# CHERENKOV FIBRE OPTIC BEAM LOSS MONITOR AT ALICE

A. Intermite[1, 2#], M. Putignano[1, 2], A. Wolski[1, 2]
[1] Cockcroft Institute, Daresbury, UK.
[2] Department of Physics, University of Liverpool, Liverpool, UK.

*Abstract*

The need for real-time monitoring of beam losses, including evaluation of their intensity and the localisation of their exact position, together with the possibility to overcome the limitations due to the reduced space for the diagnostics, makes optical fibres (using the Cherenkov effect) one of the most suitable and explored candidates for beam loss monitoring. In this contribution, we report on an optical fibre beam loss monitor based on large numerical aperture pure silicon fibres and silicon photomultipliers, tested at ALICE, Daresbury Laboratories, UK. The original design of the sensor has the advantage to combine the functions of a real time detector and a transmission line. It also allows reading the signals independently and determining the time and position of the losses without the use of an external trigger.

## OPTICAL FIBRE SENSOR DESIGN

A beam loss monitor (BLM) based on Cherenkov light in optical fibres detected at the end of the fibres by silicon photomultipliers (SiPM) allows real time monitoring of loss location and loss intensity. Lost electrons hit the vacuum pipe and create a shower of secondary electrons. These showers penetrate the optical fibre and generate Cherenkov radiation [1]. A system consisting of two parallel fibres directly coupled to two identical SiPMs, with an active surface matched to the fibre core of 1 mm$^2$, is under consideration. Each signal is read independently and the absolute position of the loss can be calculated from the properties of the signals from the SiPMs. The SiPMs have the same quantum efficiency (in the wavelength range of interest) as standard PMTs, to which they can be promising alternatives for this application.

The first fibre is used to carry a reference signal, and is chosen to be a UV low attenuation, step index fibre with a pure silicon large core diameter. This maximizes the length of interaction with the escaping particles and thus the production of Cherenkov photons. The second arm is instead a composite sensor, realized by alternating sections of a fibre identical to the one in the first arm with equally long sections of a different fibre with larger attenuation. The layout of the sensor is shown in Fig.1. Because of the increased attenuation, the number of Cherenkov photons reaching the SiPM at the end of the second arm will be smaller than the number reaching the SiPM in the first arm. The reduction factor depends on how many sections of the higher attenuation fibre were crossed and, therefore, on the position of the loss.

[#] angela.intermite@stfc.ac.uk

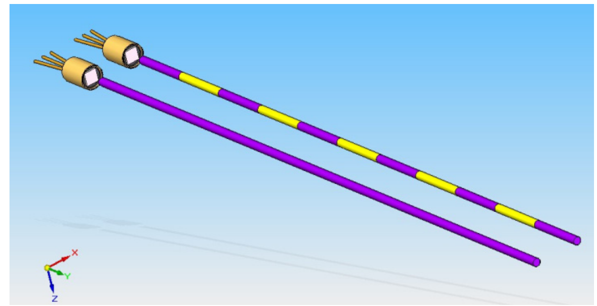


Figure 1: Schematic showing two arms of the optical fibre beam loss monitor.

Simulation studies indicate that this sensor has the ability to achieve a resolution down to a few centimetres, depending mainly on the length of the spliced fibre sections in the second arm of the sensor. Since each signal is read independently (and the absolute position calculated from the intensity ratio) there is no overlap of the signals, and it becomes possible to detect multiple signals without using clock triggers.

## EXPERIMENTAL RESULTS

### *Tests of the First Arm*

Experimental tests were carried out at the ALICE accelerator R&D facility at Daresbury Laboratory [2], with the aims: (1) to demonstrate the suitability of the sensor for loss monitoring; (2) to optimize the collection efficiency (CE) of the Cherenkov photons inside the fiber as a function of the particle incident angle; and (3) to understand the limits of temporal resolution for losses from bunches in the accelerator. For the test described here, ALICE was used to provide single bunches of charge 63 pC, electron energy 27.5 MeV, at a repetition frequency of 1 Hz. For measurements of the CE, a Be window of thickness 0.4 mm was mounted on an extraction line following a dipole in the beamline, to allow the beam to pass through. The fibre was mounted on a rotational stage (positioned on an optical table) whose angle and vertical position was remotely controlled by stepper motors. A Faraday cup internal to the accelerator was used for measuring the beam current. The fibre was connected at one end to the SiPM detector and its electronics, situated below the optical table to minimise irradiation from the beam.

Without any beam passing through the fibre, the detector signal was due only to dark noise. As soon as the beam passed through the Be window and hit the fibre, a clear signal was observed on the detector (see Fig. 2).

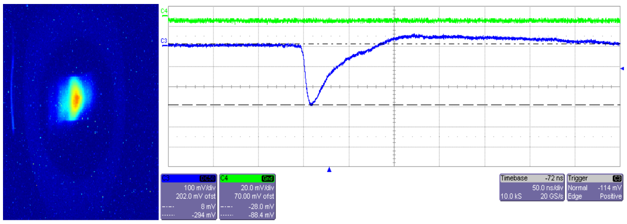

Figure 2: Left: transverse profile of a beam in ALICE with energy 27.5 MeV and bunch charge 63 pC. Right: Detector response (blue line) when the beam is passing through the fibre.

### Angular Dependence of the Cherenkov Signal

The Cherenkov effect in optical fibres has a high directionality. A C++ code was developed for modelling the system under study [3]. The software calculates the CE as a function of the incidence angle of the charged particle with respect to the fibre axis and the impact parameter, taking into account the contribution of both meridional and skew rays and the fibre cleaving angle. For a fibre with the same geometrical properties as the one used in ALICE, the angle that maximizes the CE is about 48-50° for meridional rays. In the experiment, the angle of the fibre was changed rotating the stage in steps of 5.4°, in both clockwise and anticlockwise directions. The detector response was recorded on the oscilloscope; the variation of the signal amplitude with rotation angle is shown in Fig.3.

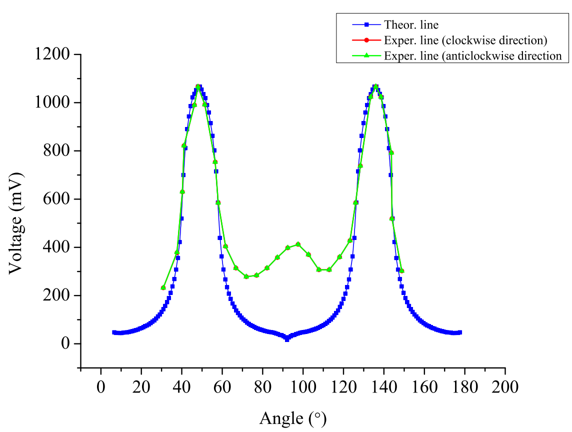


Figure 3: Maximization of the Cherenkov angle as a function of the signal amplitude in both directions compared with the theoretical curve (blue squared line).

Essentially identical results are obtained when rotating the fibre in either direction. The CE is at a maximum at an angle of 49° between the beam and the fibre: this is in excellent agreement with the theoretical results. The small peak in the CE within the range between 60° and 120° (where the model predicts that the signal should be flat) is due to beam interactions with the metallic posts that supported the fiber. The particles scattered from these posts produced additional secondary electrons detected by the sensor.

### Sensor Response to Multiple Bunches

For testing the time response of the detector, the number of bunches within a pulse was changed. The laser source is pulsed and produces electron bunches with a spacing of 12 ns. Fig. 4 shows the detector response for 50 bunches. Although the recovery time of the detector is relatively slow, the fast rise time (less than 12 ns) means that individual bunches within ALICE can be resolved.

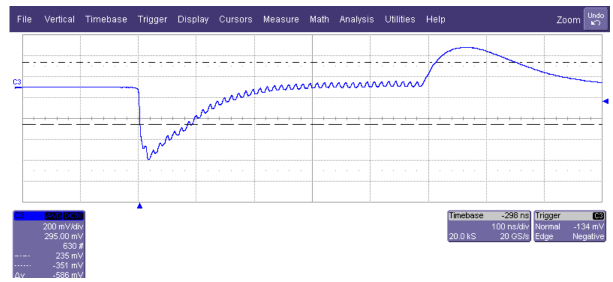


Figure 4: Detector response for 50 bunches with a spacing of 12 ns.

### Test of the Second Arm

The second arm of the beam loss monitor was assembled and tested in lab. A schematic of the experimental setup used for the experiments is shown in Fig. 5. A laser "pigtailed" with a fibre of 50 µm core (the red fibre shown in Fig. 5) was connected directly (without any splicing) to a power meter. The power as a function of laser current was measured, to provide a reference line. Then, three Si high radiation hardness fibres with different core radius (62.5, 105 and 200 µm) were spliced within the original fibre. Splicing was performed using a Fujikura splicer FMS-45PM. The variation of the measured laser power with current was measured, and compared with the reference line. The power vs current curves are shown in Fig. 6, and the percentage of transmitted light with the different spliced fibres is given in Table 1.


Figure 5: Schematic of the experimental setup used for testing the second arm of the sensor.

The 200 µm fibre was the most promising for increasing the CE of Cherenkov photons but, due to technical limitations of the splicer, the splicing was extremely difficult to realize. The poor interface quality results in losses of some tens of dB: therefore, the amount of transmitted light was very limited. In addition, removing the external plastic buffer for performing the splicing made the 200 µm fibre very fragile. A beam loss monitor using alternating sections of 200 µm fibre with some other fibre would be extremely difficult to install in an accelerator.

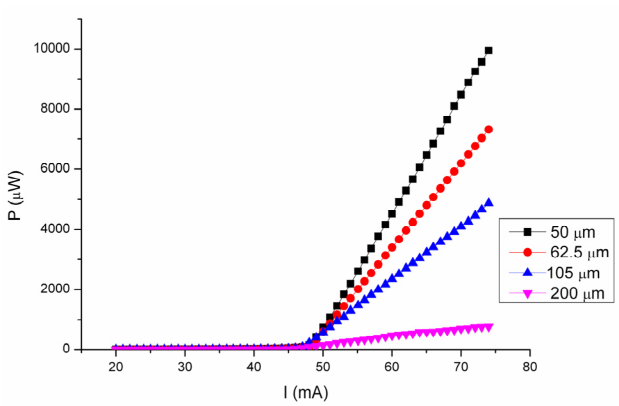


Figure 6: Measured power versus laser current with different spliced fibres. The black squares show the reference line (50 µm core, without any splicing).

Table 1: Fraction of transmitted light with different spliced fibres, relative to the unspliced fibre (with radius 50 µm).

| Spliced fibre core radius | Transmitted light |
|---|---|
| 50 µm | 100% |
| 62.5 µm | 73% |
| 105 µm | 46% |
| 200 µm | 7% |

The fibre with radius 105 µm looks to be a better solution than the fibre with core radius 200 µm. However, the loss of 54% of the light with only two interfaces between fibres is very large for purposes of the beam loss monitor (which would require many interfaces over a long distance). Furthermore, the splicing process necessitates the removal of the external buffers, resulting in an intrinsic fragility of the fibre.

To overcome the first problem, it was considered to construct the second arm using fibres with similar radius, i.e. 62.5 µm and 50 µm. However, even in this case the loss in light intensity from each interface is rather large. But also, the small numerical aperture associated with the small radius reduces the acceptance angle and, therefore, the CE. This would be a particular difficulty for monitoring losses in relatively low energy beams, with energy close to the Cherenkov threshold energy (0.192 MeV for electrons), due to the reduced number of Cherenkov photons produced and collected inside the fibre. Though for machines such as ALICE, where the beam energy is well above threshold, this may not in itself be a strong limitation.

## CONCLUSIONS

Aspects of a novel beam loss monitor using the Cherenkov Effect in optical fibres and a SiPM as detector have been tested at ALICE, Daresbury Laboratories. The sensor has a real time response to the signal passing through the fibre due to the fast rise time of the detector used in the experiment and is potentially able to resolve bunches with a spacing of 12 ns. Experimental results for the collection efficiency as a function of incident angle of the beam have been compared with simulations, showing excellent agreement.

Tests of the second arm of the sensor demonstrated the feasibility of the splicing process for selectively changing the attenuation of the fibre, although serious limitations have been identified. In particular, use of high numerical aperture (NA) fibres would result in poor quality interfaces, with resulting high loss rates for the Cherenkov photons, and very fragile fibres. Even using low NA fibres, the loss rates for the Cherenkov photons would still be higher than desired; and the CE would be significantly reduced.

The study described here was limited to commercially-available fibres, and manual splicing techniques. It is possible that use of fibres with customised specifications, and industrial fabrication processes for the second arm (including the replacement of the plastic buffer around the region of each interface), could solve the problems that have been identified, although it would add significantly to the cost of the beam loss monitor.

## REFERENCES


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