A scintillating fibre beam profile monitor for the experimental areas of the SPS at CERN

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Abstract. The CERN Super Proton Synchrotron (SPS) delivers a wide spectrum of particle beams (hadrons, leptons and heavy ions) that can vary greatly in momentum and intensity. The profile and position of these beams are measured using particle detectors. However, the current systems show several problems that limit the quality of such monitoring. We have researched a new monitor made of scintillating fibres read-out with Silicon Photomultipliers (SiPM), which has the potential to perform better in terms of material budget, range of intensities measured and available detector size. In addition, it also has particle counting capabilities, extending its use to spectrometry or Time-Of-Flight measurements. Its radiation hardness is good to guarantee years of functioning. We have successfully tested a first prototype of this detector with different particle beams at CERN, giving accurate profile measurements over a wide range of energies and intensities. It only showed problems during operation with lead ion beams, believed to come from crosstalk between the fibres. Investigations are ongoing on alternative photodetectors, the electronics readout and solutions to the fibre crosstalk.

1. Introduction

In the experimental areas of the SPS, protons are extracted during 4.8 seconds and collided with primary, secondary and sometimes tertiary targets, in order to produce beams of particles that can be selected and sent to the experimental users. These beams can be composed of hadrons (protons, kaons, pions, antiprotons...), leptons (electrons, positrons, muons...) and lead ions. Their momenta can vary greatly, from 1 to 400 GeV/Z/c, and their intensities from $10^3$ to $10^8$ particles per second. The profile and position of these beams are typically measured using particle detectors based on gaseous active materials (multi-wire proportional chambers (MWPC), delay wire chambers (DWC) and gas electron multipliers (GEM)) or scintillators (finger scan scintillators (FISC)). Replacement detectors for wire chambers are actively being sought as they are ageing and the expertise to produce them is gradually being lost.

In addition, two new beam lines dedicated to neutrino R&D will be commissioned in 2017, in collaboration with Fermilab and other institutes. These new lines will provide tertiary beams of hadrons and leptons with low energies (12 GeV down to 500 MeV), intensities of maximum $10^3$ particles per second and a beam spot of several cm in diameter. The monitors for these lines will form a spectrometer for particle momentum measurement and therefore need to count single particles, while the large spot size requires covering an area of $200 \times 200 \text{mm}^2$. This implies that the current monitors cannot be used in those beam lines: the MWPC and the FISC cannot...
provide single particle counting; the DWC, which can count individual particles is too small \((100 \times 100 \text{mm}^2)\); the GEMs are too thick in material budget for the low energy beams.

2. Scintillating fibres
Scintillating plastic fibres (SciFi) have emerged as one of the best active materials for the monitors of the experimental areas. They have a core made of polystyrene cladded with one or two layers of lower refractive index material. This gradient of refractive index allows a fraction of the light created inside the fibre to be trapped by total internal reflection. The polystyrene fibre core usually employs a two level doping system: a primary scintillator emitting in the UV and a wavelength shifter to capture the short reach UV photons and re-emit them in the visible wavelength region. This shift in wavelength also enhances the match in terms of quantum efficiency for common photodetectors. The processes of energy absorption, scintillation and wavelength shifting are mediated by very fast quantum processes that yield a photon time distribution with rise time and decay time of 1-3 ns [1]. Light production typically reaches up to 8000 photons per MeV of energy deposited, although the trapping efficiency of square fibres varies between 4.2\% and 7.3\% [2][3]. Depending on the amount of dopants, the light emitting properties of the fibres can be changed and their radiation hardness can be improved.

The two main manufacturers of scintillating fibres, Kuraray and Saint-Gobain, provide fibres with similar properties. The emission spectra from both peak between 430-450 nm, but the light yield and attenuation length differ, most likely due to differences in manufacturing, doping concentrations and scintillators used.

2.1. Radiation hardness
A very important characteristic of the detector is its radiation hardness. The detector should be able to operate continuously and reliably for years with beams of intensities of \(10^8\) particles/second or \(10^6\) Pb ions/s. The radiation damage is mainly manifested as a shorter attenuation length of the fibre resulting in less light collected by the photodetectors [4]. Short fibres are less susceptible to the effects of radiation damage with data from literature showing that short fibres can withstand doses of up to 10 kGy before showing significant damage [5].

Simulations of a SciFi detector carried out with Geant4 [6] show that for a single beam extraction of \(10^8\) particles, an absorbed dose of 100 mGy can be expected per fibre. Such short fibres should therefore withstand up to \(10^5\) of such beam extractions, guaranteeing several years of operation before having to be replaced.

2.2. Material budget
It is important for a beam monitor to perturb the measured beam as little as possible. A charged particle traversing a medium is deflected due to Coulomb scattering from nuclei, characterized by the radiation length \(X_0\) and the nuclear interaction length \(\lambda\). According to the multiple scattering theory of Molière [7], the angular distribution of the scattered particles has a root mean square (r.m.s.) given by:

\[
\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} Z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \left(\frac{x}{X_0}\right)\right].
\]  

(1)

Where \(x\) is the thickness of the material, \(Z\) the charge of the particle, \(p\) its momentum and \(\beta c\) its speed. We have studied the \(x/X_0\) of different monitors to establish a comparison between them. As shown in Table 1, a SciFi monitor composed of two planes (horizontal and vertical) of 0.5mm square fibres has a material budget slightly below the current monitors.
Table 1. Comparison of $x/X_0$ for different monitors

| Detector    | $x/X_0$ (%) |
|-------------|-------------|
| MWPC        | 0.34        |
| DWC         | 0.25        |
| SciFi 1 mm  | 0.47        |
| SciFi 0.5 mm| 0.24        |

3. First prototype
A first detector was built and tested in the H8 beam line of the SPS North Experimental Area at CERN. It was built with only one plane for simplicity. This plane is composed of 64 Saint-Gobain BCF-12 scintillating fibres of 1 mm thickness and square shape. The length of the fibres is 35 cm and they are packed together along one row, leaving no space between them. As the electronics readout chip used in this detector only has 32 channels, it was decided to read-out only every other fibre. This gives a spatial resolution of 2 mm within an active area of $64 \times 64 \text{mm}^2$. A mirror is glued on the end of the fibres to increase the light collection.

The scintillating fibre detector can be operated in vacuum, avoiding additional vacuum windows further decreasing the total material budget. A fibre feedthrough, sealed with an Epoxy glue (Araldite Standard) suitable for the primary vacuum of the North Area beam lines, was used to allow installation of the photodetectors outside the vacuum tank.

3.1. Photodetectors
The photo detector chosen to read the light from the scintillating fibres were Silicon Photomultipliers (SiPM), specifically the Multi-Pixel Photon Counter (MPPC) model S13360-1350 from Hamamatsu [8] (although other brands (SensL and KETEK) were tested in the laboratory). These silicon devices show a very good photo-detection efficiency of 40% in the relevant light-emitting wavelength range. They have high gain ($\approx 10^6$) and provide fast pulses with sub-nanosecond rise time and 50-100 ns fall time.

Other advantages are their compact size, their insensitivity to magnetic fields and their low operating voltage ($<100 \text{V}$). Their most important drawback is the high dark count rate (typically $\approx 100 \text{kHz/mm}^2$), which can have a thermal origin (due to its semiconductor nature) or can be caused by after-pulses generated some nanoseconds after a true event. These detectors also show crosstalk between pixels, resulting in artificially bigger pulses. The crosstalk in the first versions was as high as 10%, but more recent devices, like the S13360-1350 MPPC, show a much lower crosstalk (1%) and less after-pulsing.

An alternative to read multiple scintillating fibres efficiently are Multi-Anode Photomultipliers (MA-PMT). We tested the Hamamatsu H7546 [9], which has 64 channels over an active area of $18.1 \text{mm} \times 18.1 \text{mm}$. It shows a good quantum efficiency ($\approx 35\%$), large gain ($\approx 10^6$), fast rise and fall times of 1-2 ns and 2-3 ns respectively and a lower dark count rate than the SiPM ($\approx 100 \text{Hz}$). However, MAPMT have problems of gain uniformity and crosstalk between channels. For the first prototype we favoured the SiPM as they were considered to be a new technology with a big margin for improvement and potentially lower future production costs.

3.2. Electronics readout
The analogue pulses from the SiPMs were processed by the CITIROC ASIC, developed by OMEGA Microelectronics [10]. This chip allows amplification, discrimination and integration
of 32 pulses simultaneously. Another interesting feature is a fine-tuning of the SiPM voltages, allowing gain equalization, as each individual SiPM requires a slightly different operating voltage in order to achieve a homogenous detector response.

The CITIROC ASIC also has a trigger line composed of a fast shaper (≈ 15 ns) and a discriminator, which produces a logical signal whenever the incoming pulse exceeds a pre-set threshold. Thanks to the low cross talk of the MPPC used (< 1%), the spurious noise pulses rarely exceeded the four photon level, whilst the light detected in the 1 mm fibres for Minimum Ionizing Particles (MIPs) follows a Landau distribution with a most probable value of thirty photons. It was therefore considered safe to set the discrimination threshold to four photons.

3.3. Data acquisition

The logical pulses were sent to VME Scalers, where every channel corresponds to one of the fibres read in the detector. A LabVIEW module was used to read the Scalers and present and store the data on a PC. This data acquisition system was synchronized with the timing signals coming from the SPS machine in such a way that the Scalers were reset immediately before the beam extraction and their data read immediately after the extraction finished.

4. Beam tests in H8

The prototype was installed close to two other profile monitors: a DWC placed upstream and a FISC downstream. This allowed direct comparison between them. A scintillator counter placed upstream provided accurate intensity measurements.

From the 20th of October to the 11th of November of 2015, we monitored hadrons and leptons with momenta between 20 GeV/c and 180 GeV/c and intensities from $10^3$ to $10^6$ particles/second. The profiles have been analysed with Root [11] to fit a Gaussian curve and find the r.m.s.. In the following figures (2, 3 and 4) we show some of the profiles seen by the SciFi, the DWC and the FISC of beams of protons mixed with pions of momenta 180 GeV/c and different intensities. An analysis of these profiles is shown in Table 2.

![Figure 1. Schematic of the detector showing its main parts](image)

![Figure 2. Profiles of a 180 GeV/c proton/pion beam of $I = 3.4 \times 10^3$ particles/s](image)
Figure 3. Profiles of a 180 GeV/c proton/pion beam of $I = 8.2 \times 10^4$ particles/s

Figure 4. Profiles of a 180 GeV/c proton/pion beam of $I = 6.5 \times 10^5$ particles/s

Table 2. Comparison of the r.m.s. of the previous figures shown (2, 3 and 4)

| Intensity (particles/s) | $\sigma$ (mm) SciFi | $\sigma$ (mm) DWC | $\sigma$ (mm) FISC |
|-------------------------|---------------------|-------------------|-------------------|
| $3.4 \times 10^4$       | 5.6                 | 5.8               | 6.6               |
| $8.2 \times 10^4$       | 5.4                 | 11.2              | 6.2               |
| $6.5 \times 10^5$       | 0.9                 | 4.0               | 1.1               |

The SciFi monitor worked satisfactorily in all situations, whilst the DWC had troubles with the high intensities, showing distorted profiles or artificial tails; the FISC on the other hand was unable to work at intensities lower than $10^4$ particles/s. In addition to that, the intensity measured by the fibres agreed with the intensity from the scintillation counter.

4.1. Lead ion run

From the 18th of November to the 30th of November of 2015, the SPS cycle changed to lead ions, $^{208}$Pb+$^{82}$, providing beams of these heavy particles directly to the North Area. Lead ions deposit four orders of magnitude more energy than MIPs, which means that the light produced and collected also grows by four orders of magnitude. It was therefore necessary to lower the operating voltage of the SiPM to decrease the photon detection efficiency and avoid saturation.

As seen in Table 3, for lead ions the profiles from the SciFi were seen to be wider than those from the DWC, in particular for high intensity beams (comparison with the FISC was unfortunately not possible as they did not work properly with the Pb ions due to technical problems). We believe that the origin of these wider profiles in the SciFi are due to crosstalk between the fibres. This crosstalk is caused by primary UV photons created during the scintillation that can escape the fibre and travel to neighbouring fibres, where they excite the wavelength shifting dopants. Because of the larger energy deposition from Pb ions, a much larger number of these crosstalk photons are created, explaining the wider profiles. This could be avoided in the future by treating the fibre cladding with a UV absorber or reflector.
Table 3. Comparison of the r.m.s. of different Pb ion beam profiles

| Intensity (particles/s) | \(\sigma\) (mm) SciFi | \(\sigma\) (mm) DWC |
|-------------------------|------------------------|------------------|
| \(3.7 \times 10^2\)     | 5.5                    | 4.2              |
| \(2.4 \times 10^4\)     | 7.7                    | 7.0              |
| \(1.0 \times 10^6\)     | 9.6                    | 5.1              |

5. Conclusions and prospects

A scintillating fibre monitor has been successfully tested in the H8 beam line at CERN where it has shown that it can replace the existing beam monitors over a wide range of intensities, presenting less material for the beam and giving more accurate profiles.

A second prototype using MAPMT instead of SiPM for light detection has now also been built to allow both technologies to be compared before deciding on the final design. In addition, two new versions of the detector have been built to investigate solutions to the crosstalk: one detector has the fibres untreated, Whilst the fibres of the other are coated with an ultra-thin aluminium layer following the example of ATLAS ALFA [12]. This aluminium coating will act as a reflector for the ultra-violet photons coming from outside the fibre.

New front-end electronic boards will also be tested, replacing the VME Scalers to allow tagging events with both spatial and time information. This will enable the possibility of reconstructing both the transverse and longitudinal profiles of the beam.

References

[1] White T O 1988 Nucl. Instr. Meth. Phys. Res. Sect. A 273 820–825
[2] Kuraray Co., Ltd. Plastic scintillating fibres product catalogue http://Kuraraypsf.jp/
[3] Saint-Gobain Crystals Scintillating Optical Fibers product catalogue www.crystals.saint-gobain.com
[4] Acosta D et al. 1991 Nucl. Instr. Meth. Phys. Res. Sect. B 62 116–132
[5] Jakobsen S 2013 Commissioning of the absolute luminosity for ATLAS detector at the LHC Ph.D. thesis The Niels Bohr Institute, Faculty of Science, University of Copenhagen
[6] Agostinelli S et al. (GEANT4 Collaboration) 2003 Nucl. Instr. Meth. Phys. Res. Sect. A 506 250–303
[7] Olive K A et al. (Particle Data Group) 2015 The review of Particle Physics vol 38 (Chin. Phys. C)
[8] Hamamatsu Photonics K.K. MPPC (multi-pixel photon counter) S13360-1350 datasheet www.hamamatsu.com
[9] Hamamatsu Photonics K.K. Multianode photomultiplier tube assembly H7546 datasheet www.hamamatsu.com
[10] Fleury J, Callier S, de La Taille C, Seguin N, Thienpont D, Dulucq F, Ahmad S and Martin G 2014 J. Instrum. 9
[11] Brun R and Rademakers F 1997 Nucl. Instr. Meth. Phys. Res. Sect. A 389 81–86
[12] Anghinolfi F et al. (ATLAS ALFA collaboration) 2008 Alfa forward detectors for measurement of elastic scattering and luminosity Tech. rep. ATLAS-TDR-18, CERN-LHCC-2008-004, CERN, Geneva.

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