ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB021

DEVELOPMENT AND TESTING OF A CHERENKOV BEAM LOSS MONITOR IN CLEAR FACILITY

S. Benítez*[1], E. Lima[2], E. Effinger, W. Farabolini[3], A. Gilardi[4,5], P. Korysko[6],
P. Lane[1], B. Salvachua, W. Viganò, CERN, Geneva, Switzerland
[1]also at University of Huddersfield, Huddersfield, United Kingdom
[2]also at Sapienza University of Rome, Rome, Italy
[3]also at CEA-Saclay, Gif-sur-Yvette, France
[4]also at University of Naples Federico II, DIETI - IMPALab, Napoli, Italy
[5]also at Istituto Nazionale di Fisica Nuclare (INFN) Sezione di Napoli, Napoli, Italy
[6]also at University of Oxford, Oxford, United Kingdom

Abstract

Beam Loss Monitors are fundamental diagnostic systems in particle accelerators. Beam losses are measured by a wide range of detectors with excellent results; most of these devices are used to measure local beam losses. However, in some accelerators there is the need to measure beam losses continuously localized over longer distances i.e., several tens of meters. For this reason, a beam loss detector based on long optical fibers is now under study. As part of the design, several simulations, comparing different possible detection scenarios, have been performed in FLUKA and bench-marked with experimental data. An experimental campaign was performed with an electron beam in the CERN Linear Electron Accelerator for Research (CLEAR) in November 2020. The light emitted from the optical fiber was captured using Silicon Photo-Multipliers (SiPM) coupled at each fiber's end. In this paper, the first results of a beam loss detector based on the capture of Cherenkov photons generated by charged particles inside multi-mode silica fibers are presented.

INTRODUCTION

Beam Loss Monitoring (BLM) systems are widely used in accelerator facilities to detect and measure beam losses. The measurements are used either, to protect and limit the deposited dose on the various accelerator equipment by interlocking the beam, or to assist in the optimization of the machine performance by adjusting machine parameters according to the measured BLM signals. Cherenkov BLMs detectors based on optical fiber as sensing material, could be a suitable solution to detect beam losses over tens of meters.

During beam operation, the interaction of beam particles with accelerator components generates secondary showers of charged particles that can potentially induce Cherenkov light inside a silica based fiber. A fraction of these photons will be transported along the device and detected at the fiber extremities by the photo-detectors, working mostly in the Ultra-Violet capture range. This technology is currently under development in several HEP institutes around the world [1–3].

In this paper the progress of the design and characterization of such a silica fiber based detector is reported. Moreover, the experimental results, obtained with an electron beam at the CLEAR facility, are discussed with the aim of preparing the installation of a Cherenkov BLM prototype at the CERN Super Proton Synchrotron (SPS) [4], covering the slow extraction to the North Experimental Area. The challenge here will be to apply loss localisation for losses coming from unbunched proton beam, in a high radioactive environment introducing additional complexity in the maintenance and operation of this area.

TEST-BENCH SETUP

The CLEAR facility is devoted to general R&D, including beam diagnostics development for novel and existing accelerators [5]. It has accumulated a large community of users which benefit from the machine flexibility and the operation team support to carry out a large variety of different experiments. The accelerator can deliver an electron beam with a wide range of parameters [6].

The beamline is around 40 m long and offers the possibility of many experimental campaigns thanks to the high availability and access flexibility, since this facility is entirely independent of the LHC acceleration chain.

The tests presented in this report have been performed in the In-Air Test Stand, located at the end of the line, before the dump.

Different silica based fiber core-sizes have been selected, profiting from the high radiation tolerance of the quartz, to evaluate capture efficiency. The core diameters of the tested fibers have been 50, 105 and 200 µm.

The fibers have been installed on a rotating table, placing the fiber just in front of the beam path. The rotating table allowed to change the beam impact angle and cover a range between (−80, 80) degrees, where 0degree being the position where the fiber is perpendicular to the beam direction. Each fiber was tested individually, with the perpendicular position considered as the starting point. The anticlockwise and clockwise (negative and positive angles, respectively) movements have been set in 3-5 degrees steps approximately. Figure 1 shows the experimental setup.

---

[*] sara.benitez.berrocal@cern.ch

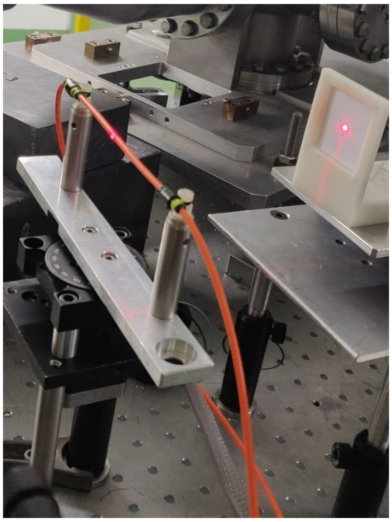

Figure 1: Test-bench of the optical fiber on a rotating table in the In-Air Test Stand at the CLEAR facility.

For the first set of measurements, the electron beam has been adjusted to a single bunch with charge fluctuation within the range of [20 - 40] pC and a transverse beam spot size of about 1.1 × 2 mm^2. This implies that part of the beam did not impact the fiber.

A secondary test performed at CLEAR was the exposure of the fiber to different beam intensities with fixed impact angle for all the shots (47.7°). The beam was setup with 30 bunches. The purpose of this test was to acquire the saturation curve of the photo-sensors.

Two models of SiPMs were used as photo-detectors. These devices are based on an array of independent single-photon avalanche diodes, so called pixels. When fired by a photon, each pixel will generate an output electric pulse [7]. These photo-sensors are connected to custom front-end read-out electronics.

The common module of the read-out system comprises a low-pass filter for the bias voltage and a high-pass RC filter on the signal output. The SiPM is mounted directly on the circuit board and an FC-PC type connector for the attachment of the optical fiber is located on the front of the module. The SiPM part numbers and their operational bias voltage used in these tests can be found in Table 1.

Table 1: Hamamatsu Silicon Photo-multipliers [8]

Code	Pixels	Op. Voltage
S12572-010C	90000	69.5 V
S12572-025C	14400	68.5 V

CHERENKOV LIGHT MODELLING

The FLUKA software [9] and its FLAIR [10] interface have been used to simulate the charged particle fluence at the fiber. The generation of Cherenkov photons, as well as their transport and capture inside the fiber has been simulated by using a custom model prepared for this study.

Each charged particle traversing the fiber at a speed larger than the Cherenkov threshold velocity, $\beta_{\text{th}} = 1/n = 0.685$, where $n = 1.46$ being the refractive index for the silica, will generate Cherenkov light. The number of generated photons, N, at a given wavelength λ, per particle travelled path length x, is given by Eq. (1) [11]

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2 sin^2\theta_C}{\lambda^2}. \qquad (1)$$

Where the α is the fine structure constant, z the particle's charge and θ_C the angle of Cherenkov light emission, in this case could be approximated to 47°. The Cherenkov radiation spectrum is mainly in the UV range and inversely proportional to the wavelength.

Light attenuation is mostly due to Rayleigh scattering in the fiber [12]. The attenuation factor is also implemented in the model and can be seen in Fig. 2. For the two meter-long multi-mode fibers considered in the experimental setup, the attenuation is mostly affecting the wavelength ranges between [200, 400] nm. For longer fibers the UV range gets heavily subtracted.

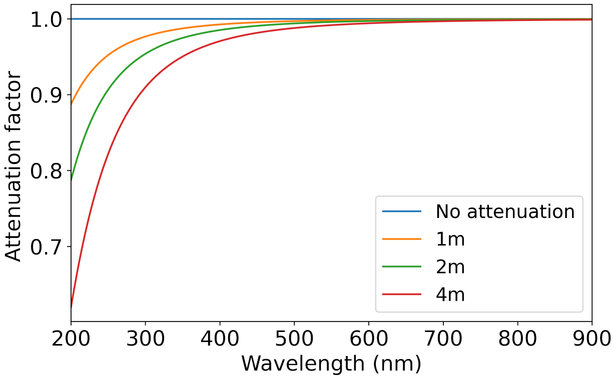

Figure 2: The attenuation factor in the optical fibers increases with length. The CLEAR setup uses 2 m silica fibers coupled with SiPM working in the range [290, 900] nm.

When a particle interacts with the quartz material of the sensor, it may generate photons but only a portion of the total amount will be trapped and propagate along the fiber to reach its extremity. This probability $\mathrm{P}_{e,n}$ has been calculated using Eq. (2) described in [13]

$$\mathrm{P}_{e,n} = \frac{1}{\pi} \arccos\left(\frac{\beta\sqrt{n_{co}^2 - \mathrm{NA}^2} - \cos\phi}{\sin\phi\sqrt{\beta^2 n_{co}^2 - 1}}\right). \qquad (2)$$

Where, ϕ is the incident angle between the particle track and the fiber axis, NA the acceptance light cone, defined by the equation $NA = \sqrt{n_{co}^2 - n_{cl}^2}$, being n_{co} and n_{cl} the refraction indexes of the fiber core and the cladding respectively and β is the velocity factor defined as $\beta = \sqrt{1 - 1/\gamma^2}$, where γ is the Lorentz factor.

EXPERIMENTAL SETUP MEASUREMENTS

Figure 3 shows the result of the angular scan performed during the test for the 105 µm core diameter fiber. For each point, the signal has been normalized at the bunch charge to compensate the fluctuation introduced by the single bunch instability between shot to shot. The result is expressed in V/bunch assuming an average bunch charge of 25 pC.

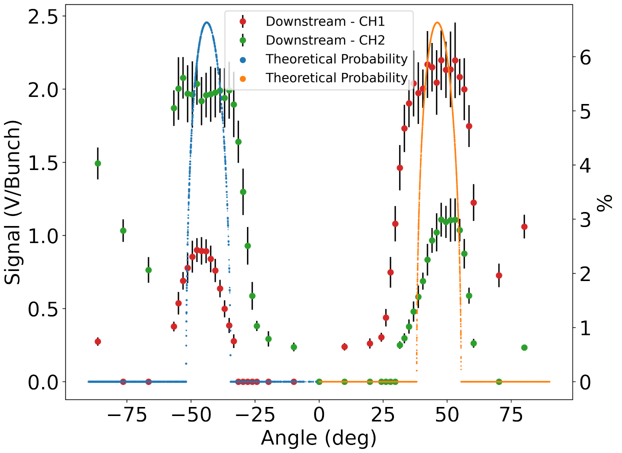

Figure 3: Probability of light capture in the 105 µm core diameter fiber at the CLEAR experiments. The maximum points are within the Cherenkov range $\theta = \pm[39°, 52°]$ for silica fibers.

The values of maximum probability of capture are close to the Cherenkov angle $\theta \approx \pm 47°$ for silica fibers, this is also expected by the model [Eq. (2)]. In Fig. 3, it is also possible to observe certain saturation of the photo-sensors for this angles. An increase in the signal's level is also observed for the angles ±80° which is attributed to multi-directional shower produced when the beam scatters on the metallic holders of the rotating table.

Figures 4 and 5 show the results obtained in the intensity scan. The raw signal from the scope during one of the beam impacts with 30 bunches is displayed in Fig. 4. The total beam charge was of 110 pC, for this particular case. The signal reveals a horizontal plateau which corresponds to the total time of beam exposure 19.98 ns, for the 30 bunches with a bunch spacing of 0.666 ns and an average bunch duration of 10 ps. The curve of the intensity scan in Fig. 5 indicates that the photo-detectors start to saturate from a bunch charge above 20 pC/Bunch.

SUMMARY AND FUTURE PLAN

A set of Cherenkov BLM experiments at the CLEAR facility have been performed to understand and analyze the Cherenkov phenomenon and its characteristics inside silica multi-mode fibers. Measurements of particle impact at different angles have been compared with the expected model, observing qualitative agreement. The results obtained in CLEAR have permitted to measure the angular dependence of the capture efficiency in the fiber. This data will be used to benchmark the simulation model, allowing for an extrapolation of the optimum fiber core size for other experiments such as the future installation of this prototype at the SPS slow-extraction. The test at the CLEAR facility was also providing very valuable information on the performance of the detector read-out. Future tests are already foreseen to study the impact of the direct radiation to the photo-sensors.

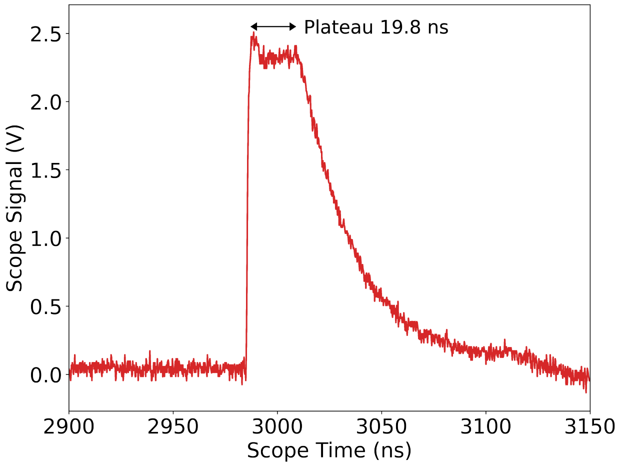

Figure 4: Signal obtained from the intensity scan for a fiber fixed at an angle 47, 7° with respect to the beam. The electron beam was set up to 30 bunches. In this example, the total beam charge is 110 pC.

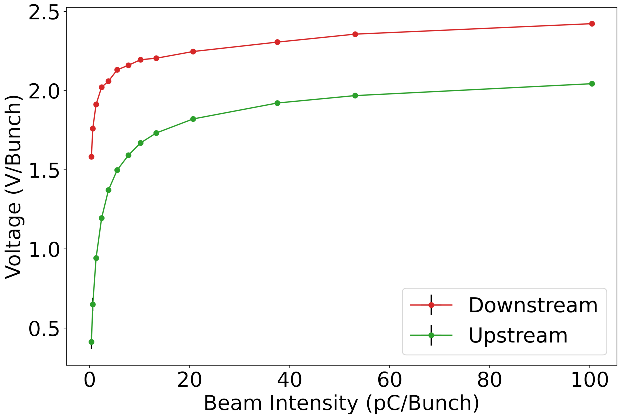

Figure 5: Peak signal from the photo-sensor as function of the average bunch charge (using a beam of 30 bunches). Saturation in the photo-sensors can be observed around 20 pC. Fixed impact angle at 47, 7°.

ACKNOWLEDGEMENTS

The authors of this paper would like to thank the SY-BI-BL section for the support and help to setup the experiments, as well as the CLEAR operation crew for their invaluable help on the preparation and execution of the tests.

REFERENCES

[1] A. S. Fisher *et al.*, "Beam-Loss Detection for LCLS-II", in *Proc. 8th Int. Beam Instrumentation Conf. (IBIC'19)*, Malmö, Sweden, Sep. 2019, pp. 229-232. `doi:10.18429/JACoW-IBIC2019-TUAO02`

[2] K. Wittenburg, "Beam loss monitors", 2020. `arXiv:2005.06522`

[3] M. Kastriotou, "Optimisation of storage rings and RF accelerators via advanced fibre-based detectors", Ph.D. thesis, The University of Liverpool, Liverpool, United Kingdom, 2018.

[4] The Super Proton Synchrotron, `https://home.cern/science/accelerators/super-proton-synchrotron`

[5] M. Brugger *et al.*, "The CLEAR facility at CERN", CERN, Geneva, Switzerland, 2016.

[6] K. N. Sjobak *et al.*, "Status of the CLEAR Electron Beam User Facility at CERN", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 983-986. `doi:10.18429/JACoW-IPAC2019-MOPTS054`

[7] S. Gundacker and A. Heering, "The silicon photomultiplier: fundamentals and applications of a modern solid-state photon detector", *Physics in Medicine & Biology*, vol. 65, p. 17TR01, 2020. `doi:10.1088/1361-6560/ab7b2d`

[8] Hamamatsu, `https://www.hamamatsu.com/eu/en/index.html`

[9] FLUKA, `https://fluka.cern/home`

[10] Flair by CERN, `http://flair.web.cern.ch/flair/`.

[11] L. Rädel, and C. Wiebusch, "Calculation of the Cherenkov light yield from low energetic secondary particles accompanying high-energy muons in ice and water with Geant4 simulations", *Astroparticle Physics*, vol. 38, pp. 53-67, Oct. 2012. `doi:10.1016/j.astropartphys.2012.09.008`

[12] M. E. Wandel, "Attenuation in silica-based optical fibers", Ph.D. thesis, Department of Communications, Optics & Materials, Technical University of Denmark and at OFS Denmark, Copenhagen, Denmark, 2005.

[13] S. H. Law *et al.*, "Optical fiber design and the trapping of Cerenkov radiation", *Applied optics*, vol. 45, no. 36, pp. 9151-9159, 2006. `doi:10.1364/AO.45.009151`