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Single-sided collimation and the effects on beam cleaning and impedance in the LHC

by

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Abstract

The Large Hadron Collider (LHC) employs a multistage collimation system to protect against unavoidable beam losses during operation. A regular collimator consists of two movable blocks placed symmetrically around the circulating beam in order to intercept halo particles. These blocks are known as *jaws* and are generally composed of a highly robust material which is designed to withstand extreme levels of temperature, pressure, and radiation.

The charged particles travelling inside the accelerator generate electromagnetic fields which interact with the surrounding structure, giving rise to forces that perturb the motion of the beam, often leading to beam degradation. This perturbing effect ultimately determines the performance of the accelerator in terms of beam quality and stored current, and is characterised by the so-called *beam-coupling impedance*.

The collimation system is the single highest contributor to the transverse impedance at top energy. This is because the collimator jaws are the closest elements to the beam, and thus interact more strongly with the electromagnetic fields generated by the particles. As the beam intensity increases, so too does the coupling impedance, and when the perturbations become sufficiently strong, the beam becomes unstable. Seeing as the High-Luminosity LHC (HL-LHC) upgrade nearly doubles the bunch population, impedance must be reduced in order to ensure beam stability.

Single-sided collimation aims at mitigating impedance by fully retracting one of the two jaws for any number of collimators. One would expect this to come at the cost of beam cleaning; however, simulations have shown that this is not necessarily the case, especially when selecting the right combination of jaws. This thesis explores the feasibility of single-sided collimation for the betatron cleaning insertion in HL-LHC by running simulations that quantify performance in terms of beam cleaning and impedance. Benchmark measurements have also been performed for LHC.

Keywords: CERN, LHC, HL-LHC, IR7, collimation, beam cleaning, beam-coupling impedance, betatron cleaning, asymmetric collimation, single-sided collimation, octupole current threshold, SixTrack, ImpedanceWake2D, simulations, measurements.

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List of acronyms

ALICE	A Large Ion Collider Experiment
ATLAS	A Toroidal LHC Apparatus
B1	Beam 1
B2	Beam 2
BLM	Beam Loss Monitor
BPM	Beam Position Monitor
CALS	CERN Accelerator Logging Service
CERN	Conseil Européen Pour La Recherche Nucléaire
CFC	Carbon Fibre Composite
CMS	Compact Muon Solenoid
Cu	Copper
DELPHI	Discrete Expansion Over Laguerre Polynomials And Head-tail Modes For Instabilities Computation
DS	Dispersion Suppressor
EM	Electromagnetic
FT	Flat Top
HL-LHC	High-Luminosity LHC
IP	Interaction Point
IR	Insertion Region
IW2D	ImpedanceWake2D
LEIR	Low Energy Ion Ring
LHC	Large Hadron Collider

LIST OF ACRONYMS

LHCb	Large Hadron Collider Beauty
LXPLUS	Linux Public Login User Service
MD	Machine Development
Mo	Molybdenum
MoGr	Molybdenum-graphite
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
RF	Radio-frequency
RMS	Root-mean-square
RW	Resistive-wall
SPS	Super Proton Synchrotron

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Overview

This thesis is intended to be self-contained, such that very little prior knowledge is required for its contents to be understood. Chapter 1 starts off with a brief introduction to CERN, the LHC, and the accelerator complex. Some information regarding the machine cycle and the main experiments is also given, along with a summary of the most prominent features of the HL-LHC upgrade. Section 1.3 discusses the basic concepts behind accelerator physics and introduces the key beam parameters used in this study.

Chapter 2 gives an overview of the collimation system, discussing the motivation behind it and the details of its hierarchical implementation. The general layout of the collimators is illustrated and the two distinct cleaning insertions are examined. A quantity known as the *cleaning inefficiency* is introduced as a way of characterising the beam cleaning performance of the collimation system. The chapter closes with a comparison between symmetric and single-sided collimation.

Chapter 3 covers the general theory behind beam-coupling impedance, and derives the longitudinal and transverse components. Chapter 4 summarises the methodology and presents the tools employed to carry out this study, also listing the tracking parameters used in beam cleaning simulations.

The analysis for HL-LHC is given in Chapter 5. Section 5.1 explores beam cleaning simulations, and uses the results to construct a number of viable single-sided configurations. Section 5.2 computes the impedance induced by these configurations in relation to the full accelerator model. The results are compared to those of the standard collimator settings in order to quantify the improvement.

Chapter 6 repeats the process for the LHC in order to conduct some benchmark measurements. The appropriate configurations were deployed in the machine and assessed in terms of beam cleaning and impedance. A comparison is made between simulations and measurements, and a conclusion is derived in Chapter 7.

Chapter 1

Introduction

1.1 CERN

The European Organisation for Nuclear Research was founded in 1954, with the aim of establishing an authoritative organisation for fundamental physics research in Europe. It is most commonly known by the acronym CERN — derived from the French *Conseil Européen pour la Recherche Nucléaire*. The term *nuclear* has become a misnomer, as contemporary research goes far deeper than the nucleus of an atom. CERN's primary mission is to design and operate particle accelerators — scientific instruments which allow particle physicists to explore the properties and interactions of subatomic particles.

CERN is situated in the north-western suburb of Geneva, astride the Franco-Swiss border. There are currently 22 member states, who are responsible for contributing capital and making important decisions concerning the organisation. Over 600 institutions and universities from around the world use CERN's facilities, with upwards of 12 000 visiting scientists from over 70 countries.

CERN is renowned for its monumental scientific achievements, such as the discovery of a particle consistent with the Higgs boson; observations of direct CP violation; creating and maintaining antihydrogen atoms; discovering weak neutral currents; and discovering a number of particle families. Incidentally, CERN is also the birthplace of the World Wide Web, which was originally developed to meet the demand for automatic information sharing between scientists around the world.

1.2 The Large Hadron Collider

The Large Hadron Collider (LHC) is at the forefront of experimental physics. It is the world's most powerful particle accelerator, capable of particle collisions with a centre-of-mass energy of up to 14 TeV. Built between 1998–2008, it is 27 km in circumference and lies beneath the Franco-Swiss border at a mean depth of 100 m, currently making it the single largest machine in the world. Its purpose is to shed some light on open questions in physics related to, but not limited to, the Higgs mechanism, supersymmetry, and antimatter [1].

The LHC is a synchrotron that consists of eight arcs and eight straight sections. A straight section is called an insertion region (IR), as it can serve as an insertion for an

experiment or utility. The first and fifth insertion regions (IR1 and IR5) house the two high-luminosity experiments; ATLAS and CMS. The ALICE and LHCb experiments are housed in IR2 and IR8 — which also serve as the injection regions for Beam 1 (B1) and Beam 2 (B2) respectively. IR3 and IR7 are dedicated to the momentum and betatron collimation systems. IR4 hosts two radio-frequency (RF) systems designed to accelerate each of the two beams. IR6 contains the beam abort system, which extracts the beams via magnetic kickers [2]. A schematic layout of the LHC can be found in Fig. 1.1.

An arc is comprised of 23 FODO cells, which are magnetic structures consisting of alternating focusing and defocusing quadrupole lenses separated by dipole magnets [3]. The dipoles are also equipped with higher-order magnets, which correct for small imperfections in the magnetic field at the extremities. There are 1232 main dipoles, designed to bend the beam into a circular trajectory; 392 main quadrupoles, meant to focus the beam; and over 4000 corrector magnets [4]. These are operated at cryogenic temperatures, often below 2 K, in order to take advantage of the intense magnetic fields generated when superconductivity is attained [2].

A dispersion suppressor (DS) is stationed between each arc and straight section, yielding a total of 16 dispersion suppressors. Its functions are to cancel horizontal dispersion arising in the arc; adapt the reference orbit to the geometry of the tunnel; and match the insertion optics to the periodic optics of the arc [2, 5].

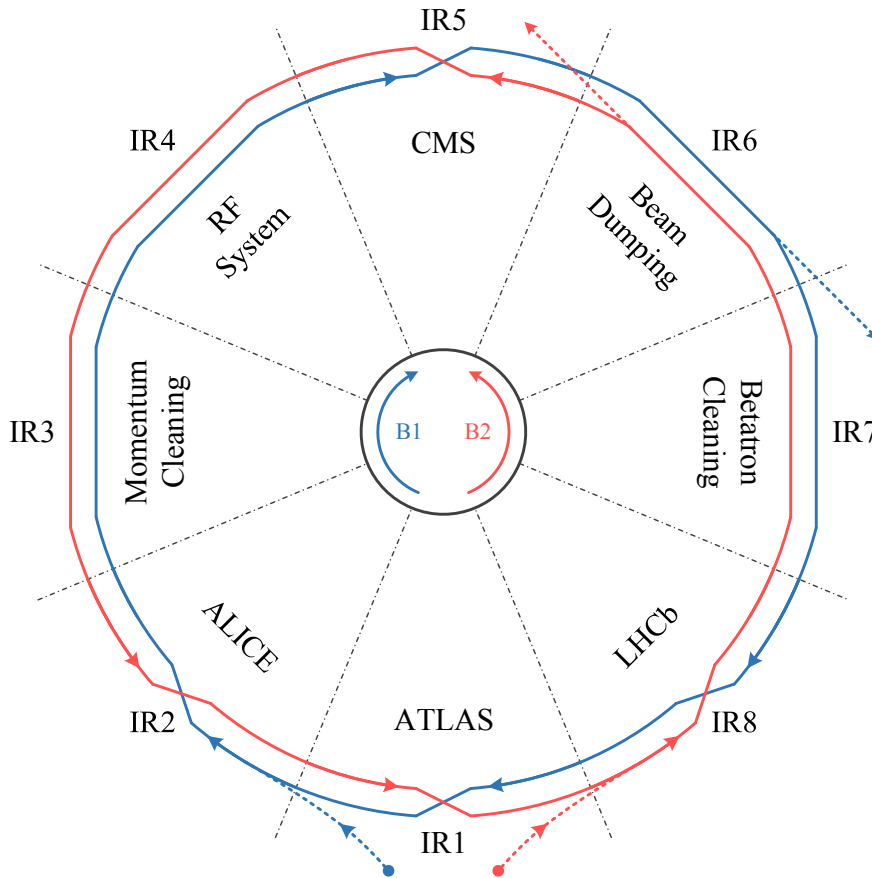


Figure 1.1: A schematic layout of the LHC illustrating the different insertion regions.

1.2.1 The accelerator complex

In order to inject a beam into the LHC, particles must first go through a sequence of machines with increasingly higher energies. The accelerator complex at CERN is illustrated in Fig. 1.2 [6].

The process starts by ionising hydrogen gas in order to procure protons, which are then bunched via a radio frequency quadrupole, and fed into Linac 2 — a linear accelerator that accelerates protons to an energy of 50 MeV. The bunch then enters the Proton Synchrotron Booster (PSB), where it is split into four bunches, one for each of the booster's rings. After being accelerated to 1.4 GeV, the four bunches are recombined and transferred to the Proton Synchrotron (PS), which pushes the beam to an energy of 27 GeV. The beam is then sent to the Super Proton Synchrotron (SPS), where it is accelerated to 450 GeV. Finally, the trains of bunches are injected into either of the two beam pipes of the LHC, where they are accelerated for 20 minutes in order to reach a maximum energy of 7 TeV.¹ When filled, the two beams circulate inside the LHC for several minutes until they are sufficiently squeezed, and are then brought into collision at the four main detectors [6].

The LHC can also accelerate heavy ions. Vaporised lead is ionised by an electron current and fed into Linac 3. The ions are then collected and accelerated in the Low Energy Ion Ring (LEIR), after which they enter the PS and follow the same sequence of accelerators as protons thereafter [1].

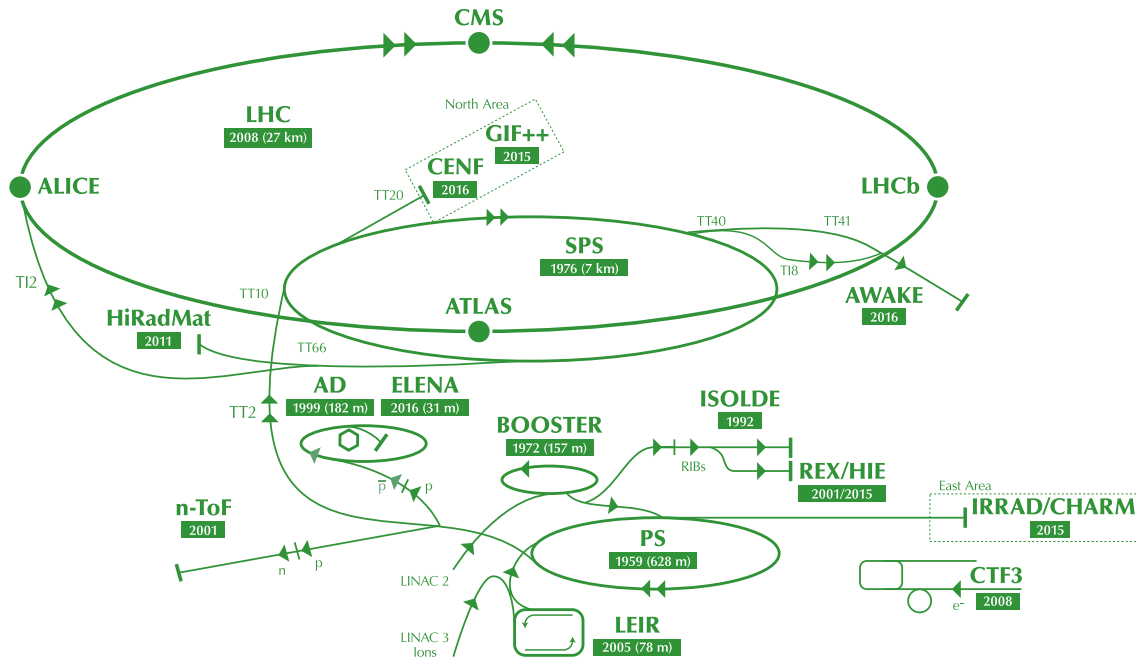


Figure 1.2: The accelerator complex at CERN (not to scale). Starting from Linac 2 (for protons) or Linac 3 (for ions) and ending up in the LHC after following a series of intermediary accelerators [1].

¹The achieved top energy so far is only 6.5 TeV, however.

1.2.2 The machine cycle

The LHC operational cycle adheres to a number of well-defined stages, as highlighted in Fig. 1.3. The duration and characteristics of each stage are described as follows.

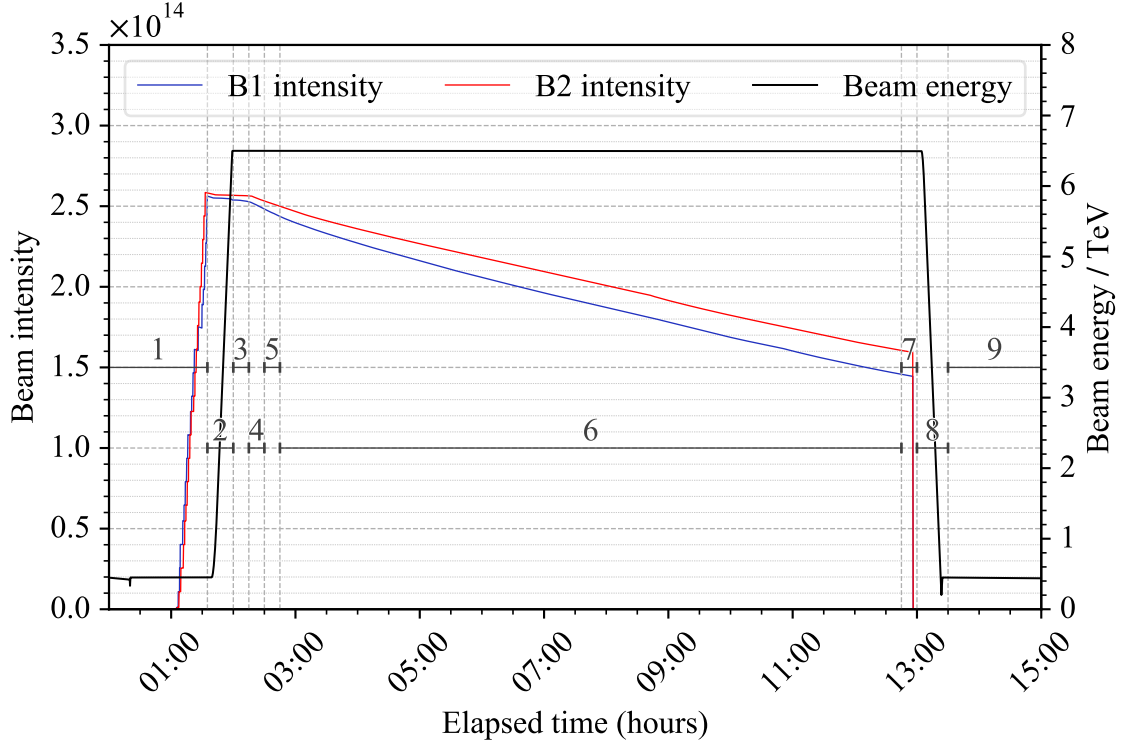


Figure 1.3: A characteristic LHC operational cycle. The demarcations denote the different stages — namely *injection* (1); *ramp* (2); *flat top* (3); *squeeze* (4); *adjust* (5); *stable beams* (6); *beam dump* (7); *ramp down* (8); and preparation for the next fill (9). Note that the steps seen in the intensity at injection represent individual bunches being injected into the machine.

Injection

At the *injection* phase, the two rings of the LHC are progressively filled with trains of bunches transferred in from the SPS. This is the most laborious stage of the cycle — taking an hour on average to complete, with deviations depending on the chosen filling scheme, the availability of the injectors, the desired intensity of the beam, and the time taken to set up and measure beam parameters [7, 8].

Ramp

Once the filling procedure is complete, the beam energy is *ramped up* for approximately 20 minutes in order to reach a maximum of 7 TeV [8].²

²The top energy for Run II (2015–2018) has been limited to 6.5 TeV in order to avoid long magnet training campaigns, which would be costly in terms of time and would introduce a small, but unacceptable risk of a double short to ground that could destroy the affected magnet.

Flat Top

The *flat top* (FT) beam stage is declared once top energy has been reached. Here, a number of steps are taken in preparation for the following stages, among which is changing the tune for collisions — all in all, taking roughly 5 minutes to complete [8].

Squeeze

At this stage, the beam is further squeezed at the collision points in order to increase the instantaneous luminosity, and hence obtain a higher collision rate. This stage takes an average of 15 minutes to complete.

Adjust

At the end of *squeeze*, the two beams are brought into collision at the interaction points by collapsing the separation orbit bumps. This stage also requires approximately 15 minutes to complete [7, 8].

Stable Beams

Finally, *stable beams* is declared once all of the previous stages have been completed successfully. It is now safe to activate the detectors and begin collecting data from particle collisions. After several hours of data taking, the beam is dumped and the machine is *ramped down* to injection energy in preparation for the next fill [7, 8].

1.2.3 The main experiments

There are four main detectors installed in the LHC, each located inside massive underground caverns. The purpose of these detectors is to analyse the properties of particles produced by beam collisions within the accelerator [1, 9].

ATLAS

ATLAS, short for A Toroidal LHC Apparatus, is a general purpose detector designed to cover a broad range of physics; from probing the Higgs mechanism to finding evidence for particle physics theories beyond the Standard Model.

CMS

Like ATLAS, the Compact Muon Solenoid (CMS) is a general purpose detector intended to carry out similar research, albeit through a different technical solution and design. Having two independently designed detectors is vital for confirming the validity of experimental observations.

ALICE

As the name suggests, A Large Ion Collider Experiment (ALICE) is a detector designed to measure and analyse lead-ion collisions. It is used to study a state of matter known as *quark-gluon plasma*, wherein quarks and gluons are no longer confined inside hadrons when matter is at an extremely high temperature or density.

LHCb

The LHCb, which stands for Large Hadron Collider beauty, is a detector that is specialised to probe the slight asymmetries between matter and antimatter present in the interaction of particles containing the *beauty* quark. This could elucidate the imbalance between matter and antimatter in the universe.

1.2.4 The High-Luminosity LHC

The High-Luminosity LHC (HL-LHC or HiLumi) project foresees a major upgrade to the LHC, which extends its discovery potential by increasing the instantaneous luminosity (rate of collisions) to 5 times the nominal value, and the integrated luminosity (number of collisions) by an order of magnitude in the first 10 years of operation [10]. This increase in luminosity will be achieved by overhauling several components of the present LHC system. Given the complexity of the machine, such an upgrade requires several years of research, prototyping, testing, and finally implementing — with current estimates projecting a completion date in the mid 2020s. The project's timeline is dictated by the life expectancy of various critical components currently present in the accelerator, which will need to be replaced due to radiation damage [11]. Thus the upgrade is crucial not only to realise the full potential of the LHC, but to also maintain the collider for future operation [10, 12]. The following list summarises some of the upgrades and installations required to meet the goals of HL-LHC, with Tab. 1.1 cataloguing the corresponding beam parameters:

- Some nested-type corrector magnets, meant to cancel out field irregularities of the main magnets, would not be able to withstand the increase in radiation produced by the new beam. This, along with other considerations lead to a redesign of the interaction regions. The new design also includes larger separation dipoles, a new electrical feedbox, and improved access to various components for maintenance.
- The main quadrupoles in the triplets are redesigned to allow the peak magnetic field strength to increase to 12 T. These will further squeeze the beams before collision, and thus increase the luminosity. High-power superconducting links with almost zero energy dissipation will also be implemented to supply current to the magnets from remote distances [10].
- Superconducting RF crab cavities will be installed to tilt proton bunches just before the point of interaction, allowing the bunches to fully overlap during collision. This increases the probability of individual particle collisions, and thus increases the luminosity.

- The impedance due to collimators would have to be reduced significantly in order to operate HL-LHC beams with any stability. This will be done in part by equipping some collimators with molybdenum coated jaws composed of molybdenum-graphite (MoGr). The dispersion suppressor (DS) is also an area of concern to the collimation system, as there tends to be a large concentration of particle losses in the region. To mitigate these losses, a main dipole will be replaced by two dipoles of equal bending strength but shorter overall length, granting sufficient space for the installation of a special collimator.
- New and improved equipment is required to monitor and act on the more formidable HL-LHC beam, including new beam loss monitors, a new beam position monitoring system which includes a high-resolution orbit measurement system, a new emittance monitoring system, halo diagnostics to control the beam halo in order to minimise losses, diagnostics for the crab cavities, and radiation-hard devices to measure the luminosity.
- The proton injector chain will also see a number of upgrades to account for the increase in luminosity, with significant changes being made to the PSB, PS, and SPS [13].

Table 1.1: The beam parameters of the nominal LHC and HL-LHC [10]. The β^* quantity denotes the value of the beta function at an interaction point (see Section 1.3.1).

Parameter	Nominal LHC	HL-LHC
Peak luminosity	$1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	$5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Beam energy	7 TeV	7 TeV
Revolution frequency	11.245 kHz	11.245 kHz
Circulating beam current	0.58 A	1.09 A
Particles per bunch	1.15×10^{11}	2.20×10^{11}
Bunches per beam	2808	2748
Particles per beam	3.2×10^{14}	6.0×10^{14}
Stored energy per beam	362 MJ	678 MJ
Crossing angle at IP1 and IP5	285 μrad	510 μrad
Minimum β^*	0.55 m	0.15 m
Bunch spacing	25 ns	25 ns
RMS bunch length	7.55 cm	8.10 cm
Maximum bunches per injection	288	288
Transverse normalised emittance	3.75 $\mu\text{m rad}$	2.50 $\mu\text{m rad}$

1.3 Linear beam dynamics

As massive particles are accelerated from rest, their initial speed increases linearly with time. However, as the energy gets higher and higher, the gain in speed grows smaller and smaller. In the ultrarelativistic limit, any increase in energy will only serve to increase a particle's mass, as a particle cannot be accelerated past the speed of light.

In accelerators, the motion of particles is driven by electric and magnetic fields. RF cavities generate electric fields which provide acceleration by applying an oscillating potential difference that is synchronised with the passage of the particles. This also compensates for the energy lost through synchrotron radiation — which is emitted when charged particles are accelerated radially. The RF system circumscribes regions of the longitudinal phase space known as RF buckets. Particles outside the buckets during ramp will lose energy turn-by-turn until they are eventually lost — ideally at the collimators.

Dipoles, quadrupoles, and higher-order magnets provide the magnetic fields responsible for steering the beam through the machine. Dipoles in particular define the average circular orbit in the accelerator. Quadrupoles provide the focusing strength needed for particles that would otherwise drift away from the closed orbit. Indeed, dipoles and quadrupoles are the optical equivalent of prisms and lenses; hence, the setup is generally referred to as the machine *optics*.

The combined effect of electric and magnetic fields acting on a particle of charge q is described by the Lorentz force

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}), \quad (1.1)$$

where $\mathbf{p}$ is the relativistic momentum of the particle, $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields respectively, and $\mathbf{v}$ is the particle's velocity. The equation demonstrates that a positively charged particle will be accelerated in the same linear orientation as the electric field. However the magnetic field will generate a force which is perpendicular to both itself and the velocity of the particle at that instance, thus bending the particle's trajectory. This gives rise to longitudinal and transverse motion, which are collectively known as *linear beam dynamics*.

1.3.1 Transverse motion

A right-handed, orthogonal, and moving coordinate system (s, x, y) derived from the Frenet-Serret frame is shown in Fig. 1.4, and shall be used throughout this description. The circular paths represent the closed orbits for B1 and B2, where s is the position along the closed orbit. The horizontal and vertical displacements relative to the closed orbit are represented by x and y respectively, which together form the transverse plane.

The alternating focusing gradient provided by quadrupoles causes particles to undergo oscillations around the design orbit [14]. In the case of an on-momentum particle³, the equations of motion in the transverse plane can be expressed through Hill's equations

$$z'' + K_z(s)z = 0, \quad (1.2)$$

³An on-momentum particle has the same momentum as the ideal reference particle ($p = p_0$).

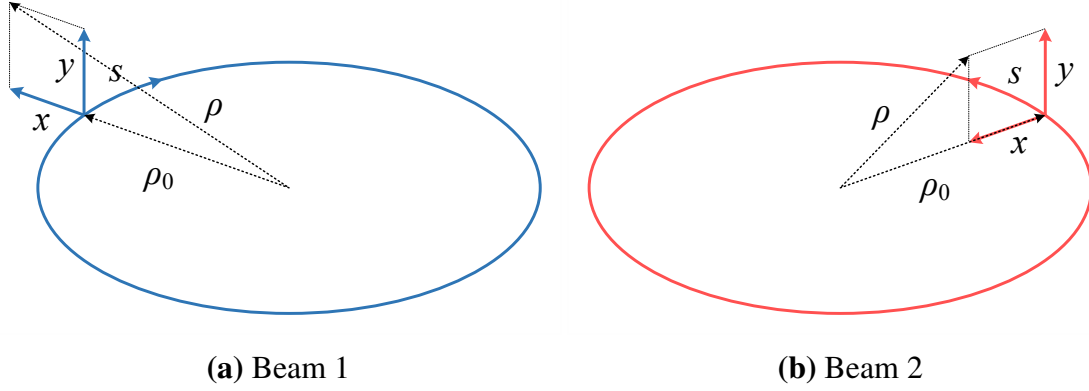


Figure 1.4: The coordinate systems for B1 and B2 in the LHC. The x -axis is directed outwards in B1 and inwards in B2.

where z stands for either x or y , a prime denotes a derivative with respect to the longitudinal coordinate s , and $K_z(s)$ is a periodic function that represents the transverse focusing strength due to quadrupoles [14–16]. The most general solution to Hill’s equations is in the form of a pseudo-harmonic oscillation given by

$$z(s) = \sqrt{\varepsilon_z} \sqrt{\beta_z(s)} \cos(\psi_z(s) + \phi_z). \quad (1.3)$$

These quasi-harmonic oscillations are known as *betatron oscillations*, as they were originally studied in the context of betatron accelerators. $\sqrt{\varepsilon_z}$ and ϕ_z are constants of integration that depend on the initial conditions. The so-called *beta function* $\beta_z(s)$ is a periodic function that modulates the amplitude of betatron oscillations, and is determined by the focusing properties of the lattice [17]. The phase advance of oscillation $\psi_z(s)$ between points $s = 0$ and $s = s_1$ in the lattice is given by

$$\psi_z(s_1) = \int_0^{s_1} \frac{ds}{\beta_z(s)}. \quad (1.4)$$

It should be noted that $\psi_z(s)$ depends on the amplitude of particle oscillations. At locations where $\beta_z(s)$ is large (i.e., when the particle has a large transverse dimension), the corresponding phase advance will be small, and vice versa. The number of betatron oscillations per revolution is nothing other than the phase advance over one turn in units of 2π :

$$Q_z = \frac{1}{2\pi} \oint \frac{ds}{\beta_z(s)}. \quad (1.5)$$

This value is known as the machine *tune*, and is one of the key parameters of any circular accelerator. The tune is an irrational number by design in order to ensure that a particle covers the entirety of the ellipse in phase space (see Fig. 1.5) at each longitudinal position. This avoids resonances which would amplify existing perturbations; hence, a good control of the tune in both transverse planes is of great importance to beam stability [17].

The angle of a particle’s trajectory relative to the closed orbit can be obtained by differentiating Eq. (1.3) with respect to s :

$$z'(s) = -\frac{\sqrt{\varepsilon_z}}{\sqrt{\beta_z(s)}} \left(\alpha_z(s) \cos(\psi_z(s) + \phi_z) + \sin(\psi_z(s) + \phi_z) \right), \quad (1.6)$$

where

$$\alpha_z(s) = -\frac{1}{2}\beta'_z(s). \quad (1.7)$$

By rewriting Eq. (1.3) and substituting it into Eq. (1.6), it is possible to obtain an expression for the integration constant ε_z :

$$\varepsilon_z = \gamma_z(s)z^2(s) + 2\alpha_z(s)z(s)z'(s) + \beta_z(s)z'^2(s), \quad (1.8)$$

where

$$\gamma_z(s) = \frac{1 + \alpha_z^2(s)}{\beta_z(s)}. \quad (1.9)$$

So long as conservative forces are considered, ε_z is a constant of motion, and is known as the single-particle emittance. The result in Eq. (1.8) is the parametric representation of an ellipse in z - z' phase space. Fig. 1.5 shows a particle's z - z' coordinates plotted turn-by-turn at a given s position. The shape and orientation of the ellipse are defined by the Twiss parameters $\beta_z(s)$, $\alpha_z(s)$, and $\gamma_z(s)$, which encapsulate the optics of the machine. The form of the ellipse also varies with the chosen s position, however the area does not change if the particle's energy remains constant. The area of the ellipse is equal to $\pi\varepsilon$, and is intrinsic to the particle. Hence it can be used to represent the quality factor of a single particle, where large areas represent large transverse amplitudes and vice versa [17, 18].

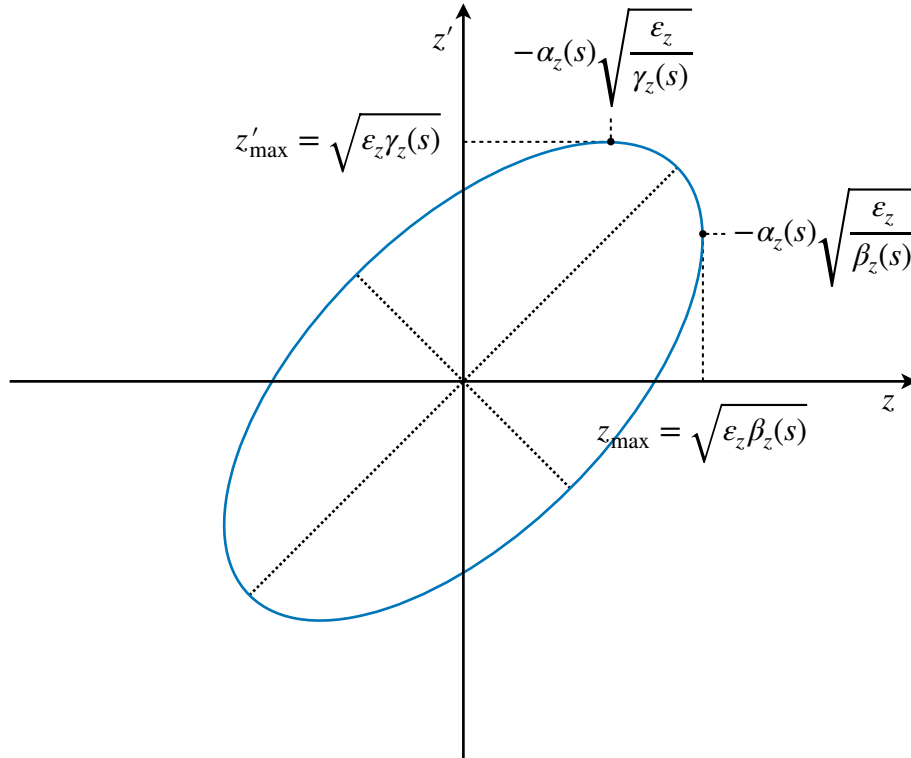


Figure 1.5: The turn-by-turn position of an on-momentum particle in transverse phase space (z - z') at a particular s coordinate. The form of the ellipse is defined by the focusing properties of the lattice, whereas the area ($\pi\varepsilon_z$), is an intrinsic property of the particle.

Particles typically assume a Gaussian distribution in position and angle. As a result, a statistical quantity known as the *geometric* or *beam* emittance $\bar{\varepsilon}_z$ can be defined as the

RMS of single-particle emittances:

$$\bar{\varepsilon}_z = \sqrt{\langle z^2 \rangle \langle z'^2 \rangle - \langle z z' \rangle^2}. \quad (1.10)$$

The beam emittance is also an invariant, however it shrinks when the particles are being accelerated. Through the beam emittance, the betatronic beam size $\sigma_z(s)$ and divergence $\sigma'_z(s)$ can be defined as

$$\sigma_z(s) = \sqrt{\bar{\varepsilon}_z \beta_z(s)}, \quad (1.11)$$

$$\sigma'_z(s) = \sqrt{\bar{\varepsilon}_z \gamma_z(s)}. \quad (1.12)$$

The beam core often refers to particles that are within $3\sigma_z$ of the beam, whereas particles outside this range populate the beam tails — also referred to as the beam halo. It is also possible to define the normalised emittance $\hat{\varepsilon}_z$ that does not vary with energy:

$$\hat{\varepsilon}_z = \gamma_{\text{rel}} \beta_{\text{rel}} \bar{\varepsilon}_z. \quad (1.13)$$

1.3.2 Normalised transverse phase space

It is convenient to express the betatron amplitude a_z of a particle in terms of the betatronic beam size;

$$a_z(s) = n_z \sigma_z(s) = n_z \sqrt{\bar{\varepsilon}_z \beta_z(s)}, \quad (1.14)$$

where n_z is the normalised betatron amplitude. The quasi-harmonic betatron motion can be converted into true harmonic motion by considering the Floquet transformations, which are applied to the canonical phase coordinates (z, z') to create a *normalised* phase space:

$$\begin{bmatrix} \hat{z} \\ \hat{z}' \end{bmatrix} = \frac{1}{\sigma_z} \begin{bmatrix} 1 & 0 \\ \alpha_z & \beta_z \end{bmatrix} \begin{bmatrix} z \\ z' \end{bmatrix} \quad (1.15)$$

$$z \longrightarrow \hat{z} = \frac{z}{\sqrt{\bar{\varepsilon}_z \beta_z}} \quad (1.16)$$

$$z' \longrightarrow \hat{z}' = \frac{z\alpha_z + z'\beta_z}{\sqrt{\bar{\varepsilon}_z \beta_z}} \quad (1.17)$$

The usual equations that describe the turn-by-turn betatron motion through an ellipse in ordinary phase space are now replaced by simpler equations that describe particle motion in terms of a circle with radius n_z , as shown in Fig. 1.6. The new phase coordinates $(\hat{z}, \hat{z}')$ given by Eqs. (1.18) and (1.19) are both unitless.

$$\hat{z} = n_z \cos(\psi_z(s) + \phi_z) \quad (1.18)$$

$$\hat{z}' = -n_z \sin(\psi_z(s) + \phi_z) \quad (1.19)$$

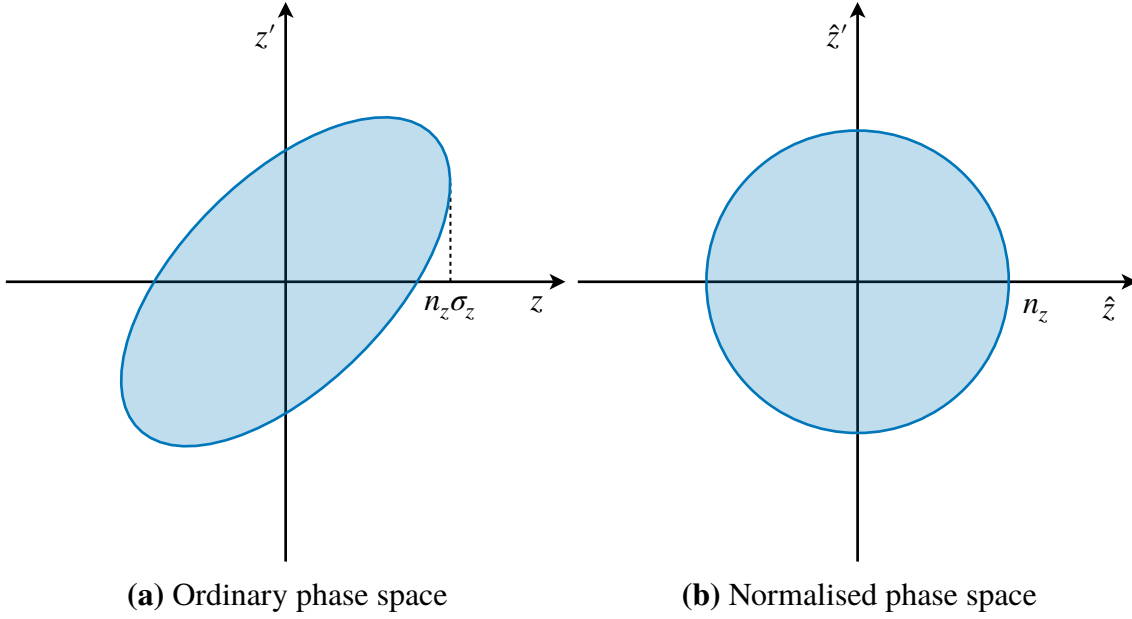


Figure 1.6: Ordinary (elliptical) phase space is transformed into a normalised (circular) phase space with radius n_z via the Floquet transformations.

1.3.3 Longitudinal motion

The RF cavities in an accelerator generate an oscillating longitudinal potential difference, which is applied across isolated gaps in the vacuum chamber. Charged particles are either accelerated or decelerated, depending on their phase relative to the electric field. In order to set particles inside the accelerating region of the RF period, the beam is split into several bunches. Thus, the frequency of the electric field ω_{RF} is an integer multiple of the revolution frequency ω_{rev} ;

$$\omega_{\text{RF}} = h\omega_{\text{rev}}, \quad (1.20)$$

where h is known as the harmonic number. The energy gain of a particle passing through a cavity is given by

$$\Delta E = qV_0 \sin \varphi(t) = qV_0 \sin(\omega_{\text{RF}}t), \quad (1.21)$$

where q is the charge of the particle, V_0 is the amplitude of the potential difference in the cavity, and $\varphi(t)$ is the relative phase between the particle and the potential field, as a function of the turn number t . A particle that has the same relative phase turn after turn is called a *synchronous particle*, and has a phase denoted by φ_s — corresponding to the nominal gain in energy [17].

Particles circulating in the machine are subject to dissipative phenomena such as synchrotron radiation. These effects contribute to a momentum deviation $\Delta p = \Delta E/c$, which leads to a variation of the length of orbit L , characterised by

$$\frac{\Delta L}{L} = \alpha_c \frac{\Delta p}{p}, \quad (1.22)$$

where α_c is known as the *momentum compaction* factor, which gives the relative orbit length change for a given relative momentum change. Particles within a bunch have slight variations in phase, leading to different gains in energy. A particle that is less energetic lags

behind the synchronous particle, and subsequently receives more energy when traversing the RF cavity. In the following turns, the particle would be ahead of the synchronous particle, which would cause it to gain less energy. As a consequence, particles oscillate around the synchronous particle. These oscillations are known as *synchrotron oscillations*.

The *phase focusing* principle determines the longitudinal stability of the bunch, and depends on the relation

$$\frac{\Delta T}{T} = \left(\alpha_c - \frac{1}{\gamma_{\text{rel}}^2} \right) \frac{\Delta p}{p}, \quad (1.23)$$

where T is the revolution period. The energy corresponding to the transition factor $\gamma_{\text{tr}} = \sqrt{\frac{1}{\alpha_c}}$ divides the longitudinal motion into two regimes:

1. Below transition; $\gamma_{\text{rel}} < \gamma_{\text{tr}}$
2. Above transition; $\gamma_{\text{rel}} > \gamma_{\text{tr}}$

Below transition, the region of stability defined by $0 < \varphi_s < \frac{\pi}{2}$, which corresponds to the rising part of the sinusoid in Eq. (1.21). In this region, particles which are slightly displaced relative to the synchronous particle will experience forces that lessen their deviation. On the other hand, particles with a slight deviation in the region $\frac{\pi}{2} < \varphi_s < \pi$ will be forced to deviate even further [19].

Above transition, where $v \approx c$, the region of stability is defined by $\frac{\pi}{2} < \varphi_s < \pi$, which corresponds to the declining part of the sinusoid. In this regime, a more energetic particle experiences an increase in path length due to relativistic effects; meaning that it will reach the RF cavity *after* the synchronous particle. The RF system needs to perform a *phase jump* when crossing the transition during acceleration, as the previously stable synchronous phase will become unstable [17].

The synchrotron oscillations performed by particles with a small longitudinal amplitude are described by the equation

$$\ddot{\varphi}(t) + \frac{\Omega_s^2}{\cos \varphi_s} (\sin \varphi(t) - \sin \varphi_s) = 0, \quad (1.24)$$

where Ω_s is a constant and a dot represents a derivative with respect to t . This non-linear differential equation highlights the separatrix that delimits the region of longitudinal stability known as the RF bucket. The space occupied by a bunch inside an RF bucket determines the longitudinal emittance ε_s , given by

$$\varepsilon_s = \pi \sigma_t \sigma_E E_0, \quad (1.25)$$

where σ_t is the bunch length in seconds, σ_E is the RMS energy spread of the bunch, and E_0 is the nominal energy [19].

1.3.4 Dispersion and chromaticity

Particles with momenta different than that of the reference particle have dissimilar radii of curvature in the main dipoles. Consequently, such particles no longer pass through the quadrupoles at the same radial positions — making quadrupoles themselves act as dipoles.

As a result, particles with deviations in momentum have different closed orbits, where the dispersion function $D(s)$ expresses the displacement from the reference orbit [16].

The transverse position of a particle is thus given by

$$z(s) = z_\beta(s) + z_\delta(s), \quad (1.26)$$

where $z_\beta(s)$ is the displacement due to betatron motion, derived in Eq. (1.3); and $z_\delta(s)$ is the displacement due to dispersion:

$$z_\delta(s) = D_z(s)\delta_p. \quad (1.27)$$

While the dispersion function $D_z(s)$ is an optical parameter that depends only on the machine lattice, the relative momentum spread δ_p is a value intrinsic to each particle, and is defined as

$$\delta_p = \frac{p - p_0}{p_0} = \frac{\Delta p}{p_0}. \quad (1.28)$$

It is interesting to note that the dispersion function alone describes the orbit of a special particle that has $\delta_p = 1$ and does not undergo betatron oscillations [18]. It is also worth mentioning that the dispersion in the vertical plane $D_y(s)$ is practically zero, as no dipoles act vertically.

Similarly, the shift in angle is given by

$$z'_\delta(s) = D'_z(s)\delta_p. \quad (1.29)$$

It is apparent that the effect of dispersion on a particle's z - z' phase space leads to a shift of the ellipse centre, as shown in Fig. 1.7a, where the new centre is coordinated at $z_\delta(s)$ and $z'_\delta(s)$. Hence, the points of interest in Fig. 1.5 can be adjusted by simply adding the terms $z_\delta(s)$ to z and $z'_\delta(s)$ to z' . Dispersion also effects the size of the beam, whereby Eq. (1.11) becomes

$$\sigma_z(s) = \sqrt{\bar{\epsilon}_z \beta_z(s) + (D_z(s)\delta_p)^2}. \quad (1.30)$$

The focal properties of lattice elements depend upon the momenta of particles — an effect akin to chromatic aberration in regular optics. This dependence on momentum results in a tune spread for particles with momenta distributed around p_0 . The *chromaticity* parameter Q' is defined as the ratio of tune shift to the relative momentum change:

$$\Delta Q = Q'\delta_p. \quad (1.31)$$

The chromaticity of an accelerator containing only linear elements (i.e., dipoles and quadrupoles) is always negative, and is known as the *natural chromaticity* of the machine [17]. This value induces a tune spread which causes particles to cross several dangerous resonance lines, leading to beam instability. The chromaticity is therefore corrected by sextupole magnets, which are placed in regions of high dispersion. The sextupole strength is chosen such that the chromaticity in both planes is adjusted to a suitable value⁴ [15, 17]. The effects of chromaticity on the z - z' phase space can be seen in Fig. 1.7b.

⁴A chromaticity of zero is not necessarily desirable due to so-called collective effects [17].

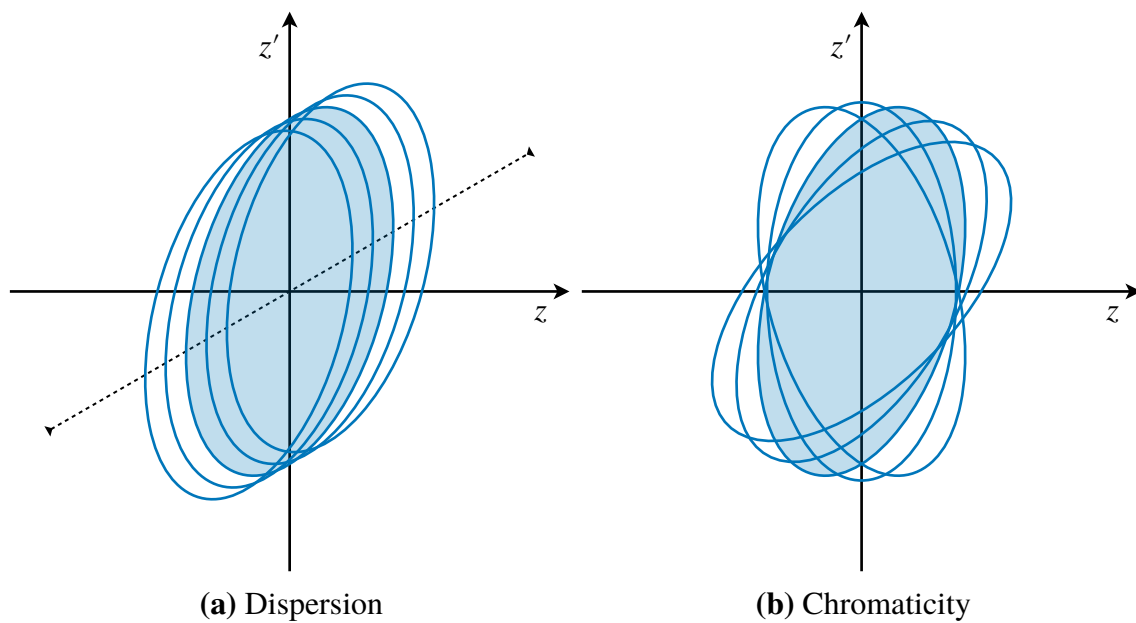


Figure 1.7: The effects of dispersion and chromaticity on a particle's z - z' phase space. Dispersion is a linear effect that shifts the centre of the ellipse to a point other than the origin. Chromaticity is a non-linear effect that alters the orientation of the ellipse.

Chapter 2

Collimation

2.1 Purpose

A multitude of processes can lead to unavoidable beam losses during operation. These losses can be devastating due to the high energy stored in each beam. The superconducting magnets are especially vulnerable, as energy depositions as small as 30 mJ cm^{-3} caused by a local transient loss of 4×10^7 protons are enough to induce a quench [2]. Any significant beam losses must therefore be avoided. For this purpose, a collimation system has been instated, which fulfils the following objectives [2, 10, 20]:

- Efficient cleaning of the betatron and off-momentum beam halos during the full operational cycle, such that beam-induced quenches are avoided.
- Minimisation of halo-induced background noise in the detectors of experiments.
- Passive protection of the machine aperture against abnormal losses, particularly around the triplet magnets. In addition, beam loss monitors (BLMs) at the collimators detect any unusually high loss rates, and can abort the beam automatically.
- Cleaning of debris produced by collisions in the high-luminosity experiments.
- Beam halo scraping and diagnostics of halo population. Primary collimators can be used to effectively scrape and shape the beams.
- Confining induced radioactivity by localising beam losses to so-called *hot* areas. This allows for easier access to the machine for maintenance.
- Local protection of equipment from radiation. Thus increasing the lifetime of various elements in the accelerator.

The collimators must be sufficiently robust to achieve these goals without being damaged during normal and abnormal operational conditions.

2.2 Multistage collimation

A typical LHC collimator consists of two movable blocks called *jaws*, which are precisely placed symmetrically around the circulating beam to intercept halo particles, as shown in

Fig. 2.1. The two jaws are individually identified as being *positive* (or *left*) and *negative* (or *right*), however these names have no bearing on a jaw's actual position relative to the beam frame. *Skew* collimators are oriented at an angle θ which is measured from the positive x -axis to the normal of the positive jaw. The opening of a collimator is described through a quantity known as the *half-gap*, which is half the distance between two jaws placed symmetrically across one another. The half-gap g is not appropriate when considering asymmetric collimator settings, therefore the displacement relative to the beam orbit must be defined separately for each jaw.

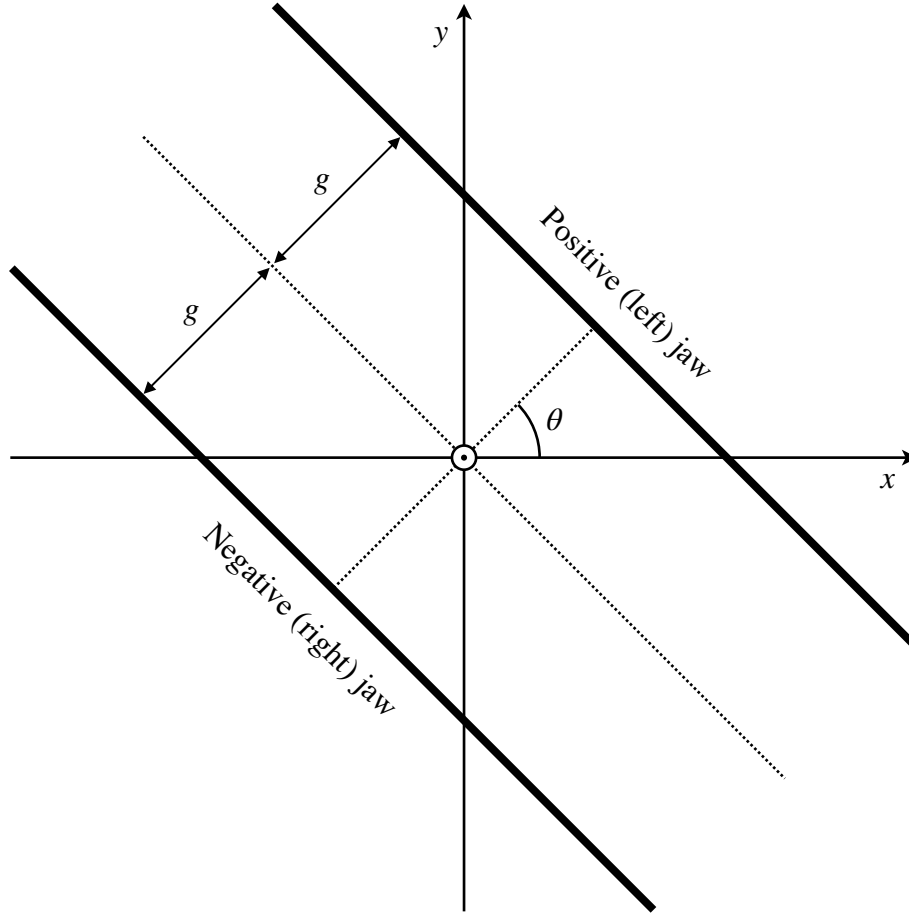


Figure 2.1: The characteristics of a collimator — illustrating the positive and negative jaws, their respective displacements, and the azimuthal angle θ . The s -axis is directed out of the plane.

A multistage collimation system is a hierarchy of such collimators, as shown in Fig. 2.2. The so-called *primary beam halo* is formed and continuously filled by various beam processes. The primary halo is intercepted by a primary collimator (TCP), whose gap is smaller than the bottleneck of the machine, but large enough to avoid scraping the beam core. A TCP is made out of a robust carbon fibre composite (CFC) material, designed to withstand high levels of energy depositions.

Particles that are out-scattered before being absorbed by the jaws leave the collimator at larger normalised amplitudes and modified energies. These particles form the so-called *secondary beam halo*, which is intercepted by secondary collimators (TCSG). TCSGs are

typically longer than TCPs in order to maximise the absorption of out-scattered particles. TCSGs must also have a wider gap to ensure that the hierarchy is respected, as otherwise the multistage system is reduced to a single-stage system.

A sparsely populated *tertiary beam halo* leaks out of the secondary collimators, and gets caught by the tertiary collimators (TCT), which are installed at the aperture bottleneck in the triplets to provide additional protection. This creates an even sparser *quaternary beam halo*, which is practically negligible for machine protection. Shower absorbers (TCLA) can be found downstream of the secondary collimators to intercept hadronic showers, which are produced when high-energy particles interact with dense matter. TCLAs and TCTs have much wider gaps and are made of a material with a high atomic number (i.e., tungsten alloy) to improve absorption.

Collimator gaps should be wide enough to avoid excessive impedance. A good approach is to position collimators at larger $\beta(s)$ values, thus allowing for wider gaps while maintaining effectiveness. The optimal gap for TCPs is generally around 6σ , with TCSGs having a relative offset of at least 1σ . The phase advances between different collimators and their orientations are optimised such as to achieve the best possible coverage in z - z' phase space [2].

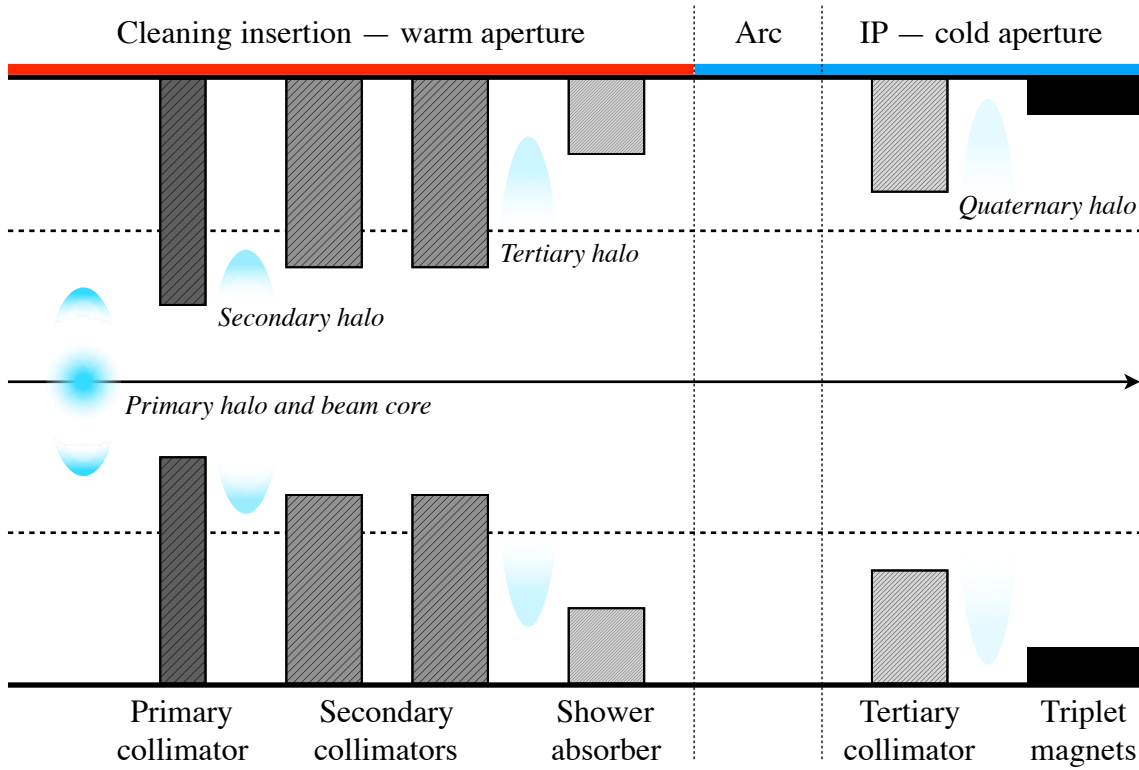


Figure 2.2: The principle of multistage collimation. As the beam travels from left to right, its halo is progressively intercepted by the hierarchy of collimators.

2.3 Cleaning insertions

In Section 1.3 it was shown that the transverse position of particles can be described by the superposition of betatron and synchrotron motion. Since cleaning both particles with

a high betatron amplitude and particles with a high momentum deviation is generally of interest, the linearity of Eq. (1.26) can be exploited to separate these two tasks. In the LHC this is done by having two different cleaning insertions [21]:

- The *betatron cleaning* insertion is characterised by low dispersion, in which large transverse deviations are purely the result of a high betatronic amplitude, where momentum offset is not a factor. This cleaning insertion is housed in IR7 and is the most prominent insertion of the collimation system.
- The *momentum cleaning* insertion is characterised by high dispersion, such that large transverse deviations are mainly the product of a high momentum offset, thus eliminating off-momentum particles. This collimation system is stationed in IR3 and has far fewer components than IR7.

These two cleaning insertions are located in warm regions of the machine, as non-superconducting magnets are much more tolerant to beam losses and particle showers generated by the collimators. Fig. 2.5 shows the general layout of the collimation system around the ring. A list of collimator families and their properties can be found in Tab. 2.1.

Table 2.1: The role, length, and material composition of each collimator family in the LHC and HL-LHC.

Type	Function	LHC	HL-LHC	Length
TCP	Primary	CFC	CFC / MoGr	0.6 m
TCSG	Secondary	CFC	CFC / MoGr	1.0 m
TCTP	Tertiary	Inermet 180	Inermet 180	1.0 m
TCLA	Absorber	Inermet 180	Inermet 180	1.0 m
TCLD	DS protection	-	Inermet 180	0.6 m
TCL	Physics debris absorber	Cu / W	Cu / W	1.0 m
TDI	Injection protection	Al / CuCrZr	Al / CuCrZr	4.0 m
TCLI	Injection protection	CFC	CFC	1.0 m
TCSP	Dump protection	CFC	CFC	1.0 m
TCDQ	Dump protection	CFC	CFC	3.0 m

2.4 Cleaning inefficiency

The performance of the collimation system is characterised by its *cleaning inefficiency*. The *global* cleaning inefficiency η_g is defined as

$$\eta_g = \frac{N}{N_{\text{tot}}}, \quad (2.1)$$

where N is the number of particles that have leaked into non-collimator elements, and N_{tot} is the total number of particles lost in the machine. A local concentration of losses could still induce a quench in the superconducting magnets, even if the global cleaning inefficiency satisfies the design requirements. Hence, a more pertinent evaluation of the cleaning performance is the distribution of losses along the machine — a quantity known as the *local* cleaning inefficiency η ;

$$\eta = \frac{N_{\Delta s}}{N_{\text{tot}} \cdot \Delta s}, \quad (2.2)$$

where $N_{\Delta s}$ is the number of particles lost over a range Δs [20]. Such a value can only be obtained through simulation, as it is impossible to track individual particles in practice. Nonetheless, it can be estimated fairly well through normalised BLM signals. A so-called *loss map* can be generated by plotting the local cleaning inefficiency over the longitudinal coordinate, as seen in Fig. 2.3. The local cleaning inefficiency can essentially be integrated to yield the global cleaning inefficiency.

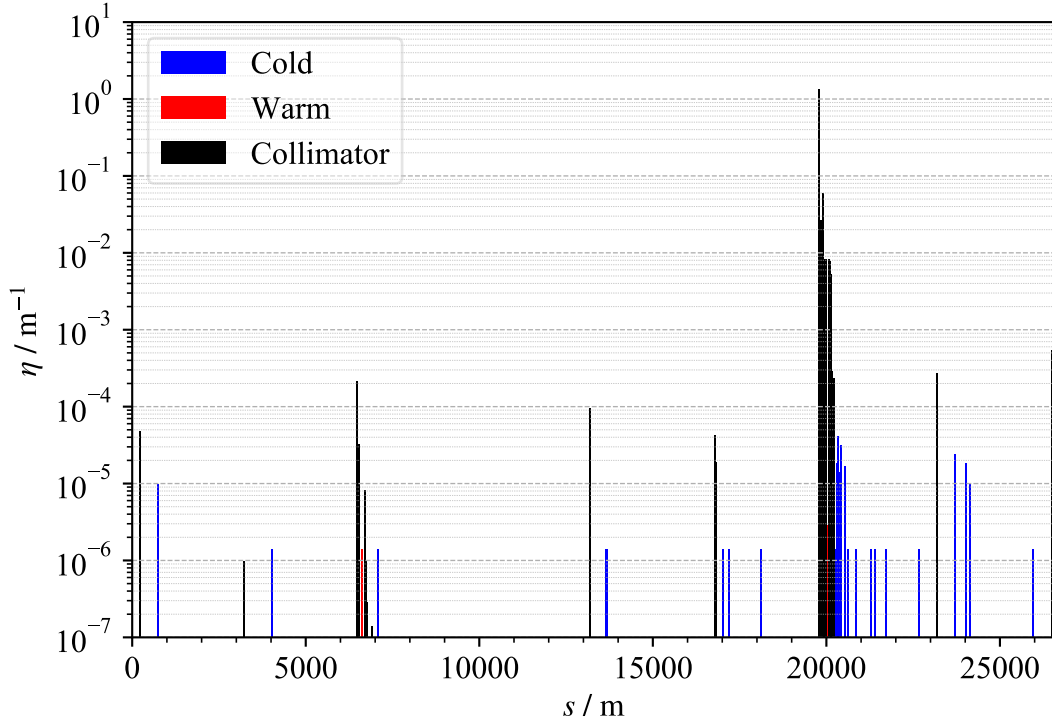


Figure 2.3: A simulated loss map for B1 of the LHC at 6.5 TeV. The black bars represent particles lost in collimators, whereas the blue and red bars represent losses in cold and warm apertures respectively. The large concentration at 20 km is the betatron collimation system in IR7. The momentum cleaning system in IR3 is located at around 6.5 km.

2.5 Symmetric versus single-sided collimation

Consider a purely betatronic cleaning process for a particular transverse plane in normalised phase space. Halo particles that slowly drift outwards are intercepted by a

primary collimator at their maximum betatron excursion. The primary collimator with normalised aperture n_1 (in σ_z units) induces a deflection kick k on particles, due to elastic interactions inside the jaw in question. As a first-order approximation, it is assumed that particles are scattered only in the plane of the analysed halo. Thus the kick experienced can be either positive or negative, with varying magnitude.

To maximise the efficiency of the collimation system it is necessary to optimise the normalised aperture n_2 and phase advance μ of secondary collimators.¹ If n_1 and n_2 are fixed, the minimum kick (in magnitude) required to reach a normalised amplitude of n_2 is given by

$$k_{\pm} = \pm \sqrt{n_2^2 - n_1^2}. \quad (2.3)$$

The phase advance between primary and secondary collimators should be such that particles are at their maximum betatron excursion when reaching the secondary collimators. There are thus two solutions for μ — each dependant on the sign of the kick k , as shown in Fig. 2.4. This reveals that two secondary collimator jaws are needed to intercept particles scattered from a single primary collimator jaw. Eqs. (2.4) and (2.5) give the phase advance required by the two jaws to intercept particles which have undergone positive and negative kicks respectively.

$$\mu_+ = \arccos\left(\frac{n_1}{n_2}\right) \quad (2.4)$$

$$\mu_- = \pi - \mu_+ \quad (2.5)$$

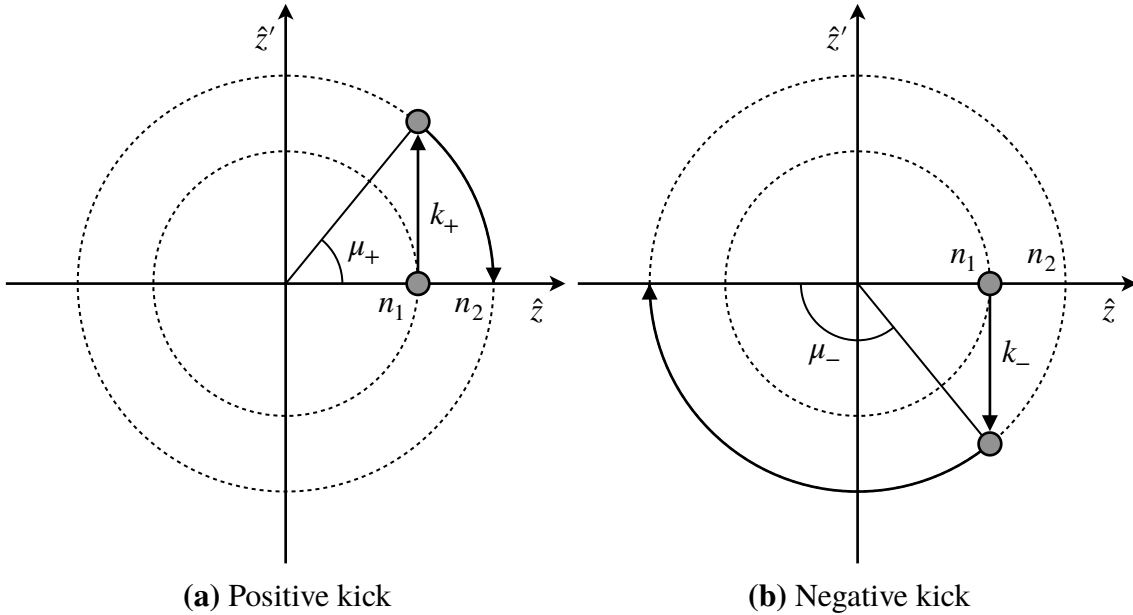


Figure 2.4: The normalised transverse phase space of a particle at its maximum betatron extension. The particle can receive either a positive or negative kick when intercepted by the jaw of a primary collimator with aperture $n_1 \sigma_z$. Two secondary collimator jaws with aperture $n_2 \sigma_z$ and phase advance μ_+ and μ_- are thus needed to capture scattered particles.

Note that although the two secondary collimator jaws are diametrically opposite one another in phase space, they do not share the same longitudinal position. Hence, they

¹Recall that a phase advance corresponds to a longitudinal position, as per Eq. (1.4).

do not form part of a two-sided collimator. However, if one considers scattering from both jaws of the primary collimator, then a total of 4 secondary jaws end up forming 2 double-sided secondary collimators.

Single-sided secondary collimators are thus most viable when the primary collimators are also single-sided. In principle, one primary jaw is enough to protect the aperture from slow diffusive losses, as the betatron motion ensures that particles cover the entirety of the phase space turn after turn (see Section 1.3.1) [20]. The LHC currently only employs symmetric collimators,² as symmetric collimation offers a number of benefits over single-sided collimation:

- Less turns are required to collimate effectively due to the increased coverage.
- Single-turn failures are less likely to be catastrophic.
- Closed orbit distortions can be intercepted regardless of the direction.
- The thermo-mechanical load is spread out over two jaws, increasing robustness.

Nonetheless, single-sided collimation has one key advantage over the standard, which is reduced impedance. However, the approach can easily lead to a loss of performance or to dangerous beam orbit distortions if not applied with care. The significance of this advantage is explored hereinafter.

²With the exception of the single-sided TCDQ dump protection collimators.

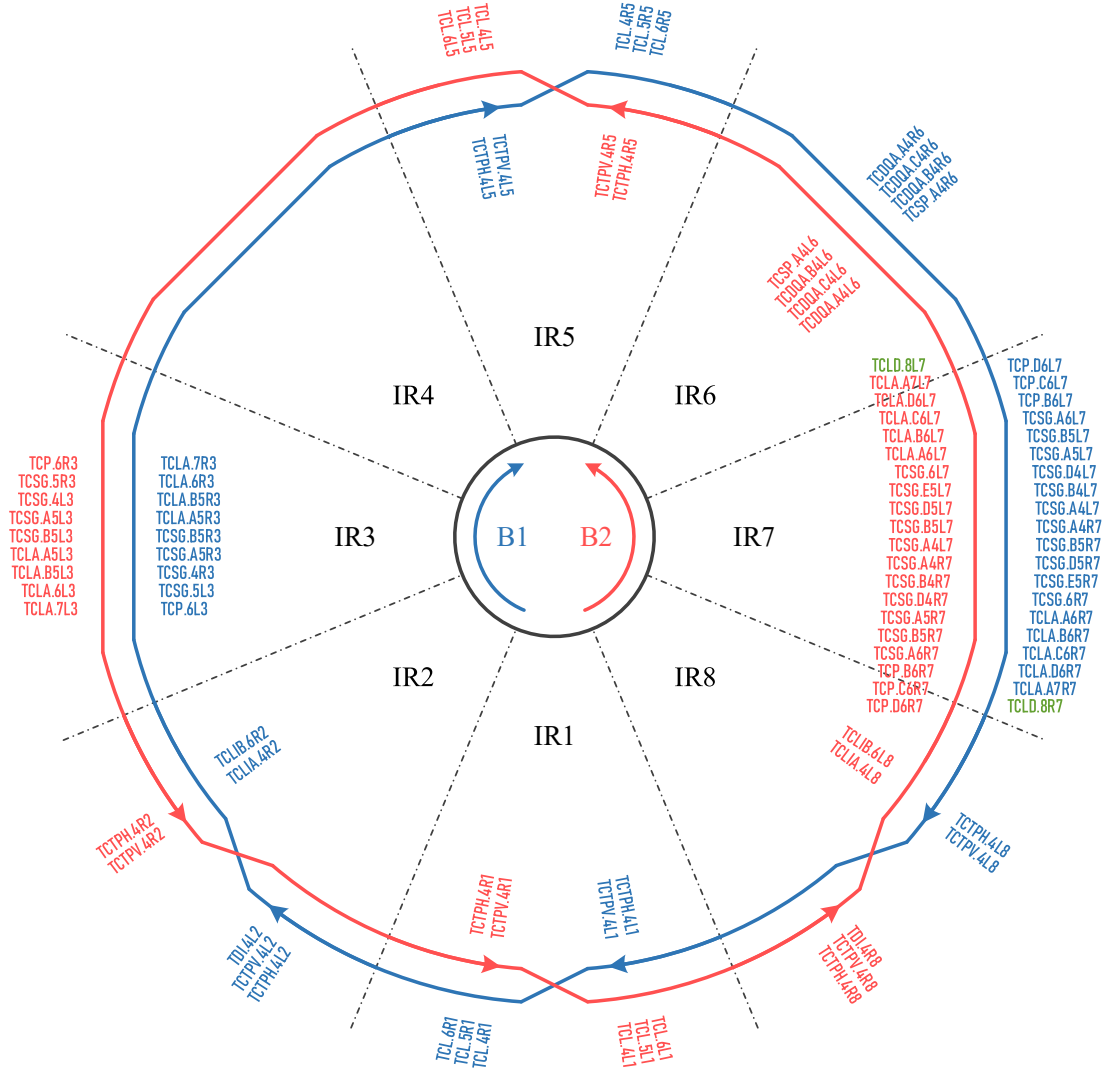


Figure 2.5: The general layout of the LHC collimation system as of Run II. Each beam has a distinct, but complementary set of collimators — located mainly in the momentum (IR3) and betatron (IR7) cleaning insertions, with some collimators distributed along the ring for dedicated purposes. The collimator in green (TCCLD) is part of the HL-LHC upgrade, and is shown as it is relevant to the work herein. Refer to Appendix B for more information on the collimators.

Chapter 3

Beam-coupling impedance

3.1 Wake fields

A charged particle traversing a vacuum chamber generates electromagnetic (EM) fields which interact with the surroundings. These fields in turn act back on the particle, perturbing its motion. Under unfavourable conditions, the perturbations on the particle further enhance the effects of the induced fields, leading to what is known as *collective instability*, and subsequent beam loss. An accelerator can therefore be seen as a feedback device, where perturbations in the beam distribution may be amplified or damped by the EM forces generated by the perturbations themselves. These so-called *collective effects* serve as an upper limit to the performance of an accelerator in terms of beam quality and stored current [22, 23].

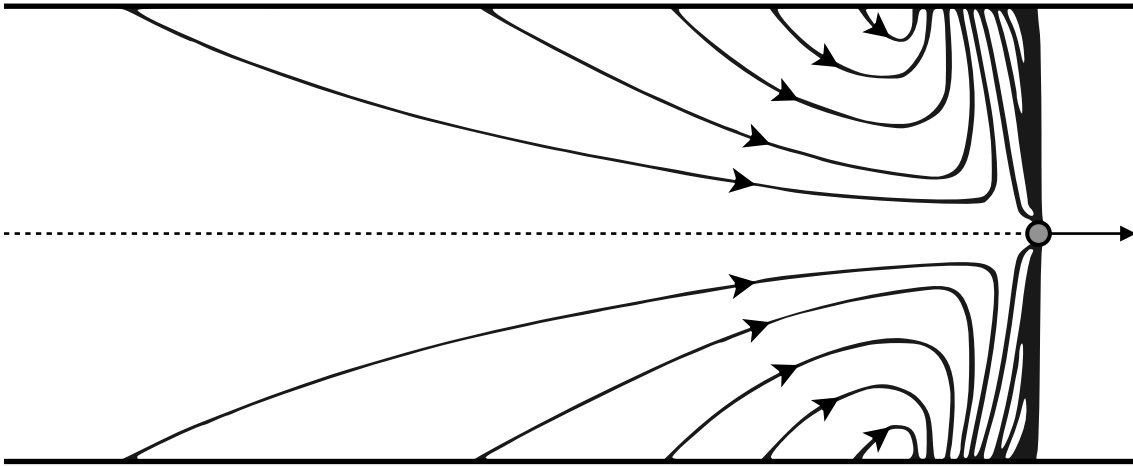


Figure 3.1: The resistive-wall (RW) wake fields generated by a charged particle travelling through a beam pipe at the speed of light.

The EM fields generated by the beam are known as *wake fields*, as they mostly lag behind the travelling charge (see Fig. 3.1). In the relativistic limit ($\beta_{\text{rel}} = 1$), it is impossible for wake fields to exist ahead of the charge due to the principle of causality. In this regime, wake fields are only generated when the beam pipe is not smooth or when it is not perfectly conducting. Hence, no wake fields are generated in a perfectly conducting and smooth

pipe. Depending on the geometry, wake fields can either propagate or become trapped in the vacuum chamber, leading to various forms of instability [22–24].

3.2 Longitudinal wake function and impedance

Consider two ultrarelativistic charged particles travelling at a constant velocity v parallel to the axis of an accelerator structure, as shown in Fig. 3.2. At any time t , the two charges have longitudinal coordinates $s_1(t) = vt$ and $s(t) = v(t - \tau)$, where τ is the time delay of the trailing charge relative to the leading charge.

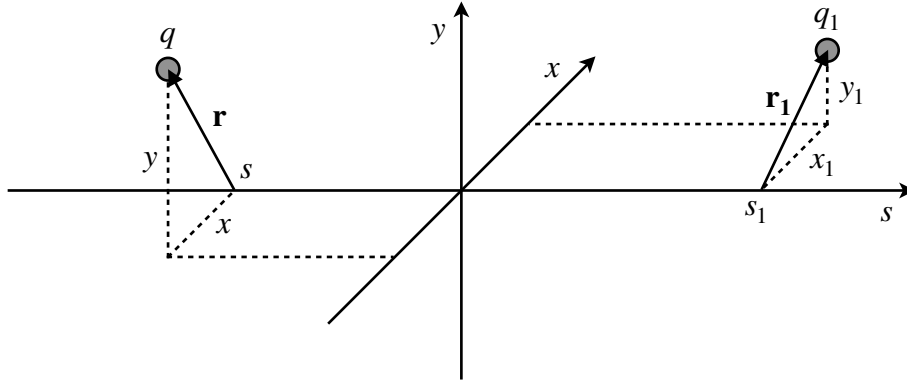


Figure 3.2: The reference frame employed for wake and impedance calculations.

The EM fields produced by the *source* charge q_1 can be derived by solving Maxwell's equations and satisfying boundary conditions. The Lorentz force acting on the *witness* charge q is given by

$$\mathbf{F}(\mathbf{r}, s, \mathbf{r}_1, s_1; t) = q \left[\mathbf{E}(\mathbf{r}, s, \mathbf{r}_1, s_1; t) + \mathbf{v} \times \mathbf{B}(\mathbf{r}, s, \mathbf{r}_1, s_1; t) \right], \quad (3.1)$$

which in general has both longitudinal and transverse field components. The witness particle undergoes a change in energy due to this force:

$$\Delta E(\mathbf{r}, \mathbf{r}_1; \tau) = - \int_{-\infty}^{\infty} \mathbf{F}_{\parallel}(\mathbf{r}, s, \mathbf{r}_1, s_1; t) \cdot d\mathbf{s}. \quad (3.2)$$

This change in energy can be either positive or negative depending on the time delay τ . Since the particles are moving parallel to the longitudinal axis, the magnetic field cannot change the energy of the witness particle, as $\mathbf{v} \times \mathbf{B} \cdot d\mathbf{s} = 0$. On the other hand, the longitudinal component of the electric field may change the effective amplitude and phase of the applied accelerating field, and the energy distribution within a bunch, along with its effective length. This influences the optics of the accelerator, thereby changing the rate of acceleration and the closed orbit [23, 24].

The longitudinal *wake function* can thus be obtained by normalising the energy lost by the witness particle to the product of charges:

$$w_{\parallel}(\mathbf{r}, \mathbf{r}_1; \tau) = \frac{\Delta E(\mathbf{r}, \mathbf{r}_1; \tau)}{q q_1}. \quad (3.3)$$

Wake functions are commonly used for linear accelerators, as the interaction is described in the time domain. For circular accelerators such as the LHC, it is more convenient to consider the frequency domain, due to the inherent periodicity. This is done by computing the Fourier transform of the wake function, which defines the *coupling impedance*:

$$Z_{\parallel}(\mathbf{r}, \mathbf{r}_1; \omega) \equiv \int_{-\infty}^{\infty} w_{\parallel}(\mathbf{r}, \mathbf{r}_1; \tau) e^{-i\omega\tau} d\tau, \quad (3.4)$$

where the name stems from the fact that its units are that of resistance (Ω). The coupling impedance is a complex quantity,

$$Z(\omega) = Z_{\Re}(\omega) + i Z_{\Im}(\omega), \quad (3.5)$$

where $Z_{\Re}(\omega)$ and $Z_{\Im}(\omega)$ are even and odd functions of ω respectively. The real part corresponds to resistive loss and is related to a beam instability rise time (growth rate). The imaginary part is responsible for real-valued coherent tune shifts and can lead to collective instabilities. In general, impedance can be minimised by having tapered transitions between chambers of different cross-sections; separating bellows from the beam by means of shielding; having the vacuum chamber be as smooth as possible; and ensuring that the accelerator elements closest to the beam are of low resistivity [22–27].

3.3 Transverse wake function and impedance

Consider two particles transversely displaced from the longitudinal axis, as shown before in Fig. 3.2. The witness charge q experiences a Lorentz force brought on by the EM fields of the source charge q_1 . It will therefore be subject to a transverse momentum kick given by

$$\mathbf{M}(\mathbf{r}, \mathbf{r}_1; \tau) = \int_{-\infty}^{\infty} \mathbf{F}_{\perp}(\mathbf{r}, s, \mathbf{r}_1, s_1; t) ds. \quad (3.6)$$

This momentum kick is measured in *Newton meters* (N m), and depends on the geometry of the beam pipe as well as the transverse position of both charges. The momentum kick need not be parallel to the transverse displacement of the source charge. Indeed, an offset in one axis often leads to a kick in both axes. Only in the case of cylindrical symmetry are the two transverse axes decoupled [23].

The transverse wake function is given by the transverse momentum kick per unit of both charges:

$$\mathbf{w}_{\perp}(\mathbf{r}, \mathbf{r}_1; \tau) = \frac{\mathbf{M}(\mathbf{r}, \mathbf{r}_1; \tau)}{q q_1}. \quad (3.7)$$

The Fourier transform of the transverse wake function multiplied by the imaginary unit defines the transverse coupling impedance

$$Z_{\perp}(\mathbf{r}, \mathbf{r}_1; \omega) \equiv i \int_{-\infty}^{\infty} \mathbf{w}_{\perp}(\mathbf{r}, \mathbf{r}_1; \tau) e^{-i\omega\tau} d\tau, \quad (3.8)$$

where the imaginary unit is introduced so that both components of the beam-coupling impedance have the same role in beam stability theory [23].

Impedance is often divided into two separate quantities: the *geometric* impedance, which stems from the geometry of the surrounding structure; and the *resistive-wall* (RW)

impedance, which arises from the electromagnetic properties of its layers. The transverse RW impedance is generally of primary concern, as it tends to drive the so-called head-tail and multi-bunch instabilities [23].

The transverse coupling impedance can be expanded into its multipole components, which have effects similar to their magnetic counterparts. The dipolar component is proportional only to the offset of the source charge, while the quadrupolar component is proportional only to the offset of the witness charge. Higher-order components are small and can usually be neglected [28].

$$Z_x(x, x_1; \omega) = x_1 Z_x^{\text{dip}}(\omega) + x Z_x^{\text{quad}}(\omega) \quad (3.9)$$

$$Z_y(y, y_1; \omega) = y_1 Z_y^{\text{dip}}(\omega) + y Z_y^{\text{quad}}(\omega) \quad (3.10)$$

The dipolar component is dominant for small transverse displacements, and has the effect of defocusing in both transverse planes — pushing the beam further out from its radial position. The quadrupolar component vanishes entirely in rotationally symmetric structures, but generally has the effect of focusing in one transverse plane, and defocusing in the other. This formalism is useful as it leads to quantities which are invariant of the offset of particles, as per Eqs. (3.9) and (3.10). The dipolar impedance leads to coherent oscillations of the bunch as a whole, thus driving coherent instabilities. The quadrupolar impedance leads to oscillations that depend on an individual particle's amplitude, thus contributing to incoherent effects such as damping and emittance growth.

The coherent stability of bunched beams is generally determined by a quantity known as the *effective impedance*, which is defined as the convolution of the coupling impedance with the bunch oscillation spectrum [24]. Although the effective impedance is not directly measurable in practice, it manifests itself as a coherent transverse tune shift [29]:

$$\Delta Q_z \propto \Im\{Z_{\text{eff}, z}\}. \quad (3.11)$$

The impedance can thus be measured indirectly — allowing for verification of the accelerator's existing impedance model. Both the dipolar and quadrupolar components contribute to this coherent tune shift.

Chapter 4

Tools and methodology

4.1 Tools employed

4.1.1 SixTrack

SixTrack is a command-line program optimised for long-term particle tracking in high energy rings [30]. Particles are tracked in pairs¹ through a specified machine lattice, taking into account the full six-dimensional phase space (x, x', y, y', s, E) including synchrotron oscillations, in a symplectic manner. SixTrack is generally used for dynamic aperture studies, tune optimisation, and collimation studies.

The collimation version of SixTrack was used for beam cleaning studies. This version tracks a large number of halo particles, and considers their interaction with arbitrarily positioned collimators. Particles are transported element-by-element through the lattice, and their phase space coordinates are transformed accordingly. Collimators can scatter particles randomly according to a set of atomic and nuclear events, which are sampled by a Monte Carlo routine. The collimation version of SixTrack also boasts the following features [31, 32]:

- Proton scattering through various collimator materials, including:
 - Multiple coulomb scattering;
 - Ionisation of collimator material;
 - Elastic proton-proton scattering and single diffractive scattering;
 - Inelastic proton-nucleon scattering;
 - Elastic and inelastic proton-nucleus scattering;
 - Rutherford scattering.
- Control over beam halo shape and type, with possibility of including diffusion.
- Ability to track large ensembles of particles over hundreds of turns.

The input parameters are divided amongst three files. The exact format of these files will not be discussed for the sake of brevity; however, this information can be found in [31]. Each file is listed below along with a brief overview of its most pertinent attributes:

¹The tracked pair have slight deviations in phase space in order to detect chaotic behaviour [31].

- *fort.2*: This file is generated by MAD-X (see Section 4.1.3) and defines the machine lattice, including the optics and closed orbit. Consecutive linear elements are grouped into one bloc and non-linear elements are placed in between such blocs.
- *fort.3*: This file contains general tracking parameters such as the number of particles, the number of turns, the halo distribution, and the type of beam. Collimation specific parameters are also specified in this file.
- Collimation database file: This file contains the name, length, orientation, material, opening, and β -function of each collimator in the lattice. It can also be used to set collimators as single-sided. The name of this file can be specified in *fort.3*.

Lattice elements are modelled after the thin-lens approximation, whereby elements have no longitudinal length and are instead represented by a marker placed at what would be their centre. A thick element can be split into several thin lenses in order to increase precision while keeping computation time to a minimum.

4.1.2 ImpedanceWake2D

ImpedanceWake2D (IW2D) is a package of codes that compute the longitudinal and transverse wake functions and beam-coupling impedances of flat or axisymmetric two-dimensional multilayered structures. The codes rely on the analytic continuation of the EM fields generated by a point charge travelling at any speed within a structure [33, 34].

A single file can be given as input which specifies the type of structure, whether flat or circular; the Lorentz factor of the point charge; the longitudinal length and axial displacement of the element; the number of layers and their physical properties, such as the thickness, resistivity, and magnetic susceptibility; and various other simulation-specific parameters.

Flat geometry is appropriate for simulating collimators, whilst axisymmetric geometry can approximate beam pipes and other cylindrical elements. It is possible to simulate an asymmetric flat structure, where the number of layers is different on each side. This is useful for studying the impedance of single-sided collimators. Each layer can be of any linear material, and the outermost layers must have an infinite thickness — usually chosen to be a vacuum.

The code outputs five files of interest, one for each multipole component, namely the longitudinal component Z^{long} , the horizontal and vertical dipolar components Z_x^{dip} and Z_y^{dip} , and the horizontal and vertical quadrupolar components Z_x^{quad} and Z_y^{quad} . Each file consists of three columns, the first of which lists frequencies in ascending order, while the remaining two list the real and imaginary parts of the impedance respectively.

The impedance computed is the so-called *wall* impedance — a quantity similar to the RW impedance, but which also includes the indirect space-charge term, that is, the impedance of a perfectly conducting chamber [35]. The LHC and HL-LHC impedance models were used in conjunction with this code to compute the impedance of virtually all the prominent accelerator elements [34]. Several dedicated Python scripts which were included in these packages also allowed for the computation of the effective impedance, and provided an interface for a simpler simulation setup.

4.1.3 Miscellaneous

LXPLUS

LXPLUS, which stands for Linux Public Login User Service, is the interactive logon service to Linux for all CERN users [36]. The computer cluster was used to submit intensive simulations (via HTCondor), and to store and share data.

MAD-X

MAD-X is a general-purpose tool used for charged-particle optics design and studies in alternating-gradient accelerators and beam lines [37]. This program was used briefly for machine optics studies, and to obtain a better understanding of results given by SixTrack.

DELPHI

DELPHI stands for Discrete Expansion over Laguerre Polynomials and Head-tail modes for Instabilities computation. This code computes eigenfrequencies (equivalently, complex tune shifts) of modes that can develop in circular machines under the combined action of a beam-coupling impedance and a damper. Modes that exhibit a tune shift with a negative imaginary part are unstable — their growth rate being proportional to the imaginary part [38]. This code was used with the sole purpose of obtaining octupole current thresholds.

TIMBER

The CERN Accelerator Logging Service (CALS) registers data coming from pre-defined signals into Oracle databases. This data can be extracted and visualised using a generic Java application known as TIMBER, or its Python library counterpart PyTIMBER. These were used to gather measurements from the LHC, such as the beam intensity, BLM signals, and the tune.

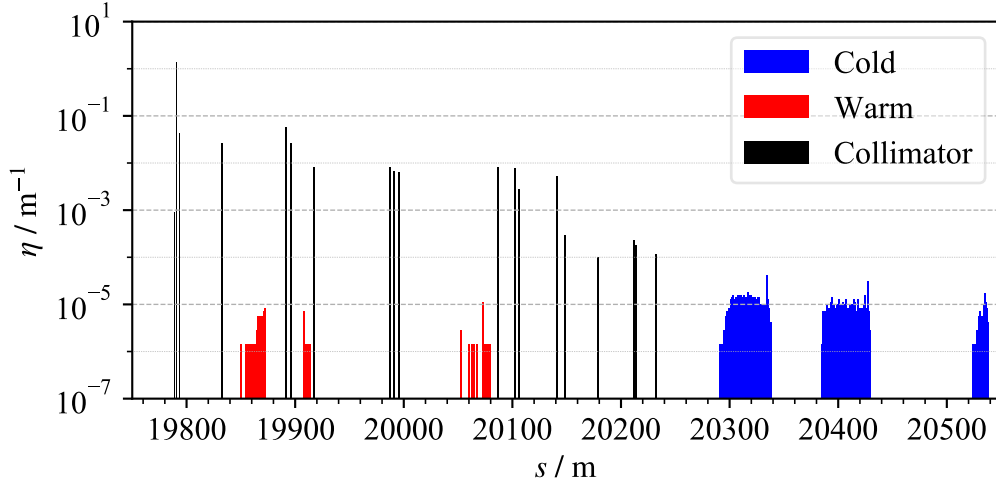
4.2 Methodology

4.2.1 General approach

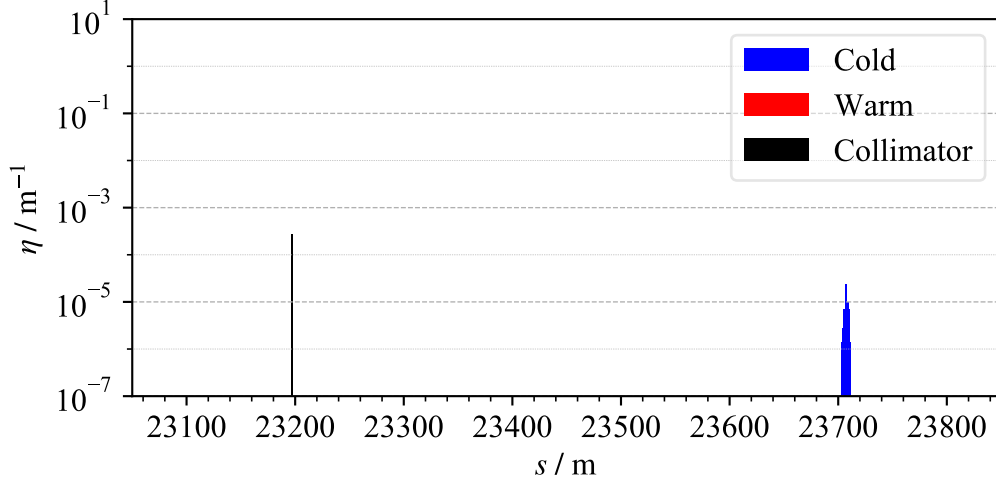
This study examines single-sided configurations of primary and secondary collimators in the betatron collimation system of IR7 (Section 2.3). The two collimator families are chosen as they are the highest contributors to the impedance budget at top energy. Only proton runs are considered, as there is no strong motivation for reducing the impedance in ion runs, due to the lower charge density of ion beams. Moreover, the IR7 collimation system is less efficient for ions, with the local cleaning inefficiency in the DS being higher by two orders of magnitude when compared to that of protons. As such, single-sided collimation may not be the most suitable approach; however, it has seen deployment (albeit limited) in 2018 ion runs in order to redistribute secondary losses [39].

Single-sided configurations are characterised in terms of beam cleaning and impedance, where the performance is compared to that of the standard settings for each scenario. While the emphasis is on HL-LHC, benchmark measurements have been taken for the LHC in

2018. Beam cleaning is evaluated by considering the cold losses in the DS downstream of IR7. These losses form three clusters which amount to the largest concentration of cold losses in the machine (see Fig. 4.1a).² A fourth cluster located in the DS downstream of IR8 is also considered, although this cluster is only present in simulation (see Fig. 4.1b). It is nonetheless included due to its peak height, which is comparable to the other clusters. Additionally, since its origin is unknown, it is kept in the analysis as a precaution.



(a) The three cold clusters in the DS downstream of IR7.



(b) The fourth spurious cluster in the DS downstream of IR8.

Figure 4.1: The four cold clusters used for assessing beam cleaning. The above loss maps were obtained after simulating B1 of the LHC during Run II in 2018 at 6.5 TeV.

The TCLD collimator in HL-LHC practically eliminates the first cluster downstream of IR7. The present HL-LHC baseline upgrade considers the installation of only one TCLD collimator, which is situated between two 11 T dipoles. Two such units were originally envisioned, in order to eliminate the two most prominent clusters; however, the project

²In B2, the third cluster is split into several smaller clusters — all of which are considered in the study.

management decided to cut one unit due to budget constraints. The leakage from IR7 is comprised of protons that experience an energy change in the order of 1 % after interacting with the primary collimators. While it is difficult for secondary collimators to intercept such particles, a 1 % energy loss is sufficiently large to lead to losses in the DS. The clusters, therefore, act as a crude spectrometer — characterising the energy of particles through their location of loss.

Configurations of single-sided collimators which are shown to have a minimal impact on beam cleaning are then assessed in terms of impedance. IW2D is used alongside the LHC and HL-LHC impedance models to determine the impedance induced by the configurations in question, together with virtually all other machine elements. The relative gain in stability is then estimated by computing the octupole current threshold, which is discussed in later Chapter 5. Machine Development (MD) sessions were used to probe a set of configurations via measurements — both in terms of beam cleaning (loss maps), and in terms of impedance (tune shift). The measurements acquired from MDs were then compared to results obtained from simulations.

4.2.2 SixTrack setup

Particle tracking simulations were carried out by generating a monochromatic beam with a halo extending in either the horizontal or vertical plane — the selected plane being classified as the *cleaning plane*. The normalised amplitude of the halo in the cleaning plane is the same as the cut of the primary collimators in IR7, but with an outwards smear of 0.04σ . The phase space is sampled at the primary collimator which is oriented along the cleaning plane. Phases which do not interact with the collimator in the first turn are not sampled in order to minimise computation time. A standard normal distribution is taken in the non-cleaning plane. An example of a sampled beam is illustrated in Fig. 4.2.

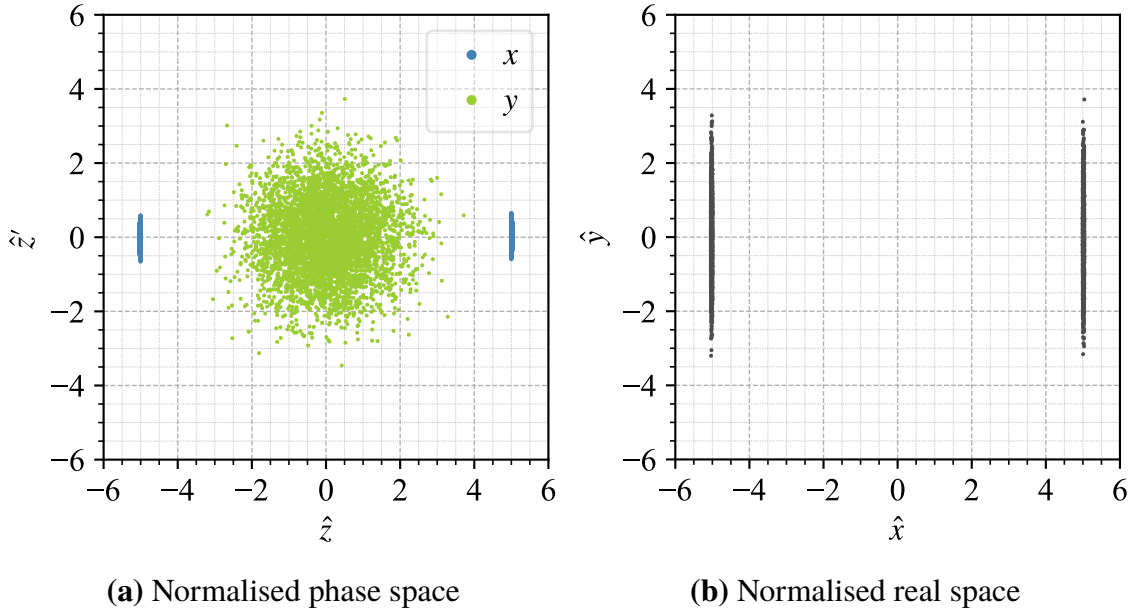


Figure 4.2: A horizontal halo sampled at the horizontal primary collimator with a 5σ cut.

Each simulation tracks a total of 8 million protons for 200 revolutions. It turns out that non-linear single particle dynamics lead to a distortion in phase space, wherein particles sampled on the side of the missing jaw have a smaller normalised amplitude when reaching the active jaw, thus never interacting with it. This issue effectively halves the statistics for some configurations, although it is not severe enough to cast doubt on the results obtained herein. Nevertheless, particles in the real accelerator are subject to diffusion, which ensures that an interaction will take place at some point in time.

Tab. 4.1 summarises the general simulation settings used in each scenario. In collimation studies, it is common practice to take a normalised transverse emittance of $3.5 \mu\text{m rad}$ for both machines, in order to be able to directly compare collimator settings. Ergo, any lengths expressed in σ units hereafter are defined in terms of the aforementioned emittance value. The exact collimator settings in both beams of HL-LHC and LHC can be found in Appendix B.

Table 4.1: The simulation settings used in SixTrack for beam cleaning studies. The exact input parameters used can be found in Appendix A. Details on the optics in each machine can be found in [40].

Parameter	HL-LHC	LHC
Machine version	Version 1.3	Run II (2018)
Particle type	Protons	Protons
Number of primary particles	8×10^6	8×10^6
Number of turns	200	200
Beam energy	7.0 TeV	6.5 TeV
Normalised halo amplitude	$(5.72 \pm 0.02) \sigma$	$(5.02 \pm 0.02) \sigma$
Normalised transverse emittance	$3.5 \mu\text{m rad}$	$3.5 \mu\text{m rad}$

Chapter 5

HL-LHC analysis

5.1 Cleaning simulations

5.1.1 Beam 1

The analysis begins with the primary collimators; namely the vertical primary collimator TCP.D6L7.B1, the horizontal primary collimator TCP.C6L7.B1, and the skew primary collimator TCP.B6L7.B1. Together, these three collimators contribute to a significant portion of the overall impedance budget, due to their exceedingly small half-gaps and rather poor electrical conductivity. Impedance could be minimised by retracting one jaw from each of the primaries, however this is expected to come at the cost of beam cleaning performance. It is, therefore, essential to find a combination of jaws that is least detrimental to beam cleaning.

Both jaws of each collimator were simulated independently as there was no previous systematic study which favoured one jaw over another. The results were compared to those of a *dry* run — that is, the standard (symmetric) collimator settings. A variable $\hat{\eta}$ is defined as the ratio of the local cleaning inefficiency in a configuration, relative to that in a dry run. Figs. 5.1 and 5.2 show the cleaning performance of both jaws for the vertical and horizontal primary collimators respectively. In the case of Fig. 5.1, all three configurations (including the dry run) were simulated with a halo in the vertical plane (B1V). Conversely, the configurations in Fig. 5.2 employed a halo in the horizontal plane (B1H).

The figures describe the cleaning performance in each cluster — both in terms of the *cluster total*, meaning the cleaning inefficiency over the whole cluster; and in terms of the *cluster peak*, meaning the peak cleaning inefficiency within the cluster over a 10 cm range.¹ Although the peaks are generally more critical in highlighting possible quench hazards, they are also much more prone to statistical fluctuations; hence, it is important to consider the full clusters as well as their peaks.² The first cluster has been excluded from these plots due to its low particle count in B1 of HL-LHC, making it highly susceptible to statistical fluctuations. The warm losses in IR7 have been included for completeness, but are largely inconsequential.

By definition, $\hat{\eta} > 1$ implies a worsening of the local cleaning inefficiency, whilst

¹The cluster peaks need not be in the same location for each configuration.

²Though, it was observed that the two quantities corresponded fairly well in general.

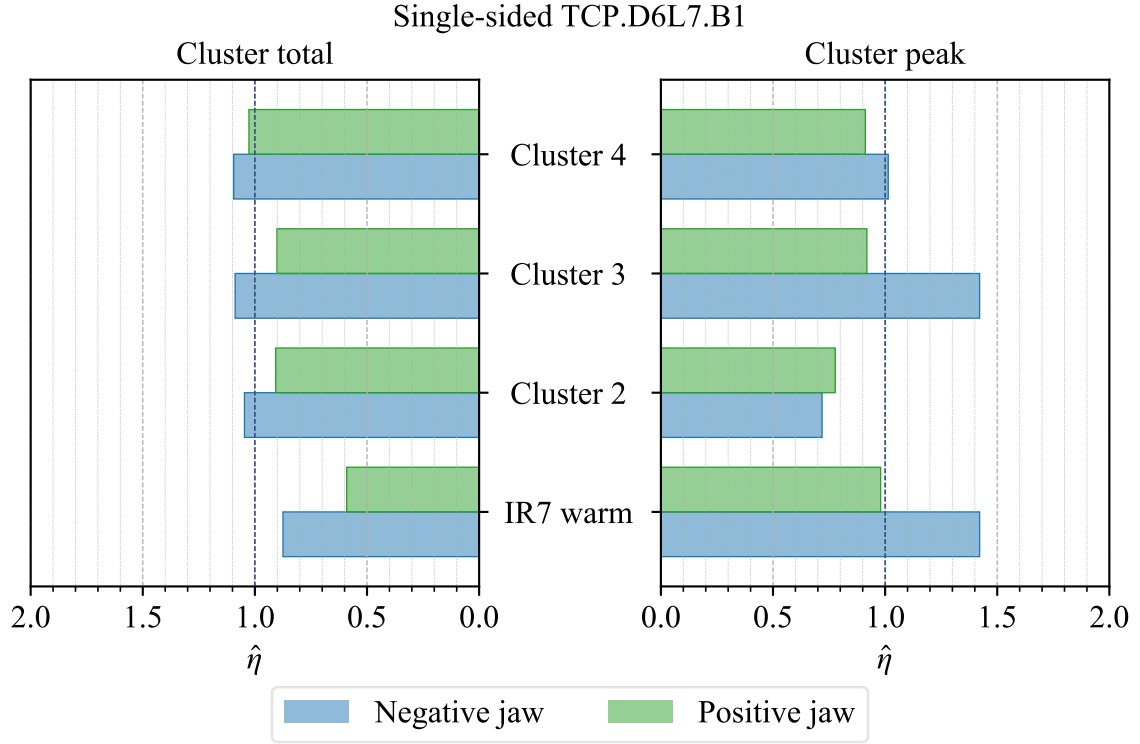


Figure 5.1: The cleaning performance for each jaw of the vertical primary collimator.

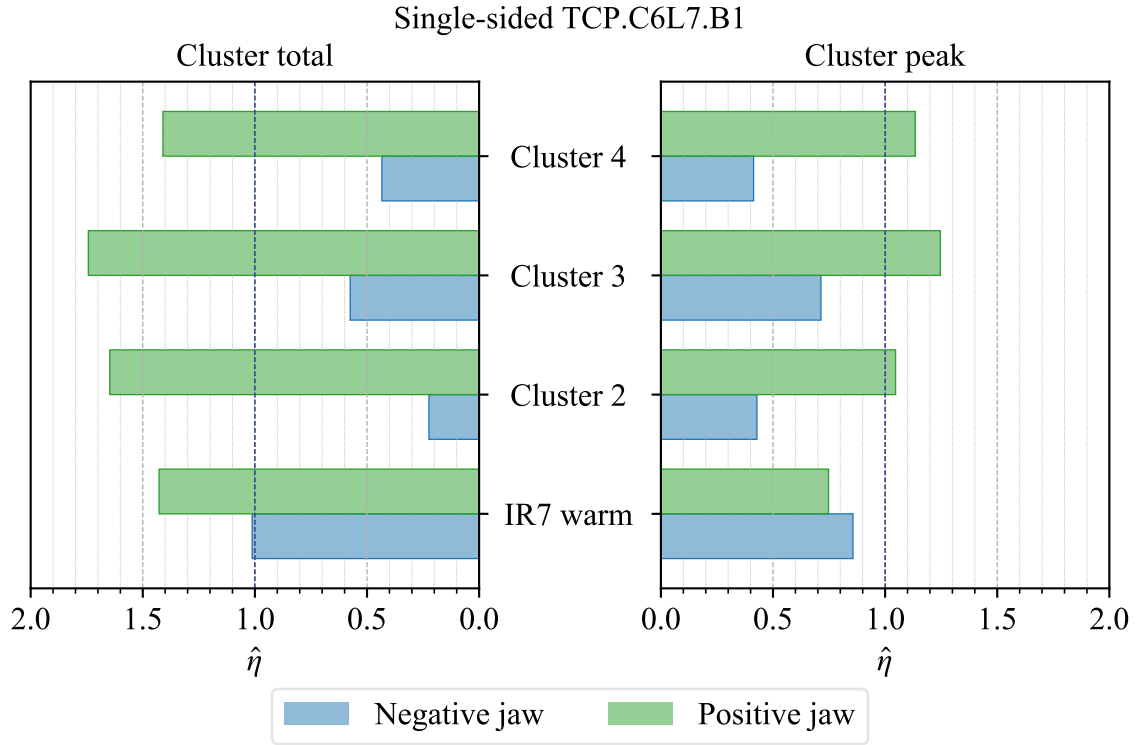


Figure 5.2: The cleaning performance for each jaw of the horizontal primary collimator.

$\hat{\eta} < 1$ suggests the contrary. An asymmetry in the cleaning performance of the two jaws is clearly visible in both collimators. While the difference is practically negligible in the case of the vertical collimator, it is quite significant for the horizontal collimator. The negative jaw of the horizontal collimator shows a remarkable improvement when by itself, whereas the positive jaw of the vertical collimator shows only a slight enhancement. Regardless, it is interesting to see that aperture losses can be reduced by merely retracting the appropriate jaws. In both cases, the two jaws appear to compensate for one another, such that their mean yields the performance of a dry run.

If the better performing jaws of the vertical and horizontal collimators are selected, then it is logical to pick the negative jaw of the skew collimator, in order to be able to intercept an orbit drift in the directions of the missing jaws. This setup, dubbed Configuration 1 (C1), keeps the beam enclosed by the primaries, whilst still retracting one jaw from each collimator, as illustrated in Fig. 5.3a. C2 is the complement of C1, and is the only other configuration of single-sided primaries which fully encloses the beam (Fig. 5.3b). The two configurations are listed in Tab. 5.1.

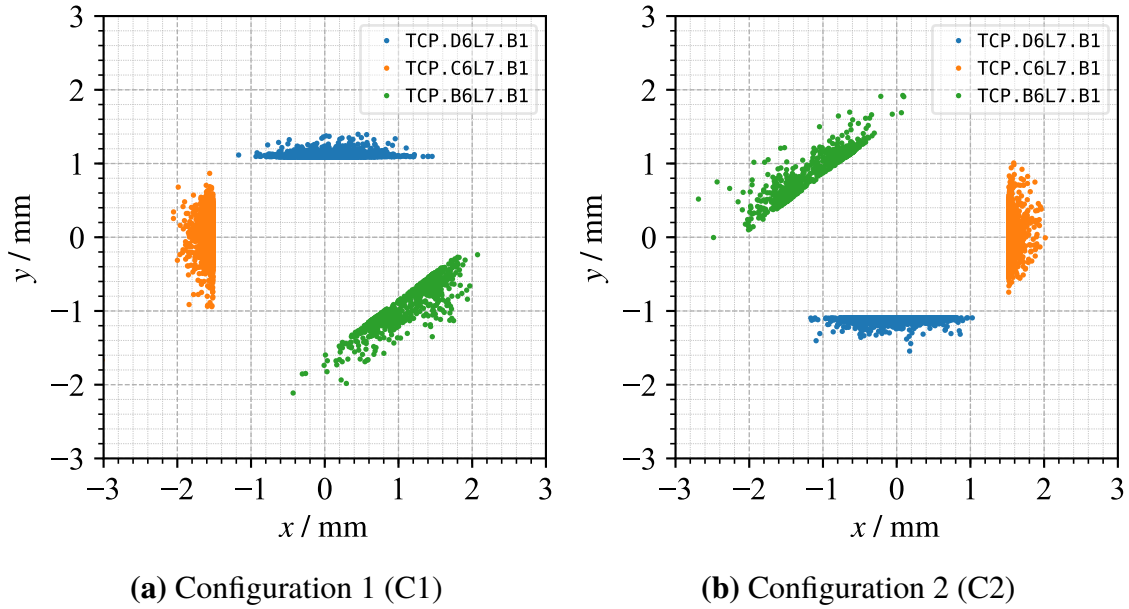


Figure 5.3: The two single-sided TCP configurations represented via particle impacts.

Table 5.1: The active jaws for the two single-sided TCP configurations.

Collimators	C1	C2	θ
TCP.D6L7.B1	Positive	Negative	90.0°
TCP.C6L7.B1	Negative	Positive	0.0°
TCP.B6L7.B1	Negative	Positive	126.9°

The previous results suggest that C1 would outperform C2, and this is corroborated in Figs. 5.4 and 5.5, which show the cleaning performance of the two configurations in B1H and B1V respectively. Once again, the results show a considerable variance in B1H, but

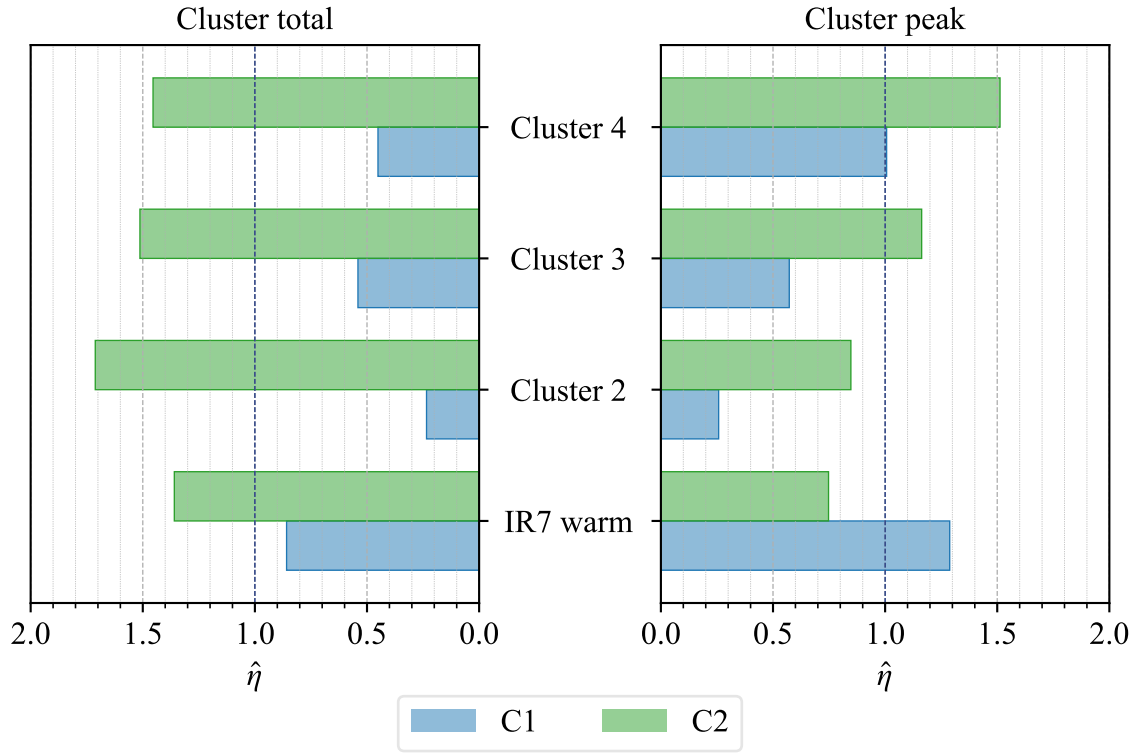


Figure 5.4: The cleaning performance of the two single-sided TCP configurations in B1H.

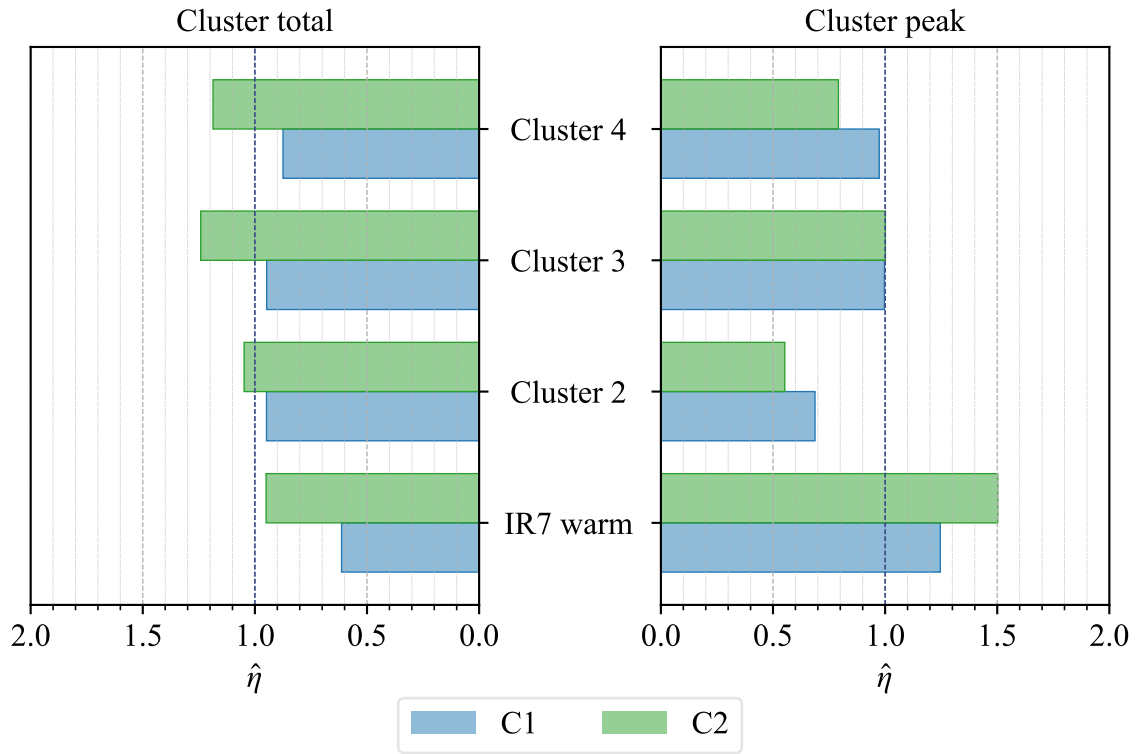


Figure 5.5: The cleaning performance of the two single-sided TCP configurations in B1V.

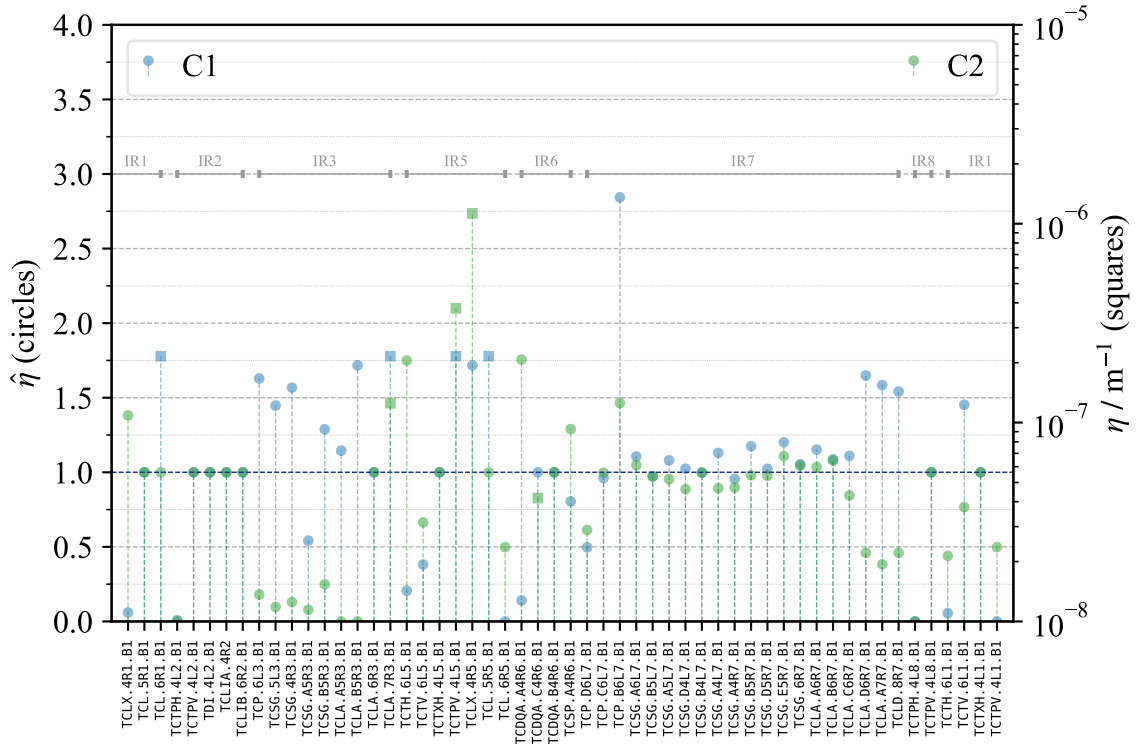


Figure 5.6: The distribution of collimator losses for the TCP configurations in B1H.

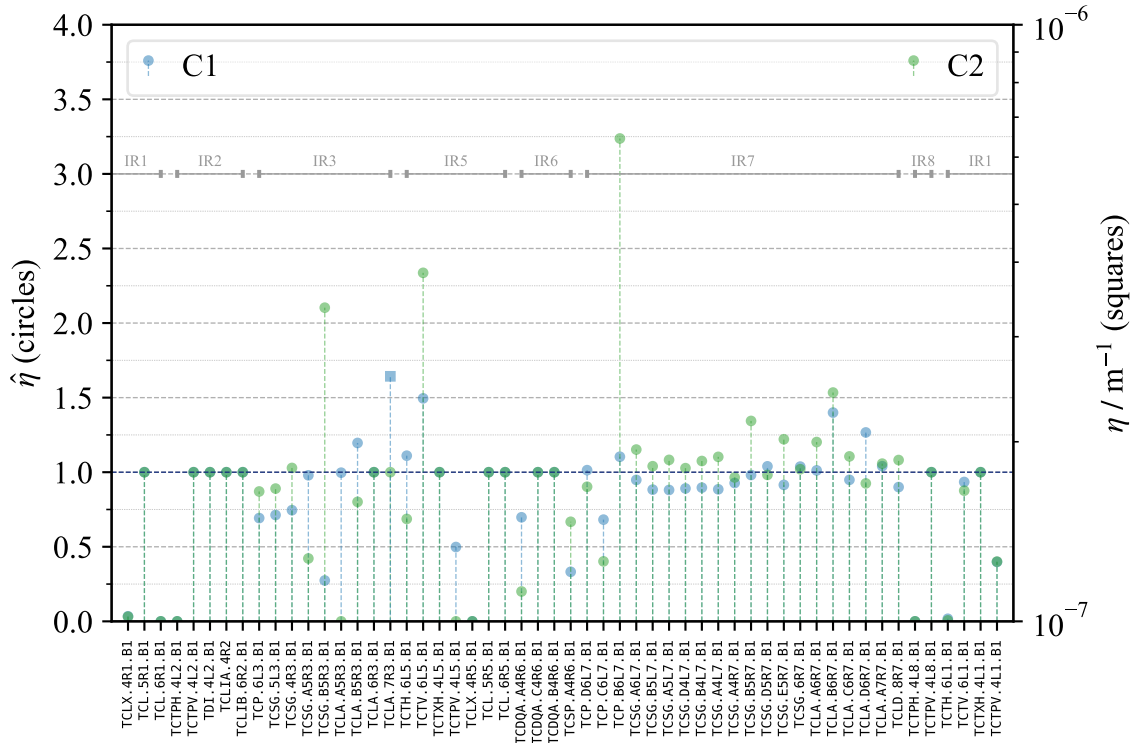


Figure 5.7: The distribution of collimator losses for the TCP configurations in B1V.

a marginal one in B1V. Any deviations from the previous results can be largely attributed to the fact that the skew collimator is now also single-sided.

Figs. 5.6 and 5.7 describe the change in the distribution of collimator losses for B1H and B1V respectively. The local cleaning inefficiency η is shown in lieu of values of $\hat{\eta} > 10$. B1V is largely unremarkable; however in B1H, C1 appears to increase losses in the TCP and TCSGs of IR3, as well as the TCLD of IR7 — all of which are of high statistical significance. C2 on the other hand, is seen to reduce losses in these collimators, hinting at an underlying connection. The skew primary collimator experiences an increase in load in either case, as the two upstream collimators now provide less cover.

The results have shown that C1 is the most viable single-sided configuration for the primary collimators, as it exhibits a general decrease in losses at the cold elements, even when compared to the standard settings. Although beam cleaning is actually improved, such a configuration may lead to hierarchy breakages, as particles that drift towards the vertices of the enclosed triangle (see Fig. 5.3a) would have a normalised amplitude that is larger than the cut of the secondary collimators.

The secondary collimators

The next step is to consider the secondary collimators, starting with the four highest contributors of impedance [41], which are listed here in order of longitudinal position:

1. TCSG.A6L7.B1
2. TCSG.B5L7.B1
3. TCSG.D4L7.B1
4. TCSG.B4L7.B1

C1 shall be incorporated by default, given that since single-sided secondaries are most effective when the primaries are also single-sided, as discussed in Section 2.5. One approach in obtaining such configurations is to observe the phase advance of secondary collimators relative to the primaries, as shown in Tab. 5.2. Two secondary collimators cover the same phase space if they are separated by a phase advance which is a multiple of 180° , provided that they have the same azimuthal angle.³ Therefore, one jaw can be retracted from each with little consequence, so long as the appropriate jaws are selected.

The table shows that TCSG.B5R7.B1 and TCSG.E5R7.B1 have a phase advance of approximately 180° from TCSG.A6L7.B1 in the horizontal plane, while also sharing roughly the same azimuthal angle. Unfortunately, no secondaries are separated by such a phase advance in the vertical plane; hence, this approach is not very useful in obtaining single-sided TCSG configurations. A different approach is to consider the load on each jaw of the secondary collimators, as shown in Figs. 5.8 and 5.9.⁴ However, it turns out that this approach does not yield the optimal configuration for minimising aperture losses.

³Recall that the two jaws of a collimator are separated by 180° in normalised phase space (Section 2.5).

⁴Similar plots have been generated for DRY and C2, and can be found in Appendix D.1 for reference.

Table 5.2: The phase advance of each collimator in IR7 relative to the primaries.

Collimator	θ	TCP.D6L7.B1 ($\theta = 90.0^\circ$)		TCP.C6L7.B1 ($\theta = 0.0^\circ$)		TCP.B6L7.B1 ($\theta = 126.9^\circ$)	
		μ_x	μ_y	μ_x	μ_y	μ_x	μ_y
TCSG.A6L7.B1	141.1°	32.9°	19.0°	32.2°	17.6°	31.4°	16.3°
TCSG.B5L7.B1	143.5°	108.8°	31.8°	108.1°	30.4°	107.3°	29.0°
TCSG.A5L7.B1	40.7°	110.1°	33.3°	109.4°	31.9°	108.6°	30.5°
TCSG.D4L7.B1	90.0°	114.9°	45.9°	114.2°	44.5°	113.4°	43.2°
TCSG.B4L7.B1	0.0°	131.6°	102.0°	130.8°	100.6°	130.0°	99.2°
TCSG.A4L7.B1	134.6°	133.3°	103.7°	132.5°	102.3°	131.8°	100.9°
TCSG.A4R7.B1	46.3°	135.1°	105.2°	134.4°	103.8°	133.6°	102.5°
TCSG.B5R7.B1	141.5°	216.2°	124.6°	215.5°	123.1°	214.7°	121.8°
TCSG.D5R7.B1	51.4°	221.9°	129.0°	221.1°	127.6°	220.4°	126.3°
TCSG.E5R7.B1	130.5°	222.9°	130.6°	222.1°	129.2°	221.4°	127.8°
TCSG.6R7.B1	0.5°	228.9°	160.1°	228.2°	158.7°	227.4°	157.4°
TCLA.A6R7.B1	90.0°	230.2°	168.6°	229.4°	167.2°	228.7°	165.9°
TCLA.B6R7.B1	0.0°	238.3°	199.2°	237.6°	197.8°	236.8°	196.4°
TCLA.C6R7.B1	90.0°	256.9°	217.2°	256.2°	215.8°	255.4°	214.4°
TCLA.D6R7.B1	0.0°	258.6°	217.9°	257.9°	216.5°	257.1°	215.2°
TCLA.A7R7.B1	0.0°	275.9°	224.1°	275.1°	222.6°	274.3°	221.3°
TCLD.8R7.B1	0.0°	318.2°	262.3°	317.5°	260.9°	316.7°	259.6°

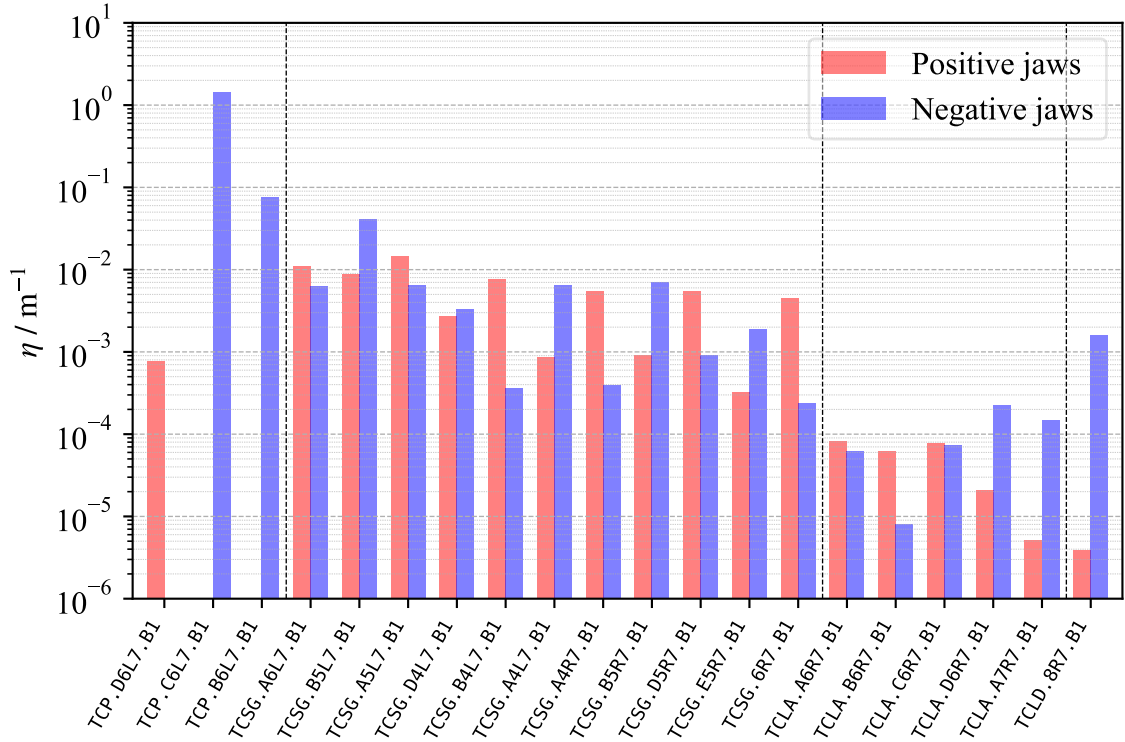


Figure 5.8: The load on each collimator jaw for C1 in B1H

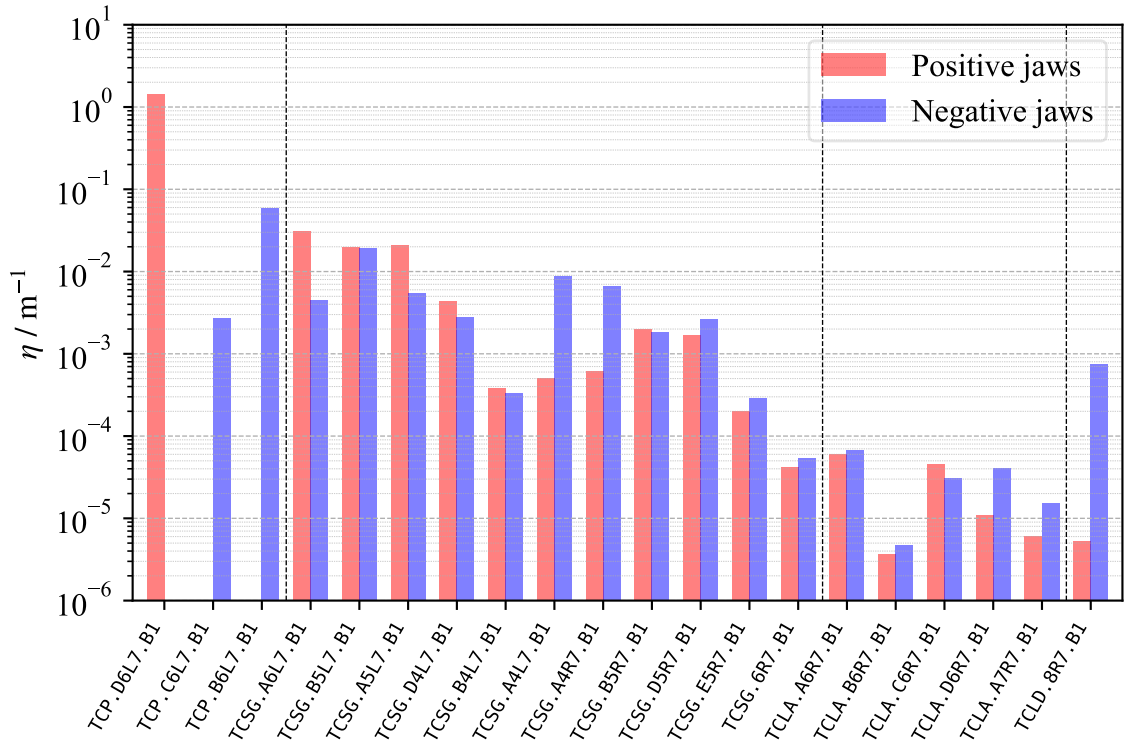


Figure 5.9: The load on each collimator jaw for C1 in B1V

Analysis of the dispersion in IR7 provides little to no insight on how to construct a configuration; hence, the last and most arduous course of action is to perform a scan of all possible combinations of jaws for the four aforementioned secondaries. Figs. 5.10 and 5.11 show the integrated cleaning inefficiency in the clusters, along with the peak value, for the combinations in B1H and B1V respectively. The former quantity describes the fraction of losses in the clusters in relation to the total losses. Each combination is delineated by the string “C1+” (symbolising the inclusion of C1), followed by four characters which denote the active jaw of each secondary in order of longitudinal position (as listed on page 56) — where “P” represents the positive jaw, and “N” represents the negative jaw. The configurations are sorted in terms of the integrated cleaning inefficiency.

In B1H it is clear that all the combinations perform almost identically in terms of integrated clusters. One might be inclined to point out that this is not the case for the peaks; however, the difference in peak values is well within the range of statistical fluctuations.⁵ Cluster losses are seen to be reduced by more than a factor of 2 when compared to the standard dry run, irrespective of the jaw combination.

The same cannot be stated for B1V, where only a few configurations appear to perform better than a dry run. Given these results, B1V determines that the most practical configurations are the ones in which the positive jaw is selected for both TCSG.B5L7.B1 and TCSG.D4L7.B1. On the other hand, TCSG.A6L7.B1 and TCSG.B4L7.B1 appear to be largely inconsequential. The latter is a horizontal collimator, thus explaining its trivial role in the vertical plane. The former is the very first secondary collimator in IR7; therefore, it is possible that downstream collimators intercept particles which may happen to escape it, thus compensating for its performance.

Both figures show that C1 is amongst the top performing secondary configurations, implying that beam cleaning cannot be improved upon as with the primary collimators, and that any minor improvements seen are the product of statistical fluctuations. The figures also show that selecting jaws based on their load is not a viable way of constructing single-sided configurations.

One would expect dispersion to play an integral role in explaining the phenomena observed in the two planes. It is known that losses in the DS are the result of protons interacting with the primary collimators and experiencing an energy loss in the order of 1 % to 3 %. These particles are then pushed via dispersion (see Section 1.3.4) towards the aperture, forming the cold DS clusters. Since examining the dispersion directly is rather unavailing, one could instead consider the trajectories of particles that form these clusters, as their paths are greatly influenced by dispersion. As it turns out, this approach accounts for not only the differences in the two planes, but also the cleaning performance of the selected jaws.

Figs. 5.12 and 5.13 show the trajectories of particles that accumulate in the second cluster for a standard dry run.⁶ Also shown are the collimator gaps as measured along the given axis, where collimators are denoted by a numeric ID transcribed in Appendix B.1. B1H exhibits two distinct paths — one for each jaw of the horizontal primary collimator. The downwards drift seen towards the end of the paths is characteristic of the dispersion that exists in the horizontal plane. It is rather striking that the two paths are so dissimilar in

⁵A detailed calculation of statistical errors was not possible in the time available.

⁶The second cluster was selected as it is the most prominent; however, the analysis is also relevant to the other clusters, as the trajectories of all cluster particles are similar in IR7.

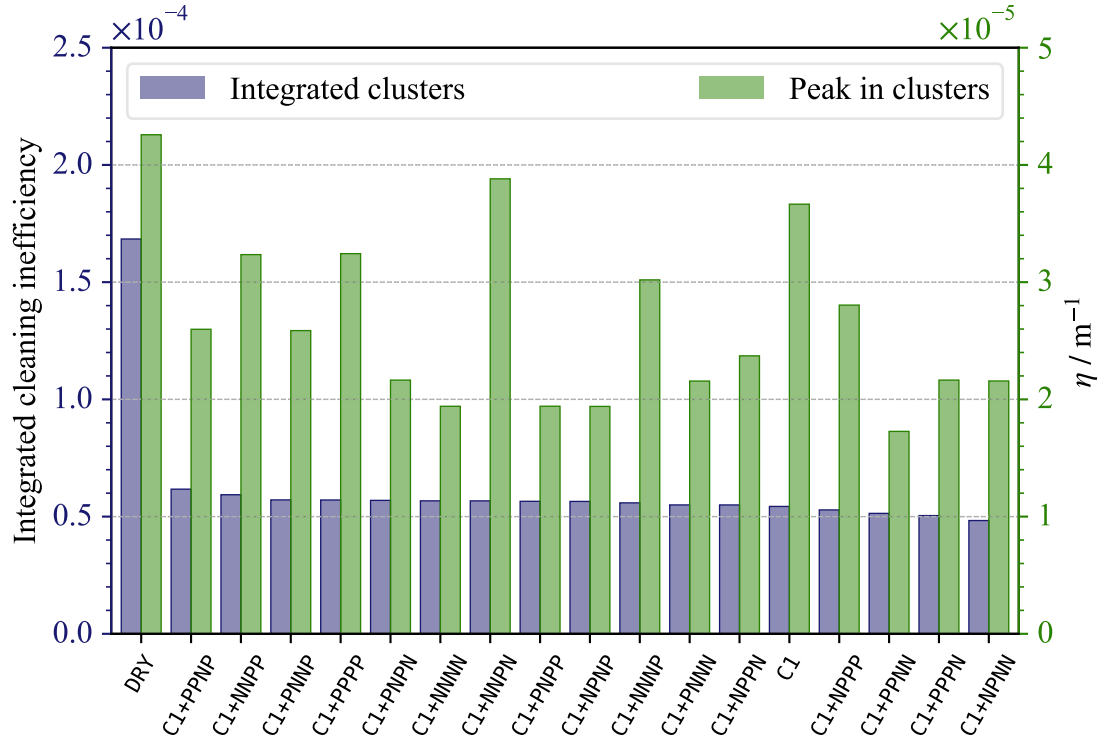


Figure 5.10: Performance scan in B1H of single-sided high-impedance secondaries.

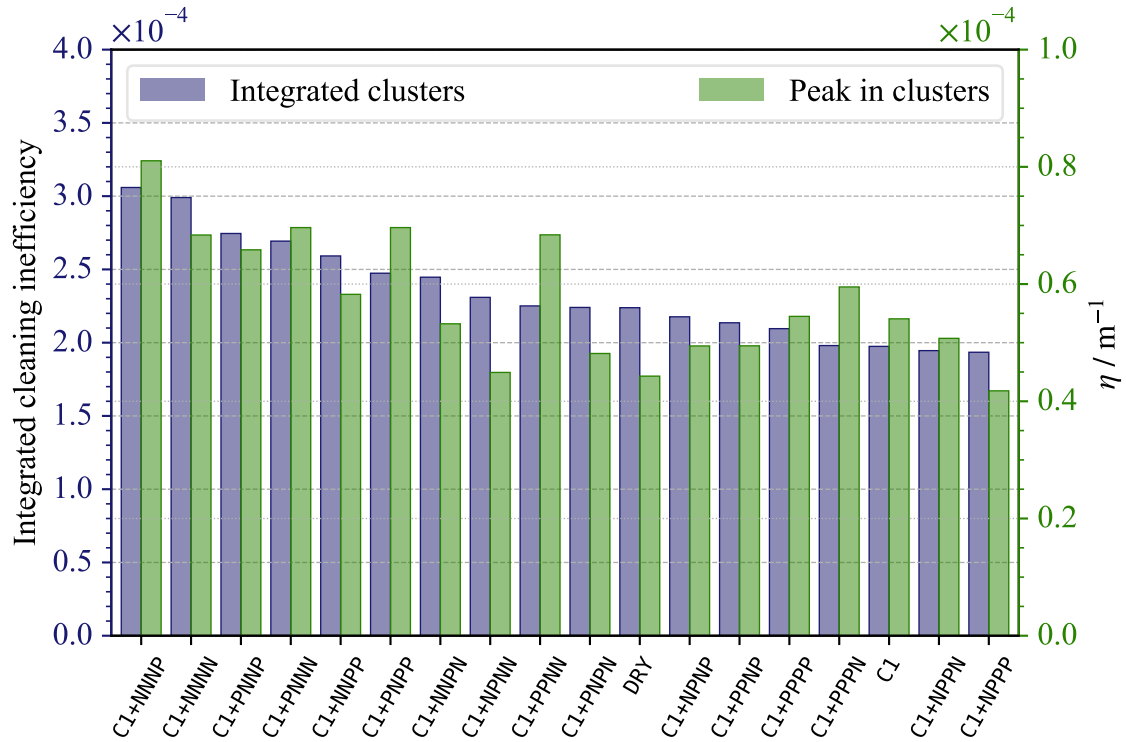


Figure 5.11: Performance scan in B1V of single-sided high-impedance secondaries.

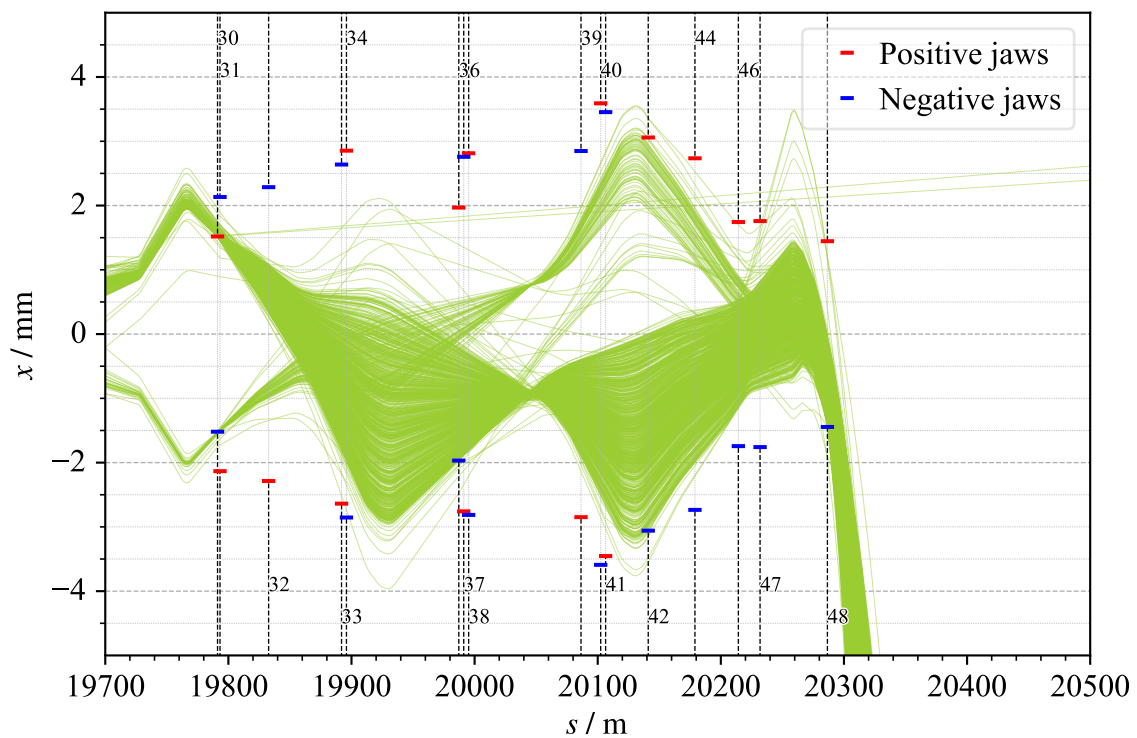


Figure 5.12: The paths of particles that accumulate in the second cluster for B1H.

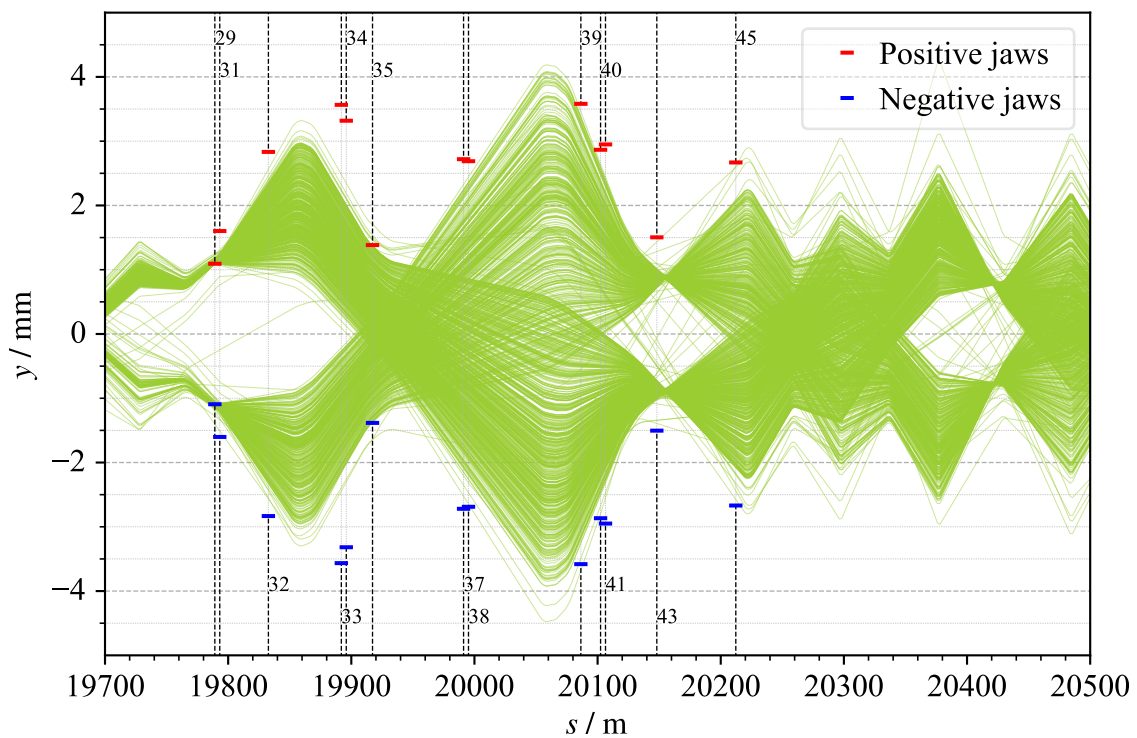


Figure 5.13: The paths of particles that accumulate in the second cluster for B1V.

form, as one would expect to observe some level of symmetry. In any case, this asymmetry depicts a narrower path for the negative jaw of the horizontal primary, resulting in far fewer cluster losses — an outcome consistent with previous observations.

There is no ambiguity in the case of B1V, as the paths generated by the two jaws of the vertical primary collimator are fully symmetric, due to the absence of dispersion in the vertical plane.⁷ By considering the path emanating from the positive jaw in relation to the four high-impedance secondary collimators (IDs: 32, 33, 35, and 36), it is possible to discern a pattern in which the jaws closest to the path are also those that best preserve beam cleaning, according to the combination scan. Conversely, combinations of jaws that are distant from the path perform significantly worse. This is with the exception of collimator 32, where both jaws perform similarly, perhaps due to the collimator being the very first secondary.⁸ If this pattern is indeed valid, then it can be used to construct single-sided configurations that utilise more than just the four high-impedance secondaries. Although the pattern's validity may seem obvious, it is difficult to know a priori which jaws would generate new cluster pathways when retracted.

Particles intercepted by a primary collimator will undergo a change in energy, as well as a deflection angle. Cluster pathways are characterised by a very narrow range of values of these two quantities. Given that the two jaws of a collimator behave identically in theory, it is rather odd that the paths in B1H are so asymmetric, even when accounting for dispersion. The range of values for the two paths in B1H are shown in Figs. 5.14 and 5.15, where the energy change δ_E and deflection angle $\Delta x'$ are given by;

$$\delta_E = \frac{\Delta E}{E_0} = \frac{E - E_0}{E_0}, \quad (5.1)$$

$$\Delta x' = x' - x'_0, \quad (5.2)$$

where E is the energy of the particle at the exit of the collimator jaw, E_0 is the energy of the reference particle, x' is the angle immediately after the collimator, and x'_0 is the theoretical angle at the collimator (see Fig. 1.5). Although the figures actually show the distributions of C1 and C2, almost all particles in B1H are intercepted by the horizontal primary; thus, C1 corresponds to the negative jaw and C2 corresponds to the positive jaw. Also shown are the range of values for the two pathways leading to the third cluster. The histograms are normalised to the total number of losses in the machine.

When considering the data of the second cluster, one can deduce that both paths comprise of approximately the same range of values of δ_E , however the distribution within the range is different for each path. The path emanating from the negative jaw (C1) tends to contain particles that have undergone a smaller energy change, whilst the path of the positive jaw (C2) appears to have a more broad distribution in δ_E . Similarly, the distribution in $\Delta x'$ of the positive jaw is seen to be broader than that of the negative jaw. However, in this case they do not share the same range of values, as the distribution generated by the negative jaw is skewed towards exclusively negative deflection angles.

The difference in the distribution of δ_E raises the question as to why larger energy changes are less common for the path emanating from the negative jaw. Such particles are either lost in the collimators before reaching the cluster, or survive both the collimators

⁷The paths extend beyond the position of the second cluster as the aperture is not considered at runtime.

⁸Note that the negative jaw is present in both the best and worst performing combinations. Hence, it is not clear which jaw actually performs better.

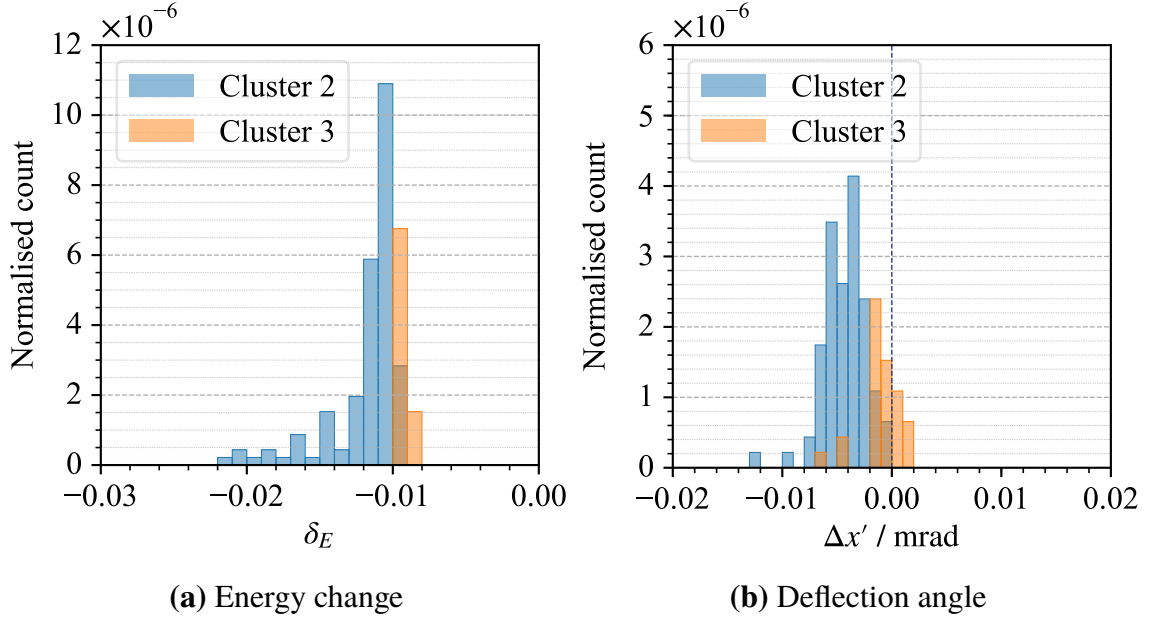


Figure 5.14: Normalised histograms of cluster particles generated by C1 in B1H.

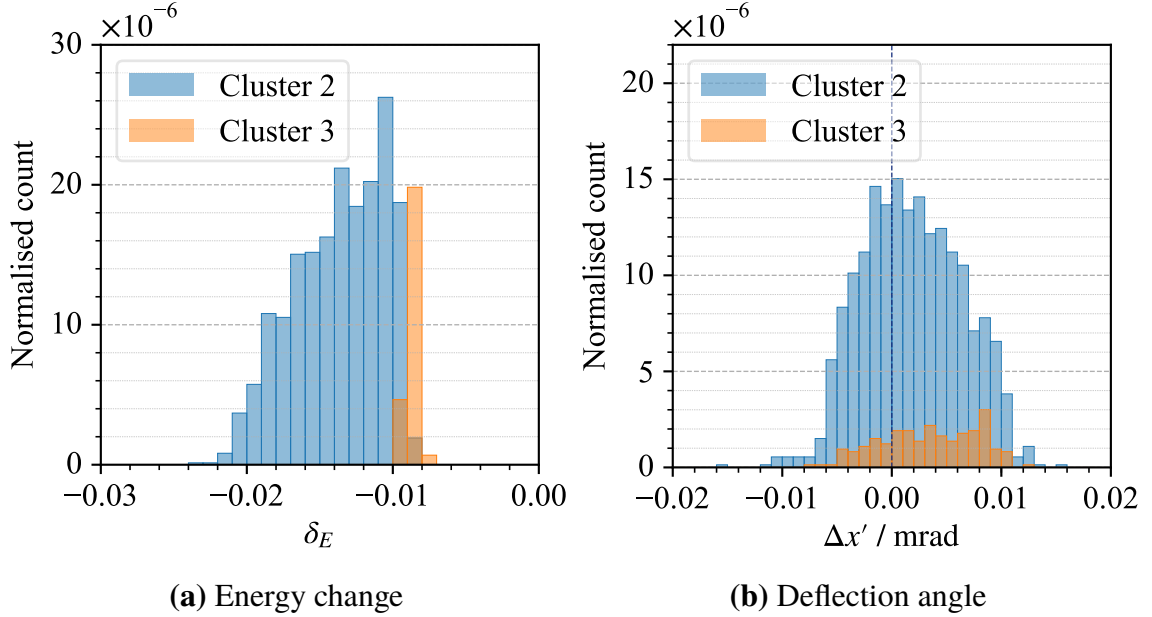


Figure 5.15: Normalised histograms of cluster particles generated by C2 in B1H.

and the DS entirely. To answer this question, one can track the trajectories of particles with $\delta_E \in [-0.022, -0.008]$ as they traverse IR7. This is shown in Fig. 5.16, where particles are differentiated based on their location of loss.

A symmetry is thus revealed, showing that the particles missing from the negative jaw's path are actually intercepted by collimator 48, which is TCLD.8R7.B1 (see Appendix B.1). In this range of δ_E , the TCLD captures far more particles coming from the negative jaw than from the positive. This is because dispersion increases rapidly in the region between collimators 47 and 48, and since particles emanating from the negative jaw are moving

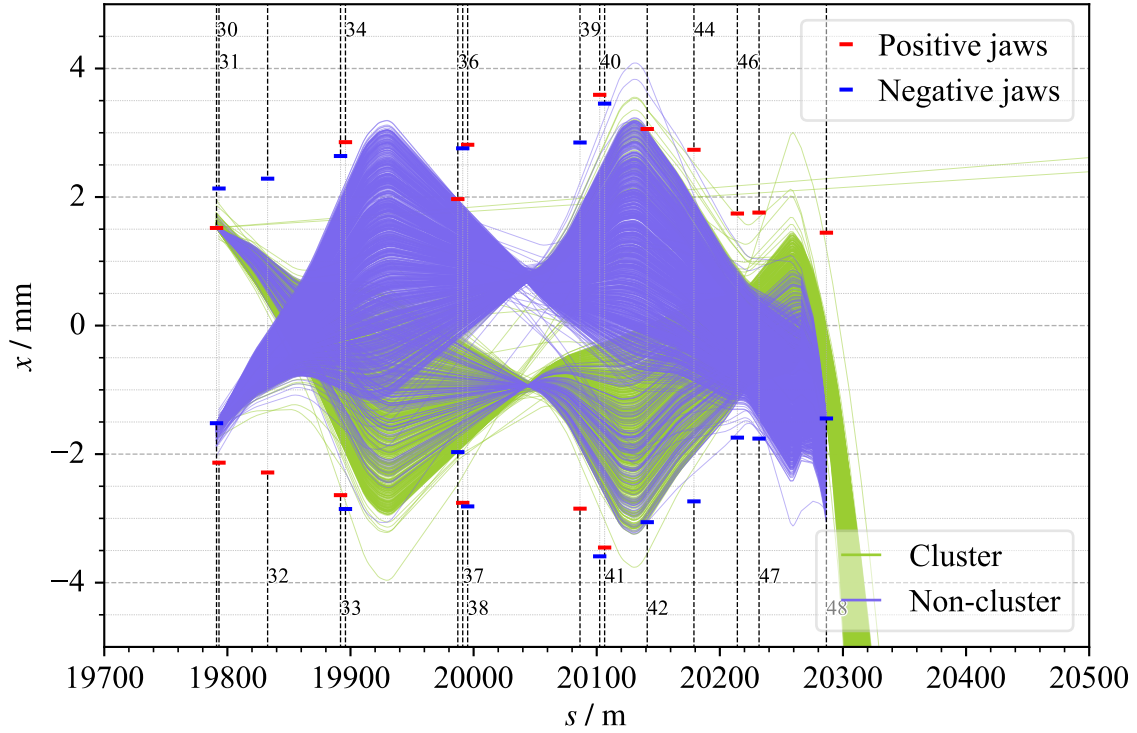


Figure 5.16: The trajectories of particles with $\delta_E \in [-0.022, -0.008]$ in B1H. Particles with a large deviation in angle were ignored as they would otherwise drown out the data.

towards the eventual push of dispersion in this region, they are far more likely to be intercepted by the final collimator. On the other hand, the path emanating from the positive jaw is directed against the push of dispersion, thus particles are given a greater chance of escaping the collimator.

Figs. 5.17 and 5.18 show the distribution of losses for C1 and C2 in terms of δ_E . The plots clearly suggest that particles escaping the clusters are predominantly lost in either the TCLD or IR3. These results are corroborated by those shown in Fig. 5.6, where the TCLD and the collimators of IR3 experience an increase in load in the case of C1, but a decrease in the case of C2. For C1, the increase in load in IR3 is speculated to come from the reduced losses in the fourth cluster — which consists of particles with δ_E values smaller in magnitude than those of the second and third clusters.

Ultimately, these results account for the differences observed in the two planes. In the case of B1H, the combination of secondary jaws is largely irrelevant as the TCLD will capture most particles on paths leading towards the clusters, due to the additional push provided by the horizontal dispersion. On the other hand, the combination of secondary jaws must be selected with care for B1V, such as to not widen cluster pathways. As discussed previously, a multi-secondary configuration can be constructed by observing cluster pathways and retracting the jaws that are furthest from the paths.⁹ In this case, one need only consider the path of C1 in B1V, as the arrangement of jaws is expected to be irrelevant for B1H. A jaw from each secondary collimator will be retracted in order to test

⁹Perhaps a more rigorous approach would be to study the load on jaws for particles within the appropriate ranges of δ_E and $\Delta x'$, and retract the least loaded jaws.

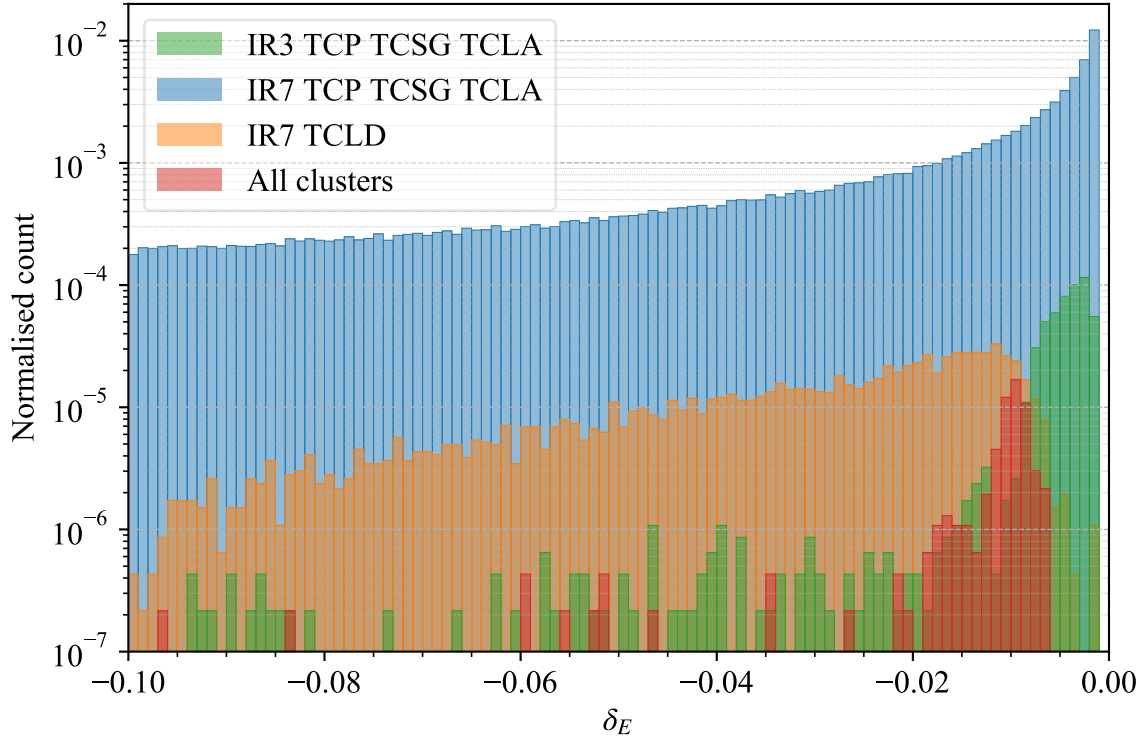


Figure 5.17: The distribution of losses in terms of δ_E for C1 in B1H.

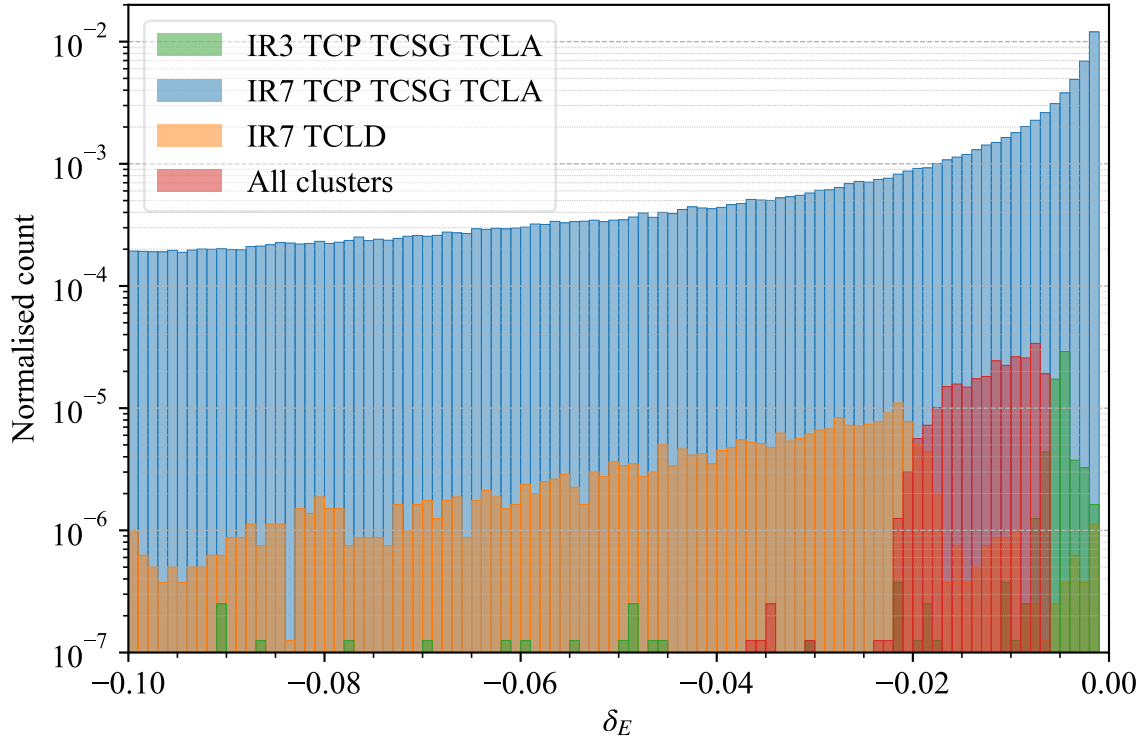


Figure 5.18: The distribution of losses in terms of δ_E for C2 in B1H.

the absolute limits of this approach. Even if this is not a viable configuration in the end, one can always choose to keep certain collimators within the configuration symmetric.

Table 5.3: The selection of jaws for the multi-secondary configuration C1+MHB1.

ID	Name	Active jaw	θ	g / mm
29	TCP.D6L7.B1	Positive	90.0°	1.0928
30	TCP.C6L7.B1	Negative	0.0°	1.5189
31	TCP.B6L7.B1	Negative	126.9°	1.2810
32	TCSG.A6L7.B1	Positive	141.1°	1.7789
33	TCSG.B5L7.B1	Positive	143.5°	2.1207
34	TCSG.A5L7.B1	Positive	40.7°	2.1637
35	TCSG.D4L7.B1	Positive	90.0°	1.3834
36	TCSG.B4L7.B1	Positive	0.0°	1.9684
37	TCSG.A4L7.B1	Negative	134.6°	1.9366
38	TCSG.A4R7.B1	Negative	46.3°	1.9437
39	TCSG.B5R7.B1	Negative	141.5°	2.2292
40	TCSG.D5R7.B1	Negative	51.4°	2.2400
41	TCSG.E5R7.B1	Negative	130.5°	2.2429
42	TCSG.6R7.B1	Positive	0.5°	3.0586

Tab. 5.3 lists the active jaws of the ultimate configuration, dubbed C1+MHB1. The jaws were selected by observing the path emanating from the positive jaw in Fig. 5.13. For the horizontal secondaries, the more loaded jaw was selected (see Fig. 5.8), given that the collimators are not visible in the plot. Figs. 5.19 and 5.20 show the cleaning performance of C1+MHB1 in comparison to previous configurations, while Figs. 5.21 and 5.22 illustrate the change in the distribution of collimator losses, with the subconfiguration C1+PPPP added for reference.

Although cluster losses are seen to increase in B1H, they are still lower than those produced by the standard collimator settings. In B1V, the cleaning performance is almost identical to that of a dry run, and the peak values are comparable in both planes. These results are encouraging when considering that all the primary and secondary collimators in IR7 are single-sided. Indeed, simulations which maintained both jaws of collimators such as TCSG.A5L7.B1 and TCSG.B5R7.B1 exhibited even further improvement in terms of beam cleaning.

There appears to be an erratic change in the distribution of collimator losses for both planes. Besides the expected upsurge in IR3 and the TCLD in B1H, several other collimators also undergo an increase in load. Strangely, the vertical primary collimator and a TCLA in IR7 experience a significant rise in losses, along with a couple of collimators in IR6, and a handful of tertiary collimators — one of which (TCTV.6L1.B1) sustains a load

of more than 200 times the usual value. B1V sees similar results with some differences in the distribution and load.

In conclusion, the proposed single-sided configurations for B1 of HL-LHC, are those which are a subset of C1+MHB1 — such as C1+PPPP, which should prove to be a good balance between impedance reduction and beam cleaning preservation. It should be noted that retracting the positive jaw from TCSG.A6L7.B1 increases warm losses by more than a factor of 8 in IR7. The significance of this needs to be examined further with FLUKA [42], as particle showers are generally of more concern than warm aperture losses. The extraordinary rise in TCT losses also warrants further study.

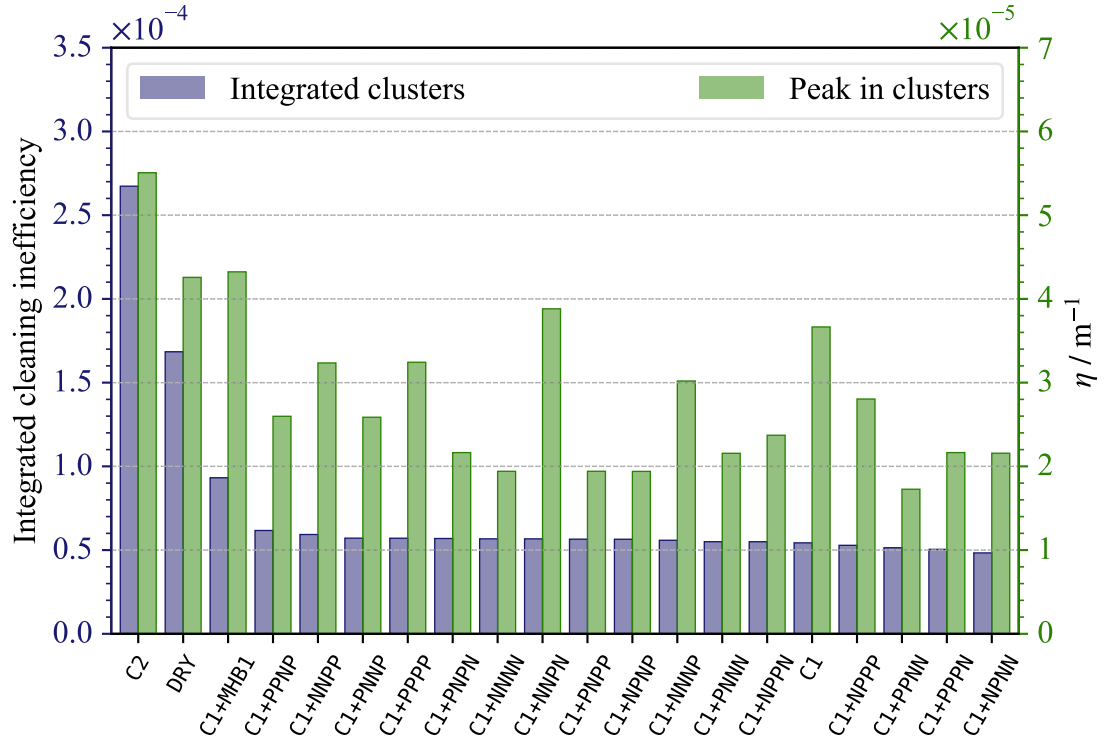


Figure 5.19: The cleaning performance of C1+MHB1 in B1H.

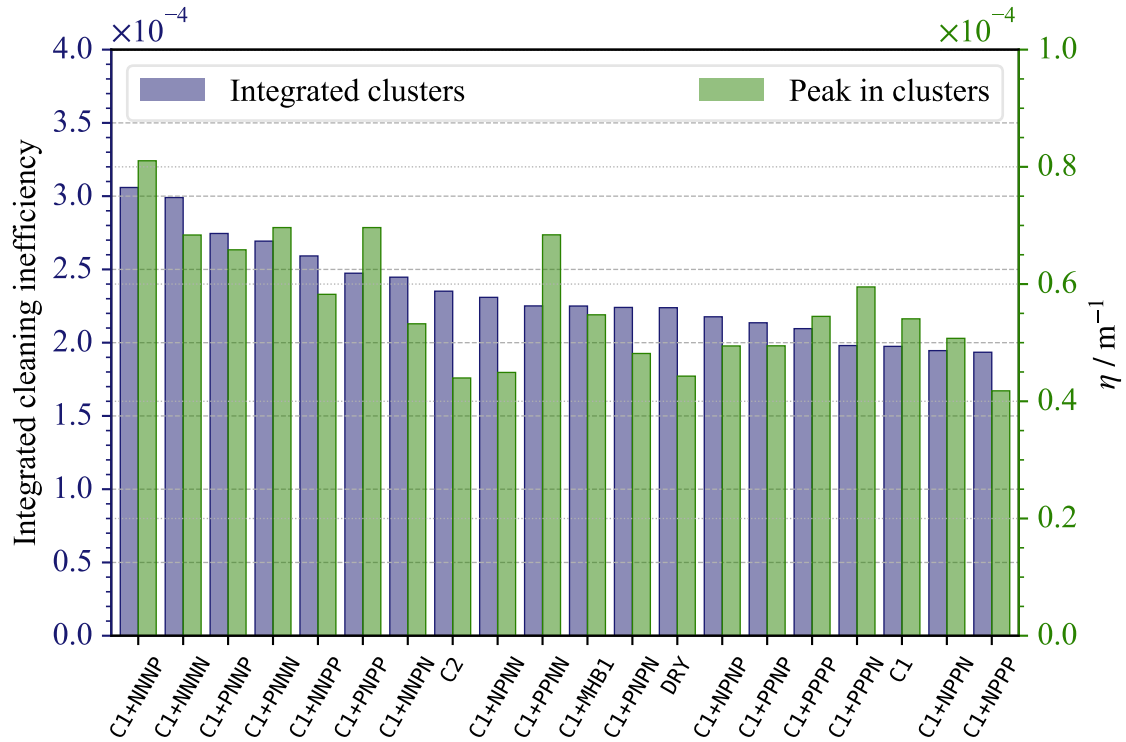


Figure 5.20: The cleaning performance of C1+MHB1 in B1V.

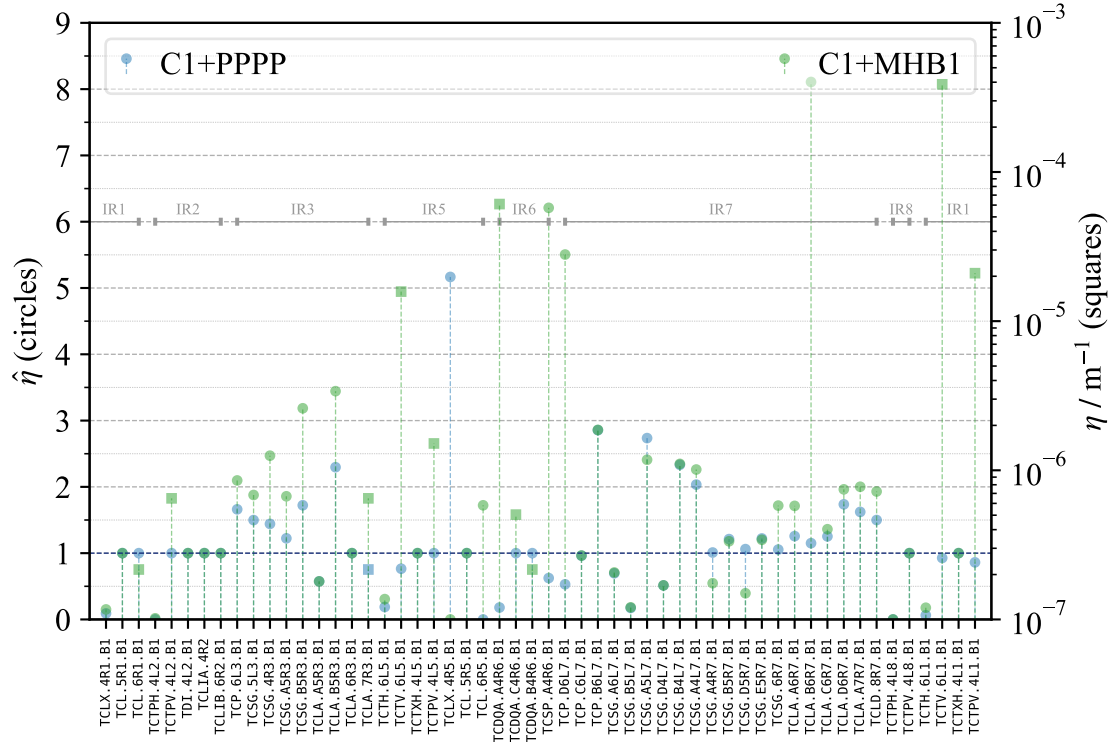


Figure 5.21: The relative distribution of collimator losses for C1+MHB1 in B1H.

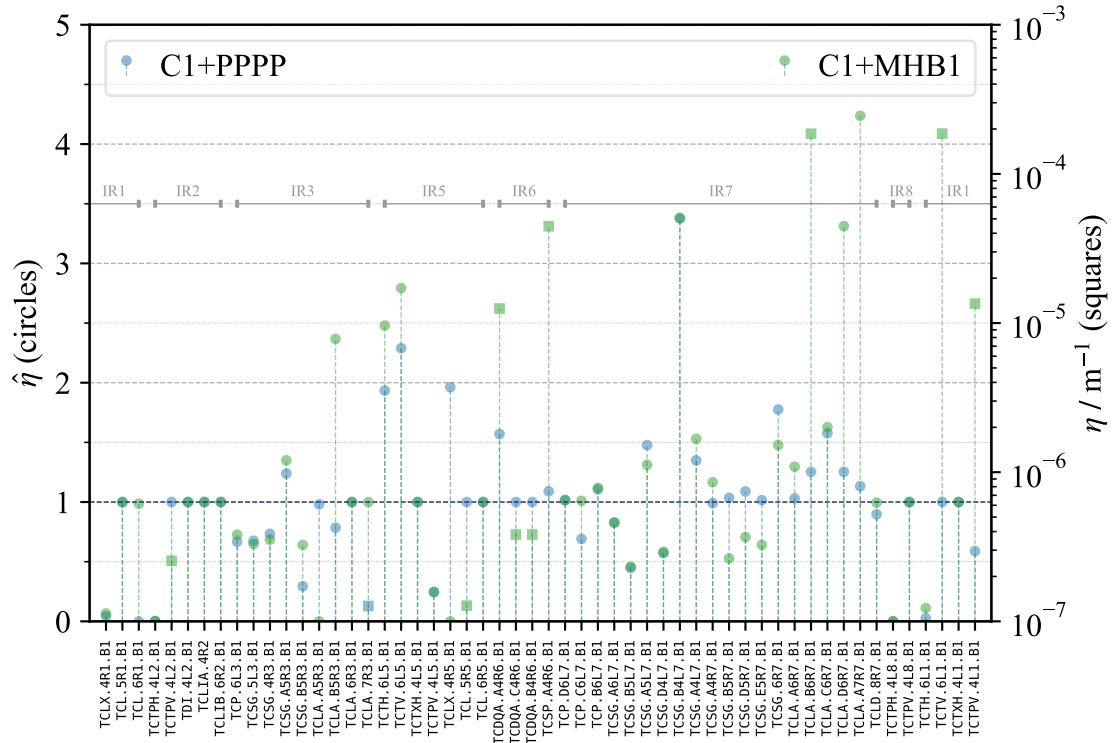


Figure 5.22: The relative distribution of collimator losses for C1+MHB1 in B1V.

5.1.2 Beam 2

Although the two beams are similar in many ways, the effect of dispersion is unique to each beam. Fig. 5.23 shows the single-pass dispersion superimposed on a *dry* loss map in both beams. The single-pass dispersion is the dispersion function when starting at a given element with flat initial conditions — where in this case, the starting element is the horizontal primary collimator. MADX is able to compute the optics of the machine by setting the initial twiss parameter values to those found at the collimator.

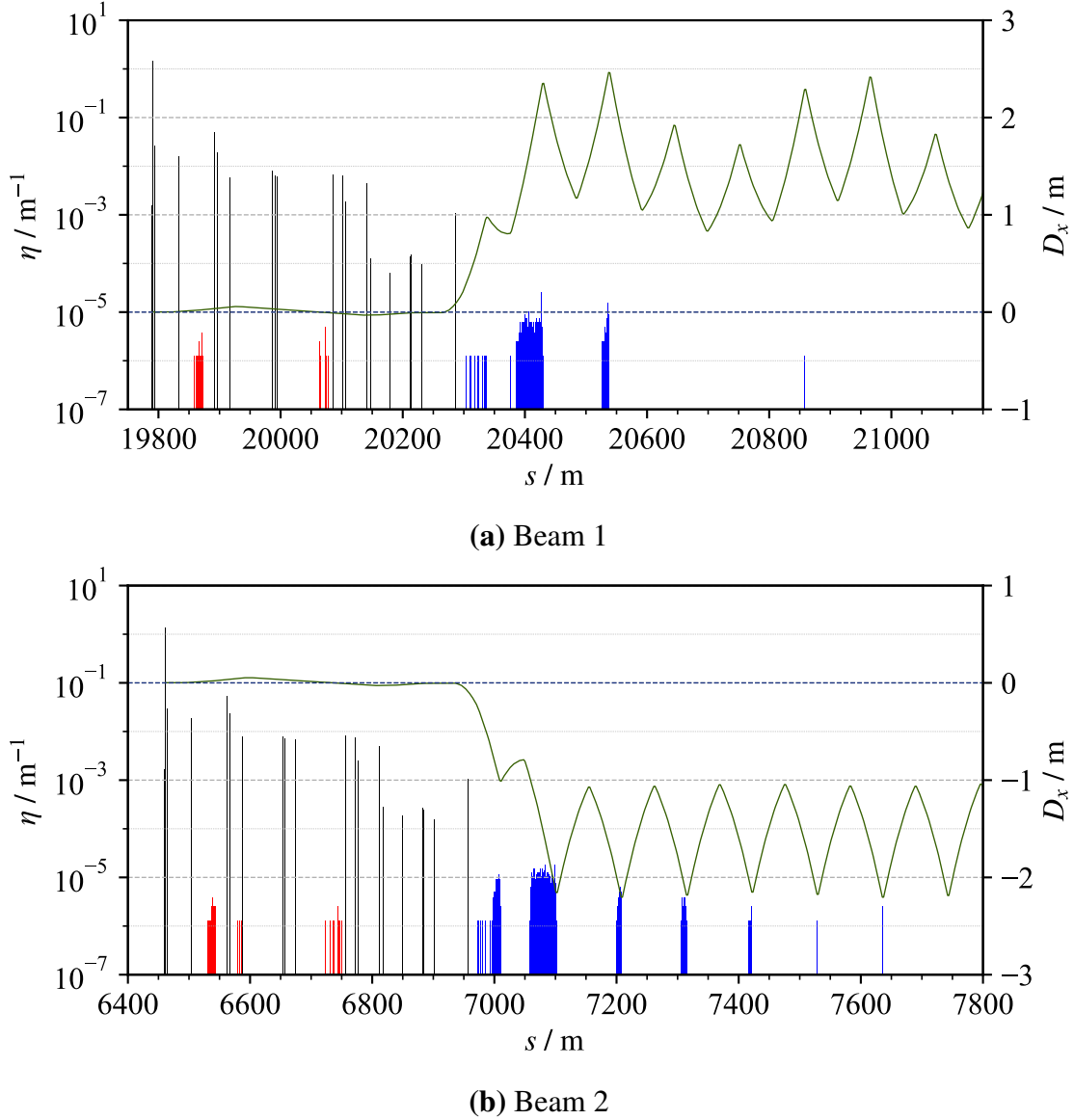


Figure 5.23: The single-pass dispersion as from the horizontal primary collimator.

The figures clearly demonstrate that the sign of dispersion in the DS is contingent on the beam — where it is positive for B1, but negative for B2.¹⁰ This entails that dispersion will push particles towards the positive x -direction in B2H, as illustrated by Fig. 5.24.

¹⁰It was previously shown that lower energy particles are overbent in the arc. Hence, given the coordinate system (see Fig. 1.4), it follows that the two beams would have an opposite sign in dispersion.

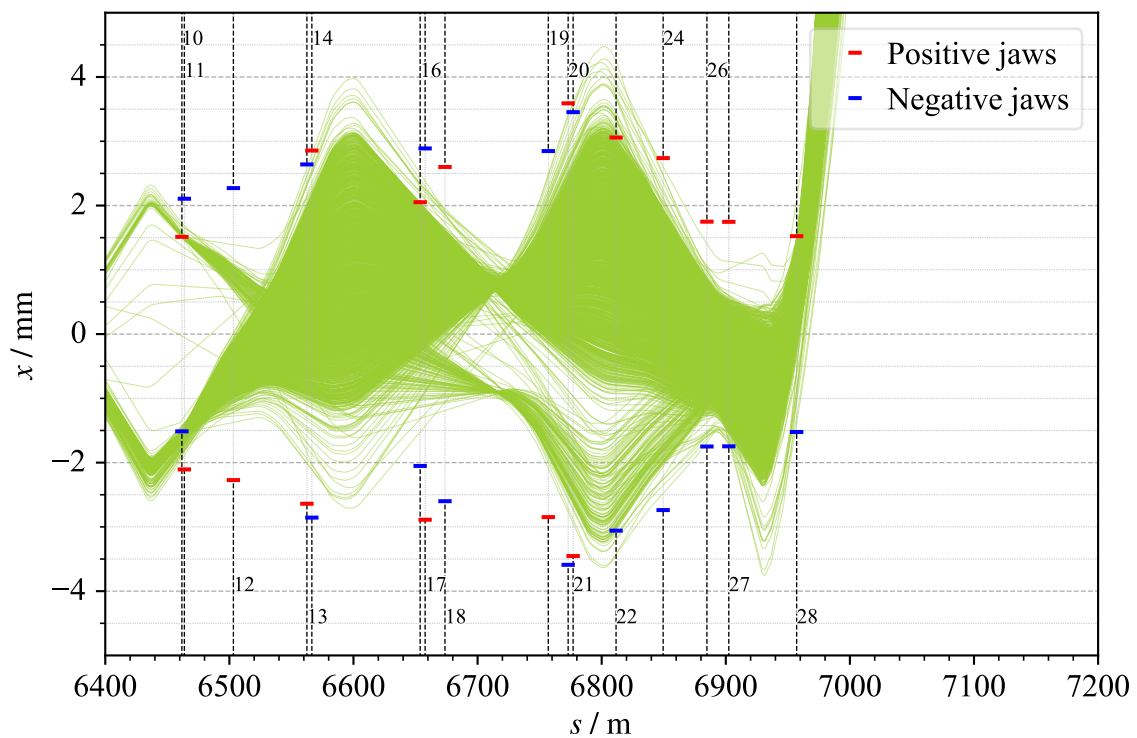


Figure 5.24: The particle pathways leading to the second cluster in B2H.

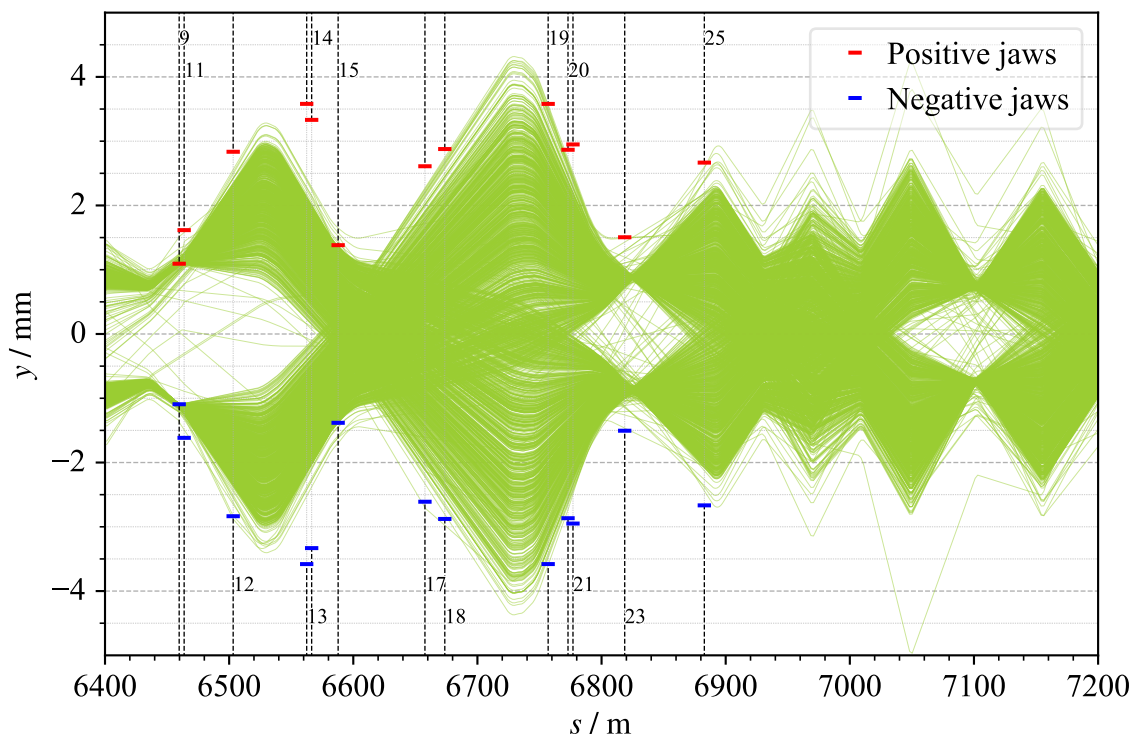


Figure 5.25: The particle pathways leading to the second cluster in B2V.

Indeed, it appears as if the cluster pathways in B2H are merely a mirror image of those seen in B1H. On the other hand, the cluster pathways in B2V are almost identical to those of B1V, as dispersion is similarly zero in the vertical plane.

Given these results, the behaviour of a particular configuration in B2 is expected to be similar to that of the opposite configuration in B1. For instance, if C1 outperforms C2 in B1, then the reverse is true for B2. Thus, one need only focus on the more prominent configurations of B1, namely C1, C2, C1+PPPP, and C1+MHB1. The B2 equivalent of these configurations would be C2, C1, C2+NNNN, and C2+MHB2 respectively, where the latter is given by Tab. 5.4.

Table 5.4: The selection of jaws for the multi-secondary configuration C2+MHB2.

ID	Name	Active jaw	θ	g / mm
9	TCP.D6R7.B2	Negative	90.0°	1.0932
10	TCP.C6R7.B2	Positive	0.0°	1.5131
11	TCP.B6R7.B2	Positive	127.5°	1.2820
12	TCSG.A6R7.B2	Negative	141.3°	1.7727
13	TCSG.B5R7.B2	Negative	143.6°	2.1247
14	TCSG.A5R7.B2	Negative	40.6°	2.1681
15	TCSG.D4R7.B2	Negative	90.0°	1.3820
16	TCSG.B4R7.B2	Negative	0.0°	2.0521
17	TCSG.A4R7.B2	Positive	132.1°	1.9365
18	TCSG.A4L7.B2	Positive	42.1°	1.9293
19	TCSG.B5L7.B2	Positive	141.5°	2.2286
20	TCSG.D5L7.B2	Positive	51.4°	2.2400
21	TCSG.E5L7.B2	Positive	130.5°	2.2427
22	TCSG.6L7.B2	Negative	0.5°	3.0582

Figs. 5.26 and 5.27 describe the cleaning performance of the configurations in B2, while Figs. 5.28 and 5.29 show the change in the distribution of collimator losses. The figures confirm expectations by showing that the behaviour of C1 and C2 is inverted for B2H. Moreover, the multi-secondary configurations appear to perform remarkably well — exhibiting major improvement in B2H, and negligible variance in B2V. The distributions of collimator losses appear to be similar to those of the equivalent configurations in B1. Thus, the same conclusions can ultimately be drawn for B2 as for B1.

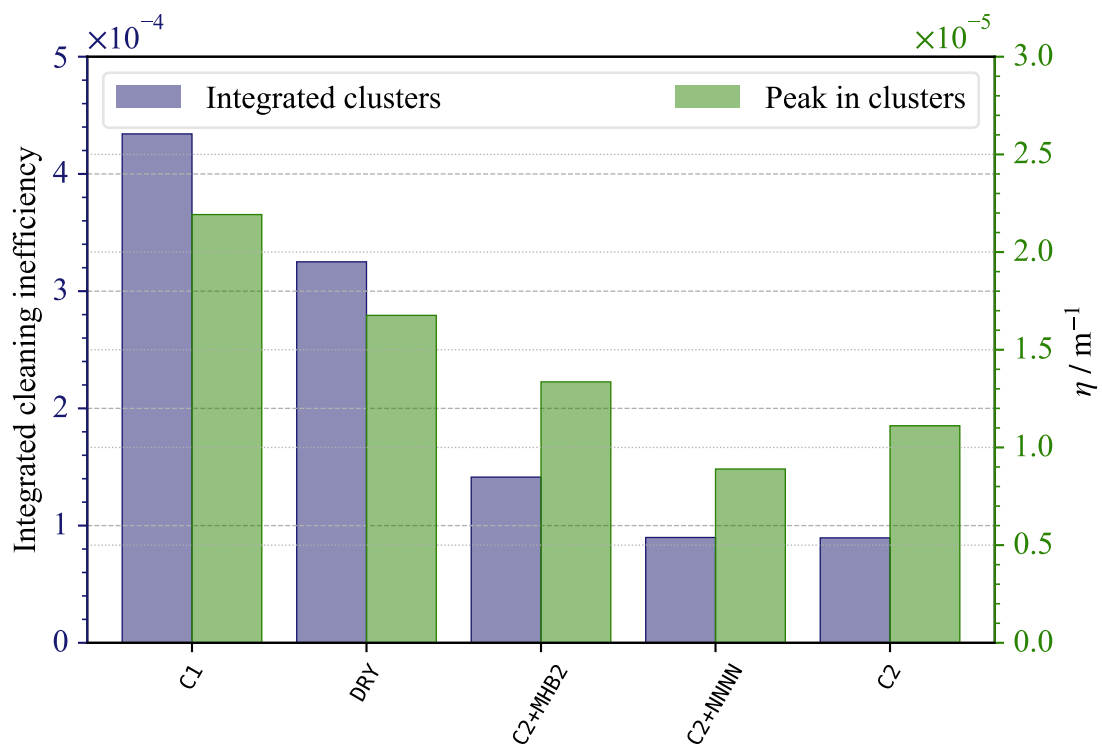


Figure 5.26: The cleaning performance of configurations in B2H.

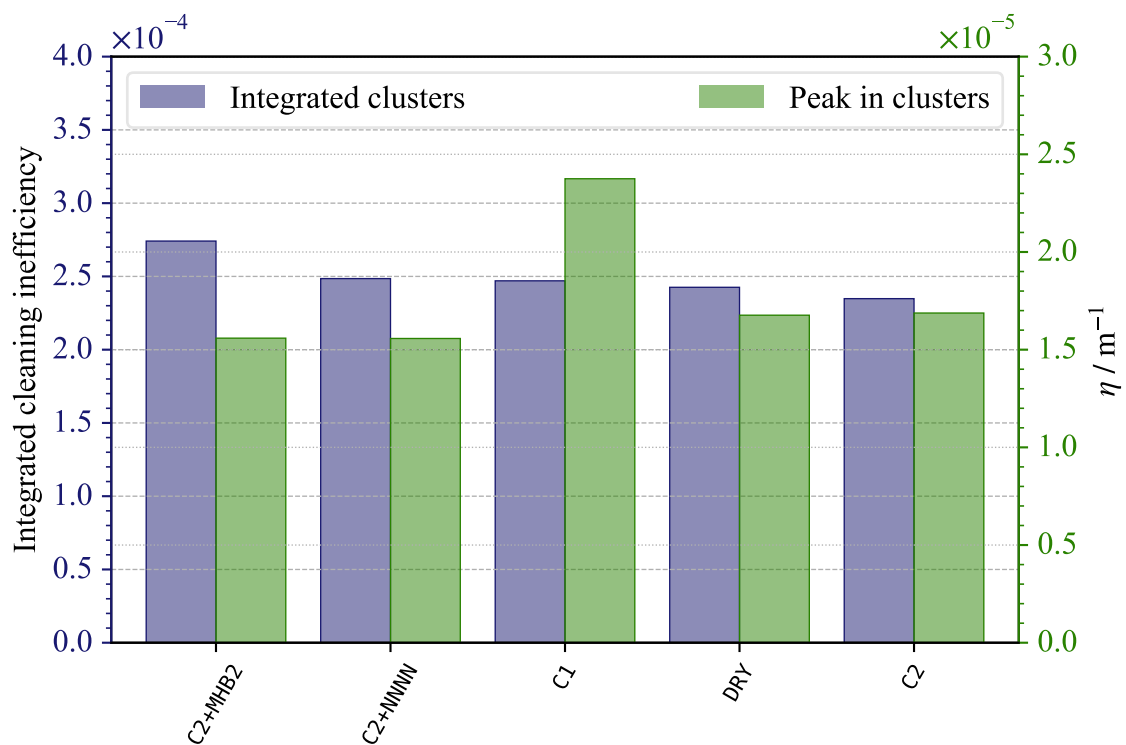


Figure 5.27: The cleaning performance of configurations in B2V.

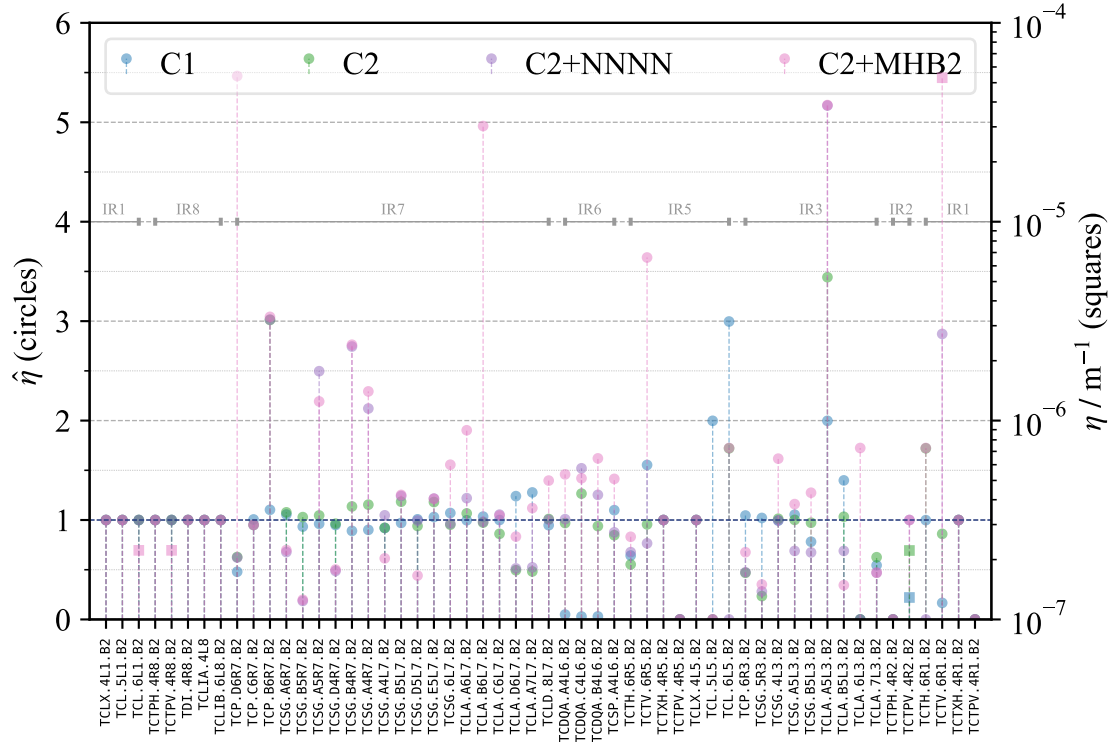


Figure 5.28: The distribution of collimator losses for configurations in B2H.

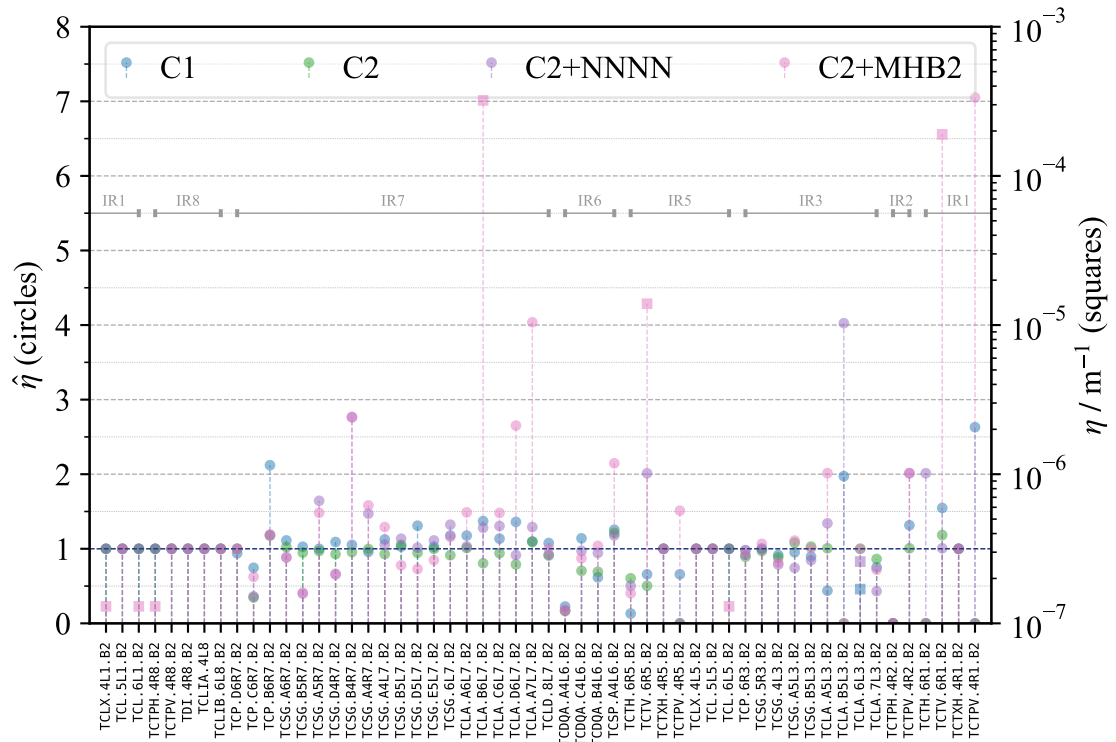


Figure 5.29: The distribution of collimator losses for configurations in B2V.

5.2 Impedance simulations

5.2.1 The case of a single collimator

The horizontal primary collimator was (arbitrarily) selected for this analysis, and IW2D was used to compute the wall impedance generated at FT conditions. Each jaw is composed of a MoGr layer that is 25 mm thick, and the outermost surrounding layer is a vacuum of infinite thickness. The full set of simulation parameters can be found in the input file presented in Appendix A.3. Note that IW2D assumes that the defined layers are horizontal; hence, the vertical axis is always the cleaning plane. Fig. 5.30 graphs the multipolar wall impedance as a function of frequency for when the collimator is symmetric and single-sided. For the single-sided case, the impedance is identical regardless of which jaw is retracted.

The longitudinal component of the impedance appears to be identical for both configurations. This is unlike the transverse components, where the impedance is reduced at all frequencies for the single-sided case; the exception being Z_x^{quad} , which exhibits a negative impedance, implying that the beam is being focused. Upon closer inspection one may notice that Z_x^{dip} and Z_x^{quad} perfectly cancel out. This is because of translational symmetry in the horizontal plane, stemming from the fact that there are no boundaries. An interesting property of single-sided collimation, when compared to the alternatives for impedance reduction, is that impedance is reduced uniformly across all frequencies — a phenomenon not typically observed when upgrading the jaw composition.

The effects of impedance on the beam can be summarised through a condensed quantity known as the *effective impedance* [22]. The effective impedance Z_{eff} is calculated using Sacherer's formula, detailed in [43]. In order to obtain a more complete picture, the quantity is computed at various positions of the retracted jaw, starting from the symmetric configuration and moving towards increasingly asymmetric settings, all while keeping the active jaw in its usual position. The parameters listed in Appendix A.4 shall henceforth be used to evaluate impedance-related quantities (such as effective impedance and tune shift), unless otherwise stated.

The results are shown in Fig. 5.31, where d is the displacement of the retracted jaw relative to the beam orbit. In each subfigure, the right vertical axis depicts the effective impedance normalised to the leftmost data point — corresponding to the conventional symmetric settings. The imaginary part of Z_{eff} is taken as it leads to an observable, real-valued tune shift. Interestingly, the longitudinal component does indeed vary with jaw displacement, though it ultimately converges to the same value as the symmetric case. A global minimum can be seen at approximately 3 mm; however, the drop in impedance is rather minute, especially when compared to the potential gain in the transverse planes. For this reason, the longitudinal component shall be largely neglected moving forward.

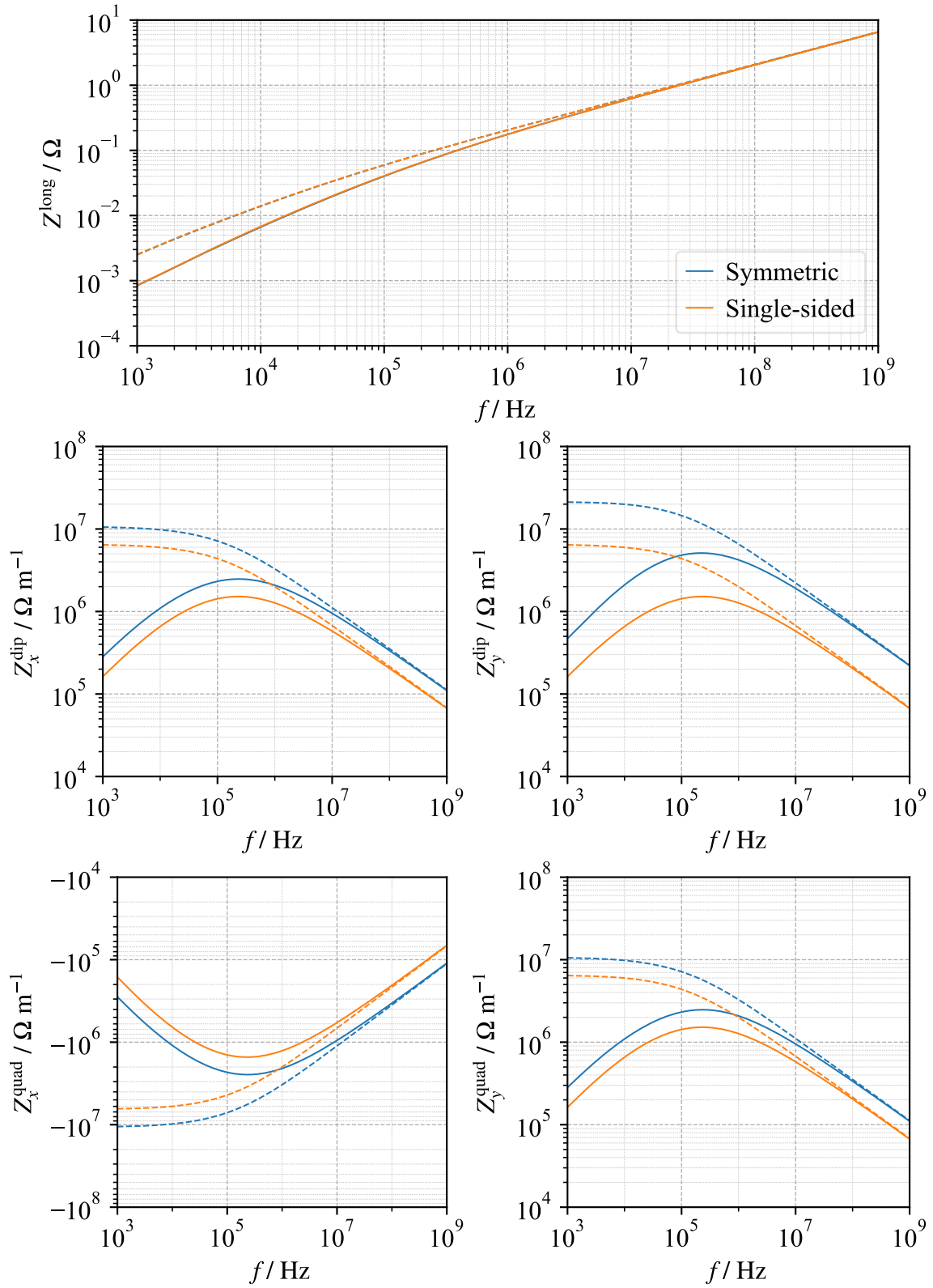
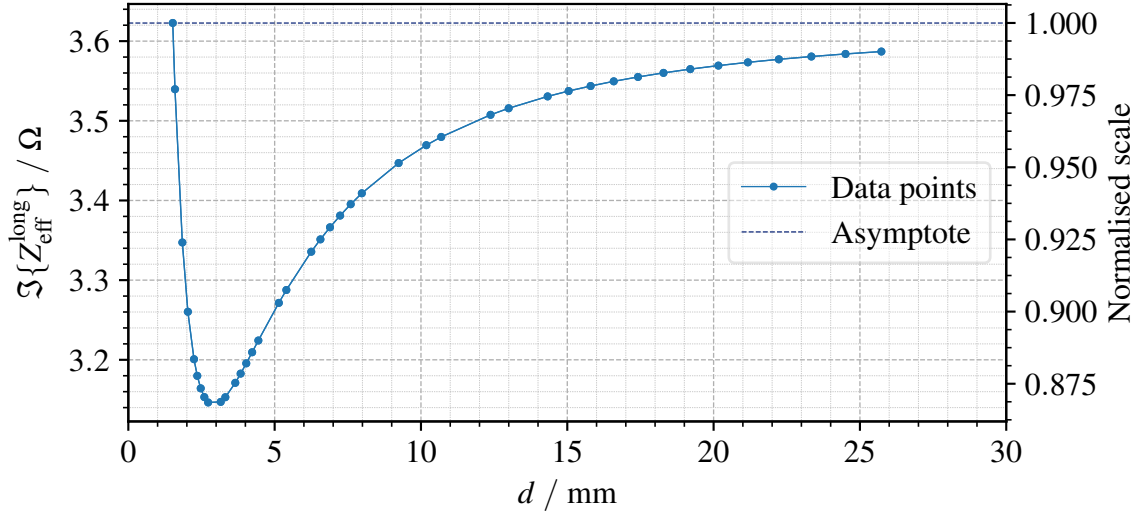
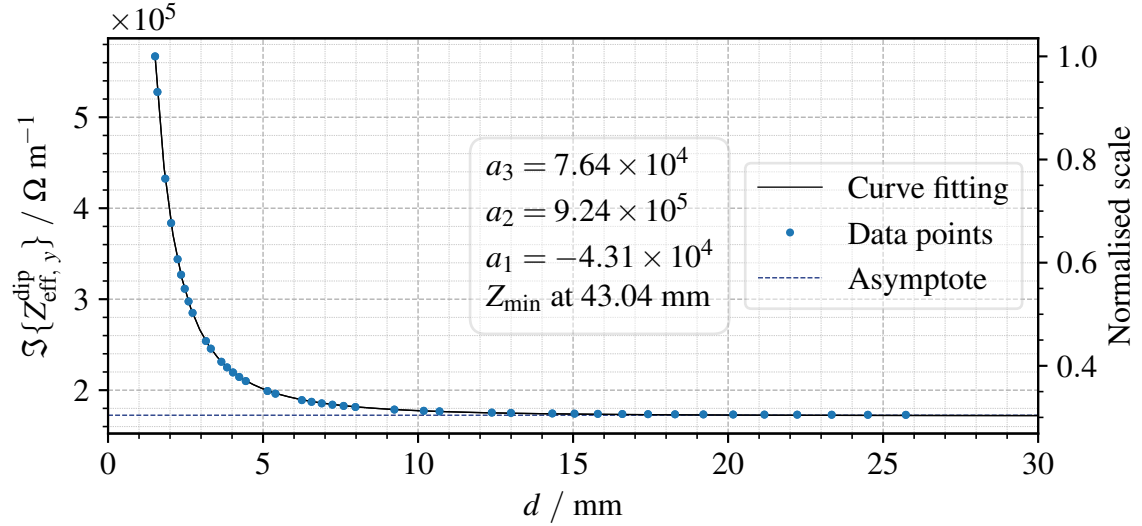


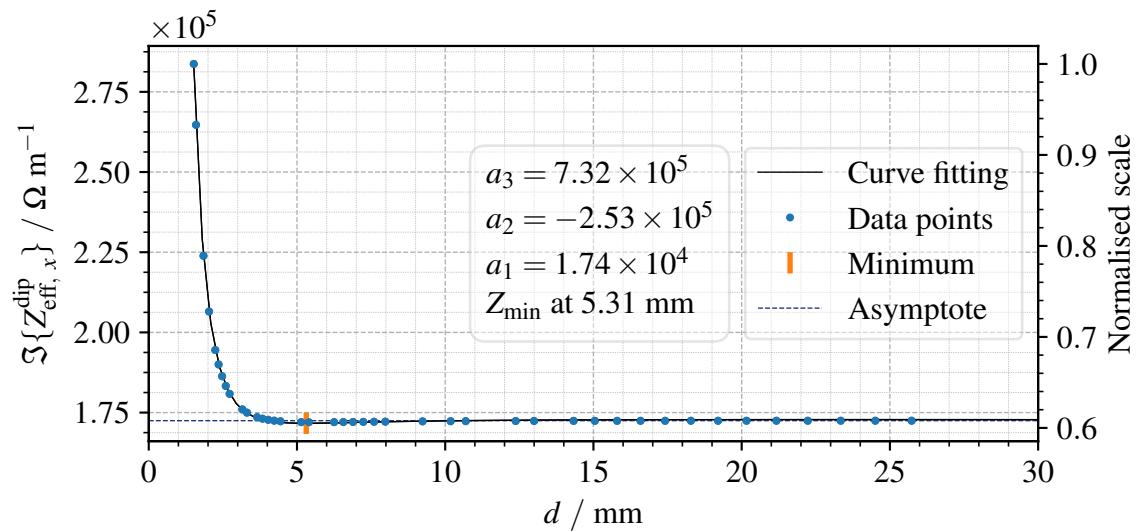
Figure 5.30: The real (continuous) and imaginary (dashed) parts of the multipolar wall impedance generated by the horizontal primary collimator at FT. Note that the collimator is oriented vertically in simulation, hence the dominant y-component.



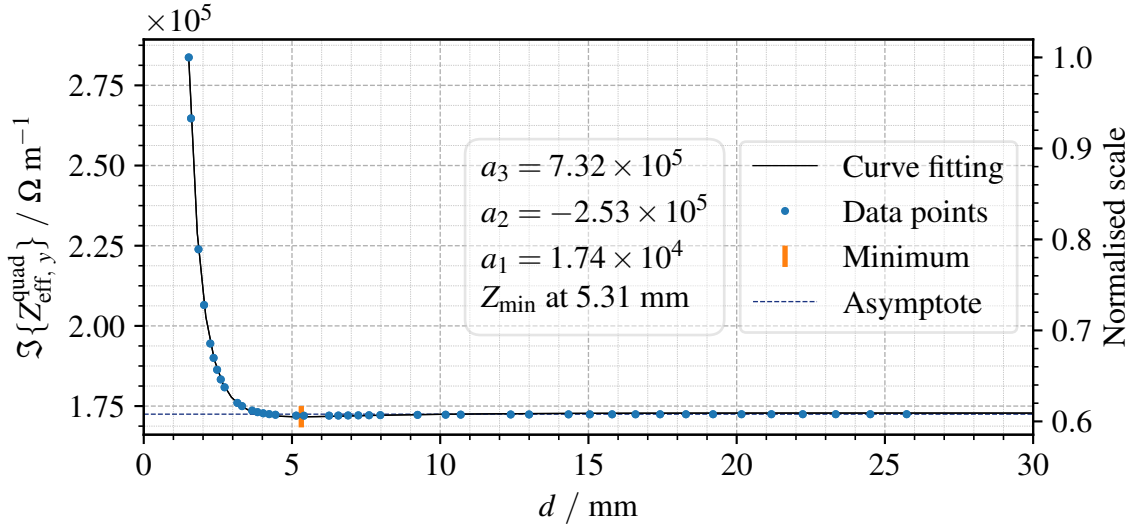
(a) The longitudinal component.



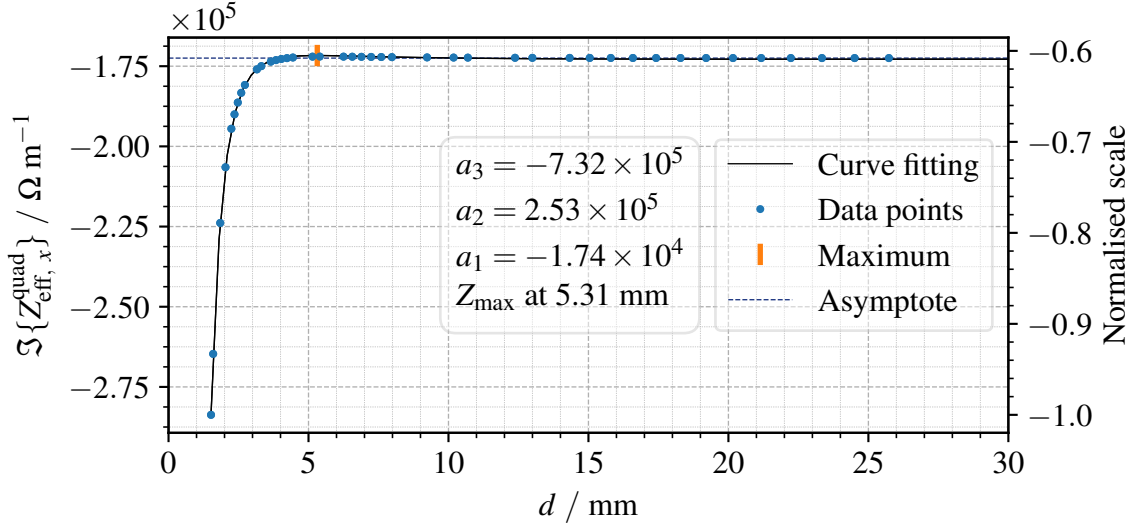
(b) The dipolar component in the collimating plane.



(c) The dipolar component in the non-collimating plane.



(d) The quadrupolar component in the collimating plane.



(e) The quadrupolar component in the non-collimating plane.

Figure 5.31: The imaginary part of the multipolar effective impedance as a function of displacement for one jaw of the horizontal primary collimator.

As seen previously, the dipolar component in the collimating plane is the dominant term. It also provides the most substantial reduction to impedance when incorporating asymmetric settings, albeit at a more gradual rate than other components. In the symmetric case, it is well-known that the transverse wall impedance is inversely proportional to the cube of the half-gap [22, 44]. Evidently, this does not hold true for an asymmetric retraction, and an equivalent formalism was not found in literature. Although deriving such an analytical expression is beyond the scope of this thesis, it is nonetheless interesting to speculate as to its form.

The simplest function that fits the data is a straightforward generalisation of the expression describing the symmetric case. This takes the form of Eq. (5.3), which introduces a few extra terms including a constant representing the asymptote as $d \rightarrow \infty$. The values of the coefficients are listed in each subfigure, with the longitudinal component being the

exception, as the function failed to fit the data accurately.

$$Z_{\text{eff}}^{\perp} = \frac{a_3}{d^3} + \frac{a_2}{d^2} + \frac{a_1}{d^1} + a_0 \quad (5.3)$$

The value of a_0 can be determined analytically, and it corresponds to the impedance of a single-sided collimator. In the normalised scale, this value is approximately 0.3 or 0.6, depending on the multipolar component and plane. The exact values can be found by considering what are known as *Yokoya form factors*. These are ratios relating the impedance of an axisymmetric geometry to that of a different geometry with the same material composition. Fig. 5.32 illustrates the relation between cylindrical and flat structures, where the Yokoya factors are given by the coefficients of the impedance. The relative drop in impedance when going from a symmetric to a single-sided flat structure can thus be determined by comparing the Yokoya factors of the two geometries. Eq. (5.4) shows the relative drop for the dipolar component in the collimating plane, whereas Eq. (5.5) shows the drop for the other transverse components.

$$\frac{1}{4} \cdot \left(\frac{\pi^2}{12} \right)^{-1} = \frac{3}{\pi^2} \approx 0.304 \quad (5.4)$$

$$\frac{1}{4} \cdot \left(\frac{\pi^2}{24} \right)^{-1} = \frac{6}{\pi^2} \approx 0.608 \quad (5.5)$$

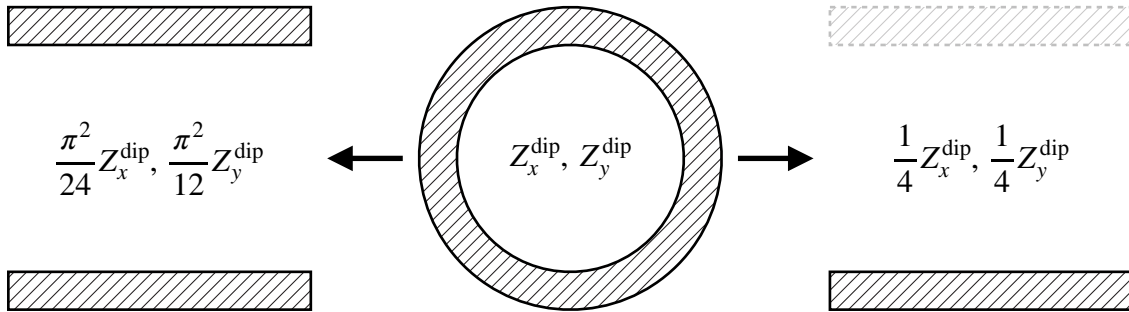
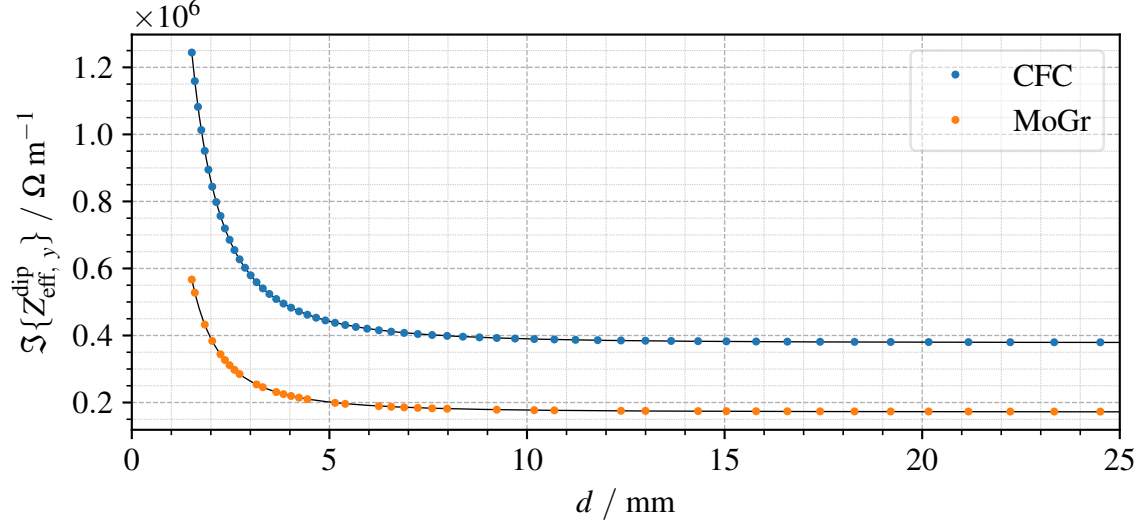


Figure 5.32: The Yokoya form factors relating the dipolar impedance of a cylindrical structure to that of a flat structure with identical composition, where the radius of the former is equal to the half-gap of the latter [45–47]. The left- and rightmost structures represent the symmetric and single-sided cases respectively.

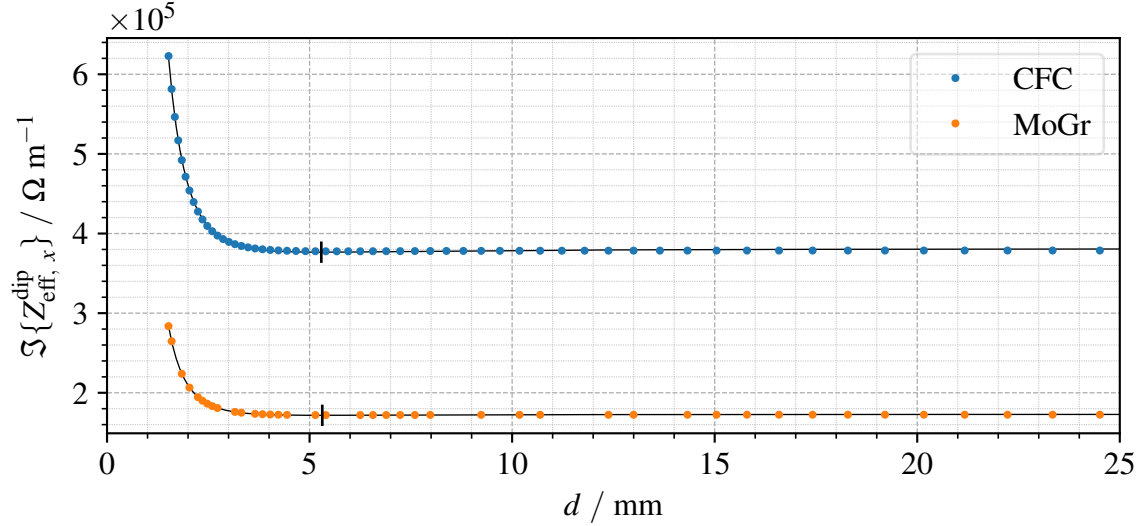
Interestingly, the absolute value of the asymptote appears to be the same in all transverse components. This is an expected result, as the Yokoya factors are the same in both planes. Moreover, rotational symmetry implies that the impedance of a cylinder is uniform throughout the transverse plane. Hence, the impedance of a single-sided structure is similarly uniform. The minimum points that exist below the asymptote are also of interest, as they imply that a fully retracted jaw may not necessarily be the most optimal configuration for impedance reduction.¹¹ Unfortunately, this phenomenon is of limited use, due to the fact that the minimum point is not always at the same position. The fitted curve of the dipolar component in the collimating plane suggests that a minimum point does indeed

¹¹The minimum points exist even when looking at individual frequencies.

exist, but is at a rather large position (see Fig. 5.31). It may be optimal to retract the jaw according to the minimum point in this component, given its dominance; however, it is unlikely that the installed collimators will allow for such a sizeable retraction.



(a) The dipolar component in the collimating plane.



(b) The dipolar component in the non-collimating plane.

Figure 5.33: A comparison between CFC and MoGr jaws for the horizontal primary collimator in terms of dipolar impedance. The leftmost data points represent the symmetric settings and the short, black stripes mark the minimum points.

The magnitude of impedance is greatly influenced by the material composition of the surrounding structure. Fig. 5.33 exemplifies the difference in impedance when employing MoGr or CFC jaws for the horizontal primary collimator — CFC being the material used in the nominal LHC. It is clear the the gain in impedance when comparing symmetric to single-sided settings is the same irrespective of material composition — an observation necessitated by the analysis of the Yokoya factors. A comparison can also be made between upgrading the material (from CFC to MoGr) and retracting a jaw as a means of reducing impedance. In the collimating plane, it is shown that a single-sided CFC

collimator induces less impedance than a two-sided MoGr collimator. This is not quite the case for the other transverse components, however. Indeed, the two methods are not mutually exclusive, so there is little in the way of combining the two effects. Similar comparisons have been done for secondary collimators, whose jaws are coated to further reduce impedance. The results are shown in Appendix D.2.

5.2.2 The impedance budget

The HL-LHC impedance model is used to compute the single-bunch impedance budget for B2 with version 1.2 of the optics ($\beta^* = 48$ cm) at FT (7 TeV).¹² The model contains contributions from the most critical components, including:

- Tapers (triplets): Tapers at the triplets.
- BPMs (triplets): Beam position monitors at the triplets.
- Pumping holes (triplets): Pumping holes in the vacuum chamber at the triplets.
- Pumping holes (rest): Pumping holes in the vacuum chamber elsewhere.
- RF & main detectors: ATLAS, CMS, ALICE, LHCb, and the RF cavities.
- Other broadband: Other miscellaneous broadband contributions.
- Collimators (geometric): Contribution due to collimator geometries.
- Collimators (RW): Resistive-wall contribution of the collimators.
- Beam screen (RW): Resistive-wall contribution of the beam screen (heat shield).
- Warm pipe (RW): Resistive-wall contribution of the vacuum pipe in straight sections.
- Crab cavities: Contribution due to crab cavities at the interaction points. Note that these were not simulated due to time constraints.

	Tapers (triplets)		Other broadband
	BPMs (triplets)		Collimators (geometric)
	Pumping holes (triplets)		Collimators (RW)
	Pumping holes (rest)		Beam screen (RW)
	RF & main detectors		Warm pipe (RW)

¹²B2 was simulated in lieu of B1 due to issues related to availability. Likewise, version 1.3 of the optics (used in the cleaning simulations) was not yet available in the impedance model. Nevertheless, the impedance contributions of B1 and B2 are known to be virtually identical, and the differences between the two optics versions are largely immaterial.

Figs. 5.34 and 5.35 illustrate the relative contributions of the aforementioned elements to the total impedance. Note that the x - and y -axes correspond not to the planes of collimation, but rather the horizontal and vertical axes of the machine, as per Fig. 1.4. In the longitudinal component, it is shown that the largest contribution comes from the resistive wall of the arc beam screen — covering a fairly wide range of frequency. Although not shown, the crab cavities are also known to contribute significantly, specifically over higher frequencies [48]. Collimators are responsible for roughly 15 % of the total longitudinal impedance. In contrast, the transverse components are overwhelmingly dominated by the collimation system — accounting for approximately 90 % of the total transverse impedance in the HL-LHC.

The B2 configurations C2+NNNN and C2+MHB2, which were shown to preserve and even enhance beam cleaning,¹³ are now selected to probe the effectiveness of single-sided collimation as a means of impedance reduction within the accelerator. The inactive jaws of single-sided collimators were set to a displacement of 2 cm from the beam orbit, which is a number close to the parking position (maximum aperture) of the currently installed LHC collimators. It should be noted that the geometric impedance contribution is always that of a symmetric collimator. This is because the geometric impedance is obtained through an expression which assumes symmetry, and a similar expression describing asymmetric geometries was not yet formulated. In essence, the results show a more conservative estimate of the drop in impedance when incorporating single-sided settings.

Fig. 5.36 shows the total simulated impedance as a function of frequency, with the DRY configuration added for reference. Notice that the dipolar horizontal and vertical impedances are of similar form and magnitude, and furthermore dominate over the quadrupolar components. The longitudinal impedance appears to be completely unaffected by the configurations, whereas the dipolar components experience a general decrease in impedance. Interestingly, the quadrupolar component in the horizontal plane undergoes a rise in impedance when utilising the single-sided configurations. Nonetheless, the dipolar components shall be the main focus of this analysis.

The effective impedance is once again determined in order to obtain a clearer picture of the results. Note that this quantity is now also influenced by the optics of the machine, more specifically, the local beta function. Fig. 5.37 breaks down the imaginary part of the effective impedance in terms of the main accelerator elements. It can be seen that the geometric and RW components of the collimators are the highest contributors to impedance, and are very much comparable in magnitude. The two single-sided configurations exhibit a similar drop in RW impedance, which suggests that retracting jaws beyond those of the four high-impedance collimators is undesirable, due to the less favourable trade-off between beam cleaning and impedance. It is reasonable to expect a similar outcome for the geometric component.

¹³That is, in the absence of closed orbit drifts.

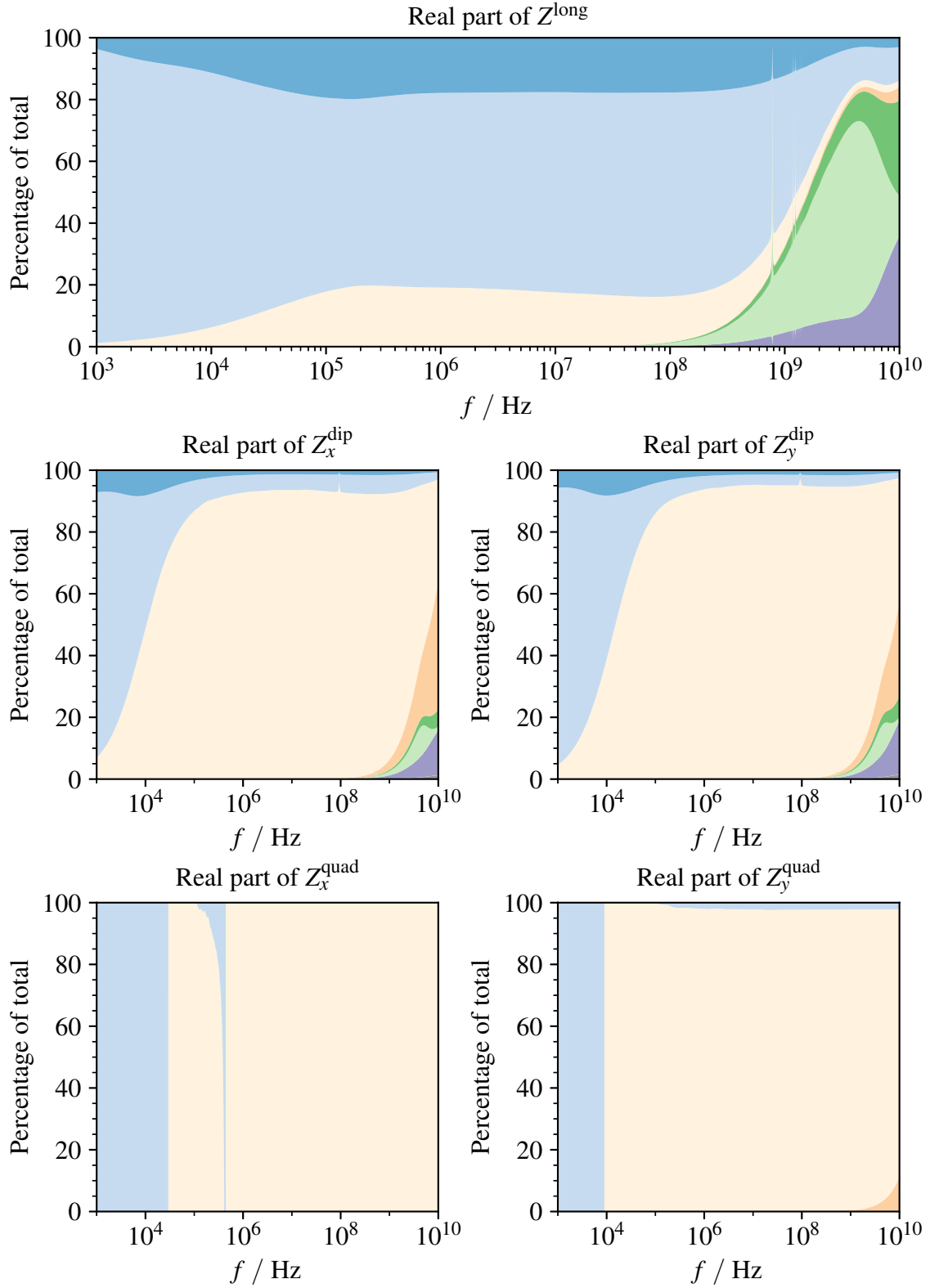


Figure 5.34: Composition of the real part of the multipolar impedance as a function of frequency for the HL-LHC at top energy. Legend on page 81.

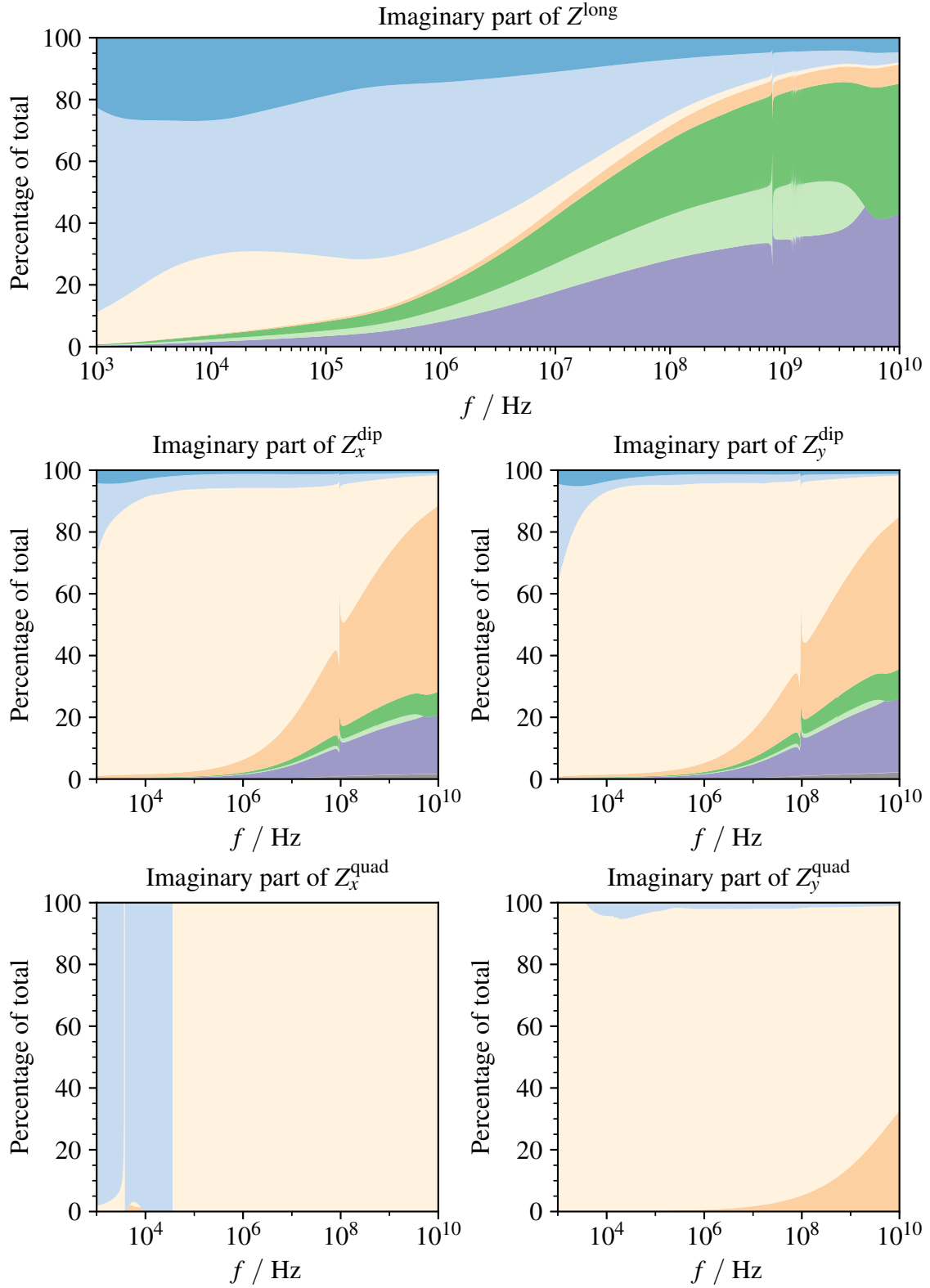


Figure 5.35: Composition of the imaginary part of the multipolar impedance as a function of frequency for the HL-LHC at top energy. Legend on page 81.

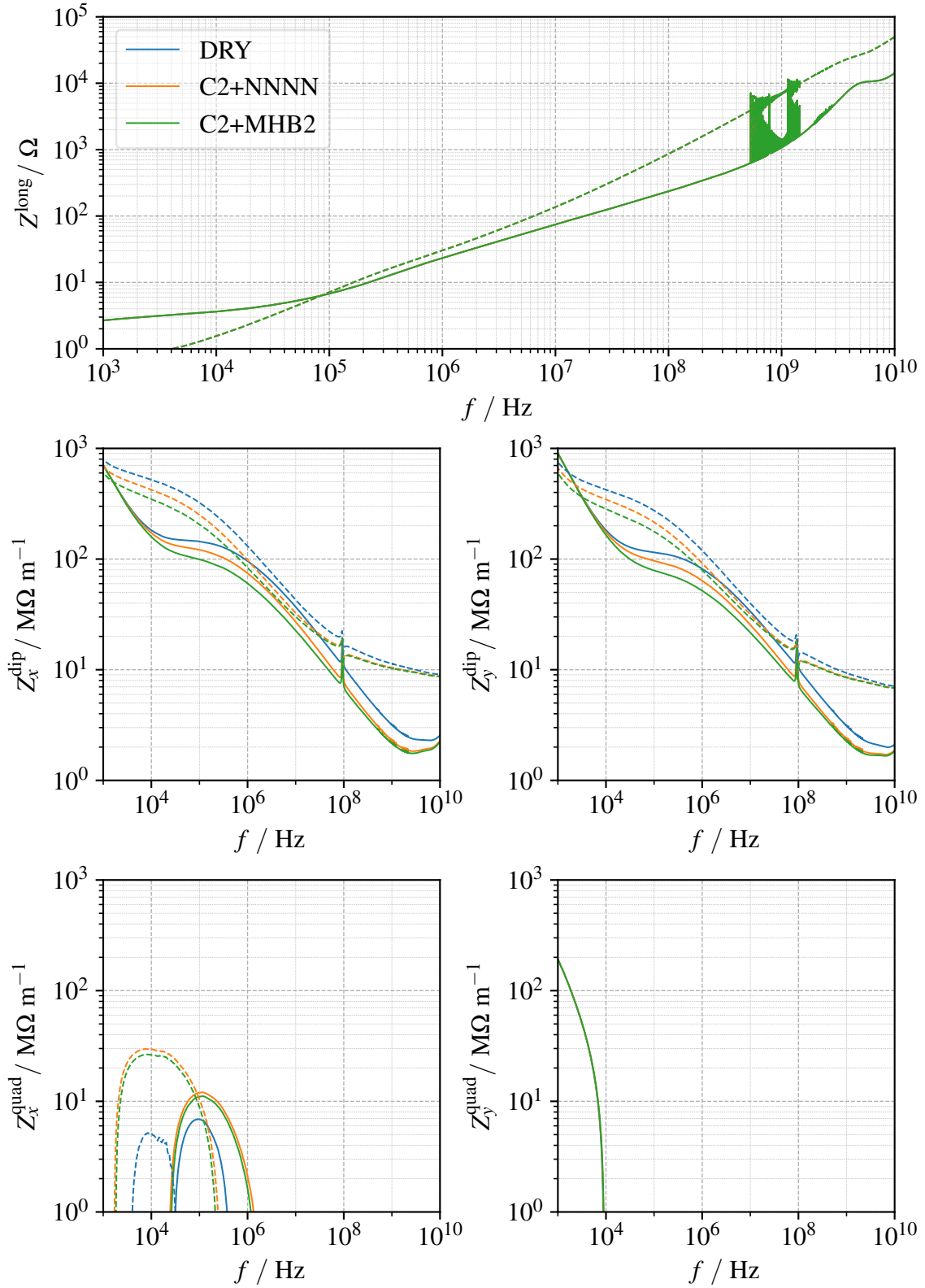


Figure 5.36: The real (continuous) and imaginary (dashed) parts of the total impedance as a function of frequency for B2 of the HL-LHC at FT.

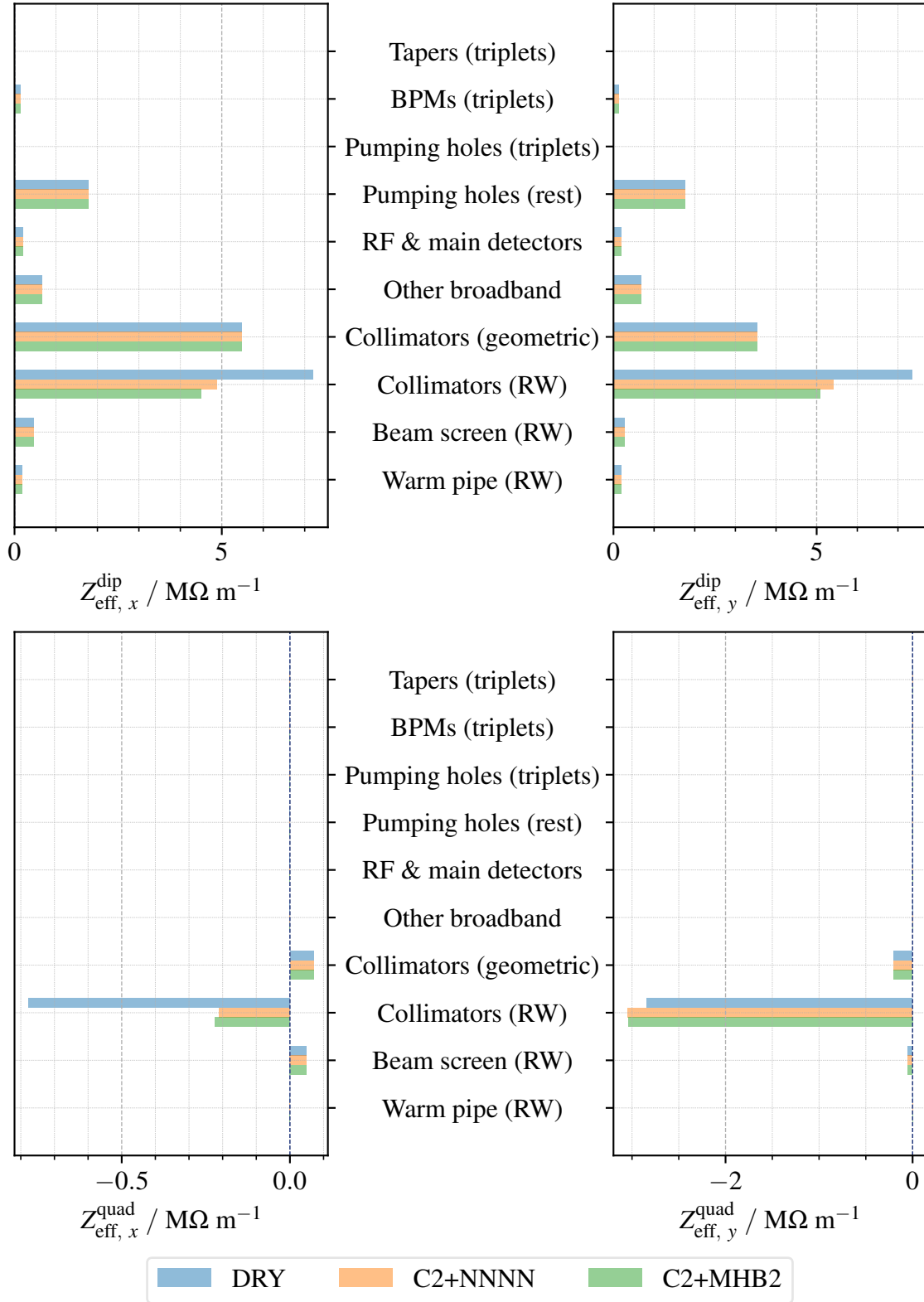


Figure 5.37: The imaginary part of the multipolar effective impedance for the most critical components of the accelerator.

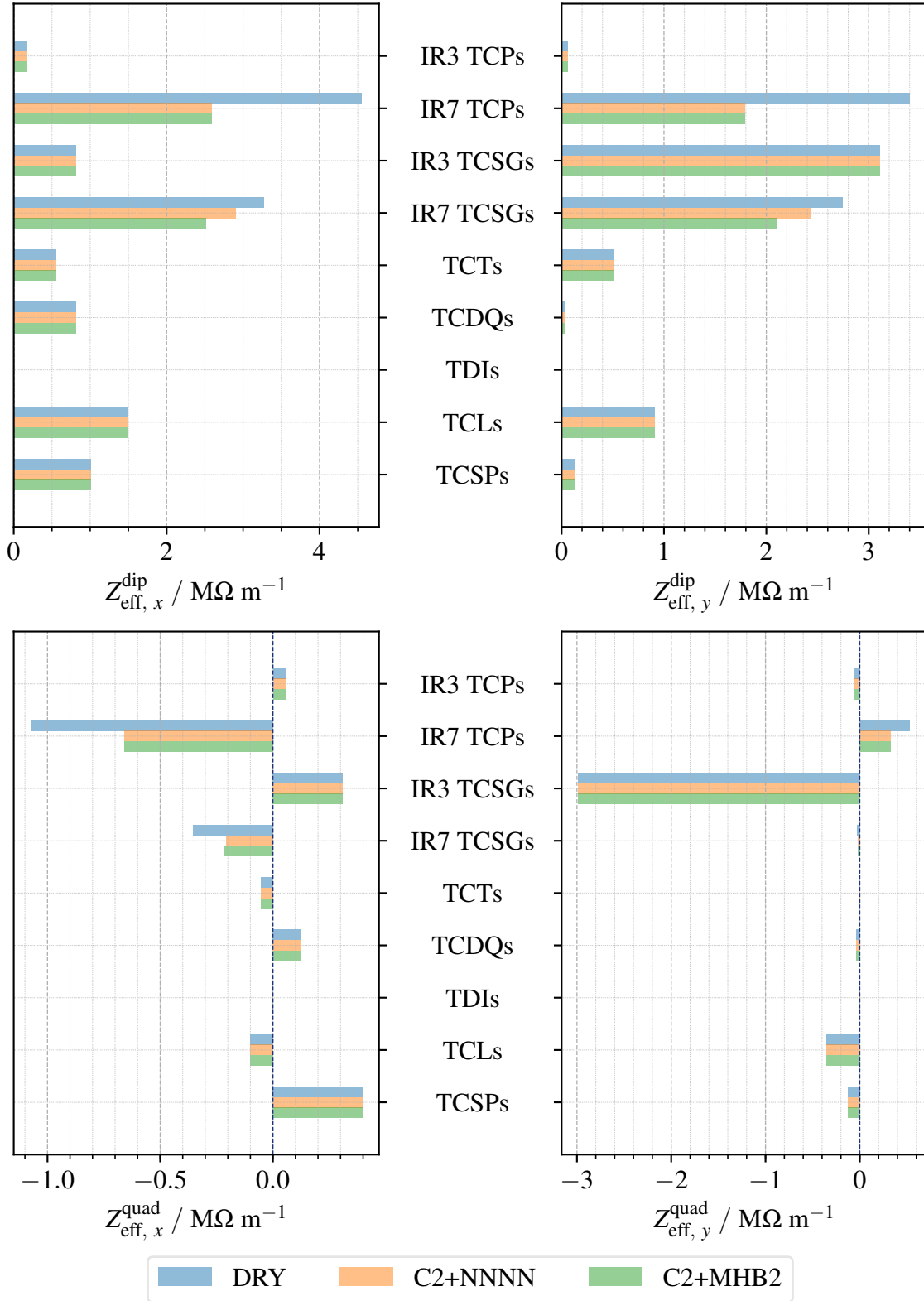


Figure 5.38: The imaginary part of the multipolar effective impedance for each collimator subgroup. Both the geometric and RW components have been considered.

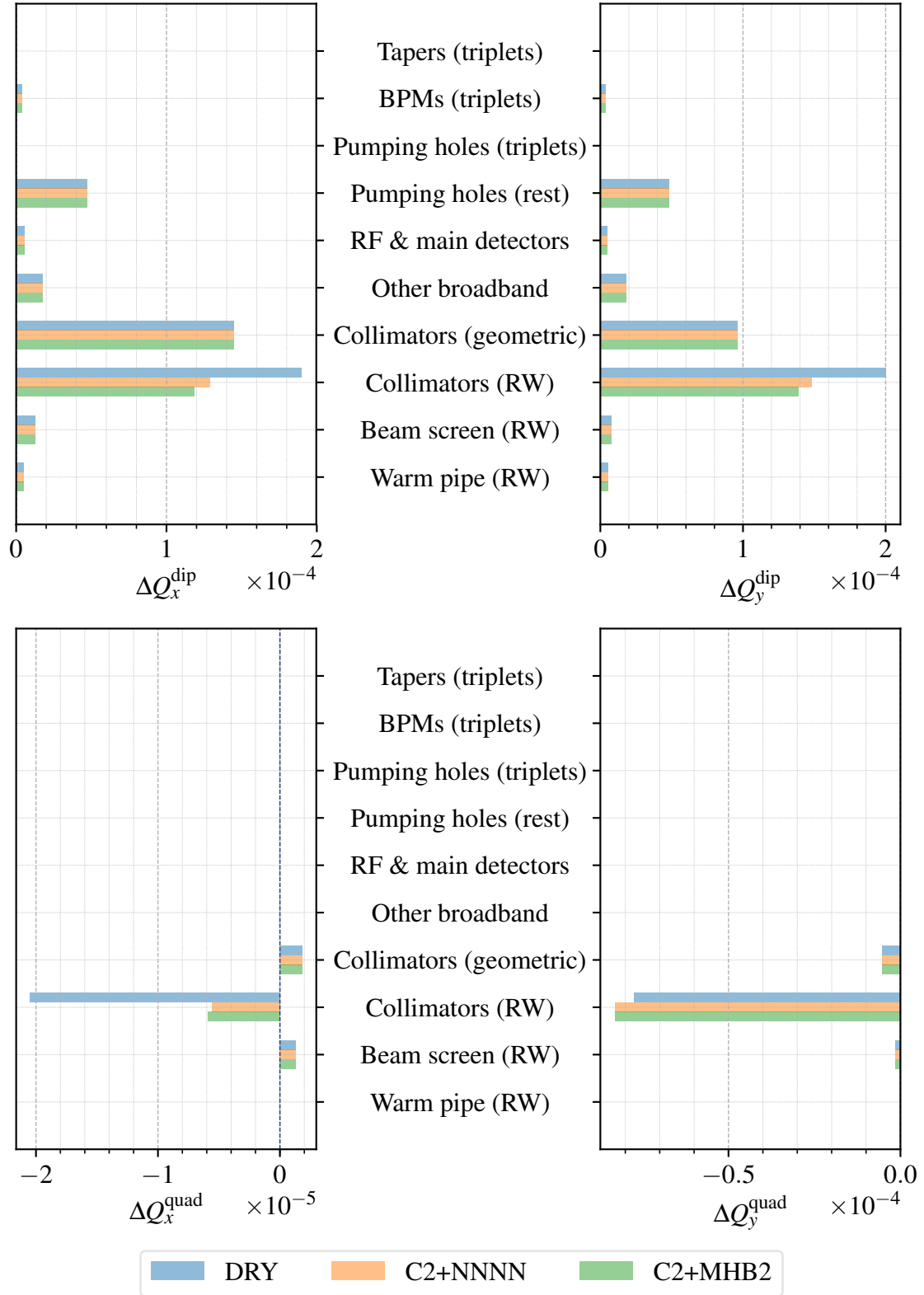


Figure 5.39: The real-valued part of the tune shift induced by the most critical components of the accelerator.

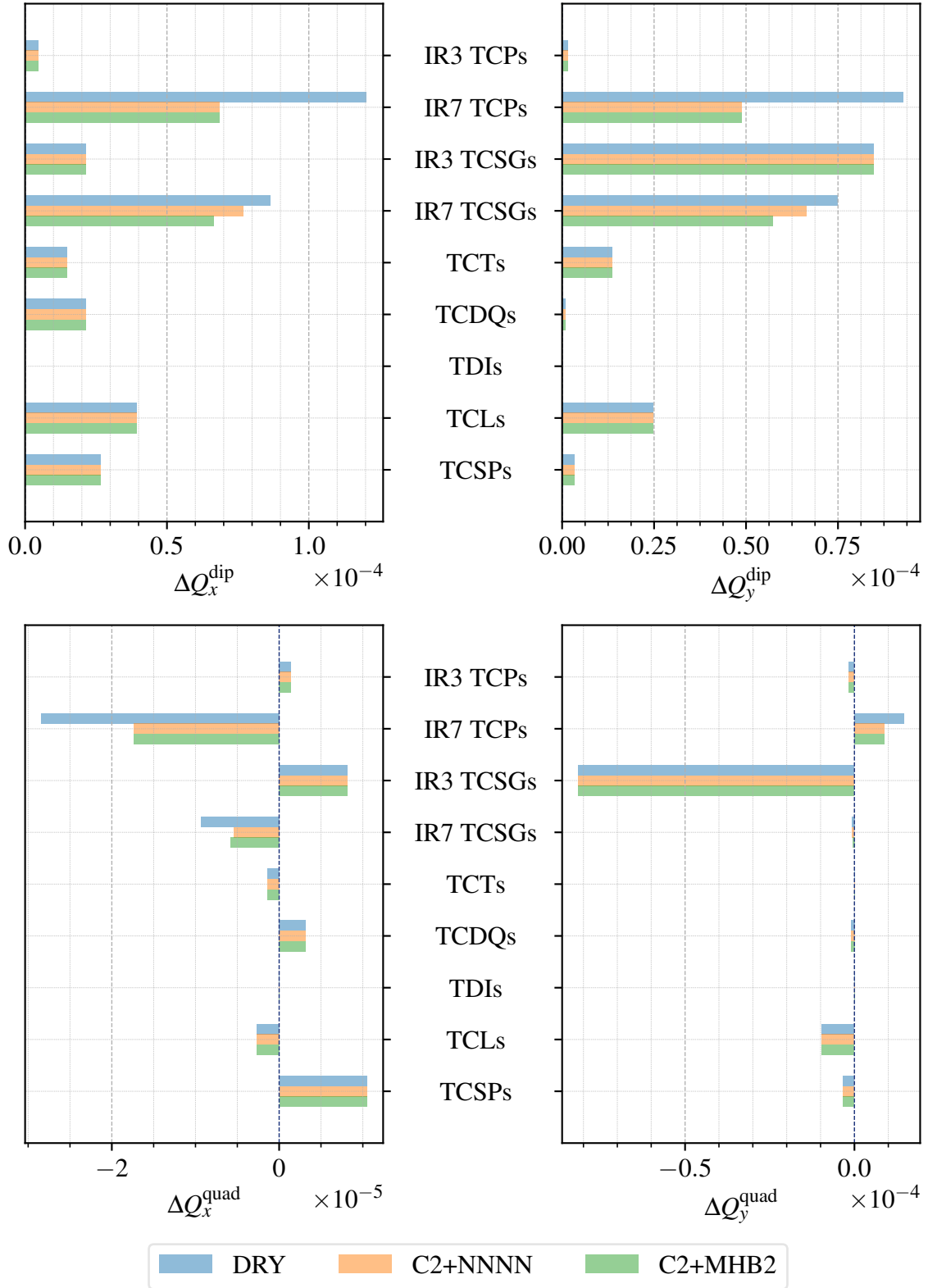


Figure 5.40: The real-valued part of the tune shift induced by each collimator subgroup. Both the geometric and RW components have been considered.

Fig. 5.38 breaks down the impedance in the collimation system according to collimator subgroups. Note that both the geometric and RW components have been considered. It is revealed that the primary collimators rival the secondaries in terms of impedance in IR7. Although it appears that the potential gain in impedance is much greater for the primaries, this is most likely an artefact of the simulation due to the fact that the geometric component is unchanging. It is easy to see that the TCSGs are dominated by the geometric component, especially when considering that there are a total of 3 TCPs and 11 TCSGs, of which the latter are coated in molybdenum to further reduce the RW impedance. Hence, it is important to assess the geometric impedance properly in future studies of single-sided collimation.

The four high-impedance collimators are implied to generate roughly the same RW impedance as all the other IR7 TCSGs combined. For the dipolar component in the vertical plane, it is shown that the TCSGs in IR3 overpower their IR7 counterparts in terms of impedance.¹⁴ Indeed, it is not unreasonable to consider single-sided collimation for the momentum cleaning insertion, given that particles are forced towards one side of the collimators thanks to the high horizontal dispersion in the region. Figs. 5.39 and 5.40 are similar to the last two figures discussed, but instead show the tune shifts associated with the accelerator elements and collimator subgroups. The quantity was calculated as from [29] using the parameters specified in Appendix A.4. Appendix C.1 also shows the impedances induced by individual collimators.

5.2.3 The octupole current threshold

There are two main observables that characterise the performance of a system in relation to impedance. The first is the tune shift, which is proportional to the imaginary part of the effective impedance. The second is the *octupole current threshold*, which is related to an instability rise time — corresponding to the real-valued part of the impedance. The impact on stability is generally of greater concern than the impedance itself; therefore, the latter observable is often deemed to be more valuable.

The octupoles are designed to produce a tune spread necessary for *Landau damping*, which damps impedance-driven collective instabilities. The larger the instabilities, the more octupole current is required to maintain stability. The octupole current threshold I_{oct} is thus the minimum octupole current required to keep the beam stable. It is commonly expressed as a function of chromaticity, as chromaticity is known to influence stability. Moreover, chromaticity and octupole current are two quantities that can be adjusted by the machine operators. Minimising the octupole current is vital, as there is a hardware limit of 550 A.

DELPHI is employed alongside the HL-LHC impedance model in order to compute the octupole current threshold for the relevant configurations. A single bunch of 2.3×10^{11} particles is simulated in the horizontal plane,¹⁵ having a gaussian transverse distribution with a normalised emittance of $2.0 \mu\text{m}$, and an RMS bunch length of 8.1 cm. The transverse damper (commonly known as the ADT) is a feedback system designed to damp oscillations and provide stability against impedance-driven transverse effects [49]. In simulation, the ADT is set to a damping time of 100 turns, meaning that it takes the ADT 100 revolutions

¹⁴Although there are less collimators in IR3, their material composition remains CFC.

¹⁵The horizontal plane is generally more unstable than the vertical plane.

to fully damp an oscillation. Due to the dependence on the previous simulations, the crab cavities are not taken into account, and the geometric component is still that of the standard collimator settings, regardless of configuration. Also note that the octupole current threshold in measurements tends to be roughly twice that in simulations.

The results in Fig. 5.41 show that there is very little difference between the two single sided configurations. The most significant deviations are at $Q' = 7$ and $Q' = 14$, and are in favour of C2+MHB2; however, the overall picture suggests that C2+NNNN is more practical, due to its lighter impact on cleaning. When compared to DRY, the largest gain in I_{oct} is given by the range $Q' \in [10, 15]$, which is encouraging as this approximate range is exercised during operation at FT. A massive gain of almost 100 A can be seen at $Q' \in [10, 11]$, although previous measurements have shown that such improvements are very unlikely. One should instead examine the overall picture, which conveys a general decrease of around 30 A. It is reasonable to expect a larger margin if the geometric component is accounted for appropriately.

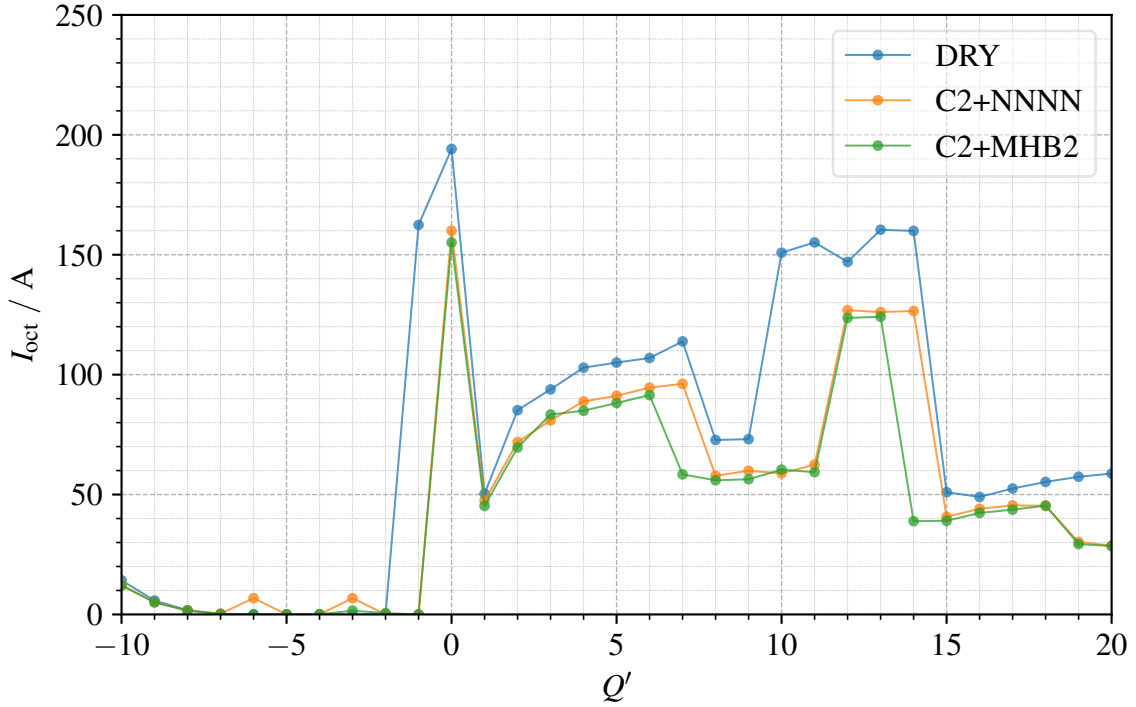


Figure 5.41: The octupole current threshold as a function of chromaticity for the main configurations in HL-LHC.

Outlook for Run III

Single-sided collimation may be most effective in Run III for a number of reasons. The increased cleaning performance observed for HL-LHC should also exist for Run III, given that the TCLD is present in both scenarios. Additionally, only a handful of the collimators are upgraded in Run III, meaning that the gain in impedance should be far more significant. The upgraded collimators include the TCPs D6L7 and C6L7, which are upgraded CFC to MoGr; and the TCSGs D4L7, B4L7, E5R7, and 6R7, which are upgraded from CFC to Mo-coated MoGr. All other collimators within these families remain in CFC as in LHC.

Simulations have been carried out in preparation for the upcoming operational run. The parameters are almost identical to those of HL-LHC, with the only difference being the material composition of the upgraded collimators. Given that Run III is somewhat of a hybrid scenario between LHC and HL-LHC, two distinct normalised apertures were considered for the primary and secondary collimators — one set coinciding with the LHC (5, 6.5), and the other with the HL-LHC (5.7, 7.7). Seeing as the specifications of the collimation system are ever-changing, the same thing was done for HL-LHC in Fig. 5.42, which shows the octupole current threshold for when the primaries and secondaries are set to a normalised aperture of 5 and 6.5 respectively. The results for Run III are shown in Figs. 5.43 and 5.44.

Although the two single-sided configurations remain very similar in HL-LHC, the margin of improvement goes from approximately 30 A to 50 A when employing the tighter gaps. It is clear that single-sided collimation is more suitable for Run III. The two configurations are no longer identical, and the margin of improvement is larger, especially with the tighter gaps. For the larger normalised apertures, the relative drop in the octupole current is around 40 A for C2+NNNN, and 60 A for C2+MHB2. For the smaller normalised apertures, the drop is roughly 50 A for C2+NNNN, and 100 A for C2+MHB2.

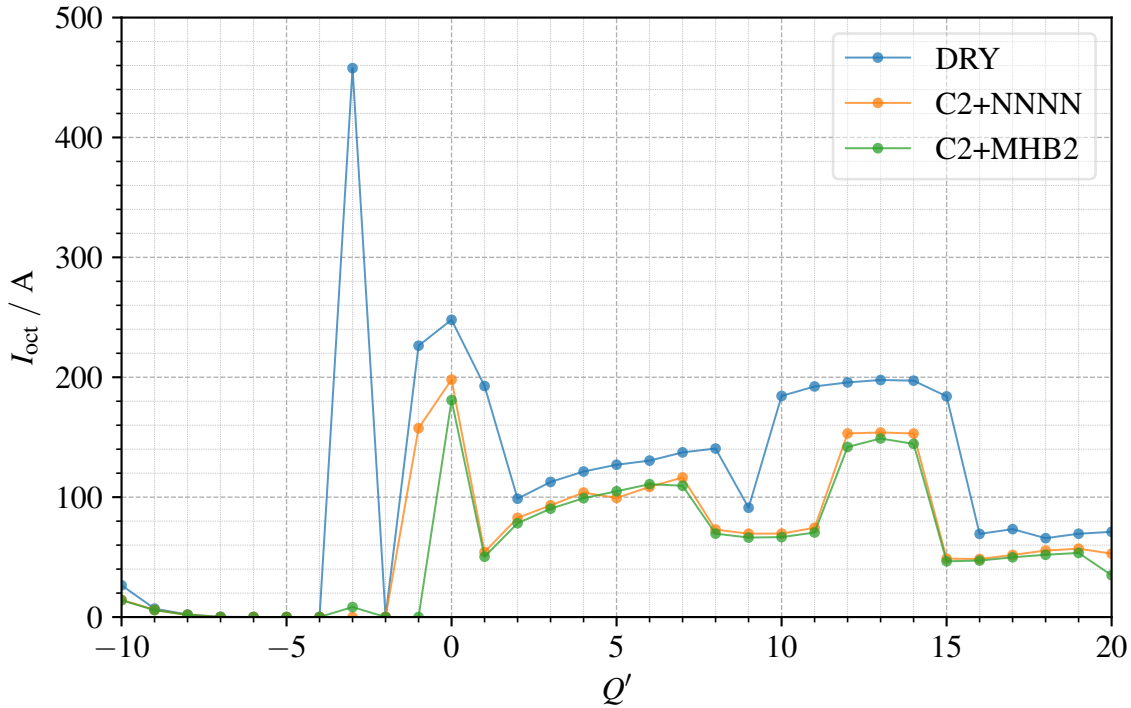


Figure 5.42: The octupole current threshold for HL-LHC, where the normalised apertures of the primary and secondary collimators are set to 5 and 6.5 respectively.

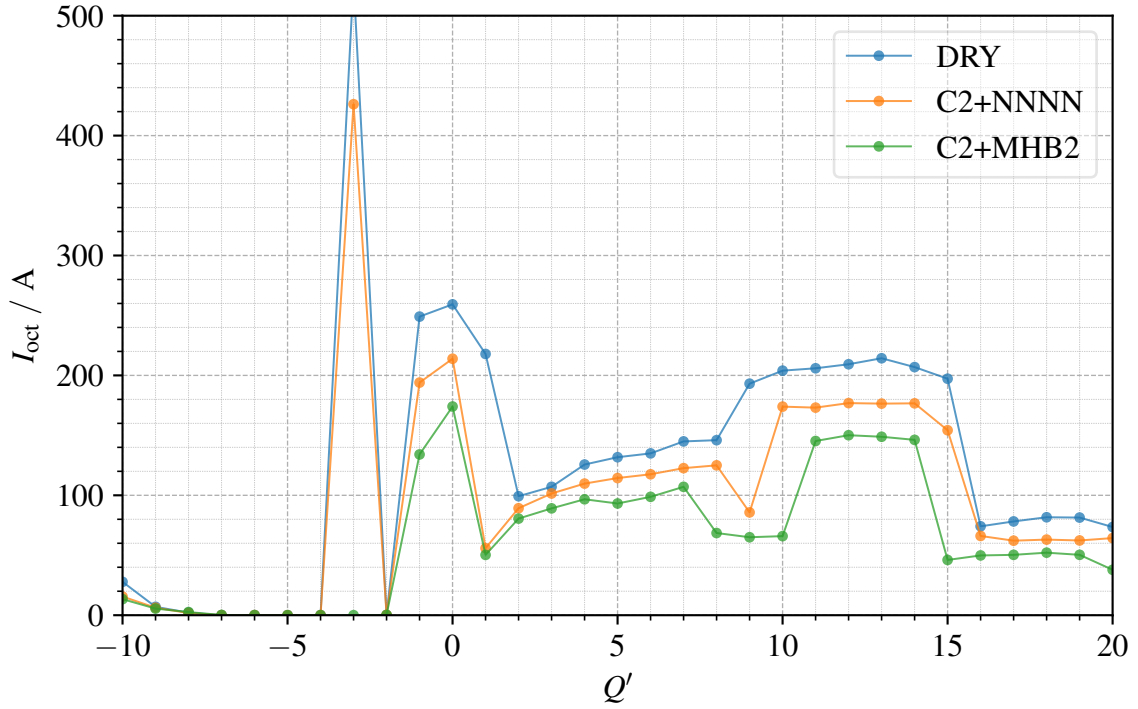


Figure 5.43: The octupole current threshold for Run III, where the normalised apertures of the primary and secondary collimators are set to 5.7 and 7.7 respectively.

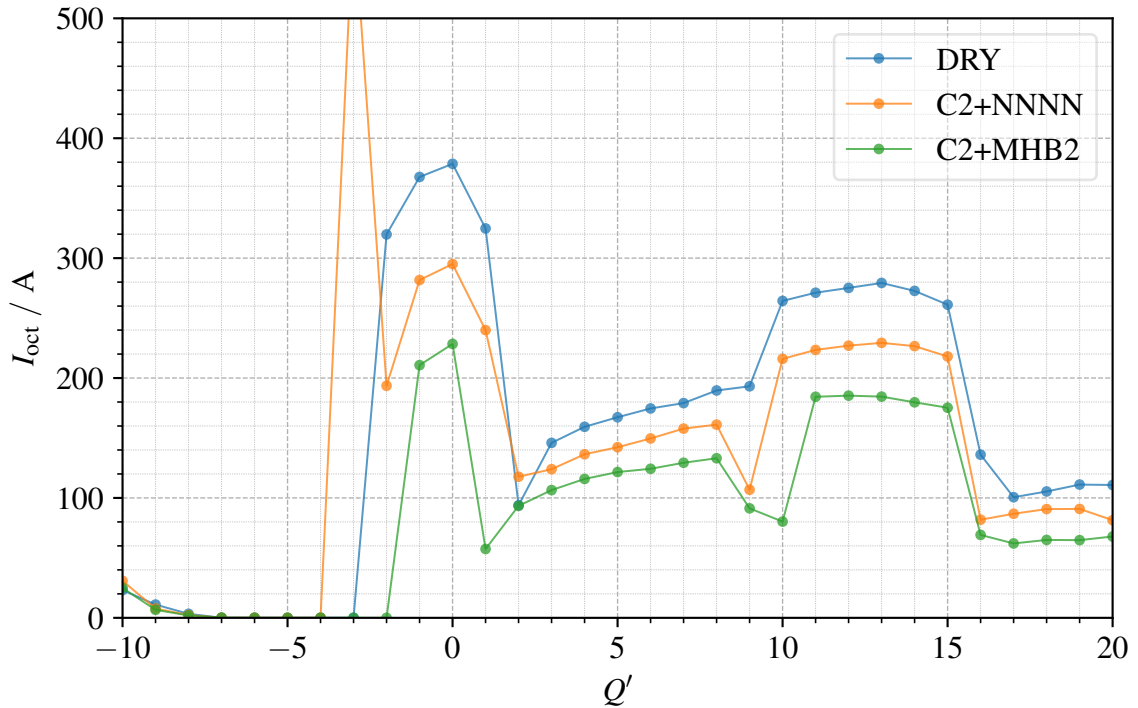


Figure 5.44: The octupole current threshold for Run III, where the normalised apertures of the primary and secondary collimators are set to 5 and 6.5 respectively.

Chapter 6

LHC benchmarking

6.1 Cleaning simulations

6.1.1 Beam 1

It is evident that the absence of the TCLD collimator in the LHC will lead to cluster pathways that are different from those of the HL-LHC, given the collimator's crucial role in the horizontal plane. Consequently, this means that the previously found configurations are not optimal for the LHC; hence, a similar approach is carried out in order to obtain the most appropriate configurations — starting with the primary collimators and transitioning onto secondaries after observing the generated pathways.

Figs. 6.1 and 6.2 show the simulated cleaning performance of the primary configurations C1 and C2 in the horizontal and vertical planes respectively. Interestingly, the results appear to favour C2 over C1 in all but the fourth cluster in B1H. Although the outcome is different than that of B1 of the HL-LHC, some patterns remain. The differences between the two configurations are, once again, marginal in the vertical plane, but fairly visible in the horizontal plane, albeit less so than those witnessed for HL-LHC. In the end, the results suggest that C2 is the most viable single-sided configuration for the primary collimators in LHC.

Cluster pathways are studied once more in order to understand the difference in the cleaning performance of the two configurations. The trajectories of particles in a dry run accumulating in the first cluster are shown in Figs. 6.3 and 6.4.¹ B1V exhibits pathways which are almost perfectly symmetric, and closely resemble their counterparts in HL-LHC. B1H also exhibits somewhat symmetric pathways, although this was not observed in HL-LHC due to the interplay between dispersion and the TCLD collimator. It is immediately noticeable that the path emanating from the negative jaw of the horizontal TCP is slightly wider than that of the positive jaw. A closer examination also reveals that the line of symmetry between the two pathways is slightly below the longitudinal axis, suggesting that the paths themselves are shifted downwards.

¹In the LHC, the first cluster is the most prominent. However, the pathways leading to the other clusters are similar when looking at IR7.

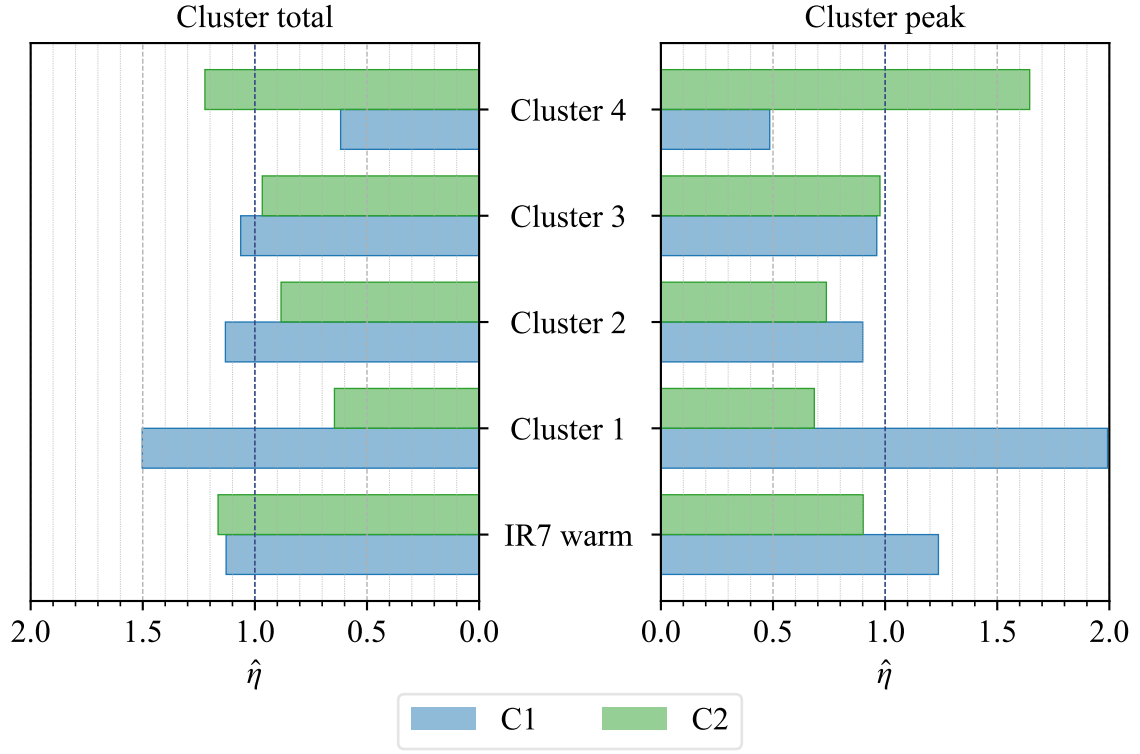


Figure 6.1: The cluster cleaning performance of C1 and C2 in B1H of the LHC.

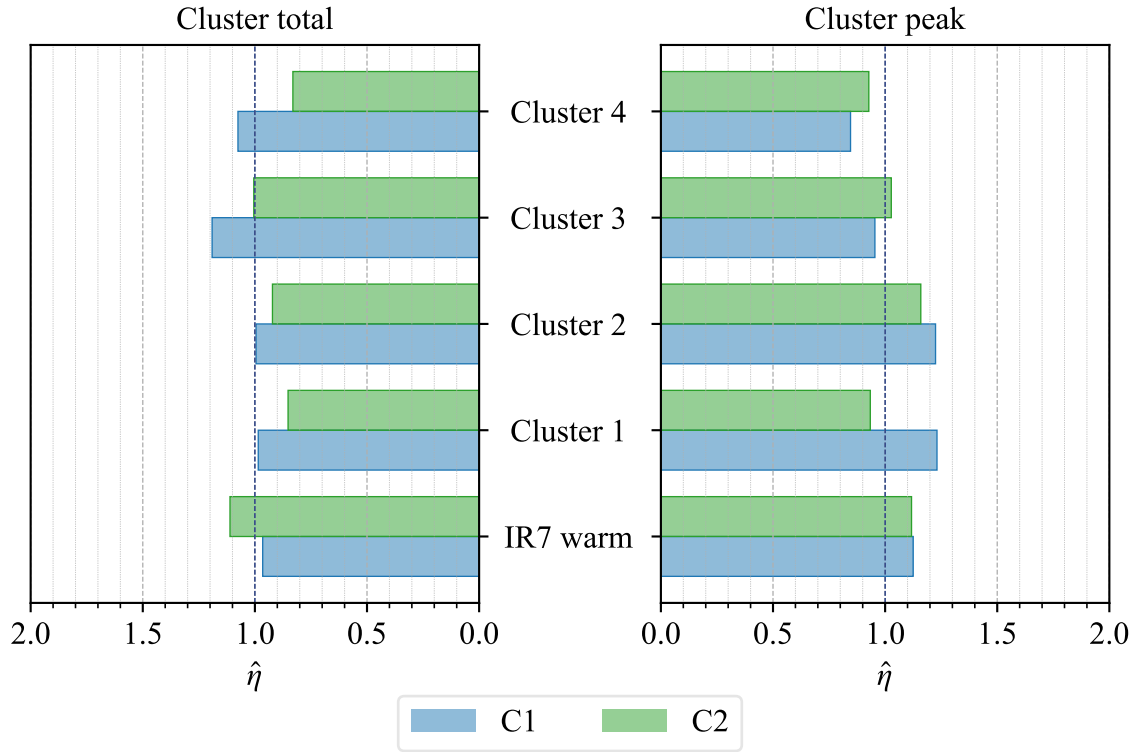


Figure 6.2: The cluster cleaning performance of C1 and C2 in B1V of the LHC.

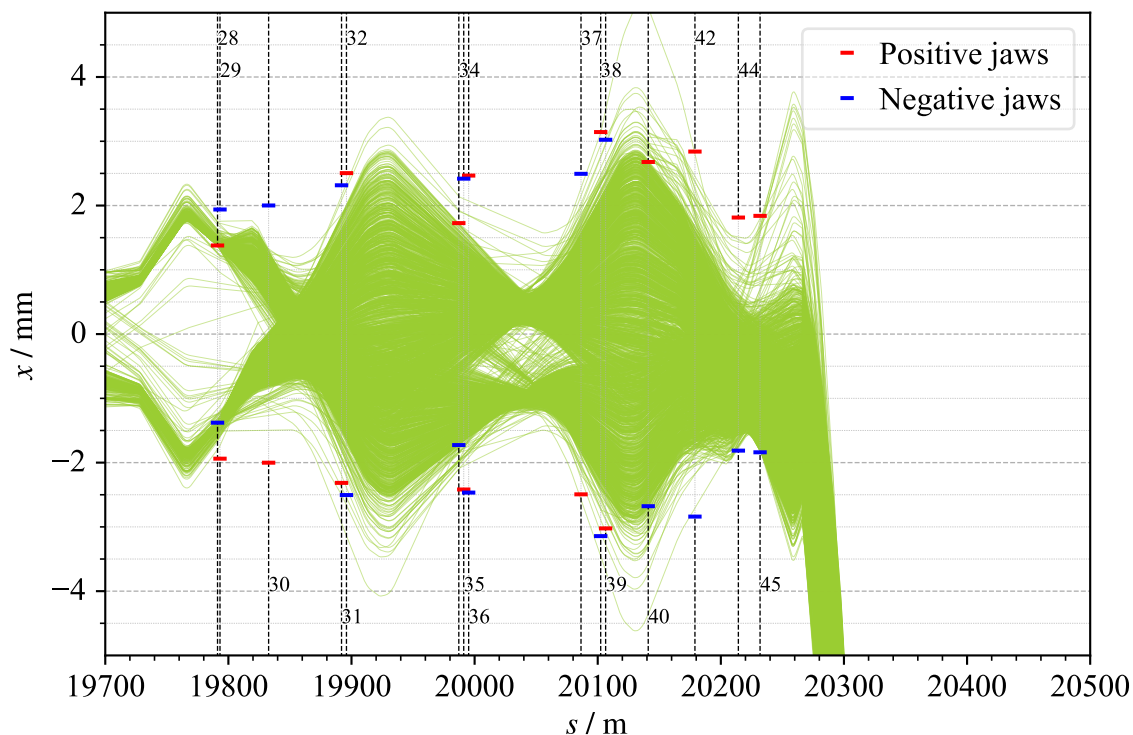


Figure 6.3: The particle pathways leading to the first cluster in B1H of the LHC.

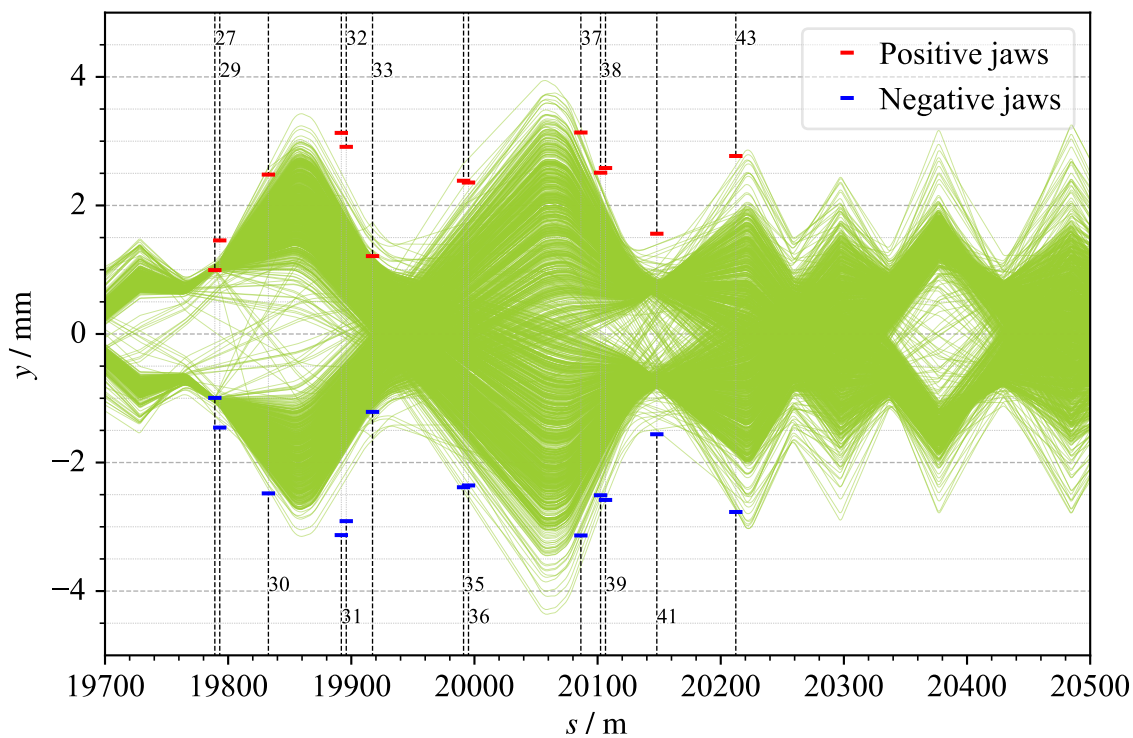


Figure 6.4: The particle pathways leading to the first cluster in B1V of the LHC.

The positive dispersion present early on in IR7 (see Fig. 5.23)² could in fact account for the downwards shift. Although the magnitude of dispersion in the region is relatively small, the magnitude of $\langle\delta_E\rangle$ in the first cluster is rather large. Furthermore, the second and third clusters, which are known to have progressively smaller magnitudes of $\langle\delta_E\rangle$, are shown to have increasingly smaller margins when comparing the two configurations, implying that dispersion does indeed play a key role.³ Because of this downwards shift, the jaws below the longitudinal axis are effectively at a lower σ cut. Hence, the path emanating from the positive jaw (C2) is more likely to interact with the secondary collimators, thus resulting in better cleaning performance.

Table 6.1: The active jaws of the multi-secondary configuration C2+MLB0, where the selection is based on the jaws closest to the pathways in B1H and B1V.

ID	Name	B1H	B1V	Active jaw
27	TCP.D6L7.B1	-	-	Negative
28	TCP.C6L7.B1	-	-	Positive
29	TCP.B6L7.B1	-	-	Positive
30	TCSG.A6L7.B1	Negative	Negative	Negative
31	TCSG.B5L7.B1	Positive	Negative	Positive
32	TCSG.A5L7.B1	Negative	Negative	Negative
33	TCSG.D4L7.B1	-	Negative	Negative
34	TCSG.B4L7.B1	Negative	-	Negative
35	TCSG.A4L7.B1	Positive	Positive	Positive
36	TCSG.A4R7.B1	Negative	Positive	Both
37	TCSG.B5R7.B1	Positive	Positive	Positive
38	TCSG.D5R7.B1	Negative	Positive	Both
39	TCSG.E5R7.B1	Positive	Positive	Positive
40	TCSG.6R7.B1	Negative	-	Negative

The next step is to consider configurations that involve the secondary collimators. As with HL-LHC, the method of constructing such configurations relies on the assumption that retracting the jaws furthest from the beam paths — which are generated by the TCPs (C2) — does not lead to a significant deterioration of the cleaning performance. Unlike HL-LHC however, there is no TCLD to safeguard the horizontal plane; hence, the jaws need to be selected such as to not jeopardise cleaning in either plane. The multi-secondary configuration is assembled by observing the paths emanating from the positive jaw in B1H, and the negative jaw in B1V. Tab. 6.1 lists the jaws that are closest to the specified pathways in both planes, and presents the assembly of the multi-secondary configuration C2+MLB0.

²The dispersion in LHC closely resembles that of HL-LHC in IR7.

³It is likely that the fourth cluster is produced under different dynamics, given its distance from IR7.

If the two planes register the same jaw of a collimator, then that jaw is left active while the other is retracted; otherwise, both jaws are retained. TCSG.B5L7.B1 overrides this rule due to its status as one of the high-impedance collimators. In this case, the positive jaw is selected because of its close proximity to the path in B1H. The subconfiguration containing only the four high-impedance collimators is given by C2+NPNN.

The cleaning performance of the amassed configurations is shown in Figs. 6.5 and 6.6. Also included are C2+PNPP and C2+RLB0, which represent the inversion of the active jaws of the secondary collimators for C2+NPNN and C2+MLB0 respectively. This is done in order to test the method of jaw selection, as the reversed configurations are expected to have an adverse effect on cleaning. Indeed, the results demonstrate that these configurations perform rather poorly in both planes, more so in B1V. On the other hand, C2+NPNN and C2+MLB0 are seen to perform remarkably well in B1H, and are largely indistinguishable from the performance of the standard settings in B1V.

The change in the distribution of collimator losses is given by Figs. 6.7 and 6.8. In IR7, two collimators stand out in terms of losses when reviewing C2+MLB0 in both planes, namely TCSG.A4R7.B1 and TCLA.B6R7.B1. The former is the most upstream collimator to have both jaws active in the configuration, while the latter has only one distinctive attribute — its horizontal orientation. Interestingly, losses in IR3 appear to increase broadly for B1H when considering C1, but reduce significantly when considering other configurations. C1 has also been characterised by an improved cleaning of the fourth cluster (see Fig. 6.1), which provides further evidence to the entanglement between it and IR3. In both planes, IR6 experiences an erratic surge in losses for all configurations except C1.

6.1.2 Beam 2

Contrary to the HL-LHC, the factor which determines the performance of single-sided configurations in the LHC, is the dispersion in IR7 ($s_{B1} \approx 19.9$ km), as opposed to the dispersion in the DS ($s_{B1} \approx 20.3$ km). Fig. 5.23 has shown that while the dispersion in the DS changes sign depending on the beam, the dispersion in IR7 maintains a positive sign. It is therefore reasonable to expect identical pathways in IR7, and hence, very similar results in terms of cleaning performance. Indeed, Figs. 6.9 and 6.10 confirm that the paths in B2 are virtually identical to those in B1 when examining the region enclosed by the collimators in IR7.

Figs. 6.11 and 6.12 show the cleaning performance for the configurations in B2, while Figs. 6.13 and 6.14 describe the change in the distribution of collimator losses. The cleaning results are practically indistinguishable from those of B1, suggesting that the exact same configurations can be used in both beams. The distribution of losses is also similar to that of B1; however, it appears that the erratic surge in IR6 has been transferred to some TCTs in IR1 and IR8 instead.

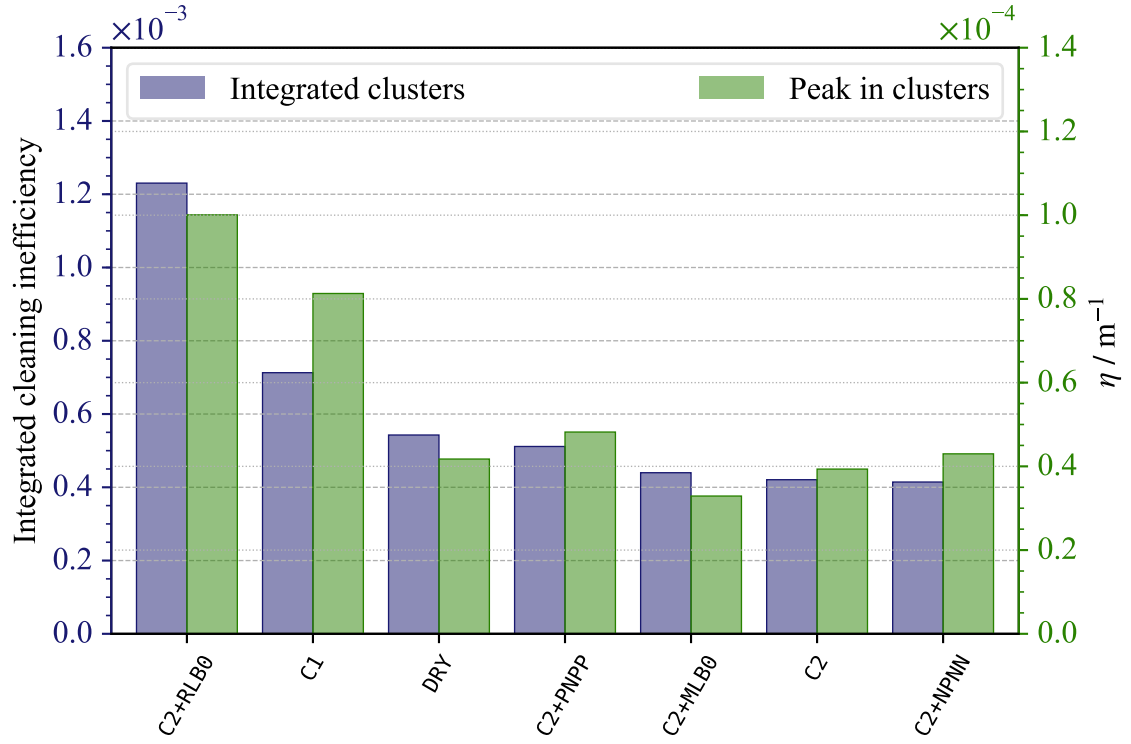


Figure 6.5: The cleaning performance of the configurations in B1H of LHC.

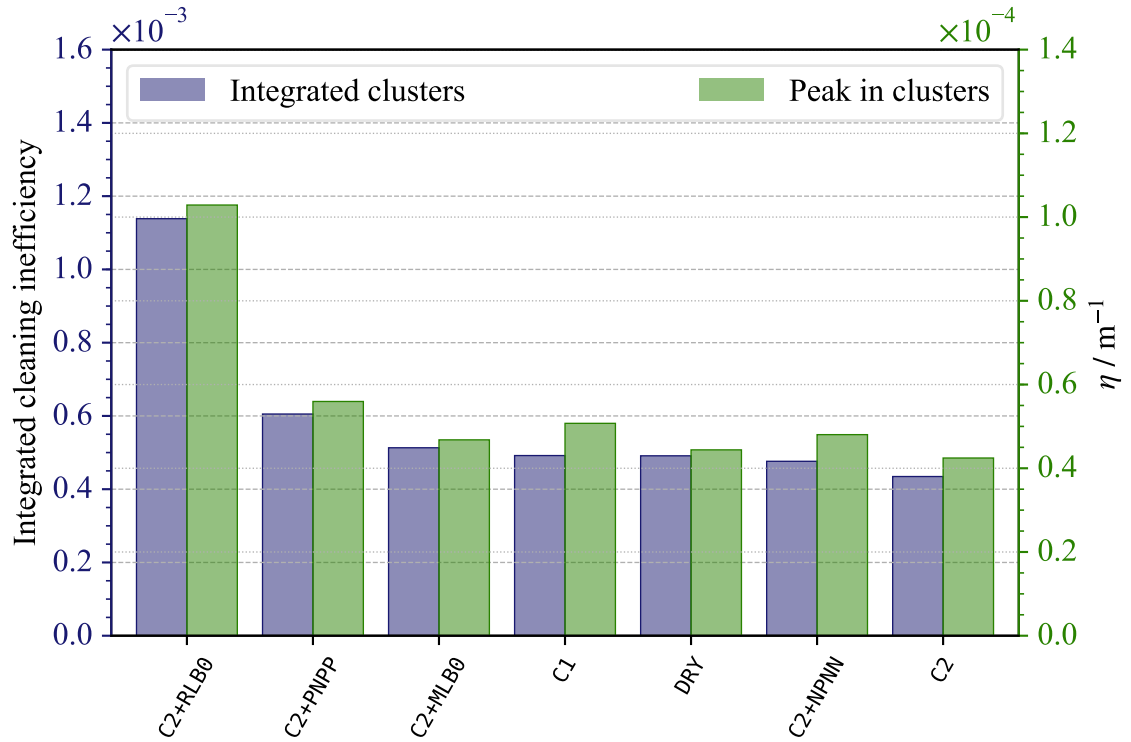


Figure 6.6: The cleaning performance of the configurations in B1V of LHC.

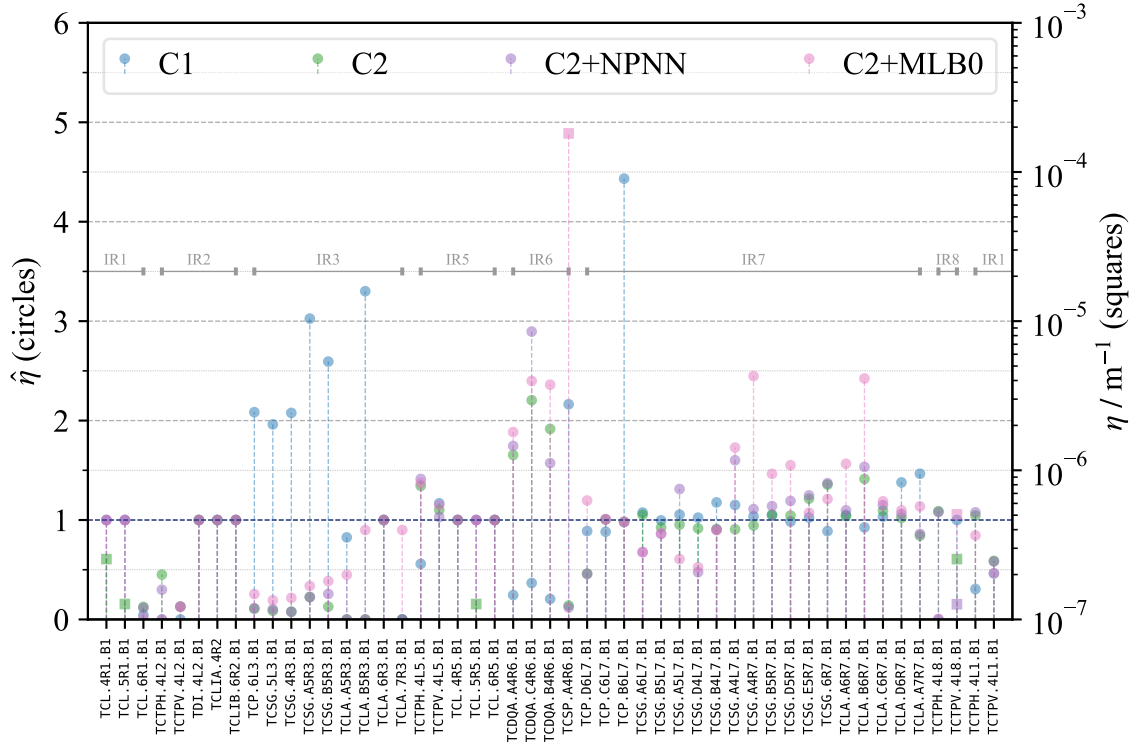


Figure 6.7: The distribution of collimator losses for the configurations in B1H of LHC.

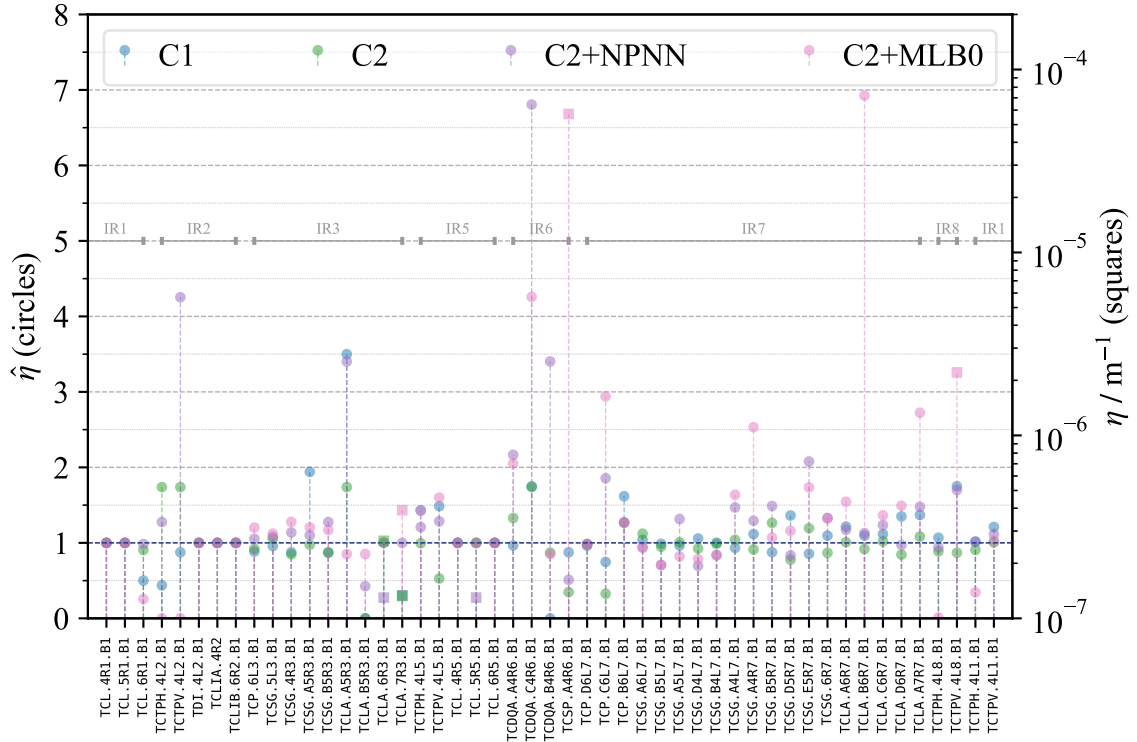


Figure 6.8: The distribution of collimator losses for the configurations in B1V of LHC.

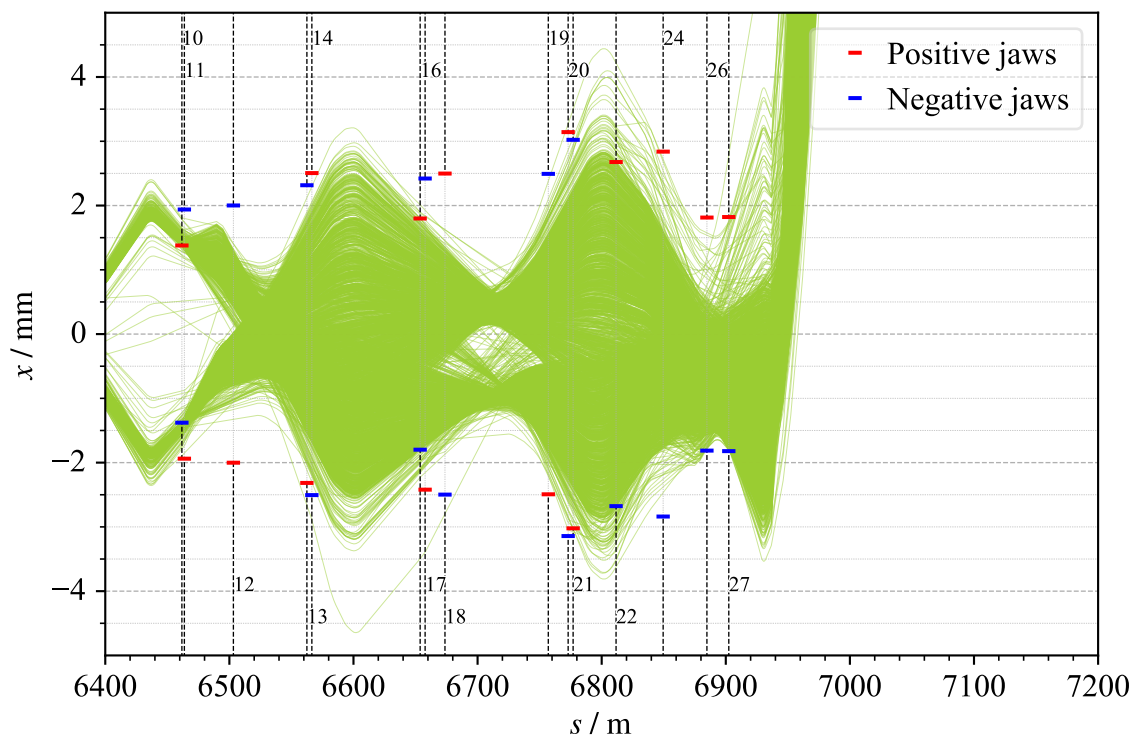


Figure 6.9: The particle pathways leading to the first cluster in B2H of LHC.

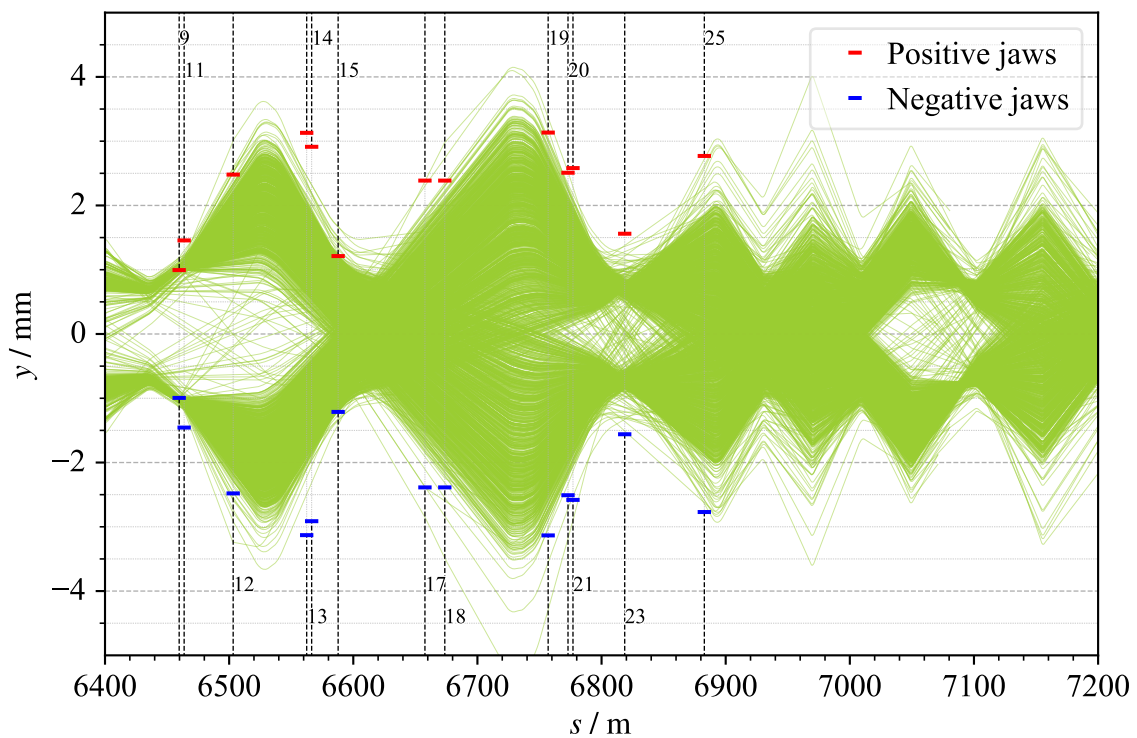


Figure 6.10: The particle pathways leading to the first cluster in B2V of LHC.

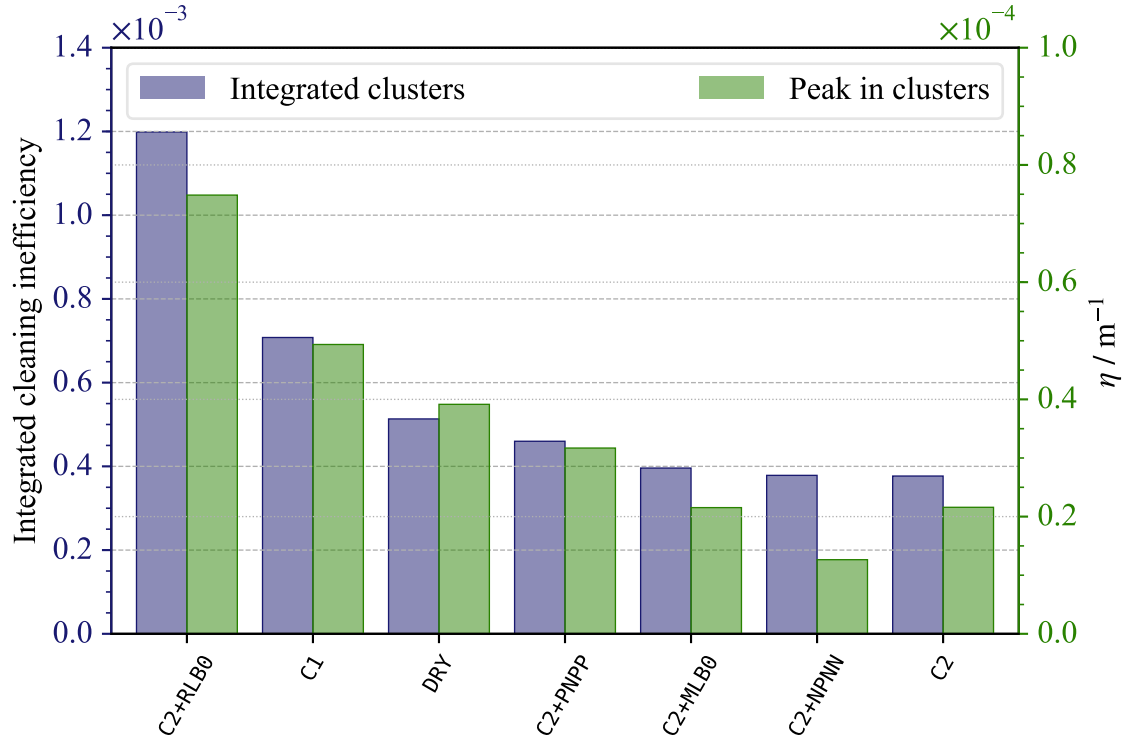


Figure 6.11: The cleaning performance of the configurations in B2H of LHC.

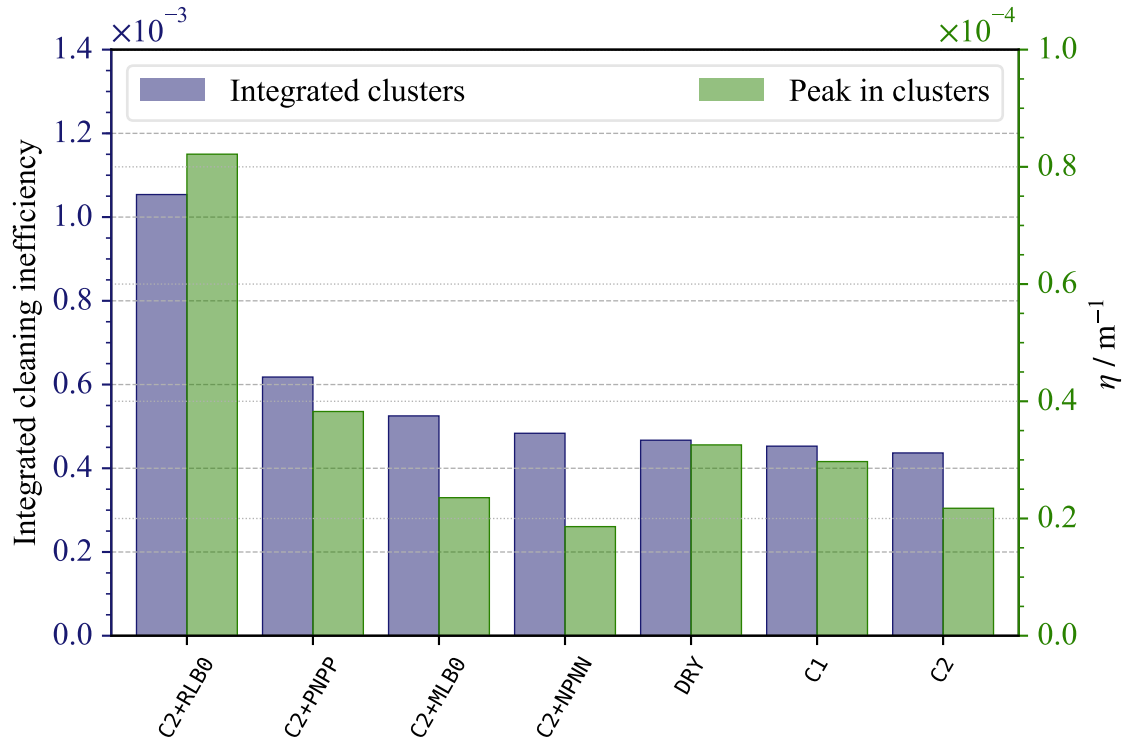


Figure 6.12: The cleaning performance of the configurations in B2V of LHC.

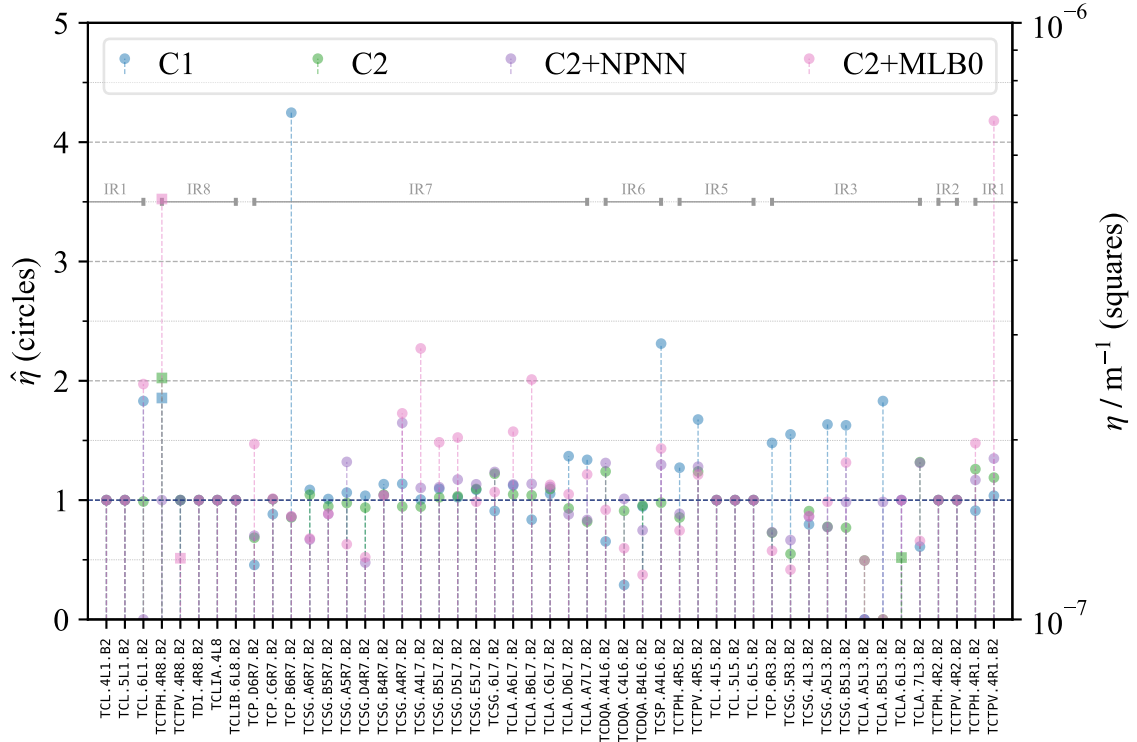


Figure 6.13: The distribution of collimator losses for the configurations in B2H of LHC.

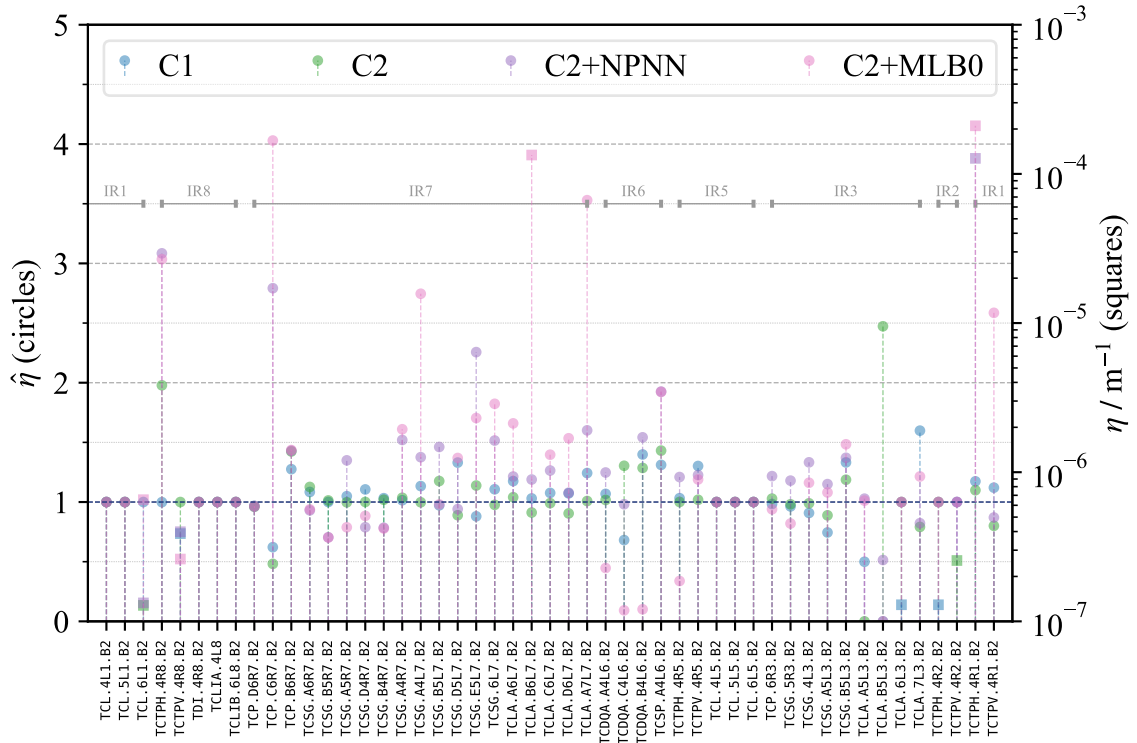


Figure 6.14: The distribution of collimator losses for the configurations in B2V of LHC.

6.2 Impedance simulations

6.2.1 The impedance budget

The LHC impedance model is employed to calculate the single-bunch impedance budget for B1 of Run II in 2018 at FT (6.5 TeV). As before, the contributions from the most critical elements are examined, with Figs. 6.15 to 6.21 breaking down the results in the same manner as shown for HL-LHC. It is clear that the collimators are even more dominant in LHC — contributing to more than 95 % of the total transverse impedance over a wide range of frequency. The contribution in the longitudinal plane also rises from about 15 % to 25 %, although the beam screen remains the most dominant element in that case.

As done previously, the multi-secondary configurations that were shown to preserve beam cleaning are now contrasted against a dry run in order to quantify the effectiveness of single-sided collimation as a means of reducing impedance. Inactive jaws are similarly displaced by 2 cm from the beam orbit, and the geometric component is once again invariant. Thus, one should bear in mind that the estimates in the potential gain are rather conservative. The results shown in Fig. 6.17 are quite similar to those obtained for HL-LHC. However, while the longitudinal impedance remains unaffected, the dipolar impedance drops by a larger factor in each configuration.

The imaginary part of the effective impedance is broken down in terms of the main accelerator elements. It is made clear in Fig. 6.18 that impedance in the LHC is driven by the RW component of the collimators, which amounts to more than three times the value in HL-LHC. Most other components (including the geometric) induce an almost equivalent amount as their counterparts in HL-LHC, despite the differences in beam energy and bunch intensity in the two machines. The drop in impedance for the two single-sided configurations is larger than what is observed for HL-LHC, both in relation to the dry run and in relation to one other.

The impedance per collimator subgroup is given in Fig. 6.19, where both the geometric and RW components are considered. The secondaries in IR7 are shown to be the most dominant subgroup in LHC — inducing up to seven times the impedance for HL-LHC, owing to the difference in material composition. The impedance induced by the primaries in IR7 also grows to double that in HL-LHC; however, all other subgroups, including those in IR3, remain largely unchanged. As a result, the TCPs in IR7 and the TCSGs in IR3 are not as significant as for HL-LHC. Given that the RW component is more significant in LHC; the gain in the single-sided configurations is far more pronounced. Once again, the results imply that the four high-impedance collimators induce roughly the same amount of impedance as all the other collimators in the subgroup combined. Appendix C.2 shows the impedances associated with individual collimators in LHC.

	Tapers (triplets)		Collimators (geometric)
	BPMs (triplets)		Collimators (RW)
	Pumping holes		Beam screen (RW)
	RF, CMS, ALICE, LHCb		Warm pipe (RW)
	Other broadband		

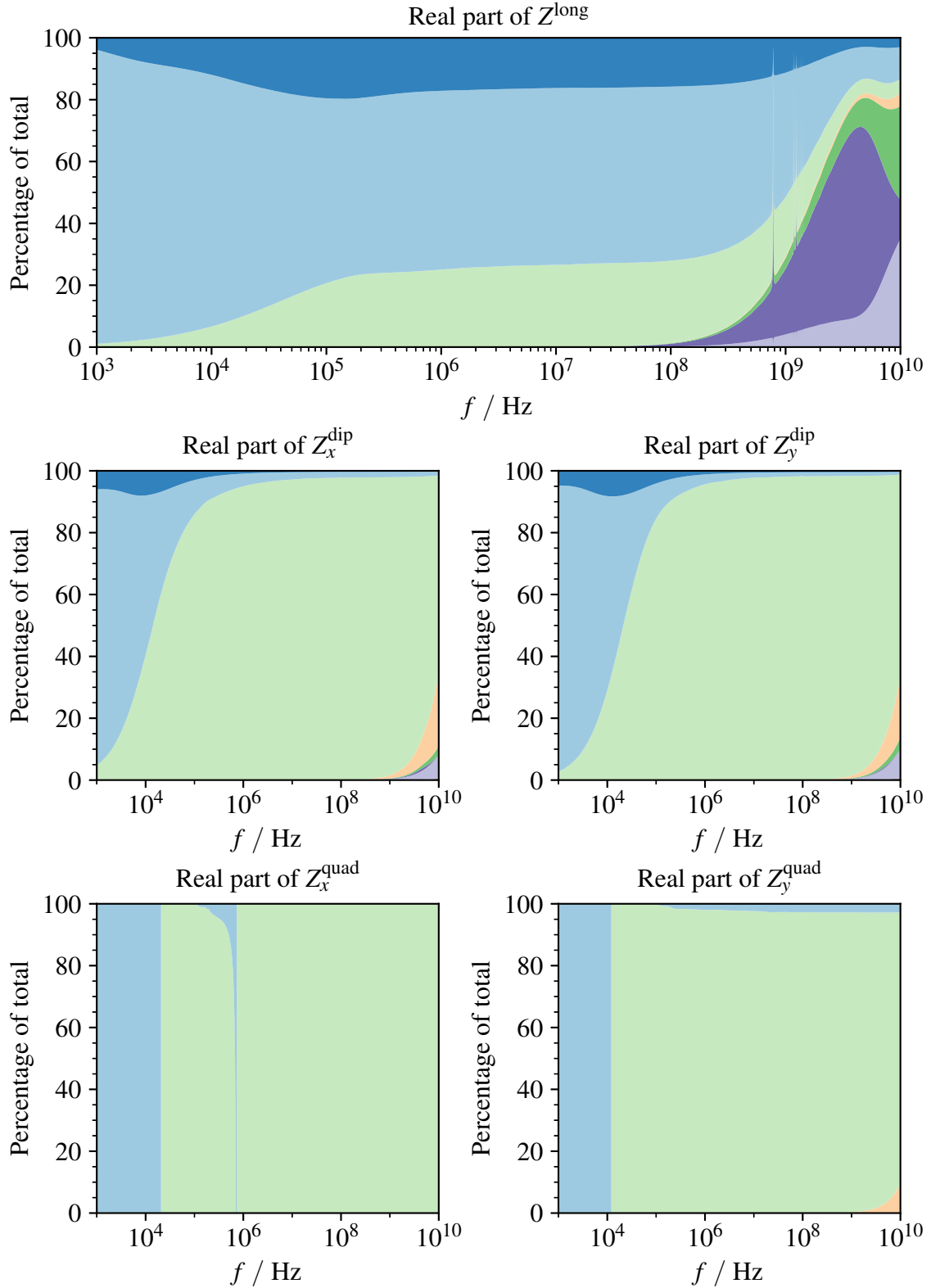


Figure 6.15: Composition of the real part of the multipolar impedance as a function of frequency for the LHC at 6.5 TeV. Legend on page 104.

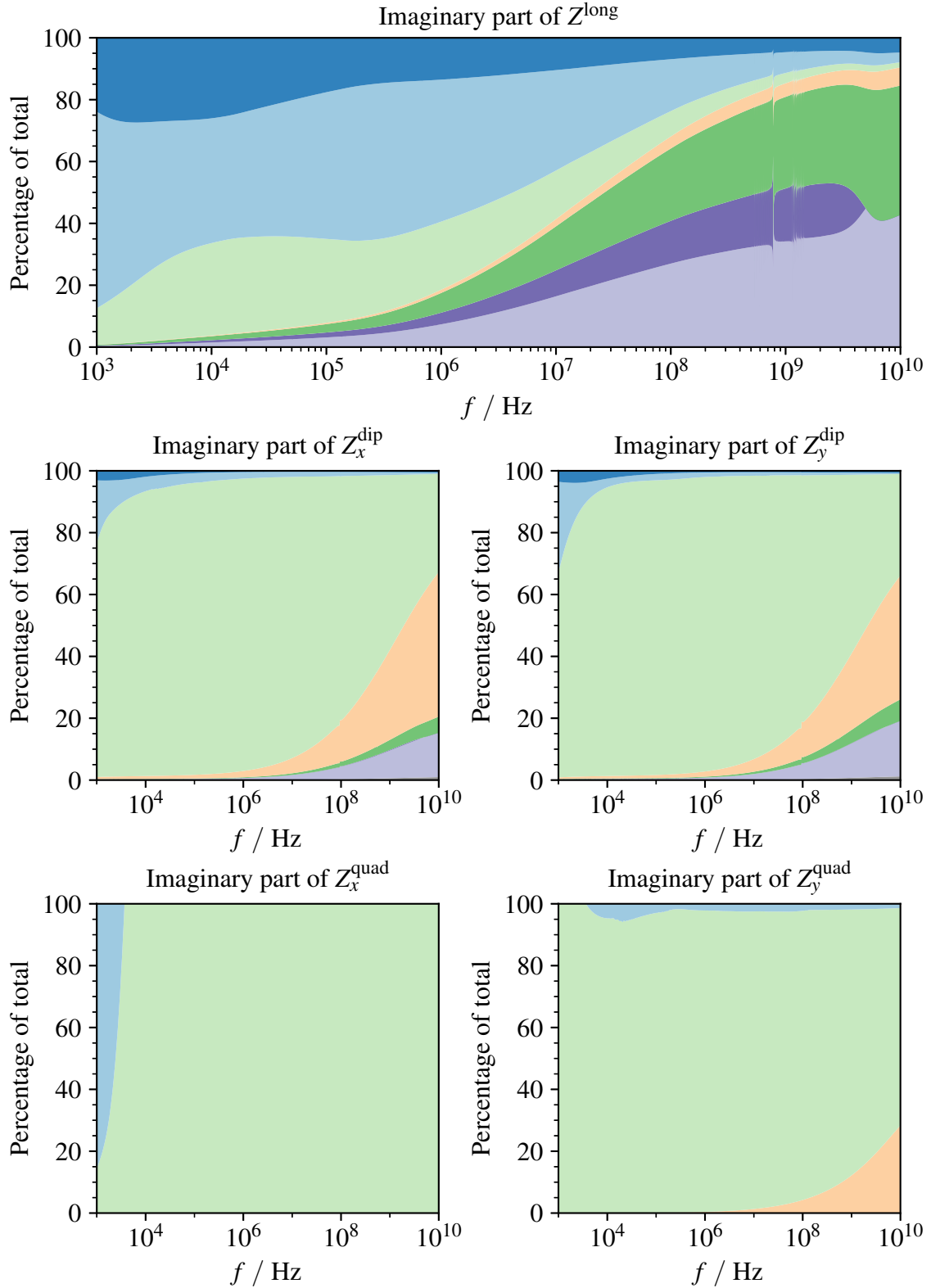


Figure 6.16: Composition of the imaginary part of the multipolar impedance as a function of frequency for the LHC at 6.5 TeV. Legend on page 104.

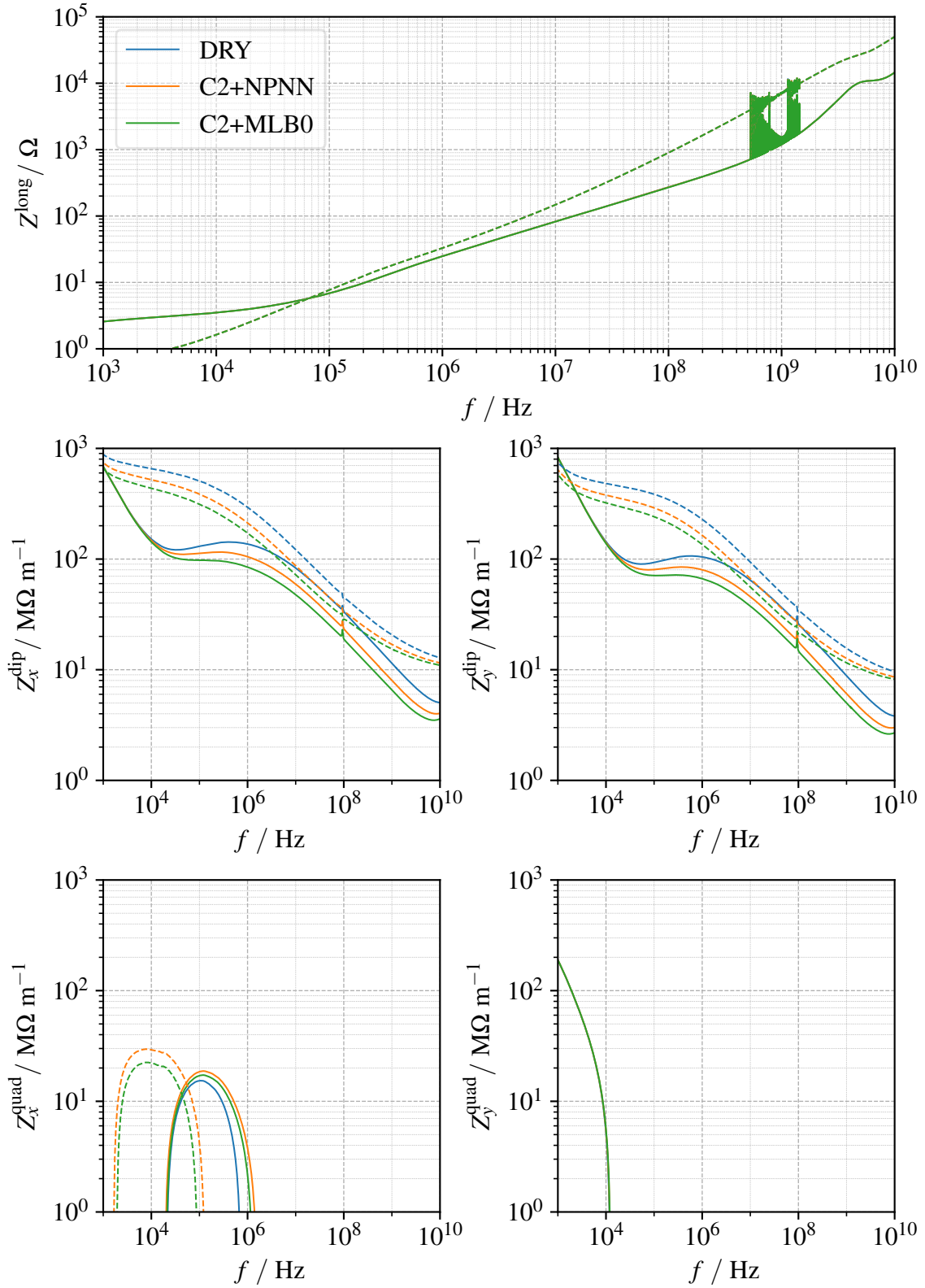


Figure 6.17: The real (continuous) and imaginary (dashed) parts of the total impedance as a function of frequency for B1 of the LHC at 6.5 TeV.

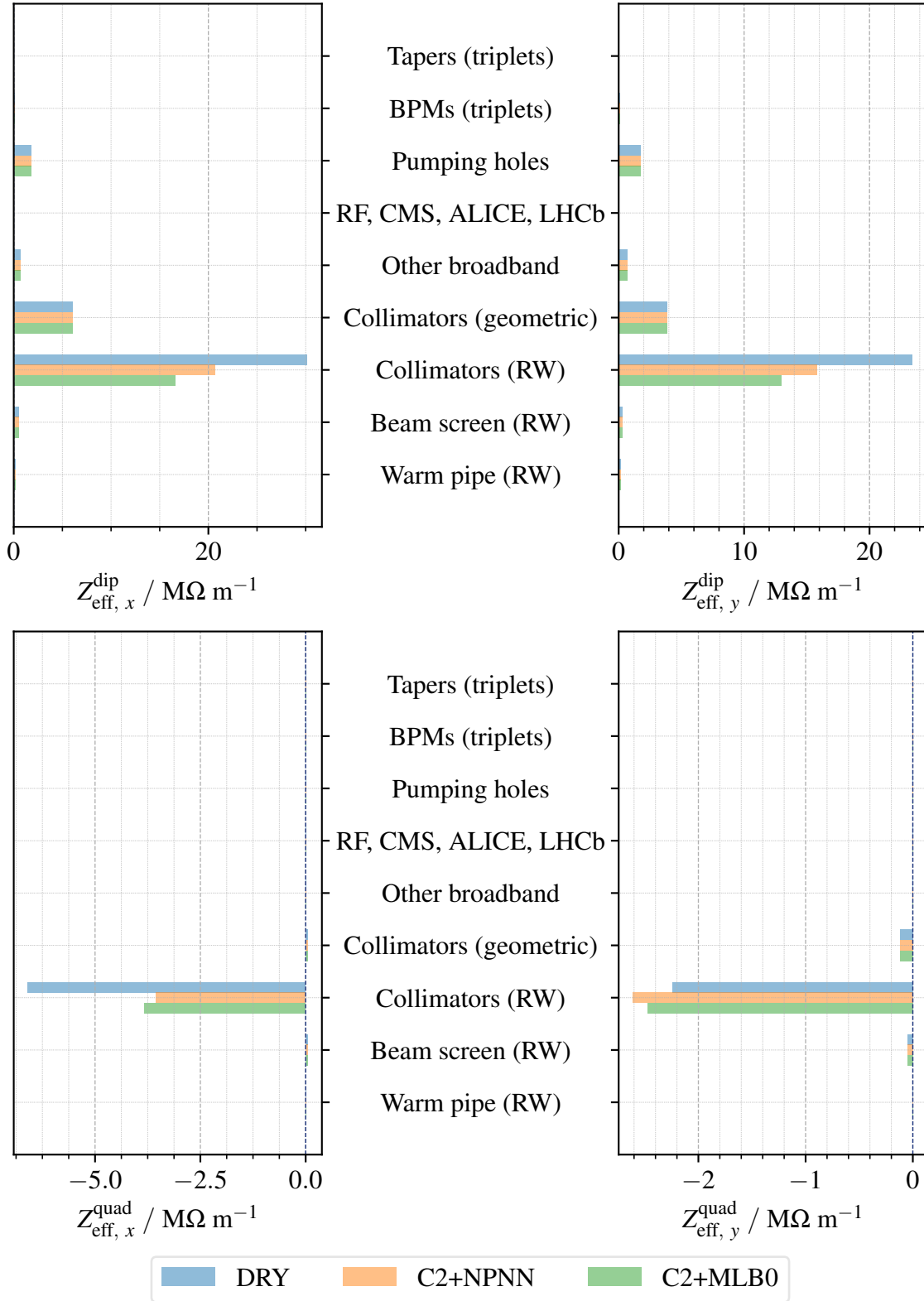


Figure 6.18: The imaginary part of the multipolar effective impedance for the most critical components of the LHC.

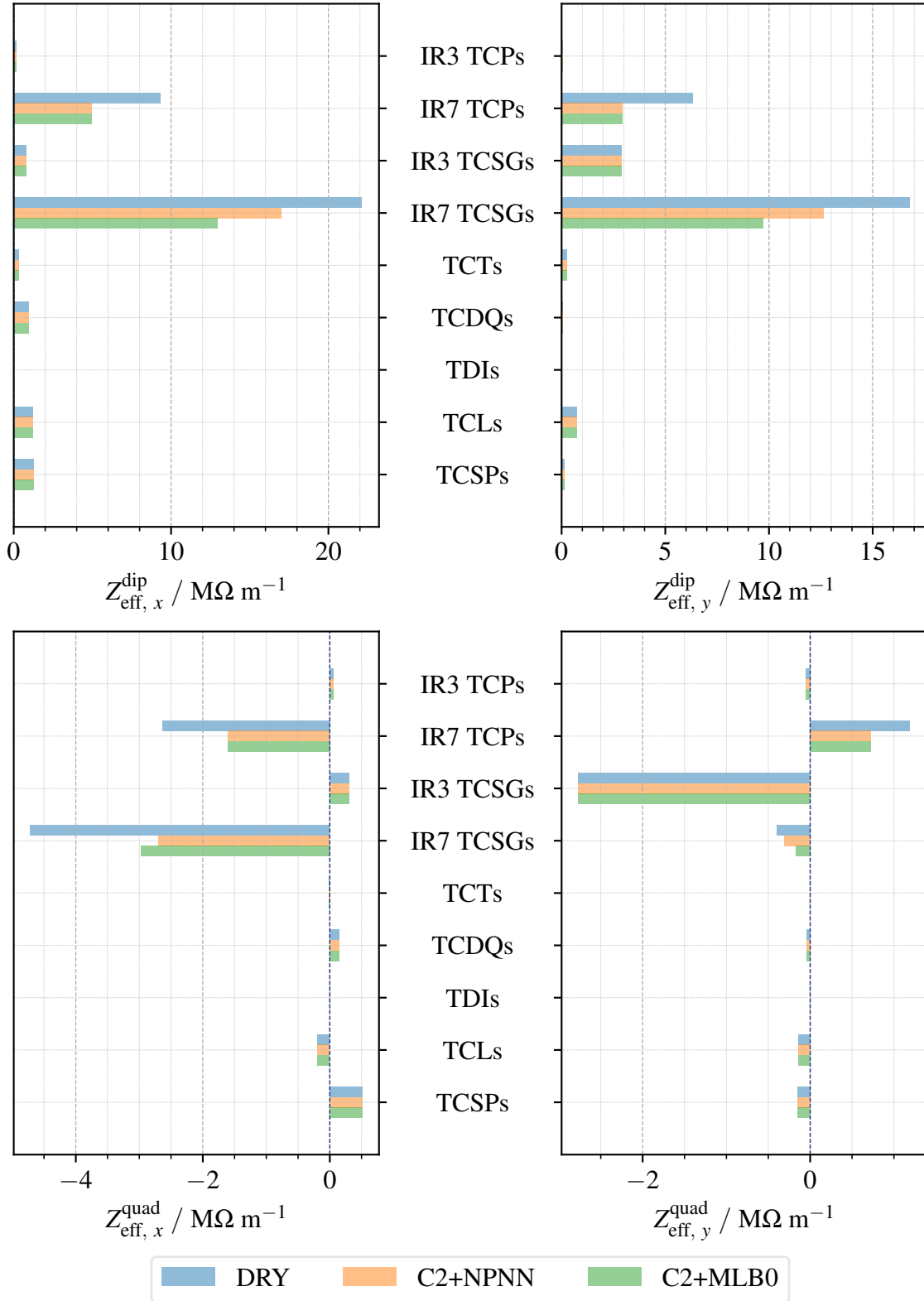


Figure 6.19: The imaginary part of the multipolar effective impedance for each collimator subgroup in LHC. Both the geometric and RW components have been considered.

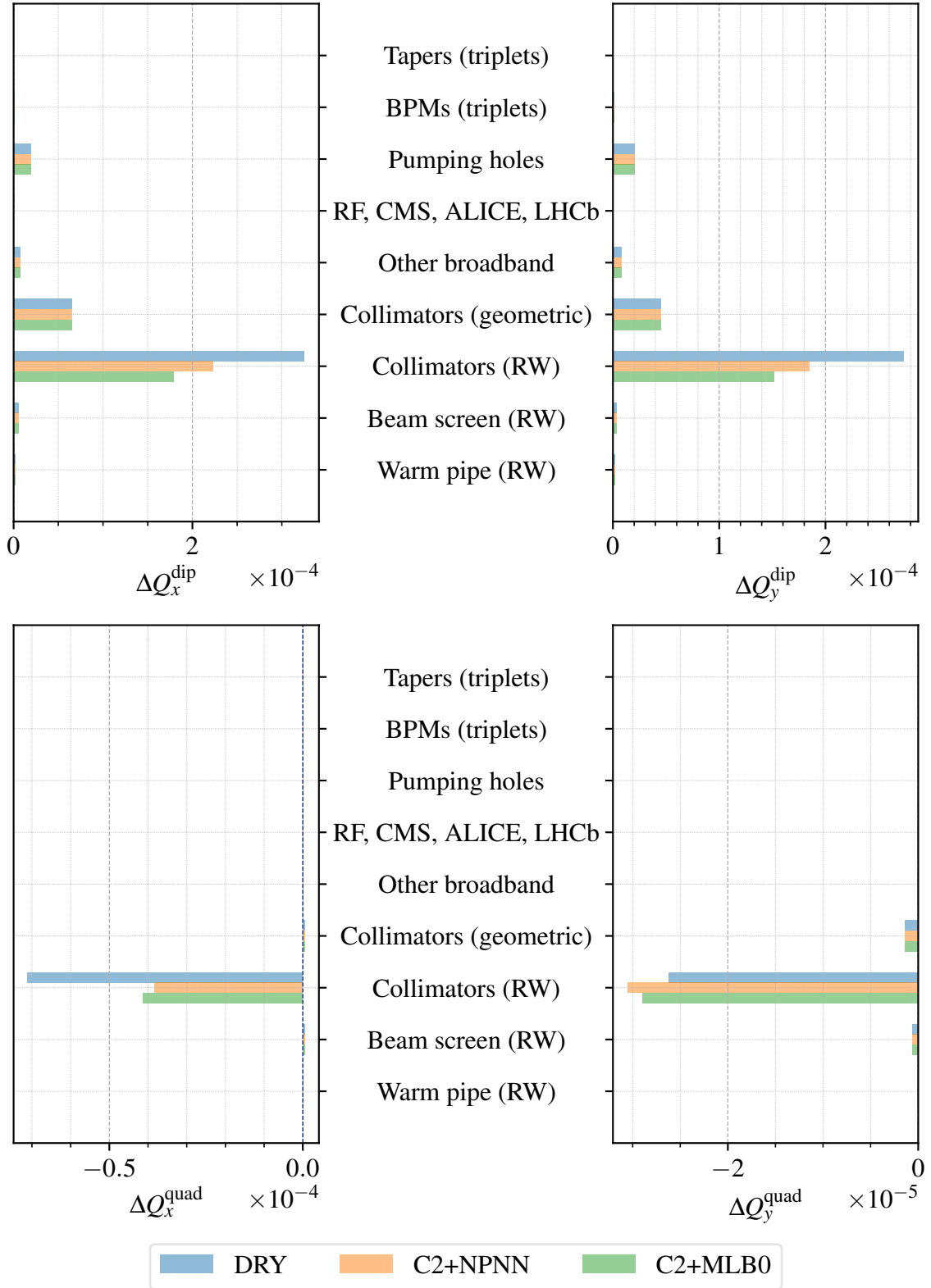


Figure 6.20: The real-valued part of the tune shift induced by the most critical components of the LHC.

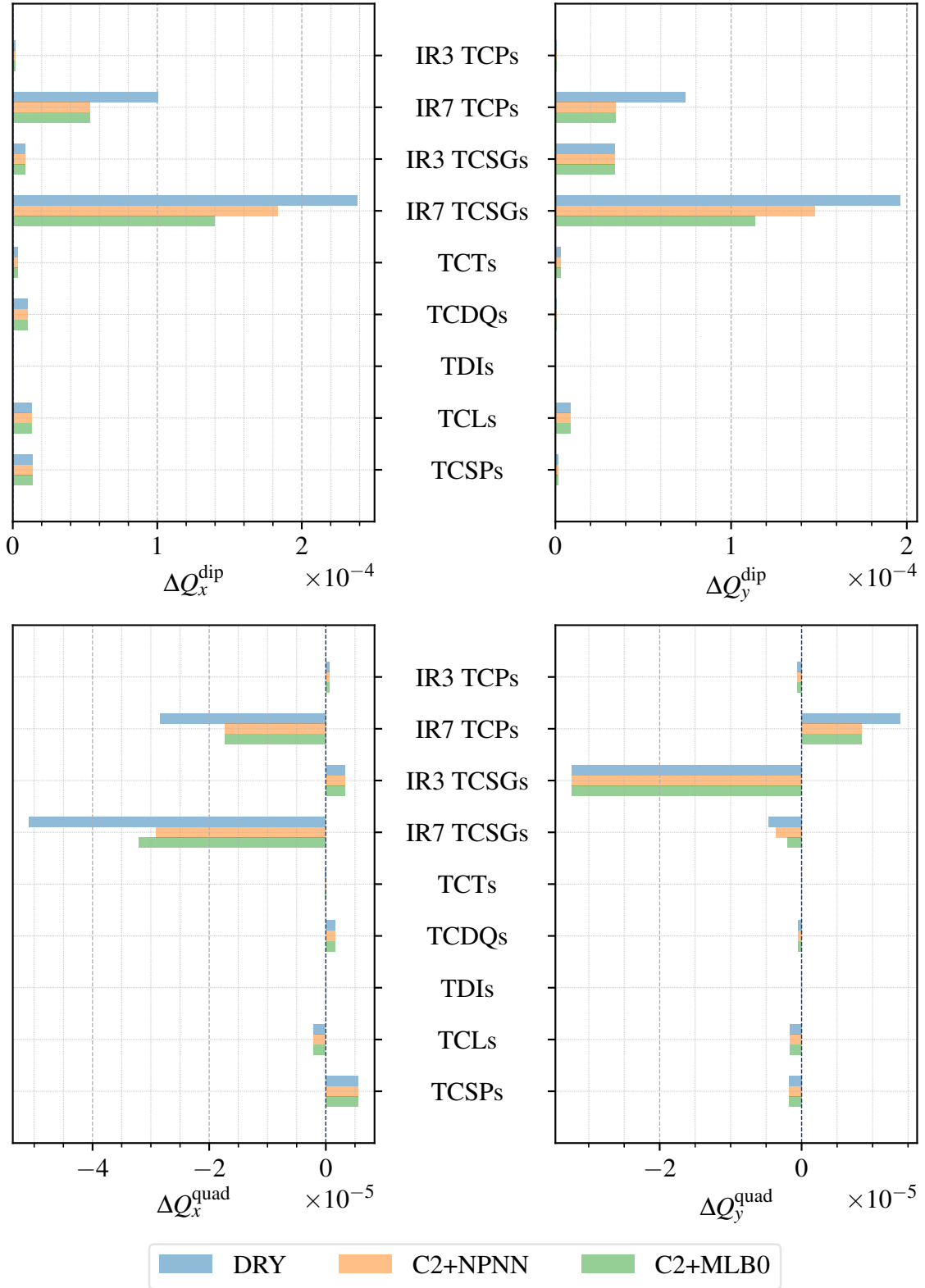


Figure 6.21: The real-valued part of the tune shift induced by each collimator subgroup in LHC. Both the geometric and RW components have been considered.

6.2.2 The octupole current threshold

DELPHI is used in conjunction with the results from the LHC impedance model in order to compute the octupole current threshold in the LHC. A single bunch of 1.4×10^{11} particles is simulated in the horizontal plane, having a gaussian transverse distribution with a normalised emittance of $2.0 \mu\text{m}$, and an RMS bunch length of 8.1 cm . The ADT is set to a damping time of 100 turns.

Fig. 6.22 shows that the dip in the octupole current is larger for the single-sided configurations in the LHC, thus making single-sided collimation more viable. The improvement is also seen across a wider range of chromaticities, with I_{oct} dropping by roughly 50 A for C2+NPN, and 70 A for C2+MLB0 over the range $Q' \in [9, 17]$. Massive improvement is also seen for chromaticities in the range $Q' \in [-2, 1]$. The octupole current scales linearly with intensity and inversely with emittance, meaning that even more current is saved at higher intensities.

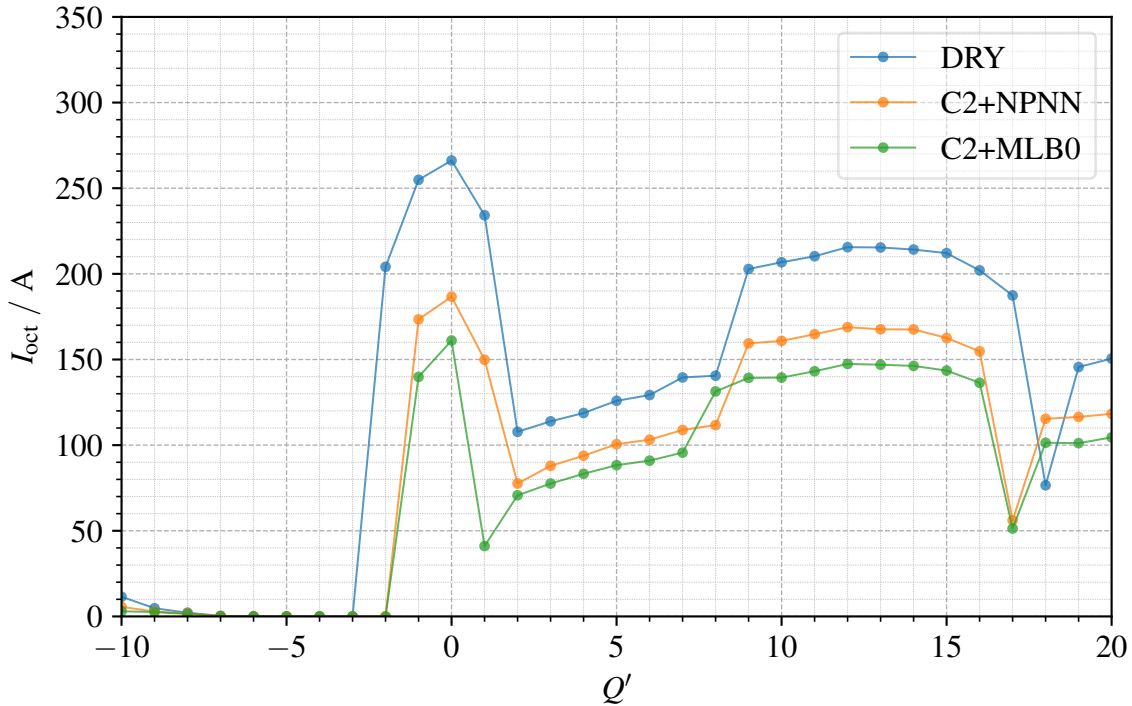


Figure 6.22: The octupole current threshold as a function of chromaticity for the LHC.

6.3 Machine measurements

Machine Development (MD) aims at a better understanding of the LHC, its equipment, and beam physics in general, with the hope of increasing performance in the long term [50]. Such studies are carried out during MD sessions (MDs), which are assigned to designated periods of the LHC schedule. Two MDs were granted for the purpose of probing single-sided collimation. The first (MD1653) took place on June 16th 2018, and was only enough to characterise the TCP configurations in terms of beam cleaning, as single-sided collimation was peripheral to this MD. The second (MD2901) was carried out on July 25th 2018, and was entirely dedicated to analysing single-sided collimation, both in terms of beam cleaning and impedance. Consequently, the following shall focus on the latter — MD2901.

6.3.1 MD procedure

Two ramps were executed in order to optimise beam parameters when carrying out different measurements. The first ramp was dedicated to studying beam cleaning, whilst the second ramp considered only impedance related measurements. Beam cleaning was characterised through loss maps generated after blowing up pilot bunches (approximately 10^{10} particles) with the ADT in both planes for B1 and B2. Impedance was characterised through tune shift measurements taken during rapid switching between symmetric and single-sided settings, all while exciting transverse oscillations through the transverse feedback system (ADT) in order to increase precision (as done successfully in similar studies [44]). The instability rise time was also measured at the end of each fill, right after switching off the ADT.

The following provides a general outline of the official procedure, with the main configurations being DRY, C1, C2, C2+NPNN, C2+PNPP, C2+MLB0, and C2+RLB0. Note that all measurements were carried out at FT, with inactive jaws set to a displacement of 2 cm. Fig. 6.23 provides a timeline of the MD by showing the beam intensities and energy during the full study — which was allotted slightly more than 8 hours in total. The octupole current threshold was not measured as the process is rather time-consuming, and it would not have left any time for other measurements.

Cleaning measurements:

1. Inject a nominal bunch (1.2×10^{11} particles) in each beam.
2. Inject 18 pilots per beam.
3. Ramp up to FT with the standard ramp.
4. Deploy a specific configuration in both beams.
5. Use the ADT to blow up pilot bunches in each plane of B1 and B2.
6. Record the generated loss maps.
7. Repeat steps 4–6 for all the main configurations.

8. Perform a wire-scan and verify the beam intensity and emittance.
9. Measure the instability rise time for a particular configuration after lowering the octupole current to 300 A and deactivating the ADT.
10. Dump the beam.

Impedance measurements:

1. Inject two nominal bunches per beam with different intensities (0.8×10^{11} and 1.8×10^{11}) to increase the sensitivity of tune shift measurements.
2. Verify the beam intensity and emittance, and adjust the ADT kicking.
3. Ramp up to FT with the standard ramp.
4. Set the octupole current to maximum (550 A).
5. Lower the chromaticity in two steps of 5 units each, thus arriving at 5–10 units.
6. Deploy a specific configuration.
7. Measure the tune shift generated by switching back and forth between symmetric and single-sided settings, whilst simultaneously kicking the beam coherently with the ADT.
8. Repeat the previous two steps for the other single-sided configurations.
9. Reduce the half-gap of primary and secondary collimators in IR7 by 1σ in order to improve sensitivity.
10. Repeat steps 6–8.
11. Perform a wire-scan and verify the beam intensity and emittance.
12. Measure the instability rise time for a particular configuration after lowering the octupole current to 300 A and deactivating the ADT.
13. Dump the beam.

6.3.2 Cleaning results

The procedure for the cleaning measurements was followed as described, with only very minor hiccups. Indeed, all the configurations were tested in both planes of B1 and B2. The individual loss maps will not be shown due to the sheer volume of results. Instead, the data is contracted to highlight the most pivotal information; that being, the aggregate and peak losses in the DS downstream of IR7. The BLM data has an integration window of 1.3 s (RS09) and is normalised to the highest signal, which is typically associated with one of the primaries in IR7. This is to account for differences in bunch intensities and other uncontrollable factors. Background noise has also been reduced from the data.

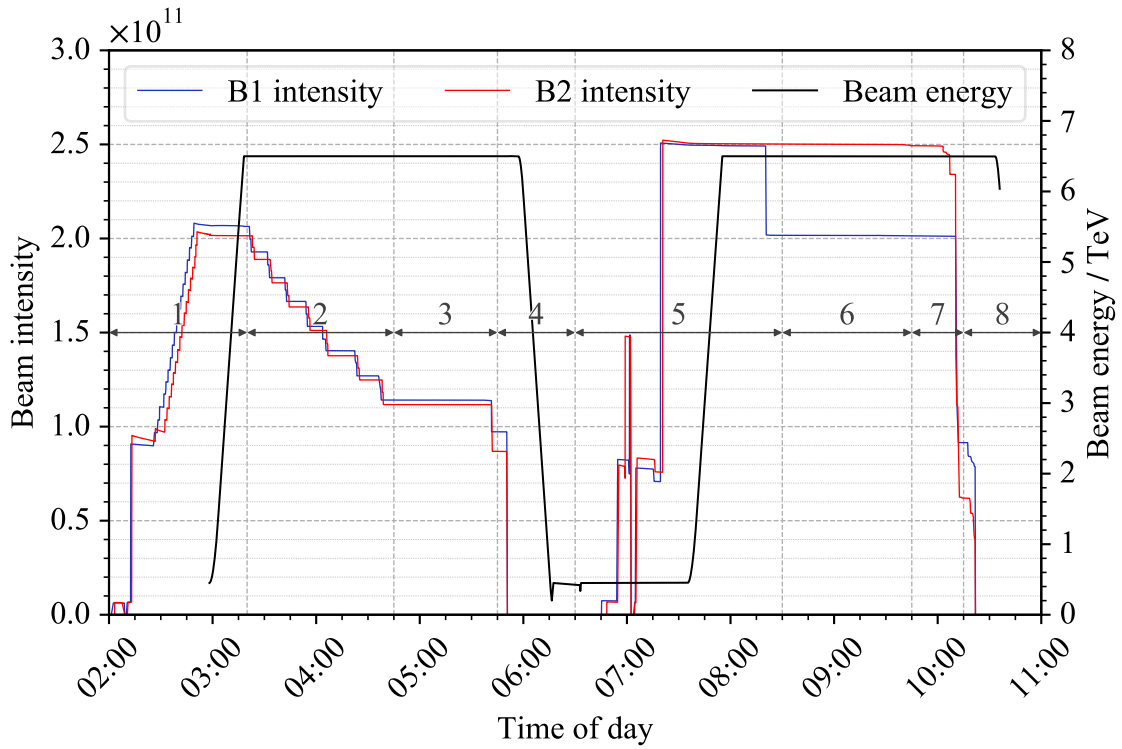


Figure 6.23: The timeline of the MD in terms of beam intensities and energy. The demarcations identify the most noteworthy events — namely: injection and ramp up of the first fill (1); generation of loss maps (2); first measurement of instability rise time (3); beam dump and ramp down of the first fill (4); injection and ramp up of the second fill (5); tune shift measurements (6); second instability rise time measurement (7); beam dump and ramp down of the second fill (8).

The increase in the normalised BLM signal of C1 and C2 relative to DRY is shown in Figs. 6.24 and 6.25. It can be observed that C2 performs only slightly better than C1, with the largest margin of improvement being given by the first cluster. The second and third clusters in B1V appear to favour C1, however the differences are practically negligible, and the third cluster is rather trivial when compared to the first. By comparing these results to those obtained from simulation (see Figs. 6.1 and 6.2) it is clear that C1 and C2 are far less divergent in measurements. Nonetheless, it should be acknowledged that C2 essentially offers the same cleaning performance as the standard settings, but with only half of the TCP jaws.

Figs. 6.26 to 6.29 characterise the cleaning performance of the main configurations in terms of aggregate and peak losses in the DS. Both simulation and measurement data is displayed, with the results from the two MDs being superimposed and assumed to have an error in the order of 20%, which is customary for loss map measurements. When comparing the results of simulations and measurements, it is important to remember that the respective quantities used to assess beam cleaning are inherently different. BLMs measure ionising radiation and EM showers, whilst SixTrack considers only primary particles. Hence, it is inappropriate to compare the quantities in terms of absolute values. Instead, one should examine trends and relative changes in the performance of configurations.

The agreement between simulations and measurements is fairly good when examining B1, as the trends for both the aggregate and peak losses are similar. Strangely, the similarities end with the last two configurations (C2+MLB0 and C2+RLB0), where measurements suggest that C2+RLB0 is the better performing of the two. Additionally, C2 appears to be the only configuration capable of outperforming DRY in reality, as the measured losses tend to be slightly higher than what the simulations would suggest. The results of B2 require further understanding, as the measured trends are in almost direct contradiction to the simulated trends — specifically in B2V, where the reversed secondary configurations (C2+PNPP and C2+RLB0) are favoured over the proper (C2+NPNN and C2+MLB0).

The discrepancy between simulations and measurements could be due to a drift in the closed orbit. Figs. 6.30 to 6.33 show readouts obtained from beam position monitors (BPMs) in IR7 during the period that loss maps were being generated. It is clear that B1 is quite homogeneous, with the beam staying close to the designated orbit. B2 however, drifts significantly at semi-regular intervals — some coinciding with the loss maps. It is perhaps for this reason that B2 sees disagreement between measurements and simulations; however, it is still unclear why C2+RLB0 outperforms C2+MLB0 in every scenario. It is worth mentioning that closed orbit drifts are not the only factor capable of contributing to this discrepancy. Simulations consider an idealised version of the machine, which is far from what exists in reality.

The fact that C2+RLB0 performs better than C2+MLB0 in every case implies that none of the multi-secondary configurations are optimal. Be that as it may, the peak value of C2+RLB0 is approximately double that of DRY in each respective case, meaning that even for a non-optimal configuration, the induced losses are still well below the quench limit; hence, an optimal configuration should prove to be more than manageable. On the other hand, it remains to be seen whether sacrificing cleaning in such a way is worth the gain in impedance.

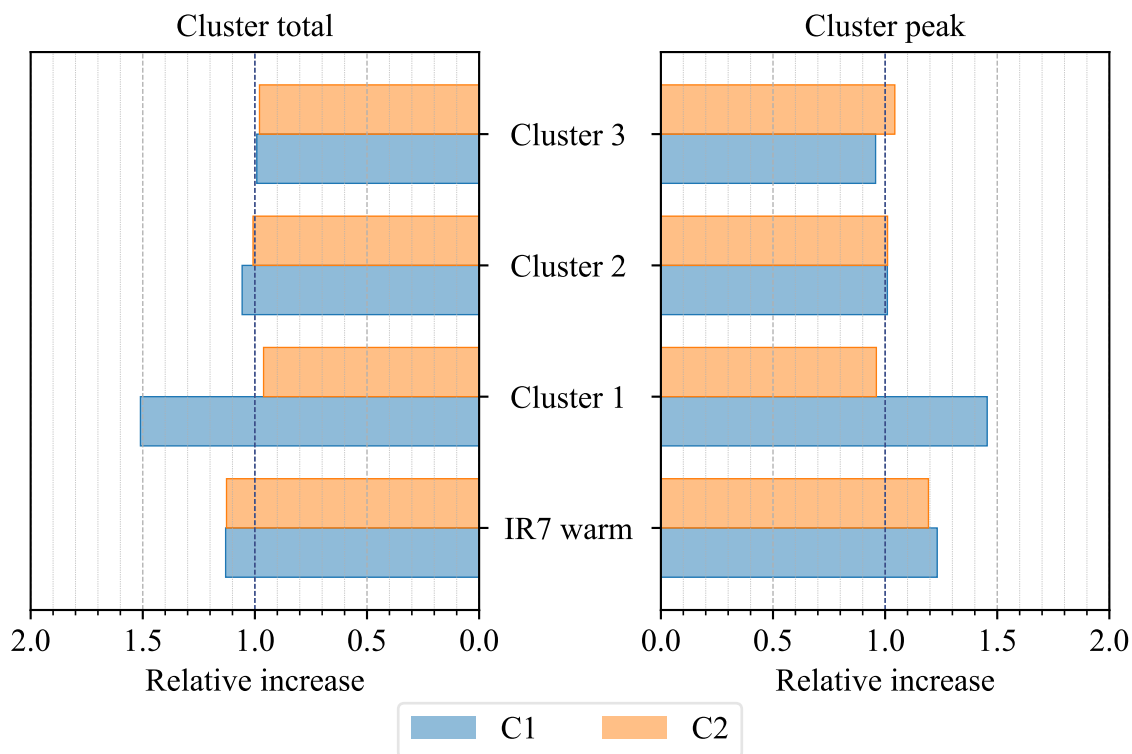


Figure 6.24: The relative increase in the normalised BLM signal for B1H (MD1653).

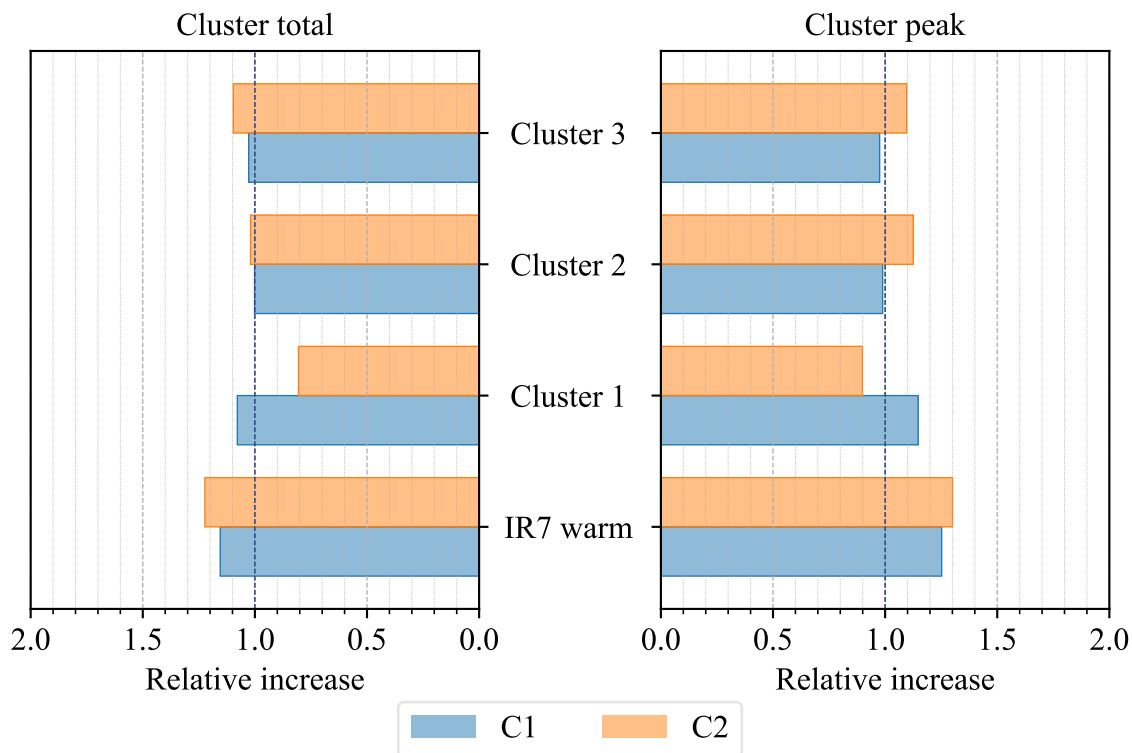


Figure 6.25: The relative increase in the normalised BLM signal for B1V (MD1653).

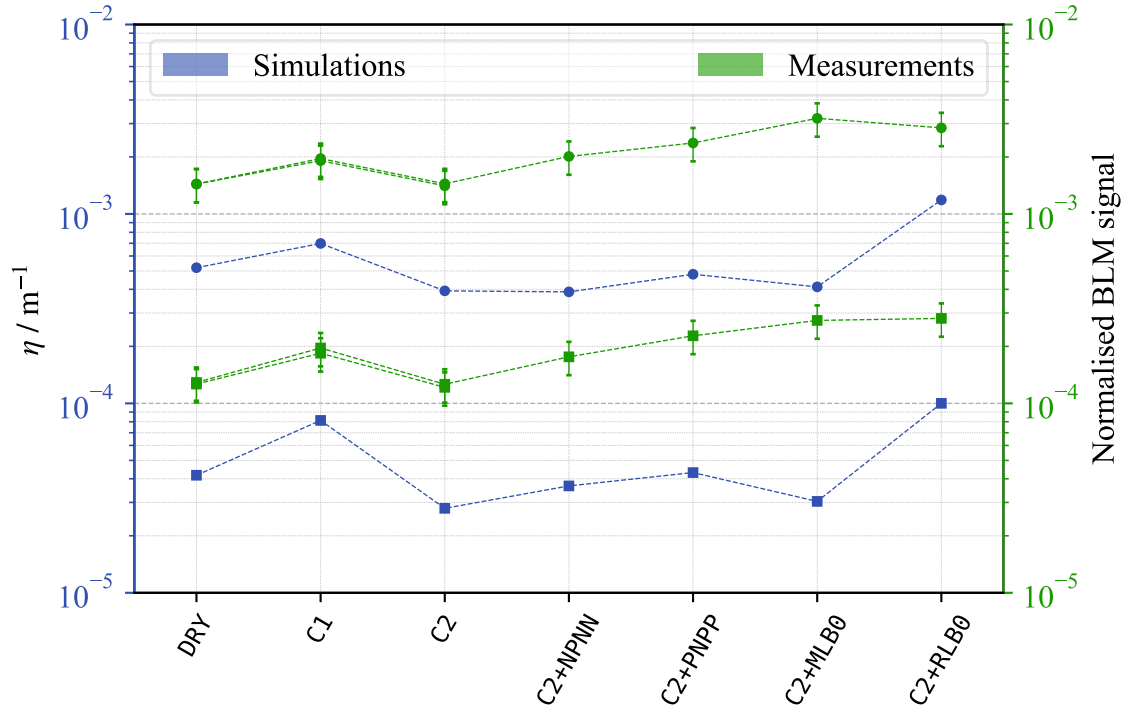


Figure 6.26: The aggregate (circles) and peak (squares) losses in the DS as given by simulations and measurements of the main configurations in B1H.

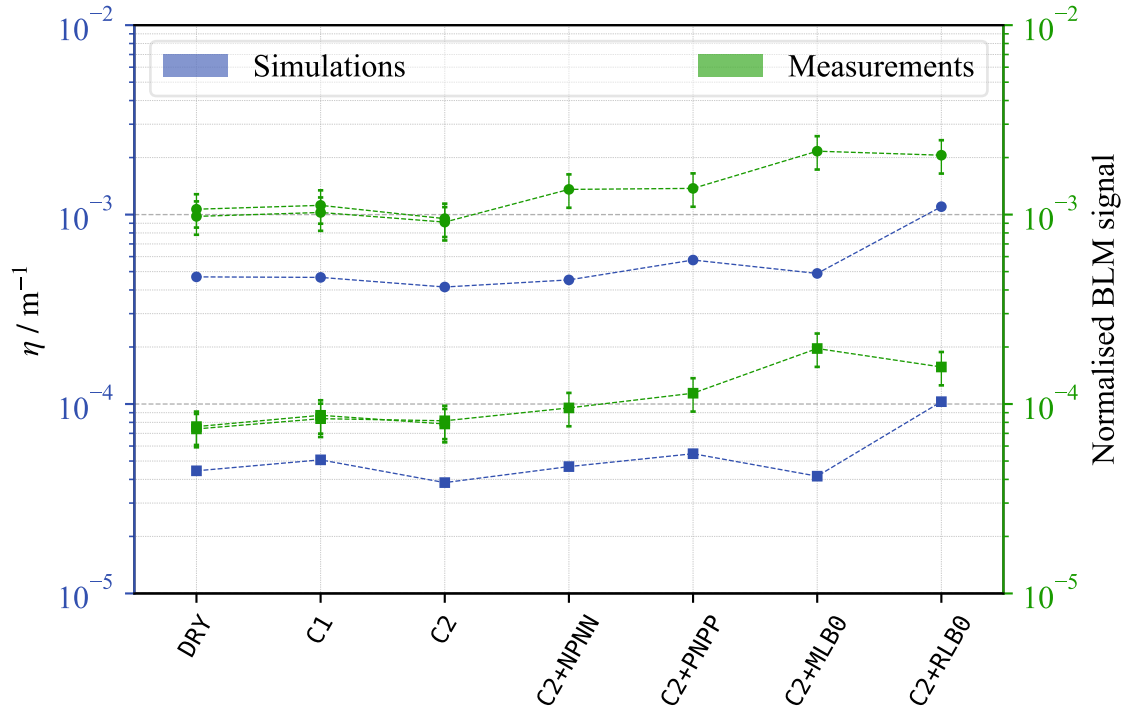


Figure 6.27: The aggregate (circles) and peak (squares) losses in the DS as given by simulations and measurements of the main configurations in B1V.

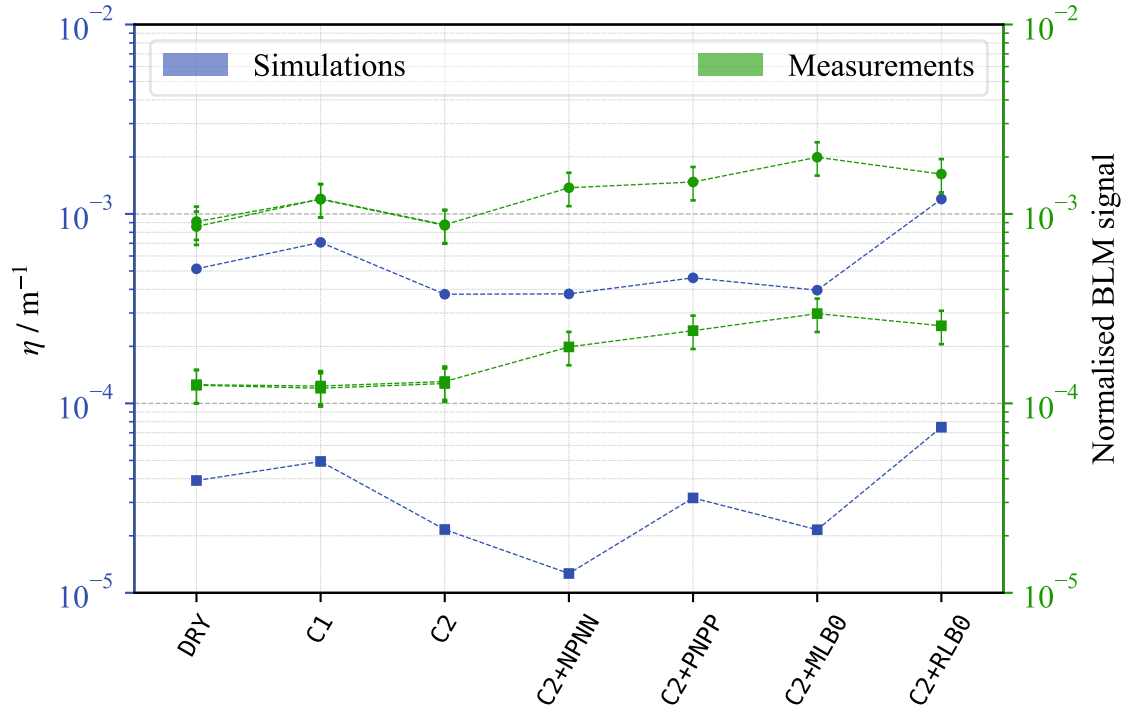


Figure 6.28: The aggregate (circles) and peak (squares) losses in the DS as given by simulations and measurements of the main configurations in B2H.

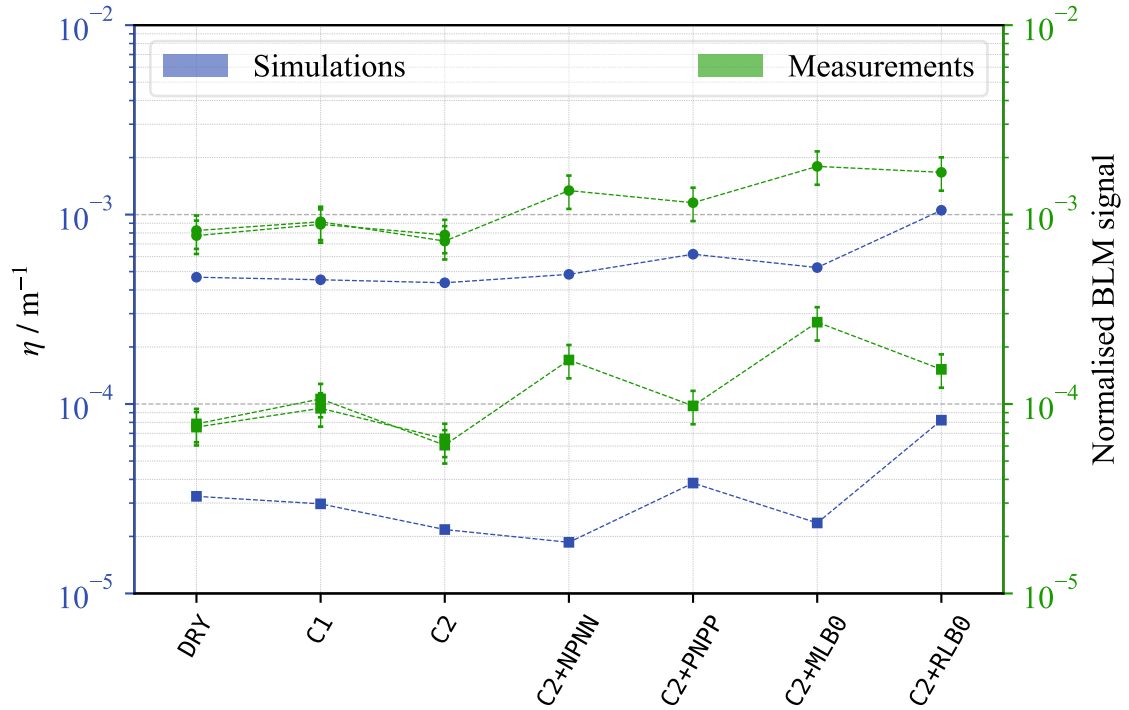


Figure 6.29: The aggregate (circles) and peak (squares) losses in the DS as given by simulations and measurements of the main configurations in B2V.

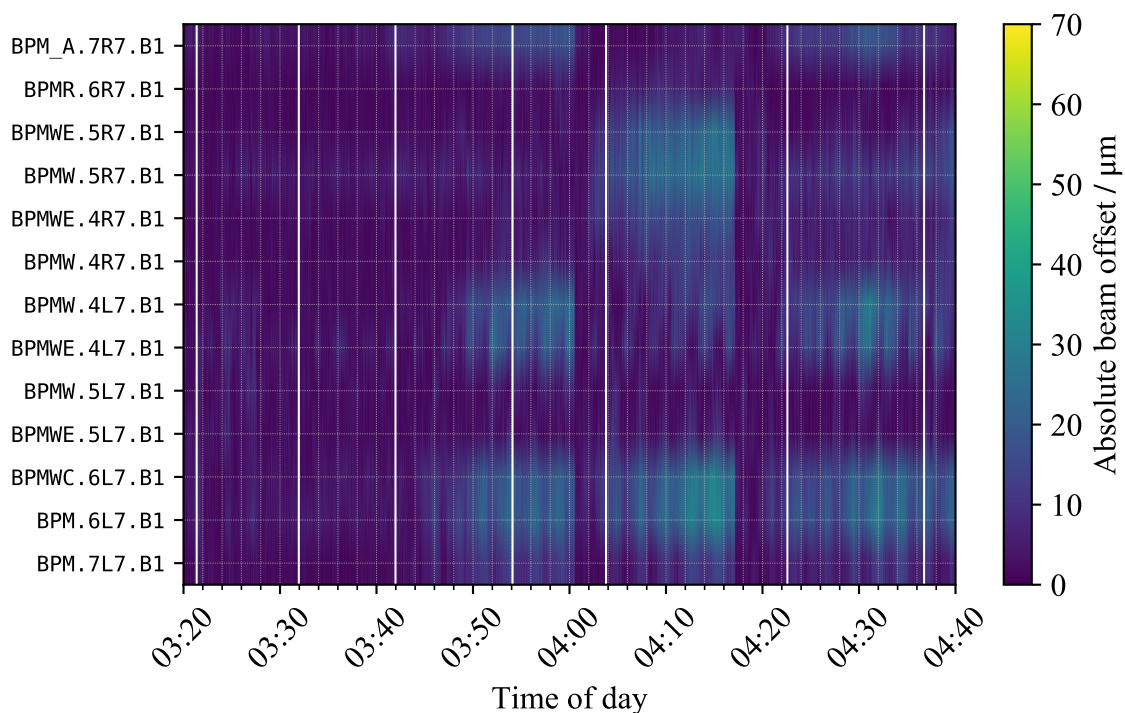


Figure 6.30: The beam offset in B1H as measured by BPMs in IR7 for MD2901. White vertical lines mark the loss maps of each configuration in the order presented hitherto.

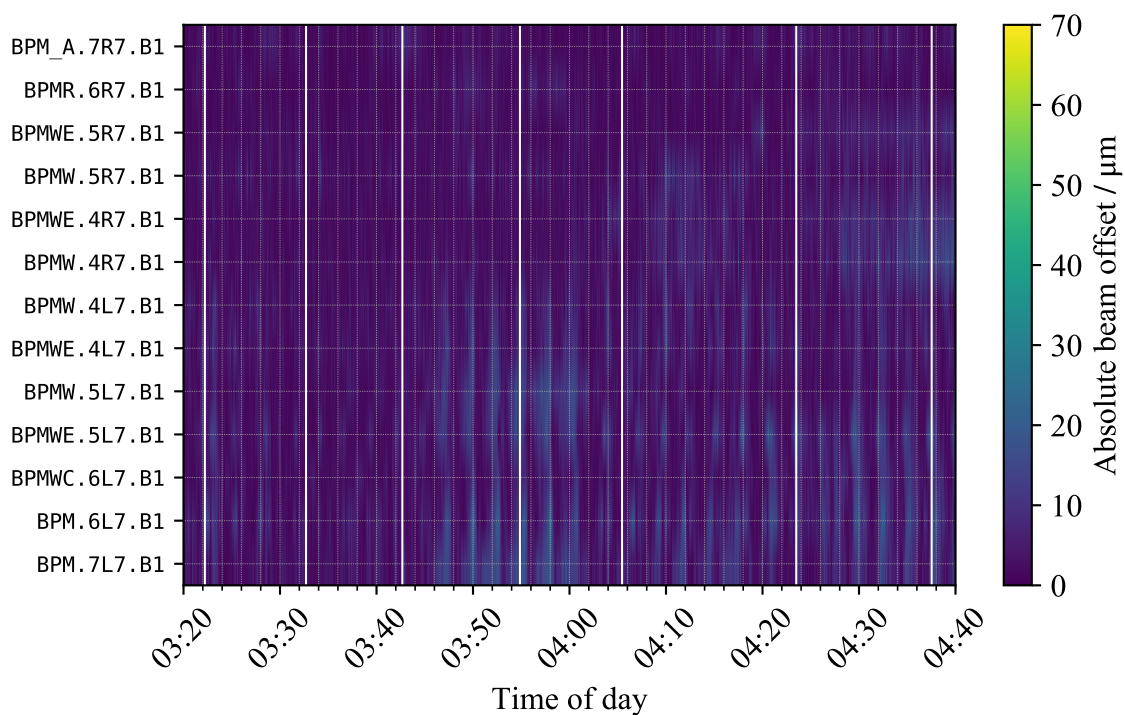


Figure 6.31: The beam offset in B1V as measured by BPMs in IR7 for MD2901. White vertical lines mark the loss maps of each configuration in the order presented hitherto.

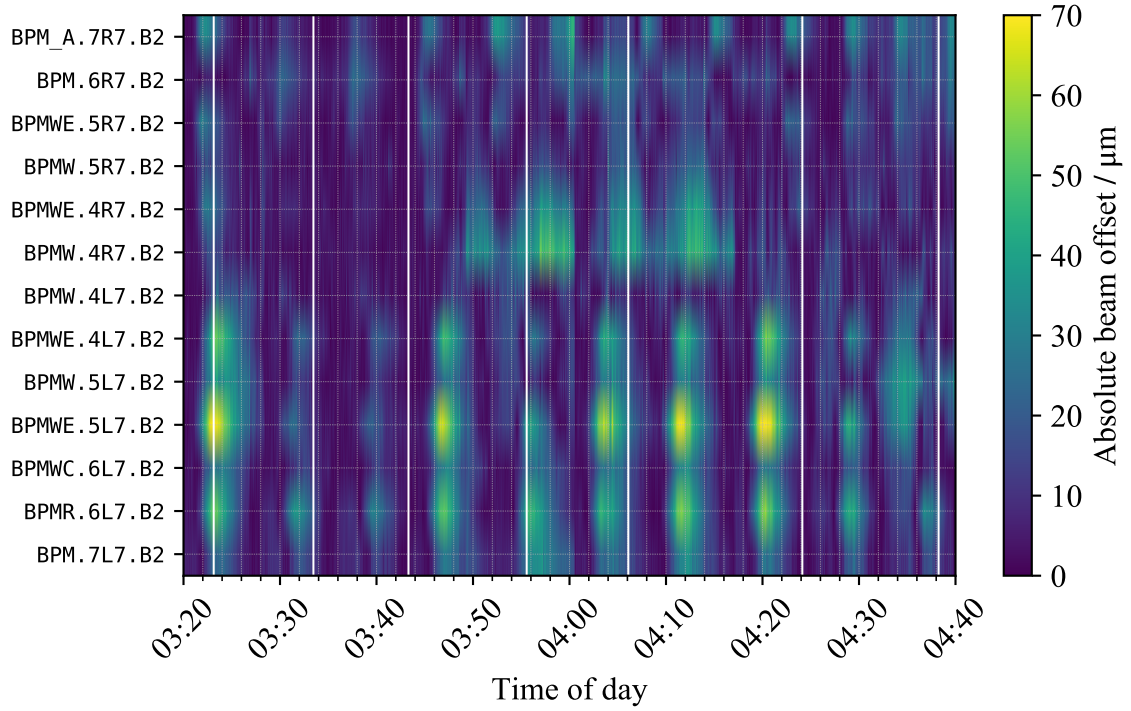


Figure 6.32: The beam offset in B2H as measured by BPMs in IR7 for MD2901. White vertical lines mark the loss maps of each configuration in the order presented hitherto.

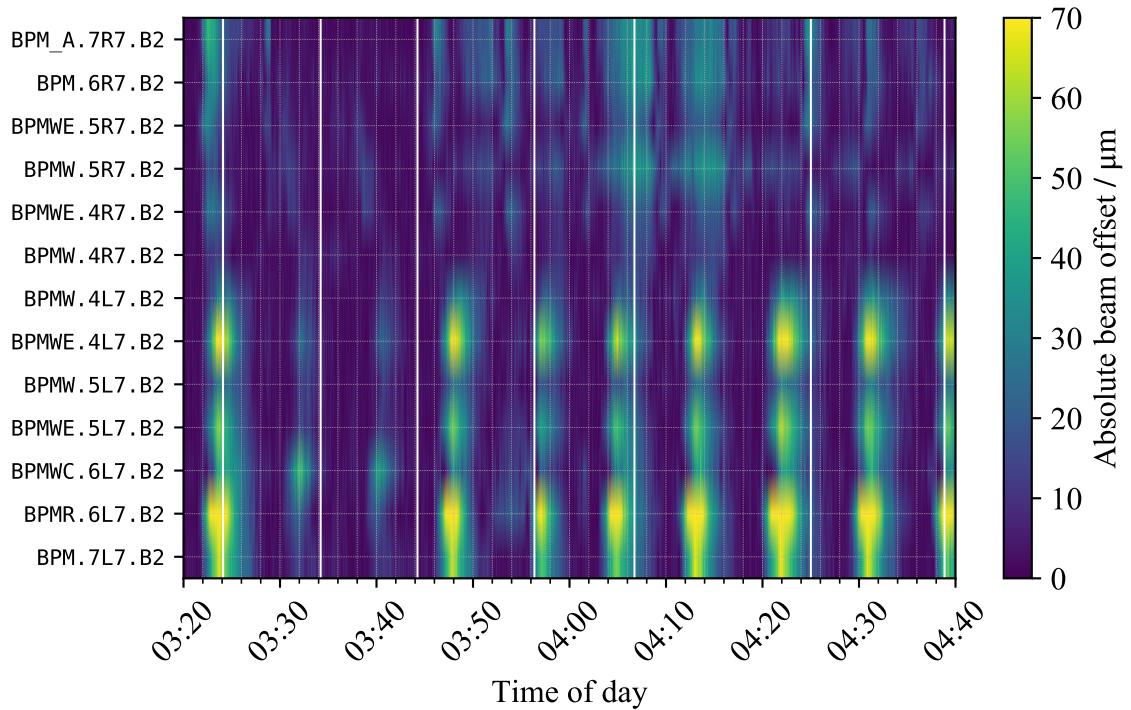


Figure 6.33: The beam offset in B2V as measured by BPMs in IR7 for MD2901. White vertical lines mark the loss maps of each configuration in the order presented hitherto.

6.3.3 Impedance results

Unfortunately, the second fill was met with some major complications prior to the tune measuring process. After having injected the two nominal bunches and ramping up to FT, the beams quickly became unstable while adjusting the chromaticity. Although the beams were stabilised shortly thereafter, the instability re-emerged while calibrating the ADT in preparation for measurements. The whole ordeal led to some considerable losses in the high-intensity bunch of B1, as shown by the sharp dip at approximately 8:15 in Fig. 6.23. The cause behind the instability is unknown, as this procedure had been executed successfully in previous MDs. In the end, C2 was deployed as a last-ditch attempt to stabilise the beams. Remarkably, this effort proved to be very effective; however, it meant that measurements could not be referenced against DRY, as stability would be lost when alternating between symmetric and single-sided settings.

With little time left in the MD, a new line of action was devised in order to secure some measurements. The focus was set on the primaries and the four high-impedance secondaries. Seeing as DRY was impermissible, a different reference point had to be selected. Thus, the tune shift was measured when alternating between C2 and C2+NPNN — effectively characterising the four high-impedance secondaries. The primaries were assessed by measuring the tune shift between C2 and fully open TCPs, with the secondaries being kept symmetric. During these measurements, the beams were to be kicked repeatedly with the ADT in order to increase the betatron amplitude and allow for more precise tune measurements; however, it was later discovered that B1 received no such kicks — adding to the list of problems faced in this fill.⁴

In order to get a coherent picture of the results, the tune measurements are processed as follows. A 100-point moving average is taken to reduce noise and smoothen the data. The points are then divided based on the gap of the relevant collimators, with intermediary points being discarded. Finally, the tune shift and associated uncertainty are quantified by examining the histogram produced by each data set. Figs. 6.34 to 6.41 show the processed tune shift measurements for each plane of B1 and B2. Tune shifts in the order of 10^{-4} to 10^{-5} are clearly visible for most cases, however the tune spread is rather large, leading to error values that are greater than the actual measurements.

Simulations have predicted a tune shift of approximately 6×10^{-5} in both planes for the four high-impedance secondaries, when cycling between symmetric and single-sided settings (see Fig. 6.21).⁵ For the primaries, the predicted tune shift between C2 and fully open TCPs is roughly 5×10^{-5} in B1H and 3×10^{-5} in B1V. Although imprecise, measurements appear to be in good overall agreement with the simulations, the exception being B2, which experienced some tune jitter whilst characterising the TCSGs, leading to deficient results.

Each fill came to a close with an instability rise time measurement. The first fill considered the DRY configuration and measured a rise time of approximately 2 s. C2 was then deployed during the same fill and saw no instability, however this could be due to the beam being spoiled by the first measurement. The second fill examined C2+NPNN, and remarkably, saw no instability. The octupole current was lowered in steps of 300 A, 150 A, 75 A, and 0 A in order to gauge the octupole current threshold (at $Q' \approx 12$), and the

⁴The tune measurements were taken using the Base Band Tune (BBQ) system.

⁵Although the geometric component is invariant in simulations, it does not drive impedance in the LHC.

low intensity bunch in B1 became unstable during the last step towards 0 A. Even then, there were no intensity losses and the beam emittances remained fairly acceptable.

All things considered, the results obtained from the second fill are of rather poor quality, and the desired measurements were not obtained due to the multitude of problems encountered, which were beyond control. It appears that simulations and measurements are in agreement; however, further studies are needed to derive anything conclusive. The fact that deploying C2 stabilised the beam prior to the tune shift measurements is at the very least, interesting, and the instability rise time measurements are also fairly encouraging.

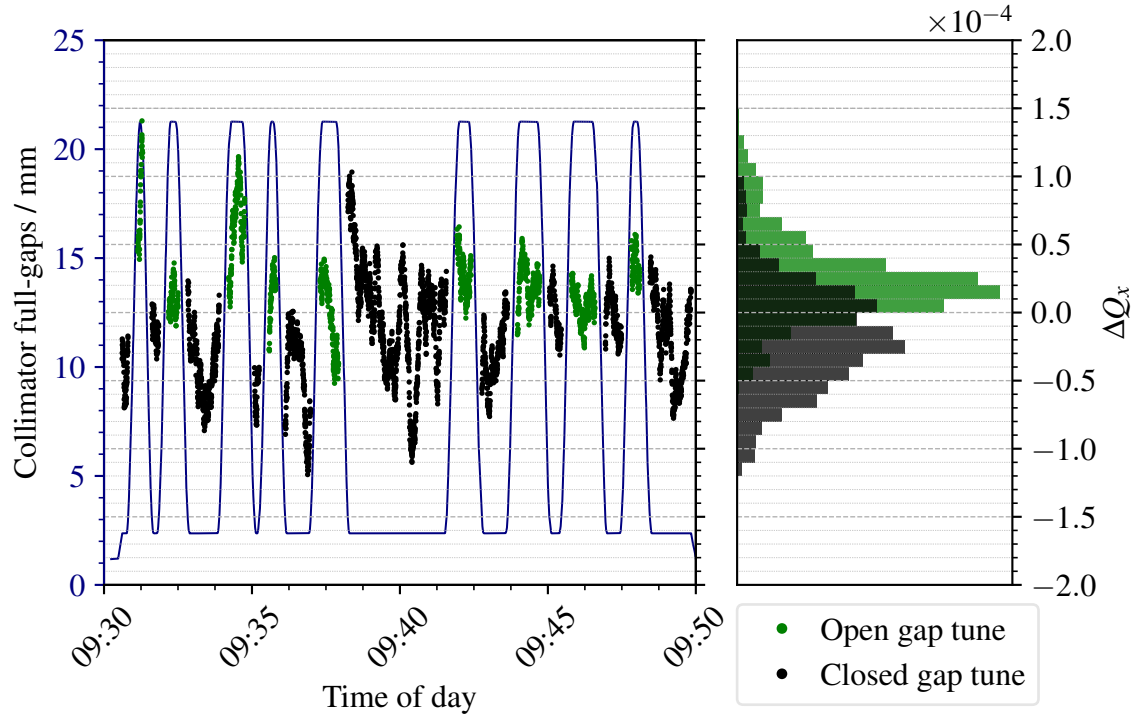


Figure 6.34: The measured tune shift between C2 and C2+NPNN in B1H. The full-gap shown is that of the four-high impedance TCSGs. $\Delta Q_x = (4.2 \pm 6.7) \times 10^{-5}$.

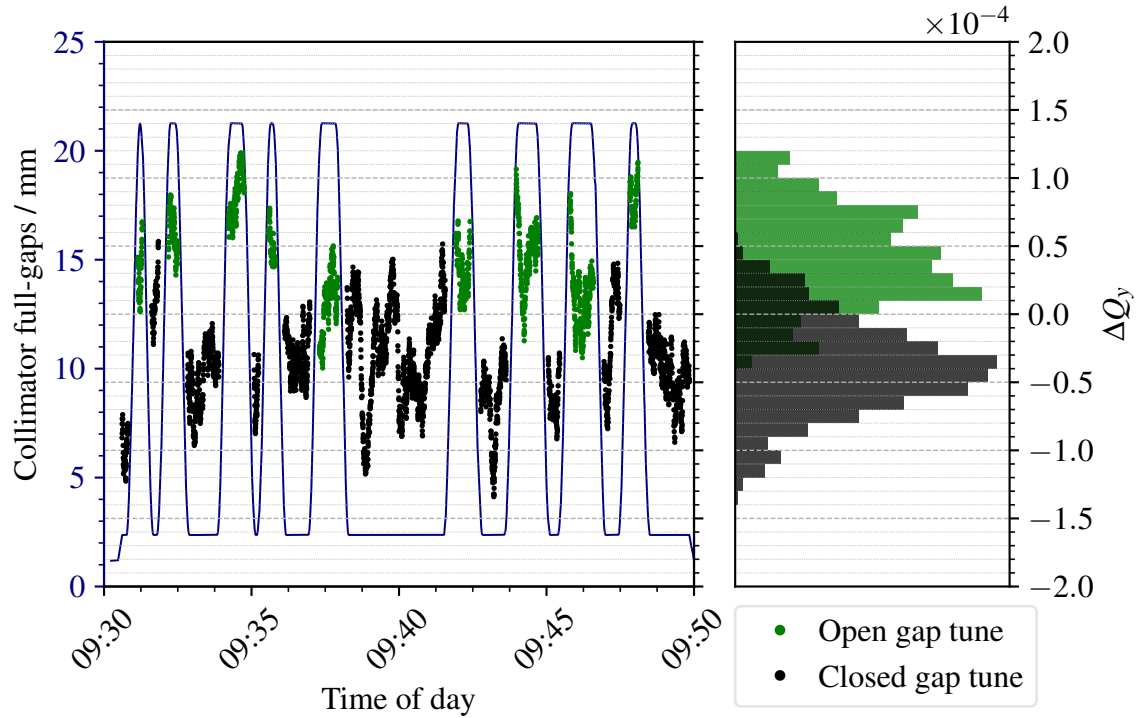


Figure 6.35: The measured tune shift between C2 and C2+NPNN in B1V. The full-gap shown is that of the four-high impedance TCSGs. $\Delta Q_y = (7.8 \pm 6.8) \times 10^{-5}$.

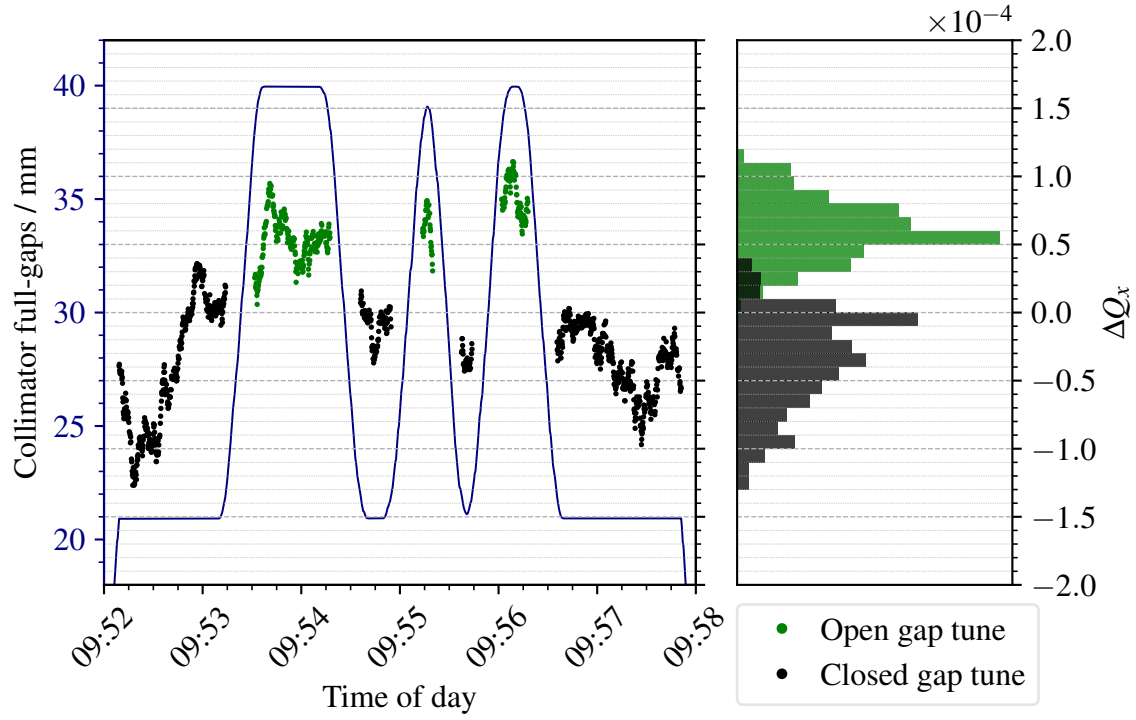


Figure 6.36: The measured tune shift between C2 and fully open TCPs in B1H. The full-gap shown is that of the TCPs. $\Delta Q_x = (9.6 \pm 5.6) \times 10^{-5}$.

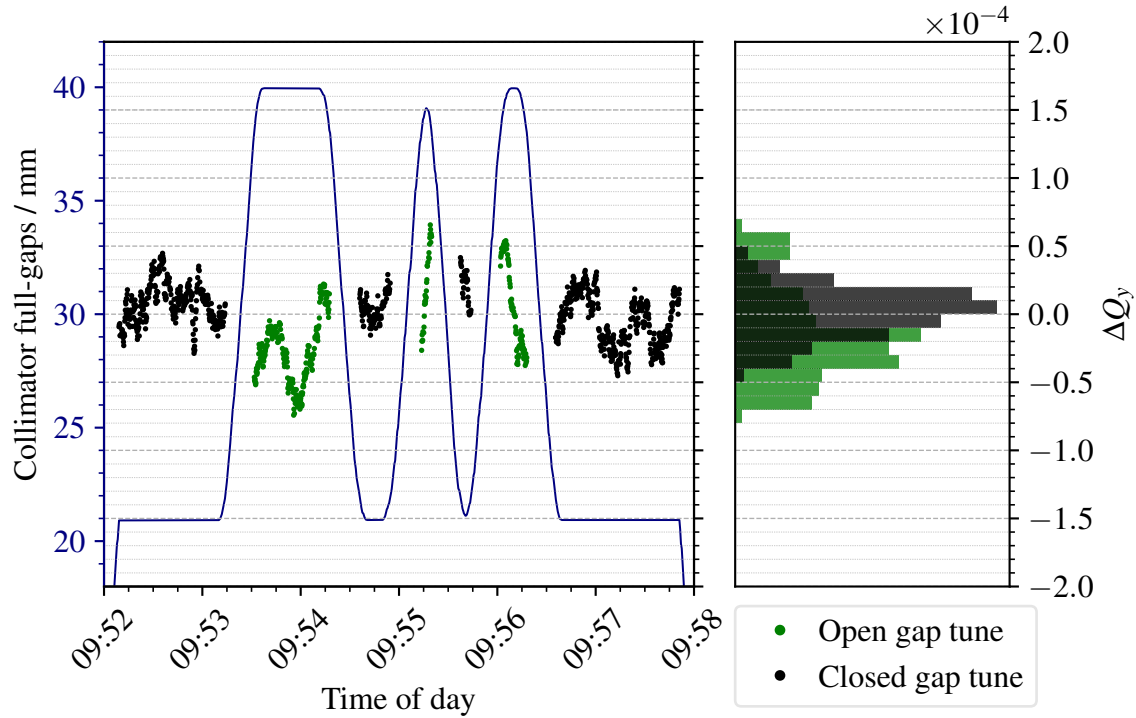


Figure 6.37: The measured tune shift between C2 and fully open TCPs in B1V. The full-gap shown is that of the TCPs. $\Delta Q_y = (-1.8 \pm 5.0) \times 10^{-5}$.

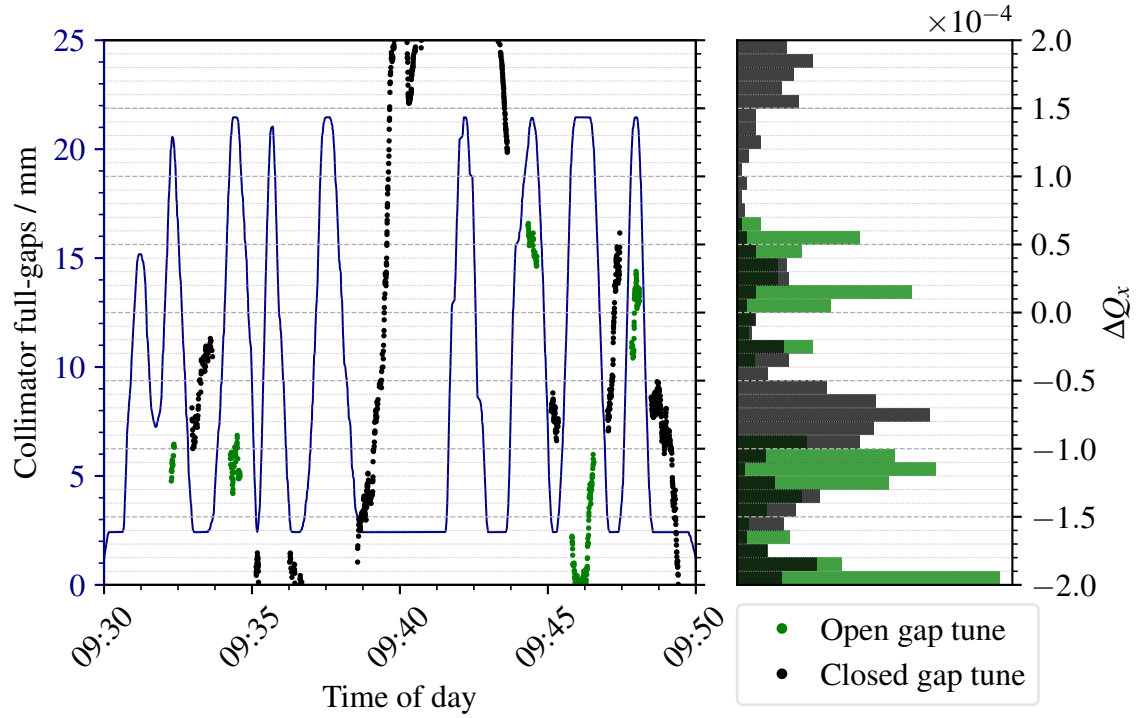


Figure 6.38: The measured tune shift between C2 and C2+NPNN in B2H. The full-gap shown is that of the four-high impedance TCSGs. $\Delta Q_x = (-1.7 \pm 4.0) \times 10^{-4}$.

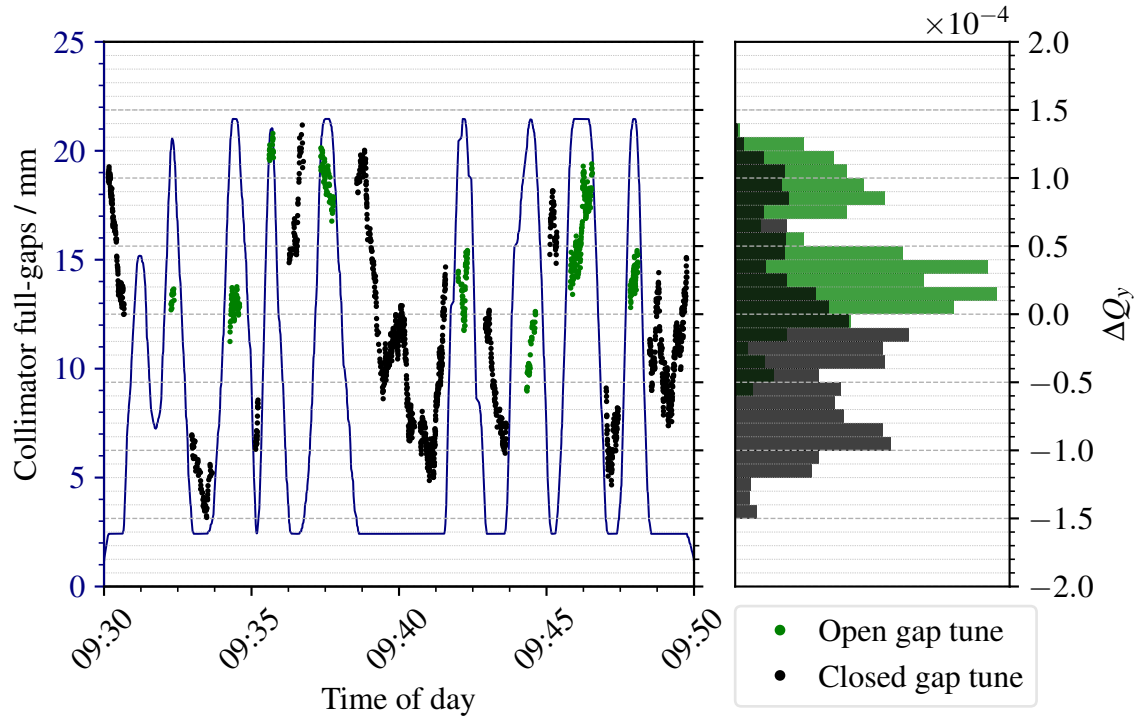


Figure 6.39: The measured tune shift between C2 and C2+NPNN in B2V. The full-gap shown is that of the four-high impedance TCSGs. $\Delta Q_y = 6.9 \times 10^{-5} \pm 1.1 \times 10^{-4}$.

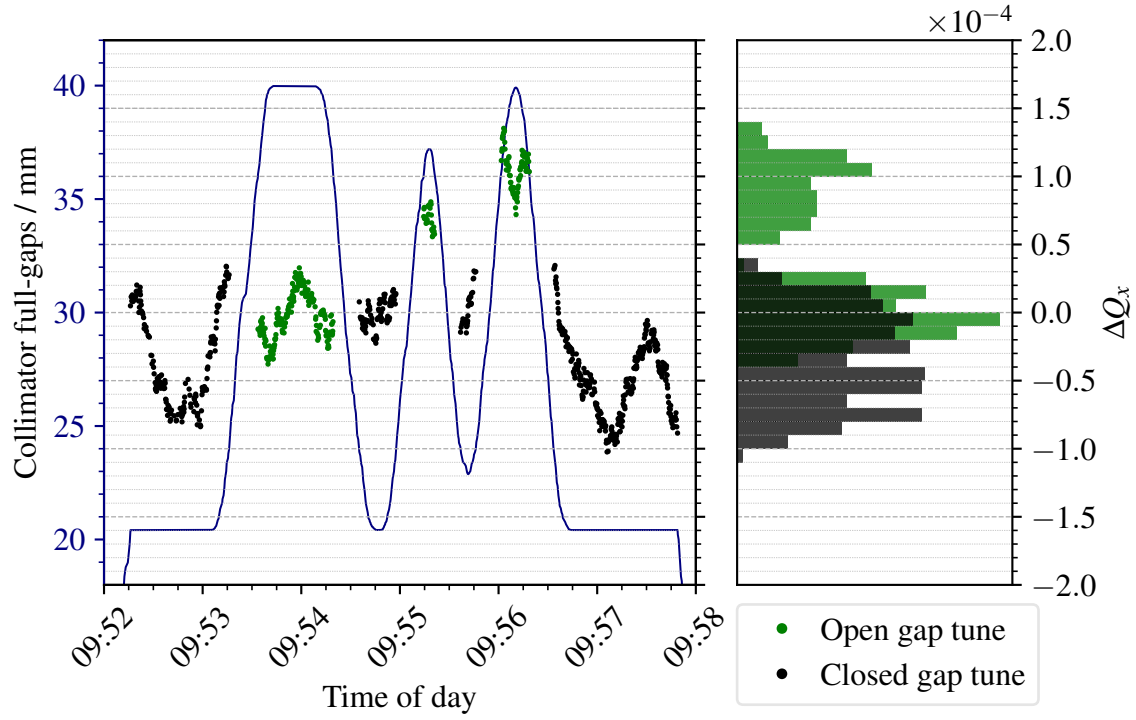


Figure 6.40: The measured tune shift between C2 and fully open TCPs in B2H. The full-gap shown is that of the TCPs. $\Delta Q_x = (6.7 \pm 8.3) \times 10^{-5}$.

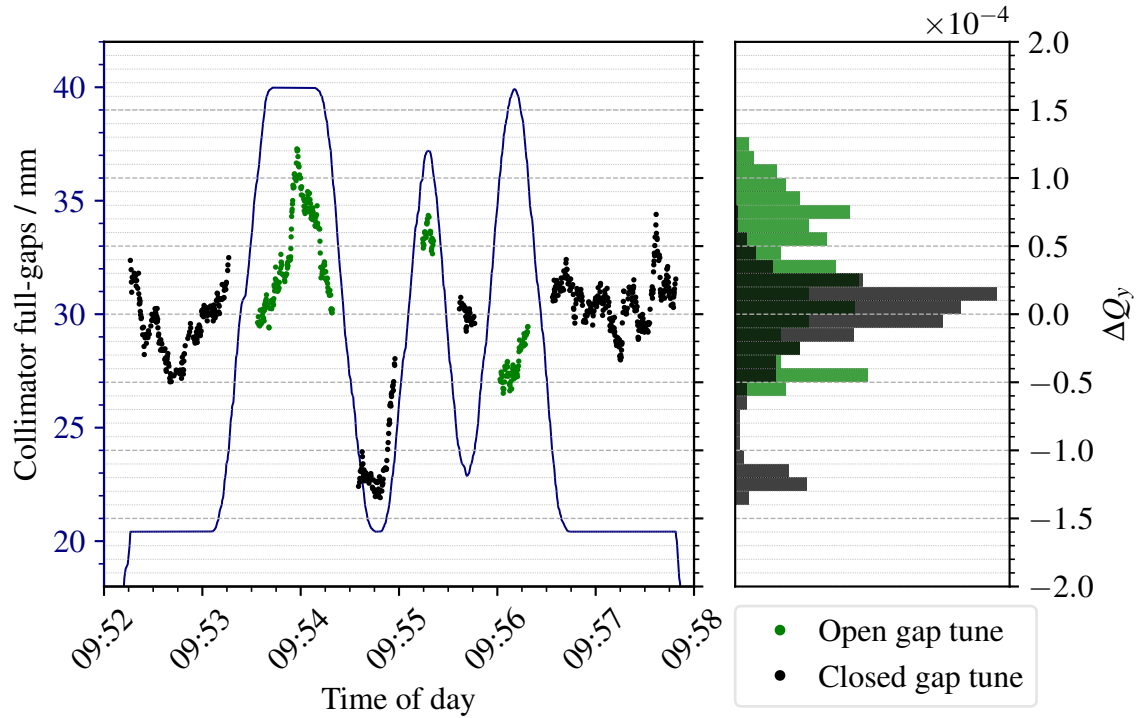


Figure 6.41: The measured tune shift between C2 and fully open TCPs in B2V. The full-gap shown is that of the TCPs. $\Delta Q_y = (3.8 \pm 9.1) \times 10^{-5}$.

Chapter 7

Conclusions and outlook

The aim of this thesis is to assess the feasibility of single-sided collimation as a mechanism for reducing impedance in the accelerator. Simulations in HL-LHC have shown that each primary collimator jaw generates a pathway which leads to the DS clusters. These pathways are accessible to particles that have been intercepted by the primary collimators and have undergone a particular change in energy and angle. It turns out that dispersion plays a key role in determining the width of these paths. Given that the magnitude of the horizontal dispersion increases greatly just before the DS, particles that have undergone a change in energy get pushed towards one side of the TCLD collimator. Consequently, one of the paths emanating from the horizontal TCP ends up being caught by the TCLD, leading to far fewer DS losses for that jaw. Interestingly, this means that the cleaning performance can be *improved* by merely retracting certain TCP jaws, and this was clearly shown to be the case in simulations.

Unfortunately, it is not possible to improve upon the cleaning performance with the secondary collimators — only preserve it. This is because secondary collimators are more likely to absorb particles, given their role in the hierarchy. The jaws of secondary collimators must therefore be selected such as to not widen the pathways generated by the primary collimators. In the end, three single-sided configurations were constructed for each beam; one involving only the TCPs, another which also includes the four high-impedance TC-SGs, and the last which incorporates the rest of the TCSGs. Beam cleaning simulations have shown that all three of these configurations have a better cleaning performance than the standard collimator settings.

For a single collimator, the dipolar RW impedance drops by a factor of 3.2 in the cleaning plane, and 1.6 in the non-cleaning plane, when fully retracting one of its two jaws. Impedance simulations of the configurations in HL-LHC have shown that retracting secondary jaws beyond those of the four high-impedance collimators may be undesirable due to diminishing returns. The octupole current threshold drops by roughly 30 A for both configurations; however, the model did not properly take into account geometric component of the collimators, and so the estimates are rather conservative.

Equivalent single-configurations were obtained for the LHC. Beam cleaning simulations have shown little improvement over the standard collimator settings, due to the absence of the TCLD collimator. On the other hand, impedance simulations predict a larger drop in impedance, which is due to the rather poor electrical conductivity of the collimators in LHC. The octupole current threshold drops by roughly 50 A for the con-

figuration involving the TCPs and the four high-impedance TCSGs. It decreases even further, by 70 A, for the multi-secondary configuration. Machine measurements were shown to follow the trends seen in simulation. However there were some disagreements in the multi-secondary configurations with regards to beam cleaning — the source of which remains unknown. The impedance measurements are encouraging but inconclusive due to the lack of precision in the data.

Future studies could include measuring the cleaning performance of the HL-LHC configurations. Run III is expected to be an ideal scenario for single-sided collimation, due to the availability of the TCLD collimator, and the non-upgraded jaw composition of most secondaries. It would also be beneficial to load the full non-linear model of the machine into SixTrack, in order to examine effects of non-linearities. Additionally, closed orbit drift should be studied to ensure that hierarchy breakages do not occur. Energy deposition analyses would also determine whether any collimators are being overloaded. In terms of impedance, the geometric component of asymmetric collimators should be accounted for properly, and further tune shift measurements would be invaluable. Lastly, it would be interesting to explore single-sided collimator for the momentum cleaning insertion in IR3. Given the high dispersion in the region, one would expect single-sided collimation to perform rather well.

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Appendix A

Simulation parameters

A.1 HL-LHC SixTrack parameters

Listing A.1: The *fort.3* input file used to simulate a horizontal halo in B1 of the HL-LHC (optics version 1.3; 2σ retraction).

```
1  GEOM
2  PRINTOUT
3  NEXT
4  TRACKING
5  200 0 32 0 17 0 1
6  1 1 0 0 2
7  0 0 1 1 1 20000 2
8  NEXT
9  INITIAL COORDINATES
10  2 0 0 1
11  0.0
12  0.0
13  0.0
14  0.0
15  0.0
16  0.0
17  0.0
18  .0000001
19  0.0
20  0.0
21  0.0
22  0.0
23  7000000.0
24  7000000.0
25  7000000.0
26  NEXT
27  FLUCTUATION
28  100000 1 7 3
29  NEXT
30  ITERATION ACCURACY
31  50 0.10E-13 0.10E-14
32  10 0.10E-09 0.10E-09
33  10 0.10E-04 0.10E-05
34  0.10E-07 0.10E-11 0.10E-09
35  NEXT
36  LINEAR OPTICS
37  ELEMENT 0 1 1 3.5 3.5
38  NEXT
39  BEAM
40  0.110E+12 3.5 3.5 0.0755E+00 0.4716E-03 1 1 1
41  NEXT
42  SYNC
```

```

43 35640 .0003225 16 0 26658.8832 938.2796 1
44 1 1
45 NEXT
46 COLLIMATION
47 .TRUE.
48 50 7000000
49 2 5.7 0.04 0. 0. "nothing" 1.129E-4 75.5
50 .TRUE. 15.0 18.0 999. 20.0 5.7 7.7 999. 10. 12. 999. 9. 8.5 999.0
51 10.9 30. 10.9 30. 10.9 30. 10.9 30. 999. 12.
52 0 19789.0 20150.0 1 1
53 -1.3899e-6 -9.345e-5 5.05324e-3 -1.6595e-2 2.15955e-2 -9.96261e-3 1.0
54 -1.3899e-6 -9.345e-5 5.05324e-3 -1.6595e-2 2.15955e-2 -9.96261e-3 1.0
55 3.5 3.5 3.5 3.5
56 .FALSE. .FALSE. 0 .TRUE. TCP.C6L7.B1 .FALSE. .TRUE. .TRUE. .TRUE.
57 0 0 0 0
58 0 0 0 0 0 0 0 0 0 0 .FALSE.
59 .FALSE. 6.003 .0015
60 0 0 .FALSE. .FALSE.
61 30 0.1 0.05 0.05 3
62 "CollDB_HL.data" 1
63 .TRUE. .FALSE. WAbsVertLowbcoll 101 1 1.
64 NEXT
65 ENDE

```

A.2 LHC SixTrack parameters

Listing A.2: The *fort.3* input file used to simulate a horizontal halo in B1 of the LHC (Run II in 2018; $\beta^* = 30$ cm, with a $160\mu\text{rad}$ crossing angle in IP1 and IP5).

```

1 GEOM
2 PRINTOUT
3 NEXT
4 TRACKING
5 200 0 32 0 17 0 1
6 1 1 0 0 2
7 0 0 1 1 1 20000 2
8 NEXT
9 INITIAL COORDINATES
10 2 0 0 1
11 0.0
12 0.0
13 0.0
14 0.0
15 0.0
16 0.0
17 0.0
18 .000001
19 0.0
20 0.0
21 0.0
22 0.0
23 6500000.0
24 6500000.0
25 6500000.0
26 NEXT
27 FLUCTUATION
28 100000 1 7 3
29 NEXT
30 ITERATION ACCURACY
31 50 0.10E-13 0.10E-14
32 10 0.10E-09 0.10E-09
33 10 0.10E-04 0.10E-05
34 0.10E-07 0.10E-11 0.10E-09
35 NEXT

```

Appendix A: Simulation parameters

```
36 LINEAR OPTICS
37 ELEMENT 0 1 1 3.5 3.5
38 NEXT
39 BEAM
40 0.110E+12 3.5 3.5 0.0755E+00 0.4716E-03 1 1 1
41 NEXT
42 SYNC
43 35640 .0003225 16 0 26658.883200 938.2796 1
44 1 1
45 NEXT
46 COLLIMATION
47 .TRUE.
48 50 6500000
49 2 5.0 0.04 0. 0. "nothing" 1.129E-4 75.5
50 .FALSE. 15. 18.0 18.0 20.0 5.0 6.5 6.5 10.0 999. 999.0 7.3 7.3 999.0
51 8.5 37.0 8.5 15.0 8.5 37.0 8.5 15.0
52 0 19789.0 20150.0 1 1
53 -1.3899e-6 -9.345e-5 5.05324e-3 -1.6595e-2 2.15955e-2 -9.96261e-3 1.0
54 -1.3899e-6 -9.345e-5 5.05324e-3 -1.6595e-2 2.15955e-2 -9.96261e-3 1.0
55 3.5 3.5 3.5 3.5
56 .FALSE. .FALSE. 0 .TRUE. TCP.C6L7.B1 .FALSE. .TRUE. .TRUE. .TRUE.
57 0 0 0 0
58 0 0 0 0 0 0 0 0 0 0 .FALSE.
59 .FALSE. 6.003 .0015
60 0 0 .FALSE. .FALSE.
61 28 0.1 0.05 0.05 3
62 "CollDB_RunII.data" 1
63 .TRUE. .FALSE. WAbsVertLowbcoll 101 1 1.
64 NEXT
65 ENDE
```

A.3 ImpedanceWake2D parameters

Listing A.3: The input file given to ImpedanceWake2D to determine the impedance of a symmetric horizontal primary collimator in HL-LHC.

```

1 Machine:          HLLHC
2 Relativistic Gamma: 7460.52
3 Impedance Length in m: 1
4 Number of upper layers in the chamber wall: 2
5 Layer 1 inner half gap in mm: 1.51889
6 Layer 1 DC resistivity (Ohm.m): 1e-06
7 Layer 1 relaxation time for resistivity (ps): 0.0
8 Layer 1 real part of dielectric constant: 1
9 Layer 1 magnetic susceptibility: 0.0
10 Layer 1 relaxation frequency of permeability (MHz): Infinity
11 Layer 1 thickness in mm: 25.0
12 Layer 2 DC resistivity (Ohm.m): Infinity
13 Layer 2 relaxation time for resistivity (ps): 0.0
14 Layer 2 real part of dielectric constant: 1
15 Layer 2 magnetic susceptibility: 0.0
16 Layer 2 relaxation frequency of permeability (MHz): Infinity
17 Layer 2 thickness in mm: Infinity
18 Top bottom symmetry (yes or no): yes
19 start frequency exponent (10^) in Hz: 3.0
20 stop frequency exponent (10^) in Hz: 9.30102999566
21 linear (1) or logarithmic (0) or both (2) frequency scan: 2
22 sampling frequency exponent (10^) in Hz (for linear): 8.0
23 Number of points per decade (for log): 20
24 when both, fmin of the refinement (in THz): 1.1e-05
25 when both, fmax of the refinement (in THz): 1e-05
26 when both, number of points in the refinement: 1
27 added frequencies (Hz):
28 linear (1) or logarithmic (0) or both (2) scan in z for the wake: 2
29 sampling distance in m for the linear sampling: 5e-06
30 zmin in m of the linear sampling: 5e-06
31 zmax in m of the linear sampling: 0.01
32 Number of points per decade for the logarithmic sampling: 100
33 exponent (10^) of zmin (in m) of the logarithmic sampling: -2.0
34 exponent (10^) of zmax (in m) of the logarithmic sampling: 6.0
35 added z [m]:
36 factor weighting the longitudinal impedance error: 100.0
37 tolerance (in wake units) to achieve: 1e+12
38 frequency above which the mesh bisecting is linear [Hz]: 1e+11
39 Comments for the output files names:

```

A.4 Sacherer parameters

Table A.1: Parameters used in the computation of tune shifts and effective impedances for HL-LHC and LHC scenarios (see [51]). For broadband impedance, the multi-bunch results are similar to those of a single-bunch [22]. Sinusoidal modes describe the oscillations of bunches with a parabolic density distribution — a good approximation for protons [43].

Parameters	HL-LHC	LHC
Energy	7.0 TeV	6.5 TeV
Bunch spacing	25 ns	25 ns
Bunch intensity	2.3×10^{11}	1.0×10^{11}
Number of bunches	1	1
Multi-bunch modes	0	0
Chromaticity (Q')	0	0
Betatron tune (Q_x, Q_y)	62.31, 60.32	64.31, 59.32
Lorentz factor (γ_{rel})	7460.52	6927.63
Angular synchrotron frequency	144.48	149.93
Angular revolution frequency	70 657.56	70 657.56
Total bunch length in seconds	1.08×10^{-9} s	1.20×10^{-9} s
Particle type	Protons	Protons
Mode type	Sinusoidal	Sinusoidal

Appendix B

Collimator data

B.1 HL-LHC B1 collimators

Table B.1: List of collimators and their properties in B1 of HL-LHC. The half-gaps listed are those at FT, with $\hat{\varepsilon}_z = 3.5 \mu\text{m rad}$.

ID	Name	s / m	θ	g / σ	g / mm
1	TCLX.4R1.B1	135.71	0.0°	12.0	21.5007
2	TCL.5R1.B1	197.58	0.0°	12.0	7.8260
3	TCL.6R1.B1	220.56	0.0°	12.0	3.1144
4	TCTPH.4L2.B1	3213.90	0.0°	30.0	5.9800
5	TCTPV.4L2.B1	3215.90	90.0°	30.0	6.5735
6	TDI.4L2.B1	3251.60	90.0°	999.0	212.0311
7	TCLIA.4R2	3406.18	90.0°	999.0	273.0223
8	TCLIB.6R2.B1	3560.09	90.0°	999.0	172.8692
9	TCP.6L3.B1	6487.67	0.0°	15.0	3.7215
10	TCSG.5L3.B1	6520.99	0.0°	18.0	2.8841
11	TCSG.4R3.B1	6707.58	0.0°	18.0	1.9903
12	TCSG.A5R3.B1	6718.92	170.8°	18.0	2.5739
13	TCSG.B5R3.B1	6724.74	11.4°	18.0	2.9131
14	TCLA.A5R3.B1	6755.22	90.0°	20.0	5.7420
15	TCLA.B5R3.B1	6757.22	0.0°	20.0	5.3397
16	TCLA.6R3.B1	6843.77	0.0°	20.0	4.9407
17	TCLA.7R3.B1	6915.18	0.0°	20.0	3.5364
18	TCTH.6L5.B1	13114.75	0.0°	10.9	8.3813

Table B.1: List of collimators and their properties in B1 of HL-LHC. The half-gaps listed are those at FT, with $\hat{\varepsilon}_z = 3.5 \mu\text{m rad}$.

ID	Name	s / m	θ	g / σ	g / mm
19	TCTV.6L5.B1	13116.75	90.0°	10.9	4.4955
20	TCTXH.4L5.B1	13195.34	0.0°	1000.0	1479.0771
21	TCTPV.4L5.B1	13197.34	90.0°	10.9	20.3049
22	TCLX.4R5.B1	13465.00	0.0°	12.0	21.4290
23	TCL.5R5.B1	13526.87	0.0°	12.0	7.7998
24	TCL.6R5.B1	13550.45	0.0°	12.0	2.9724
25	TCDQA.A4R6.B1	16804.97	0.0°	9.0	5.2694
26	TCDQA.C4R6.B1	16808.52	0.0°	9.0	5.3246
27	TCDQA.B4R6.B1	16812.07	0.0°	9.0	5.3799
28	TCSP.A4R6.B1	16815.98	0.0°	8.5	5.1388
29	TCPD6L7.B1	19789.18	90.0°	5.7	1.0928
30	TCP.C6L7.B1	19791.18	0.0°	5.7	1.5189
31	TCP.B6L7.B1	19793.18	126.9°	5.7	1.2810
32	TCSG.A6L7.B1	19832.68	141.1°	7.7	1.7789
33	TCSG.B5L7.B1	19891.91	143.5°	7.7	2.1207
34	TCSG.A5L7.B1	19895.91	40.7°	7.7	2.1637
35	TCSG.D4L7.B1	19917.24	90.0°	7.7	1.3834
36	TCSG.B4L7.B1	19987.16	0.0°	7.7	1.9684
37	TCSG.A4L7.B1	19991.16	134.6°	7.7	1.9366
38	TCSG.A4R7.B1	19995.16	46.3°	7.7	1.9437
39	TCSG.B5R7.B1	20086.42	141.5°	7.7	2.2292
40	TCSG.D5R7.B1	20102.42	51.4°	7.7	2.2400
41	TCSG.E5R7.B1	20106.42	130.5°	7.7	2.2429
42	TCSG.6R7.B1	20141.02	0.5°	7.7	3.0586
43	TCLA.A6R7.B1	20148.09	90.0°	10.0	1.5039
44	TCLA.B6R7.B1	20178.96	0.0°	10.0	2.7352
45	TCLA.C6R7.B1	20212.23	90.0°	10.0	2.6688
46	TCLA.D6R7.B1	20214.23	0.0°	10.0	1.7433
47	TCLA.A7R7.B1	20231.86	0.0°	10.0	1.7583

Table B.1: List of collimators and their properties in B1 of HL-LHC. The half-gaps listed are those at FT, with $\hat{\varepsilon}_z = 3.5 \mu\text{m rad}$.

ID	Name	s / m	θ	g / σ	g / mm
48	TCLD.8R7.B1	20286.56	0.0°	12.0	1.4452
49	TCTPH.4L8.B1	23197.15	0.0°	30.0	9.9524
50	TCTPV.4L8.B1	23199.15	90.0°	30.0	10.9916
51	TCTH.6L1.B1	26444.34	0.0°	10.9	8.4090
52	TCTV.6L1.B1	26446.34	90.0°	10.9	4.4919
53	TCTXH.4L1.B1	26524.93	0.0°	1000.0	1484.0088
54	TCTPV.4L1.B1	26526.93	90.0°	10.9	20.2894

B.2 HL-LHC B2 collimators

Table B.2: List of collimators and their properties in B2 of HL-LHC. The half-gaps listed are those at FT, with $\hat{\varepsilon}_z = 3.5 \mu\text{m rad}$.

ID	Name	s / m	θ	g / σ	g / mm
1	TCLX.4L1.B2	135.71	0.0°	12.0	21.4371
2	TCL.5L1.B2	197.58	0.0°	12.0	7.7009
3	TCL.6L1.B2	221.16	0.0°	12.0	2.9281
4	TCTPH.4R8.B2	3225.42	0.0°	30.0	9.9346
5	TCTPV.4R8.B2	3227.42	90.0°	30.0	11.0163
6	TDI.4R8.B2	3262.82	90.0°	999.0	387.5074
7	TCLIA.4L8	3417.40	90.0°	999.0	499.6424
8	TCLIB.6L8.B2	3560.34	90.0°	999.0	83.4826
9	TCP.D6R7.B2	6459.74	90.0°	5.7	1.0932
10	TCP.C6R7.B2	6461.74	0.0°	5.7	1.5131
11	TCP.B6R7.B2	6463.74	127.5°	5.7	1.2820
12	TCSG.A6R7.B2	6503.24	141.3°	7.7	1.7727
13	TCSG.B5R7.B2	6562.46	143.6°	7.7	2.1247
14	TCSG.A5R7.B2	6566.46	40.6°	7.7	2.1681
15	TCSG.D4R7.B2	6587.79	90.0°	7.7	1.3820
16	TCSG.B4R7.B2	6653.72	0.0°	7.7	2.0521
17	TCSG.A4R7.B2	6657.72	132.1°	7.7	1.9365
18	TCSG.A4L7.B2	6673.72	42.1°	7.7	1.9293
19	TCSG.B5L7.B2	6756.98	141.5°	7.7	2.2286
20	TCSG.D5L7.B2	6772.98	51.4°	7.7	2.2400
21	TCSG.E5L7.B2	6776.98	130.5°	7.7	2.2427
22	TCSG.6L7.B2	6811.58	0.5°	7.7	3.0582
23	TCLA.A6L7.B2	6818.65	90.0°	10.0	1.5051
24	TCLA.B6L7.B2	6849.52	0.0°	10.0	2.7383
25	TCLA.C6L7.B2	6882.79	90.0°	10.0	2.6664
26	TCLA.D6L7.B2	6884.79	0.0°	10.0	1.7490
27	TCLA.A7L7.B2	6902.42	0.0°	10.0	1.7466

Table B.2: List of collimators and their properties in B2 of HL-LHC. The half-gaps listed are those at FT, with $\hat{\varepsilon}_z = 3.5 \mu\text{m rad}$.

ID	Name	s / m	θ	g / σ	g / mm
28	TCLD.8L7.B2	6957.11	0.0°	12.0	1.5232
29	TCDQA.A4L6.B2	10140.25	0.0°	9.0	4.1791
30	TCDQA.C4L6.B2	10143.80	0.0°	9.0	4.2264
31	TCDQA.B4L6.B2	10147.34	0.0°	9.0	4.2740
32	TCSP.A4L6.B2	10151.25	0.0°	8.5	4.0862
33	TCTH.6R5.B2	13114.75	0.0°	10.9	8.2763
34	TCTV.6R5.B2	13116.75	90.0°	10.9	4.6243
35	TCTXH.4R5.B2	13195.34	0.0°	1000.0	1481.3904
36	TCTPV.4R5.B2	13197.34	90.0°	10.9	20.3021
37	TCLX.4L5.B2	13465.00	0.0°	12.0	21.4608
38	TCL.5L5.B2	13526.87	0.0°	12.0	7.7095
39	TCL.6L5.B2	13549.85	0.0°	12.0	3.0582
40	TCP.6R3.B2	19817.11	0.0°	15.0	3.7060
41	TCSG.5R3.B2	19850.43	0.0°	18.0	2.8713
42	TCSG.4L3.B2	20037.02	0.0°	18.0	1.9900
43	TCSG.A5L3.B2	20048.36	170.8°	18.0	2.5684
44	TCSG.B5L3.B2	20054.18	10.8°	18.0	2.8774
45	TCLA.A5L3.B2	20084.66	90.0°	20.0	5.7465
46	TCLA.B5L3.B2	20086.66	0.0°	20.0	5.3159
47	TCLA.6L3.B2	20173.21	0.0°	20.0	4.9287
48	TCLA.7L3.B2	20244.62	0.0°	20.0	3.5560
49	TCTPH.4R2.B2	23208.07	0.0°	30.0	5.9743
50	TCTPV.4R2.B2	23210.07	90.0°	30.0	6.6199
51	TCTH.6R1.B2	26444.34	0.0°	10.9	8.2673
52	TCTV.6R1.B2	26446.34	90.0°	10.9	4.6135
53	TCTXH.4R1.B2	26524.93	0.0°	1000.0	1479.7539
54	TCTPV.4R1.B2	26526.93	90.0°	10.9	20.2536

B.3 LHC B1 collimators

Table B.3: List of collimators and their properties in B1 of LHC (Run II, 2018). The half-gaps listed are those at FT, with $\hat{\varepsilon}_z = 3.5 \mu\text{m rad}$.

ID	Name	s / m	θ	g / σ	g / mm
1	TCL.4R1.B1	150.03	0.0°	15.0	11.3210
2	TCL.5R1.B1	184.36	0.0°	15.0	6.0633
3	TCL.6R1.B1	219.01	0.0°	20.0	2.0697
4	TCTPH.4L2.B1	3213.90	0.0°	37.0	7.6437
5	TCTPV.4L2.B1	3215.90	90.0°	37.0	8.4459
6	TDI.4L2.B1	3251.60	90.0°	999.0	220.7444
7	TCLIA.4R2	3406.18	90.0°	999.0	284.0650
8	TCLIB.6R2.B1	3560.09	90.0°	999.0	129.1770
9	TCP.6L3.B1	6487.67	0.0°	15.0	3.8675
10	TCSG.5L3.B1	6520.99	0.0°	18.0	2.9905
11	TCSG.4R3.B1	6707.58	0.0°	18.0	2.0713
12	TCSG.A5R3.B1	6718.92	170.8°	18.0	2.6766
13	TCSG.B5R3.B1	6724.74	11.4°	18.0	3.0278
14	TCLA.A5R3.B1	6755.22	90.0°	20.0	5.9659
15	TCLA.B5R3.B1	6757.22	0.0°	20.0	5.5368
16	TCLA.6R3.B1	6843.77	0.0°	20.0	5.1152
17	TCLA.7R3.B1	6915.18	0.0°	20.0	3.6869
18	TCTPH.4L5.B1	13181.34	0.0°	8.5	8.1027
19	TCTPV.4L5.B1	13183.34	90.0°	8.5	6.8337
20	TCL.4R5.B1	13479.32	0.0°	15.0	11.3211
21	TCL.5R5.B1	13513.55	0.0°	15.0	6.0741
22	TCL.6R5.B1	13550.86	0.0°	999.0	83.0830
23	TCDQA.A4R6.B1	16804.97	0.0°	7.4	3.9049
24	TCDQA.C4R6.B1	16808.52	0.0°	7.4	3.9487
25	TCDQA.B4R6.B1	16812.07	0.0°	7.4	3.9926
26	TCSP.A4R6.B1	16815.98	0.0°	7.4	4.0411
27	TCP.D6L7.B1	19789.18	90.0°	5.0	0.9943

Table B.3: List of collimators and their properties in B1 of LHC (Run II, 2018). The half-gaps listed are those at FT, with $\hat{\varepsilon}_z = 3.5 \mu\text{m rad}$.

ID	Name	s / m	θ	g / σ	g / mm
28	TCP.C6L7.B1	19791.18	0.0°	5.0	1.3786
29	TCP.B6L7.B1	19793.18	126.9°	5.0	1.1642
30	TCSG.A6L7.B1	19832.68	141.1°	6.5	1.5574
31	TCSG.B5L7.B1	19891.91	143.5°	6.5	1.8612
32	TCSG.A5L7.B1	19895.91	40.7°	6.5	1.8989
33	TCSG.D4L7.B1	19917.24	90.0°	6.5	1.2121
34	TCSG.B4L7.B1	19987.16	0.0°	6.5	1.7267
35	TCSG.A4L7.B1	19991.16	134.6°	6.5	1.6978
36	TCSG.A4R7.B1	19995.16	46.3°	6.5	1.7038
37	TCSG.B5R7.B1	20086.42	141.5°	6.5	1.9515
38	TCSG.D5R7.B1	20102.42	51.4°	6.5	1.9611
39	TCSG.E5R7.B1	20106.42	130.5°	6.5	1.9635
40	TCSG.6R7.B1	20141.02	0.5°	6.5	2.6779
41	TCLA.A6R7.B1	20148.09	90.0°	10.0	1.5600
42	TCLA.B6R7.B1	20178.96	0.0°	10.0	2.8397
43	TCLA.C6R7.B1	20212.23	90.0°	10.0	2.7695
44	TCLA.D6R7.B1	20214.23	0.0°	10.0	1.8133
45	TCLA.A7R7.B1	20231.86	0.0°	10.0	1.8394
46	TCTPH.4L8.B1	23197.15	0.0°	15.0	5.1643
47	TCTPV.4L8.B1	23199.15	90.0°	15.0	5.7275
48	TCTPH.4L1.B1	26510.94	0.0°	8.5	8.1025
49	TCTPV.4L1.B1	26512.94	90.0°	8.5	6.8354

B.4 LHC B2 collimators

Table B.4: List of collimators and their properties in B2 of LHC (Run II, 2018). The half-gaps listed are those at FT, with $\hat{\varepsilon}_z = 3.5 \mu\text{m rad}$.

ID	Name	s / m	θ	g / σ	g / mm
1	TCL.4L1.B2	150.03	0.0°	15.0	11.3170
2	TCL.5L1.B2	184.26	0.0°	15.0	6.0224
3	TCL.6L1.B2	219.62	0.0°	20.0	1.9401
4	TCTPH.4R8.B2	3225.42	0.0°	15.0	5.1623
5	TCTPV.4R8.B2	3227.42	90.0°	15.0	5.7269
6	TDI.4R8.B2	3262.82	90.0°	999.0	402.2201
7	TCLIA.4L8	3417.40	90.0°	999.0	518.0122
8	TCLIB.6L8.B2	3560.34	90.0°	999.0	167.2497
9	TCP.D6R7.B2	6459.74	90.0°	5.0	0.9944
10	TCP.C6R7.B2	6461.74	0.0°	5.0	1.3785
11	TCP.B6R7.B2	6463.74	126.9°	5.0	1.1642
12	TCSG.A6R7.B2	6503.24	141.1°	6.5	1.5574
13	TCSG.B5R7.B2	6562.46	143.5°	6.5	1.8617
14	TCSG.A5R7.B2	6566.46	40.7°	6.5	1.8994
15	TCSG.D4R7.B2	6587.79	90.0°	6.5	1.2123
16	TCSG.B4R7.B2	6653.72	0.0°	6.5	1.7988
17	TCSG.A4R7.B2	6657.72	134.6°	6.5	1.6996
18	TCSG.A4L7.B2	6673.72	46.3°	6.5	1.7256
19	TCSG.B5L7.B2	6756.98	141.5°	6.5	1.9509
20	TCSG.D5L7.B2	6772.98	51.4°	6.5	1.9606
21	TCSG.E5L7.B2	6776.98	130.5°	6.5	1.9629
22	TCSG.6L7.B2	6811.58	0.5°	6.5	2.6769
23	TCLA.A6L7.B2	6818.65	90.0°	10.0	1.5600
24	TCLA.B6L7.B2	6849.52	0.0°	10.0	2.8388
25	TCLA.C6L7.B2	6882.79	90.0°	10.0	2.7701
26	TCLA.D6L7.B2	6884.79	0.0°	10.0	1.8132
27	TCLA.A7L7.B2	6902.42	0.0°	10.0	1.8213

Table B.4: List of collimators and their properties in B2 of LHC (Run II, 2018). The half-gaps listed are those at FT, with $\hat{\varepsilon}_z = 3.5 \mu\text{m rad}$.

ID	Name	s / m	θ	g / σ	g / mm
28	TCDQA.A4L6.B2	10140.25	0.0°	7.2	3.6599
29	TCDQA.C4L6.B2	10143.80	0.0°	7.2	3.7011
30	TCDQA.B4L6.B2	10147.34	0.0°	7.2	3.7424
31	TCSP.A4L6.B2	10151.25	0.0°	7.2	3.7882
32	TCTPH.4R5.B2	13181.34	0.0°	8.5	8.1007
33	TCTPV.4R5.B2	13183.34	90.0°	8.5	6.8336
34	TCL.4L5.B2	13479.32	0.0°	15.0	11.3185
35	TCL.5L5.B2	13513.65	0.0°	15.0	6.0123
36	TCL.6L5.B2	13550.85	0.0°	999.0	82.2280
37	TCP.6R3.B2	19817.11	0.0°	15.0	3.8663
38	TCSG.5R3.B2	19850.43	0.0°	18.0	2.9899
39	TCSG.4L3.B2	20037.02	0.0°	18.0	2.0710
40	TCSG.A5L3.B2	20048.36	170.8°	18.0	2.6760
41	TCSG.B5L3.B2	20054.18	11.4°	18.0	3.0271
42	TCLA.A5L3.B2	20084.66	90.0°	20.0	5.9672
43	TCLA.B5L3.B2	20086.66	0.0°	20.0	5.5356
44	TCLA.6L3.B2	20173.21	0.0°	20.0	5.1152
45	TCLA.7L3.B2	20244.62	0.0°	20.0	3.6832
46	TCTPH.4R2.B2	23208.07	0.0°	37.0	7.6446
47	TCTPV.4R2.B2	23210.07	90.0°	37.0	8.4403
48	TCTPH.4R1.B2	26510.94	0.0°	8.5	8.1000
49	TCTPV.4R1.B2	26512.94	90.0°	8.5	6.8329

Appendix C

Collimator impedances

This appendix shows the impedances associated with individual collimators. Note that both the geometric and RW components have been considered; however, the geometric component is always that of a symmetric collimator. The axes shown are those of the accelerator, where x and y respectively denote the horizontal and vertical axes.

C.1 HL-LHC collimator impedances

C.2 LHC collimator impedances

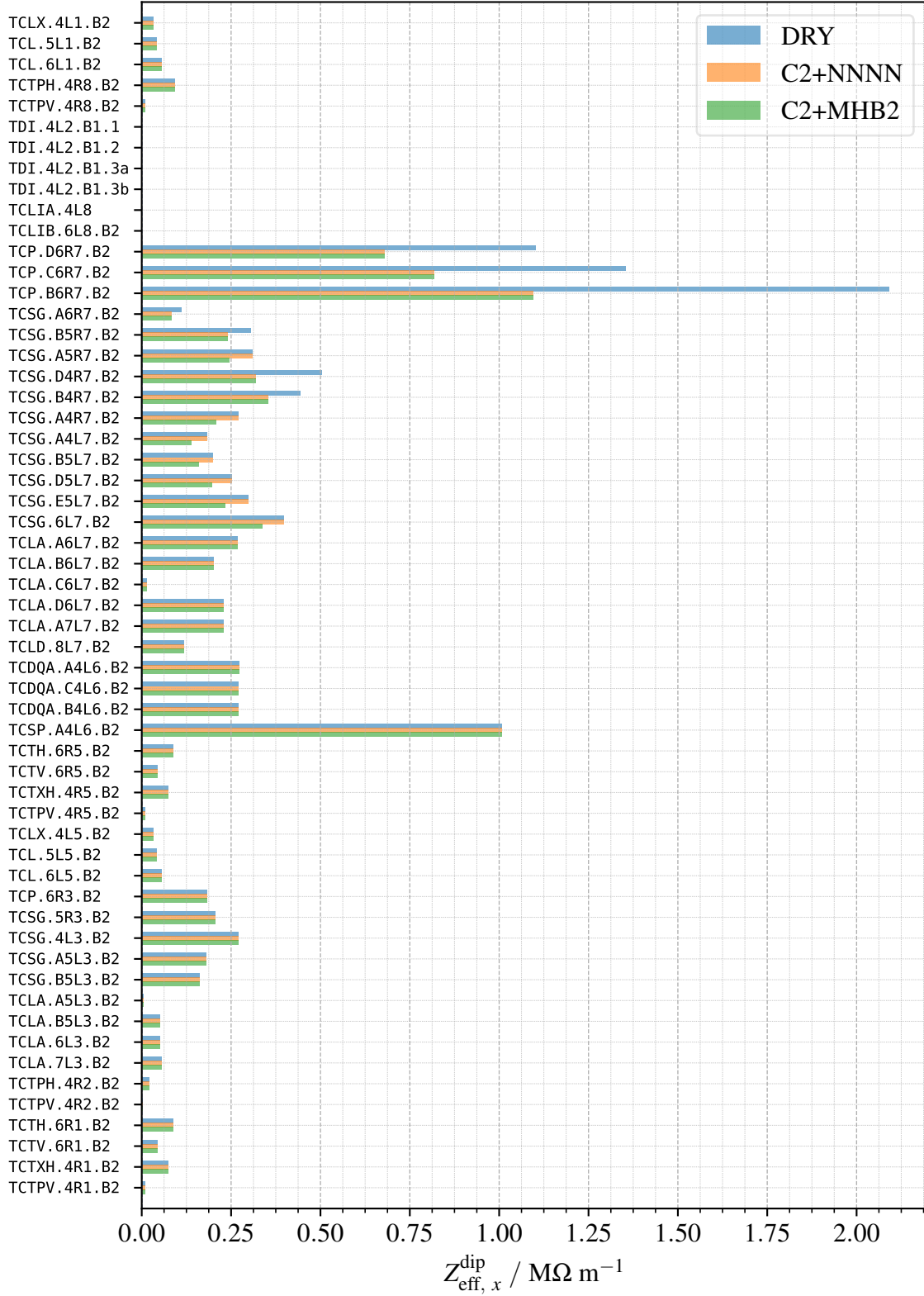


Figure C.1: The imaginary part of the dipolar effective impedance in the horizontal plane for each collimator in B2 of the HL-LHC at FT.

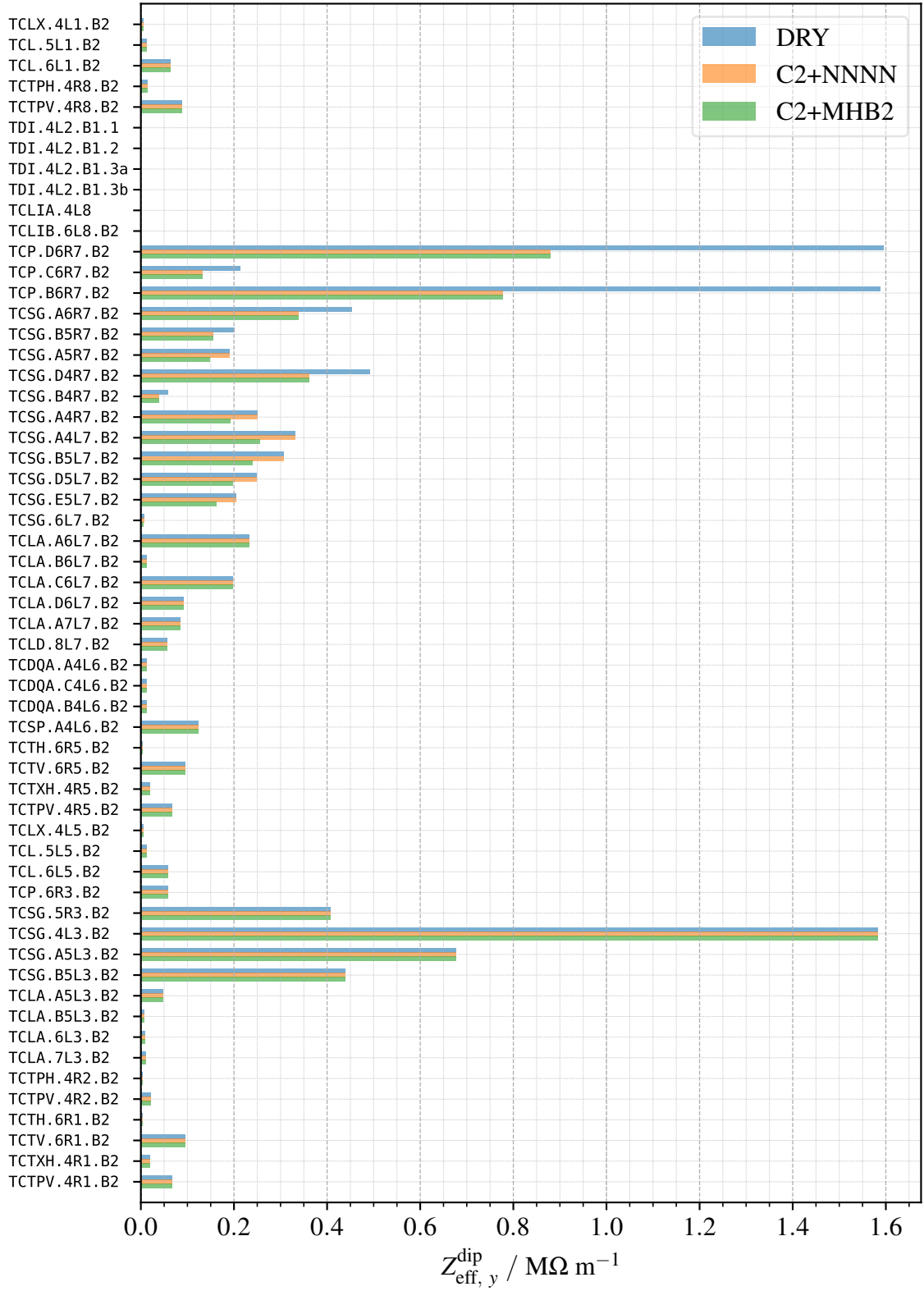


Figure C.2: The imaginary part of the dipolar effective impedance in the vertical plane for each collimator in B2 of the HL-LHC at FT.

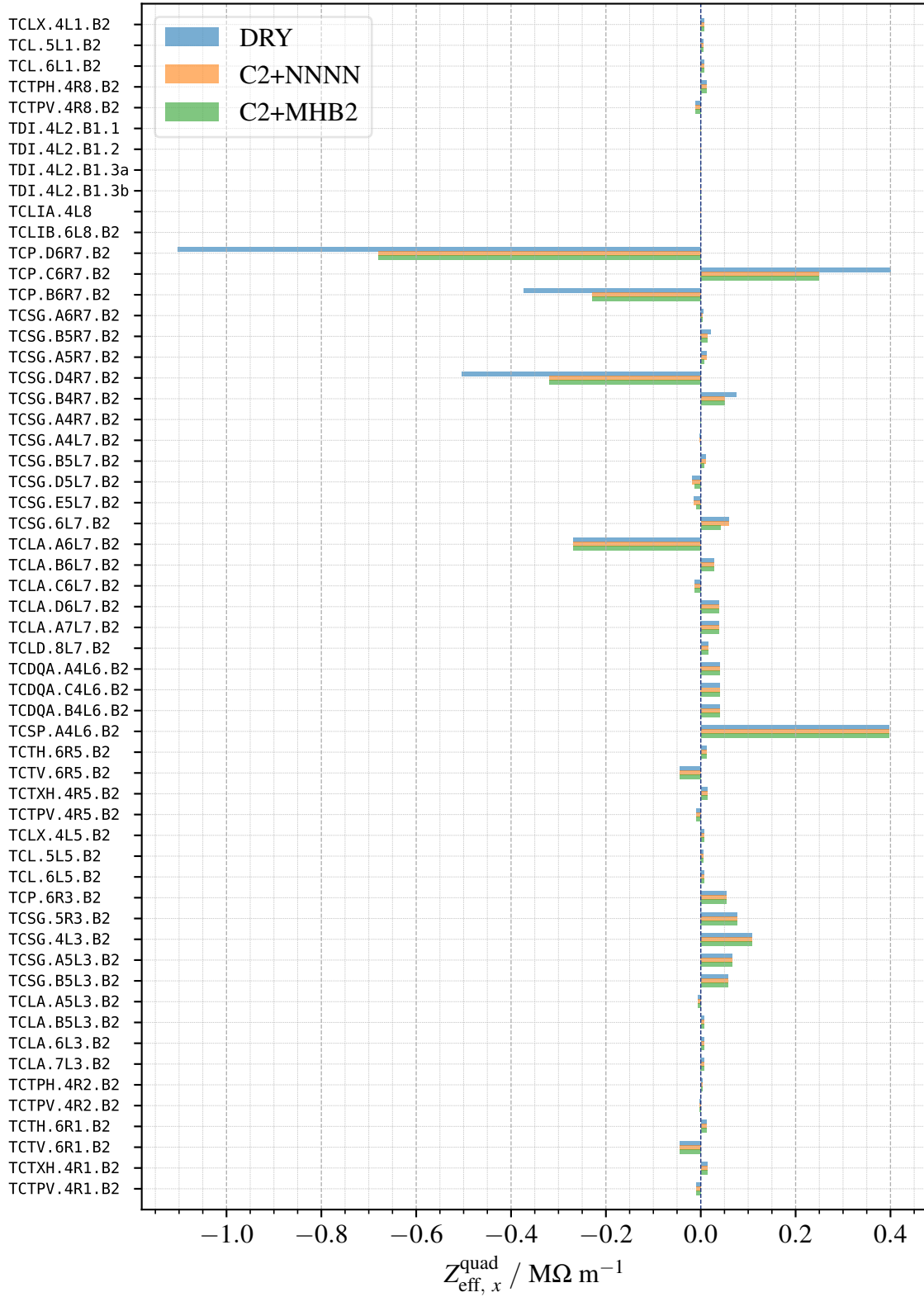


Figure C.3: The imaginary part of the quadrupolar effective impedance in the horizontal plane for each collimator in B2 of the HL-LHC at FT.

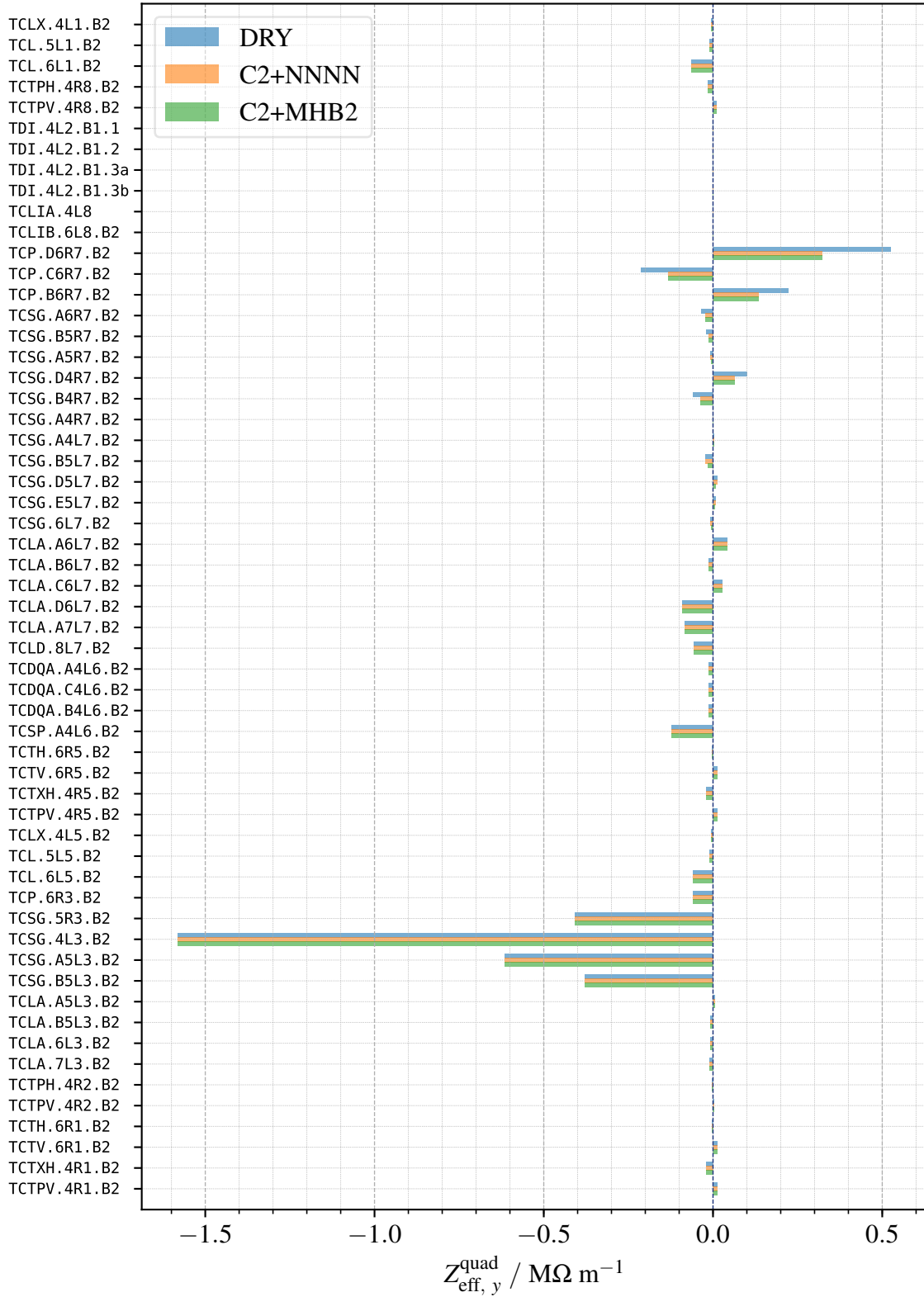


Figure C.4: The imaginary part of the quadrupolar effective impedance in the vertical plane for each collimator in B2 of the HL-LHC at FT.

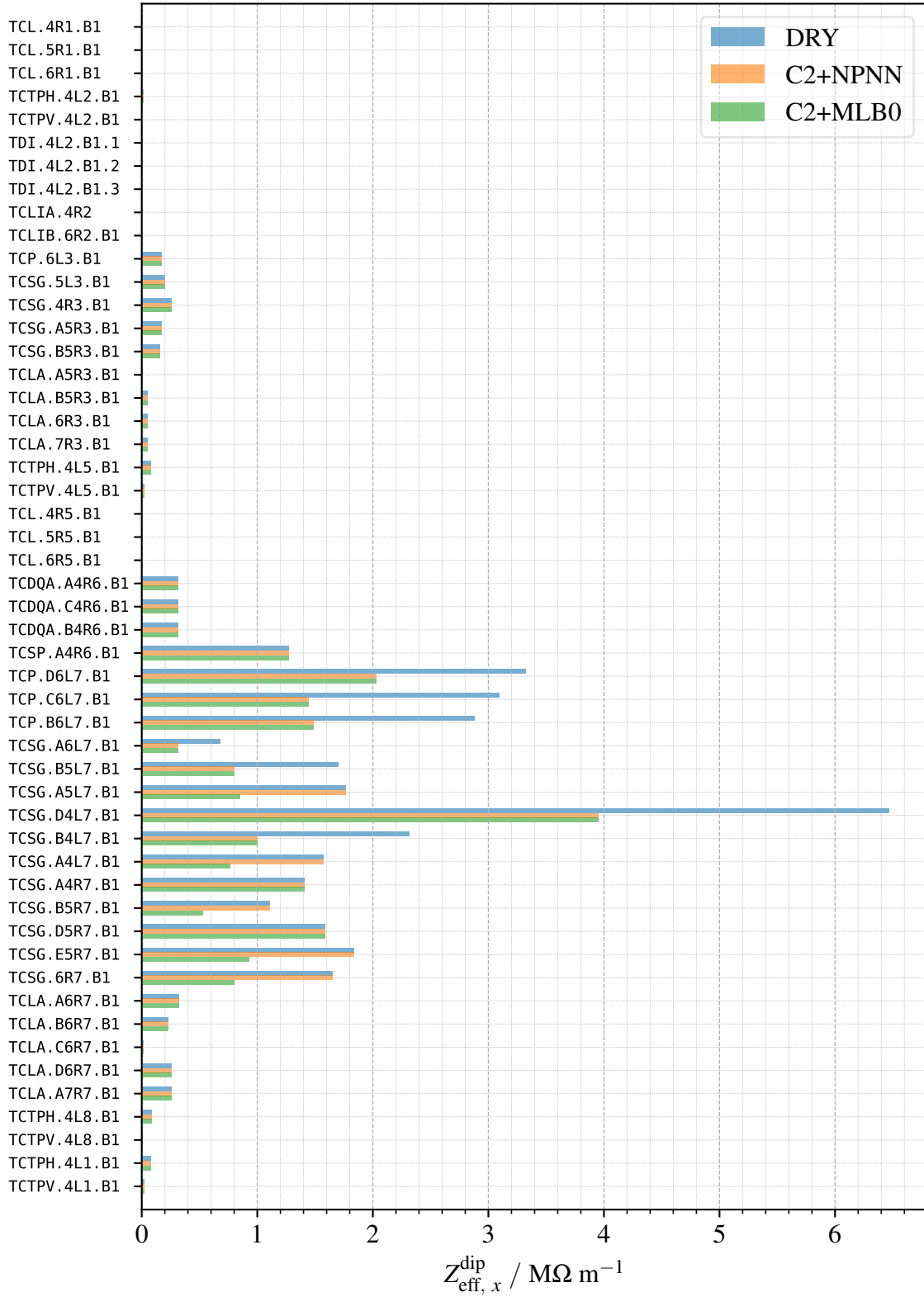


Figure C.5: The imaginary part of the dipolar effective impedance in the horizontal plane for each collimator in B1 of the LHC at 6.5 TeV.

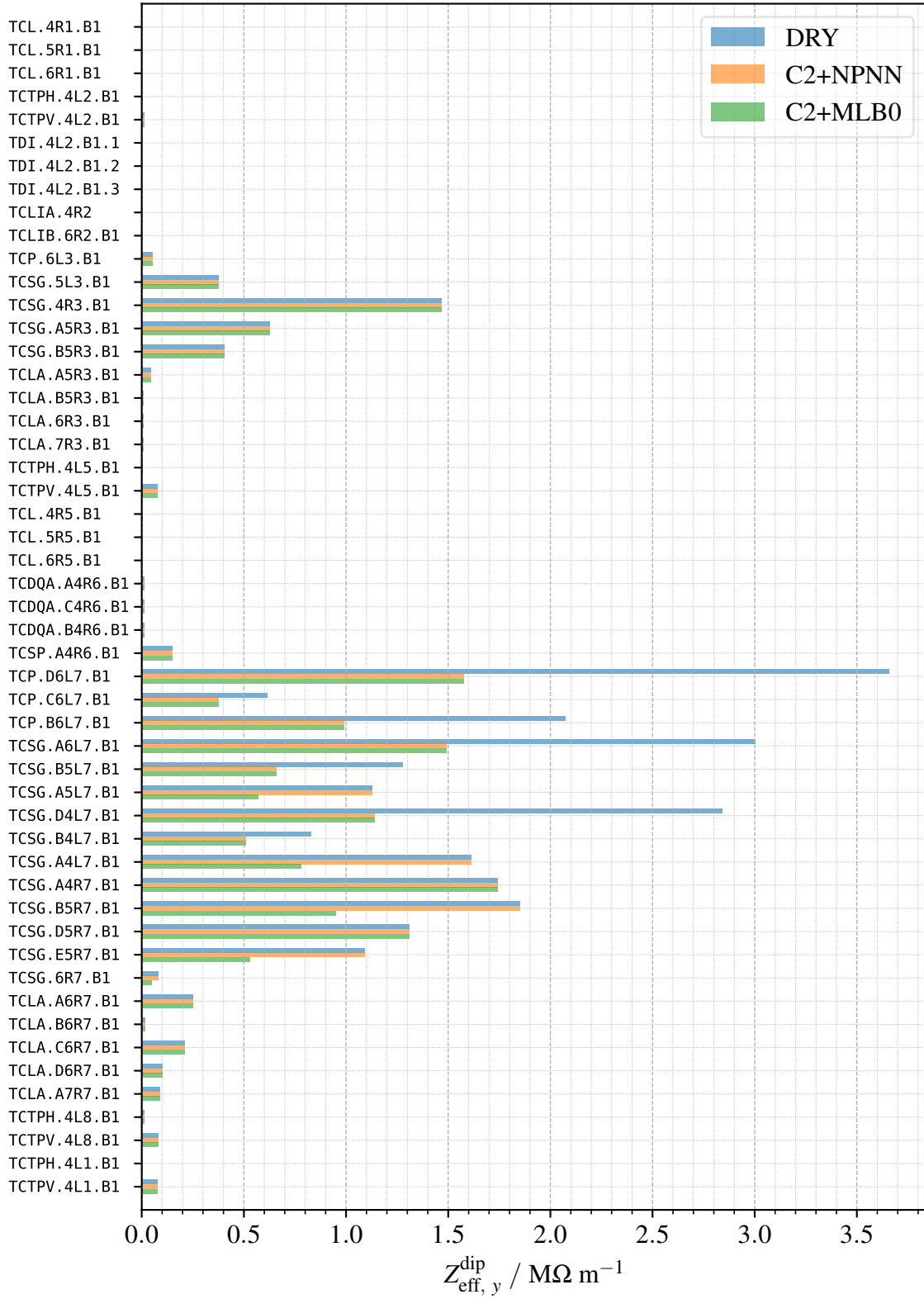


Figure C.6: The imaginary part of the dipolar effective impedance in the vertical plane for each collimator in B1 of the LHC at 6.5 TeV.

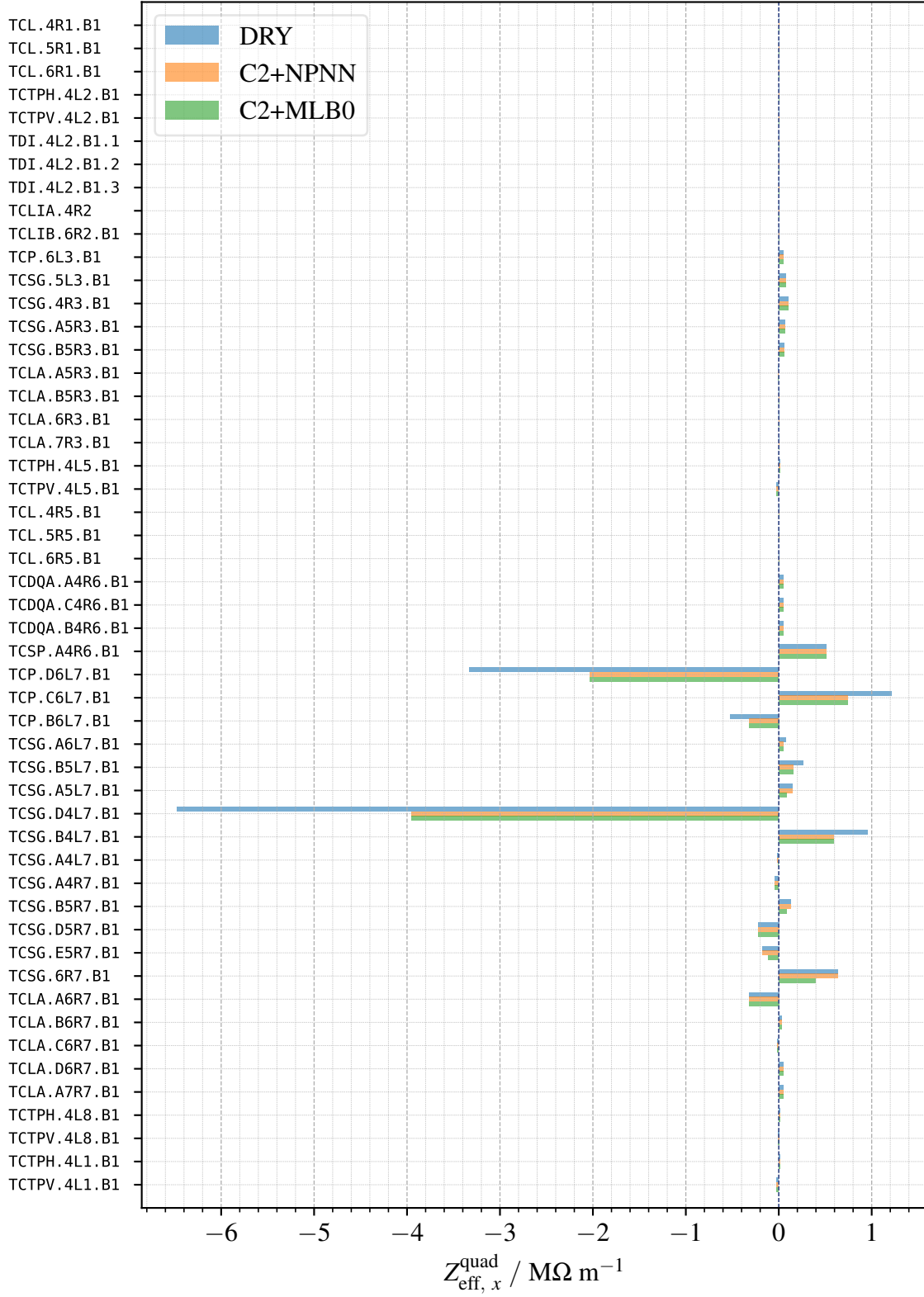


Figure C.7: The imaginary part of the quadrupolar effective impedance in the horizontal plane for each collimator in B1 of the LHC at 6.5 TeV.

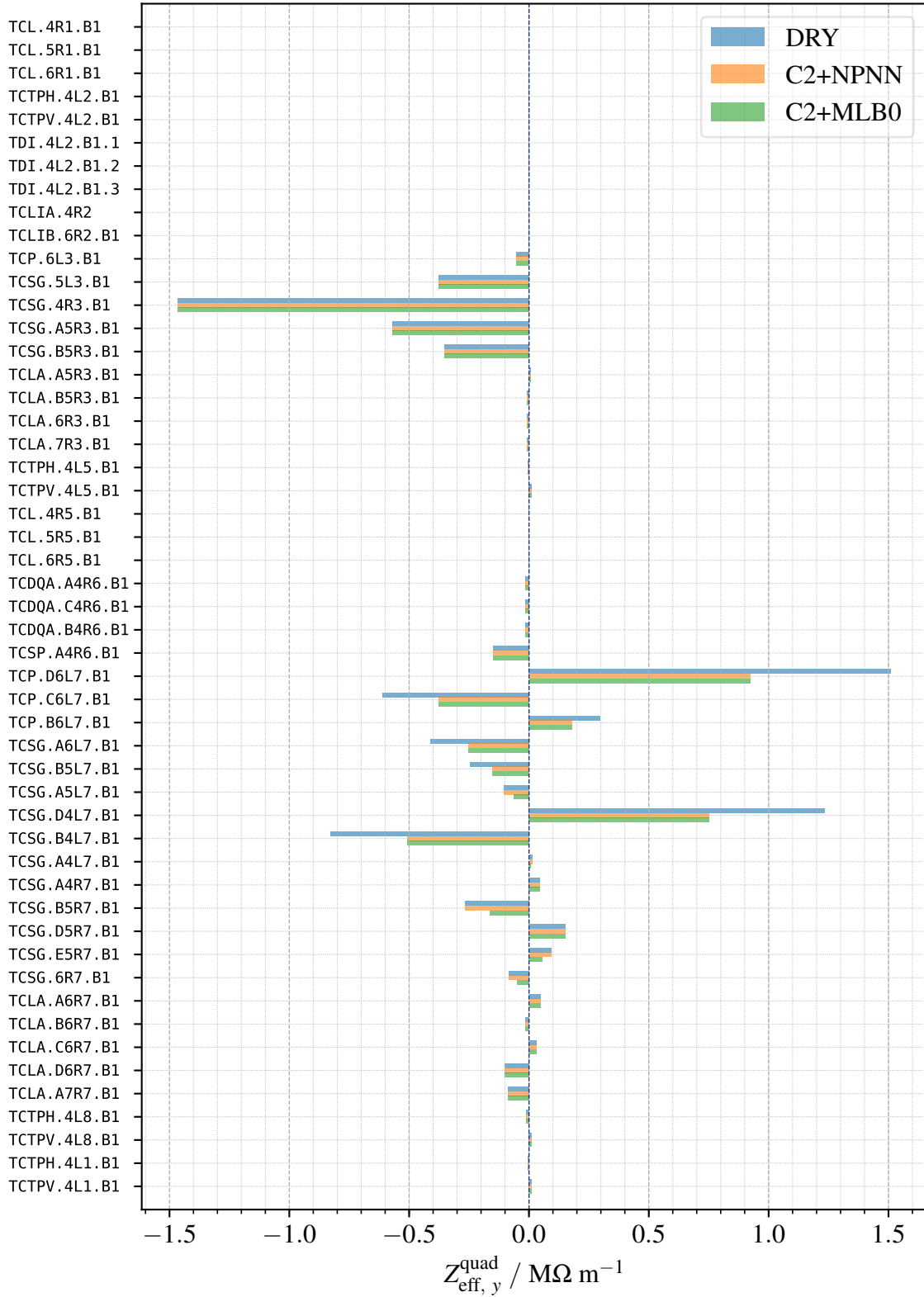


Figure C.8: The imaginary part of the quadrupolar effective impedance in the vertical plane for each collimator in B1 of the LHC at 6.5 TeV.

Appendix D

Additional figures

D.1 HL-LHC load on IR7 jaws

D.2 E5R7 impedance

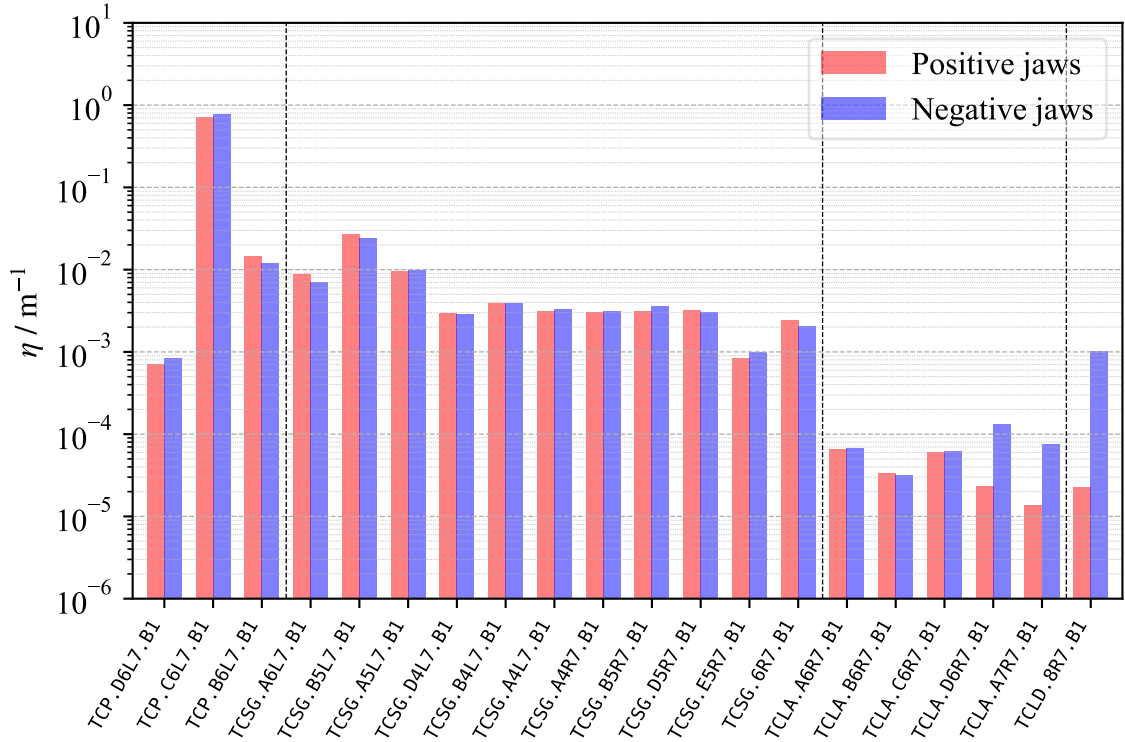


Figure D.1: The load on each collimator jaw for a dry run in B1H.

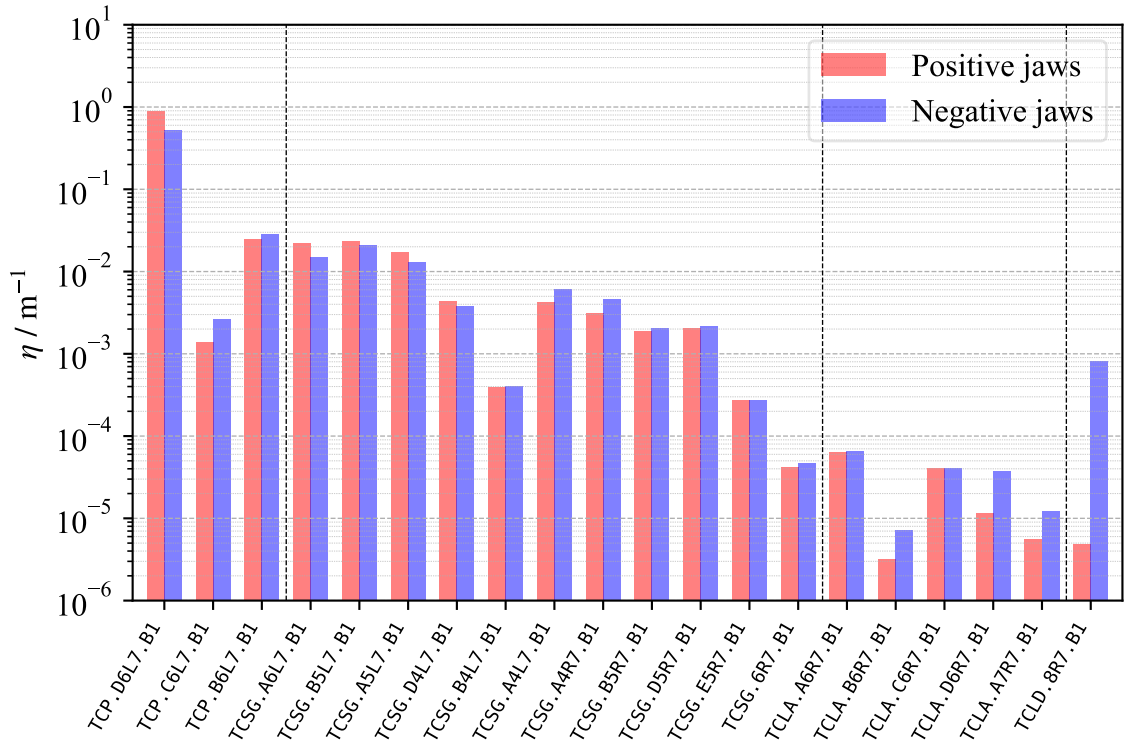


Figure D.2: The load on each collimator jaw for a dry run in B1V.

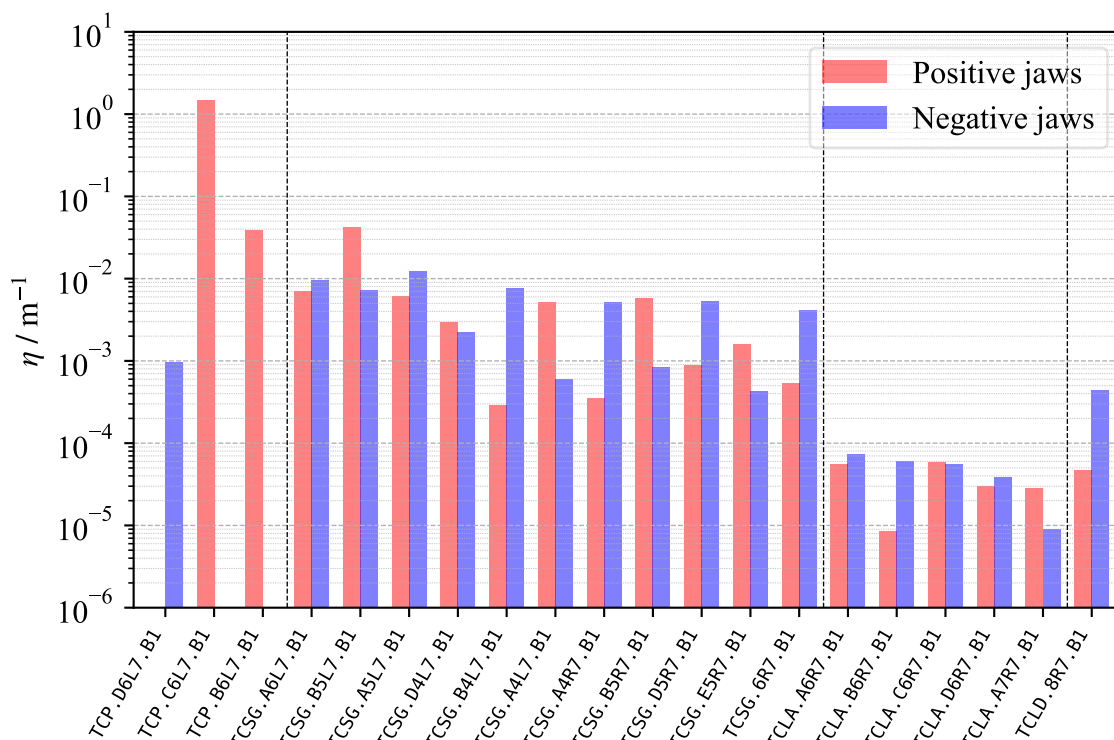


Figure D.3: The load on each collimator jaw for C2 in B1H.

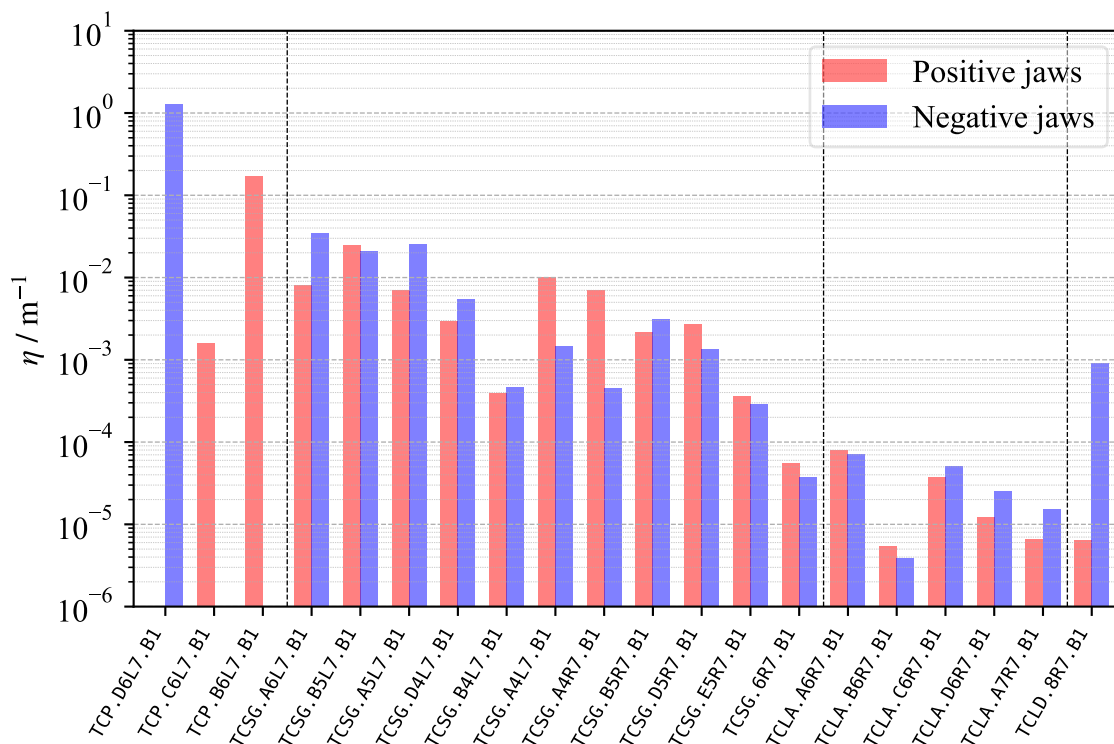
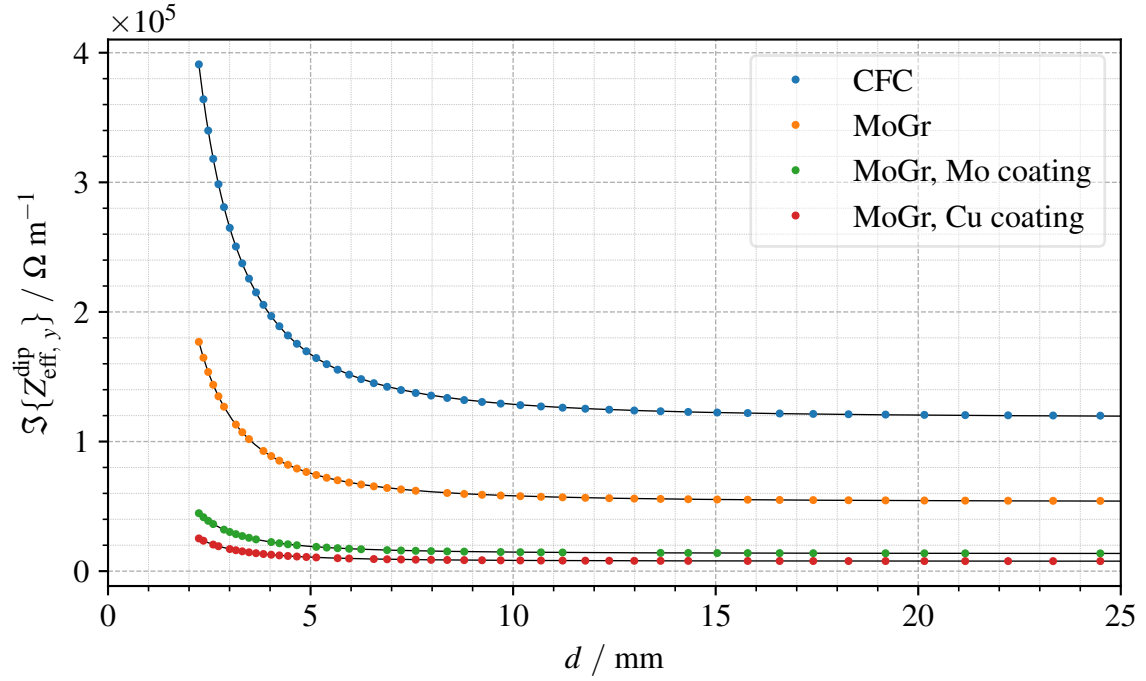
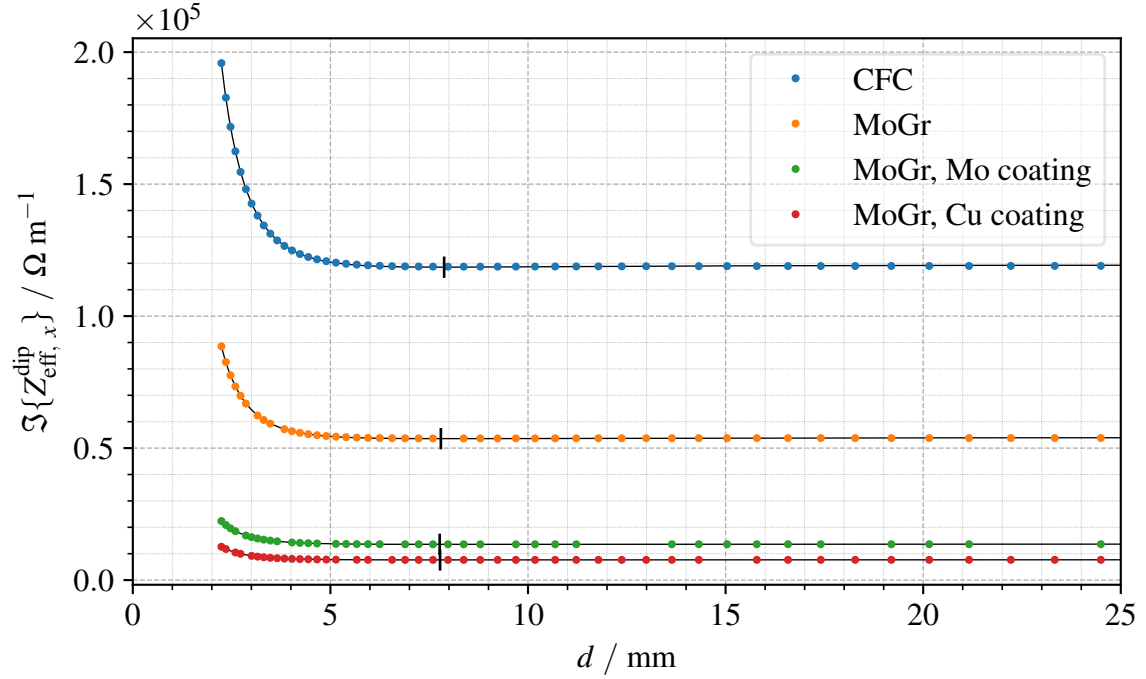


Figure D.4: The load on each collimator jaw for C2 in B1V.



(a) The dipolar component in the collimating plane.



(b) The dipolar component in the non-collimating plane.

Figure D.5: The dipolar impedance as a function of jaw retraction for different material make-up of an arbitrary secondary collimator (TCSG.E5R7.B1). The molybdenum (Mo) coating is $5 \mu\text{m}$ thick, whereas the copper (Cu) coating is $3 \mu\text{m}$ thick. The leftmost data points represent the symmetric settings and the short, black stripes mark the minimum points.