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RADIATION HARD BEAM PROFILE MONITORS FOR THE NORTH EXPERIMENTAL BEAMLINES CERN

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Abstract

A new radiation hard profile monitor is being researched and developed for the North Area Beamlines at CERN. The monitor must have a spatial resolution of 1 mm or less, an active area of 20 x 20 cm, a low material budget (0.3%) and be operational in a beam that has a rate of ~2×10^{11} p/s in the full energy range of 0.5 – 450 GeV/c. The current focus is the study of different detection mediums: silica optical fibres (Cherenkov radiation) and glass capillaries filled with liquid scintillator. Prototypes of the different fibre candidates have been tested at different beam facilities at CERN: the M2 beamline and IRRAD. The key properties tested are the light yield and radiation tolerance.

INTRODUCTION

Since the late 1970s, Multi Wire Proportional Chambers, Delay Wire Chambers and Filament Scintillators have been used in the North Area Beamlines to provide the profile and positions of the beams [1]. However, the performance of these detectors is now degrading due to aging effects and there are limitations on the maximum intensity at which they can operate. As part of an upgrade to the beamlines, starting from 2027, the majority of these detectors will be replaced [2]. For the low intensity beamlines (~ 10^8 particles per spill), a scintillating fibre detector called the eXperimental Beam Profile Fibre monitor (XBPF) will be installed [3]. The XBPF consists of a single array of 192 plastic scintillating fibres (SCSF-78) from Kuraray with a square cross-section and 1 mm thickness. Each fibre is individually read-out using si-pm's. A photograph of an XBPF is shown in Fig. 1. For the high intensity beamlines (~ 10^{11} particles per spill), the XBPF is not expected to have sufficient radiation tolerance, therefore a new radiation hard profile monitor is currently being researched and developed. Ideally the new detector will have a similar silhouette to the XBPF, but the active medium will be replaced with a material that has a higher radiation tolerance. This article describes the different detection mediums that are being studied and presents recent beam test results.

DETECTOR REQUIREMENTS

The new radiation hard profile monitor has the following requirements:

- active area of 20 cm × 20 cm,
- a low as possible material budget (~0.3% X_0),

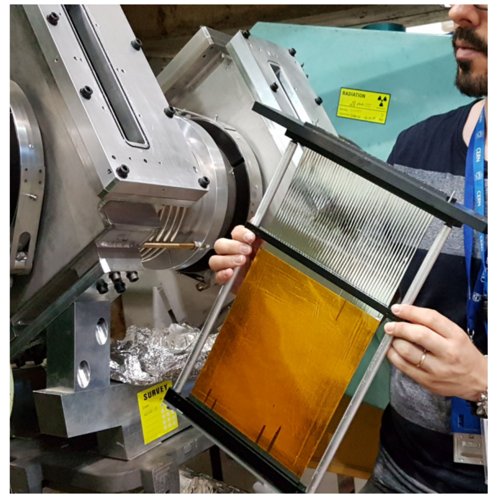

Figure 1: The XBPF detector.

- a spatial resolution of 1 mm,
- measure particle rates from ~ 10^4 to ~ 10^{11} in the full energy range of 0.5 – 450 GeV/c,
- operational up to 2 MGy, equivalent to a minimum of 8 years of operation, and
- operational in vacuum (10^{-3} mbar) and in air.

ACTIVE MEDIUMS

Two different active materials are currently being studied: silica optical fibres and silica capillary fibres filled with liquid scintillator.

Silica Optical Fibres

Silica optical fibres are widely used in the telecommunications industry. They consist of a central silica core surrounded by a cladding layer which has a lower refractive index, enabling the transmission of light via total internal reflection. A well-known phenomenon is the production of Cherenkov light in silica fibres when charged particles pass through them [4]. Often for data transmission in high radiation environments, for example high energy physics experiments, this is an unwanted source of background. However, for some applications, this phenomenon can be exploited as a signal, such as Beam Loss Monitors [5].

The Cherenkov light peaks in the UV wavelengths and is emitted in a cone relative to the impinging particles direction. The angle depends on the refractive index of the

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material and the velocity of the charged particle, which is expected to be ~ 40° in silica for relativistic particles [6]. Silica quartz is known to be more radiation hard compared to plastics [7]. There are, however, two consequences of irradiation damage that will effect the performance: radiation induced attenuation which decreases light transmission and a change in the refractive index [7].

For fibre testing, multimode optical fibre's were purchased from Thorlabs with two different diameters, 600 µm and 1000 µm. These fibres where cut to 20 cm lengths using a ruby fibre scribe. Additionally, quartz glass rods of 1000 µm, and length 20 cm were purchased from Hilgenberg GmbH. These rods have no cladding and therefore have a higher refractive index gradient with respect to air, hopefully increasing the trapping efficiency of the light.

Capillary Fibres

Capillary fibres are small tubes of quartz glass with a hollow core. They propagate light via total internal reflection if you fill them with a material with a higher refractive index than glass. One option is to fill them with liquid scintillator. Traversing charge particles will produce scintillation light which will then be propagated towards the end of the fibre. Liquid scintillators are intrinsically more radiation hard than plastic scintillators. From literature, it was found that the light yield of liquid scintillator EJ-309[1] decreases 25% per 0.5 MGy compared to a 30% decrease per 10 kGy for plastic scintillators [3, 8]. Also from literature, liquid scintillator BC-599-13, was found to have no change in light transmission up to 1 MGy [9]. Radiation damage will occur in the quartz glass capillary but as long as the refractive index remains lower than the liquid scintillator, light should still propagate.

Two different glass capillaries were purchased from Hilgenberg GmbH, both with length 20 cm and an outer diameter of 1000 µm. One fibre type had a inner diameter of 580 µm and the other, 800 µm. A larger inner diameter will give a larger light yield but are more breakable. The capillaries were filled with liquid scintillator EJ-309 from Eljen Technology. The refractive index of the scintillator is 1.57 and the wavelength of maximum emission is 424 nm. The liquid was contained in the fibre by gluing both ends using NOA61 UV cure optical adhesive [10]. A photograph of a liquid filled capillary is shown in Fig. 2.

Figure 2: A liquid filled capillary when exposed to UV torch.

BEAM TESTS

Different fibre tests have been performed at two different beam facilities at CERN: The M2 beamline and IRRAD.

[1] EJ309 liquid base containing 16% of the fluorescent dye DSB1

The M2 Prototype

The M2 beamline is part of the North Experimental Area CERN. Currently the M2 beamline can provide high-energy and high-intensity hadron beams, at a momentum of 280 GeV/c and a maximum rate of 10^8 particles per spill. The line can also provide muons and electrons [1]. A prototype device has been installed 69 m from the target.

A photograph of the M2 prototype is shown in Fig. 3. The prototype is made up of three different fibre sections with 64 fibres each of: 1000 µm optical fibres, EJ-309 filled capillary fibres with inner diameter 580 µm, and 600 µm silica optical fibres. They are readout individually by the si-pms on the XBPF readout board. The prototype can be rotated around the *y*-*z* axis and is mounted on a linear motor along the *y*-axis. A blackbox is placed over the prototype during operations.

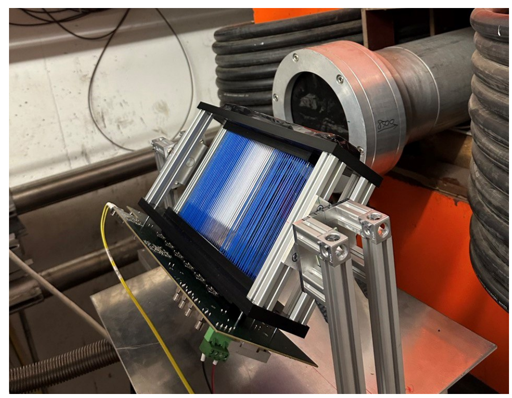

Figure 3: The M2 prototype rotated at 45°.

IRRAD Tests

IRRAD is a proton irradiation facility at CERN. IRRAD provides a slowly extracted primary proton beam of momentum 24 GeV/c delivered in spills with a maximum intensity of 5×10^{11} particles per spill over a duration of ~ 400 ms [11].

A quartz silica rod and a EJ-309 filled capillary (inner diameter of 800 µm) were installed at IRRAD to test their light yield and light transmission while being irradiated up to 2.85 MGy. The rod and fibre were each attached to a 30 m 1000 µm silica optical fibre (glued using NOA61), known as a transport fibre, to transmit the light from the irradiation area to a CMOS camera in the barracks. Two 12 V halogen bulbs where programmed to flash in between spills of the beam to check the light transmission. A photograph of the IRRAD setup is shown in Fig. 4. A blackbox is placed over the setup during operations. The exposure of the camera was set to 500 ms to ensure the full particle spill was captured and optical filters were placed over the end of transport fibres to stop camera saturation.

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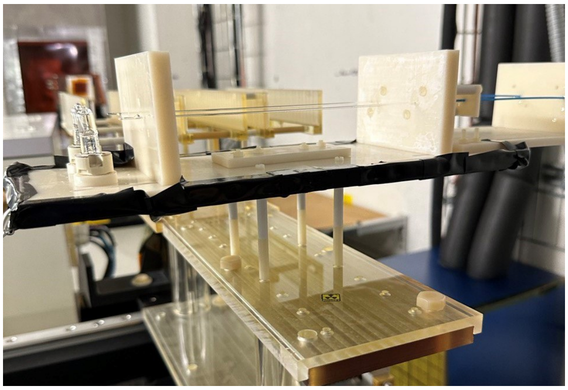

Figure 4: A quartz rod and EJ-309 capilary fibre installed at IRRAD. Two halogen bulbs are seen on the left and the transport fibres are seen on the right (blue cladding).

RESULTS

The M2 Prototype

The M2 prototype was tested with a mixed hadron beam with a momentum of 190 GeV/c and a rate of $\sim 3 \times 10^5$ particles per spill. A nearby scintillation paddle was used to trigger the detector and reduce noise. Example profiles are shown in Fig. 5, measured when the prototype was placed 45° relative to the beam. Insufficient signal was measured in the silica fibres when the prototype was perpendicular to the beam. A higher signal was measured in the capillaries compared to the silica optical fibres (30% compared to the 1000 µm silica fibre), as expected. A 76% lower signal was measured in the 600 µm compared to the 1000 µm. The reduced signal when comparing the 600 µm and the 1000 µm silica fibres is not linear, this could be accounted for by the inconsistent cutting techniques that may result in varied light losses. A summary of the beam profile σ and average efficiencies are shown in Table 1.

Table 1: M2 Prototype Results Summary

Fibre type	Profile σ	Efficiency %
1000 µm	3.50 ± -0.03	46.4
EJ-309 Capillary	3.92 ± 0.04	64.8
600 µm	3.57 ± 0.01	15.1

IRRAD Tests

The IRRAD setup, as shown in Fig. 4, was installed for one week. The average rate was 5×10^{11} particles per spill and there were limited periods of no beam. The max dose reached was 2.85 MGy in an area of 10×10 mm^2. An example image taken by the camera when the bulbs were flashing is shown in Fig. 6. The integral of each light spot was calculated and plotted for each spill as a function of the timestamp for when the bulb was flashed and when the beam was traversing. The light transmission and the light yield for the quartz rod are shown in Figs. 7 and 8 respectively.

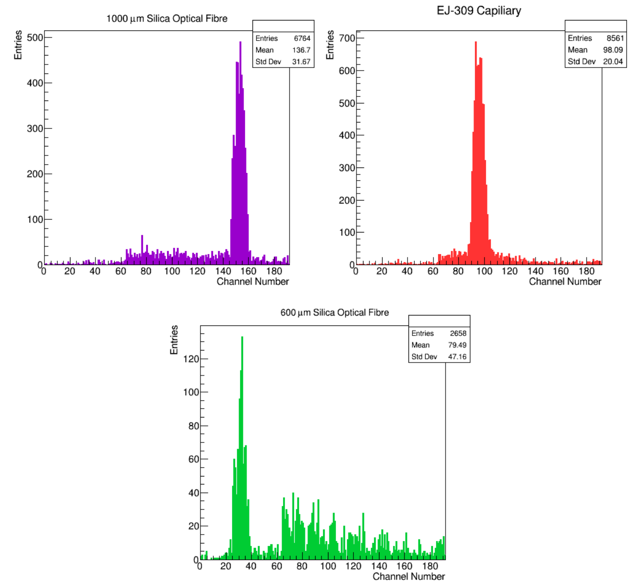

Figure 5: Beam profile measuring using 1000 µm silica fibres (top left), EJ-309 capillaries (top right), 600 µm silica fibres (bottom).

Both the light transmission and light yield decrease exponentially with a 66% drop in transmission and a 95% drop in light yield. The bulb emits a wide spectrum of wavelengths, whereas Cherenkov light peaks in the UV. The lower light yield may be due to increased absorption in the UV wavelengths. Increased light transmission is seen during short periods over the week which correlate to periods of no beam. This increase is due to annealing. The light transmission and the light yield for the EJ-309 capillary are shown in Figs. 9 and 10 respectively. The light transmission only fluctuated 3%, suggesting a negligible difference in light transmission, as reported in literature [9]. The light yield decreased 50%. These results suggest that the radiation tolerance of the EJ-309 capillary is higher compared to the quartz rod.

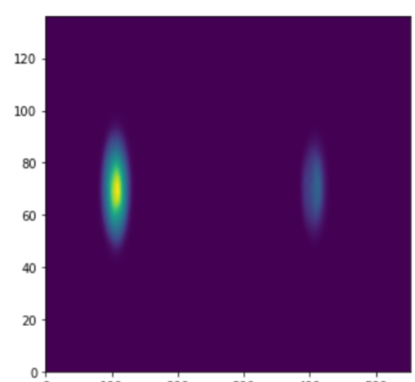

Figure 6: An example image from the CMOS camera when the bulbs are flashing. The light from the quartz rod is seen on the left and the capillary is shown on the right.

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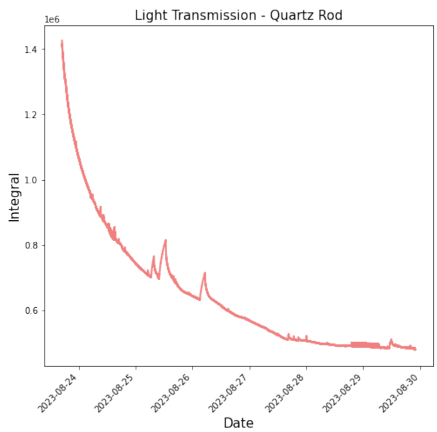

Figure 7: Light transmission of the quartz rod.

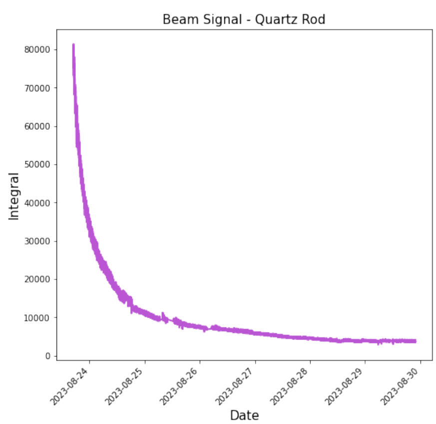

Figure 8: Light yield of the quartz rod.

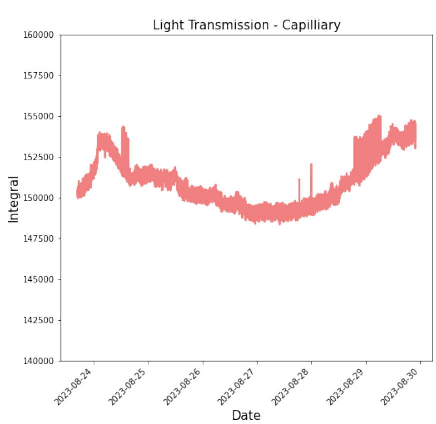

Figure 9: Light transmission of the EJ-309 capillary.

CONCLUSION

The beam profile monitors currently installed in the North Area Beamlines need to be replaced and upgraded. A scintillating fibre detector, called the XBPF will be installed in the lower intensity beamlines (~ 10^8 particles per spill). These devices do not have the required radiation tolerance for the higher intensity beamlines (~ 10^{11} particles per spill), therefore a new radiation hard profile monitor is required.

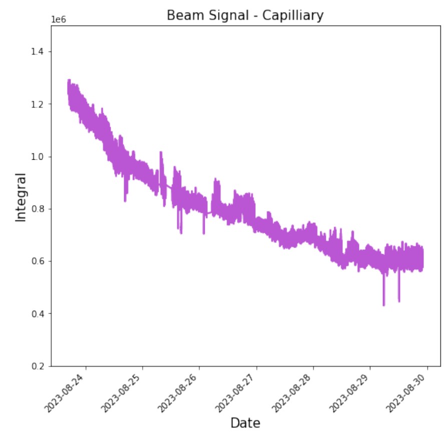

Figure 10: Light yield of the EJ-309 capillary.

Silica optical fibres and liquid scintillator filled capillary fibres were tested as options for a new active material replacing the scintillation fibres. From tests performed at the M2 beamline CERN and IRRAD, it was found that liquid filled capillaries have a higher radiation tolerance, in terms of both light transmission and light yield compared to silica quartz rods. This R&D effort is still ongoing. The M2 prototype needs to be tested at higher particle rates to check that sipms do not reach saturation. Additionally, a new fibre type will be tested: hollow core optical fibres [12] filled with a scintillation gas will be qualified later this year.

REFERENCES

[1] D. Banerjee *et al.*, "The North Experimental Area at the CERN Super Proton Synchrotron", CERN, Geneva, Switzerland. CERN-ACC-NOTE-2021-0015, Jul. 2021. `https://cds.cern.ch/record/2774716`

[2] "Medium-Term Plan for the period 2023-2027 and Draft Budget of the Organization for the sixty-ninth financial year 2023", CERN, Geneva, Switzerland. CERN/SPC/1182/Rev., Sept. 2022. `https://cds.cern.ch/record/2838413`

[3] I. Ortega Ruitz *et al.*, "The XBPF, a new multipurpose scintillating fibre monitor for the measurement of secondary beams at CERN", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 951, p. 162996, Jan. 2020. `doi:10.1016/j.nima.2019.162996`

[4] S. Girard *et al.*, "Overview of radiation induced point defects in silica-based optical fibers", *Rev. Phys.*, vol. 4, 2019. `doi:10.1016/j.revip.2019.100032`

[5] S. Benítez Berrocal *et al.*, "Beam loss localisation with an optical beam loss monitor in the CLEAR facility at CERN", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, pp. 351-354. `doi:10.18429/JACoW-IPAC2022-MOPOPT045`

[6] A. S. Beddar *et al.*, "Cerevkov light generated in optical fibres and other light pipes irradiated by electron beams", *Phys. Med. Biol.*, vol. 37, p. 925, Jul. 2000. `doi:10.1088/0031-9155/37/4/007`

[7] V. Hagopian, "Radiation damage of quartz fibers", *Nucl. Phys. B Proc. Suppl.*, vol. 78, no. 1, pp. 635-638, 1999. `doi:10.1016/S0920-5632(99)00616-7`

ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-WE3C03

[8] R. Ruchti *et al.* "Thick-wall, liquid-filled quartz capillaries for scintillation and wavelength shifting applications", in *38th Int. Conf. on High Energy Physics - Poster Session (ICHEP'16)*, Chicago, USA, Aug. 2016. doi:10.22323/1.282.0935

[9] M. Gui *et al.,* "Radiation damage effects on liquid scintillating fibers", *Radiat. Phys. Chem.*, vol. 41, no. 1, pp. 237-242, 1993. doi:10.1016/0969-806X(93)90061-X

[10] M. Montecchi and Q. Ingram, "Study of some optical glues for the Compact Muon Solenoid at the large hadron collider of CERN", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 465, no. 2, pp. 329–345, 2001. doi:10.1016/S0168-9002(01)00678-7

[11] B. Gkotse *et al.*, "IRRAD: The New 24 GeV/c Proton Irradiation Facility at CERN", in *Proc. 12th Int. Topical Meeting on Nuclear Applications of Accelerators (AccApp'15)* Washington D.C., USA, Nov. 2015. https://inspirehep.net/literature/1688990

[12] H. Sakr *et al.,* "Hollow core optical fibres with comparable attenuation to silica fibres between 600 and 1100 nm", *Nat. Commun.* vol. 11, Nov. 2020. doi:10.1038/s41467-020-19910-7

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