

University of HUDDERSFIELD

DOCTORAL THESIS

Design and Development of an Optical Beam Loss Monitor Based on Cherenkov Light Detection for the CERN Super Proton Synchrotron Accelerator

Defended by

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Abstract

As a result of the harsh LSS2 radiation conditions in SPS at CERN, exhaustive monitoring of beam losses, including a study of the loss source localisation, is required. According to studies conducted in particle accelerators worldwide, an optical Beam Loss Monitor (oBLM) composed primarily of a quartz multimode optical fibre and two photo-sensors is an appropriate candidate for loss mapping. This beam loss monitor is based on the Cherenkov light generation, which is emitted by high-energetic particles reaching the fibre. The interaction between particles and silica produces Cherenkov photons that propagate along the fibre until they are detected by the photo-sensors. The most critical factors introduced by the characteristics of the fibre are examined to determine the quality of the signal obtained by the system. Before the development of the oBLM prototype, a computational tool was developed to simulate Cherenkov light generation in optical fibres. With this model, it is possible to quantify the number of photons detected by the Cherenkov oBLM in any accelerator geometry simulated in FLUKA. Through experimental campaigns in CLEAR accelerator facilities, the computational model, the system components, and the PCB design for the signal readout were validated. Additionally, the oBLM prototype was installed in the beamline of LSS2. The system and cabling setup, the difficulties encountered in their implementation, and further optimisation are discussed.

Keywords: Cherenkov light, optical fibres, beam instrumentation, beam losses, beam loss monitoring

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List of Publications

The following are the publications of the author for this study. All experiments reported in these articles were designed and conducted by the author, as well as the analysis of the data obtained, the simulations and the Cherenkov Light Generation model development. Each drafts was prepared and written by the author of this thesis.

[1] S. Benítez, E. Effinger, W. Farabolini, A. Gilardi, P. Korysko, P. Lane, E. Lima, B. Salvachúa, and W. Viganò, “Development and Testing of a Cherenkov Beam Loss Monitor in CLEAR Facility,” in 12th International Particle Accelerator Conference, 2021.

[2] S. Benítez, B. Salvachúa, M. Chen, E. Effinger, J. C. Esteban, W. Farabolini, P. Korysko, and A. T. Lernevall, “Beam loss localisation with a Optical Beam Loss Monitor in the CLEAR facility at CERN,” in 13th International Particle Accelerator Conference, 2022.

[3] S. Benítez, M. Chen, and B. Salvachúa, “Simulation and estimation of Cherenkov Photon Generation in Optical fibres,” Being revised.

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List of Acronyms

ALICE	A Large Ion Collider Experiment	2
AMBER	Apparatus for Meson and Baryon Experimental Research	11
ATLAS	A Toroidal LHC ApparatuS	2
AWAKE	Advanced Proton Driven Plasma Wakefield Acceleration Experiment	10
BCT	Beam Current Transformer	7
BINP	Budker Institute of Nuclear Physics	32
BLM	Beam Loss Monitors	8
BPM	Beam Position Monitor	7
BTV	Beam TeleVision	111
CERN	Conseil Européen pour la Recherche Nucléaire	1
CLEAR	CERN Linear Electron Accelerator for Research	94
CLIC	Compact Linear Collider	32
CMS	Compact Muon Solenoid	2
COMPASS	Common Muon-Proton Apparatus for Structure and Spectroscopy	11
CVD	Chemical Vapor Deposition	29
FLUKA	FLUctuation KAscade	62
HiRadMat	High-Radiation to Materials	10
HL-LHC	High Luminosity Large Hadron Collider	4
IC	Ionisation Chambers	22
IP	Interaction Point	5

LHC Large Hadron Collider	1
LHCb Large Hadron Collider beauty	2
LHCf Large Hadron Collider forward	7
LIC little ionisation chambers	23
LINAC2 Linear Accelerator 2	2
LINAC4 Linear Accelerator 4	2
LSS Long Straight Sections	9
MoEDAL Monopole and Exotics Detector at the LHC	7
MPPC Multi-Pixel Photon Counter	47
NA North Area	10
oBLM optical Beam Loss Monitor	30
OTR Optical Transistor Radiation	8
PDE Photon Detection Efficiency	49
PMT Photo-Multiplier Tube	25
POF Plastic optical fibres	44
ppb protons per bunch	9
PS Proton Synchrotron	2
PSB Proton Synchrotron Booster	2
RF Radiofrequency	5
SEM Secondary Emission Monitors	23
SHINE SPS Heavy Ion and Neutrino Experiment	11
SiPM Silicon Photo-Multipliers	31

SPS Super Proton Synchrotron	2
TOTEM TOTal Elastic and diffractive cross section Measurement	7
VEPP-5 Colliding Electron-Positron Beams-5	32
WCM Wall Current Monitor	8

Introduction

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1.1 The CERN Accelerator Complex

The Conseil Européen pour la Recherche Nucléaire ([CERN](#)) is, at present, the largest particle laboratory in the world, with an increasing international collaboration of 23 member states and personnel from institutions in more than 70 countries. Scientists and engineers worldwide work together to seek answers to such fundamental questions in nuclear and particle physics. The CERN Accelerator Complex, located on the border between France and Switzerland, comprises a chain of accelerators providing increasing particle beam energies and delivering them to experiments or the next more powerful accelerator. To date, the Large Hadron Collider ([LHC](#)) [[1](#)]

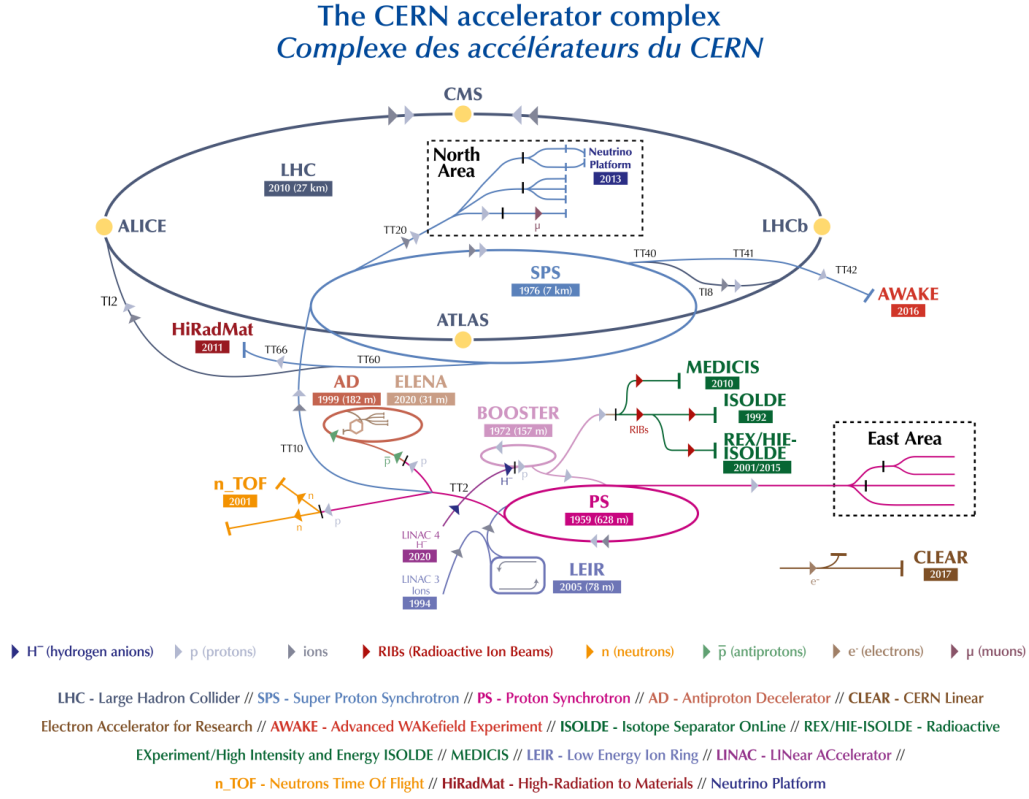
operates with the highest beam energy in the world, accelerating protons up to an energy of 6.8 TeV in Run 3.

Two proton beams are injected into the LHC from the CERN Accelerator Complex. They are accelerated and kept circulating close to the speed of light (99.9999964%) along the 27 km of ring situated 100 m underground. Beam-beam collisions happen in the four crossing points around the accelerator where the experimental caverns and detectors are located. The four main detectors are A Toroidal LHC ApparatuS (ATLAS), Compact Muon Solenoid (CMS), A Large Ion Collider Experiment (ALICE) and Large Hadron Collider beauty (LHCb).

All the protons are provided from a source of negative hydrogen ions (H^-), and they travel through a set of connected accelerators: the Linear Accelerator 4 (LINAC4)¹ and the following three circular accelerators, Proton Synchrotron Booster (PSB), Proton Synchrotron (PS), Super Proton Synchrotron (SPS) and LHC. Figure 1.1 shows an overview of the CERN Accelerator Complex.

The H^- linear accelerator, LINAC4 [4], accelerates the protons to 160 MeV and injects them into the PSB, the first circular accelerator. The two electrons are despoiled during the injection process, and the proton remains. The PSB is composed of four vertically stacked rings of around 160 meters in circumference, where the proton beam bunches are created, accumulated and transferred to the PS with an energy of 1.4 GeV. The PS was CERN's first synchrotron and the world's highest-energy particle accelerator in 1959 [5]. It consists of a cyclic particle accelerator placed on the surface, with a radius of 100 meters which pushes the beam to 25 GeV into the SPS. The next accelerator in the chain is the SPS, built-in 1976 [6]. It is housed 60 m underground with a circumference of 6.9 km, and it accelerates the bunched protons from 25 GeV to 450 GeV, 99.9998% of the speed of light. The SPS is the final injector for high-intensity proton beams for the LHC. The LHC has received protons since 2008, and it is capable of accelerating them to several tera-electronvolts (TeV). The LHC proton beam is provided via two transfer lines and injected in opposite directions from the SPS.

¹LINAC4 has replaced the Linear Accelerator 2 (LINAC2) during the upgrade in the prolonged shutdown (2019-2021) to increase the luminosity of the LHC [2].

Figure 1.1: *CERN Accelerator Complex* [3].

The first proton-proton collisions in LHC were performed between 2010 and 2013 during the so-called Run 1 [7], with bunched beams spaced by 150 ns, 75 ns, and 50 ns and energies of 3.5 and 4 TeV, dedicated to providing luminosity to the experiments with the aim of the discovery of the Higgs boson. The Higgs boson was finally detected at $125 \text{ GeV}/c^2$ by the ATLAS and CMS experiments.

In Run 2 [8], the LHC beam operation between 2015 to 2018, the proton beam was configured to reach 6.5 TeV beam energy, running bunch trains of 1.2×10^{11} ppb at 25 ns of bunch spacing.

The present Run 3 [9] began in 2022, and it will be operative until the end of 2025. The expected proton beam energy will approach the nominal 7 TeV with a bunch population of up to 2.3×10^{11} ppb exploring the limits for High Luminosity LHC.

1.2 The Large Hadron Collider and Beam Diagnostics

1.2.1 Large Hadron Collider

The LHC is, in general terms, a circular collider capable of accelerating two proton beams circulating in opposite directions up to a beam energy of 7 TeV. The beams are kept circulating inside the same cryostat using superconducting magnets. It was designed for the Higgs particle discovery and the study of events with centre-of-mass collision energies of up to 14 TeV [1]. The proton-proton collider has two separate beam pipes (see Figure 1.2), coinciding only where the four experimental detectors are located. The vacuum chambers are shared for the two beams, and a triplet quadrupole magnets assembly supports the lines. Before the proton beams enter the experimental areas, the magnet systems are used to reduce the cross-section of the colliding beams, increasing the luminosity. In particle accelerators, *luminosity* is defined as the number of interactions per second within a cross-section in a given process. The LHC is designed to provide $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ of nominal luminosity. During the Run 3 and the High Luminosity Large Hadron Collider (HL-LHC) run an upgrade on the luminosity is expected and the accelerator will provide up to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ [10].

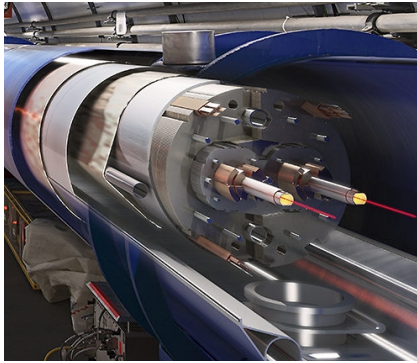


Figure 1.2: *Cross-section of the LHC beam line hypothetically opened* [11].

The LHC layout is divided into eight straight sections and eight arcs. Each arc contains more than 150 dipoles magnets to bend and lead the beam, and the straight sections are used for instrumentation or experimental insertions. Therefore,

there are 8 points, starting from the ATLAS experiment at point 1. Points 2 and 8 contain the LHC injection systems, where the ALICE and LHCb detectors are also located. The central collimation systems are located in point 3 for the off-momentum halo cleaning and point 7 for the betatron halo cleaning. The point 4 contains the Radiofrequency (RF) systems whose primary purpose is particle acceleration. The CMS experiment is located in point 5. Finally, in point 6, the critical function of extracting the beam is performed. In the experiment sections, the middle point is the Interaction Point (IP), which indicates the exact point where the beams can intersect. The LHC layout is presented in Figure 1.3.

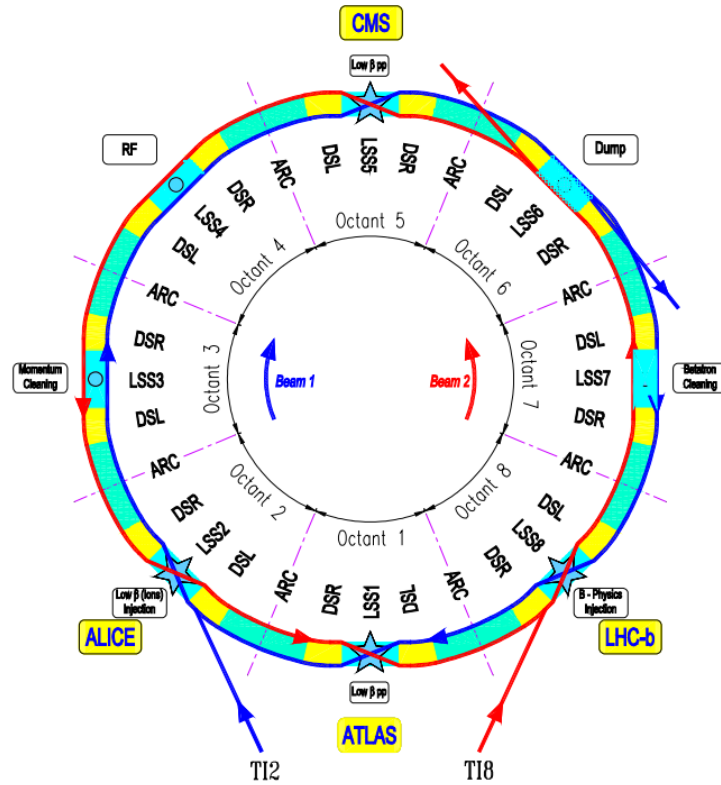


Figure 1.3: *LHC Schematic. Beam 1, in blue, circulates clockwise, and Beam 2, in red, circulates counter-clockwise. The stars indicate where the two beams collide. [1].*

1.2.2 LHC Experiments

The principal purpose of the detectors at CERN is to monitor and identify collision products, collecting all the possible information. As mentioned previously, to date there are four main experiments installed at the LHC: [ATLAS](#), [CMS](#), [ALICE](#) and [LHCb](#).

ATLAS [\[12\]](#) and CMS [\[13\]](#) are the high-luminosity detectors of the accelerator. Both experiments are very similar in instrumentation but with different designs. On the one hand, the 7000-tonne ATLAS is the largest collider-detector globally and consists of a cylinder made of eight 25 m long superconducting magnet coils surrounding the central beam pipe. On the other hand, CMS is built around an enormous superconducting solenoid. It generates a magnetic field of 4 T, around 10^5 times the field of the Earth. Thank the ATLAS and CMS collaborations, many Higgs boson properties have been analysed.

ALICE [\[14\]](#) detector is specialised in heavy-ion collisions. It studies the plasma state at very high densities and temperature conditions. This state of matter was probably the state of our Universe just after the Big Bang, where the quarks and gluons were not bounded within the hadrons. From that moment, the neutrons and protons began to exist.

Finally, the LHCb [\[15\]](#) experiment analyses the interactions of B-particles, i.e. particles containing the bottom quark, also known as the beauty quark. These studies can help to explain the matter-antimatter asymmetry.

The four extensive experiments are based on sub-detectors distributed in layers. Each layer detects different secondary particles depending on their energy and speed after the collisions. At first, a magnet system separates the particles by charge to identify their momentum and mass. Then, the tracking devices measure the curvature of the particle's path inside the magnetic field. Muon chambers and vertex detectors are two examples of tracking devices. Calorimeters measure the energy of the particles. These devices stop the particles and collect the energy deposited on them.

Outside the collision points, there are three additional experiments located in

the LHC: Large Hadron Collider forward (LHCf) [16], TOTal Elastic and diffractive cross section Measurement (TOTEM) [17] and Monopole and Exotics Detector at the LHC (MoEDAL) [18]. LHCf and TOTEM, located near the high-luminosity experiments, measure the particles created from the collisions close to the direction of the beams. The first one seeks to estimate the primary energy of the ultra-high-energy cosmic rays, and the second one measures the effective population size of the protons of the beam. Close to LHCb, MoEDAL searches for the magnetic monopole or similar highly ionising particles.

1.2.3 Beam Diagnostics

The beam characterisation is a fundamental requirement in any accelerator. The precise reading of the beam properties helps determine a general overview of the accelerator functionality. Most common measurements performed in the accelerators are [19]:

- **Beam current or beam intensity.** The beam electrical current is one of the most critical parameters for the operation of particle accelerators. Generally, it is measured by a Beam Current Transformer (BCT), being the Faraday cup its predecessor [20]. The BCT consists of a primary ferromagnetic coil with a wire wound around the torus. When the electric current of the beam passes through the transformer, a magnetic field is generated. Changes in this current will affect the magnetic flux, inducing a new current in the secondary winding. Using the transformer makes it possible to measure the beam current distribution. For non-pulsed beams, the total current can be obtained by a DC beam transformer.
- **Beam position.** The transverse position of the beam in the beam pipe can be determined by a Beam Position Monitor (BPM) [21]. The BPM is based on a pair of pick-up electrodes located in the vacuum chambers, horizontal and vertical planes, used to measure the transverse centre-of-mass of the beam. They are also used for trajectory measurements and position corrections. BPMs can also measure the relative beam current.

- **Transverse beam profile.** The measurement of the beam emittance is necessary for any circular accelerator. This property is the spread of the particle distribution in position-and-momentum phase space and characterises the transverse beam size. Determining the beam profile, injection mismatches and dispersion during the turn-by-turn shape oscillations can be avoided. The chromaticity is the change of the linear contributions in the particle transverse motion related to an energetic variation [22]. It indicates the beam stability depending on the head-tail stability. There are several devices such as scintillators, Optical Transistor Radiation (OTR) screens, secondary emission grids, wire scanners, synchrotron radiation monitors and residual gas monitors for the beam size measurements, from which the emittance is then calculated.
- **Longitudinal profile measurement.** The measurement of the bunch length and its structure can be performed by different instruments such as streak cameras, fast-sampling oscilloscopes or by using a Wall Current Monitor (WCM) among others. In addition, the BPMs can record the longitudinal behaviour of the beam [23]; for example, collecting the bunch shape as a function of time or the average velocity between two points.
- **Beam losses.** Secondary particles generated from beam impacts into accelerator components are measured by **Beam Loss Monitors (BLM)**. Their signal is used to protect the machine from lost particles by triggering a beam dump. The detection of losses also helps prevent radiation damage and is used to optimise the machine performance. Different **BLM** can be used to detect the losses.

The CERN Systems - Beam Instrumentation (SY-BI) group is responsible for all the activities related to the monitoring and diagnostics of the accelerated particle beams, including the development and design of new detector technologies and maintenance of current measurement installations.

1.3 Super Proton Synchrotron

The Super Proton Synchrotron (SPS) [6] is the second-largest ring at CERN. Its length is about 6.8 km, and it has been used to accelerate protons, electrons, their anti-particles (anti-protons and positrons) and heavy ions. One of the main functions of the SPS is the acceleration of proton beams from 26 GeV up to 450 GeV for the LHC injection via two beamlines. Beams of 288 bunches, with up to about 2.2×10^{11} protons per bunch (ppb), can be accelerated and injected into the LHC without beam instabilities [24]. The SPS layout is presented in Figure 1.4, showing the main location of the long straight sections Long Straight Sections (LSS).

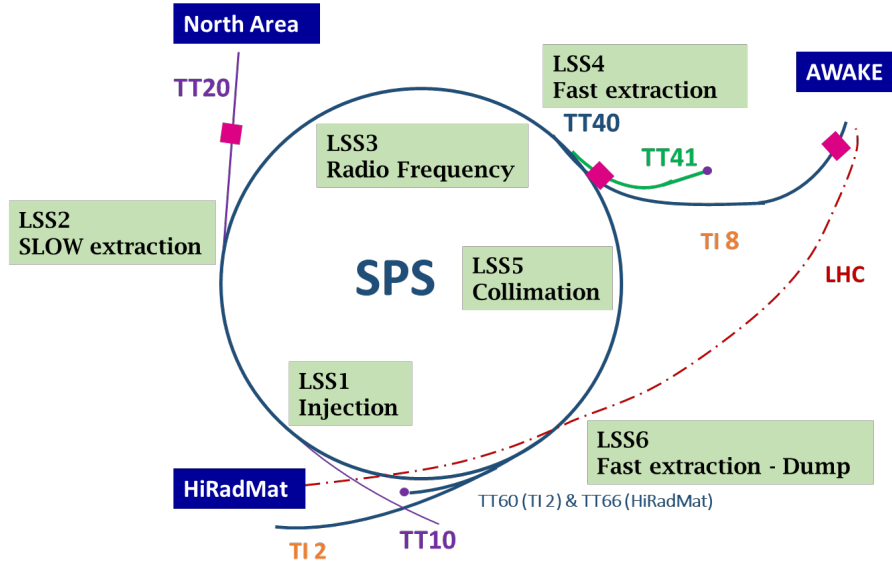


Figure 1.4: *SPS Schematic.* The ring is divided into six LSS. Apart from the two beam extraction for the LHC, there are three extractions more to the North Area, AWAKE and HiRadMat laboratories.

As opposed to the LHC, the SPS has only one beam pipe, and the beam is always travelling in the same direction. The beam is injected from PS to SPS in the LSS1. It is deflected along the transfer line TT10 by two main magnets, septa and kickers, with an energy of 25 GeV. The primary RF system of the SPS is installed in LSS3, where four cavities, two of 20 m and two of 16.5 m long, operate at a

frequency of 200.2 MHz, accelerating the beam with 8 MV of voltage [25]. Beam cleaning is provided by the collimator system in the LSS5 region and the transfer line collimators. The role of the collimators systems is to "clean" unavoidable beam losses in a controlled way before they reach the line components. The reduction of the out-scattered beam particles² is accomplished by the collimator jaws. LSS4 and LSS6 regions house the fast extraction points where the beam is transferred into the LHC by a system of fast kicker magnets [27]. The transfer line TI2 transports the beam from the LSS6 to the clockwise LHC ring in the injection point located in IR2. The TI8 transfer line connects the LSS4 with the IR8 to inject the beam counterclockwise. The beam dump system is also located in LSS6.

In addition to the beam delivery to LHC, SPS supplies beam to a wide range of experiments. The slow beam extraction to the North Area (NA) is located in LSS2, where the accelerator feeds six beamlines with more than 60 experiments. NA experiments compose a fundamental part of the CERN physics research programme. There are two other main experiments, the High-Radiation to Materials (HiRadMat) [28], which tests different components under harsh conditions and the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) [29], which investigates the interactions of the protons with the plasma state. They are located in the LSS1 and LSS4 SPS areas, respectively.

1.3.1 SPS Physics

As mentioned before, one of the main objectives of the SPS accelerator is to provide particle beams for the LHC. However, the SPS beams are used in a wide variety of experiments related to the inner structure of hadrons and dark matter studies.

The North Area [30], connected to SPS through the TT20 transfer line in the LSS2 section, is a complex of several laboratories and fixed-target experiments,

²The accumulation of these dispersive sources causes the beam halo formation [26]. The beam halo can be described as the non-regular outer part of the beam concerning the beam core distribution. There are two different types of halos: the betatron formed in the case of larger-than-nominal transverse emittance and the off-momentum halos, related to the energy error. The deviated particles are also considered beam losses, and they should be avoided during the accelerator operation.

currently ranging from NA1 to NA64. Among the results, the first studies of the quark-gluon plasma, the photoproduction of vector and scalar bosons or the first charge-parity violation evidence can be considered highlights.

Nowadays, several halls are included in the North Area, such as the Neutrino Platform for neutrino detection research, the Common Muon-Proton Apparatus for Structure and Spectroscopy ([COMPASS](#)) (NA58), SPS Heavy Ion and Neutrino Experiment ([SHINE](#)) (NA61), NA62, NA63, NA64 and UA9.

[COMPASS](#) [31] studies the internal structure of protons and neutrons, investigating the properties of quarks and gluons by firing them at a polarised target. The Apparatus for Meson and Baryon Experimental Research ([AMBER](#)) [32] will be the successor of the COMPASS experiment after its upgrading in 2022. [SHINE](#) [33] team analyses the collisions of the beam particles with fixed targets to understand the properties of the hadron production, such as the number of hadrons obtained, their charges, masses and momenta. The NA62 laboratory measures rare kaon decays by collisions between the SPS protons with stationary beryllium targets. The NA63 investigates the radiation processes within solid electromagnetic fields and studies the relativistic phenomena of photon emissions. Finally, the NA64 experiment searches for unknown particles in the dark matter and other rare events generated by collisions between the SPS beams and different targets. In addition, the UA9 collaboration studies improvements in the LHC collimator systems using tiny bent crystals.

Behind the extraction beam in LSS1, the line splits into the TT60 (TI2) and the TT66 transfer lines. The first one is connected to the LHC beam injection and the second one to the HiRadMat experiment, where the effects of the beam impacting different materials and components are evaluated. After the LSS4 extraction, the transfer line TT40 splits in the TI8 towards the LHC ring and the transfer line TT41 connects the SPS beam with AWAKE, driving the proton beams into plasma cells to generate strong wakefields.

1.3.2 LSS2 Slow Extraction

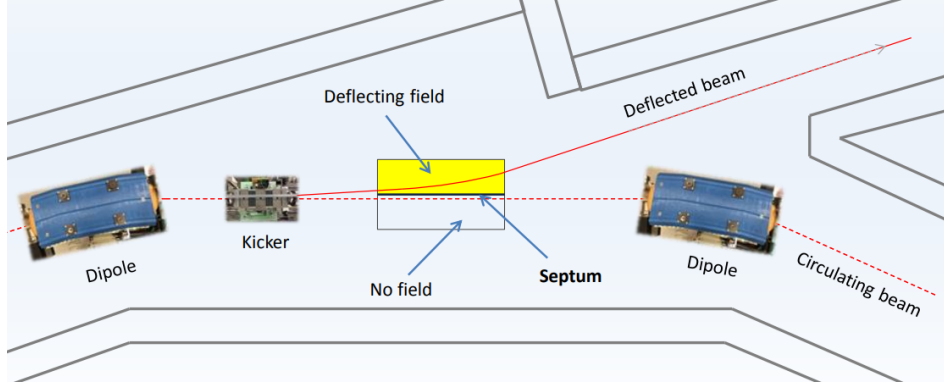
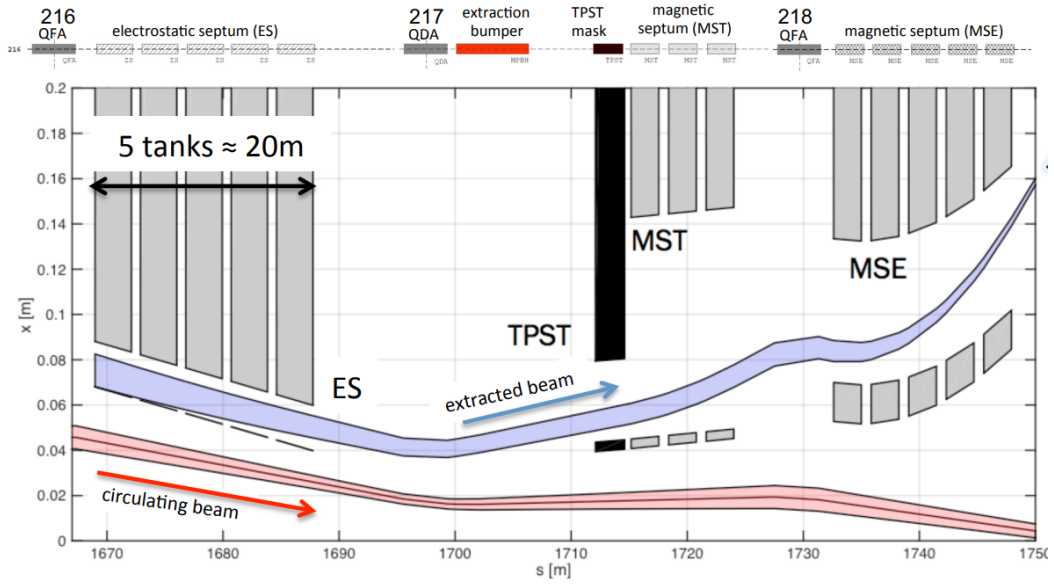
In the framework of particle accelerators, in general terms, the extraction is a beam transfer process, from an accelerating machine to the next element in the chain or another external target, after acceleration.

There are several beam extraction techniques for synchrotrons [34]: the fast single-turn (≤ 1 turn), the fast multi-turn (a few turns), slow resonant multi-turn (many thousands of turns) and other exotic types such as the charge-exchange extraction or using bent crystals.

In SPS, the beam is sent to the LHC by two fast single-turn extractions at 450 GeV of energy via the LSS4 and LSS6 transfer lines. Besides, the SPS also sends proton beams to the North Area through the LSS2 section, where the fixed-target laboratories are located. Due to the beam requirements of high integrated intensity on the targets in the experiments, around 4×10^{13} protons at 400 GeV are transferred in a constant flux by **slow resonant multi-turn extraction** in spills of 4.8 s of duration, i.e. over 2×10^5 turns [35, 36].

The SPS slow extraction system consists of an electrostatic septum (ZS) composed of five consecutive tanks, two magnetic septa (three MST and five MSE) for the beam deflection and four sextupoles to correct the chromaticity. A septum is a magnet with a partition that divides two specific field regions to deflect the beam to the external target or continue the accelerator ring. Figure 1.5 shows a simplified version of a synchrotron extraction process.

In SPS, a third-integer betatron resonance based on a set of sextupoles is used to create a stable region in the phase-space. Then the beam is sent to the ZS by using five bumpers. The septum comprises five separated tanks, 3.1 m in length, mainly stainless steel, aluminium and Invar. It contains several thin wires that generate a vertical electrical field that extracts the beam minimising the losses during the process. It is usually aligned by monitoring and reducing the induced beam loss particles [38]. Then, the beam is bent horizontally by the magnetic fields of the steel Lambertson septa magnets. The beam is veered in perpendicular to the circulating beam displacement. The slow extraction geometry is presented in Figure 1.6.

Figure 1.5: *Septum functionality representation in the beam extraction process.* [37]Figure 1.6: *LSS2 slow extraction scheme.* [36]

A constant flux of particles is the main requirement of the NA experiments. The beam suffers a momentum distribution via RF manipulation through the resonant slow extraction, so-called RF gymnastic. After this distribution, the beam is debunched, reducing the high-frequency modulation components in the spill. Figure 1.7 shows the intensity of the slowly extracted spill versus the time in the SPS.

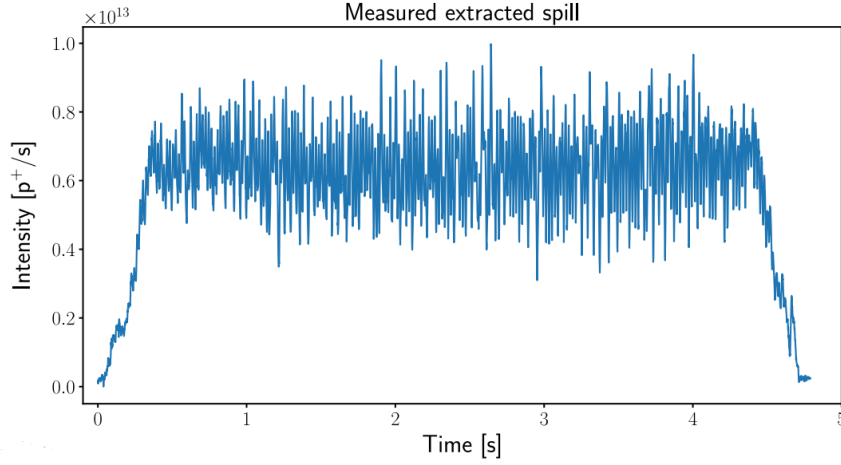


Figure 1.7: *Typical operational extracted spill.* [39]

1.3.3 Irradiation Overview and Extrapolations in LSS2

The induced radio-activation in LSS2 has been measured over many years, and, to date, it remains a critical area at CERN. The accumulated dose can be translated into a substantial reduction of the components and equipment lifetime. Figure 1.8 summarises the residual activation levels of the LSS2 area.

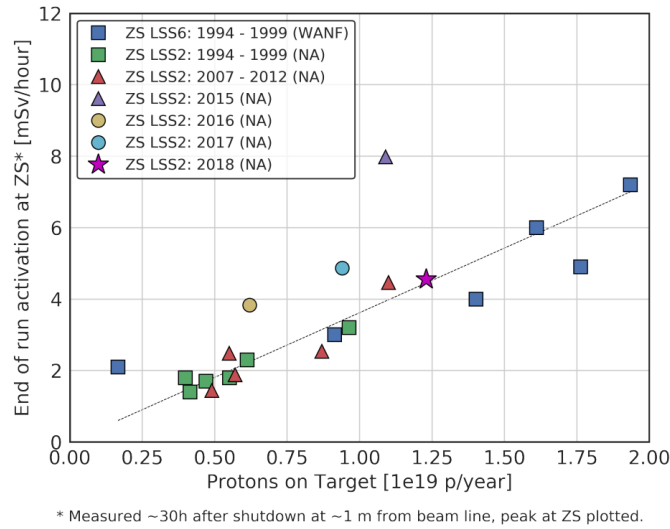


Figure 1.8: *Residual dose in LSS2 and LSS6 regions in SPS over the years. The high losses observed have been a problematic for the CERN operators* [40].

The slow extraction efficiency ε [41] is one of the most important parameters to quantify the exact number of protons injected into the North Area and is typically defined as

$$\varepsilon = \frac{1}{C} \frac{I_{ext}}{I_{circ}} \quad (1.1)$$

where I_{ext} is the extracted beam intensity measured in the external beamline, I_{circ} the intensity circulating in the SPS before extraction, and C is a calibration constant.

In addition, the Induced Radioactivity I_{Rad} is directly proportional to the beam lost in the process,

$$I_{Rad} \propto \bar{\varepsilon} \quad (1.2)$$

where $\bar{\varepsilon}$ is the extraction inefficiency, deduced from the relation,

$$\varepsilon + \bar{\varepsilon} = 1 \quad (1.3)$$

The I_{Rad} can be determined by the measurements of the losses by the area's Beam Loss Monitor (BLM) system. The BLMs can be calibrated by producing a shower of particles with a voluntary septa misalignment.

Once the calibration constants are determined, considering the equations 1.1 and 1.3, the proportionality 1.2 can be expressed as

$$k \frac{\Sigma BLM}{I_{circ}} = 1 - \frac{1}{C} \frac{I_{ext}}{I_{circ}} \quad (1.4)$$

Therefore, the extraction efficiency can be approximated to

$$\varepsilon \approx 1 - kC \frac{\Sigma BLM}{I_{ext}} \quad (1.5)$$

and the inefficiency $\bar{\varepsilon}$ can be defined by the ratio of the number of particles lost to the number of particles extracted.

More than 20 BLMs and PMIU³ were located alongside the LSS2 beamline to measure the beam losses. Figure 1.9 shows the BLM instrumentation distribution map.

³Series of ionisation chambers with fixed gain. They are used for collecting data during the cool-down. They usually saturate during the extraction operation.

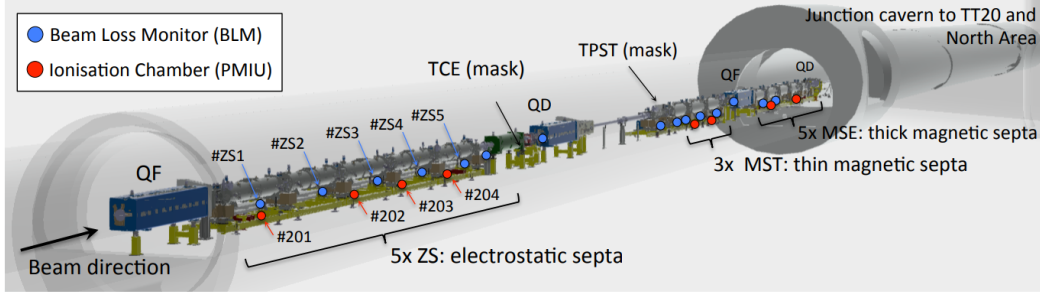


Figure 1.9: *BLM instrumentation locations in the LSS2 beam line towards the TT20 transfer line to the NA. This modelling was done by using FLUKA software [42].*

Beam losses measurements in 2016 [36] showed that at least the 4% of the beam charge was lost in the slow extraction to the NA. After several loss reduction techniques such as crystal diffusers, bent silicon crystals and phase space folding with multipoles [43], the losses were decreased over a 3.1 factor [44].

Several simulations were computed using MAD-X, *pycollimate* and **FLUKA** to process the slow extraction losses digitally. The models reproduce the last three turns of the beam before extraction⁴, covering all the elements of the beamline from the electrostatic septa ZS to the magnetic septa MST and MSE. The results revealed that the measured extraction efficiency was lower than expected from simulations [40], confirming a higher level of unexpected losses.

1.4 Motivation and Objectives

The main motivation of this project was born out of the urgent need for a beam loss monitor capable of detecting losses along the slow extraction line in SPS. Studies have confirmed radio-activation in the Long Straight Section 2 area is higher than expected, and the beam losses are induced during the extraction to the North Area in the septa magnets section. The alignment of these magnets is based on simulated and real beam losses, which are monitored by the beam loss monitor system.

⁴It is agreed that three turns of simulation give good results. These models demand many computational resources and their optimisation in running time is necessary.

However, this current system, composed of ionisation chambers, does not provide sufficient information about the loss sources. During the last years, several techniques and procedures were achieved to improve the beam extraction efficiency. At present, the principal aim is to discard a possible redistribution of the losses into an unmonitored area and finally confirm the loss decrease. Moreover, further ambitious projects will be performed shortly in the CERN complex, where higher beam intensities will be required.

The Cherenkov optical beam loss monitor is a promising candidate for fast and continuous loss detection over long distances. The functionality of this device for loss localisation was already used in several institutions worldwide.

Due to the high radiation dose measured in the LSS2 zone, the first objective of this research was focused on the simulations of loss detection scenarios. The properties of the interaction between secondary particles generated from a proton beam and optical fibres were analysed as a key point of the study. Then, a Cherenkov Light Generation Model was designed to provide all the information required for developing the Cherenkov oBLM. The model processes all the data from the Monte-Carlo software and implements the emission and transmission of the Cherenkov light within an optical fibre. The second objective was to understand the Cherenkov phenomenon and benchmark the computational model. Therefore, several experimental campaigns were accomplished with successful results.

Finally, the Cherenkov oBLM prototype was optimised and installed in LSS2 area.

1.5 Main Author Contribution and Thesis Structure

This work is dedicated to a Cherenkov optical beam loss monitor design for loss localisation in the LSS2 of the SPS accelerator. The thesis is organised into seven chapters, of which the first chapter is the introduction.

Chapter 2 overviews the principal beam loss monitor systems used in particle accelerators. In addition, a detailed description of the current BLM system used in the Super Proton Synchrotron at CERN is presented. The advantages of the

Cherenkov systems and limitations in the framework of loss detection and how they are gaining popularity among different institutions around the world are also reported.

Chapter 3 focuses on the Cherenkov phenomenon theory and how it is created and propagated within optical fibres. The intrinsic characteristics of the fibres play an essential role in the oBLM functionality. After the Cherenkov and fibre principles, the main parts of the oBLM system are presented, and the photo-sensor selection is discussed.

Chapter 4 is an introduction to the Cherenkov Light Generation Model. Quantifying the total Cherenkov light yield produced within the optical fibre is required. The model, developed and optimised by the author, calculates the final number of photons detected by the photo-sensors of the system. At first, the main characteristics and parameters used during the FLUKA simulations are described. The FLUKA simulations were carried out by the author with consultation from the FLUKA team. Then, the data treatment, the structure and different applications of the model performed by the author are detailed.

In Chapter 5, the main results from the Cherenkov Model for the Cherenkov oBLM in LSS2 are discussed and the Cherenkov oBLM prototype installation in LSS2 is reported. The BI-BL and the EN-EL CERN sections provided invaluable assistance to the author in the installation of the setup. Additionally, the LSS2 scenario is implemented as a FLUKA geometry and modelled by the computational tool developed as part of the project. Analysing the data from the LSS2 scenario simulations was the author's responsibility.

The model results validation and the oBLM system optimisation in the CLEAR facility are presented in Chapter 6. The full description of the tests and the main results obtained during three experimental campaigns are given. The system installation was performed by the author with the help of the CLEAR team. A CLEAR team members operated the beam during the tests as well. Data analysis and beam loss localisation calculations were completed by the author. The read-out electronics system was designed by E. Effinger, E. Lima and J.C. Esteban.

Finally, Chapter 7 gives an overview of the research conclusions. The thesis ends

with an outlook on possible future improvements and system implementations.

Beam Loss Monitors

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2.1 Beam Losses

In particle accelerators, beam losses generate unavoidable energy deposition due to high-energy particle interactions. This deposition increases the temperature and can affect the materials by changing their properties [45, 46].

Many processes can produce beam losses in a particle accelerator, such as collisions in colliders, the energy loss of the particles, instrumentation misalignment, aperture limitations, and more [47]. It is possible to classify different types of beam losses [48]:

- **Irregular or uncontrolled losses.** They are often produced by *avoidable* mechanisms such as vacuum problems, unintentional misalignment of machine

components or beam trajectories, or defects in the machine elements and materials. Higher beam losses cause permanent damage to the accelerator equipment, which will need to be replaced, generating a machine downtime of days or even months.

- **Regular or unavoidable losses.** They might occur continuously by unavoidable beam interactions during the collimation process, aperture limitations and other acceleration operations. In some cases, they can be used in machine diagnostics to optimise the beam tune or calibrate the instrumentation.

Consequences of the beam losses are machine degradation and downtime, low beam quality or performance and activation of the irradiated components.

2.2 Types of Beam Loss Monitoring Systems

As mentioned in Section 1.2.3, Beam Loss Monitor (BLM) system is a critical part of the equipment protection in the accelerator complex, and it comprises, in general, devices that convert the interaction of the shower of particles in the detector into an electrical current. In some cases, when beam loss threshold limits are exceeded, the system triggers the beam dump.

Several BLM types can be selected depending on how the detected beam losses interact with the material of the detector [49]. The most common devices and their main characteristics are collected in this section.

2.2.1 Gas-filled Detectors

The most widely used BLMs are gas-filled detectors [50]. Their functionality is based on the interaction of charged particles travelling within a gas [51]. There are several gas-filled detectors, such as the ion chambers, counters and Geiger tubes.

Ion chambers or Ionisation Chambers (IC) are the most elementary gas-filled detectors. They are based on the creation of positive ion-electron pairs from the ionisation and excitation of the gas molecules within an electric field. As a con-

sequence of this interaction, an electric output signal is originated. At CERN, ICs generally consist of a stainless steel cylinder filled with 1.5 L of sensitive N_2 at 100 mbar. The tube is 50 cm long and 9 cm in diameter and a pack of several parallel metallic electrodes, spaced about 5 mm, are installed inside. A high electric voltage of 1.5 kV is applied between anodes and cathodes. When the ionising particles traverse the gas, electron-ion pairs are produced, and the electrons reaching the anode create signal [52]. Figure 2.1 presents the inside view of an IC.

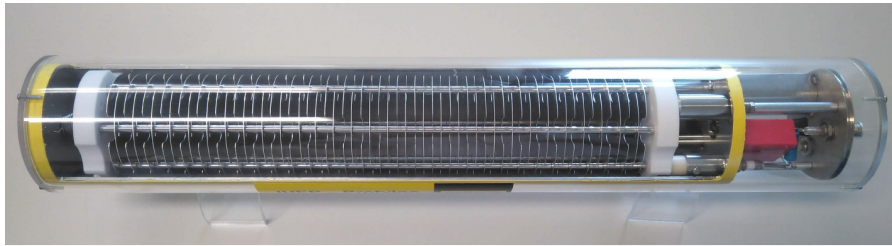


Figure 2.1: *Internal part of a CERN ionisation chamber* [53].

The typical timing of the electron collection is in the order of a few microseconds. Also, Secondary Emission Monitors (SEM) and little ionisation chambers (LIC) are BLM devices used in CERN facilities, very similar to the ICs. The LICs are smaller than the standard chambers, about 6 cm long and 9 cm in diameter, and they only have three electrodes: two cathodes and one anode. The SEMs (see Figure 2.2) are based on the secondary electron emission from solids, with pressure lower than 10^{-4} mbar, of about 6 cm long and 8.5 cm in diameter. They are high vacuum chambers that contain a signal Ti electrode which produces escaping electrons when it is reached by a charged particle. This emission is proportional to the particle energy loss in the electrode surface. Therefore, it is possible to measure the difference between the obtained signal and the bias current [54]. Unlike ICs, SEMs have a response time of a few nanoseconds.

Due to their reduced volume, LICs and SEMs are less sensitive; for that reason, the usage of these chambers is restricted for high radiation environments where the saturation of the ICs may occur [48].

The ICs are the most common beam loss monitors used at CERN. They are fast

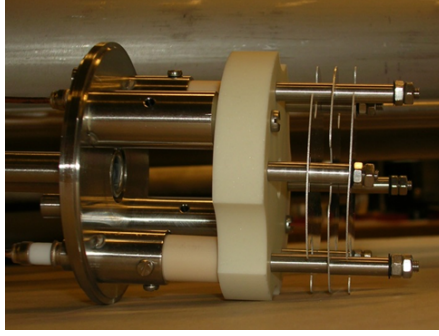


Figure 2.2: *SEM detector inside view* [55].

and reliable detectors without any indication of degradation over a prolonged period of operation [56]. Their range of detection, however, is limited by their position, only detecting losses that interact with the gas within the chamber. Manufacturing a long IC, to cover the beam loss detection over 200 m, would entail high costs.

2.2.2 Semiconductors

Semiconductor diode detectors, also known as solid-state detectors, are devices based on the hole-electron pair collection from semiconductor materials [57]. In semiconductors, electrons are confined in energy bands within the medium, separated by gaps. When excited, electrons migrate and recombine with the holes. In a semiconductor detector, electrons are excited by the charged particles passing through the material. The formed electron-hole pairs generate electrical currents as output signals in a few picoseconds. Normally, the efficiency of this type of detector depends on the purity of the semiconductor materials. Impurity compensation can be achieved by injecting electrons.

The most common semiconductors in particle detection are silicon diodes, such as PIN photodiodes, silicon photomultipliers and avalanche photodiodes, or germanium detectors. As a component of the Optical BLM of this project, the main characteristics of different photo-sensors are discussed in section 3.3.

2.2.3 Scintillators

Scintillators are used in many accelerators as fast BLMs [58] (see Figure 2.3). Light is generated, typically in the UV range, when a particle traverses the sensitive scintillation material. This light is usually absorbed by other material and converted to a more suitable light range by the process of fluorescence to be read out by a photo-sensor, usually a Photo-Multiplier Tube (PMT). These detectors are characterised by their fast response within 1-5 ns.

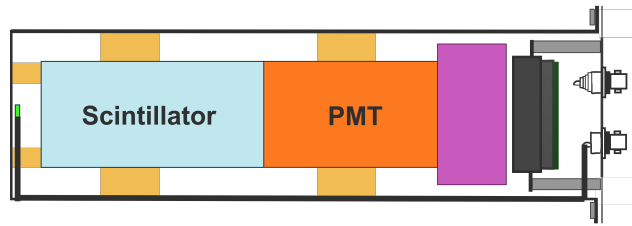


Figure 2.3: *Scintillator detector schematic.*

Scintillators can be made of liquids, crystals and polymerised plastics. They are categorised as inorganic or organic detectors depending on their material. There are usually size limitations to inorganic scintillators, and they are also very expensive, while plastic scintillators can be shaped and sized to almost any size at a lower cost.

It is also typical to use scintillating fibres as BLMs in particle accelerators since they are very sensitive to charged particles and X-rays. Scintillating materials, however, have some disadvantages, including lower radiation tolerance and faster degradation than quartz fibres¹ [60].

2.2.4 Cherenkov Detectors

Cherenkov detectors are commonly used in high-energy accelerators and experiments [61, 62]. They are very similar to scintillator detectors, where the interaction of the particles within a medium produces light, and it generates an electrical cur-

¹It is reported in the *Fast Scintillators for High Radiation Levels* Chapter in [59] that scintillating fibres are damaged by radiation at doses ranging from ≤ 1 krad to 100 krad, depending on the material used. Quartz fibres can withstand 30×10^6 krad [48].

rent when detected by a photo-sensor. However, the physical principles are quite different [63]. When secondary high-energetic charged particles cross a dielectric medium with an index of refraction greater than 1, Cherenkov light is produced in order of femtoseconds for solids or liquids. Therefore, these detectors are only sensitive to high-energy charged particles, ignoring interactions caused by neutral charge particles, slow particles, or X-rays. Additionally, Cherenkov detectors are exceptionally fast, usually limited by the photo-sensor response times ($\approx$ ns).

There are many types of detectors based on Cherenkov light emission [64, 65]. They can be used differently depending on the dielectric material characteristics. One of the most common detectors used for beam loss measurement and localisation is the quartz optical fibre. An extensive description of the theoretical background and characteristics of the Cherenkov phenomenon is reported in Chapter 3 of this thesis.

2.3 SPS Beam Loss Monitoring Systems

In this Section a general overview of the detector devices employed in SPS is provided. Approximately 450 devices are installed alongside the SPS ring to fulfil the machine protection specifications of the BLM system, protecting the machine against beam losses.

2.3.1 Ionisation chambers

A total of 268 IC are distributed along the SPS accelerator [66]. They include LHC-type chambers, which are described in Section 2.2 of this Chapter. Furthermore, SPS is also equipped with different type of ICs with similar characteristics (see Figure 2.4).

The SPS-type chambers are 26 cm long stainless tubes with a diameter of 11.4 cm, filled with N_2 at 100 mbar of pressure and a pack of 60 parallel electrodes with a separation of 5.75 mm between them [67, 68]. The electrodes are made of aluminium and have 93 mm in diameter with a thickness of 0.5 mm. They are configured alternately as signal electrodes and high voltage electrodes. A bias voltage of 0.8 kV is

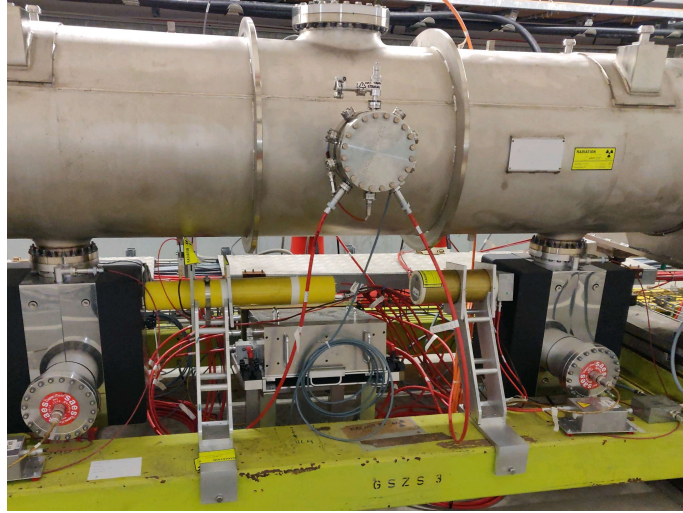


Figure 2.4: *Ionisation chambers are located underneath the beam pipe (yellow tubes: left LHC-type, right SPS-type) in the ZS area in SPS. They are the most common BLM used at CERN.*

applied to the bias voltage electrodes to create the electric field.

As mentioned in Section 2.2, ICs are robust detectors used as principal beam loss monitor in the CERN complex. Fast response, wide dynamic range (10^8 pA-mA), constant gain, and no severe ageing are just some of the advantages of ICs. Nevertheless, detection ranges of these instruments are limited by their size and location, and it would be very costly to install enough devices to cover long distances continuously.

2.3.1.1 SPS IC Read-out

There are three different BLM acquisition classes deployed on SPS based on real-time Front-End Software Architecture (FESA) [68]: *BLMINJ*, used for the injection line detectors, *BLMI*, for the LHC transfer lines, *AWAKE* and *HiRadMat* experiments and East and West extractions detectors, and *BLRSPS* for the SPS Arcs and LSS areas, North extraction and Splitter detectors.

In general terms, these three sub-systems are very similarly configured. The ICs produce a measurable current proportional to the received lost particles. This

output is continuously integrated by an integrator circuit and processed by an ADC system. Then, the acquired current signal is constantly updated and registered in windows, known as *running-sums* (RS) [69]. Running-sums are configured to add the incoming newest value measured by the BLM system and subtract the oldest value. The interval of time between the oldest and newest values determines the time of integration of the window.

Specifically for the extraction to the North Area experiments, the *BLRSPS* subsystem is composed of five running-sums that integrate the signal every 5 ms approximately during the SPS cycles and another extra running-sum for the whole cycle integration. The measurements are continuously compared to predefined thresholds, and the beam is dumped if they are exceeded. Figure 2.5 presents an overview of the *BLRSPS* acquisition system functionality.

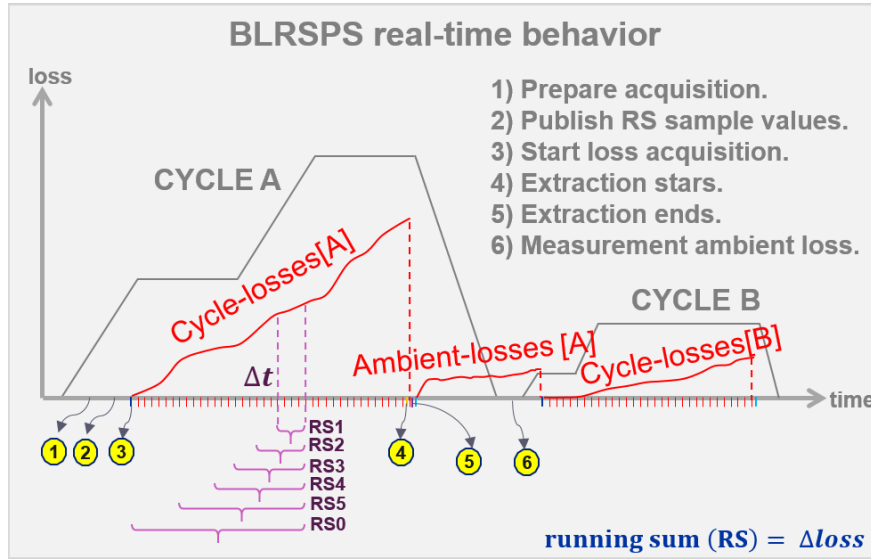


Figure 2.5: *BLRSPS* real-time behaviour schematic.

2.3.2 Diamond Detectors

Another type of BLM used in critical locations of the SPS, for instance, the injection/extraction and main collimator zones, are the Diamond Detectors (see Figure 2.6). They are solid-state ionisation chambers of $10 \times 10 \times 0.5$ mm based in

Chemical Vapor Deposition (CVD) crystals [70]. In these instruments, the synthetic diamond generates pairs of electrons and holes when a particle passing through the detector deposits its energy on it. The pairs drift toward the electrodes and produce the signal with a resolution time of nanoseconds. They are typically used for fast and precise monitoring measurements to observe the bunch spacing.

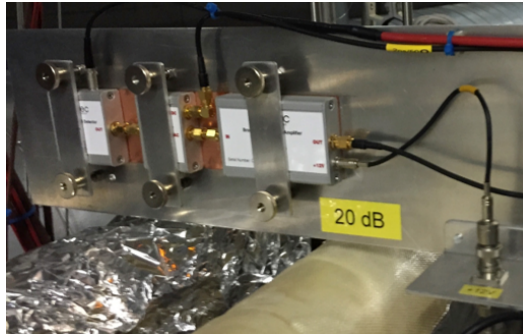


Figure 2.6: *Diamond detector boxes* [70].

As a result of their high resistance (around $10^{15} \Omega\text{cm}$), electric fields can be applied within the range of 1-2 V/ μm with almost no current leakage. These detectors operate with a bias voltage of 500 V. Furthermore, they can withstand radiation doses of more than 100 Mrad. [71]. It is common for diamond detectors to be connected to an AC/DC splitter where the two paths are configured with different amplification and attenuation settings. At present, there are five diamond detectors installed in SPS, as this technology is under commissioning.

2.3.2.1 SPS Diamond Read-out

Output signals are digitalised by a VME FMC carrier card based on an FMC digitiser module. The read-out measurements are instantaneous and continuous [72]. Similarly to the ICs in SPS, another FESA class, so-called *BLMDIAMONDVFC* is under development to control the data acquisition.

Figure 2.7 shows a diagram of the data acquisition chain of diamond detectors. The diamond detector signal can be sampled in five different acquisitions modes to be sent to the diamond cluster database, *NXCALS*. Data can be displayed in several

distributions depending on the requested information:

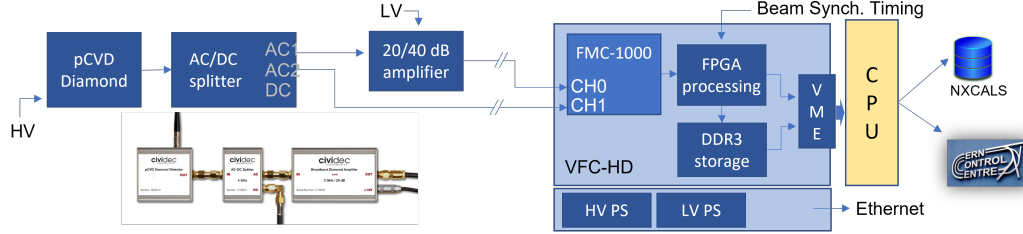


Figure 2.7: *Diamond detector read-out system* [71].

- **Histogram.** This plot gives the number of losses per turn for a given bin.
- **Integral.** The integration of the losses allows for the calculation of the losses intensity. Usually, the integration time is configured at 11200 turns.
- **Integral distribution.** Setting the same integration period as the integral calculation, it is possible to plot the bunch integral amplitude distribution.
- **Raw distribution.** The ADC sample values are represented with the integral period as the baseline.
- **Turn loss.** This distribution presents the values for the consecutive single turn losses. Also, the loss measurement of the single selected bunches can be plotted.
- **Snapshot.** As the raw ACD sample data is saved in the FMC module, a snapshot can be displayed, freezing valuable information such as the raw, integral or turn/bunch amplitudes and more advanced information.

2.4 Cherenkov Optical Fibre BLM in SPS

In the framework of this thesis, an optical Beam Loss Monitor (**oBLM**) was developed for beam loss detection in the slow extraction to the North Area in SPS.

The proposed Cherenkov oBLM is based on a quartz optical fibre sensor and two photo-sensors capable of continuously measuring losses over tens of meters.

The system is installed parallel to the beamline with the photo-sensors coupled on both ends to collect the upstream and downstream signals (see Figure 2.8). When secondary high-energetic charged particles cross the fibre, Cherenkov light is produced, and part of this signal propagates in the fibre, producing a fast response of a few nanoseconds in the photo-sensors. For the oBLM prototype, Silicon Photo-Multipliers (SiPM) were selected. A full description of the different types of photo-sensors and their selection discussion is presented in Chapter 3. Each photo-sensor is connected to its board, protected from the light within an aluminium box. The boxes are connected to the power supply via coaxial copper cables [73]. By integrating the signal amplitude and the measurement of the travelling time, the system is used to quantify the beam losses and the longitudinal position at real-time monitoring.

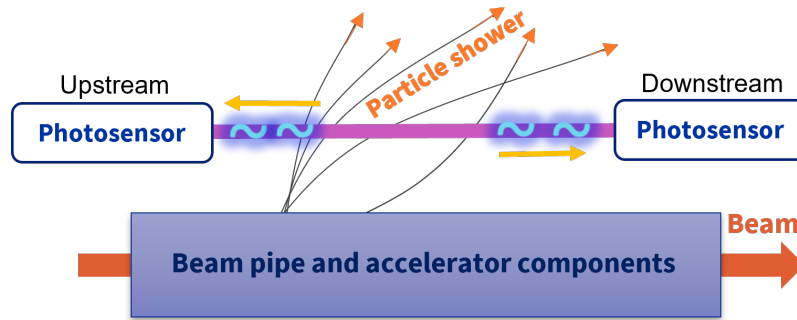


Figure 2.8: *Overview of the Cherenkov Optical Beam Loss Monitor.*

The use of the oBLM has many advantages:

- It is a continuous detection system, able to cover long accelerator distances.
- Typically, silicon fibres are selected due to their radiation hardness as they can withstand around 30×10^9 rad [48].
- They are not sensitive to X-rays or magnetic fields.
- The fibres work in both high temperature or cryogenic temperature environments.
- The system covers long distances with reduced costs if they are compared with the other BLM systems.

- The system is non-invasive, and it can be installed with no perturbations in the beamline.

Cherenkov oBLMs are gaining popularity among beam instrumentation systems in many different accelerators. However, to date, Cherenkov loss detection has always been conditioned by bunched electron/positron beams. For instance, the Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator (SLAC) [74] in California. The new LCLS-II, a superconducting linear accelerator of 4 GeV electrons bunches at 1.3 GHz has promoted updates in their beam loss detection systems, covering about 4 km of the machine with 200 m long silica fibres. The fibres used are relatively thick with a core diameter of 600 μm . The system also contains a PMT in the downstream end to detect the Cherenkov radiation. Another Cherenkov BLM was implemented for the Colliding Electron-Positron Beams-5 (VEPP-5) at the Budker Institute of Nuclear Physics (BINP) [75] in Russia. There are two different linacs in the complex where the electrons are accelerated at 270 MeV and the positrons at 510 MeV. The dumping ring also works at 510 MeV. Around 20 m were covered with the multimode optical fibre connected to a PMT detector. Also, the Free Electron Laser Hamburg (FLASH), at Deutsches Elektronen-Synchrotron (DESY) [76] in Germany, has promoted Cherenkov BLMs in their beam loss detection systems. They are interested in detecting the losses generated from a 1.25 GeV electron beam over a length of about 40 m. The Cherenkov BLM consists of 300 μm multimode fibres and PMT photo-detectors. At CERN, previous studies were carried out at the Compact Linear Collider (CLIC) test facility [77, 78], on the 150 MeV electron drive beam.

The LSS2 SPS beam extraction to the NA at CERN is highly activated by the losses of the **proton beam** accelerated at 400 GeV. The beam deflection and extraction process committed by the septum magnet (see section 1.3.2) entails an intrinsic beam loss production. In addition, the beam is **debunched**, i.e. extracted in a continuous stream of particles, adding extra complexity to the loss detection analysis. This area is equipped with ionisation chambers and diamond detectors; nevertheless, there are not enough BLMs to measure a complete longitudinal loss distribution,

and instrumenting hundreds of metres could be very costly. The Cherenkov BLM presented in this work will help deliver a continuous measurement of the beam losses over 200 m of the machine, covering the most beam loss critical area of the slow extraction where the electrostatic septa are located. The main goal of the optical BLM is to provide the total amount of beam losses per spill, integrated up to 10 s. Besides, a longitudinal map with the loss source locations can also be deducted to tune the machine and reduce the overall beam losses.

Cherenkov Radiation in Optical Fibres

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3.1 Cherenkov Radiation

When light travels through a dielectric medium, its speed is reduced. This slowdown is due to the electromagnetic interactions between light and the material atoms. Therefore, velocity of the light depends on the medium material and is defined as $v_{\text{light}} = c/n$, where n is the refractive index of the specific medium and c the constant speed of light in vacuum.

According to quantum mechanics, molecules excited by a moving charged particle in a polarizable medium (see Figure 3.1) generate photons when they return to their original ground state energy.

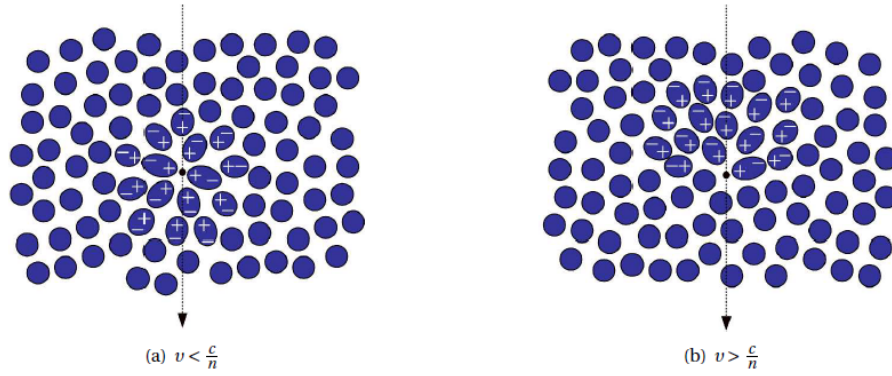


Figure 3.1: Polarisation of the molecules in a dielectric medium by a moving charged particle with speed v [77].

When relativistic charged particles traverse a material at a higher speed than the phase velocity¹ of the light in that medium, those photons generated by this interaction lead up to coherent radiation at a fixed angle θ_c (see Figure 3.2). This phenomenon is known as Cherenkov radiation.

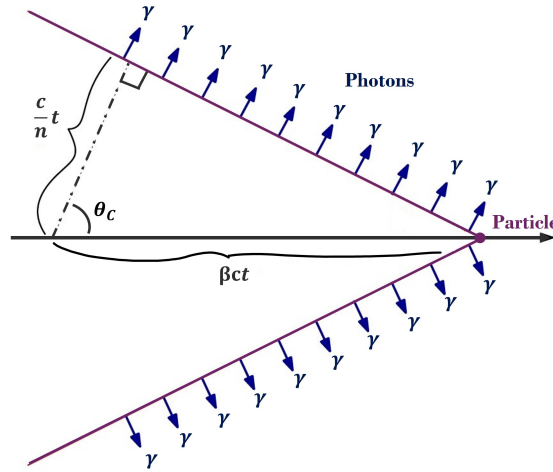


Figure 3.2: Cherenkov photon emission cone with angle θ_c .

The particle relative velocity β can be described as $\beta = v/c$. Hence, the angle

¹The phase velocity is the velocity of a single wavefront in any medium. It can be defined in terms of the time period T and wavelength λ as $v_{ph} = \frac{\lambda}{T}$.

of the emitted Cherenkov radiation can be deduced from:

$$\cos \theta_c = \frac{1}{\beta n} \quad (3.1)$$

Since the velocity of the light in the medium $v_{\text{light}} = c/n$ is the minimum velocity that must possess a charged particle for Cherenkov photon emission. By equalling v_{light} with the particle velocity mentioned above $v = \beta c$, the particle threshold velocity β_{th} can be expressed as:

$$\beta_{\text{th}} = \frac{1}{n} \quad (3.2)$$

In specific, for the average refractive index of silica in the visible range of $n = 1.46$ this threshold can be approximated to $\beta_{\text{th}} \approx 0.685$. In counterpart, in the limit of an ultra-relativistic particle ($\beta \approx 1$), the Cherenkov emission is maximum at the angle given by:

$$\theta_{c,\text{max}} = \arccos(1/n) \quad (3.3)$$

The maximum Cherenkov emission angle in quartz is then $\theta_{c,\text{max}} \approx 47^\circ$. Table 3.1 shows a list of particles with their rest energy (E_0) and their threshold kinetic energy ($E_{k,\text{th}}$) for the silica medium ($n = 1.46$). The resulting kinetic energies (E_k) are calculated as :

$$E_k = E_{\text{tot}} - E_0 = mc^2\gamma - mc^2 \quad (3.4)$$

$$E_k = mc^2 \left(\frac{1}{\sqrt{1 - \beta^2}} - 1 \right) \quad (3.5)$$

A list of charged particles with their threshold kinetic energy in the silica medium is shown in Table 3.1. It should be noted that electrons e^- and positrons e^+ will start emitting Cherenkov light in silica with total energies of about MeV while protons will need energies of about GeV.

The total number of Cherenkov photons N generated per charged particle travelled path length x at a determined wavelength λ , is given by [79, 80]:

$$\frac{d^2 N}{dx d\lambda} = \frac{2\pi\alpha z^2 \sin^2 \theta_C}{\lambda^2} \quad (3.6)$$

Particle	$E_0[MeV/c^2]$	$E_{k,th}[MeV/c^2]$	$E_{Total,th}[MeV/c^2]$
e^-, e^+	0.511	0.194	0.705
p^-, p^+	938	350	1288
μ^-, μ^+	106	39	145
π^-, π^+	140	52	192
κ^-, κ^+	494	184	678

Table 3.1: List of charged particles with their rest energy E_0 and threshold kinetic energy $E_{k,th}$ for a threshold value $\beta_{th} = 0.685$.

where $\alpha = 1/137$ is the fine structure constant, z is the particle charge and, θ_c is the Cherenkov angle.

The Cherenkov radiation spectrum is continuous and inversely related to the wavelength squared. Thus, when the wavelength decreases, the number of photons increases (see Figure 3.3). That explains why most Cherenkov phenomena produce light mainly in the blue and the UV range.

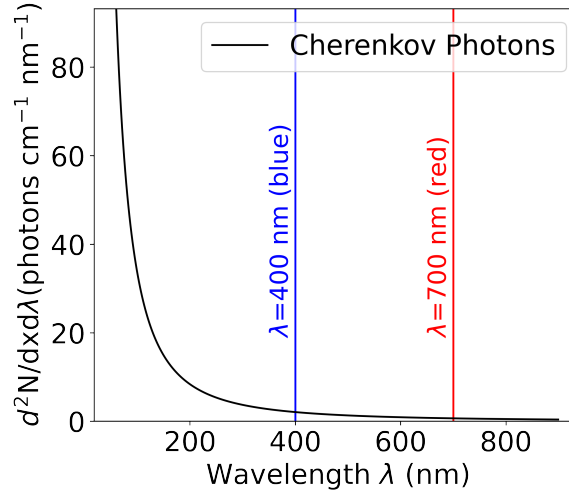


Figure 3.3: Cherenkov light spectrum.

For an experimental case of protons traversing a silica fibre, i.e. $z = 1$, producing photons with a Cherenkov angle $\theta_c = 47^\circ$, by integrating the Equation 3.6 for a range

in $[400 - 700]$ nm of wavelength, the photon yield is approximately 36 photons/mm.

3.2 Cherenkov Light Production in Optical Fibres

The main structure of an optical fibre consists of the core, the cladding and the coating, as shown in Figure 3.4. The light is transported along the core, which is generally made of silica glass SiO_2 . The cladding is the second layer in the fibre, made of plastic or glass, with a slightly lower refraction index than the core, providing proper signal guidance. The coating protects the fibre from external damage.

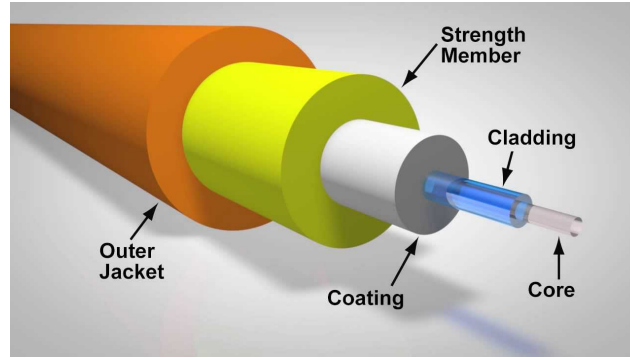


Figure 3.4: *Optical fibre structure* [81].

Figure 3.5 illustrates how light propagates through the fibre by the internal reflection effect. In an optical fibre, the refraction phenomenon occurs when the light comes from the air, with a refraction index n_0 , to the silica core, with a refraction index n_1 .

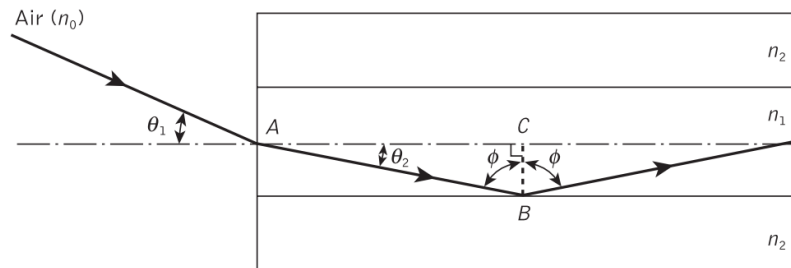


Figure 3.5: *Light propagation within an optical fibre* [82].

According to Snell's law:

$$n_0 \sin \theta_1 = n_1 \sin \theta_2 \quad (3.7)$$

Once the light is inside the core, it reflects totally at the core-cladding interface for angles $\phi > \phi_c$, being ϕ_c the critical angle. The critical angle is defined by [83]:

$$\phi_c = \arcsin \frac{n_2}{n_1} \quad (3.8)$$

where n_2 is the refraction index of the cladding medium, being $n_1 > n_2$.

Following the properties of the triangles $\phi = \pi/2 - \theta_2$, and substituting in Equation 3.7:

$$n_0 \sin \theta_1 = n_1 \cos \phi \quad (3.9)$$

Applying the critical angle definition in Equation 3.9, and considering θ_1 as the acceptance angle θ_α :

$$n_0 \sin \theta_\alpha = (n_1^2 - n_2^2)^{\frac{1}{2}} = \text{NA} \quad (3.10)$$

The fibre numerical aperture, NA, indicates the maximum angle at which light can be injected into the fibre.

In addition to the internal light reflection and propagation, the opposite condition must occur when photons try to exit the end of the fibre to the air medium. In this case, the photo-sensor only receives photons refracted from the inside of the fibre with an angle ϕ' . For a successful exit of the photons, the condition must be $\phi' < \phi'_c$. The new critical angle ϕ'_c is defined by:

$$\phi'_c = \arcsin \frac{n_0}{n_1} \quad (3.11)$$

Otherwise, photons with angles $\phi' > \phi'_c$ will be again reflected, and they will remain confined to the fibre core.

Capture Factor

When the interaction of charged high-energy particles with the optical fibre generates Cherenkov radiation, only a fraction of the total photons will be captured and propagated through the fibre, and, from this portion, not all of them will exit at the fibre extremity. The photons that will be transmitted along the fibre and able to exit at the end of the fibre are within the probability F_{cap} [84]:

$$F_{\text{cap}} = \frac{1}{\pi} \arccos\left(\frac{\beta \sqrt{n_{\text{co}}^2 - \text{NA}^2} - \cos \alpha}{\sin \alpha \sqrt{\beta^2 n_{\text{co}}^2 - 1}}\right) \quad (3.12)$$

where β is the particle velocity, n_{co} is the core refraction index, and α is the angle of incidence between the particle track and the fibre axis.

Figure 3.6 presents the capture percentage determined by Equation 3.12 for the incidence angles of the particles at a speed $\beta \approx 1$ when interacting with a fibre with $\text{NA} = 0.22$ and $n_{\text{co}} = 1.46$. Here, it is also shown that the maximum on the curve corresponds to the maximum Cherenkov angle $\theta_c \approx 47^\circ$.

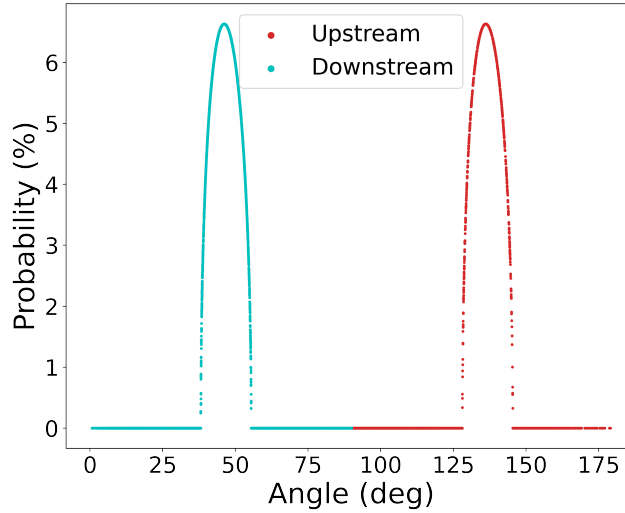


Figure 3.6: *Probability of light capture as a function of the impact angle for downstream and upstream directions.* (Parameters: $\beta \approx 1$, $\text{NA} = 0.22$, and $n_{\text{co}} = 1.46$).

Applying this factor to Equation 3.6, it is possible to determine the total number

of captured and propagated Cherenkov photons that exit the fibre and reach the photo-detectors.

Additionally, the capture factor F_{cap} is dependent on the fibre numerical aperture. By increasing the NA parameter, the range of angles would become wider with a more significant photon capture [78].

Attenuation Factor

The signal reduction in optical fibres is one of the most limiting factors in light propagation [82]. Light loss is the direct consequence of several mechanisms related to the manufacturing process and the material composition of optical fibres. The most significant contributions to light attenuation are the ultraviolet ν_{UV} and infrared ν_{IR} absorption bands and Rayleigh scattering ν_{Rayleigh} [85].

As stated by the Beer's law, the attenuation of the light transmission increases with the length L_{fib} of the optical fibre, being the resulting signal power:

$$P(L) = P(0) \cdot 10^{-\frac{\nu \cdot L_{\text{fib}}}{10}} \quad (3.13)$$

where ν is the attenuation coefficient, and it is mainly the sum of the three contributions mentioned above:

$$\nu = \nu_{\text{UV}} + \nu_{\text{Rayleigh}} + \nu_{\text{IR}} \quad (3.14)$$

Figure 3.7 shows how each factor depends on the wavelength. Whereas the absorption induced by vibrations in the IR region occurs around 1 700 nm and UV absorption affects the measurements in the 150-250 nm spectral region, in intermediate values, the dominant contribution depends mostly on the Rayleigh scattering [86].

Elastic collisions produced by the photons and the core molecules cause linear scattering. It removes energy in the directional propagating wave and transfers light to other directions. The effect on the Rayleigh scattering can be described as [87]:

$$\nu_{\text{Rayleigh}} \simeq \frac{A_{\text{R}}}{\lambda^4} \quad (3.15)$$

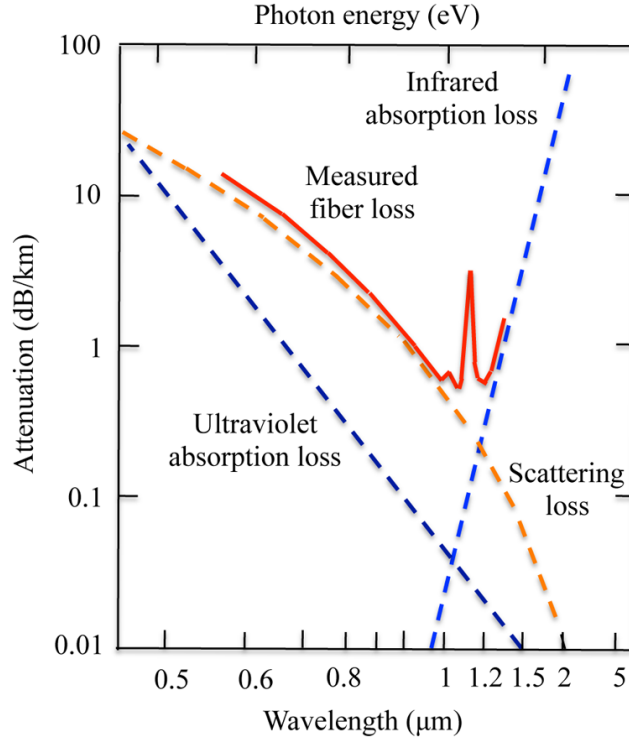


Figure 3.7: *Typical loss spectrum of a GeO_2 single-mode fibre as a function of wavelength [86].*

where the Rayleigh scattering coefficient in pure silica is $A_R = 0.83 [\text{dB } \mu\text{m}^4/\text{km}]$ [87].

Then, with 3.13 and 3.15, the attenuation factor ε_{att} can be expressed as:

$$\varepsilon_{\text{att}} = \frac{P(L)}{P(0)} \simeq 10^{-\frac{0.83 \cdot L_{\text{fib}}}{10 \cdot \lambda^4}} \quad (3.16)$$

The attenuation factor is shown in Figure 3.8 as a function of the wavelength for several fibre lengths.

Cherenkov Photons Production

The total number of Cherenkov photons generated and measured at the end of an optical fibre N_{SiPM} can be calculated by the combination of Equation 3.6, Equation 3.12 and Equation 3.16 as follows:

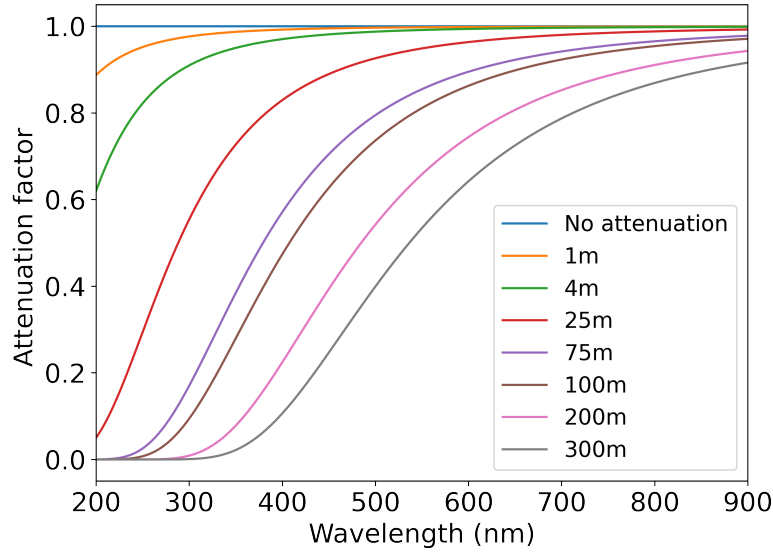


Figure 3.8: *Attenuation factor as a function of the wavelength. Signal attenuation increases considerably with the length of the optical fibre..*

$$N_{\text{SiPM}} \approx \int \frac{d^2N(x, \lambda)}{dx d\lambda} \cdot \varepsilon_{\text{att}}(\lambda) \cdot F_{\text{cap}} \cdot dx d\lambda \quad (3.17)$$

Figure 3.9 shows the expected number of photons for different fibre lengths in the wavelength range of [200-900] nm.

3.2.1 Optical Fibre Characteristics

An extensive list of characteristics should be considered when selecting optical fibres as a transmitter component in the Cherenkov BLM, some of which are mentioned below:

- **Material.** There are two principal materials for optical fibres: plastic and quartz or silica. Plastic optical fibres (POF) [88] typically are more economical and easier to handle than silica fibres. However, they are also less efficient in light transport with a higher attenuation factor (usually greater than 20 dB/km) and lower radiation tolerance. In the case of silica fibres, both the cladding and the core are made of silicon dioxide SiO_2 . By doping one of

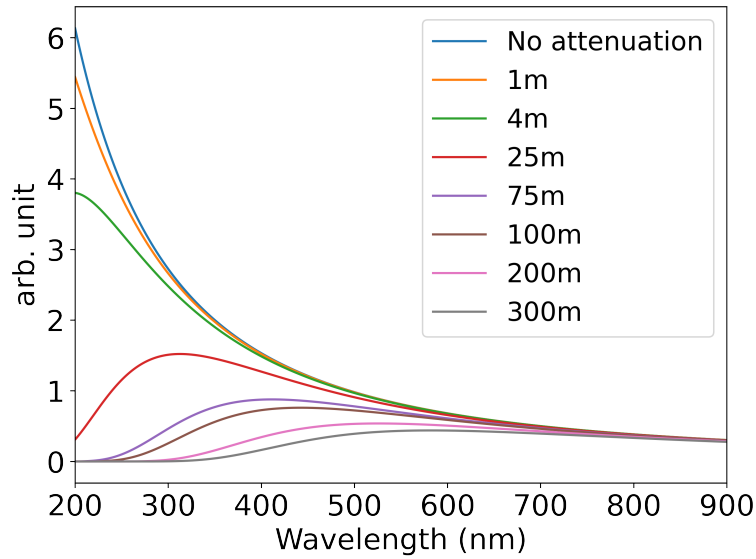


Figure 3.9: Cherenkov photons attenuated as a function of the wavelength for several fibre lengths. The blue line is the total Cherenkov photons generated with no attenuation. This line corresponds to the line of Figure 3.3.

the two parts, the gradient in the refraction indexes for the total reflection is achieved. The most common dopants are germanium, fluorine or phosphorus. For silica fibres, the attenuation coefficient is generally 0.2 dB/km.

- **Mode types.** The mode is related to the path that the light can be transmitted inside an optical fibre [89]. These different paths are discrete, finite, and determined by the photon angles to the fibre axis. The modes depend on the geometry of the fibre and the wavelength. When zero-order mode, also known as single-mode, photons propagate along the fibre core without reflections on the cladding sidewalls. Single-mode fibres are available with cores of $[3 - 10] \mu\text{m}$. Multimode graded-index fibres have a refraction index gradient in the core. This index is maximum in the centre and decreases continuously to the core boundaries. Multimode graded-index cores usually are within the range $[50 - 100] \mu\text{m}$. Multimode step-index fibres have a uniform core refraction index and a decreased cladding refraction index. The sharp difference

makes the light travel via different angles and paths. Step-index fibre cores are within $[100 - 1500] \mu\text{m}$.

- **Radiation tolerance.** This characteristic is one of the most important for Cherenkov BLM systems. In general, there are three degradation mechanisms [90]: Radiation-Induced Attenuation (RIA), Radiation-Induced Emission (RIE) and compaction. The RIA levels strongly depend on the radiation environment and the transmitted wavelength. The radiation absorption by the silica glass produces degradation in the transmission capability of the fibre. The RIE is the radiation generated inside of the fibre. Cherenkov radiation is an example of RIE phenomenon. Sometimes radiation also can change the structure of the silica, changing its refraction index. This effect is known as compaction. Pure-silica-core fibres with fluorine doped cladding are the most suitable due to their radiation tolerance (around 10^9 rad) and low attenuation levels.
- **Microstructured fibres.** These fibres, typically made of silica material, are characterised by a modified cladding structure to achieve a different total internal reflection. Microstructured Optical Fibres (MOF) contain different geometries of air-holes arrays, which can provide specific light dispersion [91]. Long period gratings (LPG) and Fibre Bragg gratings (FBG) are two examples of microstructured fibres.

3.3 Cherenkov Light Detection

One of the essential functions of the Cherenkov BLM is the photo-detection at both extremities of the optical fibre. When the particle shower-fibre interactions produce the Cherenkov emission, light travels along the fibre. Then, a portion of the photons reaches the photo-sensors, which convert the light pulses into an electrical signal.

Several types of photo-sensors can be used such as SiPM, PMT or photodiodes (see Figure 3.10). According to the requirements of the proposed Cherenkov BLM

system for SPS, the three devices seem to be profitable candidates. In this section, the main characteristics and advantages are discussed.

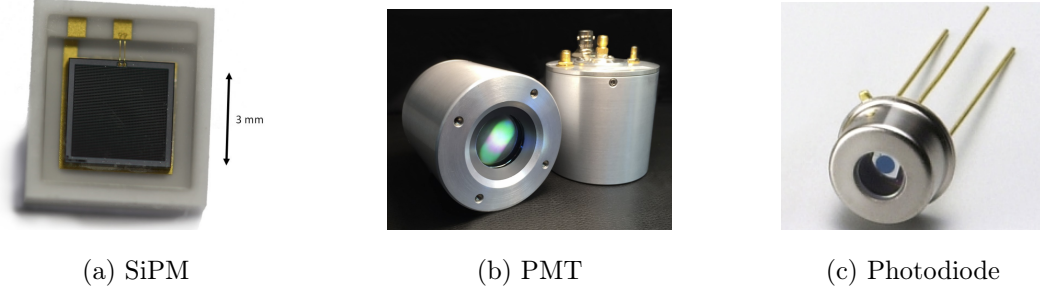


Figure 3.10: *Most common photo-sensors* [92].

3.3.1 Silicon Photo Multiplier (SiPM)

The SiPM, also known as Multi-Pixel Photon Counter (MPPC), comprises a matrix of micro pixels connected in parallel. Pixels generate an output signal proportional to the number of pixels fired by a photon. [93]. Figure 3.11 shows photons impinging on the SiPM and firing single pixels independently.

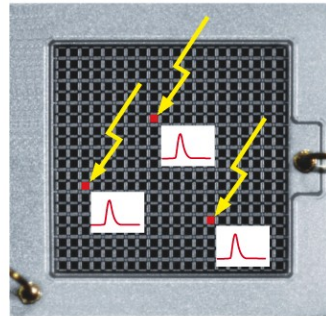


Figure 3.11: *SiPM photon counting* [94].

SiPMs are mechanically rugged detectors with many advantages, including a high detection sensitivity, low powering voltage, and low sensitivity to the magnetic field, hysteresis or warm-up considerations, unlike the PMTs. Also, these devices are mounted on simple readout circuits, and their costs and consumption are generally

low. The dynamic range of SiPMs, however, is limited by the number of pixels, and the number of photons entering the pixel cannot be distinguished. Moreover, pixels require a certain cool-down time otherwise part of the signal may be misread.

During the SiPM operation, the rise time t_{Rise} of the output signal can be calculated by:

$$t_{\text{Rise}} = C_d \cdot R_s \quad (3.18)$$

where C_d is the diode capacitance in reverse bias, and R_s is the silicon series resistance. The duration of the rise time is some hundred picoseconds. The discharge of the capacitor C_d occurs during the constant recovery time t_{Rec} , and it is determined by:

$$t_{\text{Rec}} = C_d \cdot R_q \quad (3.19)$$

where R_q is the quenching resistor, being $R_q \gg R_s$. Figure 3.12 shows the SiPM response without saturation.

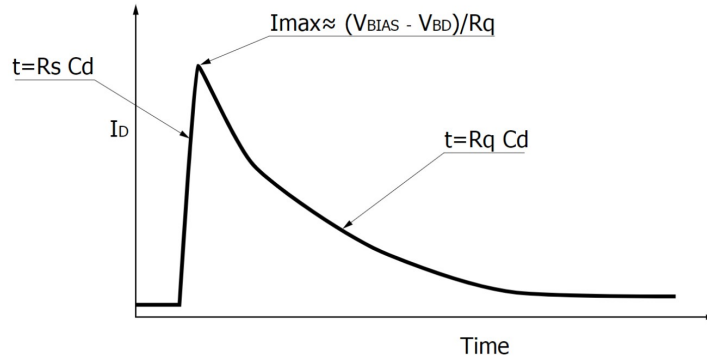


Figure 3.12: *SiPM output pulse.* [93].

The SiPM output electrical charge Q_{out} can be calculated by [95]:

$$Q_{\text{out}} = C_{\text{pix}} \cdot (V_R - V_{\text{BR}}) \cdot N_{\text{fired}} \quad (3.20)$$

where C_{pix} is the capacitance of one pixel, V_R is the bias voltage, and V_{BR} is the breakdown voltage, all multiplied by the number of fired pixels N_{fired} . The

gain of the photo-detector corresponds with the factor $C_{\text{pix}} \cdot (V_R - V_{\text{BR}})$; therefore, it depends linearly on the over-voltage $V_R - V_{\text{BR}}$. The gain also depends on the temperature, reducing the value when the temperature increases. For the correct functioning of the detector, the MPPC requires precise over-voltage control to avoid fluctuations in the temperature and maintain a constant gain. The maximum SiPM gain value is around 10^6 .

Other important parameters of a SiPM photo-detector are [96]:

- **Photon Detection Efficiency (PDE).** The PDE is the detection probability of an incident photon. It depends on the quantum efficiency $QE(\lambda)$, the avalanche probability $P_a(V)$, and the pixel fill factor f , which is the ratio of the pixel photosensitive area to total area. Therefore, the SiPM PDE can be calculated by:

$$PDE = QE(\lambda) \cdot f \cdot P_a(V) \quad (3.21)$$

Figure 3.13 illustrates different PDE curves for SiPM optimised for the UV, visible, and IR ranges of wavelength.

- **Crosstalk.** This effect occurs when one photon escapes from one pixel and triggers avalanches of photo-electrons in adjacent pixels. The output signal will double its amplitude when two cells are fired simultaneously. If the secondary cell is activated with few ns of delay, the resultant response will present a double peak. Consequently, crosstalk is classified as correlated noise.
- **After-pulses.** Similarly to the crosstalk effect, after-pulsing is another type of correlated noise. It is due to the trapping of carriers by the silicon defects during the avalanche. Eventually, they are released and able to re-fire the pixel later. If this effect occurs during the recovery phase, it will have a lower amplitude than the genuine pulses. Figure 3.14 shows an example of a signal with the after-pulses and crosstalk effects. The crosstalk and after-pulse probabilities depend on the photo-detector gain, increasing almost linearly

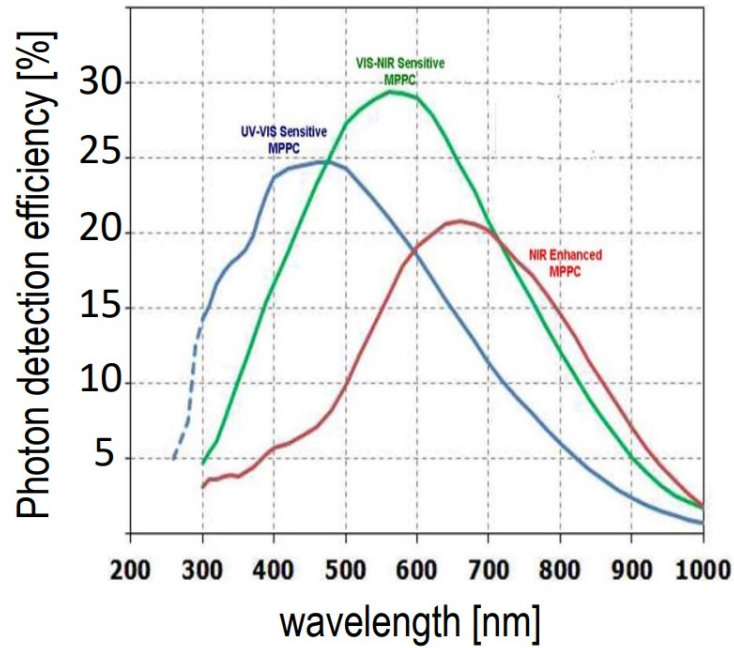


Figure 3.13: *PDE curves for different SiPM depending on the wavelength range of detection* [96].

with the over-voltage and growing second-order exponentially with the pixel size.

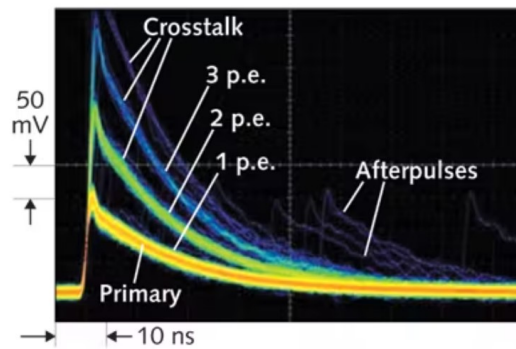


Figure 3.14: *Crosstalk and after-pulses of a SiPM signal.* [93]

- **Linearity and dynamic range.** The number of pixels available for photodetection determines the SiPM response. The dynamic range can be calculated by:

$$N_{\text{fired}}(M, \lambda) = M \left(1 - \exp^{-(PDE(\lambda)N_{\text{ph}}/M)} \right) \quad (3.22)$$

where M is the number of total pixels, PDE is the photon detection efficiency factor, and N_{ph} is the number of arriving photons. An ideal SiPM would have a linear relationship between the input light and the output amplitude pulse. This linearity is lower limited by noise and upper limited by the saturation effect [97]. Figure 3.15 shows the detection curves of the 3010PS and the 3015PS SiPM types calculated from Equation 3.22 for a 18% and a 32% of PDE, respectively.

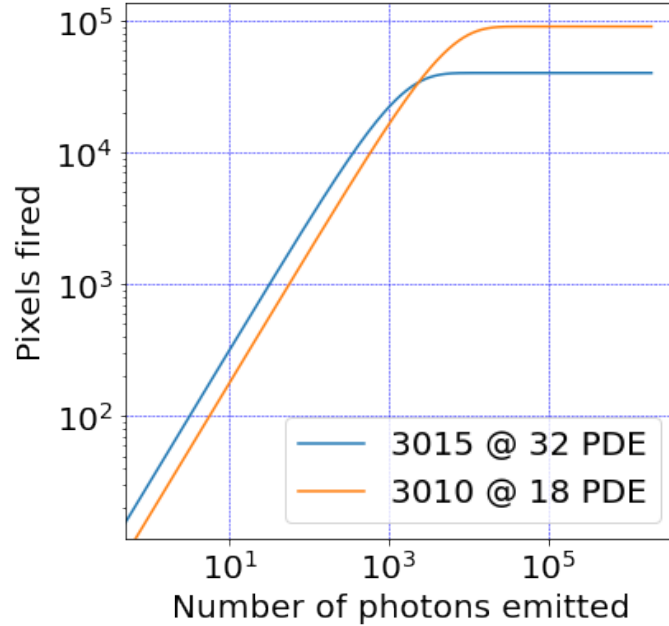


Figure 3.15: *Dynamic range linearity for the 3010 (90000 pixels) and for the 3015 (40000 pixels) SiPM types.*

3.3.2 PhotoMultiplier Tube (PMT)

A typical [PMT](#) is a photo-detector based on the photoelectric effect. It consists of a photocathode, followed by focusing electrodes, an electron multiplier or dynodes, and an anode, with all the components housed in a vacuum, as may be seen in [Figure 3.16](#).

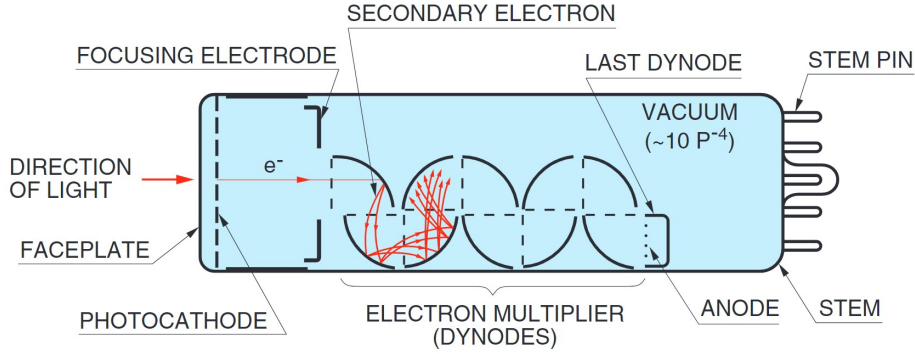


Figure 3.16: *Cross-section of a photomultiplier tube* [98].

When the light enters through the input window, the photocathode emits excited electrons. Then, these electrons are accelerated, focused by the electrodes, and multiplied by the secondary emission process. Finally, they are collected by the anode and extracted as the output signal.

The light-electron conversion sensitivity depends mainly on the light wavelength, and the window and photocathode materials determine the values of the spectral response range [99]. The spectral response is usually in terms of quantum efficiency QE and radiant sensitivity S in A/W at a given wavelength λ in nm as follows:

$$QE = \frac{S \times 1240}{\lambda} \times 100 \quad (3.23)$$

The radiant sensitivity S can be defined as the division between the photocathode current and the incident radiant flux, dependent on the wavelength. The quantum efficiency QE is the number of electrons produced by the photocathode excitation divided by the number of incident photons.

The gain of a PMT corresponds to the ratio of the anode output signal to the current produced in the photocathode ratio. It depends on the secondary emissions produced in the dynode stages where the current is amplified. The gain is within the $[10^6 - 10^9]$ range depending on the type of PMT [100]. Other PMT essential characteristics are [98]:

- **Dark current.** PMTs usually present a background output noise even with a

complete absence of illumination. The dark current increases with the power supplied and with the temperature, and it is caused by a wide variety of factors such as internal thermionic emissions, current leakages, field emissions, ion feedback and external radiation.

- **Uniformity.** The uniformity measures the difference between the output signal with respect to the photocathode position. Deviations in the electron trajectories can degrade the collection efficiency of the device in the photon counting.
- **Time response.** The time response is the sum of the electron transit time from the photocathode to the anode, the anode rise time and the transit time spread. This value depends on the power supply and the secondary emission process. Also, the time resolution can vary depending on the illuminated zone on the photocathode surface, including size and location. Figure 3.17 illustrates the typical output response from a PMT anode.

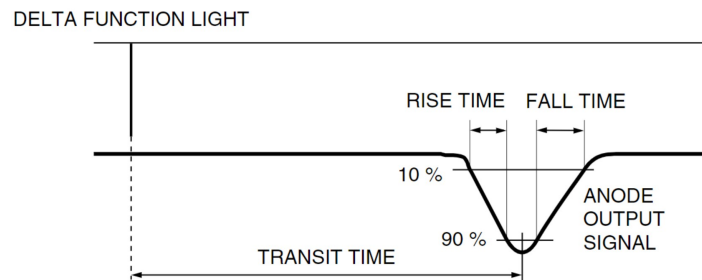


Figure 3.17: *Typical output signal of a PMT photo-detector* [99].

Normally, the electron transition time values are 1-40 ns. Then, the rise time is the time consumed in rising the peak amplitude from 10% to 90% when the photocathode is entirely illuminated by a pulse. Generally, the rise time of the PMTs varies from 0.5 to a few ns of duration. Finally, the transit time spread (T.T.S) is a fluctuation that affects the electron transit times of individual pulses, and it is expressed as the FWHM of the frequency distribution of the electron transit times. Usually, the values are within the range of 0.2-0.5 ns [100].

- **Linearity and dynamic range.** The proportionality between the amount of light received as input, and the output signal current defines the pulse linearity. The detector linearity accepts deviations of 2 % and 5 % depending on the PMT type. The leading cause of non-linearity is due to the space charge effect. It depends on the maximum output current and the electric fields in the electrodes. Generally, the dynamic range value is of the order 10^6 .

3.3.3 Si Photodiode (PD)

Photodiodes are photo-detectors that produce electrical signals when the light impinges in the PN junction. When light impinges with an energy greater than the energy of the band-gap in a photodiode, the electron-hole pairs occur in the PN layers. The electron-hole production is proportional to the number of photons received. The motion of charge carriers between the two layers generates a current flow in the semiconductor. Figure 3.18 illustrates the Si photodiode functionality when it is coupled to a material where the high energy particles create the photons.

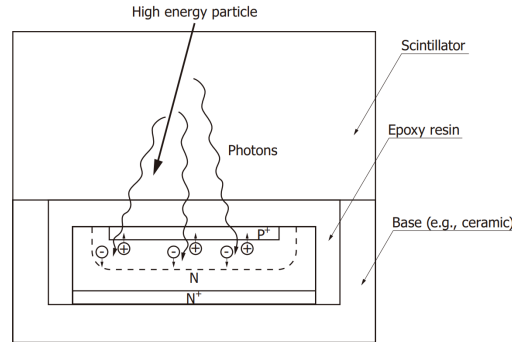


Figure 3.18: *Structure of a photodiode detector.* [101]

The output voltage signal depends on the incident light and temperature. Generally, the gain of the photodiodes is up to approximately 10^2 , i.e. one single photon can generate up to about 100 electron-hole pairs.

Photodiodes usually need to be connected with an operational amplifier. Main important parameters of the photodiodes are [102]:

- **Dark current.** Even without incident light, there is a leakage current when the photo-detector is connected to the power supply. This current flow is one of the background noise contributions, and it increases with the input voltage.
- **Spectral response.** As mentioned above, the photovoltaic effect happens with high energetic photon collection. Therefore there is a cutoff wavelength λ_C calculated by:

$$\lambda_c = \frac{1240}{E_{\text{gap}}} \quad (3.24)$$

where E_{gap} is the band gap energy in eV. For photon detection at room temperature the energy is $E_{\text{gap}} = 1.12$ eV, then the wavelength is $\lambda_C = 1100$ nm. Besides, the spectral and frequency responses depend on the PN layer thickness and the dopant concentration; therefore, different materials for the photodiode window can be selected depending on the detection scenario. Similarly to the PMT, the quantum efficiency (QE) of the photodiodes can be expressed by Equation 3.23.

- **Linearity and dynamic range.** Typically, the photodiodes are quite linear concerning the input signal. The upper limit of this linearity is given by:

$$P_{\text{sat}} = \frac{V_{\text{Bi}} + V_{\text{R}}}{(R_{\text{S}} + R_{\text{L}}) \times S_{\lambda}} \quad (3.25)$$

where P_{sat} is the upper limit energy, generally $P_{\text{sat}} \leq 10$ mW, V_{Bi} is the contact voltage, V_{R} is the reverse voltage, R_{S} is the photodiode series resistance, R_{L} is the load resistance, and S_{λ} is the photosensitivity at a given wavelength. The non-linearity component increases with the series resistance variable. The lower limit linearity depends on the noise equivalent power.

- **Response speed.** The response time is mainly determined by two contributions: the time of the terminal capacitance connected with the load resistance, and the diffusion time of the carriers to reach the electrode.

3.3.4 Photo-Detector Selection

The previously presented SiPMs, PMTs, and PDs are promising candidates for the proposed Cherenkov BLM system. In the following, the comparison and selection

between the options are discussed.

For an efficient Cherenkov BLM functionality, the photon detection process requires:

- Low dark current background noise.
- Fast time response (of about 100 ps).
- High gain.
- High sensitivity.

Figure 3.19 summarises in a table the main characteristics of the photo-detectors for their comparison.

TYPE	ADVANTAGES	DISADVANTAGES
SiPM	• High optical sensitivity and gain. • Low operating voltage. • Simple circuitry. • Robust. • Low cost. • Insensitive to E & B fields. • Uniformity.	• Large noise. • Difficulties on the detection of very low signals.
PMT	• High sensitivity and gain. • Large dynamic range. • Fast time response. • Low noise.	• High cost. • Sensitive to magnetic fields. • High operation voltage. • No ambient light immunity.
Si Photodiode	• Very low operation voltage. • Uniformity. • Ambient light immunity. • Magnetic resist. • Low temperature sensitivity.	• Low sensitivity and gain. • Complex readout circuit. • High Crosstalk noise

Figure 3.19: *Comparison of the main characteristics between the SiPM, PMT and photodiode photo-detectors.*

SiPM and PMT detectors are comparable in the gain and photosensitivity and fast response parameters. However, the photodiode has a significantly lower gain and higher cross-talk noise.

On the other hand, SiPM and photodiodes operate at low voltages, the opposite of the PMT, which operates at high voltages.

After all the above considerations, finally, the SiPM was selected. This selection was also supported by the Cherenkov Light Generation Model, described in Chapter 4, by performing a photo-sensors operational wavelength comparison (see Section 4.5.4). The SiPM detectors are robust devices that feature high gain and photosensitivity. Their low cost, fast response time and simplicity in low voltage circuitry make them the ideal candidate for photodetection in the Cherenkov BLM system. In addition, they are immunised to the electrical and magnetic fields. In this work, the SiPM from Hamamatsu Photonics series S14160-3010PS and S14160-3015PS were used [103].

3.3.5 Photo-Detector Circuit Layout

Two circuits, with and without operational amplifier, were designed and optimised during the Cherenkov oBLM system development [104].

Both circuits comprise different sets of decoupling capacitors to avoid fluctuations in the bias voltage and several resistors for protection. Each Printed Circuit Board (PCB) was connected to each case's ground, which was connected to the general ground of the rack. In addition, due to noise optimisation, the board sizes were reduced to 50 x 50 mm, and 50 x 60 mm, depending on the amplifier connections. In the board with amplifier, the components were mounted very close together to prevent leakages of voltage. The final Cherenkov oBLM PCB layouts are illustrated in Figure 3.20.

Figure 3.21 presents one of the boxes mounted for the Cherenkov oBLM opened and completely enclosed. The enclosures are made of aluminium material whose dimensions are 7 x 5 x 4 cm.

The circuit boards contain an SMA connector to send the signal to the oscilloscope and a LEMO connector for the bias voltage of the SiPM (42 V), for the ground (GND) connection, and when the signal is amplified, the supply to the amplifier (± 12 V).

The optical fibre is connected to the SiPM through an FC/PC connector.

Figures 3.22 and 3.23 show the final schematics for the two PCBs after all the design upgrades. The SiPMs were installed in a different module, as may be seen in

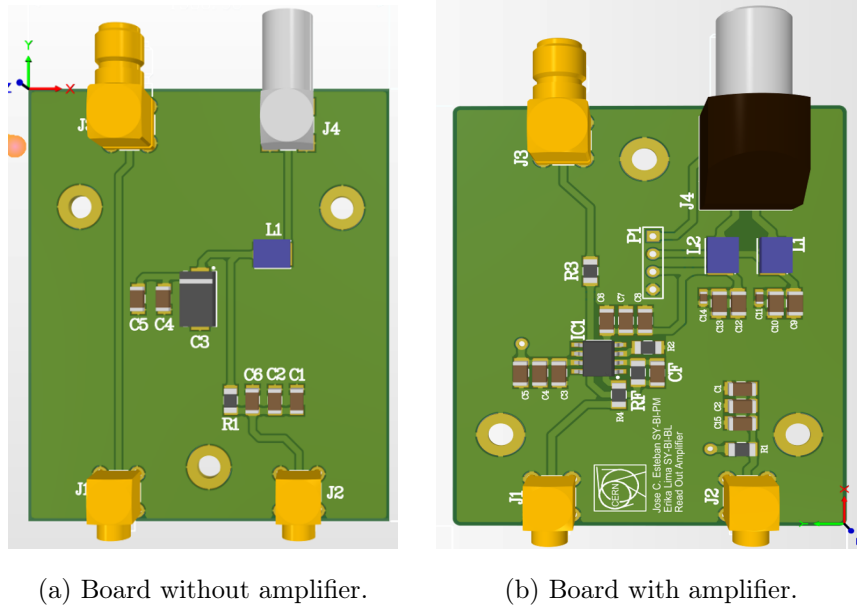


Figure 3.20: *Layouts of the Cherenkov oBLM read-out.*

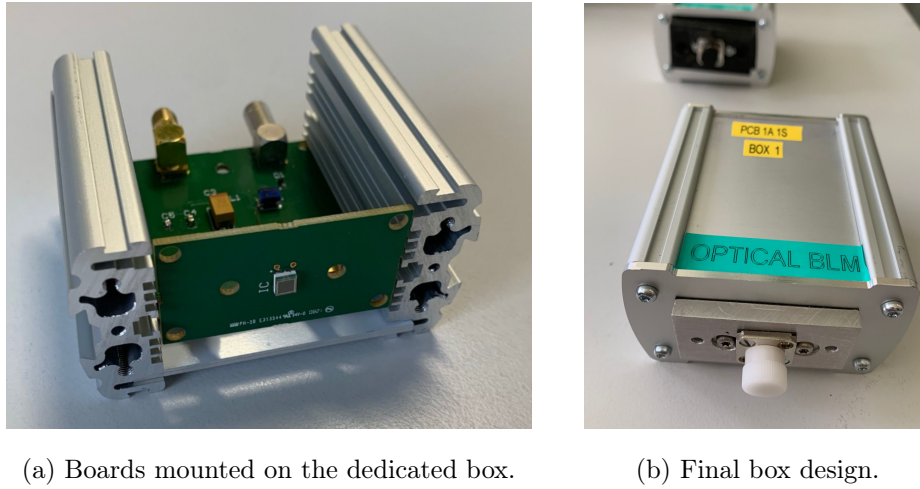


Figure 3.21: *Cherenkov BLM photo-sensor enclosure.*

Fig 3.24. The module dimensions are 20 x 30 mm.

It is worth mentioning that the photo-detector circuit layouts and schematics reported in this chapter are the optimised and definitive read-outs versions used in the Cherenkov oBLM system.

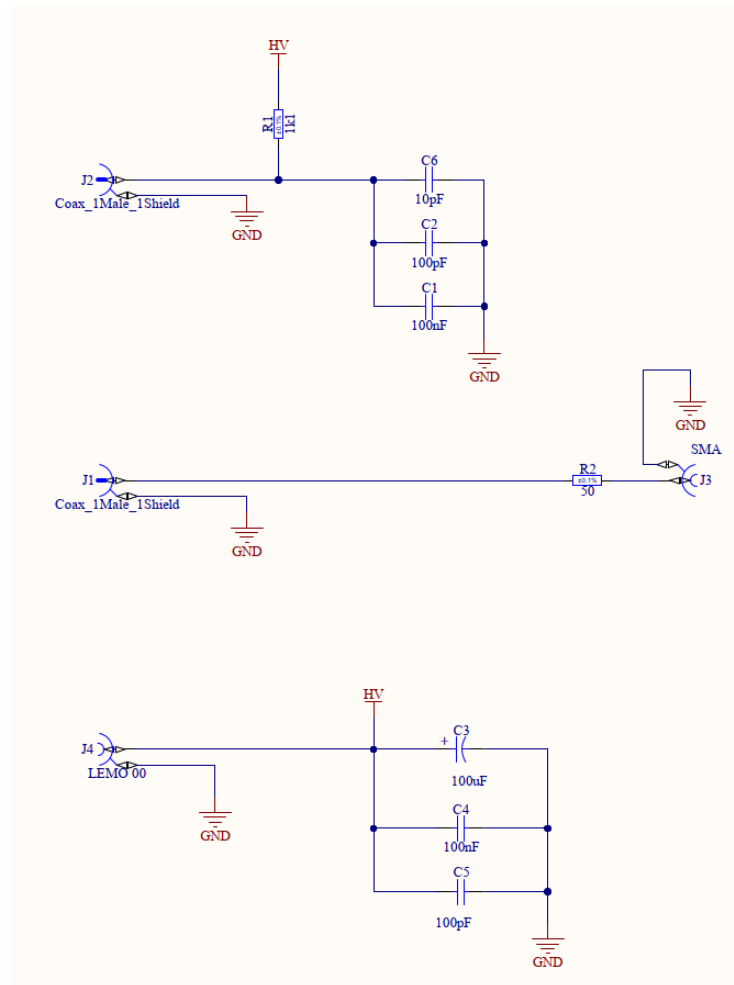


Figure 3.22: Schematic of the non-amplified signal circuit, courtesy of Erika Lima and Jose Carlos Esteban.

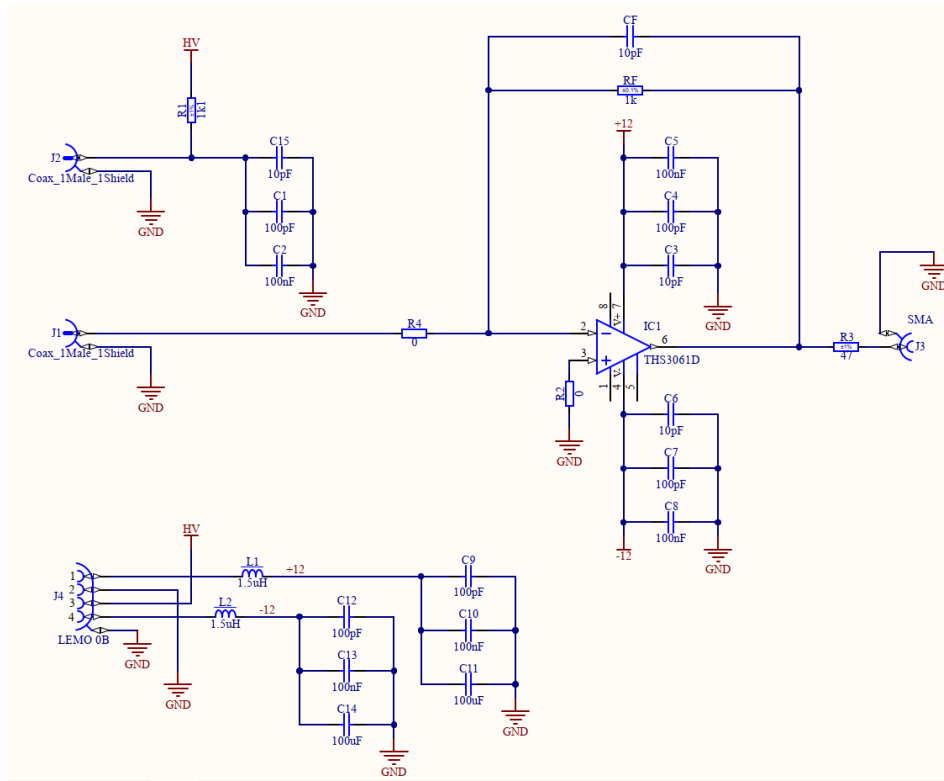


Figure 3.23: Schematic of the amplified signal circuit, courtesy of Erika Lima and Jose Carlos Esteban.

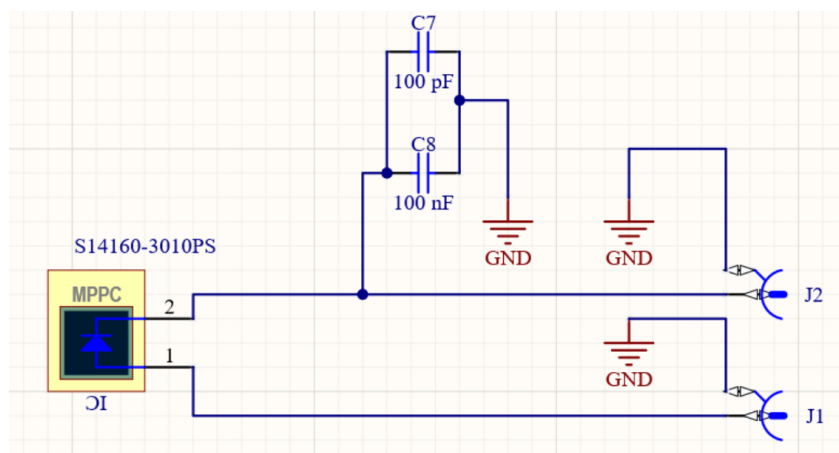


Figure 3.24: Schematic of the SiPM independent module, courtesy of Erika Lima.

Simulation of Cherenkov Light in Optical Fibres

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4.1 Model Introduction

In the framework of loss detection by Cherenkov light production in optical fibres, modelling particle interactions in the SPS slow extraction area is required. This model is an effective support to predict the magnitude of the signal of the new proposed system and evaluate its utility. The FLUKA simulations (see Section 4.2) provide predictions on the behaviour of each interaction within complex problems determining specific boundary conditions in each experiment. From the analysis of the simulation output, the Cherenkov Light Generation Model quantifies the final

yield of Cherenkov photons created by the beam loss interactions in an optical fibre per particle travelled length in a specific wavelength range. Aspects such as how light is captured and how it is attenuated along the fibre are also considered.

4.2 FLUKA Simulations

FLUctuation KAscade (**FLUKA**) transport code [105], based on Monte Carlo methods, offers the possibility to generate the interactions and the tracking of energetic particles such as hadrons, leptons and photons in any material. This code is suitable for many applications, such as accelerator design, radiation protection, detector simulation, and medical therapy. Flair is an advanced graphical user interface to design, run and monitor the simulations [106]. This interactive editor is available for FLUKA, GEANT4, PENELOPE and other simulation engines.

FLUKA is set up by building an input file which allows the user to determine and describe in pseudo-code the main parameters of the simulation. These inputs are:

- **Beam characteristics.** This section is used to define the beam position and direction within the geometry, beam transverse and longitudinal distributions, type of particle, and its energy or momentum. Also, the number of primary starting particles must be specified.
- **Geometry description.** This section describes all the components that are installed in the environment simulated. The geometry is the combination of simple *bodies* (rectangle, infinite planes, spheres, etc.) to perform *regions*. When running the simulations, the particle interactions, the energy deposition, residual nuclei production or particle fluence can be implemented and monitored in the *region* of interest.
- **Materials.** A material should be define in every region. FLUKA features a complete database of single elements and compounds. The user can also create new materials by giving their atomic number, density or atomic weight.

- **Scoring options.** FLUKA code is used to collect the statistical estimation of different radiometric quantities. The input *SCORE* provides the energy deposition in the *regions* specified. The spatial distribution of the energy deposited or total fluence in a mesh is scored by *USRBIN*, whereas *USRBDX* compiles the average of the particles on a detailed surface. Tracking the particles in a specific region or getting their collision density is given by *USRTRACK* and *USRCOLL*, respectively. The residual-nuclei generation is set up by the *RESNUCLEi* card. Finally, the estimation of different double-differential yields of particles is scored by the *URSYIELD* command.
- **Executable routines.** Depending on the simulation purposes, it may be required to reconfigure the basic code to collect specific information about the interactions. These new library routines could should be modified by the user and executed during the running of the simulations as the *SOURCE* card input.

4.3 Loss Detection and Fibre Impacts Generation

This section presents the description of the particle interaction generation in the optical fibre by the simulated losses.

After implementing the geometry components of the beamline, the fibre must be included at the considered coordinates, selecting the silica composite as the material. When running simulations, events are initialised by the primary particles, which create secondary showers of particles through the interaction with the different elements of the geometry. The so-called *Pencil beam* is the simplest beam configuration, where primary particles are monodirectional, monoenergetic and are created from the same point in space. For complex environments, special routines must be compiled and executed to generate different distributions in energy, space and direction.

The FLUKA code collects all the particle tracks covering the whole geometry space. A specific routine was compiled for particle filtering to collect information about particle interaction with the fibre, such as travel path and direction. In

addition, the simulation duration was optimised. The tracks were registered if:

- Interaction occurs on the boundary and within the fibre.
- Particles are charged. Neutrons and photons were discarded.
- Particles travel with velocities greater than threshold velocity $\beta_{th} = 0.685$.

Several physical phenomena can occur inside the optical fibre, such as annihilation, polarisation, Compton effect, Bremsstrahlung, Scattering and photoelectric interactions. Therefore, secondary particles arriving at the fibre may have sub-steps with different trajectories, angles and energies. The routine interprets every sub-step as a different event during the simulation. As example, Figure 4.1 illustrates a possible path, made by several sub-steps, travelled by a hypothetical secondary particle arriving at the fibre.

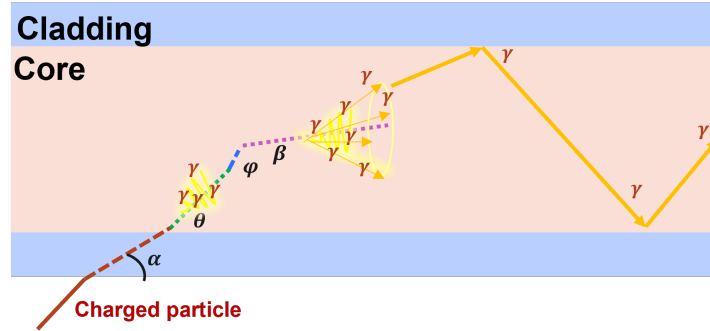


Figure 4.1: *Example of the path travelled by a secondary particle path when interacting with the fibre and generating Cherenkov photons.*

Thus, the principal aim of the FLUKA simulations in this project is to produce all the interaction tracks inside the fibre that could be potential candidates to emit Cherenkov photons. Valuable data, such as the type of particle that reaches the fibre, the particle total energy E , the velocity β , the position coordinates (X, Y, Z) , the path travelled x inside of the fibre, and the angle ϕ with respect to the z -axis, i.e. the fibre axis, is collected in an output file from the FLUKA simulations. Then, Cherenkov photons generation and propagation treatments are quantified

independently from the FLUKA environment. Section 4.4 details the methodology of the Cherenkov Generation Model developed in this thesis.

4.4 Cherenkov Light Generation Model

A model, coded in Python, based on Cherenkov light generation was developed [107]. The workflow of the Cherenkov photon generation model in optical fibres is presented Figure 4.2.

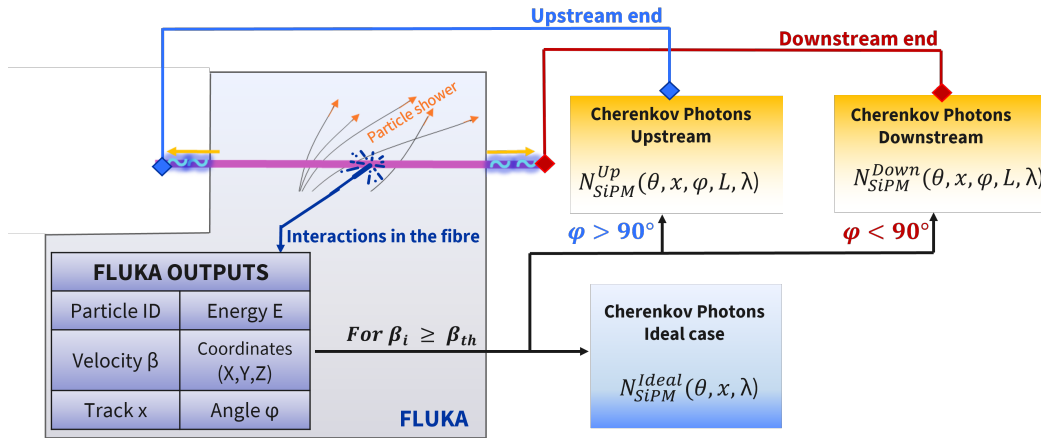


Figure 4.2: Workflow of the Cherenkov photons generation model [107].

When particles interact with the optical fibre, Cherenkov photons are emitted and transported along the fibre. After obtaining FLUKA outputs, the model provides the solution for equation 3.17, following the Cherenkov light emission in optical fibres, i.e. with photon capture-transport probability and photon attenuation, mentioned in Chapter 3.

In the code, the first commands are dedicated to identifying each interaction, verifying the charge and the minimum speed and energy of every particle in the output file.

Then, an intermediate step in the code is the calculation of the total photons generated by the track particles in an ideal case, i.e. considering that all the photons are captured and not attenuated. This solution corresponds to the previous Equation 3.6. Note that the integral is defined under the minimum and maximum

wavelength limits. For the model implemented in this thesis, the wavelength range is imposed by the SiPM photo-detectors, and it is within [290-900] nm.

Process 1 presents the pseudo-code of the total photons generation in the ideal case [107].

Process 1 Cherenkov photons generation in an ideal case. Input: minimum wavelength $\lambda_{\min}$, maximum wavelength $\lambda_{\max}$, particle velocities β_i , velocity threshold β_{th} , Cherenkov angles $\theta_{c,i}$, particle tracks $\mathbf{x}_i$.

```

1:  $N_{\text{SiPM}} \leftarrow 0$ 
2: for tracks  $i = 1, \dots, P$  with velocity  $\beta_i \geq \beta_{\text{th}}$  do
3:   Update  $N_{\text{SiPM}} \leftarrow N_{\text{SiPM}} + x(i) * \sin(\theta_{c,i}) * (\frac{1}{\lambda_{\min}} - \frac{1}{\lambda_{\max}})$ , Equation 3.6.
4: end for
```

As the photons can travel to both ends of the fibre and be detected by the two photo-sensors separately, splitting the generated photons in *Downstream* and *Upstream* directions is essential. Downstream means the direction following the beam trajectory, while the Upstream direction is the opposite. This calculation can be done by evaluating each angle of interaction. By using the angle is also possible to calculate the capture factor F_{cap} , given by Equation 3.12.

The computation of the photon direction distribution and the capture factor calculation is determined by Process 2 [107]. It also gives the total length travelled for the photons from their creation point to the end of the fibre.

For the final number of Cherenkov photons able to reach the photo-sensors, the model calculates the solution to Equation 3.17, shown in Process 3 [107].

Process 2 Calculation of capture factors $\mathbf{F}_{\text{cap}}^{\text{Down}}$ and $\mathbf{F}_{\text{cap}}^{\text{Up}}$ for downstream and upstream photons, respectively, and calculation of the total length covered per photon from the particle interaction point to the photo-sensor location. Input: angle of incidence ϕ_i of the particle with the fibre, velocity threshold β_{th} , particle velocities β_i , particle final Z-coordinate in fibre $\mathbf{Z}_i$, and fibre length $\mathbf{L}_{\text{fib}}$.

- 1: Divide the tracks P in the groups $\mathbf{P}_{\text{Down}}$ and $\mathbf{P}_{\text{Up}}$ and find the probabilities $\mathbf{F}_{\text{cap}}^{\text{Down}}$ and $\mathbf{F}_{\text{cap}}^{\text{Up}}$ and the total lengths from the interaction point to the photo-detector $\mathbf{L}_i^{\text{Down}}$ and $\mathbf{L}_i^{\text{Up}}$.
 - 2: **for** tracks $i = 1, \dots, P$ with velocity $\beta_i \geq \beta_{\text{th}}$ **do**
 - 3: **if** $\phi(i) < 90^\circ$ **then**
 - 4: Set $P_{\text{Down}} \leftarrow i$
 - 5: **else**
 - 6: **if** $\phi(i) > 90^\circ$ **then**
 - 7: Set $P_{\text{Up}} \leftarrow i$
 - 8: **end if**
 - 9: **end if**
 - 10: **end for**
 - 11: **for** Downstream tracks $i = 1, \dots, P_{\text{Down}}$ **do**
 - 12: Update $L_{\text{Down}}(i) \leftarrow L_{\text{fib}} - Z(i)$
 - 13: Update $F_{\text{cap}}^{\text{Down}}(i) \leftarrow F_{\text{cap}}^{\text{Down}}(\phi_i, \beta_i^{\text{Down}})$, Equation 3.12.
 - 14: **end for**
 - 15: **for** Upstream tracks $p = 1, \dots, P_{\text{Up}}$ **do**
 - 16: Update $L_{\text{Up}}(i) \leftarrow Z(i)$
 - 17: Update $F_{\text{cap}}^{\text{Up}}(i) \leftarrow F_{\text{cap}}^{\text{Up}}(\phi_i, \beta_i^{\text{Up}})$, Equation 3.12.
 - 18: **end for**
-

Process 3 Downstream and upstream captured and attenuated photons. Inputs: total lengths $\mathbf{L}_i^{\text{Down}}$ and $\mathbf{L}_i^{\text{Up}}$, particle tracks $\mathbf{x}_i$, minimum wavelength $\lambda_{\min}$, maximum wavelength $\lambda_{\max}$, Cherenkov angles $\theta_{c,i}$, and the capture probabilities $\mathbf{F}_{\text{cap}}^{\text{Down}}$ and $\mathbf{F}_{\text{cap}}^{\text{Up}}$.

```

1: Find the values  $\mathbf{N}_{\text{SiPM}}^{\text{Down}}$  and  $\mathbf{N}_{\text{SiPM}}^{\text{Up}}$ .
2: for Downstream tracks  $i = 1, \dots, P_{\text{Down}}$  do
3:   if  $L_{\text{Down}}(i) < 0$  then
4:     Set  $\mathbf{N}_{\text{SiPM}}^{\text{Down}}(i) \leftarrow 0$ 
5:   else
6:     if  $L_{\text{Down}}(i) > 0$  then
7:       Set  $\mathbf{N}_{\text{SiPM}}^{\text{Down}}(i) \leftarrow F_{\text{cap}}^{\text{Down}}(i) * N_{\text{SiPM,att}}(\theta_{c,i}, x_i, L_i^{\text{Down}})_{\lambda_{\min}}^{\lambda_{\max}}$ , Equation 3.17.
8:     end if
9:   end if
10:  Update  $\mathbf{N}_{\text{SiPM}}^{\text{Down}} \leftarrow \mathbf{N}_{\text{SiPM}}^{\text{Down}}(i)$ 
11: end for
12: for Upstream tracks  $i = 1, \dots, P_{\text{Up}}$  do
13:   if  $L_{\text{Up}}(i) < 0$  then
14:     Set  $\mathbf{N}_{\text{SiPM}}^{\text{Up}}(i) \leftarrow 0$ 
15:   else
16:     if  $L_{\text{Up}}(i) > 0$  then
17:       Set  $\mathbf{N}_{\text{SiPM}}^{\text{Up}}(i) \leftarrow F_{\text{cap}}^{\text{Up}}(i) * N_{\text{SiPM,att}}(\theta_{c,i}, x_i, L_i^{\text{Up}})_{\lambda_{\min}}^{\lambda_{\max}}$ , Equation 3.17.
18:     end if
19:   end if
20:  Update  $\mathbf{N}_{\text{SiPM}}^{\text{Up}} \leftarrow \mathbf{N}_{\text{SiPM}}^{\text{Up}}(i)$ 
21: end for

```

4.5 Model Applications

By combining FLUKA outputs with the model described in this chapter, Cherenkov photons collected in a setup with optical fibre as the sensitive material can be estimated. Updating the FLUKA geometry the same modelling could be used for different setups.

In this section some of the applications of the model during the development of the Cherenkov BLM are discussed.

4.5.1 Signal Scaling with Fibre Core Size

The expected Cherenkov light signal as a function of the fibre core size was studied. The purpose of this study was to determine a scaling factor based on the fibre core. By applying this factor, larger fibres could be implemented in the FLUKA geometry increasing the simulation statistics and reducing the number of simulations required. Different core diameters, from 50 μm to 2 cm, were added in the simulations and the Cherenkov Light Generation model was used to calculate the photon emission in each optical fibres.

Results presented in Figure 4.3 compare the total photon production obtained for a 2.0 cm diameter fibre scaled down with the simulated total photon production obtained for different core diameters. The scale down was considering the factors R^2 and R^3 , where R is the fibre radius. The plot is zoomed in for the diameters from 50 μm to 1 mm. Simulation results obtained for larger core fibres are quite similar to the 2 cm signal when scaled down in area. In the case of smaller fibres, neither the area nor the volume scaled down from 2.0 cm diameter fit with the expected results. As such, the expected signal can be considered as an intermediate value between both fits. In the rest of the thesis, the volume scaling was considered, as it is the most conservative. The scaling can be used as normalisation of the simulations with 2 cm which are later compared with the measurements data.

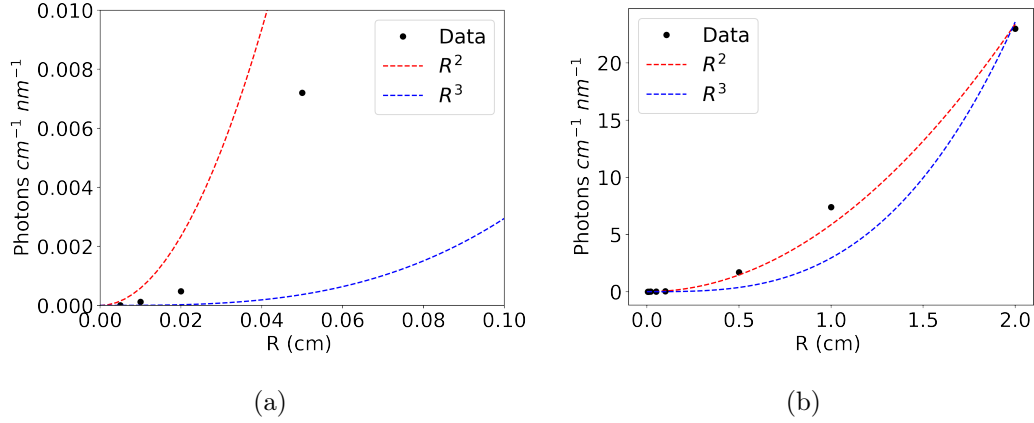


Figure 4.3: Comparison between the simulation results from a 2.0 cm diameter fibre scaled down, considering R^2 and R^3 , and different core diameter fibres.

4.5.2 Signal Scaling with Number of Fibres

In this study, signals obtained by a large core fibre were compared with signals obtained by a bundle of smaller core fibres. By using smaller core fibres, for instance 50 μm core diameter fibres instead of one fibre of 200 μm , costs could be reduced significantly. Therefore, a bundle of small core fibres equalling the area of a larger core fibre can be a promising solution.

Table 4.1 summarises the comparison of the expected number of photons emitted ideally per a single 2 cm core diameter fibre with the signals of its equivalent bundle of 1 cm core diameter fibres.

Fibre diameter (cm)	Number of fibres	Photons generated	Ratio ^a
2.0	Single fibre	1.2×10^{15}	1
1.0	Bundle of 4 fibres	1.3×10^{15}	1.08
1.0	Bundle of 2 fibres	7.1×10^{14}	0.59

^a Ratio related to the 2 cm single fibre.

Table 4.1: Comparison of the number of Cherenkov photons generated for the ideal case in the different single fibres or bundles.

The bundle of four fibres of 1 cm in diameter generates an equivalent number of

photons to the 2 cm single fibre. Accordingly, a bundle of two fibres of 1 cm in diameter generates approximately the half amount of signal. Therefore, the correlation between larger diameter fibres and bundles of smaller core fibres has been verified by the Cherenkov Light Generation model.

The Table 4.2 summarises the number of fibres of 50 μm and 200 μm core diameter required to achieve equivalent single larger fibres.

	50 μm	200 μm	1 mm	1 cm	2 cm
# 200 μm	-	1	25	2,5k	10k
# 50 μm	1	16	400	40k	160k

Table 4.2: *Required number of 50 μm and 200 μm core diameter fibres to achieve larger fibres.*

4.5.3 Signal Dependency with Particle Impact Angle

According to the Equation 3.12 described in Chapter 3, Cherenkov photons have a certain probability of being captured and transported along the optical fibre depending on the particle impact angle. The Cherenkov Light Generation model was used to verify the angle ranges determined by the theoretical background.

A set of more than 60 FLUKA simulations were performed where three silica fibres, of 200, 100 and 50 μm core diameter, were impacted by an electron beam from different angles within the range $[10^\circ - 80^\circ]$ respect to the fibre axis. The 220 MeV electron beam was described by a gaussian distribution, and the results were normalised to a total charge of 25 pC. The simulated fibres were 2 m long and the impact point was set at the middle of the fibres, thus attenuation effect was discarded. Figure 4.4 illustrates the signal dependency with the particle impact angles for the three different diameter fibres, comparing theoretical and simulated results.

Simulated Cherenkov light is emitted at the same range of angles determined by the theoretical Cherenkov capture probability. The range of angles selected is the corresponding to the downstream fibre direction. It is worth mentioning that

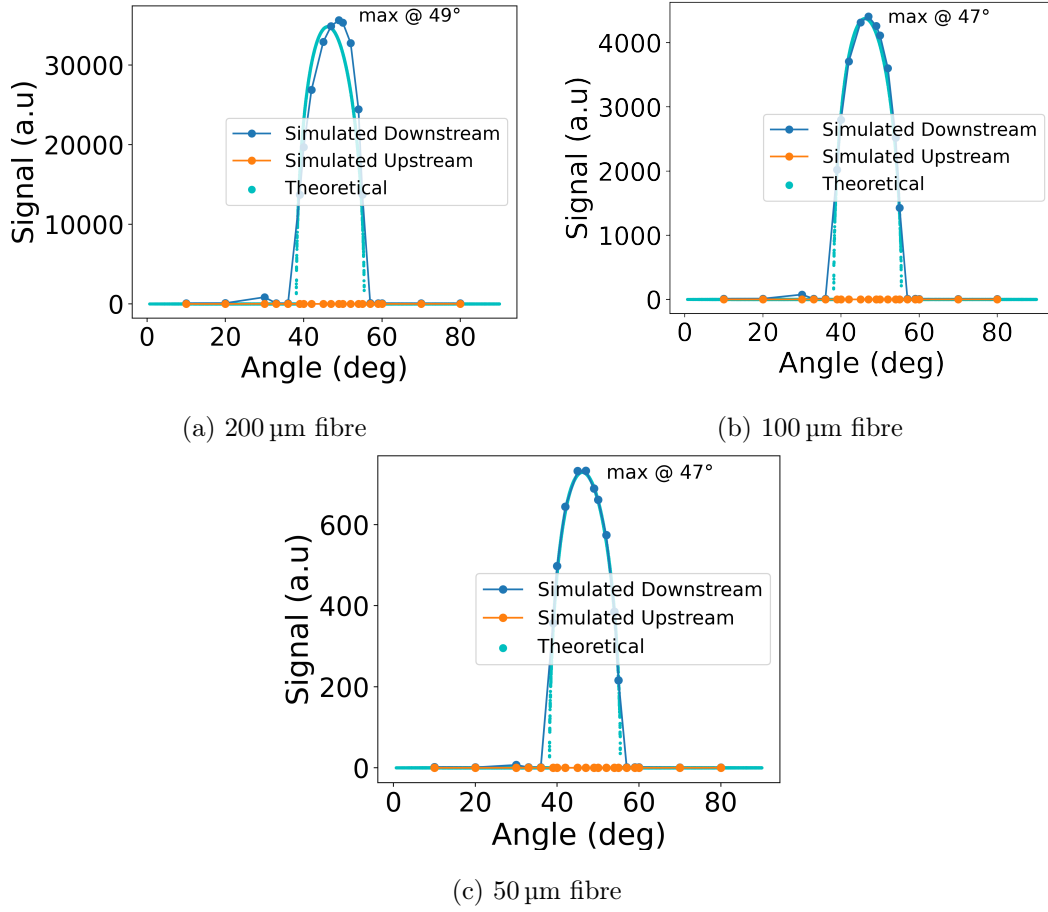


Figure 4.4: Capture angles from FLUKA simulations compared with the theoretical range of capture angles.

simulations show that there is no Cherenkov signal for the upstream direction in that range of angles, as expected. In two of the cases, the maximum angle corresponds with the maximum Cherenkov angle. In the case of 200 μm fibre, the angle seems to be two degrees greater.

4.5.4 Wavelength Range for Cherenkov Photon Detection

Another model application is the evaluation of the different photo-sensors that could be connected to the optical BLM, regarding the different ranges of the operational wavelength. Using the same FLUKA geometry and simulation configuration in all the cases, three different core fibres were considered (200, 100 and 50 μm core diam-

eter), and the fundamental influence of the wavelength for the photon generation was analysed. The fibre lengths implemented were 200 m long.

Figure 4.5 collects the results obtained from the Cherenkov photon generation model. The photo-sensors are selected to cover the three spectra (UV, visible and IR). The number of total photons generated and the detected by each photo-detector is presented. The operational wavelength ranges and the PDE values of the three photo-sensors are also provided.

	UV + Visible + IR 290 – 900 nm		UV + Visible 160 – 700 nm		Visible + IR 350 – 1000 nm	
FIBER CORE (μm)	SiPM 3015 (PDE ~12 %)		PMT (PDE ~6 %)		SiPM S13720 (PDE ~12 %)	
	Downstream (photons/spill)	Upstream (p/s)	Downstream (p/s)	Upstream (p/s)	Downstream (p/s)	Upstream (p/s)
200	2040k	240k	751k	108k	2160k	216k
105	120k	48k	46k	24k	132k	43k
50	31k	-	12k	-	31k	-

Figure 4.5: Comparison of the photons detected for different photo-sensors with different ranges of wavelength in downstream and upstream ends.

Several factors were considered when determining the final values:

- By applying the probability of capture dependent on the particle angles of incidence, the capture factor reduced the Cherenkov photons emitted in the optical fibres. The angles also determined whether the photons travelled downstream or upstream.
- The fibres are 200 m long; therefore, the signal attenuation is very significant. On the other hand, as shown in Figure 3.8, Cherenkov photons are generated mainly in the UV range when there is no attenuation. This factor considerably affects the wavelength dependency, and the predominant wavelengths tend to be closer to the IR region.

- The PDE factor determines the percentage of photons collected by the photo-sensor. An average value is considered.

So far, the SiPM detectors are the most promising option. The Cherenkov emission happens in the UV range and therefore it might indicate that the PMT would be the best photo-sensor. However, the length of the fibres and the PDE parameter affect noticeably in the final results. Signals obtained for both SiPMs are very similar and finally the SiPM 3015PS was selected.

4.6 Summary

The Cherenkov light production model is a powerful tool that provides information about the Cherenkov photon generation and transport in optical fibres complementing the FLUKA simulation results. At the moment of this thesis, FLUKA 2011.3.0 version was released. The Cherenkov photon production and transport through different materials were under development in FLUKA [108]; however, it was not entirely reliable yet due to the low energy of the Cherenkov photons [109]. In future versions of FLUKA code, where the Cherenkov photons processing will be optimised, the model implemented in this work can be used as a complementary tool to crosscheck the results. The Cherenkov Light Generation model can be used to analyse the configurations and characteristics of Cherenkov oBLM prototypes targeting different accelerator scenarios and conditions. Some model applications include the study of signal scaling with larger core fibres implemented to enlarge the statistics of the events created by the simulation, the comparison of several photo-detector types with different operational wavelengths, or the computation of the Cherenkov effect generated in a bundle of fibres to observe the similarities and distinctions between one single fibre and the bundle of smaller core fibres. The application of the Cherenkov light generation model for the SPS slow extraction line and the results obtained are discussed in Chapter 5.

Cherenkov oBLM in SPS

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5.1 Introduction

This chapter gives the Cherenkov Light Generation model results using the LSS2 FLUKA geometry and an overview of the oBLM prototype installation in LSS2 with the last signals obtained. One of the main goals of this thesis is to evaluate the signal quality of an oBLM prototype as beam loss detector for the SPS slow beam extraction. The proton beam is debunched and provided from the SPS to the North Area through the Long Straight Section 2 (LSS2) by a slow resonant extraction process in a continuous stream of particles. The radiation dose measured in the zone is mainly induced by the SPS extraction operations. Several modifications in

the machine's elements were performed in the last years to reduce the extraction losses [40]. The measurements of the Cherenkov oBLM prototype would confirm if the beam losses were certainly reduced or, on the contrary, re-distributed along the line. A deep analysis of the data collected by the system will reveal the exact location where the losses are produced.

5.2 FLUKA Simulation of SPS Slow Extraction Area

Using the LSS2 geometry, the beam losses from the slow extraction area can be reproduced and studied with the implementation of the optical fibre sensor, in order to predict and evaluate the number of Cherenkov photons reaching the photo-sensors. In this section, a detailed post-processing of the simulation results and the analysis of the photon production obtained in the oBLM by the Cherenkov light generation model in LSS2 is reported.

5.2.1 SPS Geometry

The LSS2 FLUKA geometry was developed by the STI-BMI (Sources, Targets and Interactions group - Beam Machine Interactions Section) and Radiation Protection (RP) group to analyse the beam loss patterns in the slow extraction area [110].

The geometry represents an approximately 100 m extent from the quadrupole 216 to 219 which includes the electrostatic septa ZS, the three magnetic MST septa and the five magnetic MSE septa (see 1.3.2). The LSS2 region towards the NA rendered in FLUKA software is shown in Figure 5.1 and Figure 5.2 presents the overview of the SPS slow extraction equipment in the Flair interface.

The TPST component corresponds to the extraction protection shield for the septum magnet MST. It is an absorber vacuum tank made of aluminium and copper located downstream from the MST septa magnets to intercept the beam losses and protect the line devices [111]. Each element of the extraction line was precisely laid out following the actual sizes, distances between components and material compositions. The beamline was located on the z -axis, at (0,0) in terms of x and y coordinates. Besides, the Cherenkov oBLM fibre was added in the LSS2 geometry

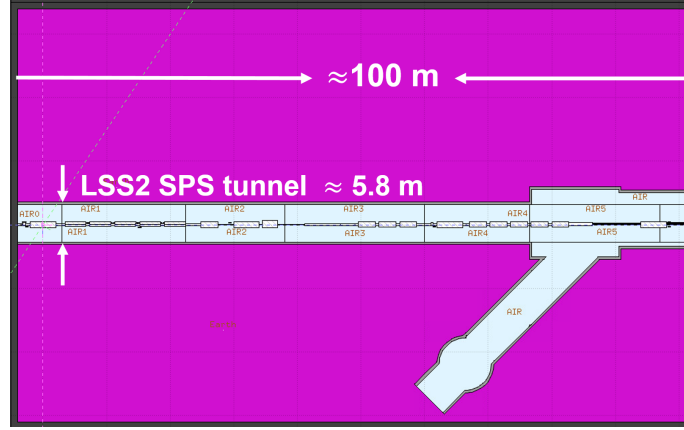


Figure 5.1: *LSS2 geometry layout in Flair interface* [107].

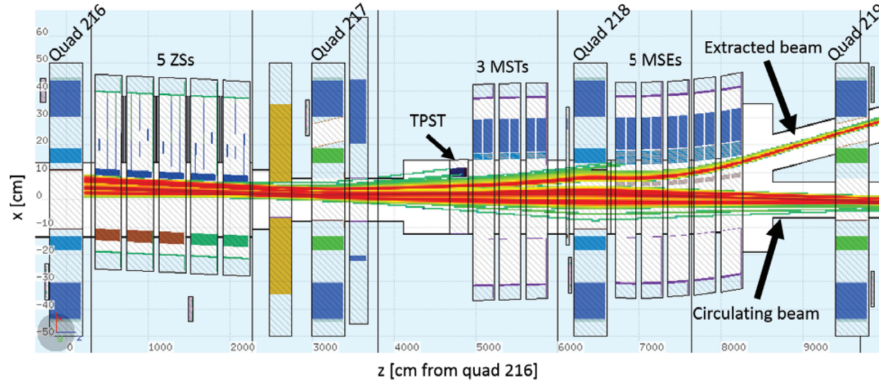


Figure 5.2: *Horizontal overview of the LSS2 extraction Flair schematic. Both circulating and extracted proton beams are shown* [110].

on the z -axis, parallel to the beam pipe at (199, 127) cm as x and y coordinates, respectively. The distance between the beamline and the fibre was 2.3 m approximately. The diameter of the fibre was 200 μm and the material selected was the quartz.

5.2.2 Input Beam Characteristics

In the SPS slow extraction to the NA experiments, the proton beam spills are extracted at 400 GeV/c with a duration from 1-10 s [112]. For the beam inputs in the FLUKA simulations [40], in order to optimise the simulation time, the last four SPS turns before extraction of each particle were computed. The particle distribution

upstream from the quadrupole QFA216 is loaded and transported along the LSS2 until the quadrupole QDA219 [113]. There are two proton distributions available that can be used:

- In the *Black distribution*, the ZS wires are considered absorbers, and the impacting protons are not taken into account. This distribution has an inefficiency of 0.7%.
- In the *Full distribution*, impacting protons with the wires are scattered back and tracked over extra turns until their extraction to the NA, their loss on the aperture or their absorption by the ZS with an inelastic interaction. Around 3% of the particles lose energy during the process and do not produce any beam loss, i.e. they are discarded. This distribution has an inefficiency of 1.2%.

For the model described in this thesis, the *Full distribution* was implemented. FLUKA particle tracks are given per simulated protons. A *weight* factor, w , should be applied to obtain the particle tracks per extracted proton [114]. This *weight* factor is generally approximated to 6 and is given by [115]:

$$w = \frac{N_{\text{simulated}}}{N_{\text{extracted}} + N_{\text{lost}}} \quad (5.1)$$

To have sufficient statistics at the scoring particles in the fibre and make reliable predictions, at least 10^5 primary particles per cycle were entered as input. When running the simulations, at least ten cycles were required.

5.2.3 Interactions in the Optical Fibre

During the FLUKA simulations a specific routine was coded to provide an output file with the tracks of every charged particle that reaches the optical fibre with the velocity parameter $\beta > 0.685$. As indicated in section 4.3, this output file registers the total energy deposited on the fibre, the position coordinates of the track particles, their velocity, their path through the fibre and their angle of incidence with respect to the fibre axis. The list of track interactions in the optical fibre obtained by the

LSS2 simulations is given in Table 5.1. In order to increase the statistics of the system detection functionality, the results were obtained for a 2 cm core diameter fibre and later scaled down for smaller core fibres of 200, 105 and 50 μm . The LSS2 simulation data are given as input to the Cherenkov light generation model, and the results are presented in section 5.3 of this thesis.

Tracks	Fibre 200 μm^a	Fibre 105 μm^a	Fibre 50 μm^a
e^+	2.6×10^9	2.9×10^8	1.9×10^8
e^-	5.9×10^9	3.0×10^9	9.6×10^7
p^+	1.7×10^8	-	-
p^-	-	-	-
μ^+	5.9×10^7	-	-
μ^-	1.5×10^7	7.2×10^7	-
π^+	2.8×10^8	-	-
π^-	3.9×10^8	7.1×10^7	-
κ^+	9.9×10^6	-	-
κ^-	9.9×10^6	-	-

^a FLUKA primary particles are normalised to the extracted protons per spill (4×10^{13} protons).

Table 5.1: *Number of track interactions in the optical fibre per spill in LSS2 from FLUKA, input to the Cherenkov model.* [107]

5.3 Cherenkov Light Production Model for LSS2

The quantitative results of the Cherenkov light generation model using the LSS2 Monte Carlo simulation outputs are summarised in this section. This analysis and the detailed model description have been submitted for publication [107].

The different energies of the particles that reach the fibre are presented in Figure 5.3. The energy distribution varies from 0.7 MeV to 10 GeV. As expected, the

largest core fibre presents more particle detection, and the number of interactions decreases with the energy due to the geometry. The highest track population corresponds to the minimum value of energy registered, approximately 0.7 MeV. It fits with the minimum total energy of the electrons and positrons for Cherenkov photon emission (see Table 3.1) and would be consistent with the fact that the electrons and positrons are the most probable interactions in the simulations.

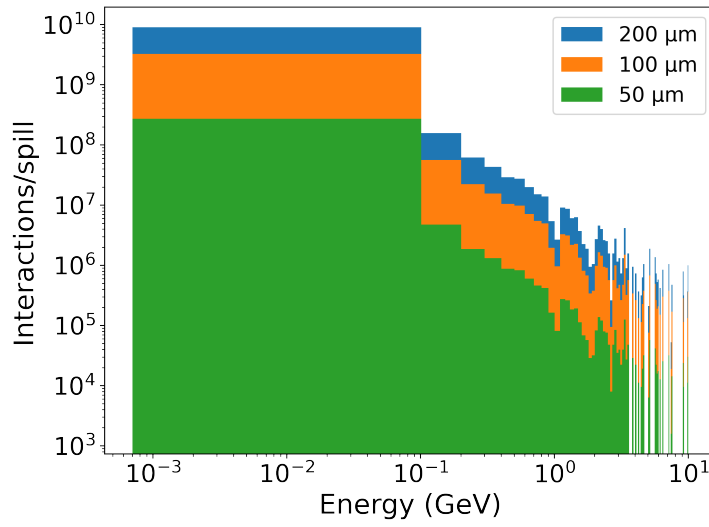


Figure 5.3: *Particle energies for each track in the fibre.*

As illustrated in Figure 5.4, the incidence angle distribution is continuous and spans from 0° to 180° with respect to the fibre axis. In this case, particles impinging and travelling with the angles 0° and 180° are considered parallel to the fibre, for downstream and upstream directions, respectively. Although the interactions are produced in a wide range of angles, only the ones within the ranges of capture shown in Figure 3.6, determined by Equation 3.12, produce Cherenkov photons transmitted by the fibre. There is a maximum of interactions in the first half of the graph, i.e. in the range of $[0^\circ - 90^\circ]$. It indicates that more particles travel in the downstream direction, as expected.

The number of Cherenkov photons generated from the interactions is directly proportional to the passage length of every charged particle within the optical fibre.

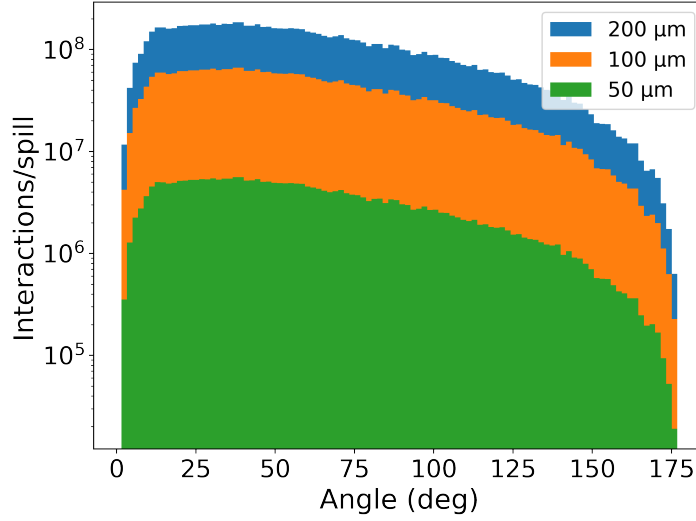


Figure 5.4: *Incidence angles of the interactions with respect to the fibre axis.*

The user routine implemented in FLUKA provides this propagation path of the interactions considering the three-dimensional view of the fibre [84]. Figure 5.5 shows the interaction track lengths in the fibre. The path distribution includes distances from several dozens of nanometres to a few millimetres inside the fibre. These results would be related to the energy and angle of incidence of the particles and are consistent with the fibre core sizes considered.

As mentioned in Section 5.2.1, the most critical LSS2 section, around 100 m, is implemented in the Flair geometry. In the real slow extraction area, the downstream and upstream fibre ends and photo-sensors are located at $z = 176$ m and $z = -24$ m, respectively. Both locations of the photo-sensors are considered during the model analysis because they are related to signal attenuation. The longitudinal distribution along the fibre was plotted and compared with the beamline components (see Figure 5.6). The interactions are distributed continuously over the line, with two maximum peaks at the ZS septa and MST magnets locations, at 15 m and 50 m, respectively.

The Cherenkov photon generation model can be used to calculate the total Cherenkov photons generated by the interactions. This value is the solution of

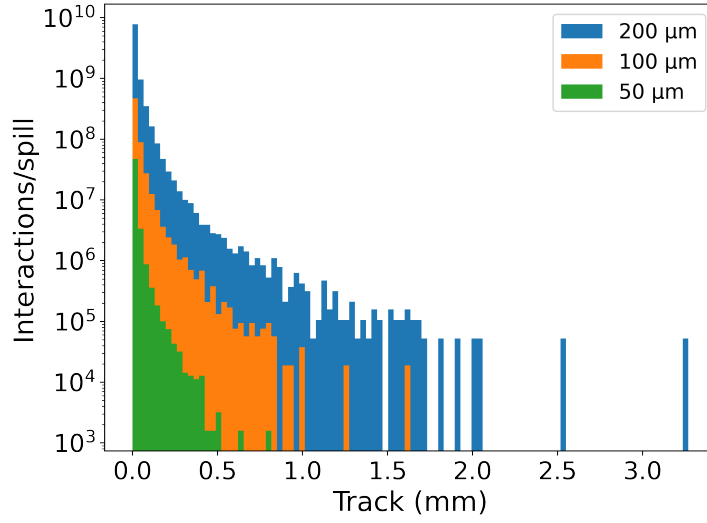


Figure 5.5: *Interaction track lengths within the optical fibre.*

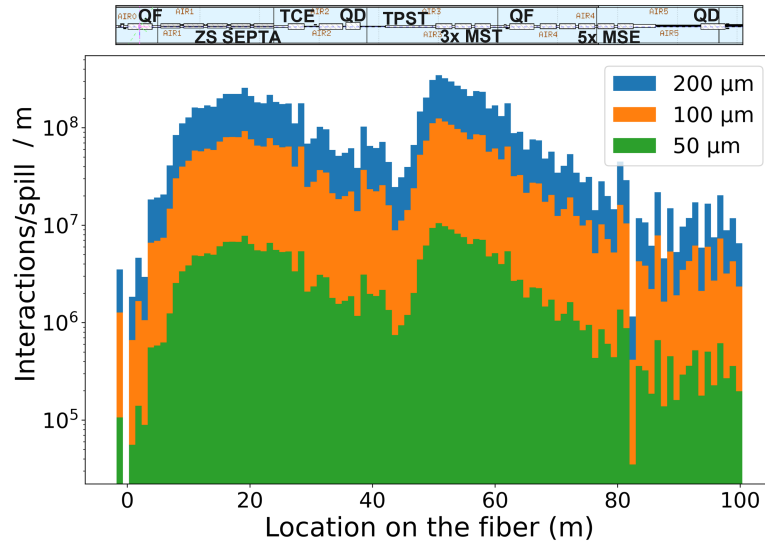


Figure 5.6: *Longitudinal distribution of the interactions along the fibre in LSS2 area.*

the Equation 3.6, implemented in Process 1. Table 5.2 provides, for each fibre, the total number of Cherenkov photons generated and the expected photons in downstream and upstream ends (see Process 2), both with no signal attenuation and capture factor considered. The division is only related to the angle of incidence of the interactions and the sum of the two quantities corresponds to the original

value. In this study, the number of photons is calculated for a range of wavelength within [290,900] nm, which corresponds to the spectral response range of the SiPM 3015 photosensors. The numbers of photons in Table 5.2 can be set as reference during the model analysis.

Core size (μm)	Photons generated ^a	Photons Downstream ^a	Photons Upstream ^a
200	1.3×10^{10}	9.9×10^9	3.1×10^9
105	2.1×10^9	1.4×10^9	7.6×10^8
50	1.3×10^8	2.6×10^7	1.1×10^8

^a FLUKA primary particles are normalised to the extracted protons per spill (4×10^{13} protons).

Table 5.2: *Cherenkov photons ideal case for 200, 105 and 50 μm core fibres. [$\lambda_{\min} = 290$ nm, $\lambda_{\max} = 900$ nm].*

Photons travel from each interaction point to their corresponding end of the fibre. The attenuation factor affects the signal depending on the fibre length and the impact location, as indicated in Section 3.2. Table 5.3 collects the results of the Cherenkov photons presented in Table 5.2 after the attenuation factor application, regardless of the capture factor. As expected, ratio values indicate that the light attenuation is the same, independently of the fibre core diameter.

The final expected signals obtained in each photo-sensor, i.e. the final numbers of photons generated, captured and attenuated by the fibre, estimated for the model (see Process 3) are shown in Table 5.4. These values are the numerical results of the Equation 3.17. The ratio value for the 50 μm core fibre in the downstream direction seems to be larger than expected. The high rate of statistical errors in the simulations of the smallest fibre case, around 70%, unavoidably affects the analysis results. Moreover, the reduction of the Cherenkov signal generated in a 200 μm fibre for an oBLM system in LSS2 is exemplified in Figure 5.7.

Results presented in Tables 5.2 and 5.4 are normalised to the extracted protons per SPS spill. On average, the duration of a spill in SPS is around 4.8s. This

Core size (μm)	Photons attenuated	Ratio Downstream ^b	Photons attenuated	Ratio Upstream ^b
	Downstream ^a		Upstream ^a	
200	1.3×10^9	0.13	1.6×10^8	0.05
105	1.9×10^8	0.13	3.9×10^7	0.05
50	3.9×10^6	0.15	5.5×10^6	0.05

^a FLUKA primary particles are normalised to the extracted protons per spill.

^b Ratio= Photons attenuated / Photons generated.

Table 5.3: *Cherenkov photons after attenuation for 200, 105 and 50 μm core fibres.*
 $[\lambda_{min} = 290 \text{ nm}, \lambda_{max} = 900 \text{ nm}]$.

Core size (μm)	Photons Downstream ^a	Ratio Downstream ^b	Photons Upstream ^b	Ratio Upstream ^b
200	1.7×10^7	0.002	2.0×10^6	6.0×10^{-4}
105	1.0×10^6	7.0×10^{-4}	4.0×10^5	5.0×10^{-4}
50	2.6×10^5	0.01	0.0	–

^a FLUKA primary particles are normalised to the extracted protons per spill.

^b Ratio = Photons captured and attenuated / Photons generated.

Table 5.4: *Cherenkov light production at the SiPMs.* $[\lambda_{min} = 290 \text{ nm}, \lambda_{max} = 900 \text{ nm}]$

means that the extraction length of every spill is $2 \cdot 10^5$ turns. The Cherenkov photons calculated per SPS turn in the LSS2 area are collected in Table 5.5. A lower quantity of extracted protons per spill can be considered as a safety factor for the Cherenkov photon production model. For instance, normalising the FLUKA interactions by 1×10^{13} protons, the values of Table 5.5 would be found divided by 4. Therefore, for a 200 μm core fibre, there would be approximately 21 photons/turn for the downstream signal and less than 3 photons/turn for the upstream signal. The Cherenkov photons obtained in 105 and 50 μm fibres would be insignificant.

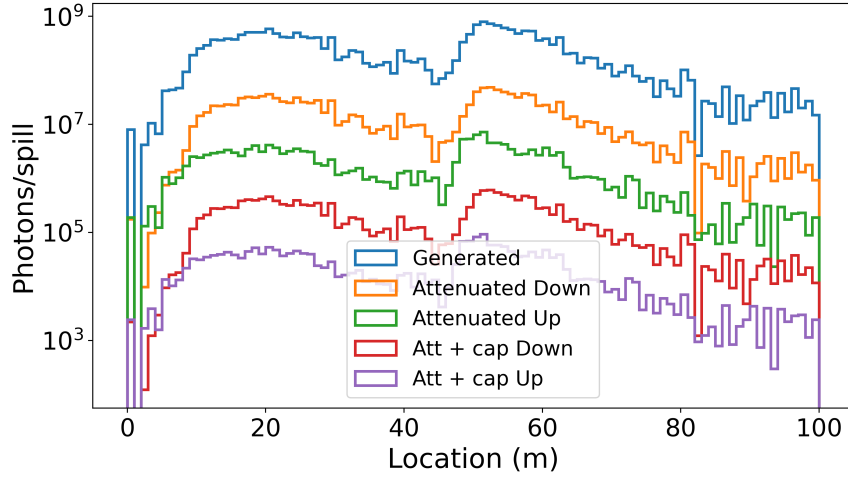


Figure 5.7: *LSS2 Cherenkov photon production in an oBLM with a fibre of 200 μm core. The signal reduction is affected by the attenuation and capture factors.*

Core size (μm)	Photons Downstream (turn) ^a	Photons Upstream (turn) ^a
200	84	10
105	5	2
50	1	0

^a One spill runs 2×10^5 turns.

Table 5.5: *Expected Cherenkov photons in an oBLM installed in LSS2 per spill turn. [$\lambda_{\min} = 290 \text{ nm}$, $\lambda_{\max} = 900 \text{ nm}$].*

5.4 First oBLM Prototype Installation

Radiation levels in the LSS2 area enforce particular protocols in the equipment interventions limiting the exposure time of the operators. The optical fibre BLM can not be installed on the beamline where the components are handled against the clock. During this study, several setups were considered to select the best location for the system without compromising both the safety of the optical fibre and the loss detection efficiency. On the other hand, although the silica fibres can withstand

high radiation levels, future studies on the fibre radiation tolerance in the SPS slow extraction will determine if installing the fibre closer to the beamline is feasible. An integration study was carried out in order to determine the fibre duct and electronics locations [116]. A 160 m long plastic duct of 32 mm in diameter was installed on the tunnel ceiling at 2.3 m from the beam pipe, approximately at a fixed height from the machine elements. The duct extends from QFA.216 to QDA.219 quadrupole magnets, where the third-integer resonance and electrostatic septa (ZS) are located. Figure 5.8 shows a small part of the beamline in LSS2 and the fibre duct installed on the ceiling. As a prototype, two fibres of 100 m long, connected by an FC/PC adaptor, were pulled inside. The fibres are multimode step index fibres with 200 μm and were manufactured by Thorlabs. The adaptor insertion loss is around 1.5 dB. Both fibre ends were connected to the detector boxes with the SiPM photo-sensors. The boxes were located outside the duct where the radiation is less intense. To ensure the light-shielding, they were introduced within a black insulating bag. The optical fibres span a total of 180 m, from MBA.21590 to MBB.22090 magnets.



Figure 5.8: A plastic duct (highlighted inside the blue rectangle) was installed in the septum area to pull the oBLM. It is located at 2,36 m from the beamline approximately.

5.4.1 Cabling and Read-Out Description

An overview of the BA2 area where the oBLM system was installed is shown in Figure 5.9. As mentioned, the oBLM setup (the optical fibre and photosensors) was installed close to the beam line for the beam loss detection. The system read-outs and power supply were installed at the surface in the BA2 building area, protected from the underground radiation. From the surface to the tunnel racks, five cables, of approximately 250 m long for the downstream box and 198 m for the upstream box, were pulled down reaching each photo-detector. In specific, the cables are:

- The SiPM output data were transmitted to the surface by two CK50 cables (N-Type). Another CK50 cable was added as spare.
- One CB50 cable for the bias voltage of the SiPM photo-sensor.
- One NG8 cable for the power supply to the operational amplifier.
- And one HVBNC cable for the high voltage supply in case a PMT photo-detector replaces the SiPM in future system configurations.



Figure 5.9: Overview of the BA2 floor plans and the different locations of the oBLM elements and cabling.

The cables are connected to the racks RX22095 (downstream) and RX21550 (upstream), which house the electronic components of the system. The cabling layout of the system electrical connections is presented in Figure 5.10.

The 42 V for the photo-sensor bias voltage and the ± 12 V for the amplifier power supply were provided by twisted pair cables with eight conductors. The power supply and read-out systems were installed on the surface (BA2 area), protected from the underground radiation. The SiPM output data were transmitted to the surface by two CK-50 High Frequency (HF) cables (N-Type). A LeCroy Wave Runner 104 MXi-A oscilloscope was used for the prototype system read-out, with a bandwidth of 200 MHz. The time baseline in the horizontal axis and the signal amplitude in the vertical axis were set up to demand, depending on the requirements of the system. The last measurements of the losses were adjusted to 500 ns/div and 200 mV/div, respectively. The trigger was set up to channel 2 (downstream photo-sensor) in Normal mode with a voltage threshold of -186 mV. The scope can be configured to be used remotely through the local network connection.

Cabling configuration SPS

23th June 2021

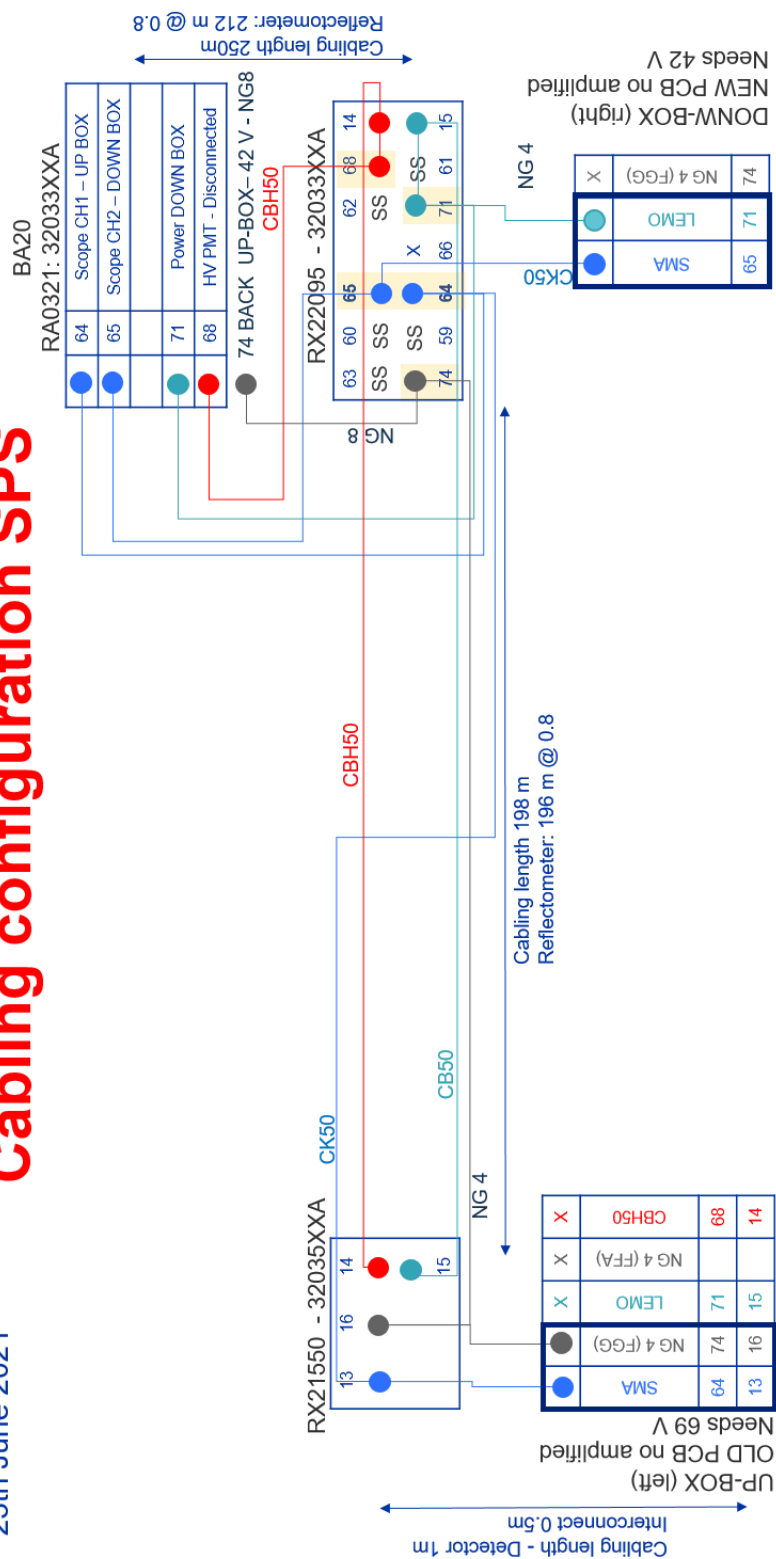


Figure 5.10: Cabling configuration for the oBLM system in LSS2. [116]

5.4.2 LSS2 Installation Difficulties

In addition to providing particle beams for the LHC, the SPS accelerator also provides particle beams to other experimental areas. Due to the tight operation schedule of the NA experiments, the LHC beam injection, and the high radio-activation of the area, access into the LSS2 tunnel was very restricted. Developing a prototype system has inherent access complications because every maintenance issue must be assessed beforehand and planned and implemented in a very short and controlled time frame. Several interventions in LSS2 were required during the oBLM setup throughout the project:

- **Fibre replacement.** After the first system installation, one of the 100 m fibres had to be replaced following the first SPS beam operation since Long Shutdown 2 (LS2).
- **Boards replacement.** Due to defective components, the photo-sensor boards overheated, and the operational amplifiers distorted the output signals. The circuitry was optimised and the new amplifiers were implemented. Figure 5.11 shows the first results obtained from the oBLM downstream SiPM installed in LSS2, before the failure.

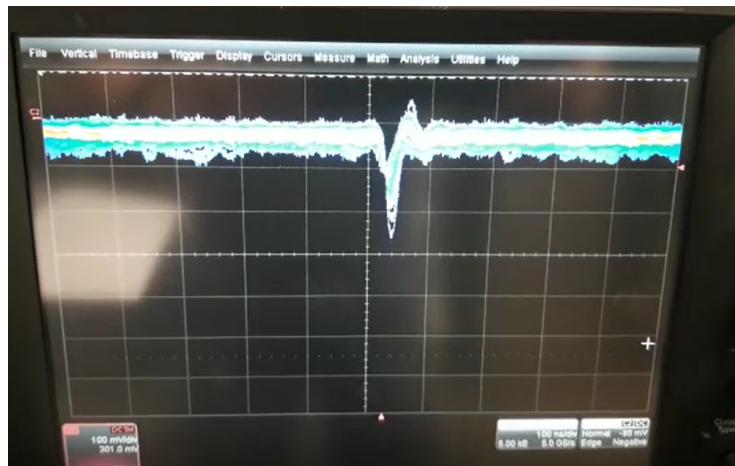


Figure 5.11: *First Cherenkov oBLM signal from LSS2 beam losses (Downstream).*
Photo taken on July 13th, 2021.

- **Cabling replacement.** One of the 4-pin LEMO cables was replaced because of a short circuit. The upstream read-out is unavailable until the next access authorisation.

5.4.3 LSS2 Loss Detection

A final prototype of the oBLM system was installed in the LSS2 area. It consisted of two optical fibres connected to each other, both operative, and connected to a SiPM 3015 photosensor. The PCBs implemented were based on the final design (see Section 3.3.5) with operational amplifiers. Slow extraction operations were resumed for SPS in July 2022. Several peaks of losses were observable in the scope, marking different sources of losses coming from the slow extraction. Improvements in the read-out and data acquisition system are being investigated. The trigger for the signals must be connected to an external signal for a complete overview of the beam losses chronology. A picoscope and Roxy box devices are among the options being considered for data acquisition systems. Figure 5.12, it is possible to observe the downstream photo-sensor signal from the loss detection.

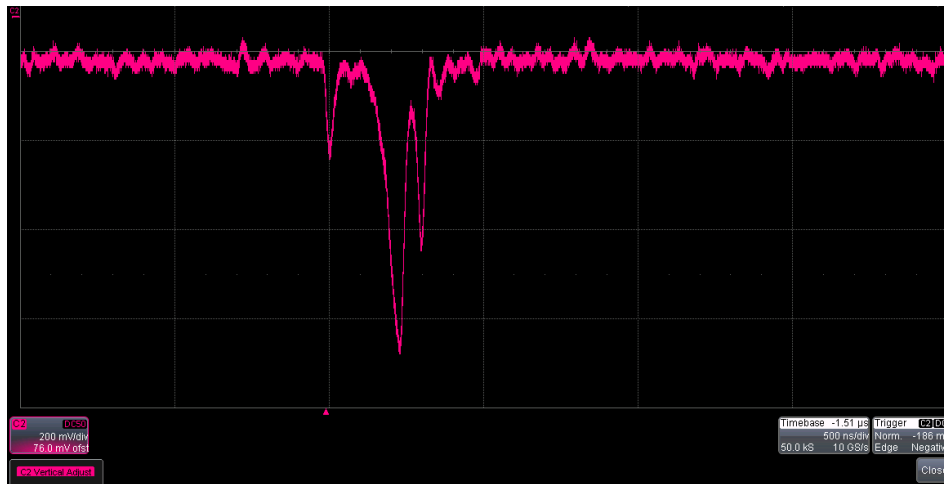


Figure 5.12: Cherenkov oBLM signal from LSS2 beam losses (Downstream) after the electronics optimisation. Photo taken on July 14th, 2022.

5.5 Summary

In this chapter, the installation of the Cherenkov oBLM prototype in the SPS, the specific cabling infrastructure and the read-out electronics are presented. The oBLM was located on the ceiling of the SPS slow extraction area, safe from the high radiation levels and protected from other external interventions in the line. Cabling for the bias voltages for the photo-sensors, the operational amplifiers and the read-out connections were provided, from the surface facilities to underground. Several defects in some of the oBLM elements or deficiencies in the signal quality have enforced interventions to maintain and optimise the equipment. In addition, the expected number of Cherenkov photons reaching each photo-sensor was evaluated with dedicated simulations of the slow extraction area. The simulations consist of the particle interactions provided by FLUKA, with the implementation of the specific user routine, and the post-processing of the output data with the Cherenkov Light Generation model described in this thesis. The model investigates the Cherenkov light emission produced by the LSS2 losses in the optical fibre, part of the oBLM detector system. The quantification of the photons obtained per SPS turn and the empirical signals collected by the scope after the last intervention in the system optimisation reveal that the Cherenkov oBLM is a suitable device for loss detection.

Cherenkov oBLM in CLEAR Facility

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6.1 CLEAR Facility

The CERN Linear Electron Accelerator for Research (CLEAR) [117] is a facility independent of the LHC chain of accelerators, dedicated to general R&D. Its feasibility and support in a large variety of experiments within and outside CERN have triggered great interest among the accelerator user community [118]. Some collaborations include beam instrumentation development and training capabilities, X-rays FELs, medical irradiation therapy, and more [119, 120].

The beamline comprises around 20 m of an electron Linear Accelerator (LINAC), followed by another 20 m of experimental machine components (see Figure 6.1). The typical beam energy range varies from 60 MeV to 220 MeV, with a maximum beam charge of around 30 nC approximately [121]. The CLEAR accelerator can provide broad types of the electron beam, optimising its parameters depending on the experiment requirements [122]. The accelerator line ends with a 1 m long In-Air stand before the dump, where the beam is led in the air without vacuum conditions. This zone allows easy and fast installation of test benches, with access flexibility to the accelerator due to the reduced radiation levels.

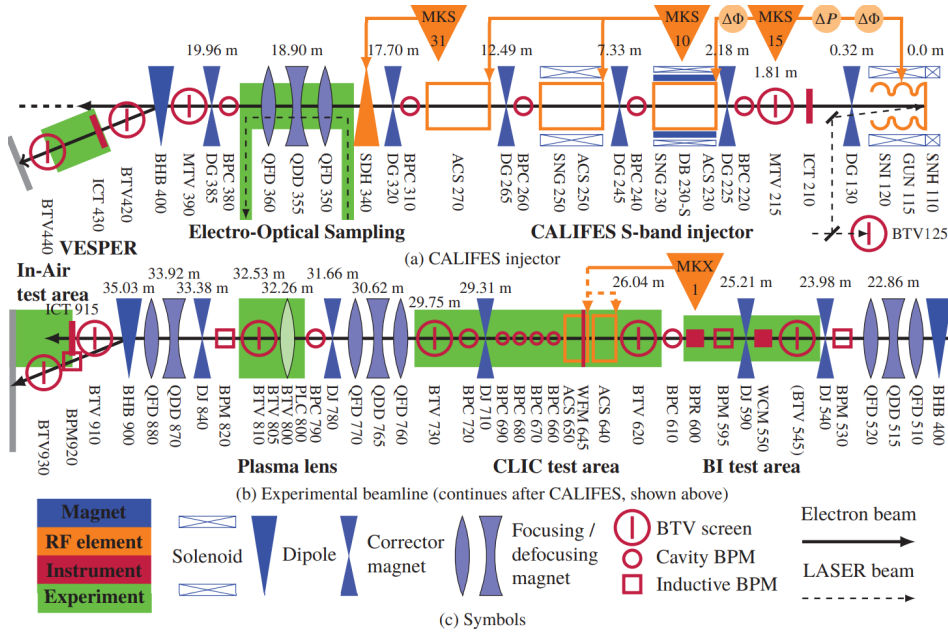


Figure 6.1: *CLEAR* beamline overview. [123]

Figure 6.2 shows the different beam characteristics that can be set up during the operations.

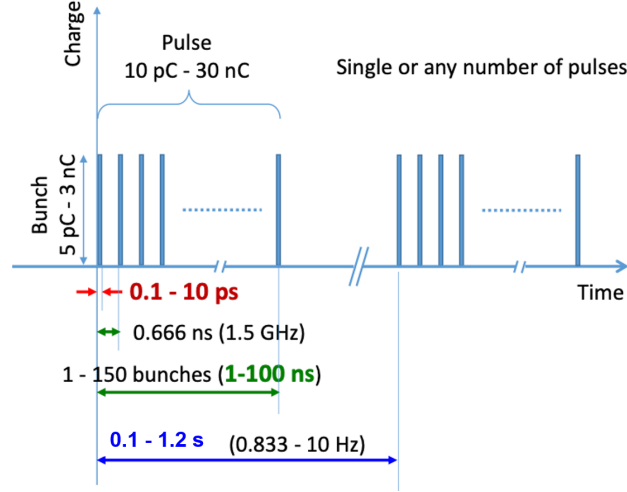


Figure 6.2: *CLEAR beam profile. Courtesy of Antonio Gilardi.*

6.2 Experiments in CLEAR Facility

In line with the Cherenkov oBLM project, several experimental campaigns were performed in order to understand, develop and optimise the optical BLM system, as well as benchmark the Cherenkov light simulations results. During the tests, the observation of the Cherenkov effect was performed.

The first Cherenkov oBLM campaign was essential for understanding the Cherenkov light capture, the signal intensity dependency on the fibre and photo-detector characteristics and the parameters of the CLEAR electron beam. The motivation of these tests were to study the light yield dependency on the diameter of the fibre and on the impact angle, which would confirm the Cherenkov capture angles equations. In addition, the sensitivity of the photo-sensors, their signals generated from a single bunch and train of bunches, their linearity and saturation levels and the rise/decay times were also investigated.

During the second tests, the beam loss detection dependency on the distance between oBLM system and beam line was analysed. These experiments also helped

on the study of the characteristics of the different components of the oBLM system, such as the length and core size of the fibres, the model of the photo-detector or the design of the read-out electronics.

Last but not least, during the last experiments in CLEAR accelerator, a Cherenkov oBLM prototype for the loss mapping was implemented [124]. The main goal of the tests was to localise the sources of losses provoked intentionally in a controlled area. Depending on the accuracy of the results, the resolution of the system can be estimated.

6.3 Campaign 1: Cherenkov Optical Fibre Experiments

Three types of fibre cores were used in this experiment: 50, 105, and 200 μm , each mounted one by one on a motorised rotating table, with the fibre halfway points exposed directly to the linear electron beam in the CLEAR In-Air area (see Figure 6.3). The fibre length selected was 2 m to minimise the effect of the attenuation in the signal.

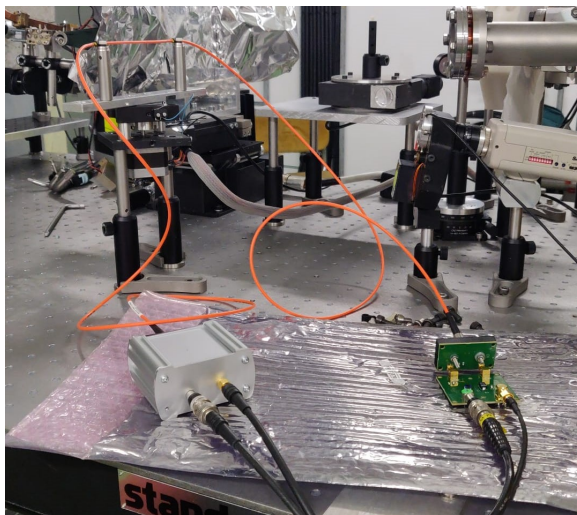


Figure 6.3: *First Cherenkov oBLM experimental setup. Different fibres were installed on a rotating table and aligned with the beam path to be impacted.*

First results of the angular and intensity scans were published in a conference contribution to IPAC21 [125]. In this Chapter, results after optimisations in the

read-out electronics and improvements in the data acquisition methods are presented.

6.3.1 Read-Out System

Each fibre end was equipped with a SiPM photo-detector connected to its printed circuit board (PCB). As the beam directly impacted the fibre, the signal was intentionally not amplified. To power the SiPMs and read the signals, PCBs were connected to the operating voltage and the oscilloscope. The fibre coupling to the photo-sensor was made using an FC-PC connector. A plastic spacer no thicker than 7 mm was used to collect the light on the 3×3 mm surface of the SiPMs from the fibre connector aperture. Different SiPMs were evaluated during the tests. Their characteristics can be found in Table 6.1.

Code	Pixels	Operating Voltage
S12572-010C	90000	69.5 V
S12572-025C	14400	68.5 V
S14160-3010	90000	43.0 V
S14160-3015	40000	42.0 V

Table 6.1: *Hamamatsu SiPMs used in CLEAR experiments.*

Also, an aluminium box was tested for light coverage and PCB protection during the tests. Figure 6.4 shows the two PCBs used during the CLEAR experiments, one of them mounted on the enclosure.

It is worth underlining that the PCB design found in Figure 6.4 is an intermediate read-out version. At first, an old PCB design based on the literature and photo-detectors type S12572 were used. Due to the low signal quality given by the boards, a new circuitry was performed by reducing the number of connectors and cables and modifying internal components. The operating voltage was stabilised by improving the box isolation and filtering noise. Photo-detectors type S14160 were installed in the read-out upgrade. This intermediate read-out was optimised again and validated during the last experiments in CLEAR facility. The schematics of the final read-out

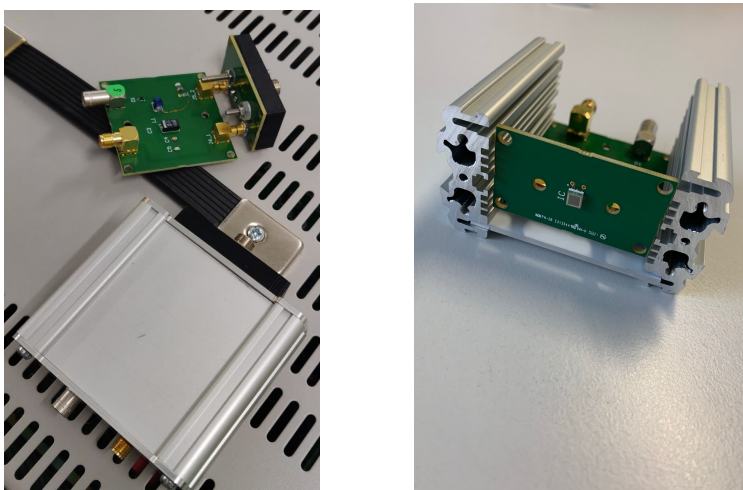


Figure 6.4: *Cherenkov oBLM PCBs tested in CLEAR.*

design can be found in Chapter 3 of this thesis.

6.3.2 Signal Linearity

Photo-sensor linearity and saturation curves were examined. Fibres remained at a fixed angle while increasing the beam intensity during the impacts. The angles selected were $\pm 40.5^\circ$, $\pm 47^\circ$, $\pm 49.5^\circ$, around the Cherenkov maximum angle for the silica medium. A single bunched beam and a train of 30 bunches, with increasing charges from 10 pC to 300 pC in steps of 25 pC approximately, were triggered to ascertain the relation between the charge and the number of photons detected. Figure 6.5 shows the fibre shot by the beam at different intensities from an IR camera installed at the beamline. The beam size is larger than the fibres, as can be verified. The outer jackets of 3 mm are the same regardless of the diameter of the fibre core. The camera shows how the fibre, horizontally centred on the screen, is impacted.

In Figure 6.6, the integral of the measured signals as a function of the total intensity of the impacting beam is recorded. The intensity scan results for the three fibres, 200, 105 and 50 μm , are distributed in the upper, middle and bottom plots, respectively. The left column reports the photo-sensor signals located in the downstream position at the moment of impact. On the other hand, the right column

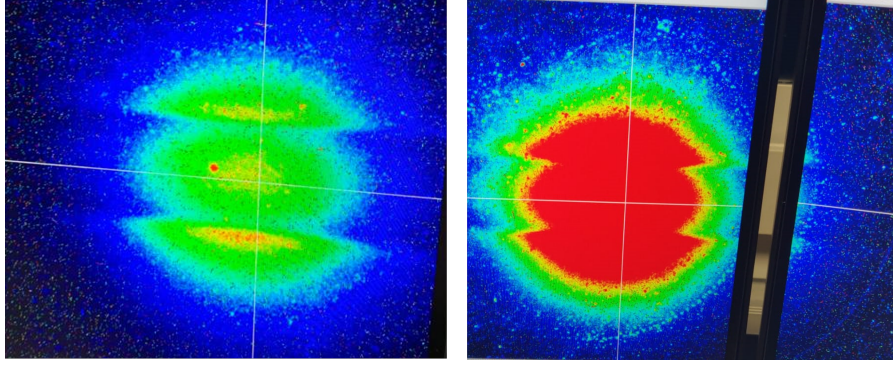


Figure 6.5: *Fibres were impacted at a fixed angle by different beam intensities. Left: Low intensity beam (≈ 30 pC). Right: High intensity beam (≈ 3 nC).*

of plots presents signal reflections registered by the opposite photo-sensors, i.e. in the upstream direction, at the moment of impact. The signal reflection occurs when part of the light cannot exit one end of the fibre and is reflected at the opposite end. As the beam impacted directly on the fibre, the photo-sensors reached the saturation level relatively fast. Looking into the data, the saturation starts around 15 pC in the three fibres, and the SiPM 3015 saturates faster than the model 3010 due to the lower number of pixels. As expected, the signal is higher with larger core fibres.

Response function of a SiPM

The number of fired pixels in a SiPM, N_{fired} , can be proportional to the electrical output amplitude R . According to the Equation 3.22, R can be fitted by a curve defined by:

$$R = a * (1 - \exp^{-(b*x)}) + c \quad (6.1)$$

where a, b and c are function coefficients and x corresponds to the number of photons arriving the photo-sensor N_{ph} . However, the quenching resistance of the SiPM may generate heat when the number of incident photons is elevated. It would produce fluctuations in the gain and the PDE coefficient [126]. As a consequence, a new fitting function was proposed. This function was defined by:

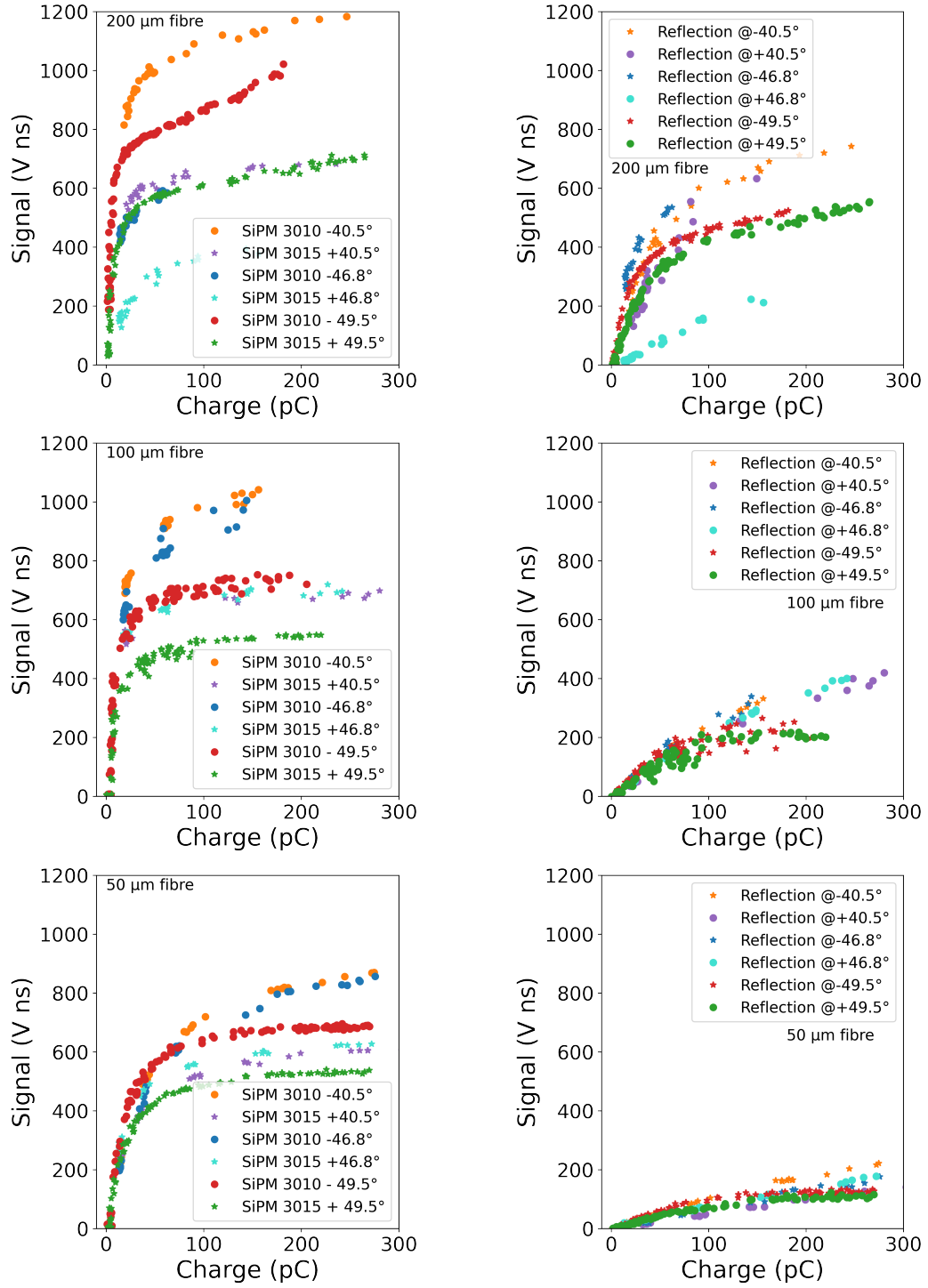


Figure 6.6: Results of the intensity scans for the different fibres (Upper: 200 µm, middle: 105 µm, bottom: 50 µm). Left column: Downstream photo-sensors, right column: Upstream photo-sensors.

$$R = a * x * (1 - \exp^{-(\frac{b}{x})}) + c \quad (6.2)$$

Figures 6.7 and 6.8 illustrate the fitting reconstruction of the saturation curves for the three fibres at a fixed angle of $49,5^\circ$ for impacts with a single bunched beam. Curves are obtained by integrating the downstream signal of the photo-sensors SiPM 3010PS and SiPM 3015PS.

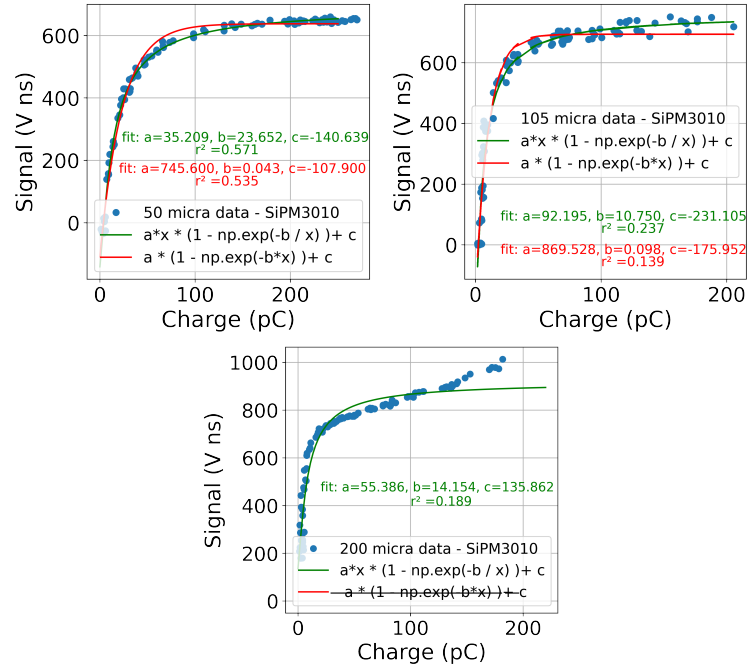


Figure 6.7: *Response function for the SiPM3010 during the intensity scans.*

Curves for 105 and 50 μm core fibres are quite adjusted to the new fitting function 6.2. However, the 200 μm fibre presents a strong saturation, and the behaviour can not be fitted by the new response function either. In addition, the function defined in Equation 6.1 has no solution for the 200 μm data in SiPM3010.

6.3.3 Bunch Length Dependency

Figure 6.9 reveals a plateau produced between the rise and decay times in the signal generated from a train of bunches. The rise time refers to the signal time from the baseline to the maximum, and the decay time corresponds to the signal time from

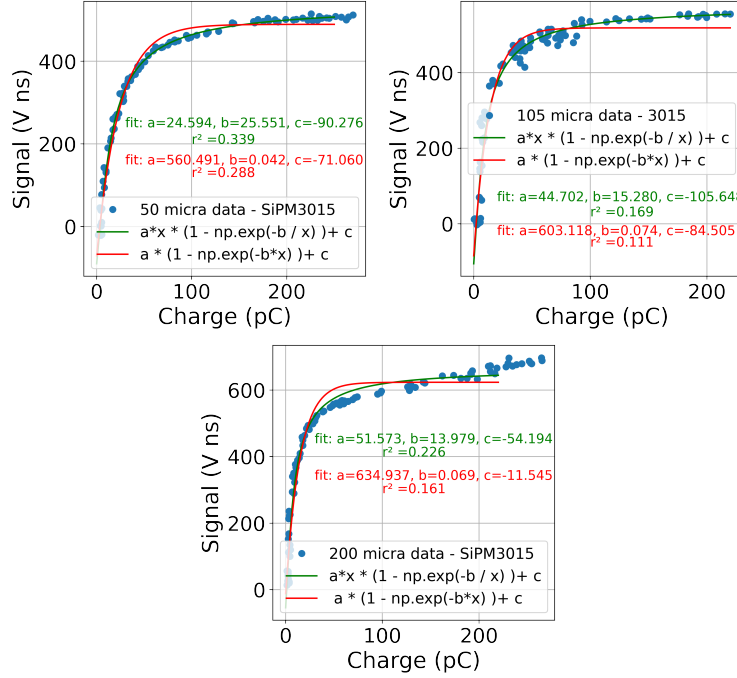


Figure 6.8: *Response function for the SiPM3015 during the intensity scans.*

the maximum back to the baseline. Both signals were obtained from the intensity scan where the 105 μm core fibre was set at the angle $47,7^\circ$ for beam impacts with charges of 30 pC for a single bunch and 110 pC for a train of bunches. As described in Figure 6.2, the average bunch duration is 10 ps, and the bunch spacing is around 0.666 ns. The beam exposure time for a train of 30 bunches is 19.98 ns. The time measurement of the signal plateau in the scope shows that the train of bunches can be detected and monitored.

6.3.4 Angular Capture Factor

The rotating table was configured to be activated remotely. The scan starting point, angle 0° , corresponds to the beam impacting perpendicularly to the fibre. Then, the anticlockwise and clockwise (negative and positive angles, respectively) movements of the table were set within the ranges $[-80^\circ, 80^\circ]$ approximately (see Figure 6.10).

With this setup, both photo-sensors receive the light in the downstream and upstream directions, depending on the angle. Generally, during the shots, the rotation

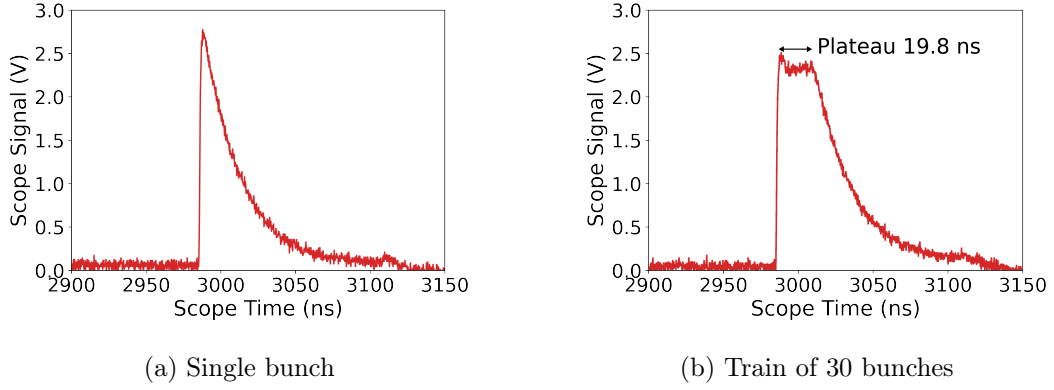


Figure 6.9: *Raw signals for a single bunch (left) and a train of 30 bunches (right) [125].*

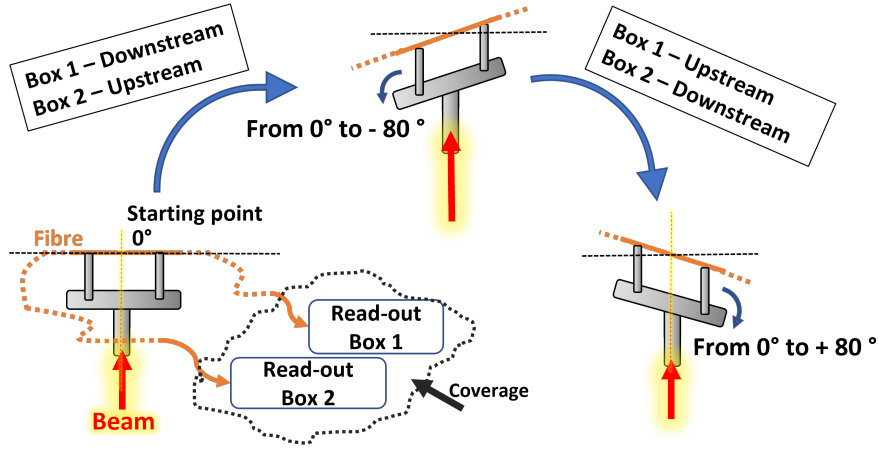


Figure 6.10: *Capture factor scans in CLEAR. The fibre was set in perpendicular to the beam (0°) and rotated until the angles $\pm 80^\circ$. At $\pm 90^\circ$ positions, the fibre would be parallel to the beam.*

step was around $3^\circ - 5^\circ$. The beam was configured to an intensity of 20-40/pC in a single bunch, with a size $1.1 \times 2 \text{ mm}^2$. Since fibre cross-sections of the 200, 105 and 50 μm diameters cover around 1.5%, 0.4% and 0.09% of the beam size, most of the beam was lost. However, these areas were sufficient to generate a measurable signal. Additionally, normalisation by charges was required to suppress the effect of beam charge fluctuations. Figure 6.11 presents the capture results obtained for the three fibres in CLEAR experiments. Results are shown together with the range

of capture angles computed by the simulations (see Section 4.5.1). Blue and orange dots, for upstream and downstream ends respectively, show the simulation results (right axes) in the three cases. Experimental data points, red for upstream and green for downstream, are the average of the integrated signals obtained from 10 beam pulses and normalising to a bunch charge of 25 pC. As expected, capture angle ranges obtained from the experimental scans are in good agreement with the angles of capture of the simulation results. However, in fibres with diameters 200 μm and 105 μm certain saturation of the photo-sensors is visible. This saturation starts over the 500 - 600 V ns approximately depending on the angle of incidence and the SiPM model. It was also observable in Figure 6.6. The three plots also present a discernible increase in the signal around the angles $\pm 80^\circ$ produced by the scattering of the beam when it impacts the fibre nearby the fibre holders. In addition to the expected curves, each photo-sensor presents a small secondary peak attributed to light reflections. The light reflections were already observed in the linearity signal study. As mentioned in Section 3.2, light can get trapped by interacting with the air medium at the exit of the fibre. This light can be reflected towards the opposite end. This reflection is considered Cherenkov light since it appears within the range of capture angles and varies with the intensity, even with the possibility of inducing saturation in the SiPMs.

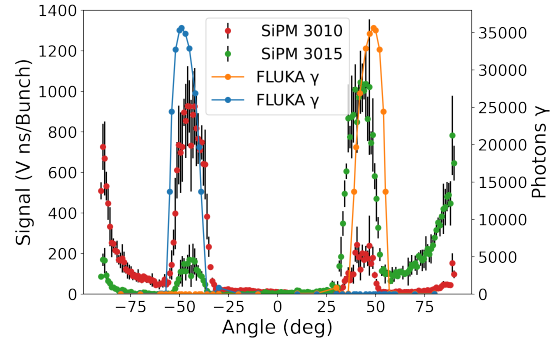
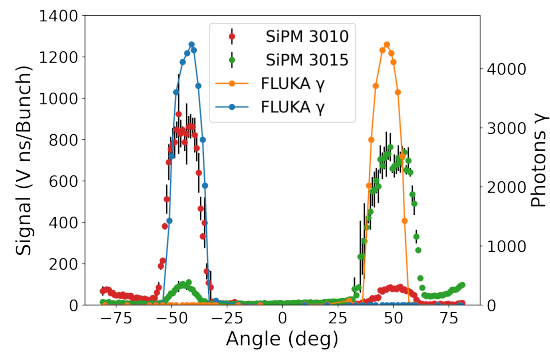
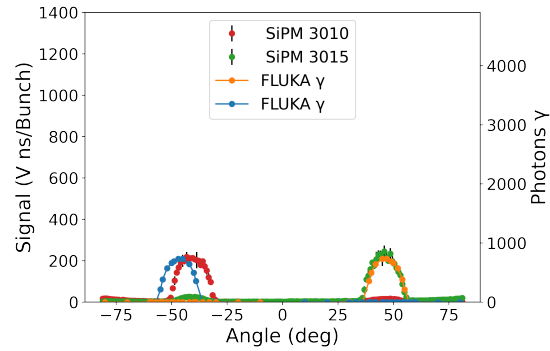
(a) 200 μm fibre(b) 105 μm fibre(c) 50 μm fibre

Figure 6.11: Results of capture angles obtained in *CLEAR* tests (red: upstream, green: downstream) compared with *FLUKA* simulations (blue: upstream, orange: downstream). Black lines indicate the measurement uncertainty. (Note the different scales).

6.4 Campaign 2: oBLM System Detection Experiments

During the second campaign of experiments in CLEAR, a 105 μm of core fibre was installed in a linear moving platform parallel to the beam path (see Figure 6.12, left), located in the In-Air area. The fibre length selected was 5 m to avoid the attenuation factor effect and to ensure the protection of the electronics from external radiation.

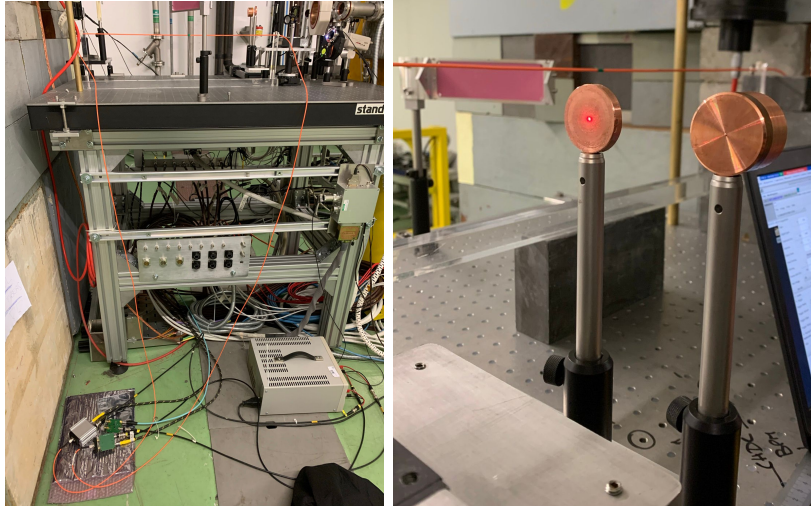


Figure 6.12: *Left: Cherenkov oBLM test-bench during the second campaign of experiments in CLEAR. Right: Two copper targets for the shower of losses production. Thickness: 0.5 and 2.0 cm, diameter: 3.0 cm.*

Two copper targets were installed in another moving platform (see Figure 6.12, right) to be impacted by the beam and produce two different loss showers. Target sizes were 0.5 and 2.0 cm of thickness and 3.0 cm of diameter. The point of impact on the targets was also investigated. Figure 6.13 presents the typical signals obtained from the loss detection of showers produced by beam impacts on the target edge (left) and centre (right). When the target is impacted on the edge, the peak amplitude is approximately three times larger than the peak generated by the impact on the target centre. However, beam fluctuations would affect the impact position. Hence, impact on the target centre was selected. Targets were impacted by a single bunched electron beam at 220 MeV, with an intensity charge of ≈ 330 pC.

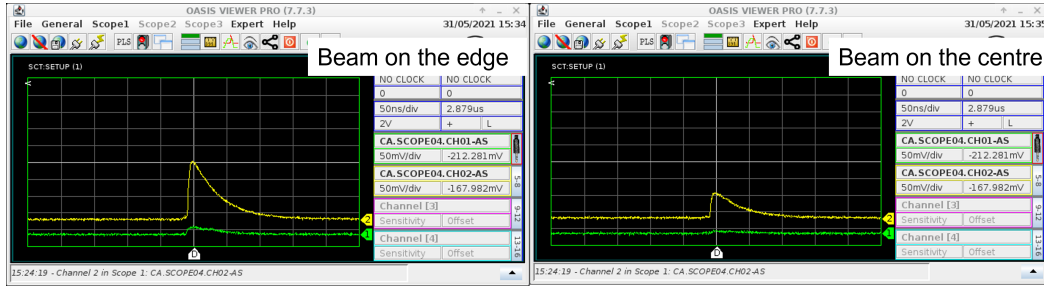
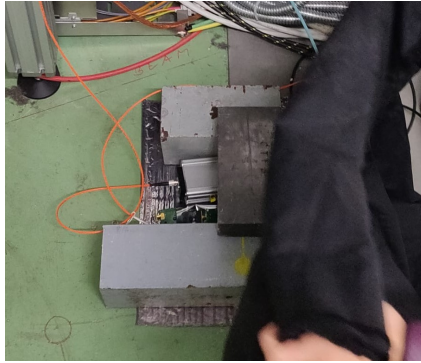


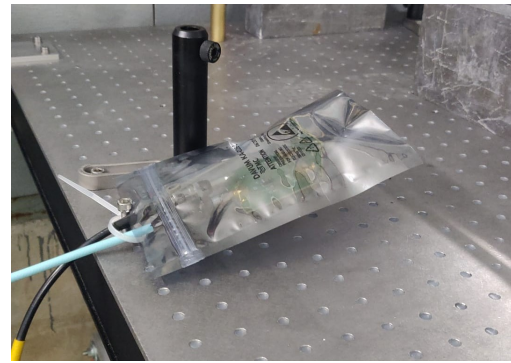
Figure 6.13: Cherenkov oBLM signals obtained from beam impacts on the edge (left) and the centre (right) of the targets.

6.4.1 Read-Out System

In order to detect beam loss at different distances, two new amplified boards were designed for the second campaign. The same metallic enclosure as the first campaign (see Section 6.3.1) was used to protect the electronics. In addition, as the beam impacted the targets to generate the shower of losses, the PCBs were installed on the floor and protected with lead bricks. Figure 6.14-a shows the setup of the oBLM electronics for the loss detection experiments. As shown in Figure 6.14-b, an extra box was located on the main table to measure the background losses.



(a)



(b)

Figure 6.14: Loss detection tests read-out. a) The oBLM PCBs were installed on the floor in CLEAR facility and protected by lead bricks from the shower of losses. b) Extra PCB box to measure the background losses.

The printed board used in this second campaign of tests is presented in Fig-

ure 6.15. This PCB corresponds to the intermediate read-out version with an operational amplifier.

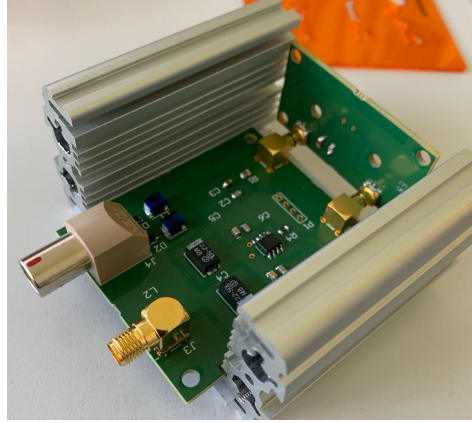


Figure 6.15: *PCB with operational amplified used during the tests.*

6.4.2 Distance Dependency

The central 0.8 m fibre length was centred on the platform and exposed to the radiation created by the impacts. Moving platforms allowed the remote swapping of the targets and the change of the fibre location during the scans. The starting distance between target and fibre was 22 cm, reaching a maximum of 55 cm in steps of 3 cm. Figure 6.16 shows the loss detection test setup.

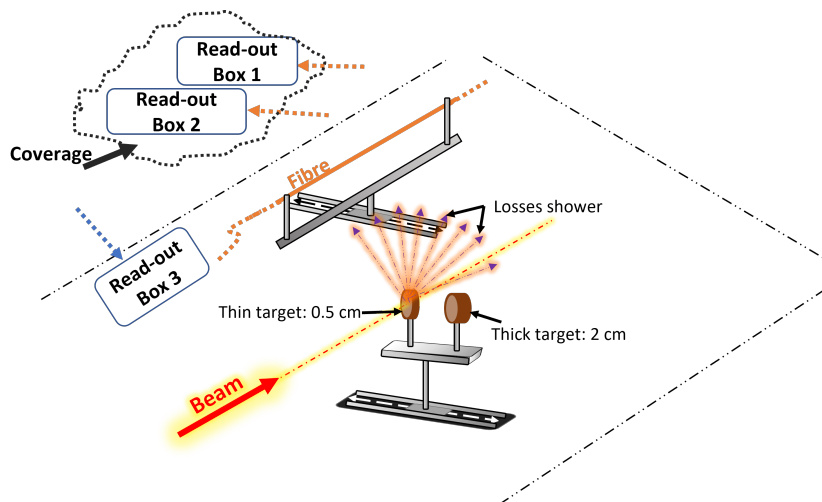


Figure 6.16: *Loss detection scans in CLEAR.*

Figure 6.17 shows the results obtained for the distance dependency scans.

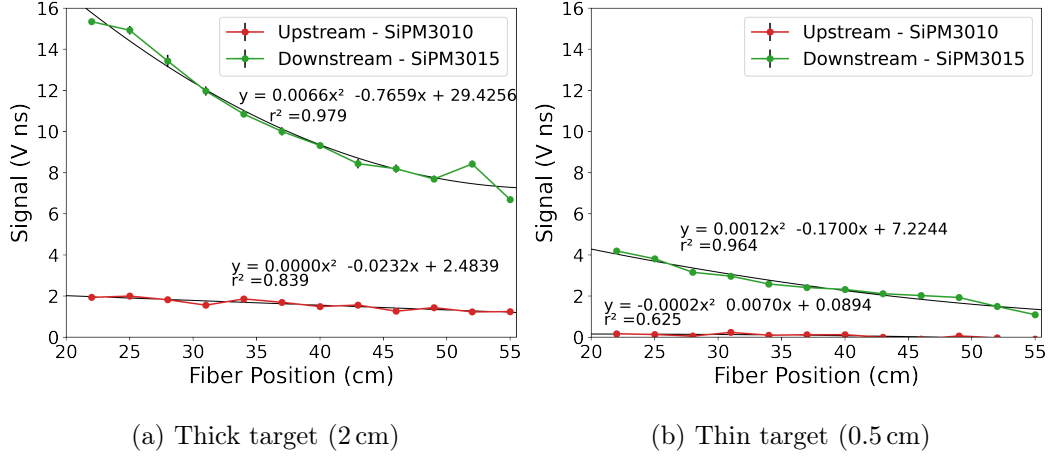


Figure 6.17: *Distance scans results.*

As expected, the oBLM detection signal was more significant in the showers produced by the thick target. On the one hand, downstream signals variation are non-linear with the increasing distance between fibre and loss source. On the other hand, upstream signals show a more linear dependency with the distance due to their low signal amplitude. Furthermore, the experimental scenario was computed in FLUKA with real parameters. Figure 6.18 reports the comparison between the results from the loss detection tests with the simulation results for the thick and thin targets.

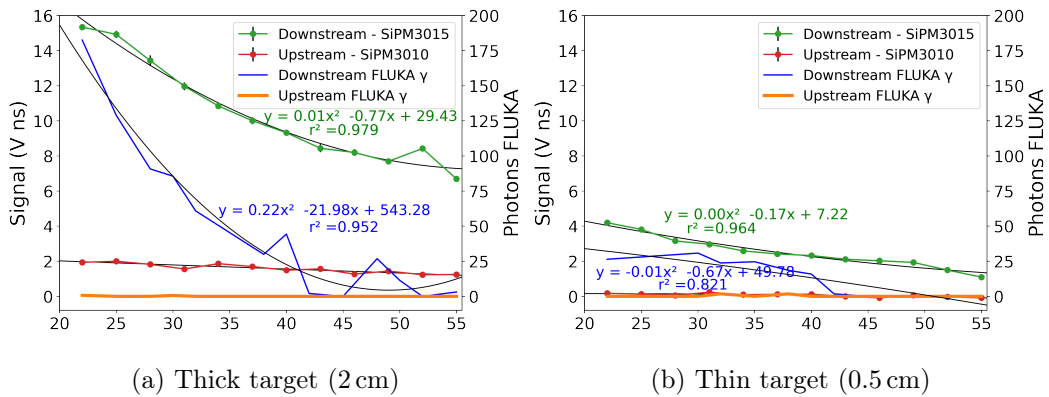


Figure 6.18: *Comparison between the loss detection tests and the simulation results.*

For the thick target case, both experimental and simulation downstream results

present a quadratic behaviour that decreases with the distance. In upstream measurements, the detection function is linear in both cases. For the thin target case, the oBLM operation can be fit to a linear function due to the lower charge exposition. Although the Cherenkov oBLM is not meant to measure absolute values of the light capture, it is possible to evaluate the FLUKA results by comparing the sensor signal with detectable photons according to the simulations. Figure 6.19 compares the experimental signal and the number of photons estimated by the simulations. Due to the low number of photons obtained in the upstream case, only the downstream signal was considered in the study. In addition, as observed in the graphs in Figure 6.18, noise predominates at a low signal, so the number of photons is unreliable. By discarding the orange values, a more accurate linear regression was achieved.

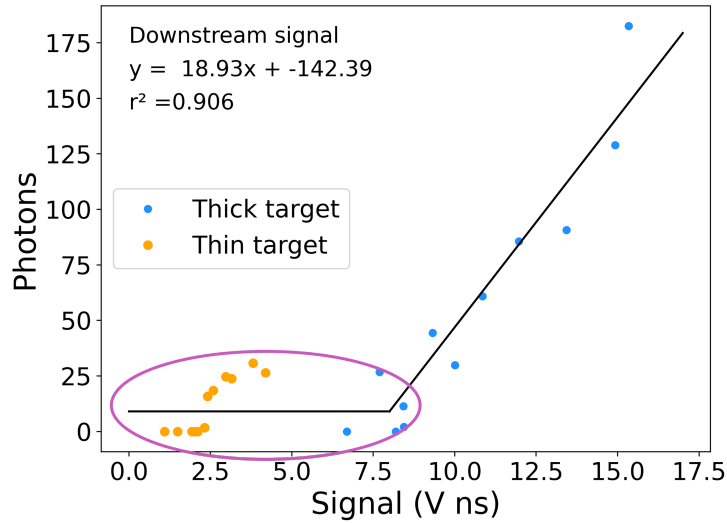


Figure 6.19: *Relation between the sensor signal from the experimental test and the number of photons given by FLUKA simulations. Points within the violet circle may be unreliable due to the background noise.*

Measurements for the intensity scan were performed to study the quality of the oBLM signal at a very low loss exposition. The fibre was located at the maximum platform distance, i.e. 55 cm from the targets. Both targets were impacted by decreasing beam charge from 420 pC to 15 pC. Results of the detection intensity

scans are reported in Figure 6.20.

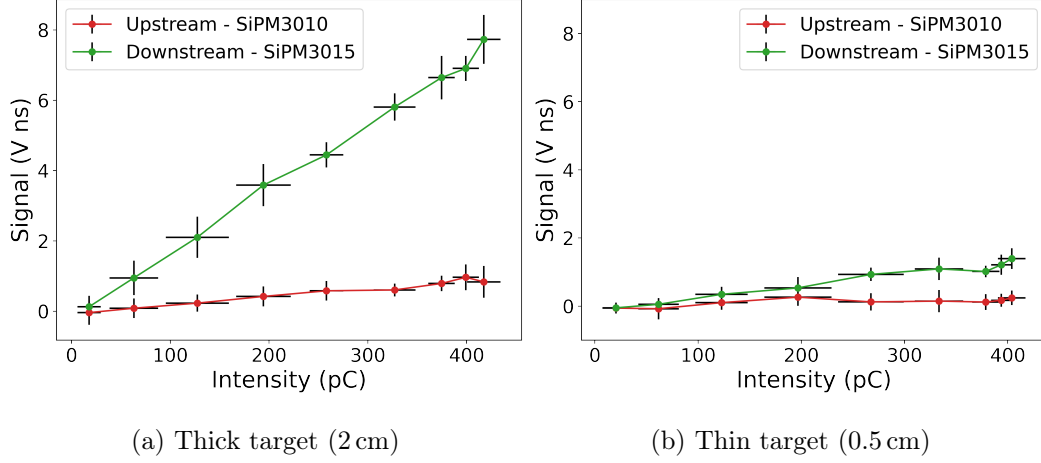


Figure 6.20: *Detection intensity scans.*

As was foreseeable, the signal amplitude grows linearly with the charge intensity.

6.5 Campaign 3: CLEAR Longitudinal Losses

The second half of the CLEAR line, 22 m approximately, was equipped with a 100 m long optical fibre of 200-220 μm core-cladding diameters, respectively. The multi-mode silica fibre was installed alongside the beamline, while the two extremities were passed through the ceiling via two holes. Thus, the read-out electronics, the oscilloscope and power supplies were situated in the gallery above the accelerator hall, protected against ambient radiation. Two different setups were proposed to examine the capability of the Cherenkov oBLM: identification of losses with the optical fibre installed on the ceiling at 1.1 m of distance from the CLEAR beamline and with the fibre installed at the closest position on the beamline (around 10 cm on average distance). In the first case, similarities with the LSS2 scenario are attempted. The second case is used as a reference to examine the system resolution. Figure 6.21 shows the two different setups for the loss localisation tests.

The loss showers were created alongside the beamline by inserting the Beam TeleVision (BTV), so-called *screens*, or by *kicking* the beam with steering magnets. Screens inserted during the tests are noted as BTV390, BTV620, BTV730 and

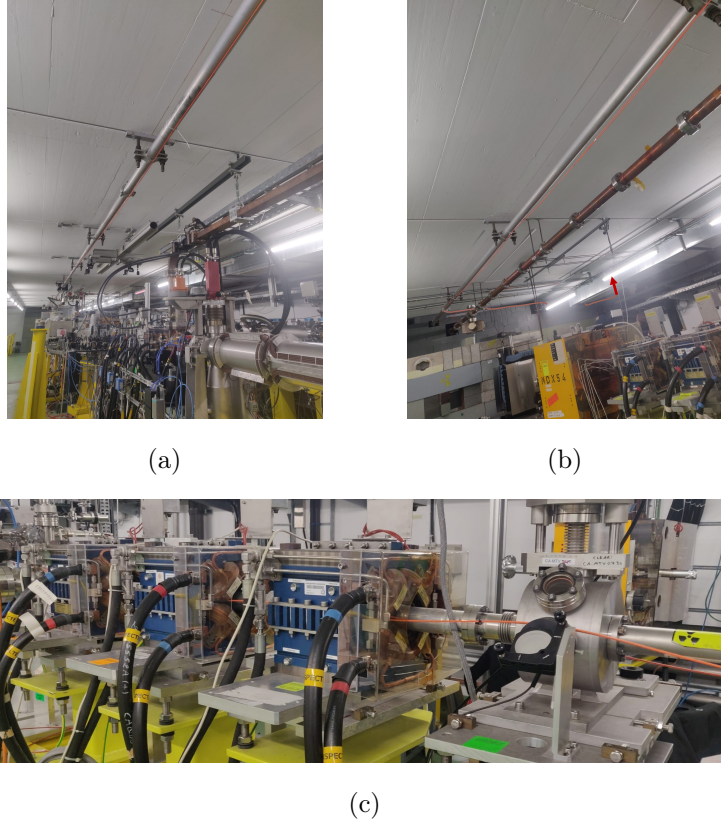


Figure 6.21: *a) Fibre at 1.1 m from the beamline. b) Downstream fibre extremity passing through the hole in the ceiling next to the corner of the hall. The hole entrance is noted by a red arrow. c) Fibre at 10 cm from the beamline. Fibres are the orange line attached to the ceiling metallic tube and beamline.*

BTV810. A screen is a movable module that measures the shape and size for the beam characterisation when inserted into the beam path [127]. Figure 6.22 shows the BTV730 as an example of a screen. *Kicker* magnets noted as K320, K540, K590, K710 and K780 were used to displace the beam in horizontal and vertical planes. Figure 6.23 shows a schematic of the screens and steering magnets distribution along the CLEAR accelerator. It is worth mentioning that there was another screen in the line, named BTV910, close to the In-Air stand. The results of this screen are not reported since the beam losses were not detected by the fibre due to the dumping wall location.

At first, the initial setup proposal consisted of installing a 100 m fibre parallel

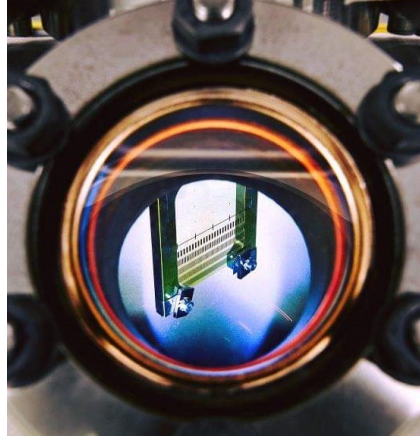


Figure 6.22: Screen BTV730 installed in the CLEAR accelerator line.

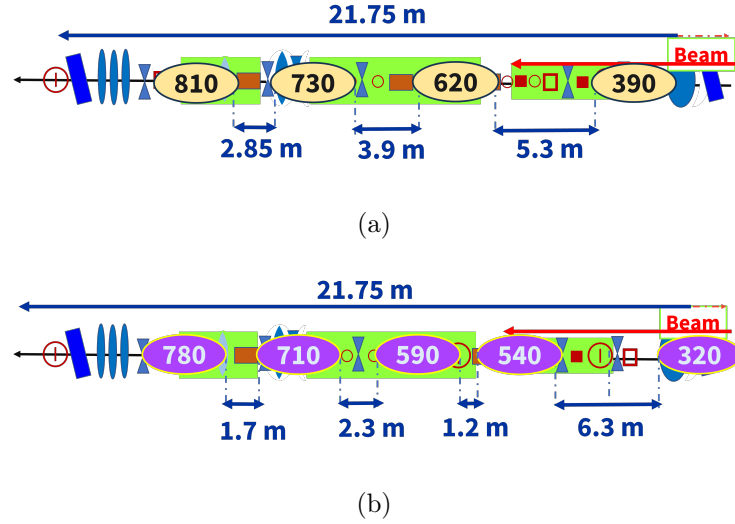


Figure 6.23: The Cherenkov oBLM was installed parallel to the second half of the CLEAR beamline (≈ 22 m). a) Screen distribution along the CLEAR beamline. b) Steering magnets distribution along the CLEAR beamline [124].

to the CLEAR beamline. During the setup handling, an unexpected fibre breakage gave rise to a new configuration in the experiments. Instead of using a 100 m long fibre, the CLEAR line was equipped with two fibres of 63 m and 37 m long approximately (see Figure 6.24). Each fibre comprised an FC/PC connector attached to the electronics and a "free" end. Therefore, upstream read-out is connected to one fibre (37 m) and downstream read-out to another fibre (63 m).

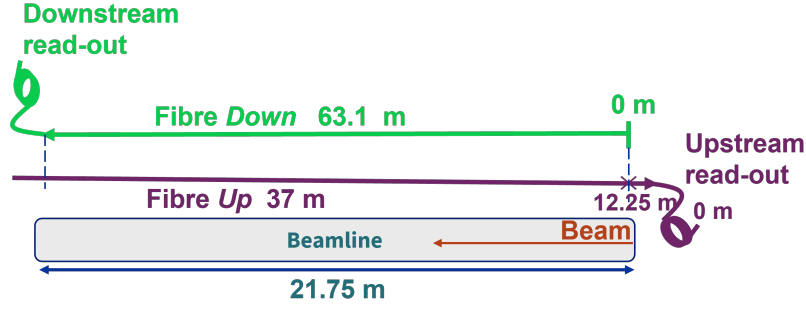


Figure 6.24: *Diagram of the test setup modification. The installation of two optical fibres with separate read-outs, instead of one 100/m long fibre, was performed.*

Once the Cherenkov oBLM was installed, screens were remotely inserted into the beam trajectory separately. The insertion of several screens during the scans was discarded to reduce the beam instabilities and preserve the same intensity conditions in each shower. After the measurements were performed, signals generated from each insertion were compared jointly. By obtaining the arrival time of the Cherenkov photons to the photo-sensors, the position of the losses can be estimated. It has been demonstrated that signals acquired from the same screen have an equal starting point, independently of the number of beam bunches (see Figure 6.25). Therefore, the arrival time was set on the dropping/rising starting edge (depending on whether the signal was amplified). As expected, signals generated by larger trains of bunches show larger amplitudes. Maximum points appear in different times due to the beam train structure.

6.5.1 Read-Out System

Both fibre ends were brought to the gallery above the CLEAR accelerator hall via two holes in the ceiling. Under these conditions, PCB electronics, power supplies and oscilloscopes were protected from the radiation with easy access to be handled.

The loss locations scans can be distributed in three parts regarding the read-out configurations: system with amplifier with fibre location at 1 m, amplified system with fibre location at 10 cm and system without amplifier with fibre at 10 cm location. During the first part of the tests, the fibre was installed on the CLEAR facility

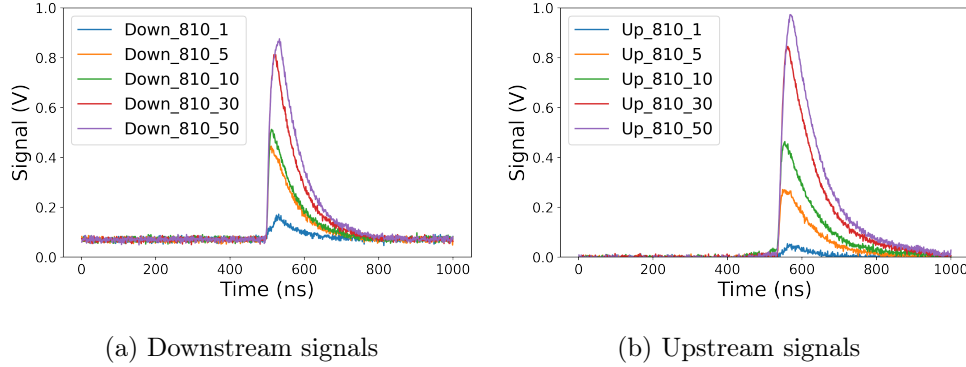


Figure 6.25: *Example of the Cherenkov oBLM signals obtained by the losses generated by the screen BTV810 with beams consisted of 1, 5, 10, 30 and 50 bunches. The non-amplified signals start at the same moment, independently of the number of bunches.*

ceiling, and the intermediate read-out version was implemented (see Section 6.4.1). During the test operation, one of the read-out boxes overheated, and the circuit was severely degraded. Final versions of the PCBs with and without amplifiers were designed (see Chapter 3), and the improvements were not only evident in the functionality of the electronics system but also apparent in the quality of the signals and the noise reduction. A SiPM 3015PS photosensor type was used in the downstream and upstream read-outs of the third experimental campaign.

Figure 6.26 shows the read-out setup implemented in the third CLEAR campaign for the loss localisation experiments.

6.5.2 Calculation Methodologies

In order to estimate the position of the beam losses, two different approaches were considered. At first, the relative times between upstream signals were compared. Upstream signals were selected over downstream signals to have a better longitudinal resolution [128]. This method has been used in other accelerator facilities and reported in [77]. In the second technique, downstream and upstream signals from the same insertion were compared to find the common interaction time.

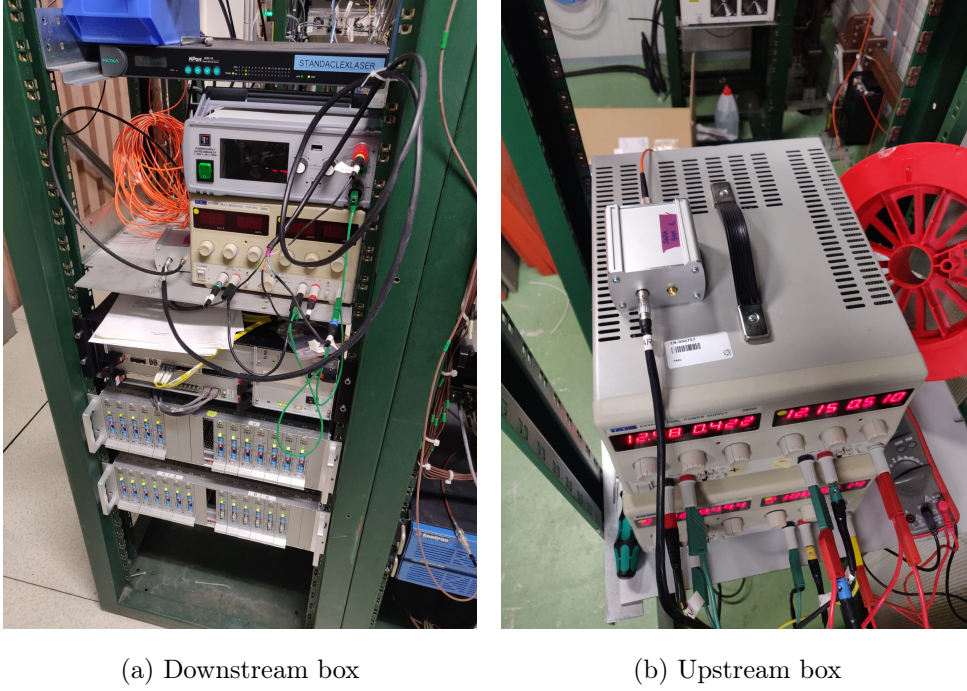


Figure 6.26: *Read-out setup during the CLEAR experiments of Loss Mapping. The photo-sensors were located on the floor above the accelerator hall. Fibre ends were passed through two holes and connected to the boxes via the FC/PC connectors.*

Method 1: Upstream Arrival Times Comparison

When the shower of particles interacts with the fibre, Cherenkov photons are emitted. These photons propagate to both ends with a velocity $v = c/n$ (see Chapter 3). With $n = 1.46$ as the refractive index of silica material and $c = 0.3$ m/ns as the speed of light in a vacuum, the velocity of the Cherenkov photons inside the optical fibre is $v = 0.2055$ m/ns.

Following the method already reported in the IPAC22 proceedings [124], the localisation of the beam losses can be estimated by comparing the upstream arrival times Δt_{up} of the Cherenkov photons generated at two different points along the line. Figure 6.27 can be used as reference for the arrival time calculations.

Two particles, A and B, from separate loss showers, reach the optical fibre with a time difference equal to $t_{\text{BA}} = (x_{\text{B}} - x_{\text{A}})/c$, considering A as the first particle that reaches the optical fibre at time $t = 0$. Particles interact with the silica and

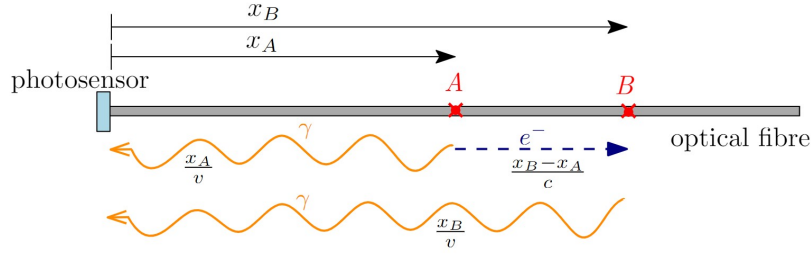


Figure 6.27: Collection of two Cherenkov photons emitted from two different particles at locations A and B in an optical fibre by the upstream photo-sensor. [77].

produce the Cherenkov photons. Then, arrival times from the points A and B to the photo-sensor are $t_A = x_A/v$ and $t_B = x_B/v$, respectively. The arrival time difference Δt between the photons A and B for the upstream sensor is:

$$\Delta t = t_{BA} + t_B - t_A = \frac{x_B - x_A}{c} + \frac{x_B}{v} - \frac{x_A}{v} \quad (6.3)$$

The upstream arrival time difference is given by:

$$\Delta t_{\text{up}} = \frac{\Delta x}{c} \cdot (1 + n) \quad (6.4)$$

Accordingly, the arrival time difference between the two photons for the downstream sensor is calculated by:

$$\Delta t = t_{BA} + t_A - t_B = \frac{x_B - x_A}{c} + \frac{x_A}{v} - \frac{x_B}{v} \quad (6.5)$$

The downstream arrival time difference is expressed by:

$$\Delta t_{\text{down}} = \frac{\Delta x}{c} \cdot (1 - n) \quad (6.6)$$

In the downstream measurements, for silica case with $n = 1.46$, the result of Equation 6.6 is negative. It means that photon B, generated later in the fibre, is detected before photon A. It is possible since particles travelling within air have a velocity $\approx c$, whereas photons within the fibre are propagated at a velocity $\approx c/n$.

Method 2: Downstream and Upstream Arrival Times Difference

In order to estimate the loss location distribution, the comparison of the downstream and upstream arrival times, t_{Down} and t_{Up} , from every scan is required. Following Figure 6.28, screen position d can be estimated by calculating the distances travelled L_{Down} and L_{Up} by the downstream and upstream photons from their respective times and compared with the oBLM system length.

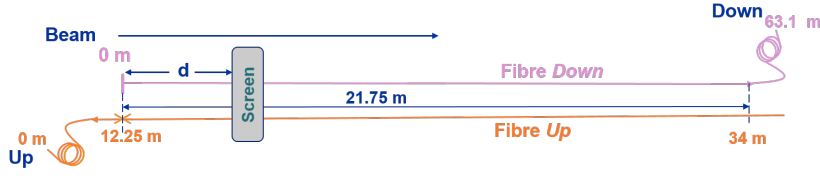


Figure 6.28: *Cherenkov oBLM setup in CLEAR.*

The screen position d can be calculated by:

$$d_{\text{Down}} \approx L_{\text{Down}} - t_{\text{Down}} \cdot \frac{c}{n} \quad (6.7)$$

The distance d_{Down} from Equation 6.7 must match with the distance d_{Up} given by:

$$d_{\text{Up}} \approx t_{\text{up}} \cdot \frac{c}{n} - \text{offset} \quad (6.8)$$

Also, the total oBLM system length must agrees with:

$$L \approx (t_{\text{Down}} + t_{\text{up}}) \cdot \frac{c}{n} \quad (6.9)$$

6.5.3 Longitudinal Location Results

The first results correspond to the Cherenkov oBLM installed on the CLEAR accelerator ceiling approximately 1,1 m from the beamline. During system operations, each SiPM signal was amplified due to the distance between the line and the oBLM. The beam was adjusted to 1, 5 and 10 bunches corresponding to 0.7, 3,3 and 6.7 ns, respectively. The scans consisted of shots of 10 pulses with 800 scope data points each. Figure 6.29 presents the signals obtained for the detection of losses created

by the screens for different trains of bunches. The signals presented are the average of the 10 beam pulses. The plots numbered 1 for downstream signals and 2 for upstream signals show CLEAR background signals (i.e. no screens inserted). In these plots, even with no screens inserted, there was an external source of losses around the 80 ns for downstream and 150 ns for upstream. Therefore, the external source was located at some point around the BTV810 location. The unexpected peak also appears very softly in the BTV620, BTV730 and BTV810 upstream scans. The impact with BTV390 seems to provoke an important beam loss; therefore, there is not enough beam intensity for the end of the line, where this additional source is produced. In a general view of all the screens, it is possible to notice that the signals start at different times. It reveals that the showers of losses generate Cherenkov photons at different locations along the optical fibre, and these photons have different arrival times to the photo-sensor. It is relevant to mention that the downstream peaks for 5 and 10 bunches are saturated. Because of this saturation, it is difficult to interpret the signals since their shape has been altered. Additionally, upstream signals have an unexpected *arrowhead* shape that could be a consequence of the distance between fibre and beamline. Unexpected secondary peaks in upstream graphs are under investigation. Similarly, Figure 6.30 shows the signals obtained when *kicking* the beam by the steering magnets at vertical plane. By causing losses vertically when *kicking* the beam, it was intended to avoid the inclination of particles mentioned in screen scans. They are also compared with the background signals (again numbered 1 and 2).

Downstream signals for K540, K590 and K710 magnets are saturated due to the signal amplification for the train of 5 and 10 bunches. In addition, the upstream *background* signal appears during the upstream measurements. In general, these results are in very good agreement with the system behaviour already reported in the screen scans. However, several inconsistencies can be observed in the *kicker* scans. The K540 upstream signal for 10 bunches is suspiciously saturated, indicating that the data may have been overwritten. Furthermore, as shown in the screen scans, upstream signals exhibit unexpected double peaks. These uncertainties are being investigated.

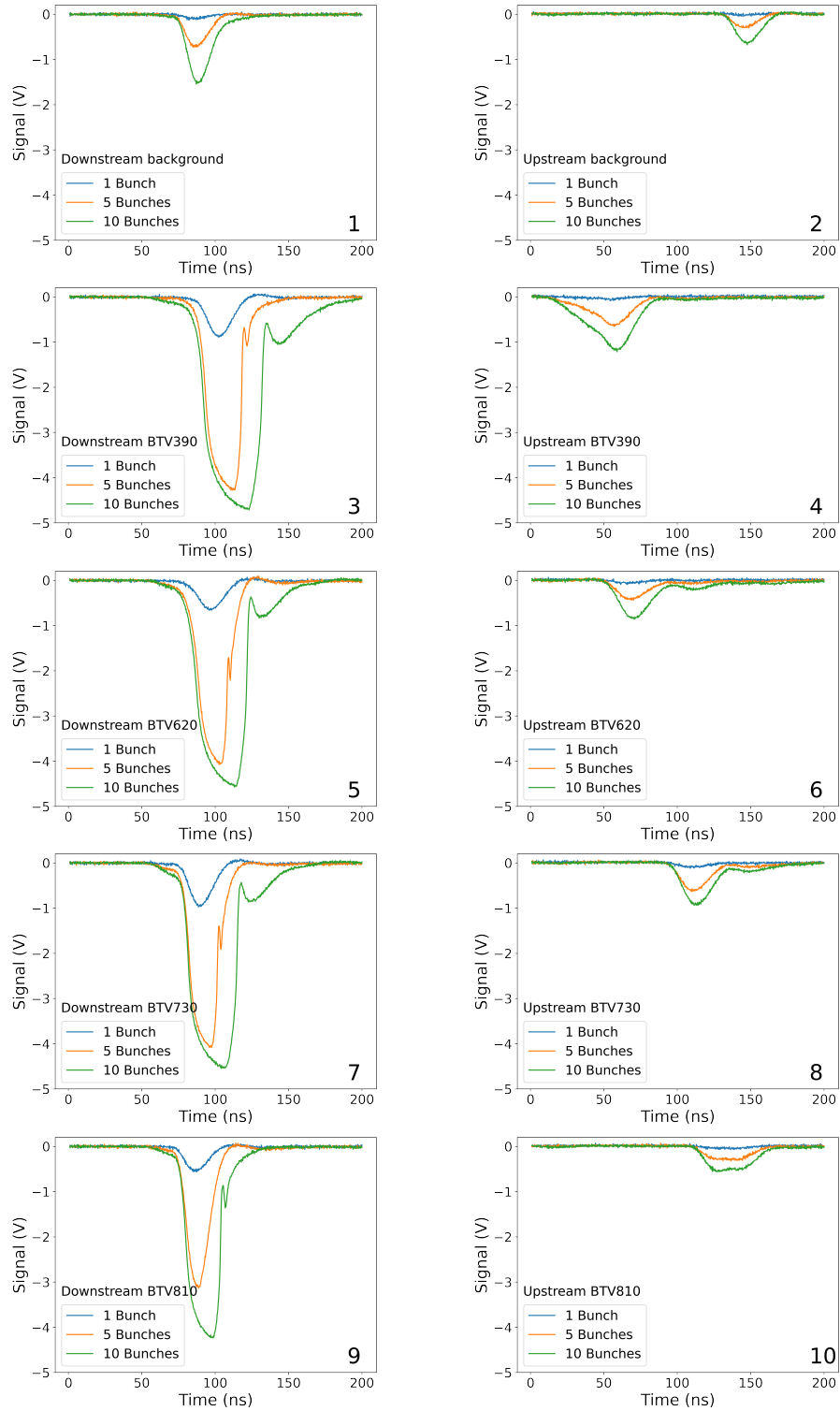


Figure 6.29: *Signals obtained from the CLEAR background and the insertion of the screens BTV390, BTV620, BTV730 and BTV810, for downstream (left column) and upstream directions (right column). The trains were set to 1, 5, and 10 bunches. (Fibre location: 1.1 m from the beamline).*

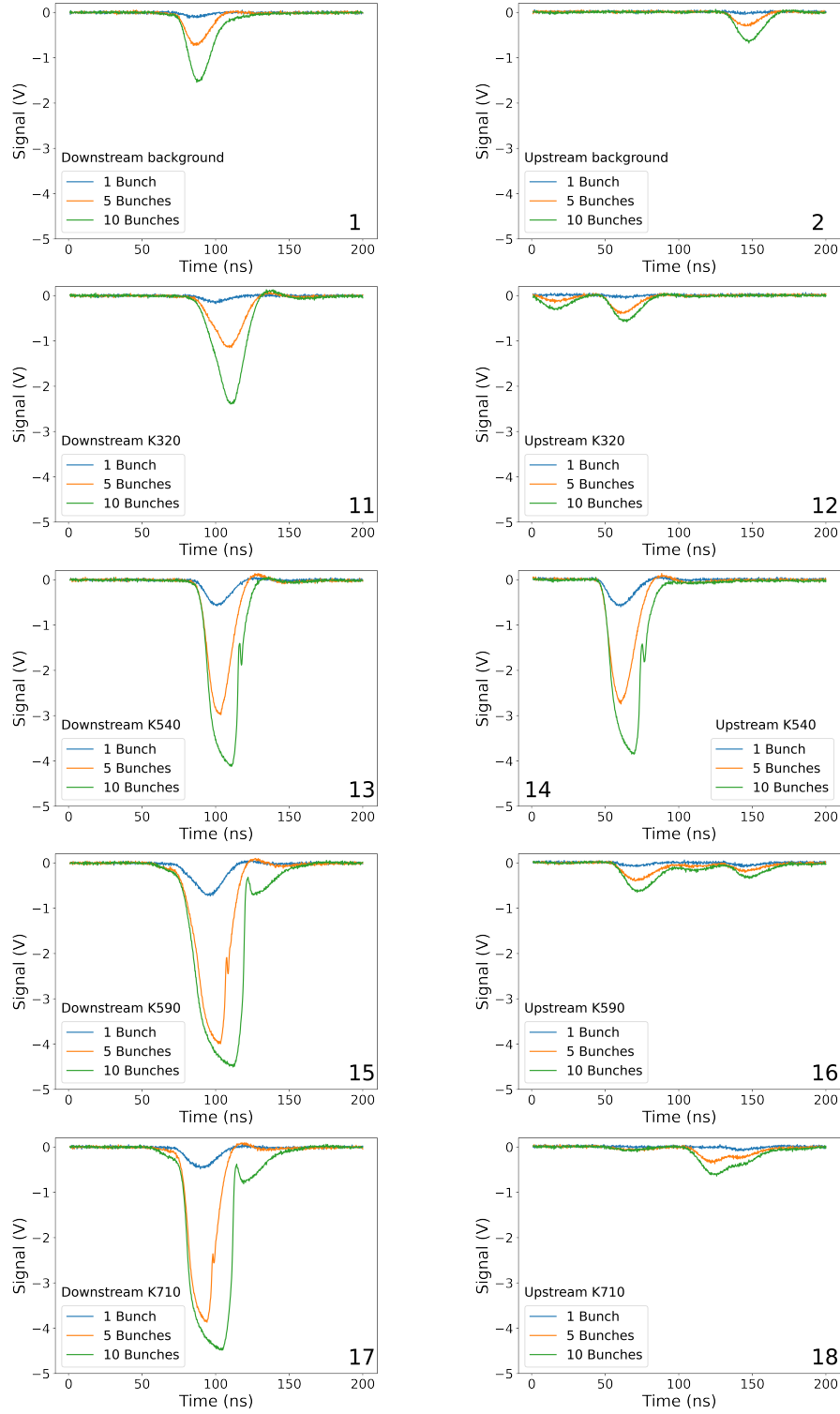


Figure 6.30: Signals obtained from the CLEAR background and the steering magnets K320, K540, K590 and K710, for downstream (left column) and upstream directions (right column). The trains were set to 1, 5, and 10 bunches. (Fibre location: 1.1 m).

During the second period of the tests, the Cherenkov oBLM was installed at 10 cm from the beamline. Same screens, steering magnets and beam parameters than in previous tests were used to provide the same scenario conditions. Apart from the oBLM location, the differences in the setup were the non-amplifier read-out circuitry and a new oscilloscope with a higher resolution. Shots of 10 pulses with 1000 scope data points each were run during the scans. The operational amplifier was discarded since many of the signals in previous tests were saturated, plus the fibre was brought closer to the beam pipe. However, before dismounting the read-out configuration, several scans were performed and later reported in the IPAC22 proceedings [124]. For the non-amplifier read-out, the beam was adjusted to 1, 5, 10, 30 and 50 bunches during the shots. The corresponding pulse lengths are then 0.7, 3.3, 6.7, 20 and 33.3 ns, respectively.

Figure 6.31 illustrates the signals created by the screens for different trains of bunches. As it is shown, the low background levels do not affect the main signals. Moreover, as the measurements were not amplified, no saturation is appreciated. It is possible to observe that each screen signal has its own starting time, independently of the number of bunches, and the rising edges are more vertical than in previous tests. The inclination of the particles reaching the fibre is also present in these measurements, even if the fibre is closer to the line¹.

Same analysis was completed for the steering magnets scans. Figure 6.32 shows the peaks obtained from the losses when the beam was horizontally deviated at several locations along the CLEAR line. The same magnets of the previous test, K320, K540, K590 and K710, and beam parameters were used.

¹Due to the scale on the horizontal axis, the inclination is not obvious. In Section 6.5.7, this effect is observed when experimental signals are compared with simulated results.

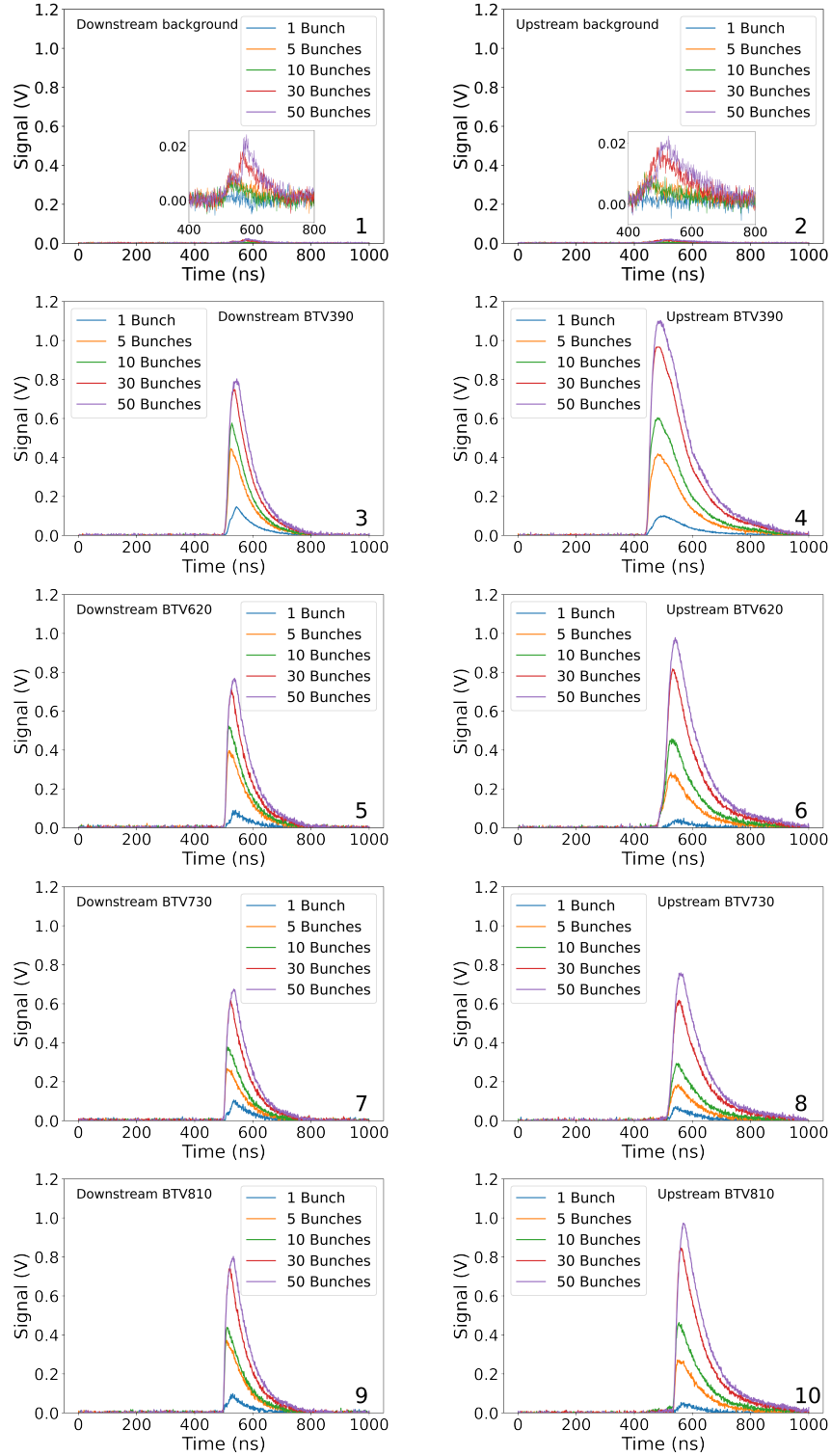


Figure 6.31: Signals obtained from the CLEAR background and the insertion of the screens. Left column: downstream signals, right column: upstream signals. Trains of 1, 5, 10, 30 and 50 bunches. (Fibre location: 10 cm).

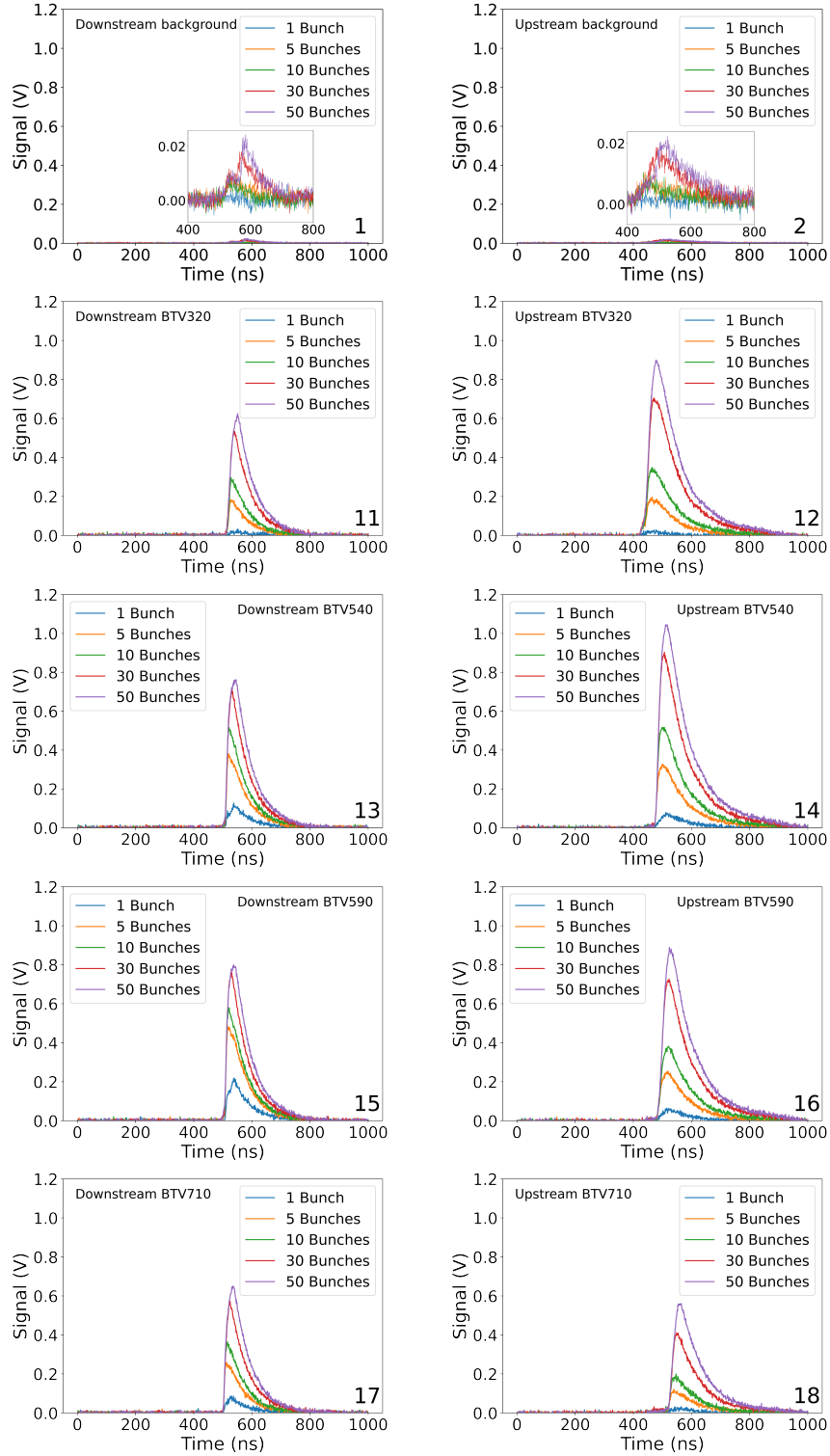


Figure 6.32: Signals obtained from the horizontal deviation of the beam caused by the steering magnets. Left column: downstream signals, right column: upstream signals. Trains of 1, 5, 10, 30 and 50 bunches. (Fibre location: 10 cm).

6.5.4 Upstream Arrival Times Comparison

This Subsection is focused on analysing the loss localisation for the Cherenkov oBLM by the upstream arrival times comparison.

Table 6.2 summarises the results obtained from the oBLM system installed on the ceiling at 1.1 m from the line during the screen scans. As been demonstrated, the dropping edges of the signals start at the same moment independently of the number of beam bunches (cf. Figure 6.25). Therefore the 10 bunches scans were selected for the calculations. For consistency, a threshold value below the signal noise is considered for determining the photon arrival times. The threshold voltage value during the scans was $V_{Th} = -0.05$ V. Also, statistical errors were considered during the signal treatment. The variation in time between the ten pulses is calculated.

	Real	Expected ^a	Signal time	Estimated
Screens	distance	Time	interval	distance
	d_R (m)	t_R (ns)	Δt_{Up} (ns)	d (m)
390 - 620	5.3	43.5	35 ± 6	4.3 ± 0.7
620 - 730	3.9	32.0	44 ± 2	5.4 ± 0.2
730 - 810	2.85	23.4	17 ± 2	2.1 ± 0.2

^a Arrival time of a photon from one screen to another, travelling a distance d_R .

Table 6.2: *Results from the loss location calculation by the upstream arrival times difference. (Fibre location: 1.1 m from the beamline).*

Several variables are compared to evaluate the oBLM system functionality: The real distance (in meters) measured between the screens in the CLEAR line is noted as d_R , being t_R the time in nanoseconds for a photon travelling a distance d_R along the fibre. Besides, Δt_{Up} is the interval time obtained from the experimental signals, also in nanoseconds, and d is the estimated distance between the screens. The variables d_R and d should be consistent in order to identify the screen locations. The average values of the estimated distances with their deviations are indicated.

The estimation of distances was also calculated with the configuration of the fibre at 10 cm from the beam pipe. The results obtained by applying the upstream arrival times methodology to the signals of the Cherenkov oBLM installed on the beamline are summarised in Table 6.3.

Screens	Real distance d_R (m)	Expected ^a Time t_R (ns)	Signal time interval Δt_{Up} (ns)	Estimated distance d (m)
390 - 620	5.3	43.5	41 ± 3	5.0 ± 0.4
620 - 730	3.9	32.0	31 ± 3	3.9 ± 0.4
730 - 810	2.85	23.4	27 ± 4	2.9 ± 0.5

^a Arrival time of a photon from one screen to another, travelling a distance d_R .

Table 6.3: *Results from the loss location calculation by the upstream arrival times difference of the screen scans. (Fibre location: 10 cm from the beamline).*

For establishing the start of the rising edges, the new threshold voltage value was set on $V_{Th} = -0.015$ V. Estimated distances d fit better with the real distances d_R , also shown in Table 6.3. Further, it is apparent that experimental time intervals Δt_{Up} are accurate when compared to the times t_R . These results coincide with the study presented in IPAC22 [124], with a improvement in the measurement error. Both tests² were performed on different days, several months apart. Thus, the Cherenkov oBLM system capability for beam loss location is verified. By applying the upstream arrival times comparison methodology, it is also possible to estimate the locations of the loss showers produced by the steering magnets. Table 6.4 compares the time and distance intervals of the real locations and the times and distances calculated by the method, for the measurements obtained by the system installed

²Note that in IPAC22 contribution the longitudinal location results of the beam losses generated by the screens and steering magnets with the fibre on the beamline were reported. The measurements were performed amplifying the signals before the operational amplifier was discarded.

on the beamline.

	Real	Expected ^a	Signal time	Estimated
Magnets	distance	Time	interval	distance
	d_R (m)	t_R (ns)	Δt_{Up} (ns)	d (m)
320 - 540	6.3	51.7	51 ± 4	6.2 ± 0.5
540 - 590	1.2	9.8	9 ± 5	1.2 ± 0.6
590 - 710	2.3	18.9	36 ± 6	4.4 ± 0.7

^a Arrival time of a photon from one magnet to another, travelling a distance d_R .

Table 6.4: *Results from the loss location calculation by the upstream relative times for the magnets tests. (Fibre location: 10 cm from the beamline).*

Estimated distances d match very well the real distances d_R . The calculation only failed to determine the distance between the magnets K590-K710. By cross-checking results with IPAC22 proceedings [124], this inconsistency was identified as caused by irregularities in the beam deviation by the K710 magnet. The loss location analysis generated by the steering magnets confirms the effectiveness of the Cherenkov oBLM for loss detection, already demonstrated by the screen scans.

6.5.5 Downstream and Upstream Arrival Times Difference

This Subsection is focused on analysing the loss localisation for the Cherenkov oBLM by combining the downstream and upstream arrival times of the interactions. The variables reported are the downstream and upstream starting signal times, t_{Down} and t_{Up} , respectively, and the estimated distances d_{Down} and d_{Up} of the screens/magnets calculated from the times. Finally, L_{oBLM} is the estimated fibre length, calculated from the sum of both distances. Table 6.5 reports the results obtained for the Cherenkov oBLM installed at 1.1 m from the beamline.

Although the scope signals seemed promising initially, many ambiguities are observed in the results. On the one hand, the saturation in the downstream mea-

Screen	t_{Down} (ns)	d_{Down} (m)	t_{Up} (ns)	d_{Up} (m)	L_{oBLM} (m)
390	84 ± 3	46.0 ± 0.6	16 ± 3	-9.0 ± 0.6	20.0 ± 1.0
620	77 ± 1	47.3 ± 0.2	51 ± 1	-1.8 ± 0.2	26.6 ± 0.4
730	76 ± 1	47.5 ± 0.2	95 ± 1	7.3 ± 0.2	35.2 ± 0.4
810	75 ± 1	47.7 ± 0.2	112 ± 1	10.8 ± 0.2	38.6 ± 0.4

Table 6.5: *Results from the loss location calculation by the downstream and upstream signals. (Fibre location: 1.1 m from the beamline).*

measurements is a significant obstruction for the starting point determination in the signals. The downstream times t_{Down} for the BTV620, BTV730 and BTV810 have few ns of difference, meaning that the screens are only 70 and 20 cm distant. On the other hand, upstream distances d_{Up} for BTV390 and BTV620 are negative. It would mean that the first photons coming from the shower of losses interact with the fibre before the starting point (0 m) of measurements (cf. Figure 6.28). Generally, distances d_{Down} and d_{Up} do not correspond to the expected location values of the screens. In addition, the total fibre length L_{oBLM} gives an incorrect value of the fibre length, which, according to the test setup, is approximately 97 m.

A summary of the results of the loss location calculation for the signals obtained by the system installed on the beamline is presented in Table 6.6. Results present the same issue with downstream starting times since they almost coincide at the same value, with a couple of nanoseconds of difference. Furthermore, the offsets of downstream and upstream times have increased.

According to the method considerations, downstream distances, d_{Down} , are negative. This information is not truthful because it would mean that the screens are located before the beamline. Upstream distance values, d_{Up} , are also invalid. Multiple reasons can be responsible for the uncertain values given by the first method. In addition, Table 6.7 summarises the rising times obtained for the steering magnets or *kickers* scans for the signals obtained by the system installed at 10 cm from the beamline. It is possible to identify that the same unexpected offset or signal delay

Screen	t_{Down} (ns)	d_{Down} (m)	t_{Up} (ns)	d_{Up} (m)	L_{oBLM} (m)
390	502 ± 1	-40.0 ± 0.2	440 ± 2	64.4 ± 0.4	193.6 ± 0.6
620	501 ± 2	-39.9 ± 0.4	481 ± 1	68.7 ± 0.2	201.8 ± 0.6
730	500 ± 2	-39.7 ± 0.4	512 ± 2	72.8 ± 0.4	208.0 ± 0.8
810	498 ± 1	-39.2 ± 0.2	539 ± 2	75.3 ± 0.4	213.1 ± 0.6

Table 6.6: *Results from the loss location calculation by the downstream and upstream signals of the screen scans. (Fibre location: 10 cm from the beamline).*

is also inherent in the case of the magnets. Hence, the first method of calculations would give incoherent results.

Magnet	t_{Down} (ns)	t_{Up} (ns)
320	512 ± 2	424 ± 1
540	506 ± 3	475 ± 3
590	502 ± 1	484 ± 2
710	500 ± 1	520 ± 4

Table 6.7: *Rising times for the downstream and upstream signals of the kicker scans. (Fibre location: 10 cm from the beamline).*

6.5.6 Methodology discussion

During the tests, the beam loss localisation was studied through two possible techniques: upstream arrival times comparison and downstream and upstream times differences.

On the one hand, based on the results of the first method, the Cherenkov oBLM system was demonstrated to be functional and the sources of beam loss were identified. Beam losses were created by different events on different days of operation. When the optical fibre was installed closer to the accelerator beam pipe, the res-

olution improved significantly. Results from the beam loss location collected in Tables 6.3 and 6.4 give a resolution of 0.5 m approximately. An improvement in location resolution over IPACC22 [124], achieving a resolution of 1 m. Both cases, however, showed an inclination in signal rising times. The uncertainties observed in the data such as the signal *arrowhead*, double-peaks are being investigated.

On the another hand, it was not possible to draw any conclusions from the comparison of downstream and upstream times. Unknown scope offset parameters easily produce a delay in the signals, adding an increment of time and distorting the results. In the upstream arrival times comparison, the first method, as the upstream times are relative measurements, they are under the same considerations; therefore, possible delays in the time measurements are cancelled and do not affect the location calculations. The cause of these unexpected values is still under investigation. Additionally, as mentioned in the system setup description, the experiment was performed using a setup composed of two fibres instead of one single fibre. It may be possible to eliminate possible offset in the signals that may be introduced by this issue by using a single fibre for downstream and upstream measurements in future tests.

6.5.7 Cherenkov oBLM Simulations for the CLEAR Line

Parallel to the experiments, FLUKA simulations were performed for the CLEAR experimental setup. The oBLM detection functionality was questioned during the simulated impacts to the different screens in the two fibre positions (1,1 m and 10 cm from the beamline). Then, FLUKA outputs were processed by the Cherenkov Generation Model without attenuation and capture factors. Figure 6.33 illustrates the signals obtained in the simulations of the Cherenkov oBLM located at 1.1 m from the beamline. The shots correspond to a single bunched beam.

The CLEAR beamline and an optical fibre of the same length, 22 m long, were considered in the FLUKA geometry. For simplicity, no extra fibre length is considered. Therefore, photon travelling times are shorter than the times in the real scenario. As expected, the model reports how upstream signals produced by the screens have different arrival times in the order they occur. For the downstream sig-

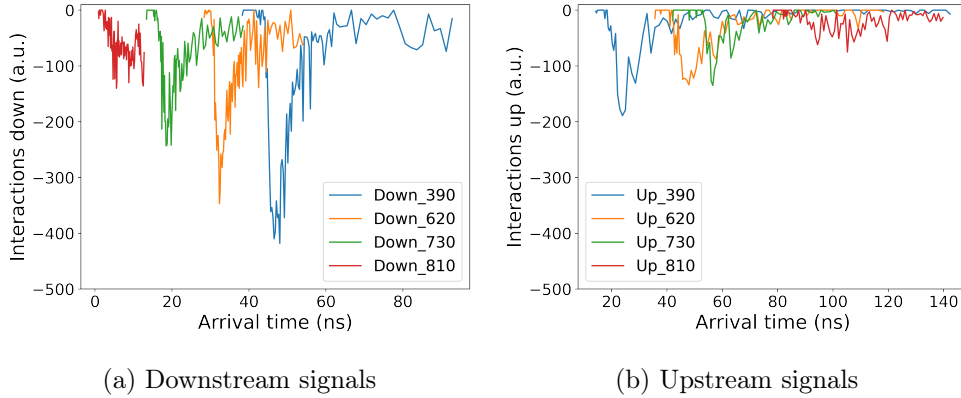


Figure 6.33: *Signals from the simulated CLEAR scenario with a fibre distance of 1.1 m from the beam line. The losses are generated by the screens BTV390, BTV620, BTV730 and BTV810 at one single bunch.*

nals, the nearest screen to the photo-sensor, BTV810, appears first. It corroborates the theory explained in Section 6.5 about the downstream times (Equation 6.6).

Analogously, signals obtained for the CLEAR environment simulation with the fibre installed at 10 cm from the beamline may be seen in Figure 6.34. As predicted by the distance dependency scans reported in Section 6.4.2, the intensity detected exponentially increases with the proximity between fibre and beam pipe. Contrary to the experimental case, simulations also show differences in signal shapes at different system distances, i.e. inclined edges for 1 m distance and sharper peaks for 10 cm distance. It could mean that in experimental situations, photons may be generated within a wider fibre segment.

This can occur because beam losses are more dispersed in practice, or parasitical beam losses coming from external sources are also being detected.

So far, simulation results have been obtained under the assumption of shots of one single bunched beam. The envelope signals corresponding to 10 bunched beam, plus delays introduced by the photo-sensor characteristics, were modelled for all the screens. Figure 6.35 shows the measured signals (for 10 bunches and the fibre at 1,1 m) together with the simulated signals.

From the CLEAR experimental downstream signals, poor information can be obtained due to saturation. It is possible to appreciate that the background losses

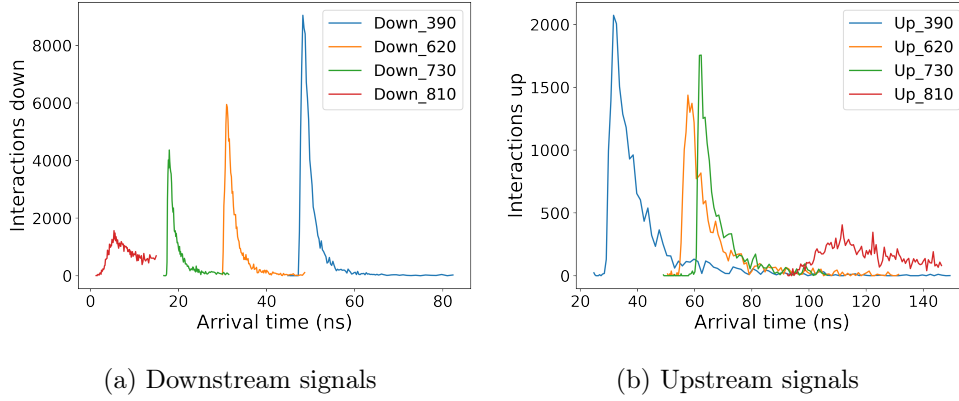


Figure 6.34: *Signals from the simulated CLEAR scenario with a fibre distance of 10 cm from the beam line. The losses are generated by the screens BTV390, BTV620, BTV730 and BTV810 at one single bunch.*

produced at some point after the last screen in the line adversely affect the over-charge. The experimental upstream signals match fairly with the modelled lines. The BTV390 experimental case has a specific shape that could include extra losses from another anterior element in the line. It is not an exclusive eventuality; for example, in the BTV620 plot, a nascent secondary peak appears at the BTV730 time. The most inexact model signal comes from BTV810, located at the line end, where a shower of losses reaches the fibre beyond the boundaries defined by FLUKA geometry.

Finally, the comparison of the CLEAR experimental signals with the simulations for the 10 cm case at 10 bunches shots is shown in Figure 6.36.

Several differences can be identified between experimental and simulated results. Modelled downstream signals indicate that the amplitude should be much higher in the experimental signals. On the other hand, the SiPM recovery process is more significant than expected by simulations. Experiments present more optimistic results regarding the detection of the losses produced by the screen BTV810 insertion, and it is possible to observe a full peak of losses. No saturation or background noise effects are observable.

Using the upstream arrival time comparisons (see Section 6.5.4), the estimation of the beam loss locations with the Cherenkov oBLM situated at 1,1 m and 10 cm far

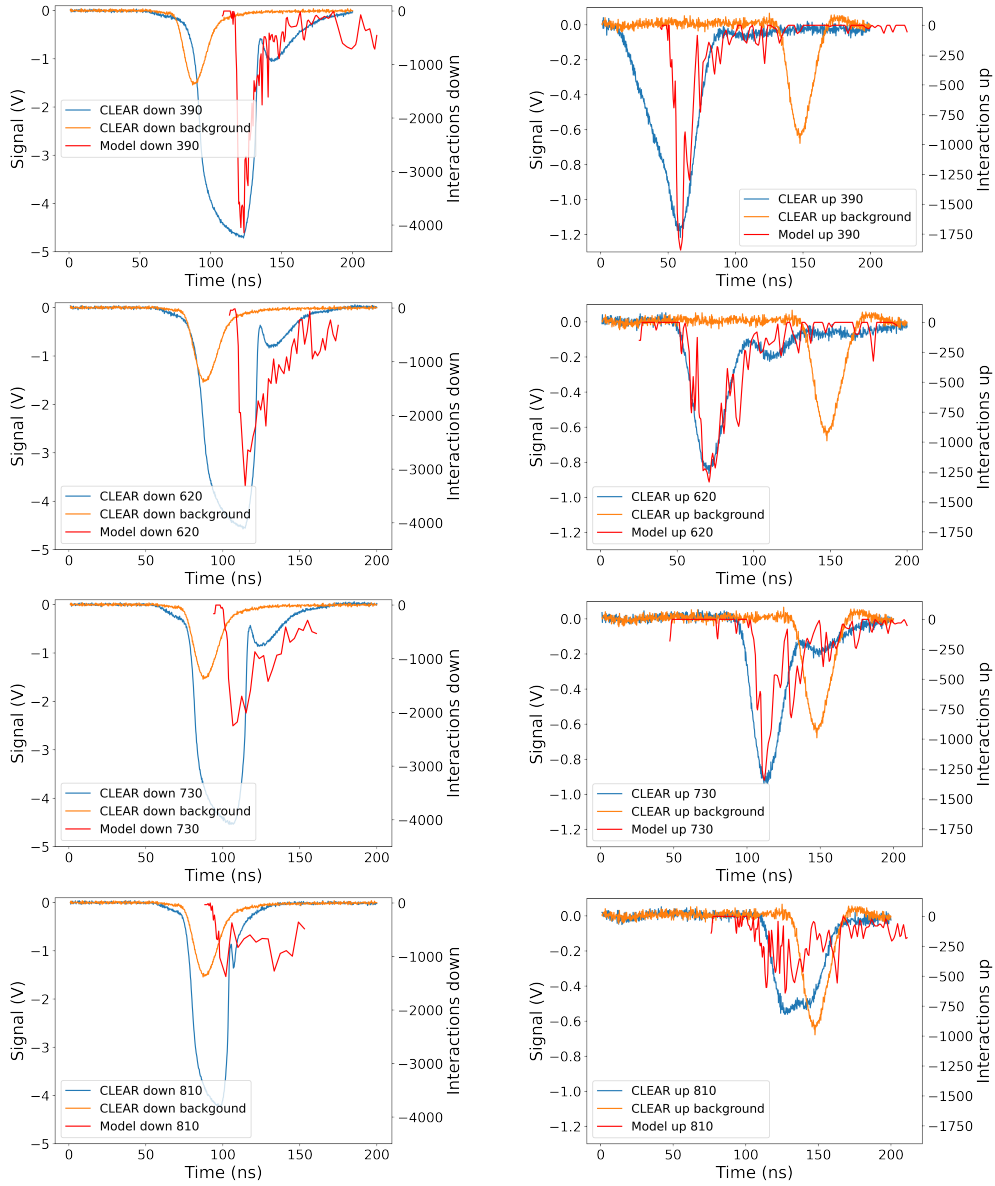


Figure 6.35: *Comparison between experimental and modelled signals for 10 bunched beam impacts to the screens BTV390, BTV620, BTV730 and BTV810. Left column: downstream signals, right column: upstream signals. Fibre distance: 1,1 m. Note that vertical axes are not in the same scale.*

from the beam pipe are performed. Results of beam loss location calculation from the simulated peaks are collected in Tables 6.8 and 6.9. In order to compare all the experimental results with the results obtained from the simulation, the estimation

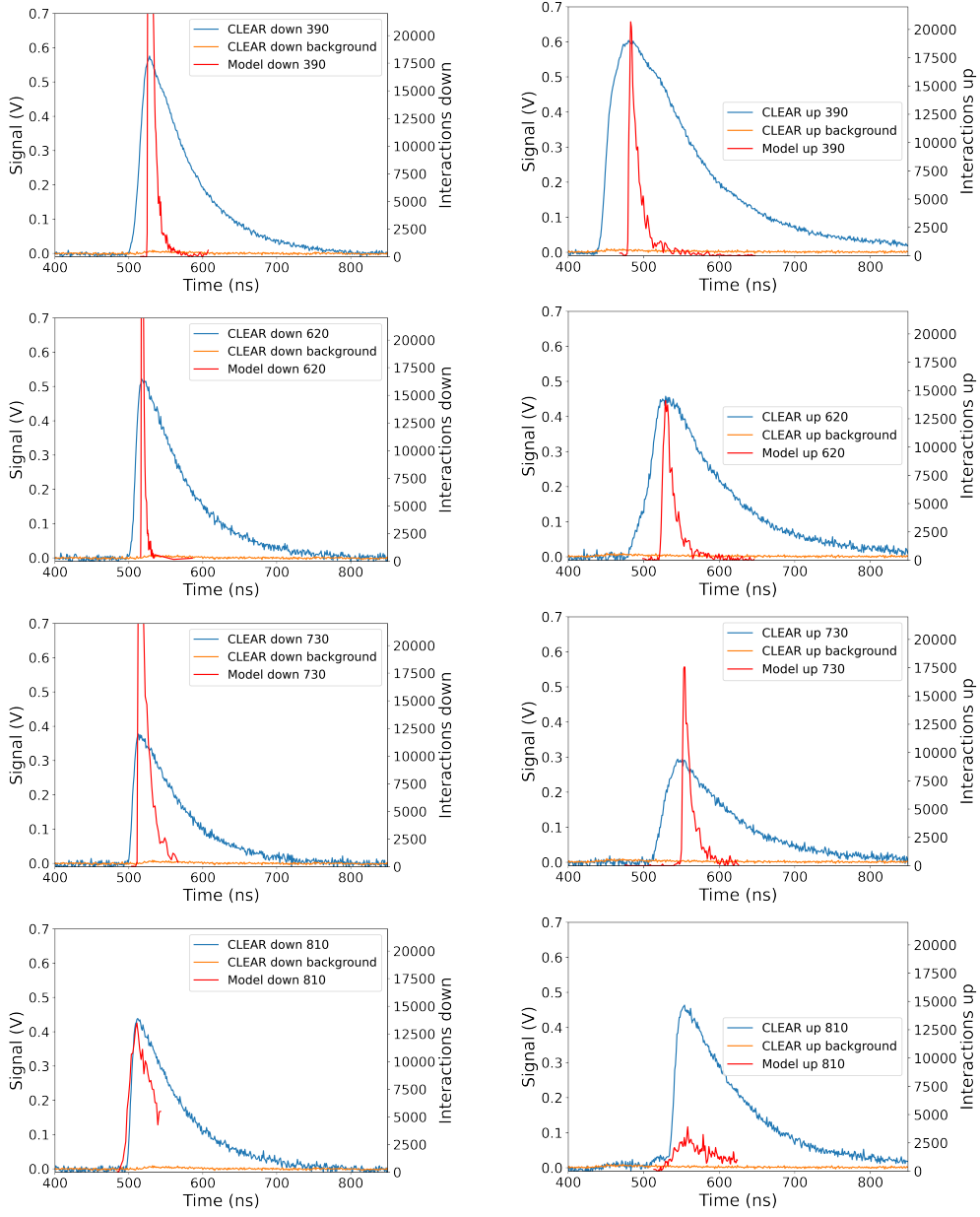


Figure 6.36: Comparison between experimental and modelled signals for 10 bunched beam impacts to the screens BTV390, BTV620, BTV730 and BTV810. Left column: downstream signals, right column: upstream signals. Fibre distance: 10 cm.

of the downstream arrival times comparison is also calculated.

Many uncertainties are obtained by applying the upstream (and downstream) arrival times methodology to the simulated signals for the fibre location 1,1 m. Only

Screens	Signal time interval $ \Delta t_{\text{Down}} $ (ns)	Estimated distance d_{Down} (m)	Signal time interval Δt_{Up} (ns)	Estimated distance d_{Up} (m)
390 - 620	8.5	5.5	5	0.6
620 - 730	7.5	4.9	46	5.6
730 - 810	6.5	4.2	-	-

Table 6.8: *Results from the loss location calculation by the downstream and upstream relative times for simulated screens. (Fibre location: 1 m from the beamline).*

Screens	Signal time interval $ \Delta t_{\text{Down}} $ (ns)	Estimated distance d_{Down} (m)	Signal time interval Δt_{Up} (ns)	Estimated distance d_{Up} (m)
390 - 620	8	5.2	43	5.2
620 - 730	6	3.9	30	3.7
730 - 810	18	11.7	-	-

Table 6.9: *Results from the loss location calculation by the downstream and upstream relative times for simulated screens. (Fibre location: 10 cm from the beamline).*

the downstream relation between BTV390 and BTV620 seems to fit with the real value. Secondly, the upstream relation between BTV620 and BTV730 matches very well with the experimental value shown in Table 6.2. In conjunction with the experimental calculations, the simulation results are inconclusive for beam loss localisation.

Results from the simulations for the Cherenkov oBLM system located at 10 cm on the beamline are in agreement with the theoretical values. Only the BTV810 screen presents uncertainties in the starting times. Due to its proximity to the fibre end in the simulated geometry, the beam losses generated by this screen are quite

unreliable. It is worth mentioning that the downstream arrival times match very well with the theoretical findings.

6.6 Summary

The Cherenkov oBLM and the Cherenkov Light Generation Model were examined together in the CLEAR linear accelerator at CERN during three campaign of experiments.

The characterisation of the Cherenkov phenomenon in optical fibres and the identification of the capture angles for silica fibres were successfully performed and verified with the simulation results. Also, it has been possible to recognise single bunched and bunched trains signals, determining the plateau or beam exposure time. In addition, relevant information such as SiPM saturation levels, operational amplifier effects or scope resolution was examined.

The ability of detection of the system was demonstrated by evaluating the distance dependency and the intensity levels as study parameters. Several targets were manufactured with different thicknesses to provoke different shower of losses. The Cherenkov oBLM loss detection has a quadratic behaviour that decays with the distance.

Finally, the Cherenkov oBLM loss mapping capability has been demonstrated. Two different methodologies were evaluated to calculate the beam loss location from different perspectives. Shower of losses created by screen insertions and beam deviations were measured and successfully localised. Different detection scenarios were tested, and a detection resolution of less than a meter was achieved. The evaluation of the Cherenkov Light Generation Model during the tests in CLEAR has shown significant agreement with experimental results.

Additionally, during the tests, differences in fibre parameters, such as the core size and length were also studied. Powerful equipment was developed to achieve the scans, and effective improvements implemented in the read-out electronics helped to understand the system requirements. They were crucial elements for the system optimisation against all the possible issues in the experimental scenario.

Conclusions and Outlook

The Slow Extraction to the North Area in the Super Proton Synchrotron (SPS) is one of the most radioactive areas at the CERN complex. The urgency for minimising the radiation levels and optimising the machine settings has motivated the study and development of a Cherenkov oBLM capable of monitoring and localising the source of unexpected losses. The oBLM system ensures the loss detection over long distances continuously by the instantaneous production of Cherenkov photons along an optical fibre when particles interact with the silica material. Two Silicon Photo-Multipliers (SiPM), attached to both fibre ends, collect the photons and generate an output signal.

The system is based on the Cherenkov effect, in which high-energetic charged particles emit photons when travelling at a higher speed than the light in that medium, and the material gets polarised. Since the oBLM comprises a quartz multimode optical fibre, the Cherenkov photons produced are subjected to two critical factors: light attenuation, which mainly depends on the length of the fibre, and the capture probability, which indicates if the photon will be trapped and propagated along the fibre depending on their angle of incidence. Additionally, the Silicon Photomultiplier was selected among the possible photo-sensors. It has many advantages, such as high dynamic range, high detection sensitivity, simplicity, low voltage requirements and costs. These made this device adequate for photon detection.

To measure LSS2 beam losses accurately, the Cherenkov oBLM must be mounted close to the beam pipe. Nevertheless, CERN operators are limited in their exposure time because of harsh environmental conditions, and the fibre would hinder interventions. Consequently, the Cherenkov oBLM prototype 200 m long was installed at a

distance of 2.3 m from the SPS beamline. Hence, a computational tool was required to predict the Cherenkov oBLM system utility before installation. The Cherenkov Light Generation Model quantifies the number of photons produced and propagated along a fibre to the photo-sensors in any accelerator environment. This model complements the FLUKA simulation outputs with the Cherenkov photons production analysis. Despite the angular capture and attenuation factors introduced by the fibre, the Cherenkov light yields predicted for different fibre diameters indicate that the system is suitable for loss detection.

The experimental study of the Cherenkov phenomenon and computational model verification were performed through three operational setups in the CLEAR facility. During the first test, the two ranges of capture angles in the quartz fibre were observed. Also, saturation levels of the photo-sensors were determined, and improvements in the read-out system were achieved. The dependency between the loss detection and the system distance was studied in the second test campaign. It was the subject of the final experiments in CLEAR to verify the functionality of the Cherenkov oBLM system as a detector of beam loss capable of locating the sources of the loss. Screens and steering magnets were used to generate beam losses in a controlled environment. Two methodologies were followed to calculate the loss location: the first determined the relative distances between the line elements using the upstream arrival times of the signals, while the second compared the downstream and upstream signal times from each component. Due to uncertainty in the signals with external offsets and saturation in the signals, the second calculation method was inconclusive. By using the first method, the Cherenkov oBLM system was demonstrated to be a viable beam loss detector, and CLEAR beam losses were successfully localised. It was possible to achieve a resolution of 0.5 m in the best cases. Additionally, the Cherenkov Light Generation model confirmed the expected results precisely. Inconsistencies in the downstream signals and the external offset are under investigation.

As an essential part of the project, the difficulties found during the optical fibre installation are worth mentioning. Optical fibres are not sensitive to X-rays or magnetic fields and can withstand extreme temperatures or radiation levels. How-

ever, from the mechanical point of view, they are fragile devices, and their breakage is quite common. In both SPS and CLEAR facilities, fibres were damaged during installation setups. As a consequence, the fibre had to be replaced or, in the case of CLEAR, the test configuration had to be modified.

Outlook

The Light Generation model quantification and the experimental data from the CLEAR facility have successfully demonstrated the Cherenkov oBLM ability for loss detection. In addition, the preliminary signals obtained in LSS2 from the debunched beam during the slow extraction confirm the system feasibility for detecting losses in SPS. Further steps comprise the optimisation of the acquisition system with a new trigger setup and new protocols of data storage. Currently, the trigger is set on one of the scope channels, activated when the signals reach the photo-sensor. The new trigger system would have a complete overview of the beam loss timing in the area. Also, possible delays in the data acquisition caused by the remote connections need to be reduced.

Upcoming tests in SPS studying controlled losses can be performed. Apart from the possible calibrations of the system in the loss location estimations, it would help to understand the inconsistencies obtained during the CLEAR tests, including the time overlapping in downstream signals. Photodetection with PMTs can be studied even though SiPMs have demonstrated a perfect candidate for use in Cherenkov oBLM systems.

After the Cherenkov oBLM data collection, the comparison of the oBLM data with the BLM database must be investigated. In this analysis, the new data could be correlated with the previous data measured by the ionisation chambers installed in the LSS2 area.

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FLUKA Simulation and Cherenkov Light Generation Model Notes

A.1 Cherenkov Light Generation Model Code

The Cherenkov Light Generation Model code can be found in: https://gitlab.cern.ch/sbenitez/cherenkov_light_generation_model

A.2 FLUKA Input Files for SPS Simulations

The SPS FLUKA geometry used in this thesis was designed by the CERN STI-BMI group. The geometry inputs can be added to the simulation through the FLuka Advanced InteRface (FLAIR). Figure A.1 shows the first part of the FLAIR platform where the beam parameters were introduced. For the specific LSS2 environment, the internal *include_settings_physics.inp* and *include_settings_beam.inp* files were included with valuable information about the SPS spill. After a complete LSS2 geometry description comprising all the LSS2 line components, the optical fibre of the oBLM system was implemented by the author of this thesis (see Figure A.2). The fibre coordinates in the geometry are (199, 127, 0) with (X, Y, Z) as the reference system. The fibre radius " $R = 0.01$ " was also included for a fibre 200 μm of diameter. FLAIR uses centimetres as the unit of measurement. The fibre material (quartz) assignation is also implemented in a *material card*, shown in Figure A.3. As an

example, the main Linux command (shown in Figure A.4) will run the input file *LSS2.inp* and will save output data in the newly created directory *data_directory*. The simulation will compute ten *jobs*, each composed of ten *cycles*. Each *cycles* will run a total of 10^6 primary particles. The executable routine *fluka_routine.x* will be executed during the simulation running (see Annex A.4).

```

Input
*****
This file has been generated using the following revisions:
LineBuilder: 6deadf02398ab8a639cb295e93a0a101782ac251 - version: 'master';
fedb: ddc799780574a99476d149ed02c4174a40bd03cf;
SPS/LSS2: 9240946c7fedad02db30b909f8b2e2d6ad128de5;
*****
...+...1...+...2...+...3...+...4...+...5...+...6...+...7..

#include include_define.inp
#include

GLOBAL Max #reg: 10000.0 Analogue: Input DNear: default
Input: Names Geometry: Free Memory: Flag:
TITLE SPS LSS2 extraction geometry
RANDOMIZ Unit: 01 Seed: 1.0

#include include_settings_physics.inp
#include

#include include_settings_beam.inp
#include

```

Figure A.1: Beam parameters input in FLUKA simulation.

		lv	8.0				
RCC	PMIBDY6	x:	5.0	y:	-100.0	z:	5800.0
		Hx:	0.0	Hy:	21.5	Hx:	0.0
		R:	8.0				
RCC	PMIBDY7	x:	5.0	y:	-100.0	z:	7096.2
		Hx:	0.0	Hy:	21.5	Hx:	0.0
		R:	8.0				
RCC	PMIBDY8	x:	5.0	y:	-100.0	z:	7743.0
		Hx:	0.0	Hy:	21.5	Hx:	0.0
		R:	8.0				
ZCC	BLMLup	x:	0.0	y:	150.0	R:	4.0
ZCC	BLMLdo	x:	0.0	y:	-65.0	R:	4.0
ZCC	fiber	x:	199.0	y:	127.0	R:	0.01

Figure A.2: Optical BLM geometry and coordinate inputs (noted in yellow).

Input			
ASSIGNMA	Mat: AIR ▼	Reg: PMI206 ▼	to Reg: ▼
	Mat(Decay): ▼	Step: ▼	Field: ▼
ASSIGNMA	Mat: AIR ▼	Reg: PMI207 ▼	to Reg: ▼
	Mat(Decay): ▼	Step: ▼	Field: ▼
ASSIGNMA	Mat: AIR ▼	Reg: PMI208 ▼	to Reg: ▼
	Mat(Decay): ▼	Step: ▼	Field: ▼
ASSIGNMA	Mat: AIR ▼	Reg: BLMLdo ▼	to Reg: ▼
	Mat(Decay): ▼	Step: ▼	Field: ▼
ASSIGNMA	Mat: QUARTZ ▼	Reg: fiber ▼	to Reg: ▼
	Mat(Decay): ▼	Step: ▼	Field: ▼
#if _quartzBLMlong_ ▼			

Figure A.3: *Optical BLM material input (noted in yellow).*

```
[sbenitez@clueet lss2]$ submit.sh -i LSS2.inp -d data_directory -j10 -c10 -p1000
000 -q testing -e fluka_routine.x
```

Figure A.4: *Linux command for running the simulations.*

A.3 FLUKA Input Files for CLEAR Simulations

Figures A.5, A.6, A.7, A.8 and A.9 show the FLUKA inputs developed by the author of this thesis for the CLEAR geometry used during the simulations. Figure A.5 presents the CLEAR beam parameters. A 220 MeV electron beam was positioned to the $(X = 0, Y = 0, Z = 0)$ coordinates with a gaussian distribution. Figure A.6 and Figure A.7 present the beam pipe, screens and fibre geometries and positions. In this case, all the screens used during the test campaigns are also defined (centimetres as default FLUKA units) . The different material definitions and their assignment to the components are shown in Figure A.8. Finally, Figure A.9 shows several FLUKA estimator cards and the starting primary particles required.

```

Input
-----
#define _LOAD_FROM_FILE_

...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+
TITLE CLEAR FULL LINE

...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+
DEFAULTS : PRECISIO ▼

...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+
*BEAM Beam: Energy ▼ E: 0.22 Part: ELECTRON ▼
      Δp: Flat ▼ Δp: Δφ: Flat ▼ Δφ:
      Shape(X): Gauss ▼ x(FWHM): 0.2 Shape(Y): Gauss ▼ y(FWHM): 0.2

...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+
#if _LOAD_FROM_FILE_ ▼

...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+
SOURCE #1: #2: #3:
sdum: LOSSES #4: #5: 1.0 #6:
          #7: #8: #9:
          #10: #11: #12:
          #13: #14: #15:
          #16: #17: #18:

...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+
#else

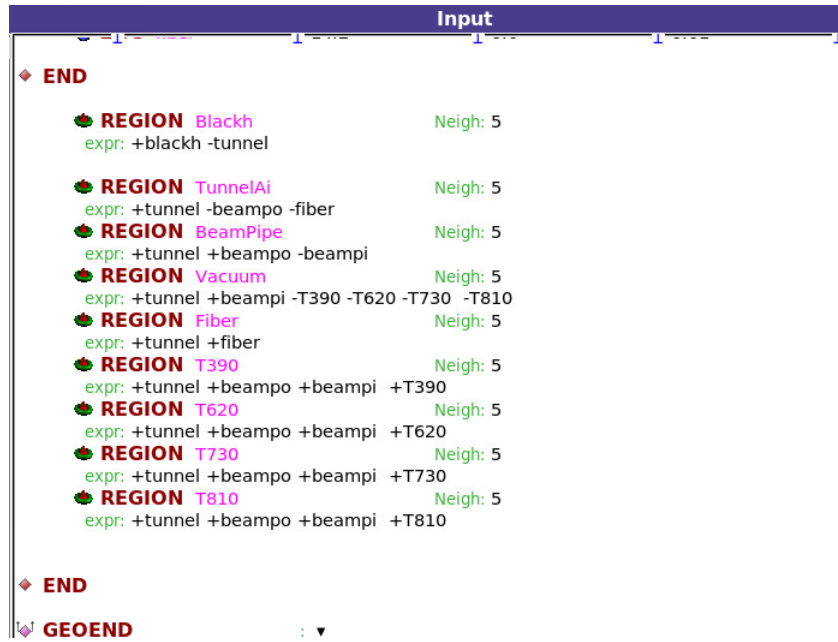
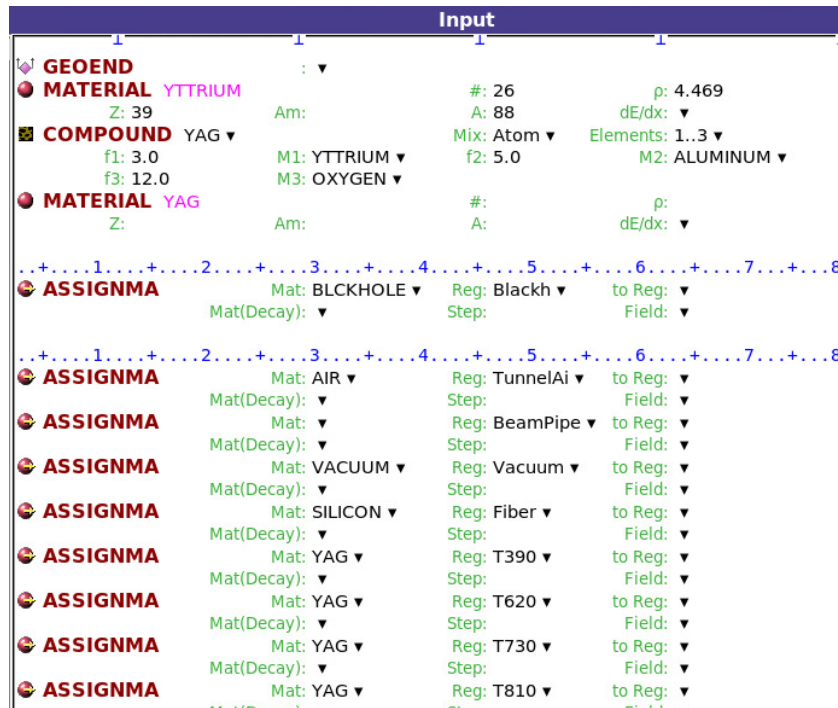
...+...1...+...2...+...3...+...4...+...5...+...6...+...7...+
BEAMPOS x: 0.0 y: 0.0 z: 0.
        cosx: cosy: Type: POSITIVE ▼

```

Figure A.5: *CLEAR* beam parameters.

Input			
GEOBEGIN	Accuracy:	Option: ▼	Paren:
Title: BG	Geometry: ▼	Out: ▼	Fmt: COMBNAME ▼
RPP blackh	Xmin: -5000000.0	Xmax: +5000000.0	
	Ymin: -5000000.0	Ymax: +5000000.0	
	Zmin: -5000000.0	Zmax: +5000000.0	
RPP tunnel	Xmin: -100.0	Xmax: +100.0	
	Ymin: -100.0	Ymax: +100.0	
	Zmin: -100.0	Zmax: 2200.0	
RPP T390	Xmin: -2	Xmax: 2	
	Ymin: -2	Ymax: 2	
	Zmin: 679.95	Zmax: 680.05	
RPP T620	Xmin: -2	Xmax: 2	
	Ymin: -2	Ymax: 2	
	Zmin: 2603.5	Zmax: 2606	
RPP T730	Xmin: -2	Xmax: 2	
	Ymin: -2	Ymax: 2	
	Zmin: 2975	Zmax: 2976	
RPP T810	Xmin: -2	Xmax: 2	
	Ymin: -2	Ymax: 2	
	Zmin: 3252.5	Zmax: 3253.5	
ZCC beampi	x: 0.0	y: 0.0	R: 4.0
ZCC beampo	x: 0.0	y: 0.0	R: 4.2
ZCC fiber	x: 14.2	y: 0.0	R: 0.01

Figure A.6: *FLUKA* geometry of each component required in the simulated scenario.

Figure A.7: *Regions of each component defined in FLUKA.*Figure A.8: *Definition and assignment of materials to each component in FLUKA.*

Input			
 ROT-DEFI	Mat(Decay): Axis: Z Polar: Δx:	Step: Id: 0 Azim: Δy:	Field: Name: Δz:
 ROT-DEFI	Axis: Z Polar: Δx:	Id: 0 Azim: Δy:	Name: Δz:
..+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...8			
 USRBIN	Type: X-Y-Z Part: ENERGY	Xmin: -200. Ymin: -200. Zmin: -2500.	Unit: 24 BIN Xmax: 200. Ymax: 200. Zmax: 2500.
Name: ENDEPOS NX: 20. NY: 20. NZ: 50.			
..+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...8			
 USRBIN	Type: X-Y-Z Part: ALL-PART	Xmin: -200. Ymin: -200. Zmin: -2500.	Unit: 25 BIN Xmax: 200. Ymax: 200. Zmax: 2500.
Name: PARTFLU NX: 20. NY: 20. NZ: 50.			
..+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...8			
 USERDUMP	Type: Dump What: Complete	Unit: 23 Score: Traj&Cont Losses	File: DIST Dump:
..+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...8			
 RANDOMIZ	Unit:	Seed: 1.0	
..+...1...+...2...+...3...+...4...+...5...+...6...+...7...+...8			
 START	No.: 10000000.	Core:	
Time: Report: default			
 STOP			

Figure A.9: FLUKA commands for different estimations and the starting card with the primary particles.

A.4 Executable Routine for FLUKA Simulations

```

===== mgdraw =====
*
  SUBROUTINE MGDRAW ( ICODE, MREG )

    INCLUDE 'dblprc.inc'
    INCLUDE 'dimpar.inc'
    INCLUDE 'iouunit.inc'

*
*-----*
*
*   Copyright (C) 2003–2019: CERN & INFN
*   All Rights Reserved.
*-----*
*
    INCLUDE 'caslim.inc'
    INCLUDE 'comput.inc'
    INCLUDE 'sourcm.inc'
    INCLUDE 'fheavy.inc'
* Start\_Devel\_seq
    INCLUDE 'flkmat.inc'
* End\_Devel\_seq
    INCLUDE 'flkstk.inc'
    INCLUDE 'genstk.inc'
    INCLUDE 'mgddcm.inc'
    INCLUDE 'paprop.inc'
    INCLUDE 'quemgd.inc'
    INCLUDE 'sumcou.inc'
    INCLUDE 'trackr.inc'
    INCLUDE 'beamcm.inc'
    INCLUDE 'ZSREG.inc'
    INCLUDE 'sloex.inc'

*
    DIMENSION DTQUEN ( MXTRCK, MAXQMG )

*
    SAVE NREG0, NREG1, NSCOOUT

*
    CHARACTER*30 FILNAM
    CHARACTER*8 MRGNAM
    LOGICAL LFCOPE, LFCOPE2, LFCOPE3, LZSINT
    SAVE LFCOPE, LFCOPE2, LFCOPE3
    DATA LFCOPE / .FALSE. /
    DATA LFCOPE2 / .FALSE. /
    DATA LFCOPE3 / .FALSE. /
    PARAMETER (BETMIN = 0.625D0)

    IF ( .NOT. LFCOPE3 ) THEN
      LFCOPE3 = .TRUE.
      IF ( KOMPUT .EQ. 2 ) THEN
        FILNAM = '/'//CFDRAW(1:8)//' DUMP A'
      ELSE
        FILNAM = CFDRAW
      END IF
      OPEN ( UNIT = IODRAW, FILE = FILNAM, STATUS = 'NEW',

```

```

&      FORM = 'FORMATTED' )

      MRGNAM = 'fiber'
      CALL GEON2R (MRGNAM, NSCOOUT, IERR)
      WRITE(LUNOUT,*) 'MGDRAW: particles inside of the fiber'
      WRITE(LUNOUT,*) MRGNAM, NSCOOUT
      WRITE(LUNOUT,*) 'BETMIN', BETMIN

      WRITE (IODRAW, 101)
101      FORMAT ( 'PID',2x,'Z',2x,'A',2x,'ETRACK',2x,'BETA',
&              2x,'X0',2x,'Y0',2x,'Z0',2x,'XN',2x,'YN',2x,'ZN',
&              2x,'CX',2x,'CY',2x,'CZ',2x,'CTRACK' )
      END IF

*      return if we are in region different from the fiber
      IF ( MREG .NE. NSCOOUT ) RETURN

*      particle charge and mass
      IF ( JTRACK .GE. -6 ) THEN
          AMASS = AM      ( JTRACK )
          ICH   = ICHRG   ( JTRACK )
          IBAR  = IBARCH  ( JTRACK )
      ELSE
          AMASS = AMNEHA (-JTRACK )
          ICH   = ICHEAV (-JTRACK )
          IBAR  = IBHEAV (-JTRACK )
      ENDIF

*      filter out neutral particles
      IF ( ICH .EQ. 0 ) RETURN

*      particle momentum and speed
      PTOT = SQRT ( (ETRACK - AMASS) * (ETRACK + AMASS) )
      BETA = PTOT / ETRACK

*      filter out particles with speed lower than BETMIN
      IF ( BETA .LT. BETMIN ) RETURN

      WRITE (IODRAW, '(3(I5),12(1PE16.8))')
&      JTRACK, ICH, IBAR, ETRACK, BETA,
&      XTRACK(0), YTRACK(0), ZTRACK(0),
&      XTRACK(NTRACK), YTRACK(NTRACK), ZTRACK(NTRACK),
&      CXTRCK, CYTRCK, CZTRCK, CTRACK

*      +-----*
      RETURN

*
*-----*
*
*      Boundary-(X) crossing DRAWing:
*
*      Icode = 1x: call from Kaskad
*              19: boundary crossing
*      Icode = 2x: call from Emfsco
*              29: boundary crossing
*      Icode = 3x: call from Kasneu
*              39: boundary crossing
*      Icode = 4x: call from Kashea
*              49: boundary crossing

```

```

*      Icode = 5x: call from Kasoph
*              59: boundary crossing
*
*=====
*
ENTRY BXDRAW ( ICODE, MREG, NEWREG, XSCO, YSCO, ZSCO )
IF ( .NOT. LFCOPE ) THEN
  LFCOPE = .TRUE.
  IF ( KOMPOT .EQ. 2 ) THEN
    FILNAM = '//CFDRAW(1:8)//' DUMP A'
  ELSE
    FILNAM = CFDRAW
  END IF
  WRITE(LUNOUT,*) 'MGDRAW to dump boundary data'
*
  MRGNAM = 'Vac0      '
  CALL GEON2R( MRGNAM, NREG1, IERR)
  WRITE(LUNOUT,*) MRGNAM, NREG1
  IF (IERR.EQ.1) CALL FLABRT ( 'BXDRAW', MRGNAM // ' not found' )
*
  MRGNAM = 'Vac000    '
  CALL GEON2R( MRGNAM, NREG0, IERR)
  WRITE(LUNOUT,*) MRGNAM, NREG0
  IF (IERR.EQ.1) CALL FLABRT ( 'BXDRAW', MRGNAM // ' not found' )
*
  WRITE(LUNOUT,*) 'dump protons at these boundaries'
  WRITE(LUNOUT,*) '0:', NREG0, NREG1
  CALL FFLUSH(LUNOUT)

END IF

*      check that it is a proton
IF ( JTRACK .NE. 1 ) GOTO 300
*      check that the proton has touched the aperture
* ->      IF ( LLOUSE .EQ. 0 ) GOTO 300

*      check if particle is crossing the right boundary
IUNIT = 0
IF ( MREG.EQ.NREG0 .AND. NEWREG.EQ.NREG1 ) THEN
  IUNIT = 60
ELSE
  GOTO 300
ENDIF

*      compute particle mass and momentum
IF ( JTRACK .GE. -6 ) THEN
  AMASS = AM ( JTRACK )
ELSE
  AMASS = AMNHEA (-JTRACK )
ENDIF
PTOT = SQRT ( (ETRACK - AMASS) * (ETRACK + AMASS) )

WRITE (IUNIT,301) XSCO, YSCO, CXTRCK/CZTRCK, CYTRCK/CZTRCK,
+      PTOT, SPAUSR(1), ISPUSR(1), LLOUSE, NPASSAGE

301  FORMAT (6(1G15.8,1X),I12,I8,I3)
300  CONTINUE
RETURN

```

```

ENTRY EEDRAW ( ICODE )
RETURN

=====
*
*   SOurce particle DRAWing:
*
=====
**
ENTRY SODRAW
RETURN
*
ENTRY USDRAW ( ICODE, MREG, XSCO, YSCO, ZSCO )

IF ( .NOT. LFCOPE2 ) THEN
  LFCOPE2 = .TRUE.
  WRITE(LUNOUT,*) 'MGDRAW to dump inel interactions',
+   ' of primary protons '
  WRITE(99,200) "NCASE", "IJ", "PLA", "X", "Y", "Z",
+   "TXX", "TTY", "TZZ", "WEIGHT", "LLOUSE", "ISAMPLE", "NEWREG"
+   ", "NPASSAGE", "LTRACK", "ZLAST"
END IF
*   select inelastic interaction of a primary proton
IF ( ICODE.EQ.101 .AND. JTRACK.EQ.1 .AND. LTRACK.EQ.1 ) THEN
*   check that the interaction occured in the ZS/diffuser wires
  LZSINT = .FALSE.
  DO I=1,MXWREG
    IF( MREG.EQ.IZSREG(I) ) LZSINT = .TRUE.
  ENDDO
  IF( .NOT. LZSINT ) GOTO 202

*   compute momentum
  PTOT = SQRT ( (ETRACK - AM ( JTRACK )) *
+   (ETRACK + AM ( JTRACK )) )
  WRITE(99,201) NCASE, JTRACK, PTOT, XSCO, YSCO, ZSCO,
+   CXTRCK, CYTRCK, CZTRCK, WTRACK, LLOUSE, ISPUSR(1), MREG
+   ,NPASSAGE, LTRACK, SPAUSR(1)
END IF
200 FORMAT ( "#", A7, A4, 8(1X, A17), A7, 5 A10 )
201 FORMAT ( I8, I4, 8(1X, 1PE17.10), I7, I12, I6, I3, I6, (1X, 1PE17.10) )
202 CONTINUE
RETURN
*==== End of subroutine Mgdrow =====
END

```

A.5 FLUKA Output Files

Figure A.10 illustrates the typical output file obtained from the FLUKA simulations. The variables are, from left to right, the particle type (in the image: 3 is electron, 4 is positron, 13 is pion⁺ and 14 is pion⁻), particle charge, atomic mass (g), particle energy (GeV), β parameter, initial and final coordinates (cm), angle of incidence (related to the cosine) and distance travelled within the fibre (cm).

[illegible]

Figure A.10: Typical FLUKA output file.

