ± 2 m. Keeping the nominal optics, but displacing the beam pipe by 1.4 mm at the impact point according to the measured misalignment of the dipole, moves the impact point to 136.0 m.

Several distributions of BFPP ions at the PHENIX IP, centered on different initial offsets and angles, were tracked to obtain their impact coordinates on the inside of the vacuum pipe. These were fed into a 3D model (see Fig. 1) of the impact region geometry, the PDs, and the dipole magnetic field, implemented in the FLUKA 2006.3 Monte Carlo code [14–16], in order to simulate the shower in the magnet and particles emerging from the cryostat. This code has been benchmarked by others in the relevant energy range [16].

Within 2–2.5 m from the average impact point most of the shower inside the magnet has died out, although particles outside propagate farther. This can be understood through a rough estimate: The typical average nuclear interaction length for the superconducting coil and the iron cold bore is about 20 cm. Convolved with the impact point spot size of about 1.8 m, this gives a total shower length of about 2.8 m, assuming that the shower lasts five interaction lengths. The maximum PD signal was expected about 2.5 m downstream of the impact point. When the shower is contained within the dipole, moving the impact point along s only translates the shower. If the impact point is moved closer toward the end of the magnet or the angle of incidence decreased, more of the shower emerges into the void before the quadrupole and the profile changes qualitatively. A second peak in energy deposition appears at the entrance of the quadrupole and eventually exceeds the first one.

The PDs count the number of minimum-ionizing particles (MIPs) that pass their active area of 1 cm^2 . In the simulation, the number of MIPs entering each PD was recorded, assuming a detection efficiency of 30%. Since the PDs are much more sensitive to particles entering

through the side orthogonal to the cryostat, only these particles were counted. At the expected BFPP ion production rate of 4 kHz, and the 0.01 MIPs expected per PD per ion, pileup from multiple interactions was not an issue. Both WPD and CPD configurations were simulated for various impact points and a typical result is shown together with measured data in Fig. 3.

Data were collected from the PDs during 14 fills of RHIC with $^{63}\text{Cu}^{29+}$ ions. An example of the recorded signal is shown in Fig. 4, together with the zero degree calorimeter (ZDC) count rate (which is directly proportional to the luminosity). The PD signals show a good temporal correlation with luminosity and are very localized along s , close to the predicted impact position. With a 1 s binning, the correlation coefficient, r , between the PD signal and ZDC is 0.7 at 141.6 m and decreases gradually to 0.1 at PDs outside the predicted impact area. With a 30 s binning the highest r rises to 0.98. This makes it very unlikely that some other source than the collisions could be responsible for the signals.

This becomes even clearer from van der Meer scans in which the beam orbits are scanned transversely across each other and the luminosity variation is recorded as in Ref. [17]. Figure 5 shows the ZDC rate and the signal of one of the PDs as a function of the orbit bump amplitude.

Since the data were taken parasitically during normal colliding-beam operation, the PD signals were often polluted by other losses, e.g., from collimation. Therefore the cleanest data sets with least interference were picked out (near the beginning of each fill) and the averaged count rate with background subtracted, normalized to luminosity, was calculated for each PD (see Fig. 3). The background noise level was calculated for each PD as the average signal without luminosity.

In the WPD, the maximum signal was recorded by the PD at 141.6 m but moved to 140.5 m in the CPD. The count rates ranged from 1 to 20 Hz depending on PD position and

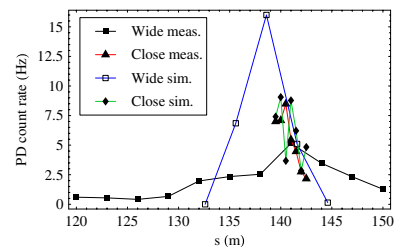


FIG. 3 (color online). The PD signals from both configurations together with simulation results, averaged over the fills and normalized to a typical average luminosity of $9.1 \times 10^{27}\text{ cm}^{-2}\text{ s}^{-1}$. The simulation was produced from the central BFPP orbit in the nominal lattice but with the beam pipe misaligned by 1.4 mm at the impact location according to measurements. Because of large statistical error bars, the simulation gives only the order of magnitude to expect in the measurement.

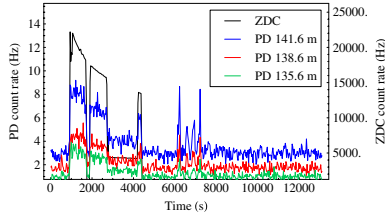


FIG. 4 (color online). Count rates measured on the ZDC luminosity monitors (black, right scale) and the three PDs with the highest signal [shades of gray, left scale (colors online)] during a store with the WPD. The data was binned in 30 sec intervals. A clear correlation between the luminosity and the PD count rates can be seen.

luminosity. This agrees well with the simulation. However, the maximum in the simulation came from the PD at 138.6 m, which does not exactly agree with the measurements. This means that, in reality, the second peak in the energy distribution outside the cryostat is actually higher than the first, while in the simulation the first peak is higher. As can be seen in Fig. 1, the peak in the shower could also escape between the PDs in the WPD. However, if the impact point is translated within the 2 m error bar, the simulated maximum moves further downstream and a fair agreement can be found. Moreover, the PD signals themselves have error bars—apart from the statistical error a small relative change in the counting efficiency between the PDs could change the result. This has not been measured so we give no numerical estimate.

One might hope to extract a value for the cross section for BFPP between colliding copper ions at 100 GeV/nucleon. However, because of the uncertainties in both the number of MIPs entering a specific diode in the simulation and the recorded count rates, we can only conclude from the good agreement that the theoretical estimate of the BFPP cross section has the right order of magnitude.

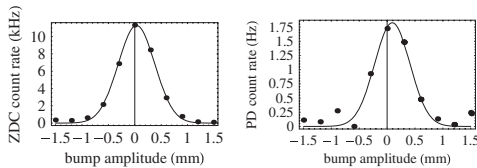


FIG. 5. The ZDC count rate (proportional to luminosity, left) and background-subtracted PD count rate (right) vs relative orbit displacement between beams in a van der Meer scan. A Gaussian fit of the form $A \exp(-\frac{(x-x_0)^2}{\sigma_x^2})$ is shown together with the data. The two fits had $\sigma_x = 0.49$ mm and 0.44 mm and $\chi^2/\text{DOF} = 0.23$ and 0.20, assuming a measurement error of 500 Hz on the ZDC signal and 0.3 Hz on the PD.

No signal was detectable at 31 GeV/nucleon, consistent with the much lower ($L \times \sigma_{\text{BFPP}}$) (see Table I).

In conclusion, we made the first measurements of the localized loss of a BFPP generated secondary beam in an ion collider. These measurements were done with copper beams at RHIC. We found the location of the maximum loss monitor signal at 140.5 m from the IP, within 2 m of its calculated location, and the measured event rates in our PD detectors within a factor of 2 of calculated ones. The deviations between calculated and measured values are consistent with estimated errors. This is a valuable test of our ability to make quantitative predictions of this effect for the LHC, where it is expected to be one of the most restrictive luminosity limits.

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PAPER III

Measurements of heavy ion beam losses from collimation

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Measurements of heavy ion beam losses from collimation

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The collimation efficiency for $^{208}\text{Pb}^{82+}$ ion beams in the LHC is predicted to be lower than requirements. Nuclear fragmentation and electromagnetic dissociation in the primary collimators create fragments with a wide range of Z/A ratios, which are not intercepted by the secondary collimators but lost where the dispersion has grown sufficiently large. In this article we present measurements and simulations of loss patterns generated by a prototype LHC collimator in the CERN SPS. Measurements were performed at two different energies and angles of the collimator. We also compare with proton loss maps and find a qualitative difference between $^{208}\text{Pb}^{82+}$ ions and protons, with the maximum loss rate observed at different places in the ring. This behavior was predicted by simulations and provides a valuable benchmark of our understanding of ion beam losses caused by collimation.

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I. INTRODUCTION

The Large Hadron Collider (LHC) [1], presently being commissioned at CERN, will collide beams of protons and later heavy nuclei [2], starting with $^{208}\text{Pb}^{82+}$, at energies never reached before. The main parameters of the beams of the two species are listed in Table I. The LHC uses superconducting magnets, which operate with a high magnetic field at 8.33 T, near the quench limit, meaning that even a small temperature rise, of the order of a 1 K, can make the magnets pass from a superconducting to a resistive state. At the same time, with a stored proton beam energy of 362 MJ (see Table I), even a small beam loss of 4×10^7 protons in a magnetic element might induce enough heating to cause a quench. Therefore, all beam losses need to be tightly controlled and, for this purpose, a collimation system has been designed [1,3–5]. This system is located in two warm insertions of the LHC and cleans halo particles from the beam in a controlled manner before they are lost elsewhere.

The LHC collimation system is primarily optimized for proton operation but will be used also during ion runs. The collimation is however predicted to be less efficient for ions than for protons [6], although the stored beam energy is almost a factor 100 lower, as can be seen in Table I. In order to understand why this is the case, we give a very brief summary of the physics processes occurring when particles traverse the collimator material in Sec. II and then of the functioning of the collimation system in Sec. III.

To better understand the LHC ion collimation, we have made an experiment on ion collimation in the CERN Super Proton Synchrotron (SPS), which is the main subject of this article. The experimental setup is presented in Sec. IV and

the simulation methods in Sec. V. In the remaining sections, the measurement results are compared to simulations and we also make a brief comparison with the case of protons.

II. PHYSICS OF HEAVY IONS IN COLLIMATORS

In order to understand the LHC ion collimation inefficiency, we give a brief overview of the physical processes occurring when heavy nuclei traverse the collimator material.

A short review of the passage of charged particles through matter can be found in Ref. [7] and an extensive theoretical treatment of ions, in particular in Ref. [8]. Here we highlight two important processes: the energy loss through ionization, which is described by the well-known Bethe-Bloch formula, and the change of direction through many small-angle scattering events, so-called multiple Coulomb scattering (MCS). Angular deviations can also be caused by nuclear elastic scattering, which is a significant effect for protons but negligible for $^{208}\text{Pb}^{82+}$ ions.

These processes are present for all charged particles, while some others are peculiar to heavy ions. An impinging

TABLE I. The parameters for the p^+ and $^{208}\text{Pb}^{82+}$ LHC beams at collision.

Particle	p^+	$^{208}\text{Pb}^{82+}$
Energy/nucleon	7 TeV	2.759 TeV
Relativistic γ	7461	2963.5
No. bunches	2808	592
No. particles/bunch	1.15×10^{11}	7×10^7
Transverse normalized rms emittances	$3.75 \mu\text{m}$	$1.5 \mu\text{m}$
Stored beam energy	362 MJ	3.81 MJ
Peak luminosity	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	$10^{27} \text{ cm}^{-2} \text{ s}^{-1}$

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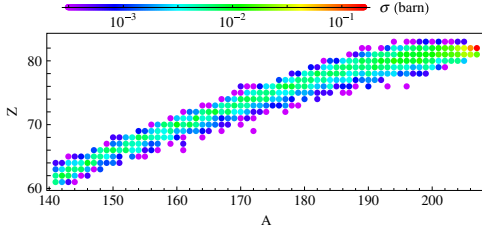


FIG. 1. (Color) The cross sections for creating heavy isotopes (mass number $A > 140$ and charge $Z > 60$) by a 106.4 GeV/nucleon $^{208}\text{Pb}^{82+}$ beam impacting on a carbon target. The cross sections were simulated by FLUKA.

nucleus may lose one or several nucleons, in particular neutrons, through electromagnetic dissociation (EMD), which is a process with a logarithmic energy dependence taking place in ultraperipheral collisions. For a review of this field, see Refs. [9–11]. The nuclei may also split up in smaller fragments through nuclear inelastic reactions (see Ref. [12] for measurements of nuclear fragmentation of $^{208}\text{Pb}^{82+}$ ions at 158 GeV/nucleon in a carbon target, a situation close to the SPS collimation experiment described in this article). The cross section for nuclear inelastic interactions is only weakly dependent on energy and the created fragments have a wide range of masses. In Fig. 1 we show the total cross sections for the creation of different isotopes, the sum of the electromagnetic and hadronic part, by 106.4 GeV/nucleon $^{208}\text{Pb}^{82+}$ ions in a carbon target, as calculated by the Monte Carlo program FLUKA [13–15]. This corresponds to the situation in the collimator in the SPS experiment.

In each interaction, a number of secondary particles are created that constitute the hadronic shower [16]. The final energy deposition in the material is to a large extent due to these secondaries.

III. LHC ION COLLIMATION

The LHC collimation system consists of primary and secondary collimators [17], both made of graphite jaws. Particles at large amplitudes hit first a primary collimator, which is shorter and the limiting aperture of the machine. There they interact in such a way that they are either absorbed or scattered back into the beam or to an even larger amplitude. The latter particles form a secondary halo, which is intercepted and absorbed by the secondary collimators, possibly several turns later. The condition on the angular kick $\Delta x'$ given by the primary collimator for a particle to be intercepted by the secondary collimator is [17]

$$\Delta x' > \sqrt{\frac{(N_2^2 - N_1^2)\epsilon_N}{\gamma\beta_x}}. \quad (1)$$

Here ϵ_N is the normalized emittance, γ the usual Lorentz factor, β_x the usual optical function at the primary collimator, and N_1, N_2 are the transverse positions of the primary and secondary collimators, given in the number of σ (the standard deviation of an assumed Gaussian beam distribution) from the center of the vacuum chamber.

We can now understand the inefficiency of the LHC ion collimation by comparing the length of material that an ion would need to traverse in order to hit the secondary collimator with the interaction length of nuclear fragmentation processes. Taking standard LHC $^{208}\text{Pb}^{82+}$ parameters in Eq. (1) ($N_1 = 6$, $N_2 = 7$, $\epsilon_N = 1.5 \mu\text{m}$, $\gamma_{\text{rel}} = 2963.5$, $\beta_x \approx 135 \text{ m}$), we see that the angular kick that a $^{208}\text{Pb}^{82+}$ ion would need to receive in the primary collimator in order to hit the secondary collimators is approximately $7 \mu\text{rad}$. To have this rms angle of the ion distribution exiting a collimator, the required length of the jaw would be 2 m if we use the Gaussian approximation of the Moliere formula [7] to calculate the rms MCS angle θ_0 :

$$\theta_0 = \frac{13.6 \text{ MeV}}{vp} Z_0 \sqrt{\frac{s}{S_0}} \left[1 + 0.038 \ln\left(\frac{s}{S_0}\right) \right]. \quad (2)$$

Here Z_0 is the charge number of the incident ion, p its momentum, v its speed, s the distance traversed in the material, and S_0 the radiation length.

However, the length of the primary collimators is only 60 cm, and typical trajectories inside them much shorter, while the interaction lengths for nuclear inelastic interactions and EMD are around 2.5 and 19 cm, respectively [6]. Since the transverse recoil of the heavy fragments is very small, it is clear that the heavy ions that are not absorbed in the primary collimator are likely to be fragmented without having obtained a sufficiently large angle to reach the secondary collimators.

The created fragments (e.g. ^{207}Pb , ^{203}Tl , and others) have a different magnetic rigidity $B\rho(1 + \delta)$ from the main beam (magnetic rigidity is defined as $p/Ze = B\rho$ for an ion with momentum p and charge Ze that would have a bending radius ρ in a magnetic field B). Therefore they are bent and focused differently. The fractional rigidity deviation δ is given by

$$\delta = \frac{Z_0}{A_0} \frac{A}{Z} \left(1 + \frac{\Delta p}{p_0} \right) - 1, \quad (3)$$

where (Z_0, A_0) are the charge and mass number of the original ion, (Z, A) of the fragment, and $\Delta p/p_0$ the fractional momentum deviation per nucleon of the fragment with respect to the main beam. These ions follow the locally generated dispersion function d_x from the collimator and may be lost downstream in the machine where the horizontal aperture A_x satisfies

$$d_x \delta \geq A_x. \quad (4)$$

Here we have assumed that the dispersive contribution to the orbit is much larger than the betatron part. Because of

the different δ of the created ion species, they are lost at different localized spots, making the machine act as a spectrometer. Some impact locations could be outside the warm collimation insertion, meaning a potential risk of quenching superconducting magnets.

To study the LHC ion collimation inefficiency, a series of simulation studies have been done [6,18]. Since a large fraction of the systematic error in those simulations comes from the generation and tracking of the fragmented ions, an experiment on ion collimation in the CERN Super Proton Synchrotron (SPS) has been performed and the results, presented in the following, are compared to simulations, not only in terms of loss locations but with the goal of reproducing the absolute value of the losses measured by the beam loss monitors (BLMs). We also make a brief comparison with the case of protons.

IV. EXPERIMENTAL SETUP

The SPS is a synchrotron of 6.9 km circumference that now serves as the last injector for the LHC [19] but also provides beam for various fixed-target experiments. It accelerates protons up to 450 GeV and $^{208}\text{Pb}^{82+}$ nuclei up to 177 GeV/nucleon before extraction.

A prototype of a secondary LHC collimator has been installed in the long straight section 5 (LSS5) [20,21]. It consists of a pair of 1 m long carbon fiber composite graphite jaws, which can be moved independently to inter-



FIG. 2. (Color) A collimator jaw of the same type as installed in the SPS. The figure is taken from [31].

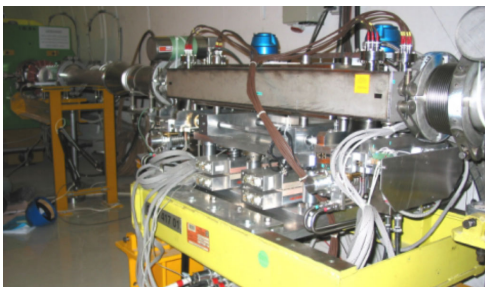


FIG. 3. (Color) The installation of the prototype LHC collimator in the SPS tunnel. The figure is taken from [31].

cept the beam in the horizontal plane. A similar jaw is shown in Fig. 2 and the installation in the SPS tunnel is shown in Fig. 3. The collimator is located in a position with small horizontal β function and dispersion in order not to introduce aperture bottlenecks. The optical functions and magnetic elements in the vicinity of the installation are shown in Fig. 4, the horizontal aperture in Fig. 5, and the vertical aperture in Fig. 6.

Moving the collimator into the beam creates losses in the ring, since no second collimator is present to absorb scattered particles. There is however no risk for quenches, since the SPS does not use superconducting magnets. The losses are recorded by 216 BLMs placed around the machine [22]. The BLMs are ionization chambers mounted close to lattice quadrupoles (the inner part of a BLM and an example of the installation are shown in Fig. 7) and filled with N_2 gas at 1.1 bar. They consist of parallel aluminum plates, acting as anodes and cathodes. The losses are read out and integrated over every machine cycle (18 s for ions). Figure 4 shows the s values of the four BLMs (called BL520, BL521, BL522, and BL523) immediately down-

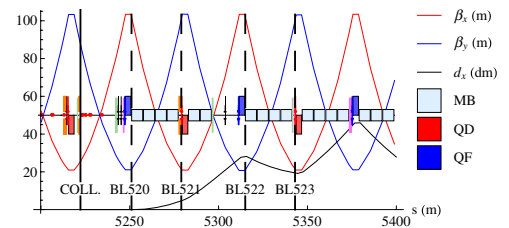


FIG. 4. (Color) The β functions of the SPS downstream of the collimator and the locally generated dispersion d_x from the collimator. We show also the magnetic elements (MB = main bend, QF = focusing quadrupole, QD = defocusing quadrupole). The BLMs and the collimator are indicated by vertical lines.

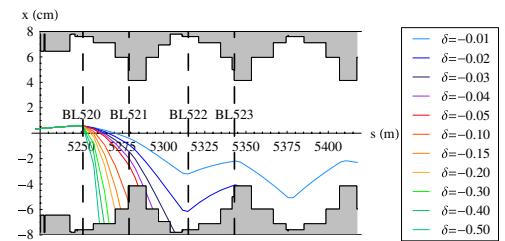


FIG. 5. (Color) Dispersive orbits of fragmented ions produced in one of the collimator jaws, shown together with the aperture. The collimator is located at $s = 5222$ m at the left edge. The vertical dashed lines indicate the locations of the four BLMs closest downstream. A large fraction of the total losses occur at the aperture limitation at $s = 5277$ m.

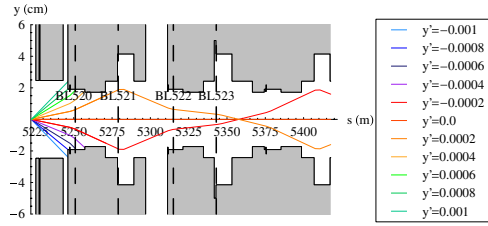


FIG. 6. (Color) Vertical betatron orbits coming out of the collimator, starting at $y = 0$, for different starting values of y' (vertical momentum normalized by longitudinal momentum). The collimator is located at $s = 5222$ m at the left edge. The vertical dashed lines indicate the location of the four BLMs closest downstream. Particles with large vertical angles are lost close to BL520.

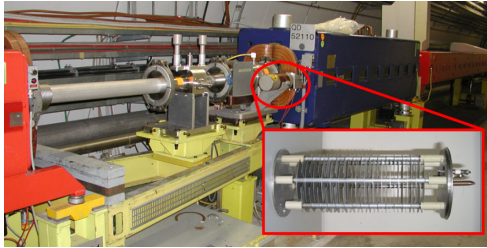


FIG. 7. (Color) The installation of a BLM (BL521) in the SPS tunnel, shown together with a close-up of the inner assembly of the chamber.

stream of the collimator. BL520 and BL522 are mounted in the vertical plane below the beam line, while BL521 and BL523 are in the horizontal plane on the inside of the ring.

Beam loss data were collected during $^{208}\text{Pb}^{82+}$ dedicated ion runs in late 2007 and the main beam parameters are shown in Table II. Data were taken both with a circulating beam at 106.4 GeV/nucleon and with a 5.9 GeV/nucleon beam intercepted by the collimator directly after injection. The corresponding momentum during the magnetic cycle of the SPS in both cases is shown in Fig. 8. In the case of the low energy beam injected on the collimator, the data were collected at the injection plateau

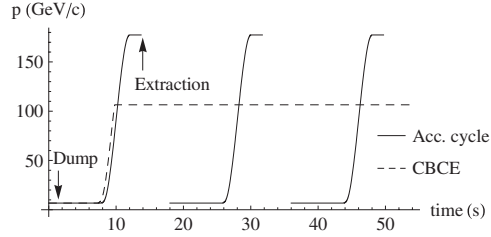


FIG. 8. The $^{208}\text{Pb}^{82+}$ momentum per nucleon during three cycles of the SPS in the case of acceleration and a circulating beam at constant energy (CBCE). In the acceleration cycle, the dumping of the beam during the collimation measurements is indicated, as well as the extraction momentum.

during the first second of the cycle. Before the magnets started to ramp, the beam was dumped.

For the high-energy measurements, the beam was instead accelerated up to 106.4 GeV/nucleon at the flattop, where the data-taking system continued to cycle while the magnets stayed at this energy and the rf system kept the beam at a constant energy. In this way the beam was circulating in the machine, while we scraped it with the collimator in several steps until all particles were lost. Because of the low intensity of the $^{208}\text{Pb}^{82+}$ beam, the collimator jaws had to be moved in close to the core of the beam (typical values are around 1σ) in order to create significant loss signals. We performed measurements using two different angles of the collimator with respect to the beam axis (0 and 2 mrad) as schematically illustrated in Fig. 9, in order to vary the effective length traveled by particles in the collimator.

The circulating beam current was measured by a beam current transformer (BCT). These measurements were used later to normalize the BLM signals by the number of lost particles. The BCT has a resolution of a few 10^8 charges and the BLMs can detect around 10^7 lost charges nearby. Since typical losses were a few 10^9 charges, the combined uncertainty on the normalized signal is around 10%. In the case where the beam was injected on the collimator, the normalization of the losses by the BCT could not be performed, since the injected intensity varied between different cycles.

TABLE II. The parameters of the beams in the SPS used for the collimation experiment.

Particle	$^{208}\text{Pb}^{82+}$	$^{208}\text{Pb}^{82+}$	p^+
Energy/nucleon (GeV)	106.4	5.9	270
Injected intensity (particles)	$6-7 \times 10^7$	$5-9 \times 10^7$	$10^{12}-10^{13}$
Horizontal normalized emittance (1σ)	$1 \mu\text{m}$	$1 \mu\text{m}$	$2.7 \mu\text{m}$
Vertical normalized emittance (1σ)	$1 \mu\text{m}$	$1 \mu\text{m}$	$4 \mu\text{m}$
Collimator steps	0.1–1 mm	Fixed	0.1–1 mm
Collimator angles	0 mrad, 2 mrad	0 mrad	0 mrad

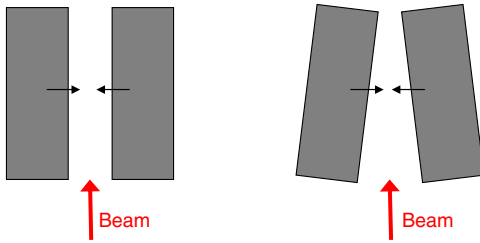


FIG. 9. (Color) Schematic sketch of collimator jaws kept parallel to the beam direction when moved in (left) and with a 2 mrad angle (right).

For comparison, data were also taken during high-intensity proton runs with the beam circulating at the flat-top in the same way as for $^{208}\text{Pb}^{82+}$ ions. These beam parameters are also presented in Table II.

V. SIMULATION TOOLS

In order to simulate the particle propagation through a lattice together with the particle-matter interactions in the collimators, a specialized program, ICOSIM (for Ion Collimation SIMulation), has been developed [6]. ICOSIM reads files from MAD-X [23] defining the optics and aperture of a machine, in order to make it straightforward to simulate any machine for which such a representation exists. The program creates an initial beam distribution that is tracked in the variables $(x, x', y, y', \delta, A, Z)$ through the lattice. The number of particles in the distribution is not constant, since interactions in the collimators may split particles into several smaller fragments with different values of A, Z and particles hitting the physical aperture are removed from the tracking. Synchrotron oscillations are neglected, because typical time scales are long ($T_{\text{rf}} \approx 500$ turns for the LHC and $T_{\text{rf}} \approx 440$ turns for the SPS) compared to the time between a first interaction of an ion with a collimator and the final loss (1–10 turns for most particles, 100 turns in rare cases).

Particles are tracked up to the first collimator impact using a linear matrix formalism between collimators with a small artificial emittance blowup on every turn, which accounts for diffusion under single beam effects, which need not be specified. The linear tracking is typically done for 10^5 turns and serves to generate impact coordinates on the collimator. This method was developed with the aim of simulating fixed jaws and a growing envelope. We have chosen to use the same method to simulate the SPS experiments, although in this case the jaws were moving into the beam with a speed of 4 mm/s. This choice was made with the intention of benchmarking the specific generation of impact coordinates on the collimator and since the steps of the jaw were small compared to the discontinuities in the SPS aperture. As explained later, this fact makes the ratio

between particles lost at different impact locations almost independent of the jaw positions. Thus, it is a very good approximation to use this simulation method also in the SPS. For the same reason, impact positions are relatively independent of orbit distortions and therefore we use the perfect machine optics in the tracking. The diffusion of the envelope for the SPS simulations was chosen to 92 nm/turn, corresponding to the jaw speed. The resulting average impact parameter (defined as the distance between particle impact and the inner edge of the collimator jaw) is $22 \mu\text{m}$.

From the first collimator impact, element by element tracking is used in ICOSIM and chromatic effects at leading order, as well as sextupoles in thin kick approximation, are included. Higher order multipoles are neglected, since particles are typically lost in less than 100 turns, which is not enough to see a significant effect of small nonlinearities. At the end of each element, a check is performed to determine which particles are outside the aperture. The impact momenta and coordinates on the vacuum chamber are estimated by a linear interpolation inside the magnetic element.

Two different methods can be used to simulate the particle-matter interaction in the collimator.

(i) FLUKA XS.—ICOSIM has a simple built-in Monte-Carlo program, which includes multiple scattering in a Gaussian approximation [7], ionization through the Bethe-Bloch formula, nuclear fragmentation, and electromagnetic dissociation. The last two processes are simulated by sampling from tabulated cross sections, created by FLUKA for all possible fragments and fragmentation channels. Only the heaviest fragment created in each interaction is tracked. In the LHC, only these fragments are important to follow, since ions with $|\delta| > 0.05$ are already lost in the warm collimation insertion.

(ii) FLUKA full.—The transport and interaction of all particles through the collimator region is evaluated on each turn by external calls to FLUKA, which simulates the full shower in a 3D model of the collimator geometry. This method is more detailed and sophisticated but significantly slower in terms of computation time.

The BLM signals depend not only on the number of ions lost nearby, but also on the mass of the ions (assuming the same energy per nucleon, a heavier ion carries more energy), the distribution of impact parameters, and the amount and type of material they have to traverse before reaching the monitor. At some BLMs, with less nearby material, particles lost far away may cause a signal, while BLMs that are well shielded by magnetic elements may only see small traces of the showers caused by the closest losses. In order to accurately simulate this for a quantitative comparison with data, the particle-matter interaction of the lost ions in the full geometry needs to be taken into account.

As discussed later, the main loss location is right downstream of the collimator. Thus, the 3D geometry of the

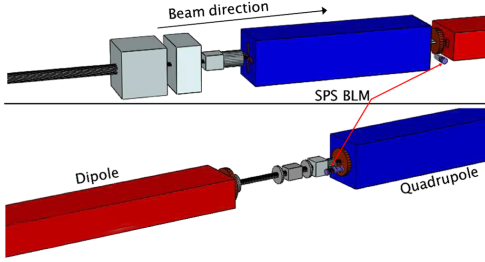


FIG. 10. (Color) The 3D geometry as implemented in FLUKA around a BLM in the vertical plane (BL520, top) and in the horizontal plane (BL521, bottom). A photo of the central part of the real geometry around BL521 is shown in Fig. 7.

magnetic elements around the monitors BL520, BL521, BL522, and BL523 was implemented in FLUKA, as illustrated for BL520 and BL521 in Fig. 10. The magnetic field in the magnets nearby was neglected. A simulation including the magnetic field of the quadrupole nearest to BL520 showed a negligible difference with respect to the case without any field. The momenta and impact coordinates on the inside of the vacuum pipe of all particles lost within a 15 m interval of each BLM were recorded in ICOSIM and fed as starting conditions into FLUKA and the resulting energy deposition in the N_2 gas inside the BLMs was converted to dose in Gy. An example of the simulation of the shower caused by the lost particles close to BL521 is shown in Fig. 11.

In the ICOSIM simulations of the SPS, typically more than 2×10^5 particles were tracked in order to arrive at a statistical uncertainty of 1%–5% on the final simulated BLM signal, depending on BLM.

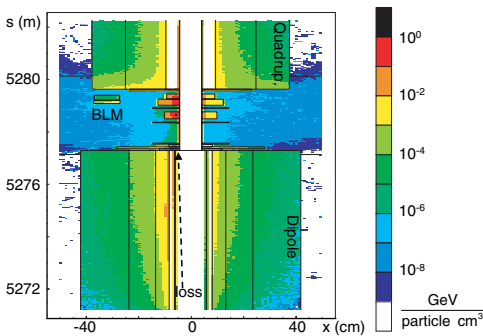


FIG. 11. (Color) The geometry as implemented in FLUKA around the monitor BL521 with the simulated energy deposition from a typical loss superimposed. The loss is indicated by the dashed arrow.

VI. RESULTS: 106.4 GEV/NUCLEON, PARALLEL JAWS

We focus first on the case of a 106.4 GeV/nucleon circulating $^{208}\text{Pb}^{82+}$ beam and parallel collimator jaws and compare with other cases in later sections.

A typical example of a loss map measured during a machine cycle with these conditions is shown in Fig. 12, together with the corresponding simulated loss map from the FLUKA *full* method. The detector background, consisting of noise and other beam losses not caused by the collimator movement, had to be subtracted. As background we used the loss map from the machine cycle before the collimator movement. A similar approach was already used in Ref. [21] to benchmark the SIXTRACK program [24] for proton beams. The only stable loss locations, clearly separable from the background, are just downstream of the collimator, both in simulations and measurements. This holds true also with jaws tilted by 2 mrad and at 5.9 GeV/nucleon. Therefore, in the remainder of this text we focus on the four BLMs downstream of the collimator which see the highest signal.

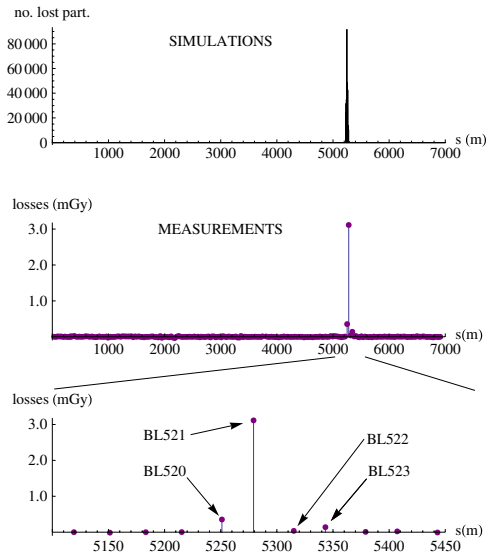


FIG. 12. (Color) Example of simulated ICOSIM (top) and measured (middle) loss map of the whole SPS ring with a 106.4 GeV/nucleon circulating $^{208}\text{Pb}^{82+}$ beam. The bottom part shows a close-up of the loss peak in the measurements, with the names of the BLMs with the highest signals indicated. The simulated losses were binned in 5 m intervals. The collimator is located at $s = 5222$ m, just upstream of the large loss peak.

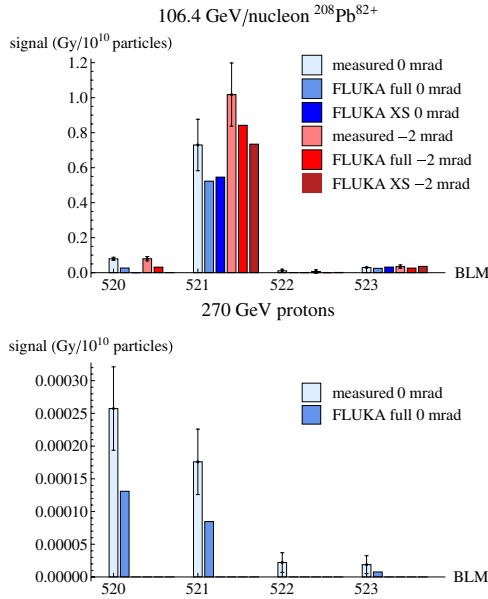


FIG. 13. (Color) Average loss map for 106.4 GeV/nucleon $^{208}\text{Pb}^{82+}$ ions (top) and 270 GeV protons (bottom) with parallel jaws (blue bars) and jaws tilted by 2 mrad (red bars). The measurements are compared with simulations using both methods of simulating the particle-matter interaction in the collimator, as described in the text. All results were normalized to 10^{10} lost particles. The standard deviation between different measurements is indicated.

The top part of Fig. 13 and Table III show the average measured BLM signals, normalized to 10^{10} lost particles (using the BCT) and averaged over several machine cycles, together with the corresponding simulation results for the different methods of representing the particle-matter interactions in the collimator, which we discuss in Sec. IX. The ion loss pattern from the measurements is qualitatively

TABLE III. The measured and simulated BLM signals (in Gy/ 10^{10} lost particles) during 106.4 GeV $^{208}\text{Pb}^{82+}$ operation, as shown in the top part of Fig. 13.

Method/BLM	520	521	522	523
Measurement 0 mrad	0.079 ± 0.012	0.73 ± 0.18	0.01 ± 0.009	0.030 ± 0.009
FLUKA <i>full</i> 0 mrad	0.027	0.52	0.0008	0.024
FLUKA XS 0 mrad	0.0	0.55	0.0008	0.032
Measurement -2 mrad	0.079 ± 0.009	1.02 ± 0.15	0.007 ± 0.009	0.034 ± 0.0019
FLUKA <i>full</i> 0 mrad	0.031	0.84	0.0007	0.026
FLUKA XS 0 mrad	0.0	0.73	0.001	0.036

very similar to the simulations, with the maximum signal on BL521.

The fact that almost all losses occur close to the collimator, as well as the ratio between signals on different monitors, can be qualitatively understood by considering first the simulated δ spectrum of nuclei leaving the collimator, which is shown in Fig. 14. We show the number of nucleons originating from ions with a certain δ , since the FLUKA simulations show that an ion impinging in a magnetic element is fully fragmented within a few decimeters, meaning that the BLMs intercept mainly secondary particles originating from the hadronic shower, which to good approximation is similar to the shower created by the corresponding number of free nucleons [25]. Therefore the BLM signal caused by an ion lost in a specific location is approximately proportional to its number of nucleons. The heights of the peaks in the figures give thus an approximate estimate of the fraction of the BLM signal caused by different values of δ .

In order to explain the loss pattern, we consider this δ spectrum in Fig. 14 together with the dispersive orbits of ion fragments with these δ values starting at one of the collimator jaws, shown in Fig. 5. Here several trajectories

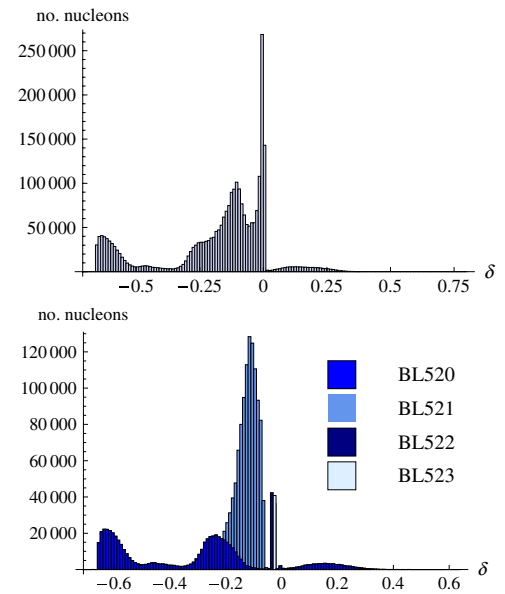


FIG. 14. (Color) The simulated distribution of δ calculated according to Eq. (3), using the FLUKA *full* method, of all high-energy nuclei except $^{208}\text{Pb}^{82+}$ coming out of the collimator (top) and of the ions lost within a 15 m interval upstream of each BLM (bottom) at 106.4 GeV/nucleon with parallel jaws. The heights of the bars show the number of nucleons belonging to ions having δ within a certain interval.

TABLE IV. The δ from fragmentation of the most common ions created in the collimator as calculated with Eq. (3) for $\Delta p/p_0 = 0$.

^{207}Pb	^{207}Tl	^{206}Pb	^{206}Tl	^{205}Pb	^{205}Tl
-0.0048	0.0075	-0.0096	0.0026	-0.014	-0.0023
^{204}Hg	^4He	^3He	^3H	^2H	^1H
0.0053	-0.21	-0.41	0.18	-0.21	-0.61

for typical values of δ are presented, together with the s values of the BLMs. Fragments with $|\delta| < 0.013$ stay inside the vacuum chamber and can make a full turn in the machine, while particles with larger $|\delta|$ are lost deterministically downstream of the collimator. Figure 5 clearly demonstrates the spectrometer effect discussed earlier, since fragments with different values of δ are lost at different longitudinal positions. Values of δ for some common fragments are shown in Table IV. Therefore, each of the four BLMs considered in detail sees a different spectrum of ions, shown in Fig. 15. This can help us to understand the origin of the signals at each BLM.

BL520.—The main loss mechanism in the vicinity is not dispersion but instead the vertical aperture, which intercepts particles with large betatron angles. This can be understood from the spectrum of vertical angles of the

fragments exiting the collimator, as shown in Fig. 16, and typical vertical orbits of particles with large scattering angles as shown in Fig. 6. The horizontal aperture is significantly larger (see Figs. 5 and 6), making the vertical aperture the limitation for large-angle particles. Mainly light fragments are lost close to BL520, consistent with the expectation that they receive significantly larger transverse recoils in the fragmentation processes. The expected signal is significantly lower than measurements, maybe because BL520 is located only 30 m downstream of the collimator. It might see traces of shower particles from the collimator, in particular high-energy neutrons created by electromagnetic dissociation, for which we have not attempted a detailed modeling. We have estimated this contribution through a FLUKA simulation of the neutron propagation through a rough model of the tunnel and around 45% of the signal shown in Fig. 13 (top) on BL520 comes from showers induced by scattering neutrons. However, since the neutron contribution is very sensitive to objects in the tunnel acting as scatterers, which are not properly taken into account in the simulation, this should be considered as a rough estimate.

BL521.—Ions with $-0.2 < \delta < -0.08$ are lost near the aperture limitation at $s = 5277$ m, close to BL521.

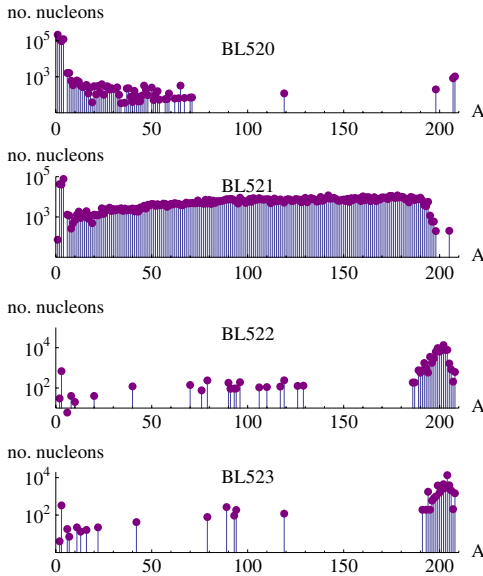


FIG. 15. (Color) The A distribution of ion fragments lost within 15 m upstream of each BLM at 106.4 GeV/nucleon and parallel collimator jaws as simulated with the FLUKA *full* method. The heights of the bars show the number of nucleons from ions having a certain A .

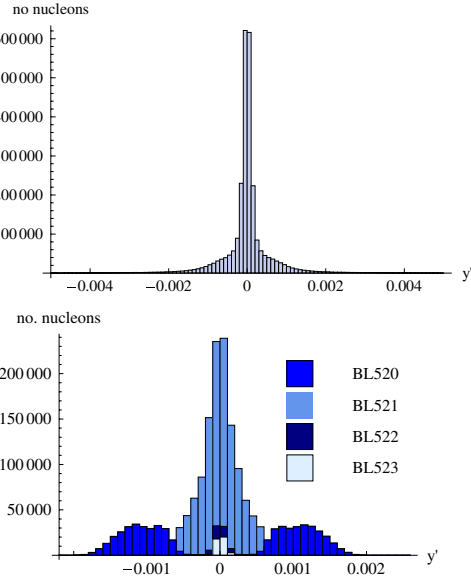


FIG. 16. (Color) The simulated distribution from the FLUKA *full* method of y' of all ion fragments coming out of the collimator (top) and of the ions lost within a 15 m interval upstream of each BLM (bottom). The heights of the bars show the number of nucleons belonging to ions within a certain interval.

Figure 14 demonstrates that this corresponds to a large fraction of the fragments and Fig. 15 shows that BL521 sees a very wide spectrum of ions. Since BL521 is located only 2 m downstream of this position in negative x with almost no shielding material in between (see Figs. 7, 10, and 11), this monitor is expected to show a very high signal when ion beams are scraped with the collimator. Consequently, BL521 has the maximum signal both in measurement and simulations, which predict a value around 30% lower than measurements.

BL522.—BL522 is placed in the vertical plane, while the dispersive losses of mainly heavy fragments occur in the horizontal plane. This makes the uncertainty of the shower simulation much higher, since the signal is caused by secondary particles very far away from the central core of the shower. BL522 showed a much higher signal in measurements than simulations, although fluctuations between different cycles were very large (of the same order of magnitude as the measured signal), a fact that is not well understood. BL522 had the lowest signal (around 1.4% of the signal on BL521) of the BLMs that we consider in detail.

BL523.—Only particles with a magnetic rigidity ($\delta \approx -0.02$) close to the original $^{208}\text{Pb}^{82+}$ ion are lost in the vicinity. Therefore the spectrum of lost ions consists mainly of heavy fragments. This situation is similar to what can be expected in the cold regions of the LHC, since all particles having $|\delta| \geq 0.05$ are already lost in the warm insertion. The signal from the FLUKA *full* simulation is 17% lower than measurements.

It is clear from Fig. 5 that the expected distribution of losses is relatively independent of closed orbit distortions (which were not accounted for in the simulations) and the position of the collimator. Displacing the trajectories in the figure vertically by a few mm does not significantly change their impact positions in s , given the large impact angles and the aperture of the SPS. Likewise, the dispersive orbits starting at the other jaw, located in negative x , have a similar longitudinal impact distribution. Thus, only the magnitudes of the measured signals, not their relative ratios, change when the collimator is moved in closer to the core of the beam and therefore intercepts more particles. This behavior was predicted by simulations and confirmed by measurements.

The magnitudes of the simulated signals agree well with measurements (see Fig. 13), although they are lower. To estimate the expected error, we assume approximately a factor 2–3 uncertainty of the FLUKA simulation of the energy deposition in the ionization chambers, since we consider secondary particles far from the core of a shower caused by ions with a grazing incidence. This is consistent with other comparisons between simulations and measurements of beam loss induced BLM signals at RHIC [26] and HERA [27].

Furthermore, the fragmentation cross sections in the collimator have significant uncertainties. A comparison

between simulation codes done in a separate study, which we intend to publish elsewhere, suggests that the uncertainty of the largest cross sections to create specific isotopes may well be 50%. Therefore, a new set of ICOSIM simulations were performed (using FLUKA XS), where we in each run resampled all cross sections with a 50% standard deviation around their initial value. This caused a standard deviation of 9% of the signal on BL521 and approximately 20% at the other BLMs, which see a narrower δ spectrum and therefore are more sensitive to variations in single cross sections.

There is also an uncertainty on the measured jaw angles, which has been estimated to be less than 0.2 mrad [28]. Further FLUKA XS simulations show that this causes a 17% deviation on the BLM signal. Other systematic errors in the measurement were estimated at 10% (see Sec. IV).

However, these errors give only small corrections to the uncertainty of the FLUKA simulations. The same holds true for the single pass tracking from the collimator to the loss point, the influence of a nonperfect machine optics (as explained in Sec. V) and for the impact coordinates on the collimator, which are much better known in the SPS than in the LHC. The SPS collimator was moved into the beam close to the core, where the distribution is Gaussian with good approximation, while the LHC collimators will intercept halo particles, scattered to high amplitudes by beam dynamics processes that are hard to quantify.

Altogether, we expect the simulation to be accurate within a factor 3 and conclude that the discrepancies between measurements and simulations are within expected error margins, except for the highly fluctuating BL522. This error margin might be too pessimistic when considering the BLMs in the horizontal plane (BL521 and BL523).

VII. RESULTS: 106.4 GEV/NUCLEON, TILTED JAWS

Figure 13 shows the average measured and simulated loss maps with the collimator jaws tilted by 2 mrad when moved into the beam (see Fig. 9). Compared to the case with parallel jaws the signal on BL521 increases by 40% in measurement, which is well reproduced by the simulations (34% in the FLUKA XS simulation and 60% in the FLUKA *full* simulation). This increase can be understood from the fact that the average distance traveled by the particles inside the collimator decreases, meaning that less particles are absorbed.

Furthermore, the signal at BL523 shows a corresponding increase with tilted jaws both in measurements and simulations, while observed differences in the very small signal at BL522 are within the statistical error margin. At BL520 an increase by 18% was predicted by the FLUKA *full* simulation but not reproduced by the measurements.

VIII. RESULTS AT 5.9 GEV/NUCLEON

In Fig. 17 we show the measured and simulated loss maps using a 5.9 GeV/nucleon $^{208}\text{Pb}^{82+}$ beam injected on the collimator with parallel jaws, together with the results at 106.4 GeV/nucleon with parallel jaws presented earlier in Fig. 13. Since the normalization to the intensity decay measured by the BCT was not possible (see Sec. IV), the normalization was instead done with respect to the sum of the four BLMs considered for both data sets and simulations. We noted however that the measured BLM signals dropped by around 5 orders of magnitude compared to the higher energy.

As shown in Fig. 17, the fraction of the total signal at BL521 decreases at the lower energy, while it increases on BL520 and BL523. This is well reproduced by both simulation methods, although they consequently predict too low a fraction on the BLMs in the vertical plane (BL520 and BL522). The FLUKA *full* method also shows lower magnitudes of the signals than FLUKA XS.

The change in loss pattern can be qualitatively understood from the energy loss in the collimator. Using the Bethe-Bloch formula, we see that a 106.4 GeV/nucleon $^{208}\text{Pb}^{82+}$ ion loses around 0.16 GeV/cm in carbon due to ionization, while a 5.9 A GeV $^{208}\text{Pb}^{82+}$ ion loses 0.13 GeV/cm. This corresponds however to very different fractional energy losses: 0.15%/cm of the total energy for 106.4 A GeV ions and 1.9%/cm at 5.9 A GeV. Since typical paths inside a collimator are several centimeters, the energy loss caused by ionization becomes significant at low energy (see the dispersive orbits in Fig. 5), meaning that the dispersion of the ions exiting the collimator is not only due to a different magnetic rigidity, but also because of a different energy per nucleon. The consequence is that most ions receive larger values of $|\delta|$ than at the higher energy and are lost further upstream in the ring. Furthermore, $^{208}\text{Pb}^{82+}$ ions that pass the collimator without fragmenting may receive a large enough $|\delta|$ to make them lost close to

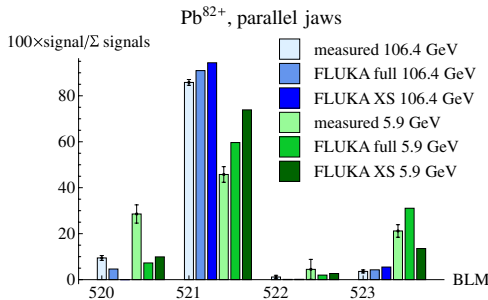


FIG. 17. (Color) Measured and simulated $^{208}\text{Pb}^{82+}$ loss maps with parallel jaws for a 5.9 GeV/nucleon beam injected on the collimator (green bars) and circulating 106.4 GeV/nucleon (blue bars).

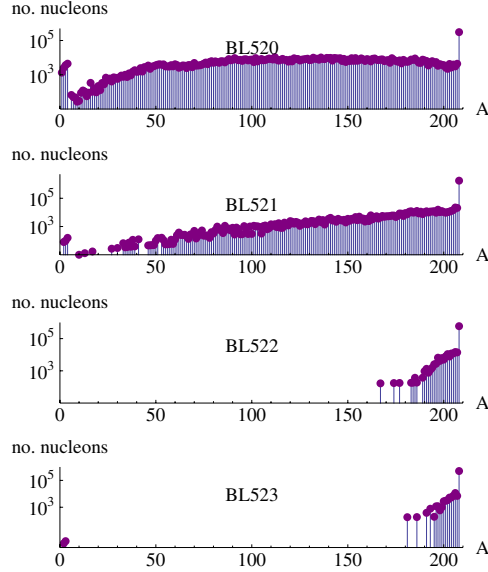


FIG. 18. (Color) The simulated A distribution of ion fragments from the FLUKA *full* method lost within 15 m upstream of each BLM at 5.9 GeV/nucleon. The heights of the bars show the number of nucleons from ions having a certain A .

all considered BLMs. This can be seen in Fig. 18, showing the mass spectrum of ions lost near each BLM.

At the same time the production of fragments changes slightly: At 5.9 GeV/nucleon, the cross section for electromagnetic dissociation goes down significantly [10], while the cross section for nuclear inelastic interaction on the other hand is only weakly dependent on the energy [29,30]. Because of the different production rates and the

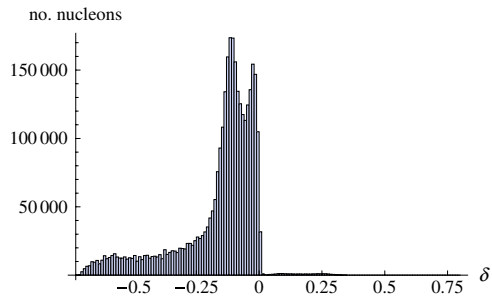


FIG. 19. (Color) The simulated distribution of δ calculated according to Eq. (3) from the FLUKA *full* method of all ion fragments except $^{208}\text{Pb}^{82+}$ coming out of the collimator at 5.9 GeV/nucleon. The heights of the bars show the number of nucleons belonging to ions having δ within a certain interval.

ionization energy loss, the δ spectrum of the ions leaving the collimator is different at 5.9 GeV/nucleon. This is shown in Fig. 19.

IX. COMPARISON OF SIMULATION METHODS

In the FLUKA *XS* simulations no signal is seen at BL520 with the 106.4 GeV/nucleon beam, since only the heaviest fragment produced in each collimator interaction is tracked, while the signal at BL520 is caused by very light fragments (see Fig. 15). During operation at 5.9 GeV/nucleon, heavy fragments are lost also at BL520 (see Fig. 18), and consequently a nonzero signal is simulated by the FLUKA *XS* method.

Furthermore, the FLUKA *full* simulation at 106.4 GeV/nucleon predicts some smaller loss peaks between BL520 and BL521, caused by very light particles with a positive energy offset. These peaks are not present in the FLUKA *XS* simulation but are also too far from the BLMs to be seen in the measurements.

However, at BL521, BL522, and BL523, where medium and heavy fragments are important, the FLUKA *XS* method gives an excellent agreement both for parallel and tilted jaws, while the gain in tracking speed is on the order of a factor 10 compared to the FLUKA *full* method. Furthermore, FLUKA *XS* reproduces well the qualitative changes of the loss pattern when the beam energy is changed. Therefore, we conclude that FLUKA *XS* is the preferred method for large machines with many collimators where light fragments are of low importance. This is the case for the LHC, since almost all light fragments are already lost in the warm regions.

X. COMPARISON WITH PROTONS

For the sake of comparison, proton runs in the SPS were also simulated with ICOSIM, using the FLUKA *full* method, and compared with measurements from September 2007 with a coasting high-intensity beam (parameters are given in Table II). More details and analyses of these measurements will be published elsewhere.

Average measured and simulated loss maps are shown in Fig. 13. The ratio between the higher peaks agrees well with measurements, although there is a factor 2 discrepancy in magnitude. This could, just as for ions, be explained with systematic errors dominated by the uncertainty in the shower simulation. Furthermore, the intensity was more than 4 orders of magnitude higher than in the ion runs, which might introduce additional losses not caused by the collimator. This is however not understood in detail.

It is clear from Fig. 13 that there is a significant qualitative difference between proton and ion loss patterns: the maximum signal for protons was found on BL520 (closest to the collimator), while in the ion runs it was found on BL521. This can be understood from the fact that the δ of the protons is much lower, since they cannot fragment, which can be seen from Fig. 20. This means that large

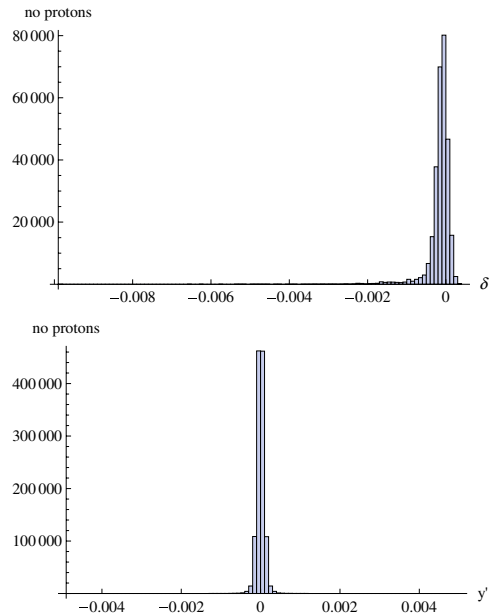


FIG. 20. (Color) The simulated distribution of δ (top) and y' (bottom) of all protons coming out of the collimator.

betatron angles caused by multiple scattering are the main loss mechanism instead of dispersion, although the spectrum of vertical angles is also more narrow than for ions (see Fig. 20). The difference in loss pattern is a striking parallel to the expected behavior in the LHC, and the ability of the simulations to quantitatively predict this behavior in the SPS provides a very valuable benchmark of the simulation studies which have been performed for the LHC.

XI. CONCLUSIONS

We have done measurements and simulations of $^{208}\text{Pb}^{82+}$ ion loss patterns induced by a collimator in the CERN SPS, in order to benchmark simulation tools used for the LHC. Qualitatively, the features of the loss pattern can be well understood from the particle-matter interactions in the collimator and the behavior of the dispersion function downstream of it. A wide range of nuclei are created in the collimator due to fragmentation of the original $^{208}\text{Pb}^{82+}$ beam. The created isotopes have different Z/A ratios and follow different dispersive orbits until they are lost, making the machine act as a spectrometer.

Quantitatively, the simulated loss distribution corresponds well to measurements. In terms of absolute BLM signals, predicted and measured values agree to about 30%

for the largest losses, while discrepancies can reach a factor 3 for lower loss peaks (excluding the highly fluctuating BL522). This is consistent with expected uncertainties. We performed measurements with different beam energies and collimator angles and observed changes in the loss pattern, which were reproduced by our two-stage simulations with ICOSIM and FLUKA. We used two methods to simulate the particle-matter interaction in the collimator—a fast simplified Monte Carlo and a full FLUKA shower simulation—and found a good agreement with measurements for both methods when the losses are dominated by heavy fragments close to the original ion. The simplified model is therefore well suited to predict limiting losses in the superconducting magnets of the LHC with good accuracy. Losses consisting of light ions are, on the other hand, not treated by the simplified method, and if such losses are important the full shower simulation should be used.

Furthermore, we have studied beam loss data taken with a proton beam and found that the loss patterns induced by the collimator in the SPS are qualitatively different for $^{208}\text{Pb}^{82+}$ ions and protons. This difference is well reproduced by simulations. The ions are lost mainly due to a change in magnetic rigidity caused by fragmentation, while the protons are lost because of large betatron angles from scattering.

These results confirm and strengthen our understanding of ion beam losses related to collimation and are a vital test of our ability to make predictions for the LHC.

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PAPER IV

Time evolution of the luminosity of colliding heavy-ion beams in RHIC and LHC

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Time evolution of the luminosity of colliding heavy-ion beams in RHIC and LHC

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We have studied the time evolution of the heavy ion luminosity and bunch intensities in the Relativistic Heavy Ion Collider (RHIC), at BNL, and in the Large Hadron Collider (LHC), at CERN. First, we present measurements from a large number of RHIC stores (from Run 7) with colliding 100 GeV/nucleon $^{197}\text{Au}^{79+}$ beams without stochastic cooling. We compare the data with simulations based on multi-particle tracking, taking into account collisions, intrabeam scattering, radiation damping, and synchrotron and betatron motion. A very good agreement with data is found. We then use the code to make predictions of the time evolution of the future $^{208}\text{Pb}^{82+}$ beams in the LHC at injection and collision energy. For this case, we compare with another simulation method, in which a system of ordinary differential equations describing the emittances and bunch populations is solved numerically. This method is faster but has the disadvantage of assuming Gaussian bunch distributions.

PACS numbers: 29.20.db, 25.75.-q

I. INTRODUCTION

During the design and operation of a heavy-ion collider, e.g., the Relativistic Heavy Ion Collider (RHIC) [1] or the Large Hadron Collider (LHC) [2], one of the main goals is to maximize the time-integral of the luminosity $\mathcal{L}$ at the experiments. As usual, luminosity is defined as the event rate per unit cross section and depends only on the spatial density distributions of the colliding beams at the collision points.

The time-evolution of the spatial densities is determined via single-particle dynamics from that of the phase-space distributions, i.e., the kinetics of the beams. This, in turn, is determined by the combined influences of several inter-dependent physical processes that generally act on much longer time scales. The action of some of these (e.g., beam-beam collisions, scattering on residual gas) principally remove particles from the beams. Others (e.g., intra-beam scattering (IBS), radiation damping) predominantly change their distribution in space and momentum. To maximize $\int \mathcal{L} dt$, losses caused by other processes than the collisions themselves need to be minimized and the beam sizes should stay small. These processes therefore need to be understood and modeled in quantitative detail.

There have been numerous previous studies of the time evolution of luminosity (in colliders) or other performance parameters such as the emittances (e.g., in synchrotron light sources or the damping rings of linear colliders). Among many possible references, we cite [3–6] which are particularly close to the applications of this

paper.

Many of these are based on the solution of systems of coupled ordinary differential equations (ODEs) that describe the time-evolution of a few parameters characterising the beam distributions, typically the intensities and the first- and second-order moments of the distributions (beam centroids and emittances). Such systems can only be closed with additional assumptions on the nature of the beam distributions. Typically these are assumed to be Gaussian in all three degrees of freedom. Besides closing the system of equations, this can also allow convenient analytical forms for some of the terms, e.g., those describing intra-beam scattering or the way in which the luminosity is modified by crossing angles at the interaction point. This approach was applied to the evolution of heavy-ion luminosity in the LHC in Ref. [6]. Alternative approaches involve solving the Fokker-Planck equation for the beam distribution functions [7, 8] and single particle tracking. In Ref. [9] both the ODE method and particle tracking were implemented in the same simulation code.

In this article, we study the time evolution of colliding heavy-ion beams in RHIC and LHC. In Sec. II, we present measurements of luminosity and beam intensities during a large number of physics stores during Run-7 [11] in RHIC and give a summary of the running conditions.

In Sec. IV we compare the data with a multi-particle tracking simulation, described in Sec. III. It is based on an extended version of the code presented in Refs. [12–14], motivated by the fact that the longitudinal bunch distributions in RHIC are not Gaussian, as discussed in Sec. III E. It is important to have a simulation that can model IBS for arbitrary profiles of bunched beams.

In Sec. IV, the simulations are compared with the data from RHIC, and in Sec. V we make predictions for the LHC and compare the precise but slow tracking with an

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TABLE I: Typical beam and machine parameters for RHIC Run-7 and the LHC, given for the beginning of store. The transverse emittance in RHIC showed large variations between stores [10].

Parameter	Unit	RHIC collision	LHC collision	LHC injection
Species	...	$^{197}\text{Au}^{79+}$	$^{208}\text{Pb}^{82+}$	$^{208}\text{Pb}^{82+}$
Beam energy	GeV/nucleon	100	2759	177.4
Lorentz factor γ_{rel}	...	107.4	2963.5	190.5
Bunch intensity N_b	10^9	1.1	0.07	0.07
Bunches per beam	...	103	592	592
Normalized transverse rms emittance	μm	3.1	1.5	1.4
Long. rms emittance	eV s/nucleon	0.25	0.25	0.07
rms bunch length	cm	30	7.94	9.97
rms energy spread	10^{-3}	0.8	0.11	0.39
N.o. active interaction points (IPs)	...	2-4	1-3	0
Envelope function at IP β_{xy}^*	m	0.8	0.5	—
Crossing angle at IP	μrad	0	70	—
Peak luminosity	$10^{27} \text{ cm}^{-2} \text{ s}^{-1}$	3	1	—
RF harmonic numbers h	...	360, 2520	35640	35640
RF gap voltage	MV	3 ($h = 2520$) 0.3 ($h = 360$)	16	8

other simulation method based on ODEs. This method, discussed in Sec. V, is fast but lacks in accuracy when the beam distributions are not Gaussian. Therefore it is not suited for simulations of RHIC.

II. MEASURED LIFETIMES IN RHIC

The RHIC Run-7 consisted of 191 physics stores in 2007 with colliding $^{197}\text{Au}^{79+}$ beams at an energy of 100 GeV/nucleon. The main beam and machine parameters for Run-7 are summarized in Tab. I.

During Run-7, longitudinal stochastic cooling became operational for the Yellow ring [14] (the two rings of RHIC are called Blue and Yellow). Stochastic cooling counteracts the longitudinal diffusion caused by intra-beam scattering (IBS) that eventually pushes particles outside the longitudinal acceptance (RF bucket). This loss process, discussed in Sec. III E, is responsible for a large fraction of the beam losses in RHIC. In this article, we focus on stores without stochastic cooling in order to make a comparison with the LHC.

The time-dependent average bunch intensities N_i ($i = 1, 2$ for Blue and Yellow) were measured using DC transformers [1] and can be fitted empirically by an exponential function

$$N_{\text{fit}}(t) = N(0) \exp(-t/T_N). \quad (1)$$

The beam lifetimes T_N fitted to data from the first 3 h of all physics stores are shown in Fig. 1 and the mean and standard deviation values are listed in Tab. II. Regular physics stores last 5 h, but some stores terminate prematurely. Almost all stores have data for 3 h.

The luminosity was recorded during every store by detecting neutrons emitted by ions that have undergone mutual electromagnetic dissociation in the colli-

TABLE II: Average and rms values of fitted lifetime parameters for all 191 physics stores of RHIC Run-7.

Parameter	Unit	Average	Standard deviation
Blue beam lifetime T_N	h	9.9	1.7
Yellow beam lifetime T_N	h	10.9	3.3
Luminosity, fast decaying component $A/(A+B)$	%	33	12
Luminosity lifetime T_f , fast decaying	h	0.6	0.5
Luminosity, slow decaying component $B/(A+B)$	%	67	12
Luminosity lifetime T_s , slow decaying	h	3.9	2.5

sions [15, 16]. It turns out that it can be well fitted by a sum of fast- and slow-decaying exponential functions

$$\mathcal{L}_{\text{fit}}(t) = A \exp(-t/T_f) + B \exp(-t/T_s) \quad (2)$$

with the fit parameters A, T_f, B, T_s . This is a 3-parameter fit since $\mathcal{L}_{\text{fit}}(0) = A + B$. The fit function (2) is purely phenomenological: it is not chosen on the basis of any particular physical model but rather for the fact that it generally fits rather well and is convenient to implement. The fit parameters for all stores are shown in Fig. 2 and the means and standard deviations in Table II.

III. PARTICLE TRACKING SIMULATION

The tracking program is based on a code initially used for stochastic cooling [12–14], which has been developed further to simulate the time evolution of two circulating and colliding bunches.

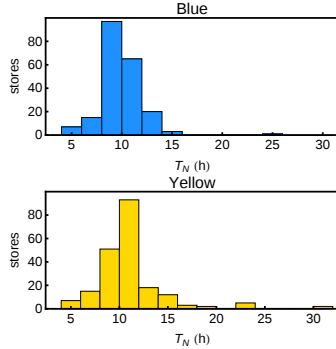


FIG. 1: Blue and Yellow beam lifetimes T_N obtained by fitting Eq. (1) to measurements. Only stores without stochastic cooling are included.

Each bunch contains a number of macro particles (in the simulations, 5×10^4 were used), which are tracked in a 6D phase space. Normalized coordinates (x, p_x, y, p_y) are used in the transverse planes and (t, p_t) with $p_t = \gamma - \gamma_0$ in the longitudinal (γ_0 is the Lorentz factor of the reference particle). The particle coordinates are updated on a turn-by-turn basis as a function of the physical processes acting on them. The following processes are taken into account:

- Synchrotron and betatron motion: All coordinates are updated deterministically on every turn, taking into account the machine tune, chromaticity and RF voltage. Particles outside the acceptance of the RF bucket are removed. Linear betatron coupling is taken into account in thin-lens approximation. A detailed description can be found in Ref. [12].
- Collisions: collision probabilities are sampled as a function of the local density of the opposing beam at (x, y) . This is described in Sec. III A.
- IBS: Each particle is given a random kick, calculated with the Piwinski model in the smooth lattice approximation, but modulated by the local particle density in order to account for non-gaussian longitudinal bunch profiles. This is described in Sec. III C.
- Radiation damping and quantum excitation: All particles receive a deterministic amplitude decay and a random excitation. This is described in Sec. III D.

Other processes are neglected. A detailed treatment of beam-gas scattering has been done elsewhere for RHIC [17, 18] and LHC [19, 20]. In both cases, lifetimes of the order of 100 or several hundreds of hours were found. The emittance blowup at RHIC is fractions

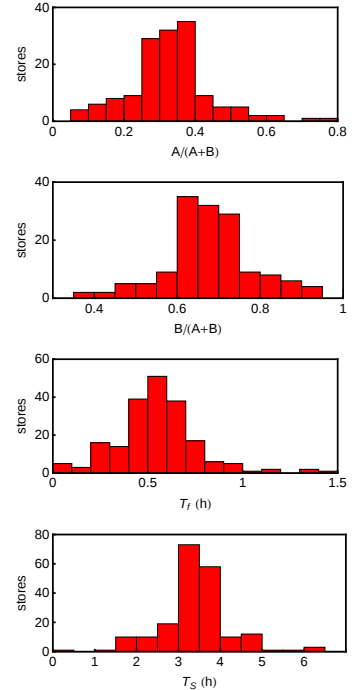


FIG. 2: Distributions of fitted luminosity lifetime parameters defined by Eq. (2), where T_f is chosen to be the faster decay time and T_s the slower.

of a percent per hour [18] and standard formulas [21] give a similar result for the LHC with predicted vacuum conditions [2, 19]. Therefore, beam-gas scattering has a negligible impact on the dynamics in RHIC and LHC when compared to collisions or IBS.

The strengths of the processes are scaled up to account for both the smaller number of macro particles and by an additional factor, set by the user, that reduces the computational time, so that the number of turns in the simulation corresponds to a much larger number of turns in the real machine. Typically one simulation turn corresponds to 2×10^4 real machine turns in our simulations to achieve a relatively fast execution without loss in precision.

A. Collisions

A collision probability P_1 is calculated for every particle on every turn, and a random number is sampled to determine if an interaction takes place. In that case, the

particle is removed. To calculate P_1 we perform an overlap integral of the density of the opposing bunch with a Dirac δ -function that represents the trajectory of a single particle. The details of this are shown in Appendix. The most general collision routine makes no assumptions on the beam distributions and uses a discrete binning of the particles. The integration is then replaced by a sum over the bins. This routine is slow and a much faster code is obtained with some simplifications.

First we assume gaussian distributions in x and y , which is generally a very good approximation (in RHIC, the longitudinal distribution is however non-gaussian as explained in Sec. III E). Furthermore, we assume a common luminosity reduction factor instead of computing it for every particle, so that P_1 is a function of the transverse coordinates only. In the transverse plane we use action-angle variables (J_x, ϕ_x) defined for a particle in bunch 1 by

$$\begin{aligned} x_1 &= \sqrt{2J_x\beta_{xy}^*} \cos \phi_x \\ x'_1 &= -\sqrt{\frac{2J_x}{\beta_{xy}^*}} (\sin \phi_x + \alpha_{xy}^* \cos \phi_x), \end{aligned} \quad (3)$$

with the angle variables given at the IP and an analogous definition in y . Here β_{xy}^* is the value of the optical function (assumed to be the same in x and y) at the IP where we define the longitudinal coordinate to be $s = 0$ and $x' = dx/ds$. We note that $\alpha_{xy}^* = -\beta'_{xy}(0)/2 = 0$.

Since every simulation turn corresponds to a large number of machine turns, where ϕ has a uniform distribution on the interval $[0, 2\pi]$, we average P_1 over ϕ . The resulting collision probability for a particle in bunch 1, derived in Appendix, is a function of the betatron actions J only:

$$P_1 = \sigma N_2 \frac{\exp\left(-\frac{J_x}{2\epsilon_{2x}} - \frac{J_y}{2\epsilon_{2y}}\right) I_0\left(\frac{J_x}{2\epsilon_{2x}}\right) I_0\left(\frac{J_y}{2\epsilon_{2y}}\right)}{2\pi\beta_{xy}^* \sqrt{\epsilon_{2x}\epsilon_{2y}}} R_{\text{tot}} \quad (4)$$

Here σ is the interaction cross section, N_2 the intensity of bunch 2, I_0 a modified Bessel function, $(\epsilon_{2x}, \epsilon_{2y})$ are the geometric rms emittances of bunch 2 and R_{tot} is the global luminosity reduction factor, which takes into account the hourglass effect and a crossing angle 2θ . Writing the longitudinal distributions of the two bunches, normalized to unity, as $\rho_{zi}(z_i)$, with z_i being the distance to the center of bunch i and $i = 1, 2$, the reduction factor is given by

$$\begin{aligned} R_{\text{tot}} &= \int \exp\left(-\frac{2\beta_{xy}^* \sin^2 \theta}{(\epsilon_{1x} + \epsilon_{2x}) \left(1 + \frac{2\beta_{xy}^{*2} [1 + \cos(2\theta)]}{(z_1 + z_2)^2}\right)}\right) \\ &\quad \times \frac{\rho_{z1}(z_1) \rho_{z2}(z_2)}{1 + \frac{(z_1 + z_2)^2}{4\beta_{xy}^{*2} \cos^2 \theta}} dz_1 dz_2. \end{aligned} \quad (5)$$

When collisions occur at several IPs, P_1 is summed up over all of them (only the factor $R_{\text{tot}}/\beta_{xy}^*$ varies). Furthermore, P_1 has to be scaled to account for the smaller

number of macro particles and the shorter time scale in the simulation.

If the transverse action in bunch 1 is assumed to be distributed as $\rho_{1u} = \exp(-J_u/\epsilon_{1u})/\epsilon_{1u}$ for $u = x, y$, equivalent to a gaussian distribution in u_1 and p_{u1} , we calculate the luminosity as

$$\begin{aligned} \mathcal{L} &= k_b f_{\text{rev}} N_1 \int \rho_{1x} \rho_{1y} \frac{P_1}{\sigma} dJ_x dJ_y \\ &= \frac{k_b f_{\text{rev}} N_1 N_2}{2\pi\beta_{xy}^* \sqrt{(\epsilon_{1x} + \epsilon_{2x})(\epsilon_{1y} + \epsilon_{2y})}} R_{\text{tot}}, \end{aligned} \quad (6)$$

where k_b is the number of bunches circulating at frequency f_{rev} in each ring. Eq. (6) agrees with standard formulas [21].

B. Interaction cross section

To calculate P_1 we need the total cross section σ for interactions in which colliding particles are lost from the beam. Apart from inelastic hadronic interactions, bound-free pair production (BFPP) and electromagnetic dissociation (EMD) have to be taken into account. These electromagnetic processes create particles with a charge-to-mass ratio different from the main beam, which eventually leads to particle loss. Detailed discussions of these loss mechanisms in heavy ion colliders can be found in Refs. [2, 5, 6, 22–24].

Cross sections were calculated for BFPP in Ref. [25] and for EMD in Ref. [26]. We have taken standard values for the inelastic cross sections as used by the RHIC and LHC experiments [2, 27–29]. In Table III we summarize the cross sections of the different processes that were used in the simulation. As can be seen, the majority of the luminosity is used up by BFPP and EMD rather than the inelastic interactions, which are the usual object of study of the experiments.

TABLE III: Interaction cross sections σ in RHIC and LHC for different processes removing ions from the beam. Values are taken from Refs. [2, 25–27]. The EMD cross sections include all decay channels.

Process	σ in RHIC (barn)	σ in LHC (barn)
BFPP	117	281
EMD	99	226
Inelastic	7	8
Total	223	515

C. Intrabeam scattering

The standard formalisms for describing IBS [30–32] assume gaussian profiles. To simulate RHIC, where the longitudinal distributions are known to be non-gaussian,

an IBS model has to go beyond this assumption. Such a model has been implemented in Refs. [12, 14], which we summarize here for completeness. It assumes that the longitudinal and transverse degrees of freedom are independent and that the transverse distributions remain gaussian.

The IBS routine starts from the Piwinski model in smooth lattice approximation [30]. We define the rise times $T_{\text{IBS},u}$, $u = x, y, z$ by

$$\frac{d\epsilon_u}{dt} = \frac{\epsilon_u}{T_{\text{IBS},u}}. \quad (7)$$

The rise times are calculated for gaussian distributions but are then modulated for every particle by the local beam density to account for arbitrary longitudinal profiles. Thus, particles are given normally distributed momentum kicks Δp_u in each plane on every simulation turn:

$$\Delta p_u = r \sigma_{pu} \sqrt{2T_{\text{IBS},u}^{-1} T_{\text{rev}} \sigma_t \sqrt{\pi} \rho_t(t)} \quad (8)$$

Here r is a gaussian random number with zero mean and unit standard deviation, T_{rev} the revolution time, σ_t the standard deviation of t and σ_{pu} the standard deviation of the momentum p_u in plane u . It can be shown that if the longitudinal distribution ρ_t , normalized to unity, is gaussian, integrating over all particles yields exactly the growth given by Eq. (7). The strength of the IBS kicks are also scaled up by the time ratio of the simulation.

The calculated rise times for the beginning of a store, with parameters in Table I, are shown in Table IV. As can be seen, IBS is strong in RHIC and at injection energy in the LHC.

TABLE IV: IBS rise times for the emittances in RHIC and LHC, calculated using both the Piwinski model, as described in this section, and MAD-X, as discussed in Sec. V. The calculations for RHIC are done for gaussian bunches and listed only for comparisons, since they are not directly applicable to the machine. The Piwinski model gives around 20% shorter rise times on average.

	RHIC coll.	LHC coll.	LHC injection
$T_{\text{IBS},x}$, Piwinski (h)	1.9	12.2	2.4
$T_{\text{IBS},x}$, MAD-X(h)	2.3	13.2	3.0
$T_{\text{IBS},z}$, Piwinski (h)	1.8	7.8	5.2
$T_{\text{IBS},z}$, MAD-X(h)	2.4	7.8	6.7

D. Radiation damping

Radiation damping and quantum excitation are modelled in each plane u by a deterministic decay, given by the emittance damping time $T_{\text{rad},u}$, and a random excitation, as described in Ref. [33]. Since $T_{\text{rad},u} \gg T_{\text{rev}}$, we expand to first order in $T_{\text{rev}}/T_{\text{rad},u}$, so that the decay coefficient for one turn becomes $\exp(-T_{\text{rev}}/T_{\text{rad},u}) \approx$

$1 - T_{\text{rev}}/T_{\text{rad},u}$. The quantum excitation is determined by the usual radiation integrals over the lattice [21] and would lead, in the absence of other dissipative effects, to stationary gaussian distributions with rms sizes $\sigma_{\text{eq},u}$. The corresponding one-turn map for the momentum coordinate p_t is therefore

$$p_t \rightarrow p_t(1 - T_{\text{rev}}/T_{\text{rad},z}) + \sigma_{\text{eq},z} r \sqrt{2\langle r^2 \rangle T_{\text{rev}}/T_{\text{rad},z}}. \quad (9)$$

where r is a unit, zero-mean random number. Similar maps are used in the transverse planes.

In both RHIC and LHC, the photons emitted by heavy nuclei are very soft [2] so the $\sigma_{\text{eq},u}$ are several orders of magnitudes smaller than the real beam and quantum excitation has no significant effect on the dynamics. In RHIC, radiation damping is also negligible but it is important, enough to counter IBS, in the LHC at collision energy [2, 6]. The damping times are summarized in Table V.

TABLE V: Calculated radiation damping times for the emittances in RHIC and LHC. The damping is equal in the transverse planes.

	RHIC collision	LHC collision	LHC injection
$T_{\text{rad},z}$ (h)	825	6.3	23749
$T_{\text{rad},xy}$ (h)	1650	12.6	47498

E. Starting distribution

It is important to choose an appropriate, realistic, starting distribution of the particles in the tracking; otherwise agreement between measurement and simulation is poor. In the transverse plane, the beams are well approximated by gaussian distributions, both in RHIC and (it is expected) LHC, and the initial coordinates are generated by the code from the starting emittances. The data from the RHIC stores does not in fact include the measured transverse beam sizes so these have been inferred from the logged initial bunch populations and luminosity using Eq. (6). A strong coupling between the horizontal and vertical planes, keeping the beams round on a short time scale, was assumed. We also assumed equal transverse beam sizes in every bunch of the two beams. Despite not being justified by measurements, this reduces the dimensionality of the problem to a tractable level; there is, in any case, insufficient data to attempt a fit to the small variations in intensity and size of individual bunches. Indeed we have found that, if different beam sizes are used in the simulation, the luminosity remains approximately unchanged while the bunch currents show small variations.

In the longitudinal plane, the distribution is expected to be gaussian in the LHC but not in RHIC. An example of the bunch current measured at RHIC when the beams

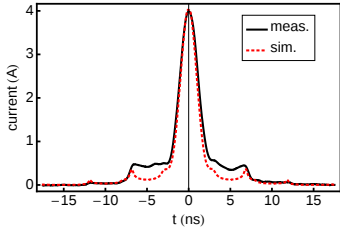


FIG. 3: Example of a measured bunch profile in RHIC after the ramp when collisions are turned on. We show also the simulated profile used as starting conditions in the simulations. It was generated by letting an initially gaussian bunch circle in the machine under the influence of IBS.

were put into collision is shown in Fig. 3. To understand the bunch shape, we discuss briefly the synchrotron motion in RHIC.

RHIC uses a double RF system (see Tab. I) and the longitudinal emittance is comparable to the bucket size of the $h = 2520$ system. The combined RF voltage from both systems is shown in Fig. 4. We show also its negative time integral, which is proportional to the “potential energy” term in the Hamiltonian of the synchrotron motion. One can thus picture the particles “sliding” on this surface. As a particle in the central bucket continuously receives small momentum kicks from IBS, it oscillates with higher amplitudes until it has enough energy to enter the next $h = 2520$ bucket. When it has a high enough amplitude to leave the $h = 360$ bucket, defining the acceptance, the motion becomes unbounded and it is considered lost by the simulation. This loss process is called debunching and is very strong in RHIC. For this reason, very significant improvements of the lifetimes and integrated luminosity were possible through the implementation of stochastic cooling [12–14].

The profile in Fig. 3 results from the RF gymnastics performed after the energy ramp, when the storage RF system is turned on. To make the bunches fit in the $h = 2520$ buckets, they are shortened through a rotation in the longitudinal phase space, but it is inevitable that some particles escape into neighboring buckets [34].

To reproduce the profile in Fig. 3 and keep the phase space consistent with the RF motion, we used as starting conditions coordinates generated by tracking an initially gaussian bunch, located only in the central $h = 2520$ bucket, under the influence of IBS only. In Fig. 5 we show the longitudinal phase space from this simulation on different turns. Only particles with an amplitude high enough to pass from the central $h = 2520$ bucket are present in the neighboring buckets. Therefore, the centers of these buckets are empty in phase space. This gives a time profile similar to the expected result of the bunch shortening (see Ref. [34]).

Fig. 3 shows the resulting bunch current for the popu-

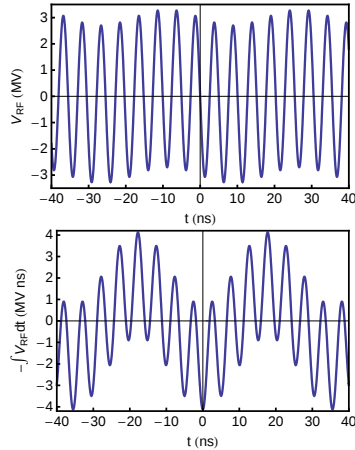


FIG. 4: The RF voltage (parameters given in Tab. I) and its negative time integral. Since synchrotron radiation is negligible, the synchronous phase is at the origin at $V_{RF} \approx 0$.

lation that was used as starting distribution in the RHIC simulations. It corresponds well to the measured profile except around $t = \pm 5$ ns, at the centers of the first side buckets (see Fig. 4). The discrepancy means that in the measurement, the phase space distribution is less hollow than in Fig. 5.

Even though it would be possible to recreate the measured time profile exactly, this ad-hoc construction would depend on an arbitrary choice of the energy deviations of the extra particles in the side buckets. We prefer to keep the starting conditions as simple as possible in order to test the predictive power of the code for a large number of different conditions and therefore use the profile shown in Fig. 3.

In Fig. 6 we show an example of the simulated losses caused by IBS and collisions in RHIC. Simulations show that if no particles are present in the outer $h = 2520$ buckets in the starting population, losses from debunching do not occur from the beginning of the store. With such a longitudinal starting distribution, the initial slope of $N_i(t)$ is less steep and the agreement with measurements is significantly worse.

IV. COMPARISON BETWEEN SIMULATIONS AND MEASUREMENTS IN RHIC

As an example of the detailed time evolution in a store, we show in Fig. 7 the measured and simulated luminosity and bunch populations for store 8908 (parameters are given in Tab. VI). This store is above average in luminosity performance but not exceptionally good. The

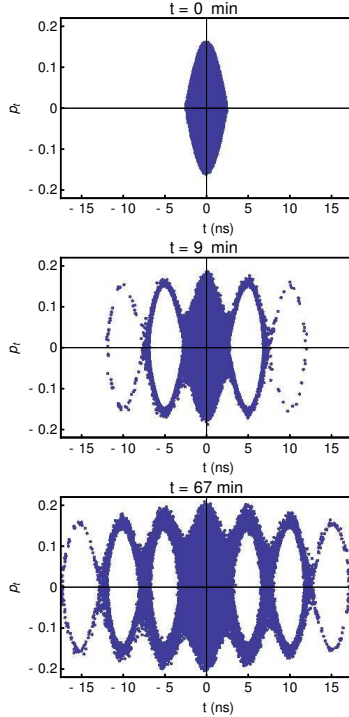


FIG. 5: A simulated bunch under influence of IBS only in longitudinal phase space at different times. Each point represents one particle out of 50000. The center of the bunch is located in the central bucket at $t = 0$. The longitudinal momentum is defined as $p_t = \gamma - \gamma_0$, where γ_0 is the Lorentz factor of the synchronous particle. The figure shows an idealised situation, where all particles start in the central bucket (reality is different because of the RF gymnastics). The distribution at 67 minutes was used as starting conditions in the longitudinal plane for the full tracking, due to its similarity with the measured bunch profile in Fig. 3.

agreement with simulations is very good.

In order to have more statistics, we simulated 139 stores without stochastic cooling with varying bunch populations and luminosity from RHIC Run-7. We use the fits to the measurements (1) and (2) for comparisons as they are rather accurate during the first 3 hours. We used the same current, shown in Fig. 3, for all stores, which introduces an error, but allows us to better test the predictive ability of the code.

To measure the goodness of the tracking simulation, we use a benchmark parameter ξ defined as the average ratio between a simulated and measured quantity U over

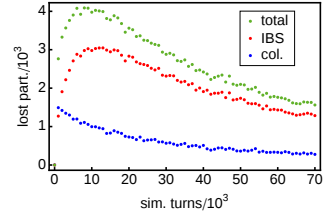


FIG. 6: The amount of macro particles lost (averaged over 1000 simulation turns) due to IBS and collisions from bunch 1 (blue) during the simulation of the test store 8908. In total 5×10^9 macro particles were simulated over 7×10^4 turns, corresponding to a bunch population of 1.056×10^9 and 5.26 h in the real machine.

TABLE VI: Starting parameters for the example store called 8908. The transverse starting emittance was not measured, but inferred from the measured luminosity, bunch populations and hourglass factor using Eq. (A.9). It was assumed to be equal for both beams and planes.

Parameter	Unit	value
N_1 (Blue)	10^9 particles	1.056
N_2 (Yellow)	10^9 particles	1.004
$\mathcal{L}$	$10^{27} \text{ cm}^{-2} \text{ s}^{-1}$	3.0
transv. geom. rms emittance	mm mrad	2.34
FWHM of bunch length	ns	2.6

the first three hours:

$$\xi = \frac{1}{3h} \int_{t=0h}^{t=3h} \frac{U_{\text{sim}}(t)}{U_{\text{fit}}(t)} dt \quad (10)$$

Here U is one of the quantities $\mathcal{L}, N_1, N_2$. Histograms of ξ for 139 stores are shown in Fig. 8. We have deselected 9 stores, where the automatically calculated fit parameters were unrealistic or the beam current or luminosity dropped too rapidly to possibly be accounted for by collisions and IBS. The mean values and standard deviations of ξ are shown in Tab. VII. An overall good agreement is found.

TABLE VII: The mean $\langle \xi \rangle$ and the standard deviation σ_ξ of the ratio between simulated and measured quantity over 139 stores in Run-7 without stochastic cooling in RHIC.

Quantity	$\langle \xi \rangle$	σ_ξ
$\mathcal{L}$	1.11	0.054
N_1	1.015	0.032
N_2	1.004	0.033

Several possible sources of the discrepancies exist. Apart from the uncertainty resulting from the approximations in the simulation model, and the use of the same longitudinal initial conditions in all stores, variations of

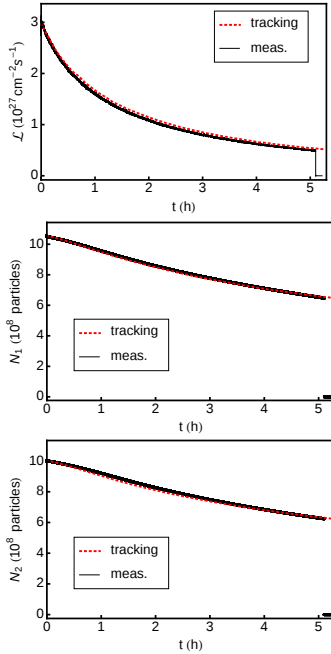


FIG. 7: The luminosity (top), blue bunch intensity (middle) and yellow bunch intensity (bottom) from measurements for store 8908 in RHIC shown together with the result from tracking simulations.

the machine optics, in particular β_{xy}^* , between different stores could give rise to errors. The logged data show that in some stores, the luminosity varies between the IPs at STAR and PHENIX, although they have nominally the same β_{xy}^* .

The interaction cross sections have uncertainties of the order of a few 10%. Decreasing σ to 180 barn in the simulation changes the luminosity by 4% after 3 h. The cross section for mutual EMD, which was used to convert event rate to measured luminosity, has an uncertainty of not less than about 5% [15]. The uncertainties in cross sections could therefore explain a large part of the overestimation of the luminosity in the simulation.

Finally, orbit variations and non-linearities could cause additional beam losses, which are not accounted for. Beam-beam tune shifts, RF noise, ground motion, triplet errors, current noise and the effect of dynamic aperture were not included in the simulation.

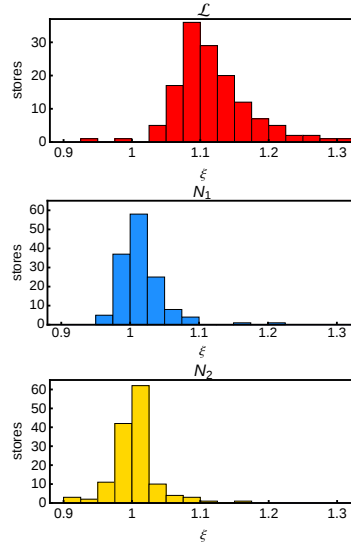


FIG. 8: Comparison of tracking simulation and measurement of luminosity (top), blue bunch intensity (middle), and yellow bunch intensity (bottom) for 139 stores in RHIC without stochastic cooling. The parameter ξ is defined by Eq. (10).

V. PREDICTIONS FOR THE LHC

As the overall agreement with data from RHIC is very good, we use the tracking code to make predictions for the LHC, both at injection and collision energy. Run parameters are presented in Table I. There are important differences with respect to RHIC. The LHC uses a single RF system and bunches are expected to have a gaussian distribution in the longitudinal plane.

In Fig. 9 we show simulations of the time evolution at the injection plateau, where bunches are kept circulating without colliding while the ring is filled. This is expected to take about 10 minutes per ring but, to cover cases where there may be some delay in starting the ramp, we have simulated 1 h. IBS rise times are similar to RHIC in the transverse plane but longer in the longitudinal (see Table IV). The transverse emittance is expected to be 3% larger after 20 minutes and 8% larger after 1 h. The simulated bunch current is 1.7% lower after 20 min and 5.7% after 1 h because of debunching losses. The profile stays approximately gaussian.

Simulations of the time evolution at collision energy using a different simulation method were done in Ref. [6]. Here we repeat these simulations, including also the luminosity reduction factor, and compare with tracking for 1–3 active IPs (the three experiments ALICE, ATLAS and CMS are expected to study heavy-ion collisions). We

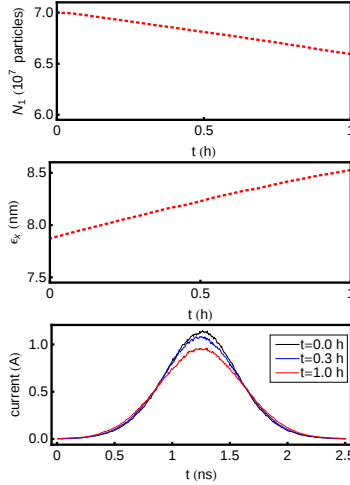


FIG. 9: The simulated time evolution in the LHC of the bunch intensity and transverse rms emittance during 1 h at the injection plateau without collisions. The bottom plot shows the longitudinal bunch profile at different times.

describe briefly the simulation method for completeness.

Instead of following single particles, the rms emittances and intensities are used to describe the bunches, and their time evolution is computed by solving numerically a system of coupled ODEs (similar to Refs. [3, 4, 9]). We assume round beams ($\epsilon_{xi} = \epsilon_{yi} \equiv \epsilon_{xyi}$ for beams $i = 1, 2$) due to a strong coupling between the horizontal and vertical planes. As in the tracking simulation, we take only collisions, intra-beam scattering and radiation damping into account. In total we have six dynamical variables: $\epsilon_{xyi}, \epsilon_{li}, N_i$, where ϵ_{li} is the longitudinal emittance. The time evolution of the system is given by [6]:

$$\begin{aligned} \frac{d\epsilon_{xyi}}{dt} &= \frac{\epsilon_{xyi}}{T_{\text{IBS},xy}(N_i, \epsilon_{xyi}, \epsilon_{li})} - \frac{\epsilon_{xyi}}{T_{\text{rad},xy}} \\ \frac{d\epsilon_{li}}{dt} &= \frac{\epsilon_{li}}{T_{\text{IBS},l}(N_i, \epsilon_{xyi}, \epsilon_{li})} - \frac{\epsilon_{xyi}}{T_{\text{rad},z}} \\ \frac{dN_i}{dt} &= -\frac{\sigma N_1 N_2 f_{\text{rev}} n_{\text{IP}} R_{\text{tot}}}{2\pi\beta_{xy}^* (\epsilon_{xy1} + \epsilon_{xy2})} \end{aligned} \quad (11)$$

Here $T_{\text{IBS},xy}, T_{\text{IBS},l}$ are the instantaneous IBS rise times, and n_{IP} the number of IPs with collisions. By adding additional terms to the equations, e.g. as was done for beam-gas scattering in Ref. [6], the method can easily be expanded to account for other effects leading to particle loss or emittance growth.

To solve the system numerically or, in certain special cases, analytically we use Mathematica [35]. Our implementation allows the kinetics of unequal beam intensities

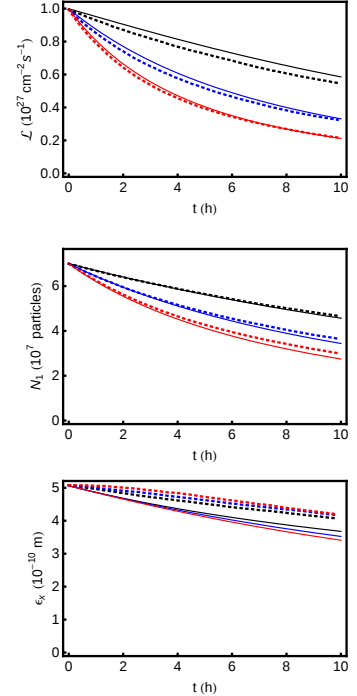


FIG. 10: The simulated time evolution in the LHC of the luminosity, bunch intensity and transverse rms emittance during a 10 h store at top energy with colliding beams. Results are shown from the tracking method (dotted lines) and the ODE method (solid lines) for the cases of one (black lines), two (blue lines) or three (red lines) active IPs taking collisions.

and emittances to be treated although we shall restrict ourselves to equal beams in this paper. When using the method of pre-calculated and interpolated values of $T_{\text{IBS},l}$ and $T_{\text{IBS},xy}$, as explained below, the gain in execution speed when simulating the time evolution in a store is more than a factor 1000 compared with the tracking. A 10 h store takes on the order of a second to solve on a normal desktop computer.

A disadvantage of the ODE method is that Gaussian bunches are assumed, so it is not suitable for simulations of RHIC. Furthermore, for that purpose a term would need to be added to describe debunching.

For convenience, we used the program MAD-X [36] to calculate $T_{\text{IBS},l}$ and $T_{\text{IBS},xy}$. The theoretical framework [37] is an extended version of the Conte-Martini model [32], which includes also vertical dispersion. Gaussian beam distributions are assumed in all planes. The evaluation of $T_{\text{IBS},l}$ and $T_{\text{IBS},xy}$ for just one set of val-

ues $N_i(t)$, $\epsilon_{xyi}(t)$, $\epsilon_{li}(t)$ requires a significant amount of computer time, so it is impractical to do this at runtime.

We therefore use pre-calculated values of the rise times evaluated on a grid of points in the relevant region of $(\epsilon_{xy}, \epsilon_l)$. Since $T_{\text{IBS}} \propto N_i^{-1}$, it is only necessary to evaluate the rise times for one typical value of N_i and then scale. The result is a smooth surface, which can be interpolated with cubic polynomials in the two emittances. This initial step, which has to be done for each optical configuration and beam energy under consideration, takes less than an hour of computer time on a normal desktop machine. In the Mathematica framework, $T_{\text{IBS},xy}$ and $T_{\text{IBS},l}$ are replaced by rapidly evaluated interpolating functions with no loss of precision. This is the key step that allows a fast interactive analysis of many cases of interest. Since we assume round beams, we use $T_{\text{IBS},xy}^{-1} = (T_{\text{IBS},x}^{-1} + T_{\text{IBS},y}^{-1})/2$ (above transition in a flat accelerator lattice the uncoupled IBS calculation gives a large positive growth rate in the horizontal plane and a small damping rate in the vertical). The calculated rise times from MAD-X for the initial distributions are shown in Table IV.

At collision energy the dynamics in the LHC changes significantly, since radiation damping (see Table V) becomes important and compensates the emittance blowup from IBS. As particles are removed from the beams by collisions, IBS becomes weaker while damping stays constant. Therefore, the emittance shrinks during the store. The agreement between the simulation methods is good except for the emittance, which shrinks significantly faster with the ODE method. Losses from debunching are predicted to be negligible in the conditions simulated for the LHC. Beam losses from collisions are by far the dominant effect. Some of the discrepancies can be accounted for by the difference in IBS model.

VI. CONCLUSIONS AND OUTLOOK

We have presented measurements of the time evolution of the luminosity and bunch intensities in both beams during RHIC Run-7 and compared with multi-particle tracking simulations, which give a very good agreement all measured quantities. Simulations of 139 stores without stochastic cooling show that the parameter ξ , defined as the average ratio between a simulated and measured quantity, is distributed around 1 with a standard deviation of only 3% for the bunch populations. An average over-estimate of the measured luminosity by around 11% was found. Possible sources of the discrepancies include the use of the same longitudinal starting profile in all stores, variations in β_{xy}^* , the cross section used to convert the measured luminosity and the neglect of certain factors including dynamic aperture.

We have also made predictions of the time evolution in the LHC, where Gaussian bunches are expected. Here we compared the tracking with the numerical solution of a system of ODEs, describing the emittances and bunch

intensities, and a good agreement was found. The dynamics in the LHC is significantly different, since radiation damping is a stronger effect than IBS. This gives rise to a shrinking emittance (although this benefit will vanish rapidly if the LHC is operated at less than full energy). Therefore, debunching is not an issue in the LHC and the collisions are the main source of particle losses.

Both simulation methods are suitable as testing tools to optimize the luminosity. For example, if also stochastic cooling were to be included, the tracking could be used to make precise predictions of the improvement in luminosity using stochastic cooling in one or both beams.

VII. ACKNOWLEDGMENTS

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Appendix: Collision probability

To derive the phase collision probability in Eq. (4) we consider the movement of a particle in bunch 1 through bunch 2 at an IP, using the coordinate systems defined in Fig. 11 and consider first the case with zero crossing angle. The two bunches move with opposite velocities v so their centers have $s = \pm v\tau$. Both centers are at $s = 0$ at the IP at time $\tau = 0$. We write the density of bunch i , normalized to one, as $\rho_i(x, y, z_i)$. The total number of reactions $\mathcal{L}_{sc}$ per interaction cross section σ during a single bunch crossing is [38]:

$$\mathcal{L}_{sc} = MN_1N_2 \times \int \rho_1(x, y, s - v\tau) \rho_2(x, y, s + v\tau) dx dy ds d\tau, \quad (\text{A.1})$$

where M is a kinematic factor defined as

$$M = \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - (\vec{v}_1 \times \vec{v}_2)^2/c^2}. \quad (\text{A.2})$$

With zero crossing angle and bunch velocities $|\vec{v}_1| = |\vec{v}_2| = v$, we have $M = 2v$.

To obtain P_1 , we define a distribution function ρ_{p1} for a single particle in bunch 1 using the Dirac δ -function. Since a negligible transverse magnetic field is assumed at the IP, a particle in bunch 1 with spatial coordinates (x_1, y_1, z_1) in the bunch and transverse angles (x'_1, y'_1) follows approximately a straight line so

$$\rho_{p1}(x, y, s - v\tau) = \delta(s - v\tau - z_1) \delta(x - [x_1 + x'_1 s]) \delta(y - [y_1 + y'_1 s]). \quad (\text{A.3})$$

In the most general collision routine in the tracking code, ρ_2 is determined by sorting the particles in bunch 2 in discrete bins along the directions (x, y, z_2) . We assume that the transverse distributions at $s = \tau = 0$ are

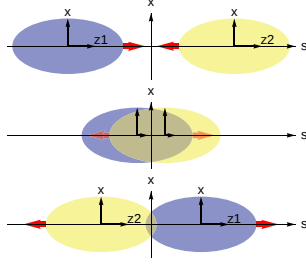


FIG. 11: Schematic view of the collision between two bunches at an IP, showing the three coordinate systems used: the s -axis is fixed in the laboratory frame and with $s = 0$ at the IP, while the z_1 and z_2 axes move with the origin fixed in the center of the two bunches. The bunch movement is indicated by the red arrows. The transverse coordinates of all systems coincide, since zero crossing angle is assumed. All distances are measured in the laboratory frame.

independent, writing them as $\rho_{2x}^*(x)\rho_{2y}^*(y)$, and that the longitudinal density ρ_{2z} is independent of x and y . The transverse binnings are performed at $s = \tau = 0$.

However, we must take into account that the transverse distributions change along s with the optical function $\beta_{xy}(s)$, which we assume to be equal in both planes in the proximity of the IP. In the drift section around the IP $\beta_{xy}(s) = \beta_{xy}^*(1 + s^2/\beta_{xy}^{*2})$, where β_{xy}^* is the presumed minimum at the IP. At a given s close to the IP, the transverse distributions are wider by a factor that we call $\kappa(s)$, defined as

$$\kappa(s) = \sqrt{\frac{\beta_{xy}(s)}{\beta_{xy}^*}} = \sqrt{1 + \frac{s^2}{\beta_{xy}^{*2}}}. \quad (\text{A.4})$$

Inserting ρ_{p1} in Eq. (A.1), multiplying by σ , and integrating, gives P_1 for a particle with given coordinates $(x_1, x'_1, y_1, y'_1, z_1)$:

$$P_1 = 2\sigma N_2 \int \frac{\rho_{2x}^*\left(\frac{x_1+x'_1 s}{\kappa(s)}\right) \rho_{2y}^*\left(\frac{y_1+y'_1 s}{\kappa(s)}\right)}{\kappa(s)} \rho_{2z}(2s - z_1) ds. \quad (\text{A.5})$$

In the code, the integral in Eq. (A.5) is replaced by a sum over all bins that a specific particle passes through.

This method is however slow. A faster code is obtained by assuming Gaussian distributions in x and y . Eq. (A.5) then becomes

$$P_1 = 2\sigma N_2 \times \int \frac{\exp\left(-\frac{(x_1+x'_1 s)^2}{2\epsilon_{2x}\beta_{xy}^*\kappa^2(s)} - \frac{(y_1+y'_1 s)^2}{2\epsilon_{2y}\beta_{xy}^*\kappa^2(s)}\right)}{2\pi\beta_{xy}^*\kappa^2(s)\sqrt{\epsilon_{2x}\epsilon_{2y}}} \rho_{2z}(2s - z_1) ds. \quad (\text{A.6})$$

Here the standard deviation of coordinate u in bunch 2 at $s = 0$ is given by $\sqrt{\beta_{xy}^*\epsilon_{2u}}$. We then change to action-

angle variables (J_x, ϕ_x) using Eq. (3) and average P_1 over ϕ_x . The x_1 -dependent exponential in Eq. (A.6) becomes

$$\int_0^{2\pi} \exp\left[-\frac{J_x}{\epsilon_{2x}} \left(\frac{\sqrt{\beta_{xy}^*} \cos \phi_x - \frac{s}{\sqrt{\beta_{xy}^*}} \sin \phi_x}{\sqrt{\beta_{xy}^* + \frac{s^2}{\beta_{xy}^*}}}\right)^2\right] \frac{d\phi_x}{2\pi} = \exp\left(-\frac{J_x}{2\epsilon_{2x}}\right) I_0\left(\frac{J_x}{2\epsilon_{2x}}\right). \quad (\text{A.7})$$

With a similar phase averaging over ϕ_y , Eq. (A.6) gives

$$P_1 = \sigma N_2 \frac{\exp\left(-\frac{J_x}{2\epsilon_{2x}} - \frac{J_y}{2\epsilon_{2y}}\right) I_0\left(\frac{J_x}{2\epsilon_{2x}}\right) I_0\left(\frac{J_y}{2\epsilon_{2y}}\right)}{2\pi\beta_{xy}^*\sqrt{\epsilon_{2x}\epsilon_{2y}}} \times \int \frac{2\rho_{2z}(2s - z_1)}{1 + \frac{s^2}{\beta_{xy}^{*2}}} ds. \quad (\text{A.8})$$

Eq. (A.8) is the exact phase-averaged collision probability for a particle in bunch 1 with coordinates (J_x, J_y, z_1) . We note that the integral represents the hour glass factor for a particle at a given z_1 .

Furthermore we approximate the hourglass factor to be equal for all particles, by averaging over all z_1 -values. Changing integration variable from s to z_2 for ease of implementation, the global hourglass factor R_h is

$$R_h = \int \frac{\rho_{z1}(z_1)\rho_{z2}(z_2)}{1 + \frac{(z_1+z_2)^2}{4\beta_{xy}^{*2}}} dz_1 dz_2. \quad (\text{A.9})$$

It can be shown that, if ρ_{zu} are Gaussian, Eq. (A.9) is equivalent to the well-known formulas in Ref. [39].

With this approximation, P_1 becomes

$$P_1 \approx \sigma N_2 \frac{\exp\left(-\frac{J_x}{2\epsilon_{2x}} - \frac{J_y}{2\epsilon_{2y}}\right) I_0\left(\frac{J_x}{2\epsilon_{2x}}\right) I_0\left(\frac{J_y}{2\epsilon_{2y}}\right)}{2\pi\beta_{xy}^*\sqrt{\epsilon_{2x}\epsilon_{2y}}} R_h. \quad (\text{A.10})$$

Simulations show that the errors introduced for single particles by using a global R_h are insignificant when considering the whole bunch. For the cases considered in this article, only negligible changes in the simulated time evolution of the luminosity and bunch intensity appear if Eq. (A.10) is used instead of Eq. (A.5), while the execution time drops by a factor 15. Therefore, we only use the faster method for the results in this article.

If the bunches collide with a small crossing angle 2θ , we replace R_h by a more general luminosity reduction factor R_{tot} , which accounts for both the crossing angle and the hourglass effect. Such a factor is derived in Ref. [40] for equal Gaussian beams by integration of Eq. (A.1). Our calculation is completely analogous, with the generalization that we assume unequal transverse beam sizes and unknown longitudinal distributions. The integrations over (y, τ) can be carried out directly yielding Eq. (6), with R_{tot} given by Eq. (5).

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PAPER V

Monitoring heavy-ion beam losses in the LHC

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MONITORING HEAVY-ION BEAM LOSSES IN THE LHC

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Abstract

The LHC beam loss monitor (BLM) system, primarily designed for proton operation, will survey particle losses and dump the beam if the loss rate exceeds a threshold expected to induce magnet quenches. Simulations of beam losses in the full magnet geometry allow us to compare the response of the BLMs to ion and proton losses and establish preliminary loss thresholds for quenches. Further simulations of beam losses caused by collimation and electromagnetic interactions peculiar to heavy ion collisions determine the positions of extra BLMs needed for ion operation in the LHC.

INTRODUCTION

In order to monitor particle losses in the LHC and dump the beam if the losses risk to quench the superconducting magnets, a beam loss monitor (BLM) system will be installed around the ring [1]. This system consists of ionization chambers that will detect secondary shower particles outside the magnet cryostat. The BLMs are primarily designed for protons but will also be used during heavy-ion runs, starting with $^{208}\text{Pb}^{82+}$ beams. Changes need to be made to the present design in order to also monitor the Pb^{82+} losses. Simulations of the ratio between heat deposition in the superconducting coils of a magnet and the signal in the BLM system for both heavy ions and protons allow us to evaluate the species dependence of the thresholds for dumping the beam. Furthermore some extra BLMs need to be added to monitor loss locations that are specific to ion operation. These losses are caused by the inefficiency of the collimation system and by nuclear electromagnetic interactions at the interaction points (IPs).

BEAM DUMP THRESHOLDS

Simulation Setup

In order to evaluate whether the thresholds for beam dumping need to be adjusted between the Pb^{82+} and proton runs, the Monte Carlo code FLUKA [2,3] was used to simulate the shower development in a magnet. The detailed geometry of a main dipole magnet (MB) was implemented in FLUKA and the BLMs were schematically modelled as thin rectangular iron boxes filled with nitrogen, placed outside the MB cryostat. A detailed description of the geometry can be found in [4].

A generic beam loss was represented by a pencil beam at nominal LHC energy impinging on the inside of the vacuum chamber with an incident angle of 0.25 mrad and the shower was simulated in FLUKA. During the simulation, the energy deposition in the beam screen, the superconducting coils and in the BLMs was scored.

Simulations were done with both 7 TeV protons and 2.76 A TeV Pb^{82+} ions.

Results

The resulting energy deposition profiles in the hottest superconducting wire in the MB coil and in the BLMs are shown in Figure 1. In order to facilitate the comparison, the curves for the Pb^{82+} ions have been scaled with energy per nucleon and number of nucleons, which is the same as scaling with charge, since the magnetic rigidity has to be constant. As can be seen in the figure, the two particle types have almost identical profiles. This means that the ratio between the heat deposited in the coils and the energy deposition in the BLMs is about the same for ions and protons and thus that the same thresholds for the beam dump can be used.

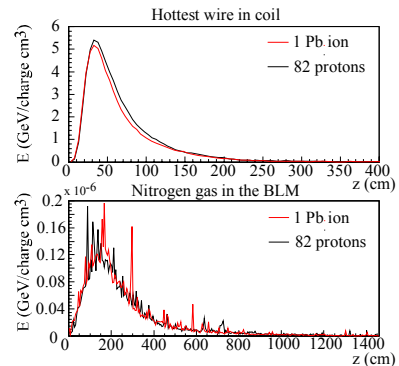


Figure 1: The energy deposition in the hottest wire in the coil and in the N_2 gas inside the BLM for Pb ions and 82 protons.

Physics Discussion

The fact that the thresholds are the same for both species might seem counter-intuitive at first. Therefore we shall give a short account of the important physical processes to explain why this is the case.

The most important process where the energy loss in a material differs between heavy ions and protons is the ionization, which is well described by the familiar Bethe-Bloch formula. From this formula it is clear that the stopping power depends on the square of the charge of the impinging particle, which would imply that the Pb^{82+} ions should lose a factor 82^2 more energy per unit path length than protons after the entry into the material. This different stopping power might be a reason to expect that the heating of the coils should be much higher from Pb^{82+} ions.

However, the heavy ions lose only a small part of their energy through ionization. When ions penetrate into a

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material, they start to break up into fragments through nuclear interactions and electromagnetic dissociation and the stopping power from ionization decreases until the nucleus is either totally fragmented into independent nucleons or the remaining fragments are so slow that they stop. Further FLUKA simulations show that, after 10 cm on average, the heaviest fragment of a 2.76 A TeV Pb^{82+} ion hitting a copper block has around 15% of the initial mass and after 27 cm it is totally decomposed into individual nucleons. Over this distance, the initial Pb^{82+} ion loses much less than 1% of its energy through ionization according to the Bethe-Bloch formula. The main part of the energy is instead deposited through the hadronic shower, which behaves similarly for ions and protons. This means that the macroscopic energy deposition should be roughly the same for the two particle types and that is what is important to consider, since the heat deposition on a 1 cm scale (on the order of the minimum propagating zone of the superconducting cables [4]) is what determines if the magnet quenches.

One must bear in mind that the lost particles in the LHC first hit the beam screen at a small angle before the shower spreads to the coils. This means that the primary lost particle will actually traverse a large distance inside the beam screen. The ionization energy loss is a very local process, since low energy electrons are created that do not travel far before they stop. Therefore it is reasonable to expect that the energy deposition from ions and protons should differ on a small scale in the beam screen but not in the coil, which is only reached by the hadronic shower.

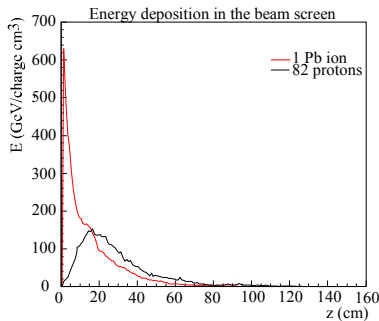


Figure 2: The energy deposition for Pb ions and protons at LHC energy in the innermost 0.1 mm of the beam screen.

A FLUKA simulation shown in Figure 2, where the energy deposition in the beam screen was scored in a mesh of $0.1 \times 0.1 \text{ mm}^2$ transversely, shows that this is the case. If instead the energy deposition is averaged over 1 cm^3 , the difference between ions and protons is very small, meaning that the same thresholds can be used.

Only a main dipole magnet was simulated, but the above result is valid also for other magnet types where the design of the beam screen is similar.

EXTRA BLMS FOR COLLIMATION

The LHC collimation system has been designed for proton beams of high intensity and is based on a two-stage collimation concept, with short primary collimators intercepting particles, and long secondary collimators downstream where the halo particles, scattered off the primaries, deposit their energy in hadronic showers. In spite of having 100 times less beam power, problems arise for ion collimation owing to different mechanisms of particle-collimator interaction: hadronic fragmentation and electromagnetic dissociation upon impact on primary collimators result in the production of particles with small angular divergence and different Z/A ratio. These can fail to be intercepted by secondary collimators and produce significant heat load in the superconducting magnets with risk of quenches. At present the cleaning efficiency falls short by about a factor of 2 for the nominal $^{208}\text{Pb}^{82+}$ ion beam at collision energy and therefore a suitable system of monitoring loss spots has to be put in place. Simulation studies for ion collimation have been carried out using the ICOSIM program, which combines particle tracking capabilities with treatment of heavy ion specific interactions. A detailed description of the program can be found elsewhere [7].

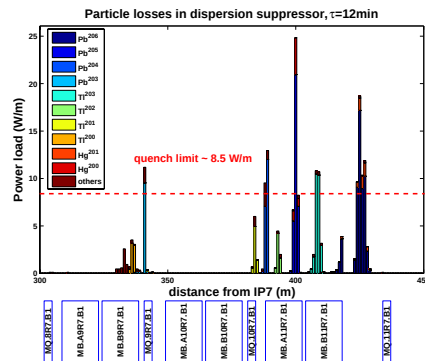


Figure 3: Heat deposition in the dispersion suppressor at collision energy.

Figure 3 shows a loss map produced by ICOSIM for a nominal LHC heavy ion beam at collision energy; losses are limited to the dispersion suppressor region downstream of the betatron collimation section and the heat load exceeds the conventional quench limit of the SC magnets [5] by more than a factor of 2 (but note that [4] makes a case for a higher limit).

A similar pattern of losses has been observed at collision energy in simulations for the second beam, circulating counter-clockwise. At injection energy, on the other hand, losses tend to be more spread out longitudinally, while keeping well below the expected quench limit (generally less than 1 W/m). The loss pattern's dependence on orbit movements has been estimated for the time being with a study of the effect of

changes in the aperture on the peaks positioning and heat load distribution. An increase (decrease) of the aperture by a few mm tends to produce a shift downstream (upstream) of the loss peaks of up to 10 m, but still keeping within the limits of the dispersion suppressor region. Given this uncertainty and the fact that the loss peaks at collision energy tend to be very sharp and localised, a very tight coverage of the dispersion suppressor area with BLMs is proposed: a 2.5 m spacing in between chambers, corresponding to the FWHM of the energy deposition signal in gas (as shown in Figure 1), has been assumed in this scheme for both circulating beams to ensure full detection of losses in the region.

BLMS FOR MONITORING COLLISIONAL PROCESSES

When the Pb^{82+} ion beams collide at an IP, a number of nuclear electromagnetic processes peculiar to ion operation take place [5,6]. Some of these cause the ions to change their charge to mass ratio, meaning that the affected ions will create secondary beams that will leave the design trajectory and be lost somewhere in the machine. These secondary beams can cause a high localized energy deposition that may quench a magnet and it is thus important to monitor the spots where these ions are lost.

The most dangerous process is Bound Free Pair Production (BFPP), where one of the colliding ions captures an extra electron resulting in a secondary beam emerging from the IP. The danger of a quench due to the BFPP beam has already been investigated [4] and it was concluded that the BFPP beam is not likely to quench a main LHC dipole if it hits in the middle of the magnet. However, if the beam instead hits near the end it could be more dangerous. Experiments at RHIC have shown that orbit errors can easily move the BFPP spot by several metres [8]. Therefore it is of highest importance to monitor this loss and add extra BLMs if the expected impact locations are not already covered by those foreseen for protons. The latter are mounted on all quadrupoles in the arcs and dispersion suppressors.

To determine the impact locations of the BFPP beam on both sides of every IP where ions may collide (IP1, IP2, IP5), ions with the appropriate change of magnetic rigidity were tracked in the LHC lattice in the Madtomma environment, as in [6]. An example of the tracking is shown in Figure 4.

From the tracking, locations of BLMs that needed to be added were determined. The losses follow the dispersion function along s , and in all cases a part of the beam envelope at one σ escapes the first impact location and is instead lost further downstream. Both these loss locations have to be covered by extra BLMs.

Another process that takes place at the IP is electromagnetic dissociation (EMD). Here an ion loses one or two neutrons. In the first case, the change in magnetic rigidity remains within the momentum

acceptance of the arcs so that these ions will be absorbed in the momentum-cleaning insertion with a rate determined by the contribution of this process to the luminosity lifetime, $1/(a \text{ few hours})$ at most [5,6]. In the second case, loss spots are formed in the dispersion suppressors but the rate is too small to provoke quenches. Thus no extra BLMs need to be installed to monitor losses from EMD.

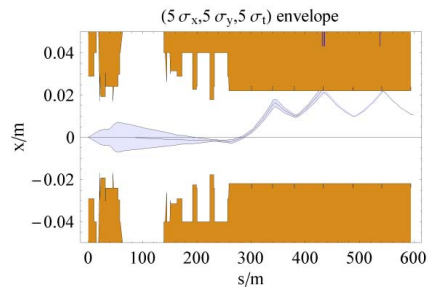


Figure 4: The 5σ envelope of the BFPP beam in the x - s plane coming out of IP 1 and hitting the beam screen 430 m downstream. Proposed extra BLMs for the nominal scheme are shown as blue lines at the top of the picture. A small fraction of the beam continues further downstream.

CONCLUSIONS

The energy loss of $^{208}\text{Pb}^{82+}$ ions and protons inside a material is different because of the high ionization cross section of the ions. However, when lost particles hit the inside of an LHC magnet, the difference is only visible in the beam screen. This implies that the ratio between heat deposition in the coils and BLM signal is approximately the same for Pb^{82+} ions and protons and that the same thresholds for dumping the beam can be used.

Extra BLMs are needed for the ion operation to monitor losses from collimation and from BFPP. The expected loss locations have been determined by appropriate tracking methods in each case and an installation of BLMs has been specified. EMD does not pose a threat to the machine and no extra BLMs are needed for this process.

Acknowledgements: We thank B. Dehning, A. Ferrari, J-B. Jeanneret, M. Magistris and G. Smirnov for profitable discussions and information.

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PAPER VI

Performance with lead ions of the LHC beam dump system

R. Bruce, B. Goddard, L. Jensen, T. Lefevre, and W. Weterings.
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PERFORMANCE WITH LEAD IONS OF THE LHC BEAM DUMP SYSTEM

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Abstract

The LHC beam dump system must function safely with $^{208}\text{Pb}^{82+}$ ions. The differences with respect to the LHC proton beams are briefly recalled, and the possible areas for performance concerns discussed, in particular the various beam intercepting devices and the beam instrumentation. Energy deposition simulation results for the most critical elements are presented, and the conclusions drawn for the lead ion operation. The expected performance of the beam instrumentation systems are reviewed in the context of the damage potential of the ion beam and the required functionality of the various safety and post-operational analysis requirements.

INTRODUCTION

The LHC beam dump system is built to extract the beams without losses from the two rings and steer them onto absorber blocks (TDE) at the end of dedicated extraction lines. The system for each of the two beams consists of extraction kicker magnets (MKD) that deflect the beam to the septum magnets (MSD) in IR6. The MSDs guide the beam in the vertical plane out of the main ring into the extraction line, where it is finally dumped on the TDE, which is located in a cavern some 650 m away. A set of horizontal and vertical dilution kickers (MKBH and MKBV) in the extraction line sweep the beam in a Lissajous figure approximately 100 cm long on the TDE. The system also contains beam intercepting devices: diluters designed to protect other LHC elements against badly extracted beams, specifically the TCDS in front of the MSD septum and the TCDQ in front of the superconducting magnet Q4; a large 60 cm diameter carbon-composite window (VDWB) used to separate the vacuum of the extraction lines from the TDE block; a 60 cm diameter fixed beam profile screen (BTVDD) used to measure the impact position of the dumped beam.

The beam dump system has been primarily designed for protons but will be used also during operation with $^{208}\text{Pb}^{82+}$ ions. Tab. 1 summarizes the beam parameters. Although the stored beam energy per beam is only 3.81 MJ compared to 362 MJ for protons [1], ions require additional considerations since the interactions between heavy ions and matter are very different from the proton case, as discussed in [2]. The cross-section for ionization in a material (described by the Bethe-Bloch formula [3]) is proportional to Z^2 , Z being the charge of the impinging particle. This means that the ionization energy loss of a proton is exceeded by a factor 82² by a $^{208}\text{Pb}^{82+}$ ion of the same energy. The electrons set free during this process are mostly soft (they deposit their energy close to the trail of the in-

coming particle) and give rise to a very localized energy deposition. This in turn makes the peak temperature much higher in the case of ions. The peak energy deposition for ions is usually found very close to the impact point, since the ions fragment as they propagate through the material. When they are fully fragmented the shower resembles a shower of independent nucleons.

The different physics means that it is necessary to determine the energy deposition from the ion beam in critical elements where one might fear heat induced damage very close to the impact locations. In the beam dump line these elements are the VDWB, TCDS, TCDQ, TDE and the BTVDD screen. Another performance issue is the response of the various beam instrumentation (BI) devices during ion operation.

Table 1: LHC beam parameters for $^{208}\text{Pb}^{82+}$ and p^+ operation (nominal collision).

	$^{208}\text{Pb}^{82+}$ ions	Protons
Energy per nucleon	2.76 TeV	7 TeV
Number of bunches	592	2808
Ions per bunch	7×10^7	1.25×10^{11}
Bunch spacing	100 ns	25 ns
Peak luminosity	$10^{27} \text{ cm}^{-2} \text{ s}^{-1}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

BEAM INTERCEPTING DEVICES

Beam Dump Window VDWB

Before hitting the TDE dump block, the beam has to pass through the VDWB. This window is made of 15 mm thick carbon-composite (CC) backed by a 200 μm stainless steel foil on the high pressure side and has a diameter of 60 cm.

The geometry of the window was implemented in the FLUKA 2006.3 [4, 5] Monte Carlo code and the energy deposition from one $^{208}\text{Pb}^{82+}$ bunch hitting the window was simulated. The resulting energy deposition from the full bunch train was obtained through a superposition of all the bunch positions in the sweep. This profile was converted into temperature rise using the temperature dependent specific heat $C_p(T)$ of the CC plate and the steel foil. The heating process was approximated as instantaneous without heat flow. The resulting temperatures for the nominal sweep are shown in Tab. 2 and Fig. 1 for the CC plate, where it can be seen that the maximum temperature rise, assuming a starting temperature of 300 K, is only 4.7 K.

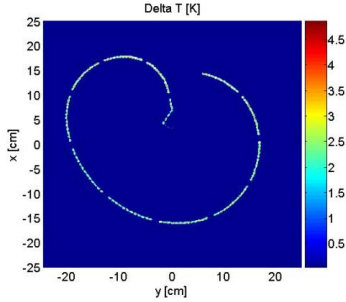
It was also considered that the dilution kickers might fail—either horizontal or vertical or all—meaning that the bunches would be swept over a much shorter length. The

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Figure 1: ΔT in the CC plate during the nominal ion sweep.

maximum temperature increases in all these scenarios are summarized in Tab. 2. In the case of a total failure of all dilution kickers, the temperature rise is 209 K in the CC plate and 301 K in the foil. These numbers should be compared to the melting points: approximately 4270 K and 1670 K in the plate and foil respectively. As a comparison, during proton operation in the event of a total dilution failure, the temperature rise in the plate is 891 K and 3580 K in the foil [6]. The result is plausible, as every ion is expected to give much less than a factor $82^2 = 6700$ higher temperature, but the number of particles is a factor 7800 higher in the proton beam with a much larger overlap between the bunches due to the smaller bunch spacing.

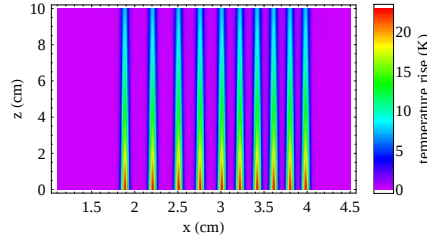
Table 2: ΔT in the CC plate and steel foil for different $^{208}\text{Pb}^{82+}$ ion load cases

Load case	ΔT CC (K)	ΔT foil (K)
Single bunch	1.5	1.6
Nominal 592 bunch sweep	4.7	5.2
592 bunches no MKBH	35.2	39.1
592 bunches no MKBV	39.6	43.9
592 bunches no MKB	209	301

Septum Protection Diluter TCDS

The TCDS [7] will protect the elements in the extraction from particles in the abort gap and unsynchronized beam aborts. The TCDS should dilute around 1.8% of the nominal LHC energy by intercepting 40 proton bunches or 10 ion bunches, to prevent damage of the downstream septum elements. It consists of two 3 m long and 24 mm thick blocks with a graded composition of different materials. The first 0.5 m is made of graphite, followed by high density CC and titanium.

Since the large difference in peak energy deposition is found very close to the impact point, only the first part of the diluter block was simulated for the comparison. An ion bunch hitting the graphite block was simulated in FLUKA and the total energy deposition from the 10 bunches calculated through post-processing routines. Again, the tem-

Figure 2: ΔT in the first 10 cm in the carbon part of the TCDS during nominal ion operation.

perature rise was calculated pessimistically using $C_p(T)$ assuming no heat flow. The resulting superposition can be seen in Fig. 2. Since there is negligible overlap between the bunches for the ions, it was found that the maximum temperature rise is only 23 K, which is almost exactly the same as for one bunch. Thus there is no risk of instantaneous material damage in the TCDS due to the $^{208}\text{Pb}^{82+}$ ion beam.

Mobile Diluter TCDQ

The TCDQ is made of graphite and is installed in front of the Q4 magnets. In case of an asynchronous firing of the MKD, the load case here will be less severe than for the TCDS, due to the larger beam size. However, the TCDQ might intercept a significant part of the beam halo during normal operation, causing shower particles to hit the Q4. During $^{208}\text{Pb}^{82+}$ operation however, ICOSIM simulations show that no significant losses are expected at the TCDQ [8]. Detailed simulations of the shower in the TCDQ with ions were therefore not performed.

Beam Dump Block TDE

The TDE itself is of course also subject to impacting beam particles. However, no detailed study of it was needed. The peak temperature might differ significantly from the proton case only in the CC close to the impact point. Simulations in the previous sections show that even during a complete failure of the dilution kickers, the peak temperature in this material for the ions will be a factor of about 4 less than that for protons, due to the much smaller number of particles. Since the temperature rise in the TDE during proton operation is about 1100 K with the ultimate intensity, the conclusion is that ion operation poses no problems for the TDE block.

Beam Imaging Screen BTVD

The Beam TV system (BTV) systems [9] are used to monitor the transverse shape of the beam, intercepting it on a single passage. There are BTVs in the extraction line after the ejection septum, after the dilution kicker and at the end of the dump line. The first two are based on a retractable mechanical system, equipped with two screens: a

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12 μm thick titanium foil (50% reflectivity) producing Optical Transition Radiation (OTR) [10] and a 1mm thick luminescent screen in chromium doped Al_2O_3 . The last (and most critical) one, BTVDD, is a fixed 3mm thick screen made of chromium doped Al_2O_3 . The impact of a single ion bunch on the BTVDD was again simulated in FLUKA and the energy deposition superimposed on the sweep pattern and transformed into temperature rise for the different failure cases. This is summarized in Tab. 3. Even in the total dilution failure case the screen may survive, which is not the case for protons.

Table 3: Maximum ΔT in the Al_2O_3 BTVDD screen for different load cases

Load case	ΔT (K)
Single bunch	1.6
Nominal 592 bunch sweep	4.1
592 bunches no MKBH	27.6
592 bunches no MKBV	32.0
592 bunches no MKB	223

BEAM INSTRUMENTATION PERFORMANCE

The dedicated BI for the dump lines has to be considered. This has been done elsewhere for the main LHC ring [1, 2] and apart from the BTV screens the instrumentation in the beam dump extraction line consists of the same type of hardware.

The sensitivity of the BTV screens (OTR and luminescent) to ions was evaluated. For luminescence, the number of photons is directly proportional to the deposited energy in the material [11]. Simulated with Fluka, we found that a 2.76 TeV/nucleon $^{208}\text{Pb}^{82+}$ ion produces 3320 more photons than a 7 TeV proton. The OTR intensity scales linearly with the particle charge and is therefore 82 times higher for a $^{208}\text{Pb}^{82+}$ ion than for a proton. The expected number of photons for each type of screen was calculated as in [9, 11] and is shown in Tab. 4. Using radiation hard-cameras, the detection is limited to intensities higher than 10^9 photons (assuming a beam size of 8 pixels per sigma), which would be sufficient to observe a single bunch with the alumina and higher beam charges with the OTR screen.

Table 4: The expected photon intensities from the BTV screens for one bunch.

	p+ nominal 1.15×10^{11}	p+ pilot 5×10^9	$^{208}\text{Pb}^{82+}$ 7×10^7
OTR	2.2×10^9	9×10^7	9×10^7
luminescent	4×10^{10}	1.9×10^{10}	8×10^{10}

The Beam Position Monitors (BPMs) and Fast Beam Current Transformers (FBCTs) are insensitive to particle type, since they function via induced currents. However, the dynamic range for the BPMs may be inadequate. The resolution limit of the BPMs is 2×10^7 $^{208}\text{Pb}^{82+}$ ions per

bunch [1] while the nominal ion scheme is only a little more than a factor three over this limit (see Tab. 1), so problems might arise during commissioning. This is however an already well-known issue for the main ring. The FBCTs have a resolution limit of 5% of the proton pilot bunch, equivalent to a bunch current of 0.45 μA , so the $^{208}\text{Pb}^{82+}$ ion bunch current of 10 μA should be clearly visible.

The response of the Beam Loss Monitors (BLMs) to $^{208}\text{Pb}^{82+}$ ions has been simulated in [2]. There it was concluded that when considering magnet quenching, the ratio of energy deposition from a generic beam loss in a main dipole magnet, averaged over the minimum propagating zone of 1 cm^3 , to the energy deposition in the N_2 gas in the BLM outside the cryostat, is the same for $^{208}\text{Pb}^{82+}$ ions and protons. Because the hadronic shower, similar for the two species, is the dominant factor for energy deposition on this volume scale, the BLMs protecting against quenches can be used without any modifications in $^{208}\text{Pb}^{82+}$ operation. However, if we are interested in the ionization dominated peak temperature in the material, the ratio might change.

CONCLUSION

The energy deposition from $^{208}\text{Pb}^{82+}$ ions in sensitive elements in the beam dump extraction line was simulated with FLUKA, both for nominal operation and failure scenarios, and the resulting temperature rise was calculated. It was concluded that although the energy deposition from a single ion is much higher than from a proton, the total number of protons in the beam is much larger and the ion bunches more spread out, meaning that the resulting temperature rise for ions is lower. Therefore these elements should work just as safely with $^{208}\text{Pb}^{82+}$ ions as with protons. Also the beam instrumentation was considered, and the only issue found was the resolution of the BPMs, which, due to the lower ion bunch population, could be wished to be higher. This is however an already known problem that exists also for the main ring.

We wish to thank G. Bellodi for the ion loss map in IR6.

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PAPER VII

Effects of ultraperipheral nuclear collisions in the LHC and their alleviation

R. Bruce, S. Gilardoni, and J.M. Jowett.

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EFFECTS OF ULTRAPERIPHERAL NUCLEAR COLLISIONS IN THE LHC AND THEIR ALLEVIATION

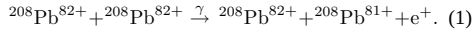
R. Bruce*, S. Gilardoni, J.M. Jowett, CERN, Geneva, Switzerland

Abstract

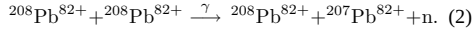
Electromagnetic interactions between colliding heavy ions at the LHC are the sources of specific beam loss mechanisms that may quench superconducting magnets. We propose a simple yet efficient strategy to alleviate the effect of localized losses from bound-free pair production by spreading them out in several magnets by means of orbit bumps. We also consider the consequences of neutron emission by electromagnetic dissociation and show through simulations that ions modified by this process will be intercepted by the collimation system, without further modifications.

INTRODUCTION

Collisions of beams of $^{208}\text{Pb}^{82+}$ nuclei in the LHC [1] will present new challenges, not present in proton runs. Some of these arise from strong electromagnetic interactions between the colliding beams. In bound free pair production (BFPP), an e^+e^- pair is created with the electron caught in a bound state of one ion, thus changing its charge:



Another process is electromagnetic dissociation (EMD), where an ion loses one or two neutrons. The one-neutron reaction can schematically be written as



Both these processes create ions with an altered magnetic rigidity $(B\rho)(1 + \delta)$, where $(B\rho)$ is the rigidity of the original beam and δ is given by

$$\delta = \frac{Z_0}{A_0} \frac{A}{Z} (1 + \delta_{\text{kin}}) - 1. \quad (3)$$

Here (A_0, Z_0) are the atomic mass and charge number of the original beam, (A, Z) of the altered beam, and δ_{kin} is the fractional momentum deviation. These ions might be lost where the locally generated dispersion function from the IP has grown sufficiently. If that occurs in a superconducting magnet, the induced heating may result in quenches [2, 3].

Measurements at RHIC [4] confirmed that losses caused by BFPP exist and that the simulation procedure used to quantify their effect in LHC operation, described in Refs. [1, 3, 5, 6, 7] is accurate within a factor two. This means that quenches caused by lost BFPP particles are possible in the LHC and that methods to avoid them have to be found. In the following sections, we describe such a method, as well as simulations to further quantify the effect of losses caused by EMD.

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ALLEVIATION BY ORBIT BUMPS

The horizontal orbit of the BFPP particles coming out of IP2 in a perfect lattice, as calculated by MAD-X [8], is shown in the top part of Fig. 1 together with the nominal beam. The BFPP orbit oscillates with the *locally generated* dispersion function, d_x , and the affected particles are lost very close to its first maximum. Thus, if a local horizontal orbit bump displaces the beam towards the centre of the beam pipe, a fraction of the losses escapes downstream to the next maximum. Similarly, other bumps can be introduced at consecutive local maxima of d_x in order to make a certain fraction of the BFPP particles continue. To displace the orbit, we propose to use the existing orbit correctors, which are found close to the quadrupoles in the LHC lattice. By tuning the orbit bumps we distribute the losses caused by BFPP over n dispersion maxima by $n - 1$ orbit bumps using $n + 1$ correctors in such a way that a fraction $1/n$ is lost at each impact point. This decreases the maximum heating power in a single element by $1/n$ and could bring it below the quench limit if n is made large enough.

To determine the required bump amplitudes Δ_m at each impact location s_m we consider the initial phase space at the IP. The particles lost at a location with horizontal aperture $A_x(s_m)$ satisfy (for $m \in [1, n - 1]$)

$$C_m x_0 + S_m p_{x0} + x_B(s_m) + \Delta_m > A_x(s_m), \quad (4)$$

where x_B is the central off-momentum trajectory, (x_0, p_{x0}) the starting conditions at the IP and C_m, S_m the elements of the transfer matrix from the IP to position s_m . These inequalities define regions R_m in the initial phase space, which vary with Δ_m . The fraction f_m of particles lost at s_m is the integral of the assumed Gaussian distribution function $P_\beta(x_0, p_{x0})$ over the phase space area outside the aperture limitation (4) and not outside any previous aperture limitation:

$$f_m = \iint_{R_m \cap (R_1^c \cup R_2^c \dots \cup R_{m-1}^c)} P_\beta(x_0, p_{x0}) dx_0 dp_{x0} \quad (5)$$

where R^c denotes the complement of region R .

The Δ_m can then be determined by demanding

$$f = 1/n, \forall m \quad (6)$$

and solving Eqs. (5) recursively, starting at $m = 1$, which can be solved analytically to yield

$$\Delta_1 = \sqrt{2}\sigma_1 \text{erf}^{-1}\left(\frac{n-2}{n}\right) + x_B(s_1) - A_x(s_1). \quad (7)$$

Here $\sigma_1 = \sqrt{\beta(s_1)\epsilon_x}$ is the RMS beam size and ϵ_x the beam emittance. Numerical integration and solution has to be used for higher values of m .

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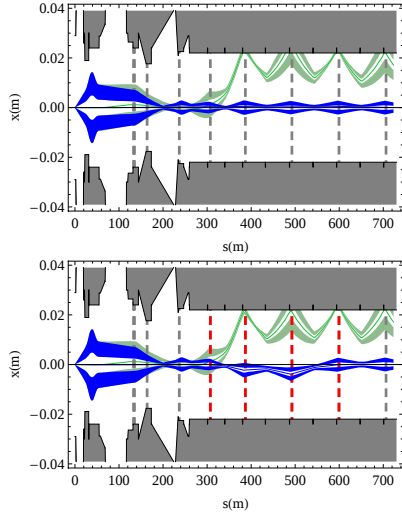


Figure 1: The horizontal 6σ envelopes of the nominal (top) and with 2 orbit bumps (bottom) $^{208}\text{Pb}^{82+}$ beam (blue) and the $^{208}\text{Pb}^{81+}$ BFPP beam (green) coming out of IP2, shown together with the aperture. The white space in the centre of the envelopes represents the uncertainty in the closed orbit. The vertical dashed lines show the locations of horizontal corrector magnets and the ones indicated in red are active.

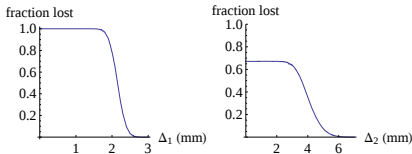


Figure 2: Left: The fraction f_1 , given by Eq. (5), as a function of the bump amplitude Δ_1 . Right: The fraction f_2 lost at the second max, when Δ_1 is chosen so that $f_1 = 1/3$.

BUMPS AFTER IP2

We illustrate the method with the example of 2 orbit bumps with 4 correctors ($n = 3$) after IP2 (ALICE experiment). The parameters Δ_m , presented in Tab. 1, should be chosen such that $1/3$ of the BFPP beam is lost at each impact location, with Δ_1 given directly by Eq (7) and Δ_2 determined numerically. Fig. 2 shows f_1 and f_2 as a function of Δ_1 and Δ_2 . The cuts in initial phase space introduced by the first two aperture limitations, according to Eq. 4, are shown in Fig. 3.

We then use the calculated values of Δ_m together with the condition that the nominal orbit should be flat after the bump to calculate the required angles of the four corrector magnets. The location of available corrector magnets

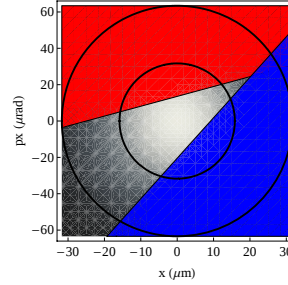


Figure 3: The initial phase space at IP2, with the areas in blue and red covering the losses at the first and second impact locations. The remaining part is lost at the third location where no orbit bump is present. The bumps are tuned so that $1/3$ is lost at each location. The black circles represent 1σ and 2σ of the distribution.

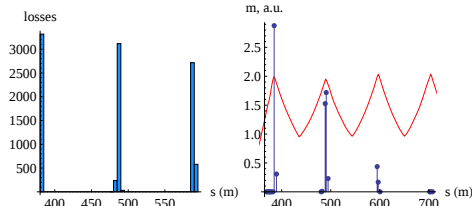


Figure 4: The loss map (left), binned in 5 m intervals, and the estimated BLM signals (right), obtained by single particle tracking downstream of IP2 using 2 orbit bumps. Each loss location receives $1/3$ of the total losses. The red line shows the locally generated dispersion from IP2.

are shown in Fig. 1 and the ones used in the example are marked in red. The obtained values are presented in Tab. 1 together with the required strengths.

The resulting orbits of the BFPP beam and the nominal beam are shown in Fig. 1. The maximum deviation of the nominal orbit is 3.8 mm in this configuration and it is clear from the figure that the 6σ envelope is still far from the aperture. A histogram of the resulting loss map using single particle tracking is shown in Fig. 4. As required, $1/3$ of the initial particles is lost at each impact location.

Table 1: The distance s between IP2 and each corrector magnet, the bump amplitudes Δ , angle θ , field strength B and the percentage r of maximum strength needed in the case of $n = 3$.

s (m)	Δ (mm)	θ (μrad)	B (T)	r (%)
307.394	2.23	-17.5	0.45	14.6
386.922	4.06	-28.5	0.74	23.8
492.547		-14.4	0.52	17.7
599.444		-22.2	0.80	27.3

OPERATIONAL ASPECTS

Operationally the orbit bumps have to be introduced at low luminosity, in order to avoid potential quenches. This can be achieved by a vertical van der Meer scan, in which the luminosity is varied by scanning the beam orbits transversely across each other at the IP.

The orbit correctors have to be fine-tuned around the theoretically predicted values of the kicks due to imperfections in the real machine. Simulations show that steps on the order of 0.1% of the total strength of the magnets is the necessary resolution. In order to ensure a correct distribution of the losses, the beam position monitors (BPMs) and the beam loss monitors (BLMs) have to be used. The BPM signals for a certain configuration can be obtained by calculating the offset of the nominal orbit. However, this might be inaccurate since BPMs are placed very close to the BFPP impact positions and therefore might be perturbed by the losses. Furthermore, there is a 1 mm uncertainty on the LHC aperture, meaning that the bump amplitudes have to be changed correspondingly to have the same loss distribution. This means that the BPM readings change by the same value and can therefore not be used alone to tune the orbit bumps.

To estimate the ratio between different BLM signals in a certain configuration we consider the energy deposition $\varepsilon(s)$ in a hypothetical infinite BLM outside the cryostat caused by a single particle impacting at $s = 0$ in an LHC magnet, as simulated in Ref. [7]. An approximation of the total energy deposition from all ions lost at positions s_i , obtained by single particle tracking, is the sum $\varepsilon_{\text{tot}}(s) = \sum_i \varepsilon(s - s_i)$. Since the BLM signal is proportional to energy deposition, the ratio between the signals on two BLMs located at s_1 and s_2 is estimated by $\varepsilon_{\text{tot}}(s_1)/\varepsilon_{\text{tot}}(s_2)$. This method gives the approximate loss pattern shown in Fig. 4, which one should try to obtain operationally. However, a more accurate estimate of the BLM signals is desirable, since the difference in angles between the impacting particles and variations along s in the physical design of the magnetic elements are neglected. Thus it is wished to perform FLUKA simulations of the BLM signals in the full magnet geometry at each impact position.

With the given uncertainties on the expected BPM and BLM signals, we can not expect to achieve exactly 1/3 of the losses at each location. Depending on where the actual quench limit is, more bumps might have to be introduced to compensate for the uncertainties.

It should also be noted that the locations of the impact point along s can change by a few metres because to the orbit bumps. With two bumps, the centre of the first loss spot moves from a dipole magnet to an MQML quadrupole.

The β -beating is at most 1.7% using two bumps, which is well within the limits of what can be corrected [9].

ELECTROMAGNETIC DISSOCIATION

The ions affected by 1-neutron EMD stay within the acceptance of the ring [7] due to the lower $\delta \approx -0.0048$ but

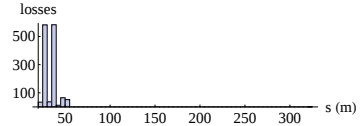


Figure 5: The loss map of ions affected by EMD downstream of IP2. A total of 10^5 particles were tracked.

should be intercepted by the collimation system. The collimation of ions is however predicted to be less efficient than requirements due to fragmentation processes [10]. Therefore tracking from IP1, IP2 and IP5 of ions affected by EMD was performed with ICOSIM [10], which includes the particle-matter interaction in the collimator. It was found that around 99% of all ions stopped in the collimators and that 1% was lost in the ring. A loss map downstream of IP2 is shown in Fig. 5.

A rough estimate of the heat load from the EMD beam is obtained by scaling the predicted heating from the BFPP beam (7.2 mW/cm^3 [6]) by the ratio of the cross sections ($\sigma_{\text{in}}^{\text{EMD}} \approx 215 \text{ barn}$ [11], $\sigma_{\text{BFPP}}^{\text{BFPP}} \approx 281 \text{ barn}$ [12]). Taking 1% of that gives a heat load of 0.055 mW/cm^3 , which is much lower than the quench limit (estimates for different magnet types range from a few up to several tens of mW/cm^3). The 2-neutron process does create particles outside the acceptance lost in localized loss spots but has a lower cross section ($\sigma_{2n}^{\text{EMD}} \approx 0.2 \sigma_{\text{BFPP}}^{\text{BFPP}}$ [11]). Thus we conclude that the heating induced by losses caused by EMD should pose no danger.

CONCLUSIONS

Beam losses due to BFPP during $^{208}\text{Pb}^{82+}$ operation might quench magnets in the LHC but can be alleviated by distributing the losses over several locations through orbit bumps, thus lowering the heat load in single elements. Losses caused by EMD are cleaned by the collimation system and are not expected to cause quenches.

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