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SCINTILLATING FIBERS USED AS PROFILE MONITORS FOR THE CNAO HEBT LINES

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Abstract

The CNAO (Centro Nazionale di Adroterapia Oncologica, Pavia, Italy) is the first Italian center using Proton and Carbon ion beams for radioresistant tumors therapy. Scintillating fibers detectors are used in the HEBT (High Energy Beam Transfer) lines of the CNAO accelerator in order to monitor the therapeutic beam parameters. Twenty SFHs (Scintillating Fibers Harp) and one QPM (Qualification Profile Monitor) have been already installed for the beam transverse profiles measurement. One SFP (Scintillating Fibers plus Photodiodes) prototype, that is a SFH upgrade project, has been assembled and tested on beam. One WD (Watch Dog) detector, not already installed, has been assembled and tested to check the beam position at the HEBT end through the intensity of the beam tails. The present work describes the beam detectors, their achieved performances and the most recent beam measurements.

HEBT LINES LAYOUT

The HEBT [1] (High Energy Beam Transfer) is the extraction line of the CNAO [2] accelerator. It consists of three horizontal and one vertical transfer lines, coming from one first common sector (called H sector) and reaching three different treatment rooms.

The energy range of particles running in the HEBT line is 60 to 250 MeV/u for Protons, and 120 to 400 MeV/u for Carbon ions. The beam is slowly extracted from the synchrotron so that the spill length is settable from 1 to 10 seconds. The nominal intensities per spill are 1×10^{10} for Protons and 4×10^{8} for Carbon ions.

SFH AND QPM: DETECTORS OVERVIEW

The SFH (Scintillating Fibers Harp) and the QPM [3] (Qualification Profile Monitor) are detectors based on grids of adjacent scintillating fibers, installed in the HEBT lines for the beam profiles measurement (position and width). They have been both designed and built by the *LLR (Louis Leprince Ringuet) laboratory*, belonging to the French *CNRS*, according to the specification provided by CNAO. The CNAO Beam Diagnostic group provided the detector actuators, the installation on the beam line, and their implementation in the control system.

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The SFHs are usually placed out of the nominal beam trajectory not to perturb the therapeutic beam. They are moved onto the beam path through a pneumatic actuator only during the daily beam quality controls. The QPM can be used during patient treatments, since it is installed in front of the "dump", namely a tungsten block placed in the H sector along the extracted beam trajectory. The dump is needed to stop the beam at each machine cycle, during few milliseconds after the extraction, until an orbit bump is created by four fast magnets in order to send the beam towards the selected treatment room.

Detectors Description

The SFH and the QPM active area (Fig. 1) is made up of two orthogonal planes of Polystyrene scintillating fibers, 0.5 mm thick and 0.5 mm wide (*Kuraray SCF-78 type*), each other adjacent and aluminized all around their surface and at one end to avoid any light cross-talk.

Figure 1: SFH (left) and QPM (right) active area.

Both SFH planes are made up of 128 fibers ($64 \times 64\, mm^2$). The QPM horizontal and vertical planes are respectively made up of 34 and 90 fibers ($17 \times 45\, mm^2$). Fibers are installed under vacuum at a pressure of $10^{-6} - 10^{-8}\, mbar$: the detector outgassing is mainly due to the glue that fixes the fibers.

When crossing fibers, the beam particles release energy and produce an amount of photons proportional to particles number and energy. The generated light is guided and focused, through a viewport, onto a CCD chip (1344 × 1024 pixels) of a digital camera (*Hamamatsu-C8484-03G, Peltier cooled,12 bits*) which acquires and processes the signals. The maximum camera acquisition rate is 50 Hz.

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Profiles Reconstruction and Beam Parameters Computation

Each fiber is matched with a group of pixels of the camera chip. The camera output per fiber is a digital number proportional to the collected light, to the CCD shutter time and to the CCD electronics gain. Due to the high sensitivity of the camera, an attenuating filter can be placed at the image sensor entrance to avoid the camera electronics saturation.

Profiles are reconstructed through the association between the mechanical fiber position on the detector active area and the corresponding digital output signal. Camera electronic noise is subtracted and a calibration factor is applied to compensate the different fibers response (including optics).

For each acquired beam profile the barycenter [mm] and the standard deviation [mm] can be evaluated as the discrete distribution mean and standard deviation.

Figure 2 represents one SFH acquisition of a whole 65 MeV/u Proton spill on the horizontal plane.

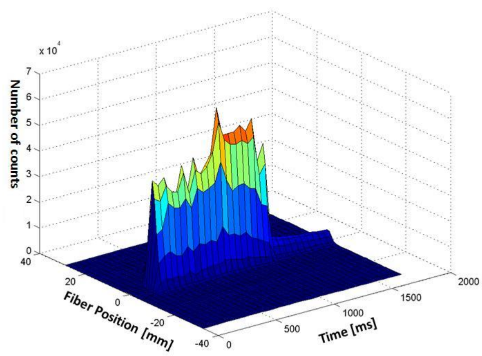

Figure 2: SFH acquisition (20 Hz acquisition rate, 20 ms shutter time) of a 65 MeV/u Protons spill (about 10^8 particles) on the horizontal plane.

On Beam Measurements

Figure 3 shows the measured SFH sensitivity for Protons of different energies, by using an attenuating filter of factor 100. The experimental data (red dots) are in agreement with the theoretical curve (blue line) within the errors. Figure 4 shows the barycenter and the standard deviation values computed for 37 horizontal profiles acquired by the QPM during one spill extraction. The whole spill of 65 MeV/u Protons is intercepted. Although the detector spatial resolution is expected to be connected with the fiber width, the data processing algorithm allows to distinguish very small displacements, of the order of one tenth of a millimeter.

THE SFP MONITOR: SFH IMPROVEMENT

The SFP (Scintillating Fibers plus Photodiodes) is the SFH evolution, introducing several advantages and new features. The CCD camera is replaced by two photodiode (PD) arrays (*Hamamatsu-S8866-128-02*), one per plane, operating in vacuum. Each array consists of 128 photodiodes and is connected to one controller circuit (*Hamamatsu-C9118*). The output, for each plane, is an analogue signal with serial trasmission of all the PD generated photocurrent.

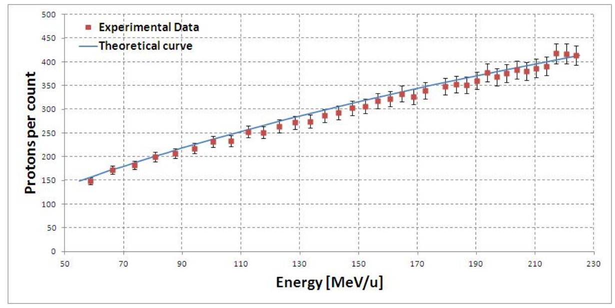

Figure 3: SFH monitor sensitivity for Protons of different energies by using an attenuating filter of factor 100.

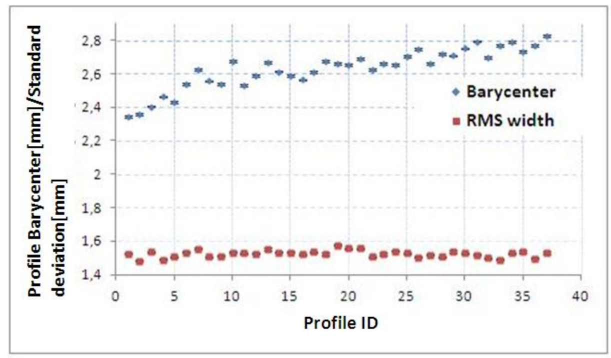

Figure 4: Computed barycenter and standard deviation values for 37 horizontal beam profiles acquired by the QPM during one spill extraction.

The SFP features, with respect to the SFH, are:

- overall dimensions reduction, particularly along the beam direction;
- faster readout, with a more flexible acquisition, up to 1kHz profile rate;
- the univocal coupling fiber-photodiode allows a smaller loss of light signal and an easier profiles reconstruction;
- cost reduction, namely its overall cost is about half the SFH cost.

Although the PD array is less sensitive than the CCD camera, the abundance of fibers light makes the detector sensitivity and resolution not affected. Finally the outgassing rate is slightly increased, but still suitable for CNAO operating vacuum level.

One SFP prototype has been assembled and tested at CNAO with good results. As an example Fig. 5 shows a SFP acquisition of a whole 111 MeV/u Protons spill on the horizontal plane. The detector has been calibrated with Protons and Carbon ions of different energies, and the reliability in the beam barycenter and the width computation has been proved. Experimental results demonstrated the opportunity to replace the SFHs with the SFPs in the next future.

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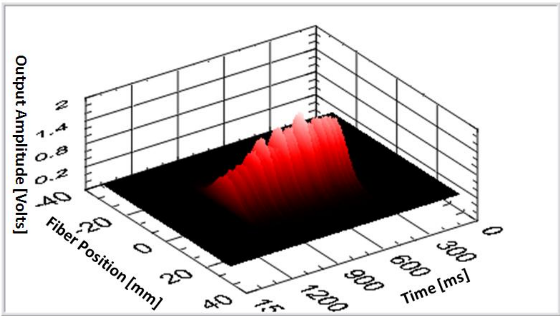

Figure 5: SFP acquisition (300 Hz acquisition rate, 2.8 ms integration time) of one 111 MeV/u Protons spill (about 10^8 particles) on the horizontal plane.

THE WATCH DOG DETECTOR: DESCRIPTION AND USE

The Watch Dog (WD) [4] (Fig. 6) is a beam monitor that will be installed at the end of each HEBT line.

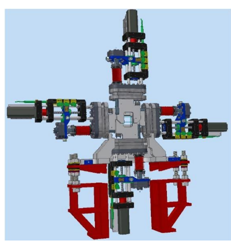

Figure 6: The WD detector layout.

Its sensitive part consists of four scintillating fibers (*Kuraray type SCSF-3HF(1500)*) parallel two by two, and hortogonal in pairs, displaced transversely to the beam direction and operating under vacuum. Each fiber is mounted on a brushless motorized mechanism and can be moved independently of the others. The fiber position is constantly measured by a linear potentiometer. The fibers are coupled to four Avalanche Photo-Diodes (*APDs by Hamamatsu, S8664-10K*), whose analog output signal is proportional to the number of particles crossing the related fiber.

The WD has been designed to not increase the beam emittance and to be used permanently on the therapeutic beam (contrarly to the SFH and to the SFP). Its main goal is to monitor the beam position during patient treatments in real time and to generate an interlock signal if the measured quantity is out of the nominal range. For this purpose fibers are moved up to a fixed position at beam spot borders, in order to intercept only the beam tails. The beam center of gravity (c.g.) can be reconstructed through the measured quantity:

$$\frac{I_1 - I_2}{I_1 + I_2} \propto c.g. \qquad (1)$$

where I_1 and I_2 are two APDs output signals corresponding to a couple of parallel fibers.

The WD may also be used as profile monitor by scanning the entire beam spot with each fiber. This mode of use can not be exploit during treatments because the beam perturbation is no more negligiable.

Preliminary Beam Test

Up to now only one preliminary beam test has been performed with the WD in order to check the detector response. The WD has been placed in one treatment room. One vertical fiber position is fixed at the center of the detector active area ($x_0 = 0\,mm$). Sixty 112 MeV/u Proton spills with a fixed number of particles are extracted. Scanning magnets are used to horizontally shift the beam position from one spill to the next one (from $x = -30\,mm$ to $x = 30\,mm$, in 1 mm steps). The average signal acquired per step versus the beam horizontal position gives the beam horizontal profile reconstruction (Fig. 7).

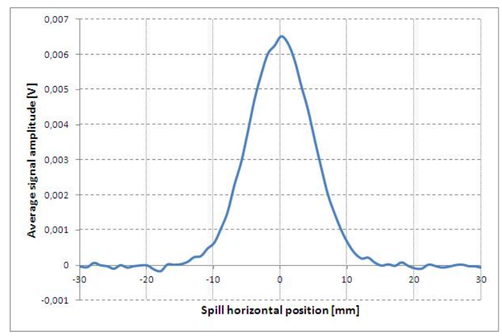

Figure 7: Beam horizontal profile reconstruction performed with the WD by using one vertical fiber.

The obtained results demonstrated the possibility for the WD to be used as beam monitor. Several tests more have to be performed in the next future.

CONCLUSION

This paper presented scintillating fibers-based beam instrumentation used in the CNAO HEBT lines. They are aimed to check the therapeutic beam parameters both during treatments and during the daily beam quality controls, in order to guarantee patient safety and a high treatment quality. Thanks to the scintillating fibers features, to their robustness and flexibility, scintillating fibers detectors turn out to be more performing and easier to be used than classical gas based detectors.The SFHs and the QPM have already been installed on the beam line they are correctly operating. The SFPs will replace the SFHs in the next future. More experimental tests are planned with the WD detector in order to make it operational in the next future.

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