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Characterisation of the secondary-neutron production in particle therapy treatments with the MONDO tracking detector

M. FISCHETTI(1)(5), G. BATTISTONI(6), M. DE SIMONI(4)(5), Y. DONG(7)(6), E. GIOSCIO(2), I. MATTEI(6), R. MIRABELLI(4)(2)(5)(*), V. PATERA(1)(2)(5), A. SARTI(1)(2)(3), A. SCHIAVI(1)(5), A. SCIUBBA(1)(2)(5), G. TRAINI(4)(2)(5), S. M. VALLE(7)(6) and M. MARAFINI(2)(5)

(1) *Università di Roma "La Sapienza", Dipartimento di Scienze di Base e Applicate per l'Ingegneria Rome, Italy*
(2) *Museo Storico della Fisica e Centro Studi e Ricerche "E. Fermi" - Rome, Italy*
(3) *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati - Frascati, Italy*
(4) *Università di Roma "La Sapienza", Dipartimento di Fisica - Rome, Italy*
(5) *Istituto Nazionale di Fisica Nucleare, Sezione di Roma - Rome, Italy*
(6) *Istituto Nazionale di Fisica Nucleare, Sezione di Milano - Milan, Italy*
(7) *Università degli Studi di Milano, Dipartimento di Fisica - Milan, Italy*

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Summary. — Particle Therapy (PT) is a non-invasive technique that exploits charged light ions for the irradiation of tumours that cannot be effectively treated with surgery or conventional radiotherapy. While the largest dose fraction is released to the tumour volume by the primary beam, a non-negligible amount of additional dose is due to the beam fragmentation that occurs along the path towards the target volume. In particular, the produced neutrons are particularly dangerous as they can release their energy far away from the treated area, increasing the risk of developing a radiogenic secondary malignant neoplasm after undergoing a treatment. A precise measurement of the neutron flux, energy spectrum and angular distributions is eagerly needed in order to improve the treatment planning system software, so as to predict the normal tissue toxicity in the target region and the risk of late complications in the whole body. The MONDO (MOnitor for Neutron Dose in hadrOntherapy) project is dedicated to the characterisation of the secondary ultra-fast neutrons ([20–400] MeV energy range) produced in PT. The neutron tracking system exploits the reconstruction of the recoil protons produced in two consecutive (n, p) elastic scattering interactions to measure simultaneously the neutron incoming direction and energy. The tracker active media is a matrix of thin squared scintillating fibers arranged in orthogonally oriented layers that are read out by a sensor (SBAM) based on SPAD (Single-Photon Avalanche Diode) detectors developed in collaboration with the Fondazione Bruno Kessler (FBK).

(*) Corresponding author. E-mail: `riccardo.mirabelli@roma1.infn.it`

1. – Introduction

Particle Therapy (PT) is a non-invasive technique mainly devoted to the treatment of tumours that are radioresistant or localised closely to organs at risk. Even if a large fraction of the dose is released by the charged particles directly in the tumour volume, a non-negligible dose amount, carried mainly by neutrons, can reach other body regions far away from the target volume increasing the risk of developing a radiogenic second malignant neoplasm, after undergoing a treatment. A precise measurement of the secondary neutrons flux, production energy and angular distributions is not yet available [1], while it would greatly help understanding how to reduce such unwanted additional dose release. Measurements are eagerly needed to improve the Treatment Planning System (TPS) software, so as to predict the normal tissue toxicity in the target region and the risk of late complications in the whole body. The request becomes particularly relevant in the case of paediatric treatments where life expectancy is a fundamental parameter [1]. The MONDO (MOnitor for Neutron Dose in hadrOntherapy) project addresses the requirements of a high efficiency and good backtracking precision for a complete characterisation of secondary ultra-fast neutrons in the energy range [20–400] MeV. In this contribution the detector is described in sect. **2** together with the description of the simulation work performed for the layout optimisation while sect. **3** presents the experimental results.

2. – The MONDO project

The MONDO project principal aim is the development of a compact, high-resolution tracking device optimised for the detection of secondary ultra-fast neutrons produced in PT treatments. The technique used for the secondary neutrons tracking aims at the simultaneous reconstruction of the neutron energy and direction exploiting the detection of two consecutive Elastic Scattering (DES) interactions in the tracker active material (fig. 1).

In a (n,p) elastic interaction, the proton and the neutron momenta $\vec{p_n}$ and $\vec{p_p}$ are correlated by the relation

$$\vec{p_n} = \frac{\vec{p_p}}{\cos^2\theta_p}, \qquad (1)$$

where θ_p is the angle between the recoil proton and the primary neutron tracks. If the direction and the energy of the incoming neutron are unknown, DES events can be used to get simultaneous access to both physical quantities reconstructing the two recoil protons [2].

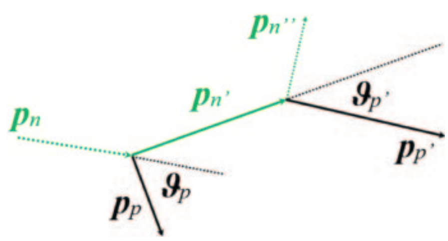

Fig. 1. – Scheme of the DES reaction [3].

The detector is composed by a matrix of thin squared scintillating fibers (250 μm side) arranged in orthogonal layers and it has the total size of $10 \times 10 \times 20\,\mathrm{cm}^3$. The readout of the fibers is performed through a dedicated sensor, SBAM (SPAD Based Array for the MONDO experiment) that implements several SPAD (Single-Photon Avalanche Diode) arrays. The sensor, implemented using the CMOS technology, has been developed in collaboration with the Fondazione Bruno Kessler (FBK) [4]. SBAM is composed by a tile of several small sensors (each $2 \times 2\,\mathrm{mm}^2$ area) equipped with 16×8 pixels ($125 \times 250\,\mu\mathrm{m}^2$ is the area of each pixel). A two-level trigger logic is implemented: the readout of the event is performed only when the number of fired pixels and the number of fired sensors becomes greater than a user programmable threshold.

2˙1. *Monte Carlo simulation.* – A FLUKA Monte Carlo (MC) simulation [5] has been used to optimise the detector layout and evaluate its expected performance. The simulation was used to evaluate the proton energy spectrum expected in clinical-like scenarios, the predicted neutron energy resolution and the background contamination from anelastic neutron collisions. Figure 2 shows the energy spectrum of the protons generated by a monochromatic neutron beam of 100 MeV impinging on the detector, both for Single Elastic Scattering (SES, black) and for DES (green and orange) events. When studying DES events, both protons are requested to be fully contained in the detector.

As expected, for single elastic scattering interactions, the recoil proton energies are distributed uniformly from ∼12 MeV (at least 3 x-y planes of fibres traversed) up to the primary energy of the neutrons (the maximum energy available). For DES interactions, where the presence of a second elastic scattering interaction is required, the maximum energy of the first recoil proton is forced to be lower than the maximum available energy (80 MeV) [3].

The neutrons kinetic energy was studied using DES events. The relative energy resolution is shown in fig. 3 as a function of the neutrons kinetic energy. For monochromatic neutrons, the achievable accuracy improves as a function of the secondary-protons energy increase, as expected in the case of straighter and longer tracks. The average preliminary relative energy resolution for neutrons has been evaluated to be in the 4–6% range.

The occurrence of elastic scattering interactions events must be compared with the expectations of the main intrinsic backgrounds represented by events in which inelas-

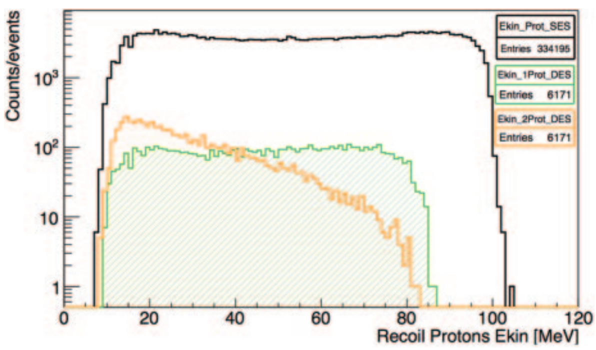

Fig. 2. – Energy spectrum of protons emitted in a single elastic scattering interaction (black) compared with the energy spectrum of the first (green) and second (orange) protons emitted in a DES interaction for a neutron incoming beam of 100 MeV [3].

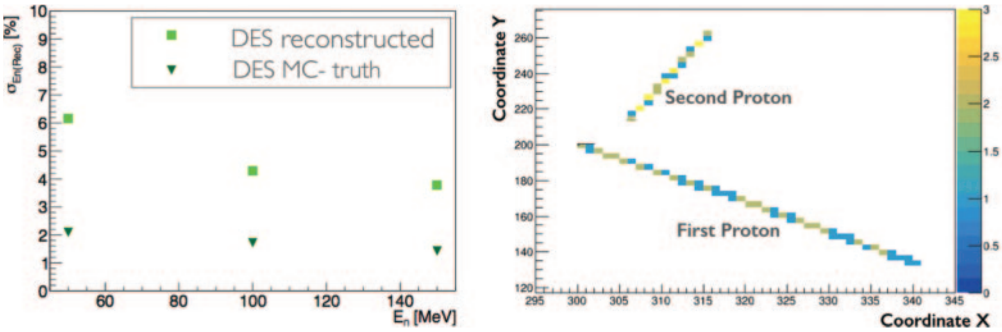

Fig. 3. – Left: the relative energy resolution (in %) for DES is shown as a function of the neutron kinetic energy. Only statistical uncertainties are included. Right: example of a DES interaction event display (in a projected X-Y view): the first and the second recoil protons are clearly tracked by the detector.

tic scattering interactions occur (fig. 4). In this analysis monochromatic neutrons with energies in the range [20–300] MeV have been studied considering only protons that cross at least 3 layers of fibers in both directions. In fig. 4 the single elastic scattering interactions (black full circles) are dominant below 100 MeV, while the inelastic scattering interactions (red empty squares) are not negligible for higher energies. As a result, DES interactions (green full circles) are dominant for low-energy neutrons.

The probability of mixed interactions elastic-inelastic/inelastic-elastic or double inelastic interactions (magenta and grey triangles) could have a considerable impact on the detector performance below 120 MeV. The double inelastic scattering interactions (blue empty squares) are dominant in the upper energy range. These contributions could have a non-negligible impact on the detector performances and have to be taken into account

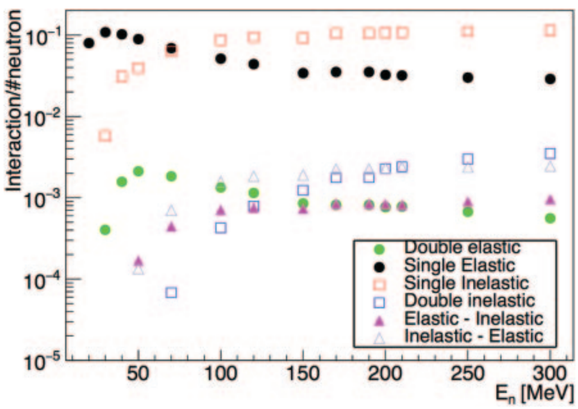

Fig. 4. – Number of neutrons interacting in the detector as a function of the kinetic energy of the neutrons for: single elastic scattering (black full circles), double elastic scattering (green full circles), single inelastic scattering (red empty squares), double inelastic scattering (blue empty squares), elastic scattering followed by inelastic scattering (magenta full triangles), inelastic scattering followed by elastic scattering (grey empty triangles). The error bars (not visible) are only accounting for the statistical contribution [3].

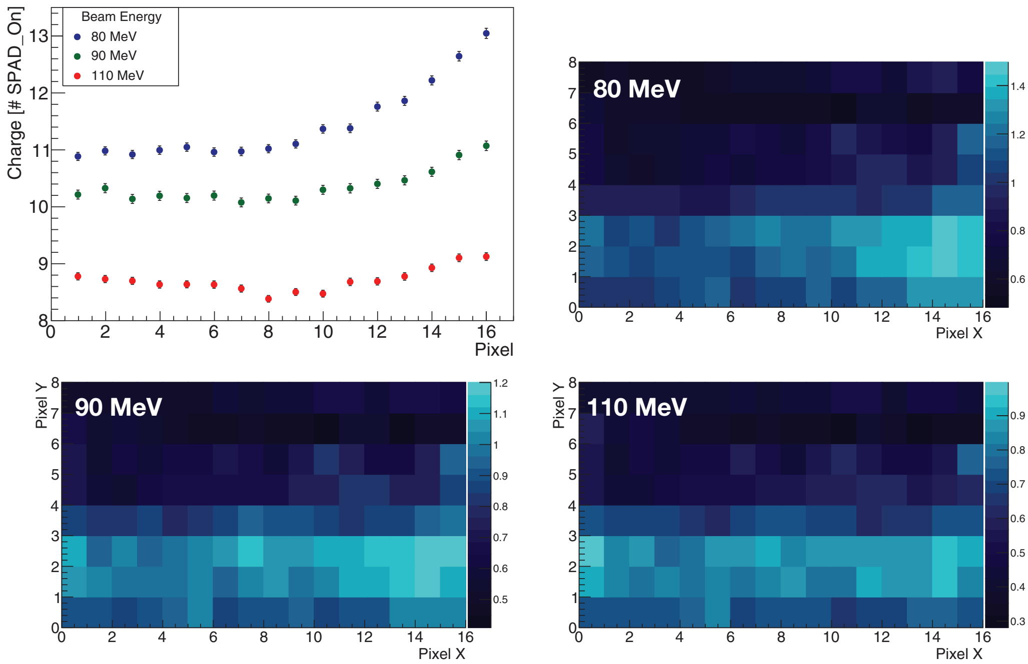

Fig. 5. – Energy released in spad-net sensor from different energies protons. (a) Top left: Charge release in number of detected photon per pixel column. At $E_p = 80\,\mathrm{MeV}$ there is an increase in the energy release thanks to the Bragg Peak presence; (b)–(d) Top right, bottom left and bottom right: Average energy sensor map. Each square box represent a pixel. The average number of photoelectrons detected are shown with different brightness

when calculating the intrinsic background. The reduction of the background contamination and the rejection of inelastic events is currently being studied: the track multiplicity at the interaction vertex will be one of the main ingredients of the algorithm, but other strategies are being pursued as well.

3. – Experimental results

In May 2017 a first MONDO prototype has been tested at the TIFPA experimental line of the Trento Proton Therapy Center. The prototype consists in a small tracker (PENELOPE, $4 \times 4 \times 4.8\,\mathrm{cm}^3$) read out by a SPAD-based sensor prototype, *spad-net* [6]. The total area of the sensor is $1 \times 0.5\,\mathrm{cm}^2$ and only a small area of the tracker could be read out: the sensor position was chosen to allow the observation of the less energetic protons, that stopped inside PENELOPE. The aim of the test was the characterisation of the $\mathrm{d}E/\mathrm{d}x$ release reconstruction capability of the sensor. Three proton beams of 80, 90 and 110 MeV kinetic energies have been considered. In fig. 5 (top right, bottom left and bottom right, respectively, for the three different energies) the energy sensor map, averaged over 75k events, is shown. Each bin in the x-y plane represents one pixel (side $600\,\mu\mathrm{m}$) while the content of each bin in the z-axis represents the average number of detected photons in that pixel: the lighter band represents the track of the protons traversing the detector. The total number of photo-electrons as a function of the pixel column is shown in fig. 5 (top left). When looking at the 80 MeV distribution, the Bragg peak appears in the last two pixels along the X view. When going to higher energies, the BP slowly exits from the detector and the energy release does not show a peak anymore. The deposited energy (shown in terms of the total measured charge) in the pixels is greater for protons of 80 MeV kinetic energy, when compared to the 110 MeV one, as the Bragg peak is fully contained in the detector portion read by spad-net in the former case.

4. – Conclusions

MONDO is a project dedicated to the complete reconstruction of neutrons that have a kinetic energy in the range [20–400] MeV. The MONDO detector layout has been optimised for the characterisation of secondary neutrons emitted during Particle Therapy treatments, exploiting the detection of the double elastic scattering events in the tracker scintillating fibers. A tracker prototype, with dimensions that are smaller than those of the final full size detector, has been tested with protons of different energies and a readout prototype. A new sensor, capable of reading out the full size final detector is currently under development in collaboration with FBK. The new design will be optimized considering the final tracker geometry and will implement a two-levels trigger logic capable of reducing the combinatorial background events to a negligible level.

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REFERENCES

[1] Newhauser W. and Durante M., *Nat. Rev. Cancer*, **11** (2011) 438.
[2] Marafini M. *et al.*, *Phys. Med. Biol.*, **62** (2017) 3299.
[3] Giacometti V. *et al.*, *Radiat. Meas.*, **119** (2018) 144.
[4] Mirabelli R. *et al.*, *Trans. Nucl. Sci.*, **65** (2018) 744.
[5] Battistoni G. *et al.*, *Ann. Nucl. Energy*, **82** (2015) 10.
[6] Braga L. H. C. *et al.*, *IEEE J. Solid-State Circuits*, **49** (2014) 301.