

A SCINTILLATING FIBRE BEAM PROFILE MONITOR FOR THE EXPERIMENTAL AREAS OF THE SPS AT CERN

I. Ortega Ruiz*, J. Spanggaard, G. Tranquille, CERN, Geneva, Switzerland

A. Bay, G. J. Haefeli, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

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.

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/ Zc , and their intensities from 10^3 to 10^8 particles per second. The profile and position of these beams are typically measured using Delay Wire Chambers (DWC), Multi Wire Proportional Chambers (MWPC) or Scintillator Finger Scanners (FISC). Replacement detectors for the 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. The monitors for these lines will form a spectrometer for particle momentum measurement and therefore need to count single particles, while covering an area of $200 \times 200 \text{ mm}^2$.

* inaki.ortega@cern.ch

SCINTILLATING FIBRES

Scintillating plastic fibres (SciFi) have emerged as one of the best active materials for the monitors of the experimental areas. They are extensively used for charged-particle tracking in high energy physics, for example in the LHCb and ATLAS ALFA experiments at CERN [1, 2].

The scintillating fibres have a core made of polystyrene clad 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 [3]. 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% [4, 5]. Depending on the amount of dopants, the light emitting properties of the fibres can be changed and their radiation hardness can be improved.

Radiation Hardness

A very important characteristic of a beam monitor 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. Data from literature shows that short fibres of less than 40 cm can withstand doses of up to 10 kGy before showing significant damage [6].

Simulations of the SciFi monitor carried out with Geant4 [7] 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.

Material Budget

It is important for a beam monitor to perturb the measured beam as little as possible. A charged particle traversing a medium of thickness x is deflected due to Coulomb scattering from nuclei, characterized by the radiation length X_0 and the nuclear interaction length λ [8]. Comparing the

x/X_0 of different monitors it is possible to establish their relative propensity for scattering. Table 1 shows a study of the most common monitors. A SciFi detector made of two planes (horizontal and vertical) of 0.5 mm 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

FIRST PROTOTYPE

A first detector was built with only one plane for simplicity. It 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 $64 \times 64 \text{ mm}^2$. The SiPM are directly coupled to one end of the fibres [Fig. 1], while a mirror is glued on the other end to increase the light collected.

The scintillating fibre detector can be operated in vacuum, avoiding additional vacuum windows and so further decreasing the total material budget.

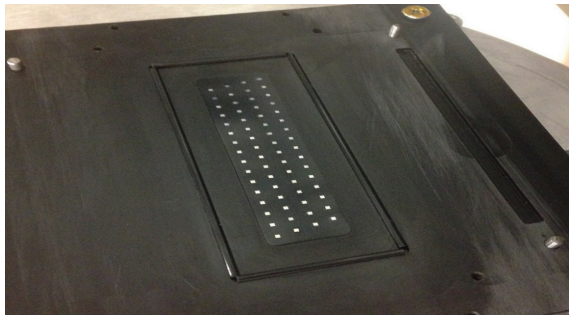


Figure 1: Fibre connector showing the part where the SiPM are coupled.

Photodetectors

The photodetectors 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 [9] (although other brands (SensL and KETEK) were also tested in the laboratory). These silicon devices show a very good photo-detection efficiency of 40% in the relevant light-emitting wavelength range (435 – 450 nm). 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 drawbacks are the high dark count rate (typically $\approx 100 \text{ kHz/mm}^2$) and their temperature dependence, which can cause changes in the gain.

An alternative to read out multiple scintillating fibres efficiently are Multi-Anode Photomultipliers (MAPMT). We have tested the Hamamatsu H7546 [10], 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, the MAPMT has problems with 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.

Readout Electronics

The analogue pulses from the SiPMs were processed by the CITIROC ASIC [Fig. 2], developed by OMEGA Microelectronics [11]. This chip allows amplification, discrimination and integration of 32 SiPM signals 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 has a trigger line composed of a fast shaper ($\approx 15 \text{ ns}$) and a discriminator, which produces a logical signal whenever the incoming pulse exceeds a pre-set threshold. The logical pulses were sent to VME Scalers, where the profile was reconstructed, with every channel corresponding to one of the fibres read out from the detector [Fig. 3].

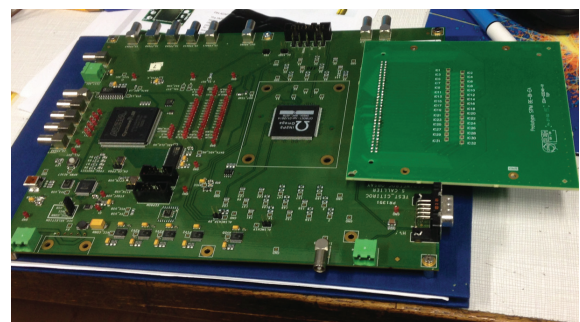


Figure 2: The CITIROC board with the SiPM PCB plugged into it.

BEAM TESTS AT CERN

The prototype was tested in the H8 beam line of the SPS North Experimental Area at CERN [Fig. 4]. It was installed close to two other profile monitors: a DWC placed upstream and a FISC downstream. This allowed direct comparison be-

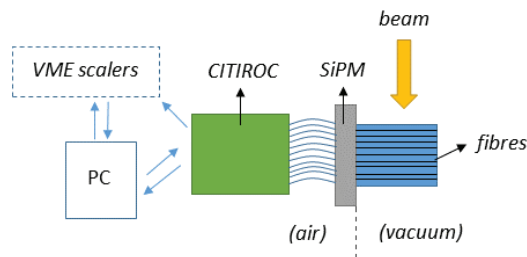


Figure 3: Schematic of the detector showing its main parts.

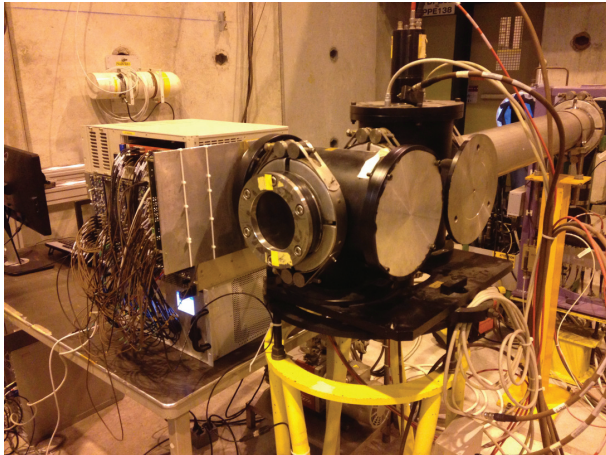


Figure 4: The SciFi monitor installed in H8: the vacuum tank in the centre houses the fibres, while the SiPM and the electronics stay on the outside (left of the figure).

tween them. A scintillator counter placed upstream provided accurate intensity measurements.

We monitored hadrons and leptons with momenta between 20 GeV/c and 180 GeV/c and intensities from 10^3 to 10^6 particles/s. The profiles have been analysed with Root [12] to fit a Gaussian curve and find the *r.m.s.*. In the following figures [5, 6 and 7] 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.

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. The intensity measured by the fibres was also seen to agree well with the intensity from the scintillation counter.

Lead Ion Run

Once per year, the SPS cycle changes to lead ions, Pb(82, 208), providing beams of these heavy particles directly to the experimental areas. 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 operat-

ing voltage of the SiPM to decrease the photon detection efficiency and avoid saturation.

As shown 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. 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.

CONCLUSIONS AND PROSPECTS

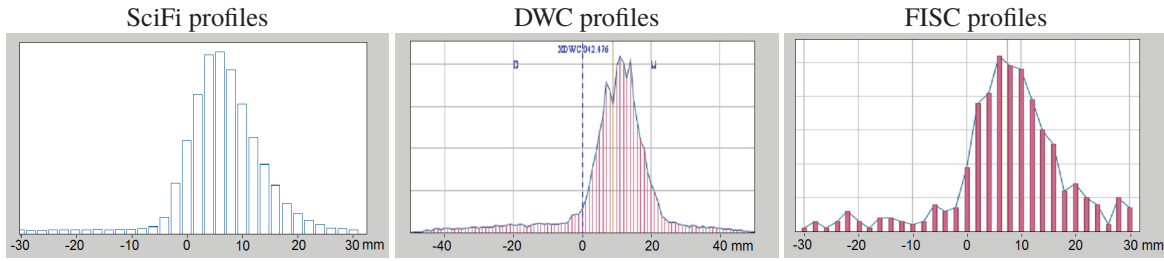
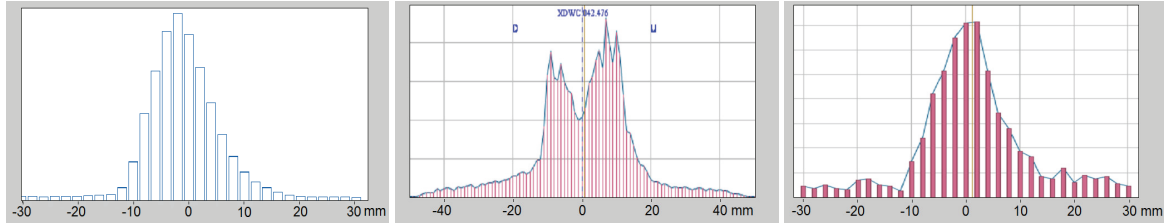
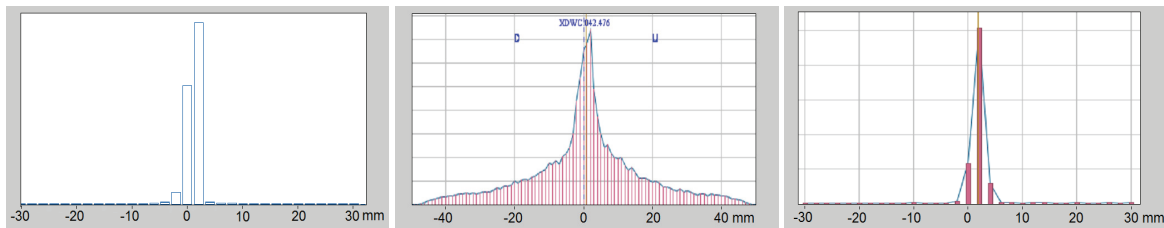
A scintillating fibre monitor has been successfully tested in the H8 beam line at CERN where it has shown that it can replace the existing beam monitors over a wide range of intensities, presenting less material for the beam and giving more accurate profiles.

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. It was planned to be tested in the beamlines in the summer of 2016, but technical problems have pushed the tests to October of the same year. 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 [2]. New front-end electronic boards will also be tested, replacing the VME Scalars 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.

It is foreseen that the CERN neutrino platform will use this fibre monitor as a spectrometer, with the possibility of using it as a Time-Of-Flight (TOF) system also being investigated. The use of a specialized ASIC, such as the STiC [13], would theoretically allow TOF measurements with sub nanosecond time resolution.

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Figure 5: Profiles of a 180 GeV/c proton/pion beam of $I = 3.4 \times 10^4$ particles/sFigure 6: Profiles of a 180 GeV/c proton/pion beam of $I = 8.2 \times 10^4$ particles/sFigure 7: Profiles of a 180 GeV/c proton/pion beam of $I = 6.5 \times 10^5$ particles/sTable 2: Comparison of the $r m s$. of the Previous Figures Shown (5, 6 and 7)

Intensity(particles/s)	σ (mm) SciFi	σ (mm) DWC	σ (mm) FISC
3.4×10^4	5.6	5.8	6.6
8.2×10^4	5.4	11.2	6.2
6.5×10^5	0.9	4.0	1.1

Table 3: Comparison of the $r m s$. of Different Pb(82,208) Beam Profiles

Intensity(particles/s)	σ (mm) SciFi	σ (mm) DWC
3.7×10^2	5.5	4.2
2.4×10^4	7.7	7.0
1.0×10^6	9.6	5.1

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