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BEAM PROFILE MONITORS FOR THE CNAO EXPERIMENTAL LINE

C. Viviani†, G. M. A. Calvi, L. Lanzavecchia, A. Parravicini, E. Rojatti, M. Manzini,

CNAO Foundation, Pavia, Italy

Abstract

The CNAO (Centro Nazionale di Adroterapia Oncologica) Foundation is the first Italian center for deep hadrontherapy. Since 2011, more than 2000 patients have been treated using Protons and Carbon ions. During the last 3 years an experimental line for research purposes has been built. The experimental line is equipped with three Scintillating Fibers with Photodiode array (SFP) detectors. The SFP is a profile and position monitor, whose sensitive part is made up of two harps of scintillating fibers. Each fiber is readout by a cell of a photodiode array. The SFP has been developed from the Scintillating Fibers harp Monitor (SFM) detector, the monitor presently installed along the CNAO extraction lines. The passage to the SFP results in a significant advantage in terms of cost, dimension, acquisition rate and flexibility. On May 19th, 2019 the first beam was extracted in the CNAO experimental room and the first in-line beam measurement with SFP was performed. The present work describes the SFP detectors, their achieved performances and the results obtained during experimental line commissioning.

DETECTOR OVERVIEW

The Scintillating Fiber with Photodiode array detectors (SFP) [1] are the beam profile monitors installed along the Experimental extraction line (XPR) of the CNAO (Centro Nazionale di Adroterapia Oncologica) accelerator (Fig. 1) [2].

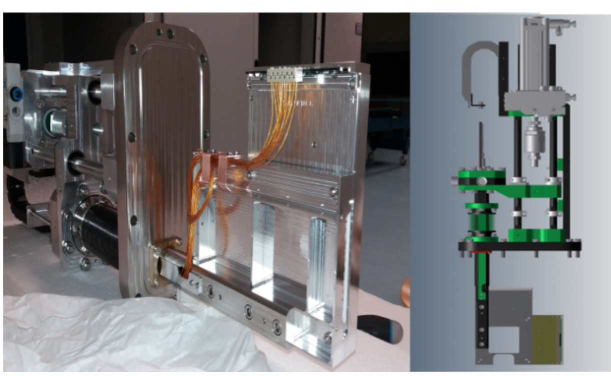

Figure 1: XPR layout with the SFP position

The SFP detector is the development of the Scintillating Fiber harp Monitors (SFM), the current profile/position monitors installed along the CNAO extraction lines. The main difference between SFM and SFP concerns the signal acquisition system: the CCD camera has been replaced by a photodiode array. The SFP working principle consists in the collection of light produced by the beam crossing the scintillating fibers. The light is collected and converted in an electrical signal that depends on the number of particle crossing the sensitive area and on the beam energy. The integrated signal readout on the whole photodiode array gives the reconstructed profile of the beam. Three SFPs are mounted along the XPR line in order to reconstruct the beam trajectory (Fig. 2).

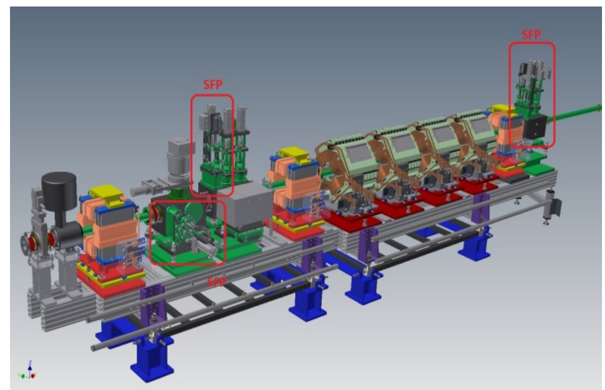

Figure 2: XPR layout with the SFP positions.

Mechanics

The sensitive area, whose dimensions are 64x64 mm^2, is made up of two orthogonal harps, with 128 fibers each. Fibers are arranged horizontally and vertically for vertical and horizontal profile measurements respectively. Scintillating fibers are of the SCSF-78 S type from Kuraray. They are 0.5 mm, square section plastic fibers. Each fiber is metalized all around in order to prevent signal crosstalk and light acquisition from other sources. Each harp is read-out by a photodiode array made up of 128 elements (mounted close to the beam line). The detector works under vacuum, with an expected vacuum pressure expected of 10 E-7 mbar. Signals are transmitted to the front end electronics by means of two vacuum connectors. The SFP can be moved into the beam trajectory by a pneumatic actuator (FESTO-DNC-50-100-PPV-ELH_2_03) and its position is checked by two mechanical limit switches that are engaged when the detector is IN or OUT respectively.

Electronics

As previously stated, the core of the SFP electronics readout is constituted by two photodiode arrays (Hamamatsu S8866-128-02), for the horizontal and the vertical plane respectively. Each array is associated with dedicated controller (Hamamatsu C9118). Consequently, one photodiode + controller system manages 128 fibers and has an independent readout. The photodiode integrated light is

† Claudio.viviani@cnao.it

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converted to an analogical serial signal (VIDEO signal, 0-4 Volts). The Front End Electronics (FEE), built around the Hamamatsu controller, is in charge of transmitting the signal produced by the controller from the synchrotron room to the electronics room through 100 m long cables. The Back End Electronics (BEE), installed in the electronics room, consists of a standard Europa 3U crate that houses two types of printed circuit boards. The first one, called FPGA board, collects the trigger, resets and clocks signals from the FPGA installed in the PXI and distributes them differentially (through 3 dedicated line drivers) to the FEE and then to the Hamamatsu controller. The second one, called CTRL, collects VIDEO signals from the FEE to the PXI crate. Also, the analog VIDEO signals are differentiated to suppress common mode noise over long cables and terminated on 50 Ohm loads. In addition the CTRL board manages the IN/OUT digital output signals to pneumatic actuators with the relative IN/OUT status control. Finally it checks that all systems are powered properly.

Data Acquisition

A National Instruments PXI crate is in charge of controlling the detector, collecting and acquiring signals. The VIDEO signal looks like an analog train of 128 pulses, each one proportional to the light collected by the single associated photodiode. Signals are acquired by a NI 6132 PXI board by means of a 2 MHz clock and are post-processed by a NI 8840 PXI CPU. The value associated to a single photodiode is the average of four points acquired on the flat-top of each VIDEO signal pulse (plateau). Processed data are transmitted to the control system of the accelerator through theOPCUA protocol.

SFP – SFM comparison

As it was said before, the main difference between SFP and SFM detectors consists in the acquisition system. The SFP detector has multiple advantages:

- It is cheaper: the cost of photodiode + processing electronic is much lower than that of the CCD camera.
- It is smaller: SFP mechanics is much more compact, in particular with a lower occupancy along the beam direction.
- Each SFP fiber is read by one photodiode, basically no electronics is needed in between and no complex data processing is required.
- It is faster: the frame rate can be in the kHz range while the current CCD camera is limited to 43 Hz.
- The fiber and photodiode array calibration is quite easy to be performed.

Table 1 shows the comparison between some SFP and SFM parameters.

Table 1: SFP and SFM Comparison

Parameter	SFP	SFM
Max. Frame Rate	3.5 kHz	43 Hz
Fiber pitch	0.5 mm	1mm
N. of fibers	128	64
Min. Int. Time	10 µs	10 µs
Max. Int. Time	1 s	10 s
Cost of sensor	2.5 k€	10 k€
Longitudinal dimension	110 mm	190 mm

SFP COMMISSIONING

Before the installation on the beam line each SFP was tested and commissioned in the CNAO treatment rooms, at the isocenter, using both Proton and Carbon ion beams. Acquired data have been compared with the CNAO Dose Delivery System data, which is the most reliable monitor installed in the treatment rooms.

Pedestal

The VIDEO signal output has a global offset of about 227 mV. The detector pedestal for each single photodiode was calculated by performing about 500 acquisitions of noise at the isocenter position. Noise is intended as signal acquired with no beam crossing the detector sensitive area. For each photodiode the average value over the 500 acquisition was calculated. Figure 3 and Figure 4 show the average pedestals per each photodiode and the relative standard deviation (about 1.3 mV).

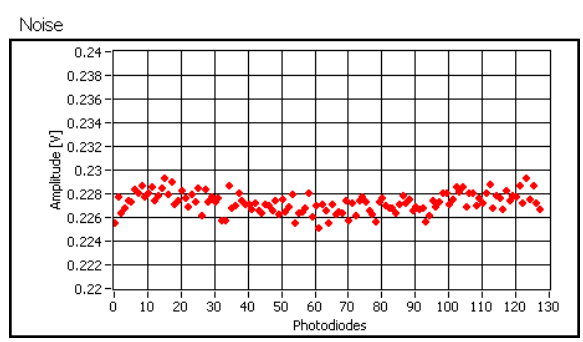

Figure 3: Pedestal of photodiodes (in Volt).

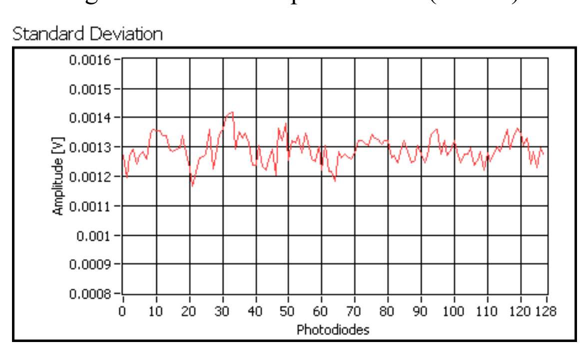

Figure 4: Standard deviation of photodiodes pedestal (in Volt).

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Calibration

A beam tests session was performed in order to calculate the so called Calibration Factors, which are implemented in the profiles reconstruction algorithm in order to equalize the system response to light. During the tests, the beam position and the number of particles per spill were controlled by the Dose Delivery system. For data computation, the beam profiles acquired with different barycenter values on both planes were normalized with respect to the beam intensity. An appropriate fit was applied on each normalized profile and the correction factors of single photodiodes were calculated as the average of the ratio between the fitting curve and the raw beam profile. Figure 5 shows three raw profiles and the corresponding reconstructed profiles.

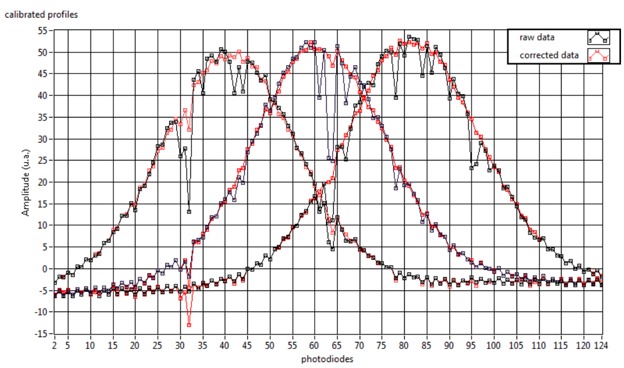

Figure 5: Three raw and reconstructed profiles.

Sensitivity and Response Linearity

The sensitivity and the linear response of the SFP detector were tested by means of two sets of dedicated measurements performed at CNAO in the treatment rooms at the isocenter, using both Proton and Carbon ion beams. The first measurement consisted in a scan with fixed energy and increasing number of particles, while the second one in an energy scan with fixed number of particles. In both cases the profiles of the beam spills were integrated and the total integral value was taken into account. Figure 6 shows the response linearity versus the number of particles for both planes: the linearity guarantees the possibility to use the detector not only for position and profile measures but for intensity measures too.

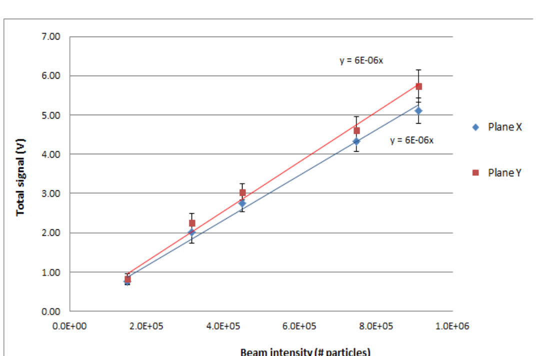

Figure 6: Integral signal versus the number of proton.

Considering the energy scan, the trend of the total integral value reflects the Bethe-Block trend as shown in the Figure 7 (proton beam) and Figure 8 (carbon ion beam). The average sensitivity is about 130 particles/mV for the proton beam while is about 8 particles/mV for the carbon ion beam.

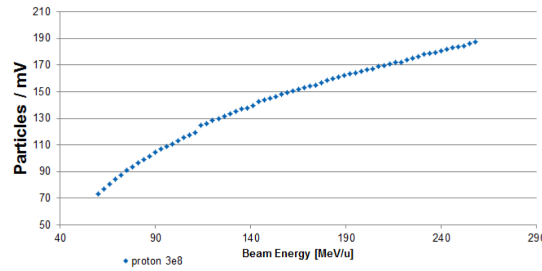

Figure 7: SFP sensitivity: the ratio between the number of particles and the integral signal as function of the proton beam energy.

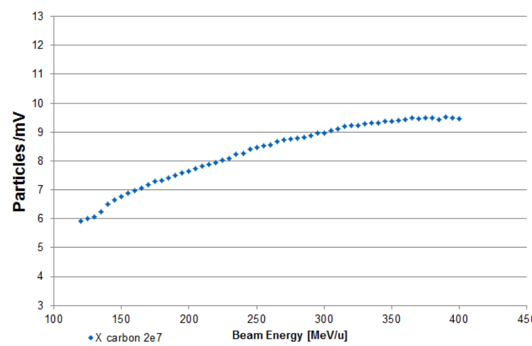

Figure 8: SFP sensitivity: the ratio between the number of particles and the integral signal as function of the carbon beam energy.

Barycenter and Position Reconstruction

The last test at the isocenter was performed to cross-check the capability of the SFP detector to correctly reconstruct the beam position. A 2-dimension scan was performed by means of the Dose Delivery system, displacing the beam into 16 different positions with 1 mm pitch. The reconstructed barycenters on the two axes were compared with the Dose Delivery set position. Figure 9 shows the results, where the red dashed line shows the scanning path of the beam. In both axes the absolute error between the beam position measured by the Dose Delivery and that one measured by the SFP is less than 0.05 mm, with an average variance of 0.01 mm.

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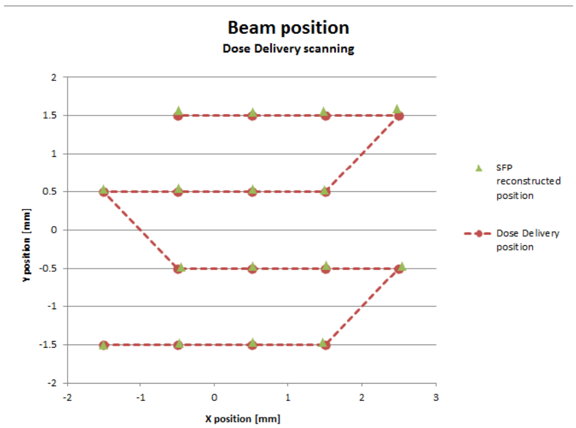

Figure 9: SFP reconstructed position versus Dose delivery beam position.

XPR COMMISIONING

The CNAO experimental room [3] is designed to be "general purpose", devoted to research in different fields (cells irradiation, beam monitor tests, radiation hardness study, etc.). In order to make the best use of the available space, the part of the beamline inside the XPR room can be assembled in four configurations, with different iso-center positions. Three SFPs are installed along the CNAO experimental line in three different positions in order to correct the beam trajectory and fit the beam optics for all configurations. The XPR commissioning has started at the beginning of May and will last up to the end of September [4].

SFP Beam Data

The SFPs measurements performed for the XPR commissioning have been demonstrating that the SFP detectors are able to correctly reconstruct beam profiles both for Protons and Carbon Ions and for the whole range of beam energies and intensities, according to the detectors design. Figure 10, Figure 11 and Figure 12 show one spill acquisition on the SFP installed at the end of the experimental line, for a 60 MeV energy Proton beam with 2E9 particles per spill.

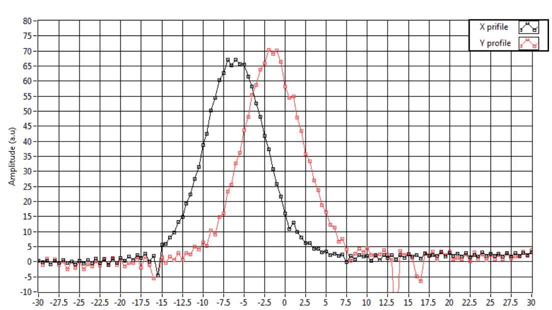

Figure 10: Horizontal profile (black line) and vertical profile (red line) of a 60 MeV energy Proton beam measured by the SFP installed at the end of the experimental line.

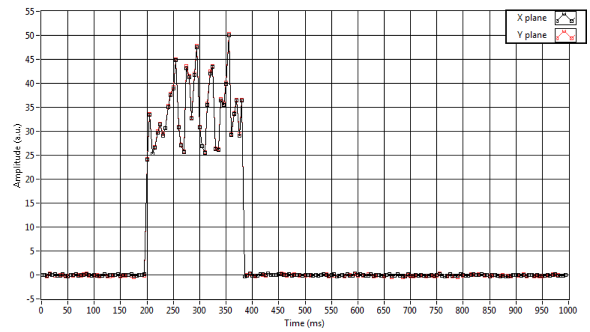

Figure 11: Time profile (intensity of the beam versus extraction time) for a 60 MeV energy proton beam of 2E9 particles per spill.

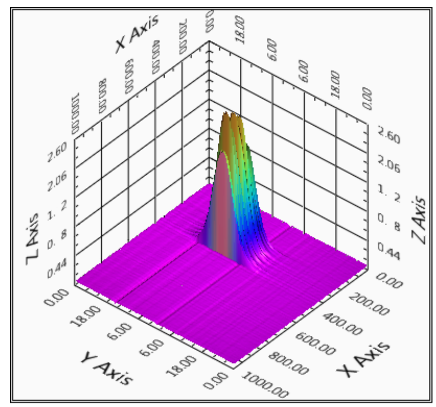

Figure 12: 3D plot of intensity versus extraction time (X axis in ms) and position (Y axis in mm).

CONCLUSION

The commissioning of the CNAO experimental line is ongoing and will be concluded by the end of September. The SFP detector was developed in order to acquire the beam profiles along the experimental line, to determine beam position, standard deviation and intensity. The first data confirm that the SFP monitors satisfy the design requests, being able to describe beam characteristics in all the XPR configurations.

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