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MONDO: A tracker for the characterization of secondary fast and ultrafast neutrons emitted in particle therapy

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Abstract. In Particle Therapy (PT) accelerated charged particles and light ions are used for treating tumors. One of the main limitation to the precision of PT is the emission of secondary particles due to the beam interaction with the patient: secondary emitted neutrons can release a significant dose far from the tumor. Therefore, a precise characterization of their flux, production energy and angle distribution is eagerly needed in order to improve the Treatment Planning Systems (TPS) codes. The principal aim of the MONDO (MOnitor for Neutron Dose in hadrOntherapy) project is the development of a tracking device optimized for the detection of fast and ultra-fast secondary neutrons emitted in PT. The detector consists of a matrix of scintillating square fibres coupled with a CMOS-based readout.

Here, we present the characterization of the detector tracker prototype and CMOS-based digital SPAD (Single Photon Avalanche Diode) array sensor tested with protons at the Beam Test Facility (Frascati, Italy) and at the Proton Therapy Centre (Trento, Italy), respectively.

1. Introduction

Nowadays Particle Therapy (PT) is more and more diffused as proven by the number of treatment centers with light ions (mainly protons and carbon ions) that are continuously increasing. The main advantage of PT, compared to conventional radiation therapy, is its power in concentrating the dose release in the tumor region preserving the surrounding tissues. The charged particles, protons and light ions, release the maximum dose at the end of their path in the well known Bragg Peak: the position of that peak, as well as its width, depends on beam energy and on type of particles used. The abundant components of secondary particles (neutral and charged particles) produced by the nuclear fragmentation of the beam (and of the target) and by the de-excitation of the isotopes exited by the beam interaction in the matter, has been previously studied [1-3]: charged particles, prompt photons and photons from $\beta+$ annihilation. In general, the additional dose due to charged secondary products and photons is negligible compared to the beam one. However, the secondary particles have been carefully characterised

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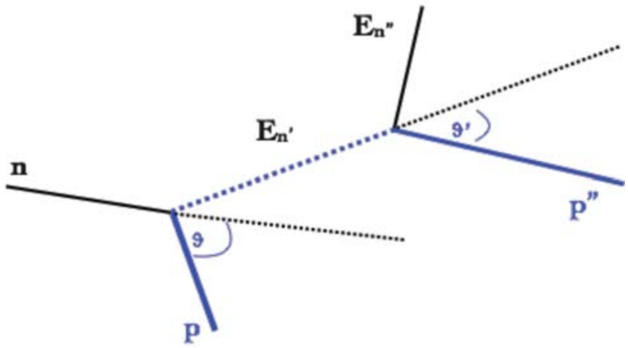

Figure 1. Schematic representation of a neutron double elastic scattering. Measuring protons tracks, kinetic energies and angles, it is possible to calculate the kinematics and establish direction and energy of the neutrons.

because of their usefulness in beam range monitoring and partially contribute to the effective dose delivered in treatments. For the neutron component instead the characterization is not complete: fluxes and energy spectra in function of the emission angle have been measured for thin target [4] and no efficent tracking detector for neutrons are nowadays available in the energy range of PT interest. Available measurements are based on the combination of different experimental setups, e.g. with an extended range Bonner sphere [5] or on the use of detectors with long and complex calibrations. Secondary neutron production is one of the main cause of Secondary Malignant Neoplasms (SMN), which develop significantly later (many years) after the treatment [6]. Therefore, it is crucial to characterise the secondary neutron production in the patient and the limit of the application of PT in the treatment of paediatric tumors is in this context evident.
The aim of the MONDO project (MOnitor for Neutron Dose in hadrOntherapy) is to characterise the secondary neutrons production in PT in order to improve the Monte Carlo and the analytical models at the base of the Treatment Planning System (TPS) [7]. A tracker dedicated to the measurements of neutrons in the energy range of 20 - 400 MeV will be built. Specifically, Sec. 2 presents the detector principle of operation, while some results with electrons and protons beam are reported in Sec. 3 testing a detector prototype.

2. The MONDO Project

In the MONDO tracker the complete reconstruction of the neutrons quadri-momentum is performed through the detection of recoiled protons emitted by neutrons Double Elastic Scattering (DES) with the interacting material. When two consequent recoiled protons emitted in DES are completely contained in the active area of the detector, the energy and the direction of the incoming neutrons are calculated using the following equation:

$$E_n = \frac{E_p}{cos^2\theta} \tag{1}$$

where E_i $(i = n, p)$ is the neutron/proton kinetic energy and θ is the angle between the recoil proton and the incoming neutron. Fig. 1 shows an example of a DES event.

The final design of the detector includes a $10 \times 10 \times 20$ cm^3 matrix of scintillating plastic fibers (square cross section, 250 μm side) arranged in orthogonal layers. The active volume acts both as a target for neutrons and as a detector for secondary emitted protons. The light produced by the proton interaction with the fibers is collected with a dedicated system developed

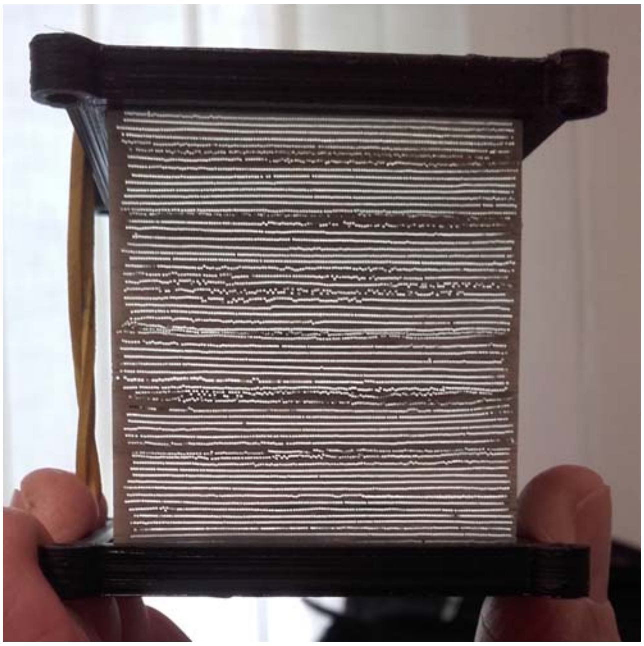

Figure 2. PENELOPE: a MONDO tracker prototype.

in collaboration with Fondazione Bruno Kessler (FBK).
The readout consists of a SPAD-array built with the same technology presented in [8], but with some characteristics optimized for our goal. In particular, the sensor trigger logic is based on a double threshold logic with a smaller pixel size (250×125 μm).
In order to characterise the fibers and to finalize the construction of the MONDO detector, a small prototype (called PENELOPE) was built (total dimension: $4 \times 4 \times 4.8$ cm^3). The device is shown in Fig. 2.

3. Experimental results

PENELOPE was tested both with electrons and protons; its efficiency and light production were characterised. The prototype was readout with three different devices: (1) a commercial Hamamatsu H10580 PhotomultiplierTube (PMT), (2) a Multianode H8500C and (3) a spad-net sensor (described in the previous Section).

3.1. Test with an electron beam

In May 2016 PENELOPE was tested at the Beam Test Facility (BTF) at the Frascati INFN National Laboratory. The goal of the test beam was the evaluation of the charged produced by a 450 MeV electron crossing a layer of fiber. In fact, at that energy electrons act like a mip (minimum ionizing particles) thus allowing to study the worst case scenario in energy release and light production. The Hamamatsu PMT response is presented here. Fig. 3 shows a schematic representation of the experimental setup and the average PMT output signal. The integral of the signal corresponds to the total charged produced and 250 ± 50 photoelectrons were measured. Considering that the PMT covers an equivalent area of 30 ± 2 layers, the calculated charged produced by a single layer is 7.2 ± 1.4.

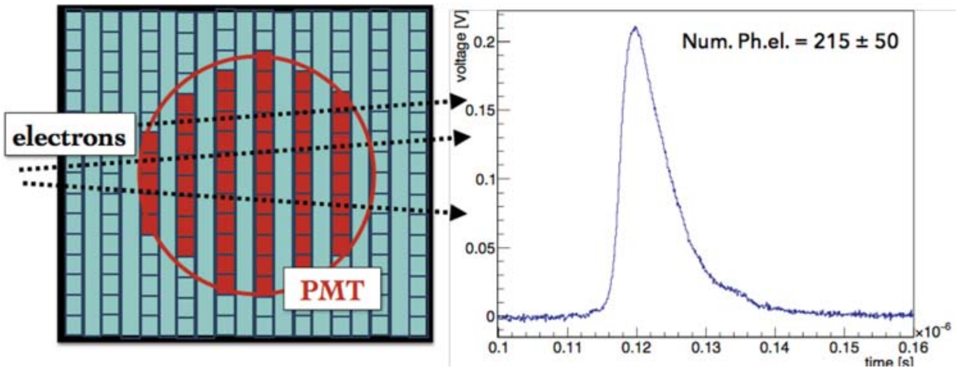

Figure 3. (Left) Experimental setup at the BTF: the area covered by the PMT is smaller than the total area covered by PENELOPE. (Right) Average waveform signal produced by the PMT. [9]

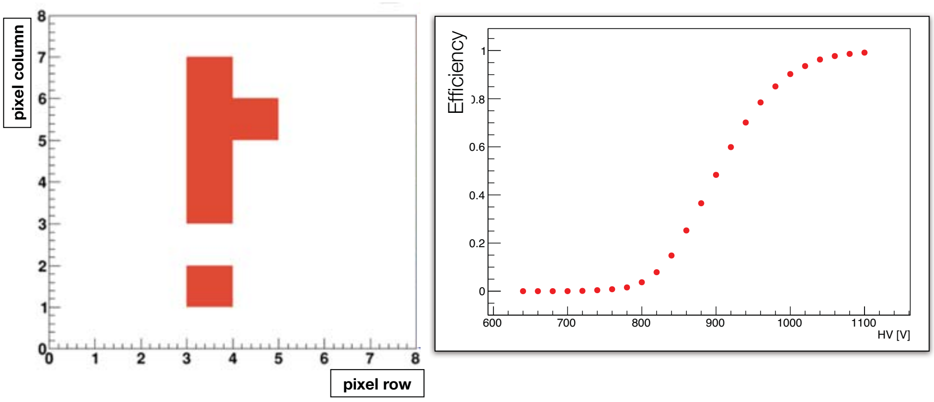

Figure 4. (Left) Example of an event with a track, in which 6 pixels in a row are activated. (Right) Efficiency in function of the multianode HV.

3.2. Test with a proton beam

In May 2017 PENELOPE was tested at the Proton Therapy Center (PTC) at the Trento Hospital, using protons in the energy range of 70 - 230 MeV, which corresponds to the energy spectra of the recoiled protons produced in DES neutron events. The multianode and spad-net sensor responses are presented here.

3.2.1. Multianode readout: efficiency A study of the efficiency in function of the multianode High Voltage (HV) supply was performed. The multianode H8500C has 64 pixel (8×8, 6 mm side) individually readout covering a total area of $\sim 5 \times 5$ cm^2. The efficiency is calculated as the number of events with at least 6 pixels in the same row showing a signal (i.e. a proton track) over the total number of events (Fig. 4).

The efficiency increases with HV. So we decided to operate our multianode with the maximum HV suggested by the multianode data-sheet.

3.2.2. Spad-net sensor: tracks reconstruction An analysis of the proton tracks extracted using the spad-net sensor was also performed: the single event maps, obtained counting the number

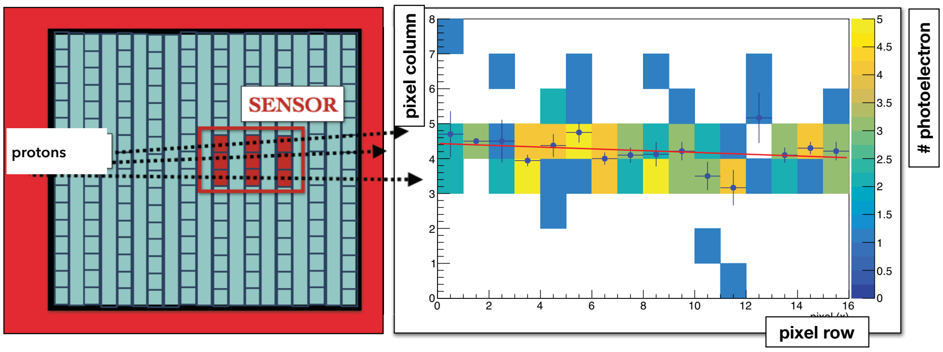

Figure 5. (Left) Expermental setup at the PTC: the area covered by the spad-net sensor is very small compared to the total area covered by PENELOPE. (Right) Example of a proton track reconstruction.

of photo-electrons detected from each pixel, were fitted with a linear function to reconstruct the proton direction (Fig. 5). In order to reduce the background noise, pixels with less than 2 activated spads were not included in the fit.

4. Conclusion

The MONDO project is dedicated to the characterization of secondary neutrons produced during particle therapy treatments. The system is based on the detection of double elastic scattering events (neutron on scintillating fibres) and the readout requirements are quite stringent.
The data colleced at BTF and CPT revealed that a fully digital CMOS approach is suitable for the MONDO tracker. The prototype shows good characteristics in efficiency, track reconstruction, light production and collection. A new readout sensor (SBAM: SPAD-Based Acquisition readout for MONDO experiment) is under development: the new design will match the tracker geometry and implement a smart discrimination mechanism specifically tailored to the proton tracks.

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