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Design of a tracking device for on-line dose monitoring in hadrontherapy

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ABSTRACT

Hadrontherapy is a technique for cancer treatment that exploits ion beams (mostly protons and carbons). A critical issue is the accuracy that is achievable when monitoring the dose released by the beam to the tumor and to the surrounding tissues. We present the design of a tracking device, developed in the framework of the INSIDE project [1], capable of monitoring in real time the longitudinal profile of the dose delivered in the patient. This is possible by detecting the secondary particles produced by the interaction of the beam in the tissues. The position of the Bragg peak can be correlated to the charged particles emission point distribution measurement. The tracking device will be able to provide a fast response on the dose pattern by tracking the secondary charged fragments. The tracks are detected using 6 planes of scintillating fibers, providing the 3D coordinates of the track intersection with each plane. The fibers planes are followed by a plastic scintillator and by a small calorimeter built with a pixelated Lutetium Fine Silicate (LFS) crystal. A complete detector simulation, followed by the event reconstruction, has been performed to determine the achievable monitoring spatial resolution.

1. Particle therapy and monitoring

Protons and carbon ion beams are presently used in particle therapy (PT) to treat many different solid cancers. Compared to the standard X-rays treatments the main advantage of PT technique is the better localization of the dose in the tumor region sparing healthy tissues and surrounding Organs At Risk (OAR). This is a consequence of the way in which heavy charged particles loose most of their energy when interacting with matter: near the end of beam range, in the Bragg peak, while X rays exponentially decrease their energy along the path traveled in matter (Fig. 1). Up to now most of PT treatments have been performed with proton beams, but routinary use of carbon beams has increasingly started.

The intrinsic precision due to the peculiar features of dose release at the end of the range in PT with respect to photon radiotherapy (RT) is somewhat jeopardized by uncertainties in the knowledge of actual primary particle range. Inhomogeneities, metallic implants, Computed Tomography (CT) artifacts, conversion to electronic density, inter session anatomical/physiological changes can lead to sensible range variations with sensible change in dose release. For these reasons a real time monitoring of beam range in PT treatments is highly recommended. New techniques and detectors have to be introduced in the clinical use for this purpose.

A first attempt concerns the use of PET scanners to detect back-to-back photons (PET-γs) from the annihilation of positrons emitted by β^+-decaying isotopes produced in the patient by the therapeutic beam. New monitoring possibilities are connected to the detection of other secondary particles produced by the beam interaction in the patient: prompt photons from nuclear de-excitation in the 1–10 MeV range [2,3] and charged particles [4] (mostly protons). It has been shown that the position of the released dose peak can be correlated with the emission pattern of

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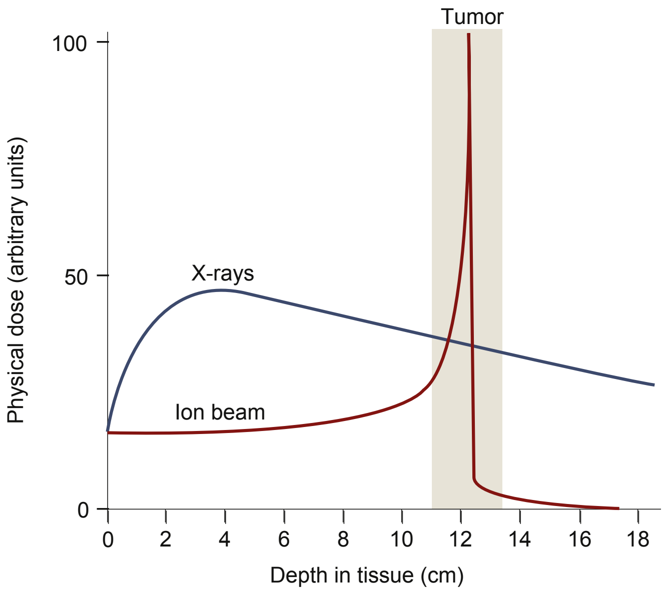

Fig. 1. Physical dose release along the path traveled in matter for X-ray and ion beam.

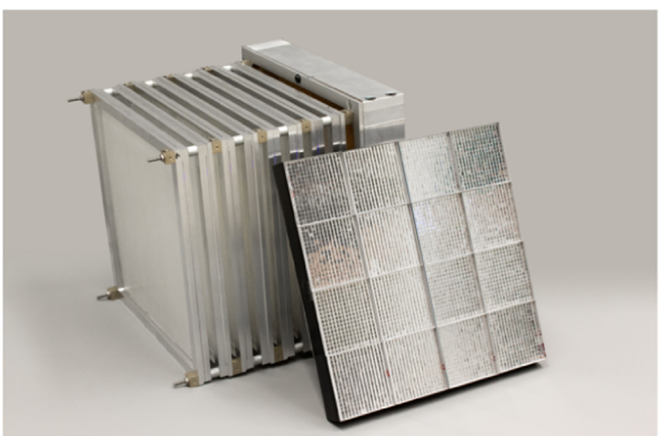

Fig. 2. Dose profiler. In foreground the calorimeter composed by 64×64 matrix of pixelated LYSO crystals arranged in 4×4 blocks, as described in Section 2.3. In background the 6 tracking planes of the tracker, as described in Section 2.1 and the plastic scintillator as described in Section 2.2.

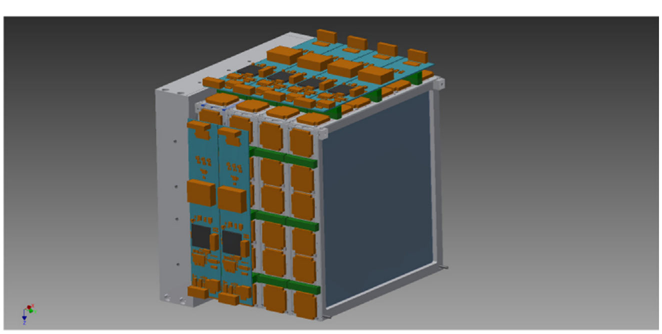

Fig. 3. The front-end electronics readout structure: in yellow the BASIC32_ADC; in blue the FPGA controller (1 FPGA every BASIC32). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

these secondary particles. Secondary protons, emitted at energies in the range 50–200 MeV, can be also detected at large angles with respect to the beam direction and can be easily back-traced. Despite multiple scattering in tissues, a 2–3 mm resolution in the distribution of emission point can be achieved, as shown in Ref. [4].

In this work we describe a new detector designed to track charged secondaries in PT treatments to be used for real time range monitoring in clinical operation.

2. The INSIDE project: the dose profiler

The proposed detector is being developed in the framework of the Innovative Solutions for In-beam Dosimetry in hadrontherapy (INSIDE) project [1] which proposes a multimodal in-beam dose monitor including both a PET-γ detector and a charged particle tracker. Such a monitor is designed to be integrated in a treatment room of Centro Nazionale di Adroterapia Oncologica (CNAO) [7].

The device for charged particle tracking (Dose Profiler) makes use of 6 planes of scintillating fibers with *X*–*Y* readout, providing the 3D cartesian coordinates of the track intersection with each plane. The fibers planes are followed by a plastic scintillator and by a small calorimeter built with a pixelated LFS crystal.

The design requirements are compactness, reliability, large geometrical acceptance and high tracking efficiency. The Dose Profiler mechanical structure, the scintillating fibers planes and the LFS crystal are shown in Fig. 2.

2.1. The tracker

The tracker is composed by 6 tracking planes, each made by two orthogonal (X–Y) placed scintillating fiber layers. Each layer is constituted by 384 scintillating fibers (0.5×0.5 mm^2) per side, with the minimal plane separation (2 cm) allowed by fibers front-end electronics readout in order to increase the geometrical acceptance and the compactness of the detector.

Dimensions, spacing, thickness and materials have been optimized using Monte Carlo simulations in order to maximize the geometrical acceptance, and to control multiple scattering contribution to charged particles trajectories.

The readout will be performed by means of 1×1 mm^2 silicon photomultipliers (SiPM 12571-050P from Hamamatsu) hosted on the same board that supports the front-end electronics. Each SiPM will be coupled with two adjacent fibers. Due to the lateral dimension of the SiPM case (1.9 mm), couple of fibers are alternatively read from the two fibers ends.

In total the 19.2×19.2 cm^2 sensitive area is read by 192 channels per layer. The SiPM are readout by BASIC32_ADC [8] ASIC (JLCC68 package) that has 16 input channels per side. The compactness of the device requires that each board manages 96 double fibers of one plane and 96 double fibers of the contiguous plane. For each front-end board 96+96 SiPM are read by 6 BASIC32_ADC.

The BASIC32_ADC is a CMOS 0.35 μm ASIC developed for the INFN DASiPM2 project. It manages 32 analog inputs (250 MHz bandwidth) providing independent HV offset, threshold, gain, shaping, an 8-bit ADC with zero suppression at 20 MHz project frequency, and a fast output for triggering purposes.

On top of the analog SiPM board a digital one is used to produce the SiPM HV, to distribute the trigger signal and to send data to a further concentrator board.

The front-end electronics readout structure is shown in Fig. 3. The system is designed to substain a rate of 20 kHz. The noise rate from photoelectrons generated in the fibers is expected to be of 10 Hz. The overall noise will be reduced at trigger level to a negligible rate by using the coincidence of 3 planes.

The spatial single hit resolution is 300 μm (double fiber readout).

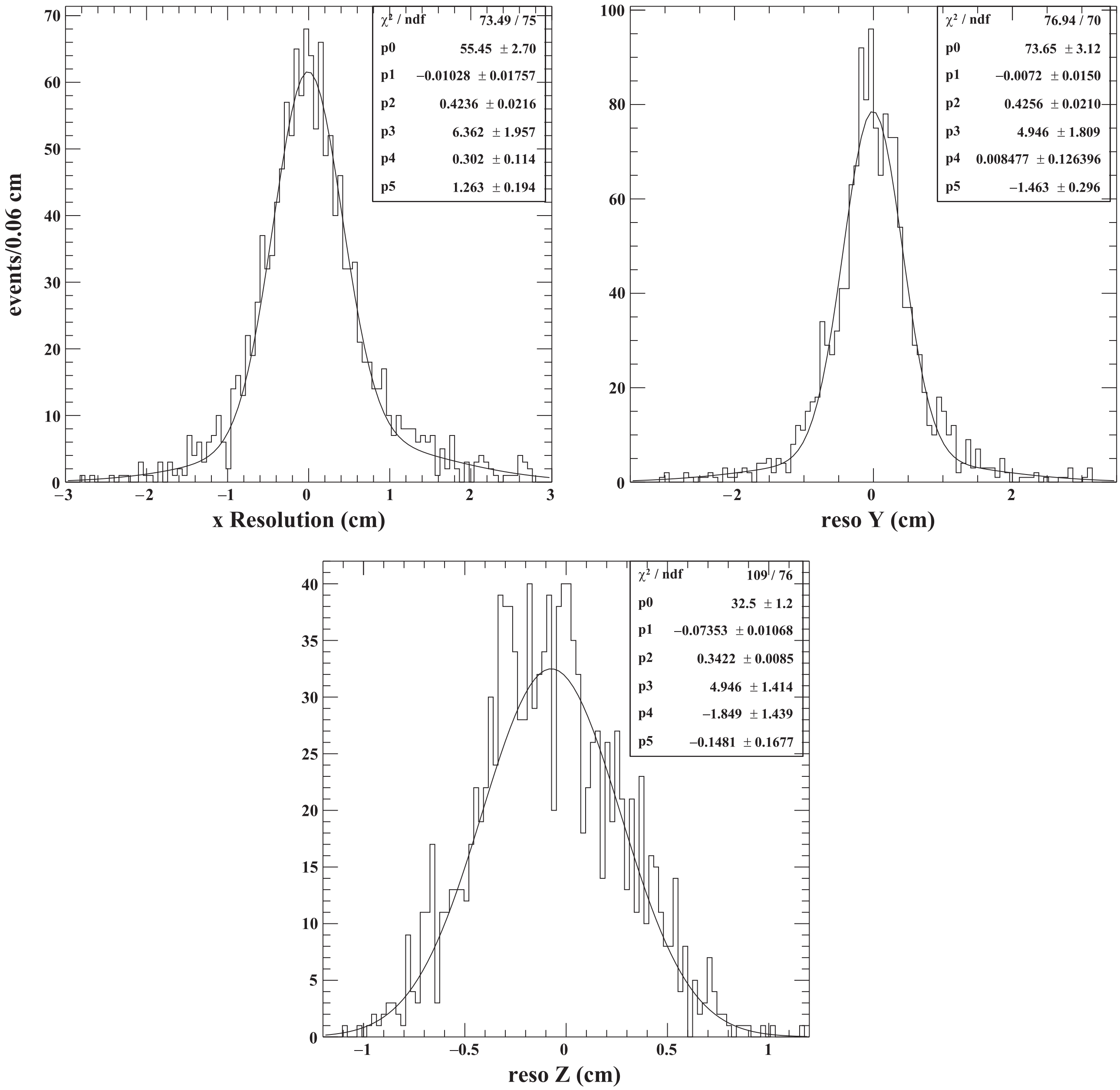

Fig. 4. Distribution of the difference between the measured and the true value of the proton origin coordinate x (beam direction), y, z (profiler axes) for the full simulation (carbon ion beam coming along the x direction, at 90° with respect to the profiler axis and 2.5 cm radius of the target PMMA cylinder). Double Gaussian fits are superimposed to give an estimate of the corresponding resolutions.

2.2. The electron absorber

A plastic scintillator (EJ-200 from Eljen) has been placed just after the tracker, in order to prevent electrons from reaching the calorimeter and from back-scattering in the tracker, deteriorating pattern recognition. It is also used, through its energy measurement, for event selection purposes. It is a polyvinyltoluene based scintillator with low atomic number (Z_{eff}=3.4).

To avoid the development of a dedicated readout subsystem, the front-end board of the tracker is also used to read the scintillator. For this reason the absorber is made of 4 independent layers, with the same external dimensions of the fibers frames (21.2 cm × 21.2 cm × 0.6 cm) and with the same 2 cm spacing. Each layer is made of 6 slabs 20 cm × 0.6 cm × 0.12 cm. It is expected that this set-up will provide about 50 photoelectrons for each slab per MIP with a 20–25% energy resolution measurement.

2.3. The calorimeter

The role of the high density compact crystal scintillator placed behind the tracker is to measure the protons energy helping in track reconstruction (trigger and event selection).

We chose a 64 × 64 matrix of pixelated LYSO crystals arranged in 4 × 4 blocks (LFS 16 × 16 matrices 5 cm × 5 cm × 2 cm from Hamamatsu) that, with its high atomic number (Z_{eff}=66), allows a compact design together with a high energy resolution (which depends on the energy, about 15–8% in the range 10–50 MeV). The pixel layout allows to insulate proton position in the transverse plane at the cost of loosing the depth of interaction reconstruction capability.

The crystal readout will be performed by means of Multi Anode Photo-Multiplier (MAPMT H8500 from Hamamatsu). The 4 ×4 blocks are mechanically contained in a square aluminum structure 2 cm thick, 3 cm wide. This structure is also used to substain the

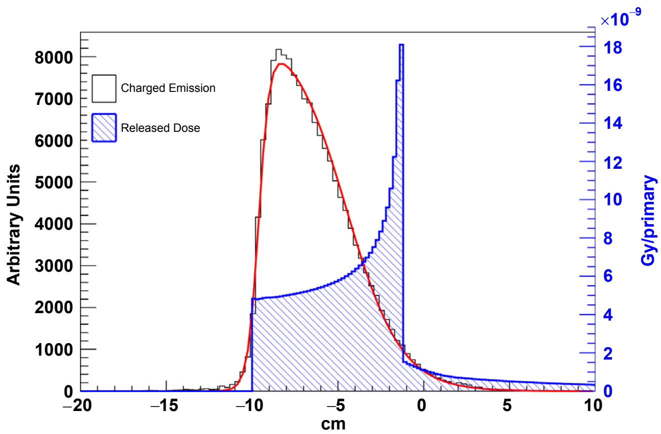

Fig. 5. Charged emission profile (red curve) and released dose (hatched figure) for a carbon ion beam impinging on a PMMA target from simulation.

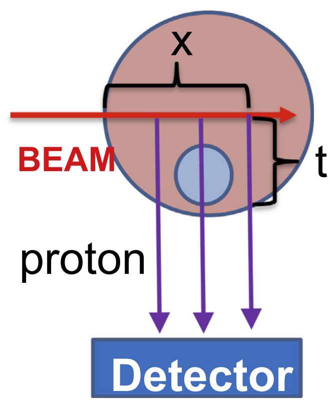

Fig. 6. Simulation setup for a proof of concept of the material absorption interpretation.

tracker and the electron absorber on the front and to house, on the back, the MAPMT, their acquisition board (based on BASIC32_ADC) and the data concentrator.

3. The dose profiler performances

A detailed simulation of the detector has been developed in order to optimize the detector design. The Monte Carlo software used for the simulations is FLUKA, release 2011.2 [5,6].

For the study of proton events, in order to save computing time, we decided to build a parametrized generator to reproduce the experimental data about protons emitted from a ^{12}C beam of 220 MeV/u at 90° and 60° with respect to the detector axis impinging on a PMMA (cylindrical) target of 2.5 cm radius measured at GSI [4]. Starting from the experimental data, different thicknesses have been considered (up to 10 cm) to study material effects and proton flux attenuation. Also, different energies (lower than 220 MeV/u) have been simulated. In the parametrized sample only protons are present. A full simulation of a ^{12}C beam of 220 MeV/u with the same setup has been performed in order to study proton selection. We refer to these two simulations as to "parametrized simulation" and to "full simulation" in what follows.

Protons interact in all the crossed fiber planes. Charged secondary particles are reconstructed with a track finding algorithm that starts from deposits in the fibers grouped together to form 3-dimensional clusters.

Fiber hits in the x and y views are clustered separately by grouping consecutive hit fibers to form 2-dimensional clusters (xz and yz views). The z coordinate of the cluster is given by the middle position of the fiber plane while the x and y coordinates are given by the middle coordinate of the two fibers read out by the same SiPM. 3-Dimensional clusters are formed by taking all the possible combinations of x and y clusters in a plane. A track finder algorithm is run to build track candidates starting from the list of 3-D clusters as summarized as follows: Track seeds are made from two hits in consecutive layers. Each seed is prolonged to the subsequent layer. The closest hit (a 2-dimensional distance is computed) to the seed prolongation is added to the track. This is iterated until the last plane is reached and a list of track candidate is formed.

The track candidates are first parametrized as straight lines and a simple χ^2 fit is performed to obtain an estimate of the track parameters. A Kalman filter [9] is also applied to take into account the multiple scattering in the detector material. A back-tracking extrapolation towards the patient is performed by reconstructing the point of closest approach (x,y,z coordinates) of the proton to the primary beam axis.

Proton track angular resolution resulting from reconstruction of simulated tracks is in agreement with the expected multiple scattering of the proton in the patient and in the tracker.

The resolution on the proton origin can be obtained from the distribution of the difference of the measured and the true value of the x,y,z proton coordinates. These are shown in Fig. 4 from which $\sigma_X \simeq \sigma_Y \simeq 0.4$ cm , $\sigma_Z \simeq 0.3$ cm, evaluated on the full simulation with the Carbon ion beam along the x direction, at 90°, and the

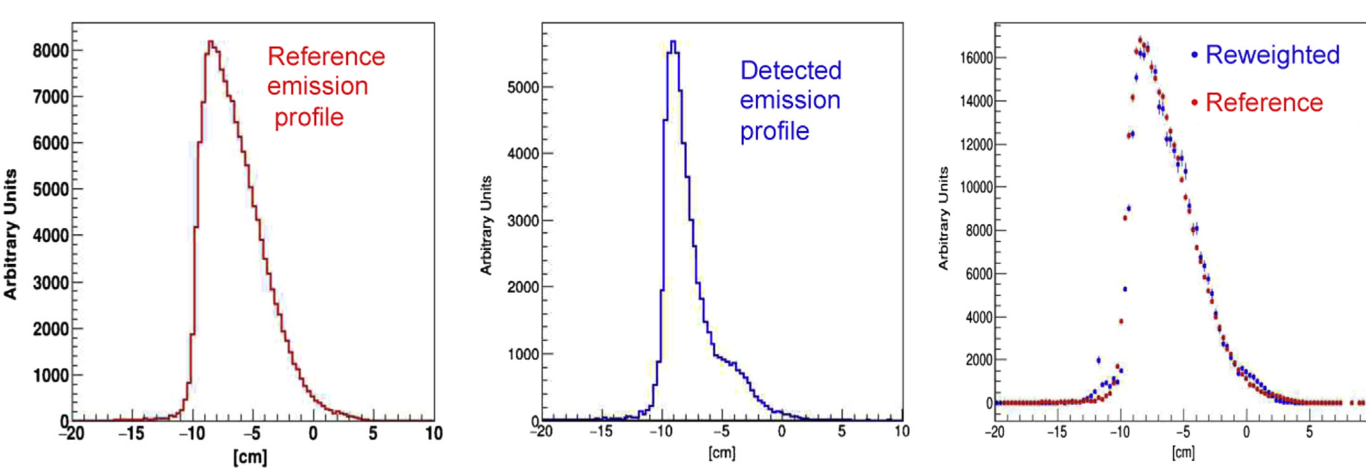

Fig. 7. Left panel: the MC profile of the emitted charged secondary as produced by the beam. Central panel: the emitted profile as reconstructed by the detector. Right panel: results of the re-weighting procedure.

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2.5 cm radius of the PMMA cylinder. The quantity we are interested in is the reconstructed coordinate along the beam direction (as discussed later) which is x in this case.

The resolution has been also evaluated with a simulation with the profiler at 60° with respect to the beam axis. For angles different from 90° the spatial resolution on the emission shape worsen , due to the transverse spread of the primary beam. For protons detected at 60° with respect to the beam axis is worsen by a factor $\frac{1}{\sin(60^\circ)}$.

4. Proton emission shape attenuation inside the patient

As demonstrated in [4], for a carbon ion beam impinging on a cylindrical target with 2.5 cm radius, the secondary proton emission shape along the beam axis can be correlated with the Bragg peak position (see Fig. 5).

By means of the attenuation study of the proton emission shape for different material thickness, we get a method to correlate the shape detected by the profiler coming out from the patient with the Bragg peak position.

We apply to the proton reconstructed track a weight which takes into account the thickness and density of the material crossed.

This procedure has applied to the system shown in Fig. 6 where a ^{12}C beam propagate in a PMMA sphere of 10 cm radius (density $\rho = 1.2\ \text{g/cm}^3$), that in turn contains a smaller sphere of density $\rho_0 = 0.6\ \text{g/cm}^3$ with radius =3 cm. The simulated detector is at 40 cm distance from the sphere center.

In Fig. 7 is reported on the left panel the MC profile of the emitted charged secondary as produced by the beam, while in the central panel the emitted profile as reconstructed by the detector. The distortion in the emission shape due to the material effect is evident and would heavily affect the correct evaluation of the Bragg peak position using the reconstructed profile. The results of the re-weighting procedure is shown in the right panel, where the re-weighted profile is superimposed to the generated one. The results indicates the possibility to extract the original profile of the charged secondaries if the detailed map of the material crossed by the detected protons is known.

5. Conclusions

We designed a new device capable of dose pattern online measurements that is tailored for particle therapy applications. It detects and reconstructs charged particles, mainly protons, coming out from the patient.

The software tools needed for the full simulation and the event reconstruction have been developed. The detector expected resolution, estimated by means of a detailed MC simulation, meets the requirements set for online dose range monitoring applications for particle therapy.

We developed a method to correlate the charged particles emission shape with the measured one, taking into account the matter absorption effect and complex geometries.

This detector, particularly suited for carbon ion beams, is under construction. At present readout electronics is under test.

A prototype will be installed at CNAO within 2016.

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