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New reconstruction algorithm for the fast neutron MONDO tracker

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Summary. — Particle Therapy employs charged light ions to treat cancer with localized energy deposition, so that damages to healthy tissues are significantly reduced with respect to conventional radiotherapy. When using carbon ion beams fragmentation has to be taken into account: the ultra-fast secondary neutrons can be responsible for additional dose also far from the treated volume, and are likely candidates for the occurrence of secondary malignant neoplasms. MONDO is a neutron tracker dedicated to the characterization of the secondary neutrons produced in the interaction between human tissues and the therapeutic beam. It is made of a compact matrix of plastic scintillating fibers coupled with a CMOS-based SPAD sensor (SBAM) developed specifically for MONDO. Its technique of measuring the neutron four-momentum is based on the detection of recoiled protons scattered during two consecutive elastic collision events. A Monte Carlo simulation based on the FLUKA code has been developed to optimize the MONDO detector geometry and study its characteristics. The sensor has been fully implemented in the simulation, and an algorithm for event reconstruction, operating with a cluster building technique, has been written to evaluate detection efficiency, energy resolution and backpointing rejection capability from the chip readout. The algorithm description and first results are presented in this manuscript.

1. – Introduction

Particle Therapy (PT) is a technique of solid tumors treatment which employs beams of light ions, with energies of order 100 MeV per unit atomic mass, to irradiate diseased tissues, causing breakages of DNA bonds and inhibiting cancer growth by apoptosis. The main advantage of PT with respect to other external beam radiotherapy methods (for example, treatment with X-rays) lies in the fact that the energy deposit along the ion path is strongly peaked inside a region defined as Bragg Peak, located just before the particle loses all its momentum and comes to rest; therefore, sane tissues in the area surrounding the tumor are largely spared, and the highest amount of dose (absorbed dE/dm) is concentrated in the desired target volume. It is therefore the preferred option when treating tumors close to organs at risk (OAR). Protons and carbon-12 ions are the two particles more commonly exploited; the use of other low-Z ions (He, O, Ne) is currently under investigation [1].

During irradiation, the beam can interact via strong interactions with atoms encountered across its direction, starting a fragmentation process which results in the production of secondary particles, both charged and neutral. Additional dose caused by nuclear fragments is the subject of multiple studies; in particular, secondary neutrons in the ultra-fast range of energies (hundreds of MeV) are generated. The expected flux of neutrons per primary ion in the energy range of interest for PT can be extrapolated from available measurements published in [2]. The neutron yield for 200 MeV/u ^{12}C ions against a water target has been evaluated to be $0.54 \pm 20\%$ neutrons per primary ion [3].

Since their electric charge is null, neutrons interact less frequently with the patient body, and can travel a distance of several centimeters before releasing all their energy [4]. This causes a deposit of an absolute non-negligible amount of energy both in- and out-of-field, potentially dangerous for healthy tissues and responsible for the insurgence of long-term complications such as secondary malignant neoplasms (SMN) [2,5]. Thus, the contribution of secondary neutrons to the total dose needs to be measured with high precision; to do so, a thorough characterization of the particles in terms of energy and angular distributions is required.

Experiments measuring neutron radiation produced during PT sessions with H and C ions have focused on the total production yields and energy spectra, summing up contributions of particles being generated at various positions and instants, and through different processes. These include the main beam and target fragmentation mechanism (secondary component) and moderation processes, by which neutrons gradually lose energy from successive scatterings with the treatment apparatus and the patient body itself (ternary component). The comprehensive approach has been used to determine the fraction of equivalent dose carried by high-energy neutrons [2, 6]. Conversely, separating the secondary neutrons from the ternary neutral component, that acts as an irreducible background depending on a considerable amount of parameters, is a goal still to be achieved, though necessary for a precise measurements of their impact on the Treatment Planning System (TPS).

The proposed solution, experimentally challenging, is to build a tracking detector, able to reconstruct the production site of neutrons in the ultra-fast region and, at the same time, measure their energy spectra and angular distribution [7, 8]. The MONDO (MOnitor for Neutron Dose in hadrOntherapy) project aims at developing a secondary neutron tracking detector to be implemented in a clinical environment, with high efficiency and good background rejection capability. Outside of its primary goal, MONDO provides a suitable experimental environment for the purpose of improving measurements of the neutron cross-section on tissue-equivalent compounds, which is of interest for other fields in applied radiation physics, like radio-protection in space.

2. – Methods and materials

2˙1. *Detection strategy.* – The four-momentum of the neutron (energy and direction) is reconstructed by measuring both the direction and the energy of the recoiled protons produced in double elastic scattering (DES) events, out of which the maximum amount of information can be extracted in the ultra-fast regime. Protons and neutrons have very similar masses, so the incoming neutron can transfer up to all its kinetic energy to

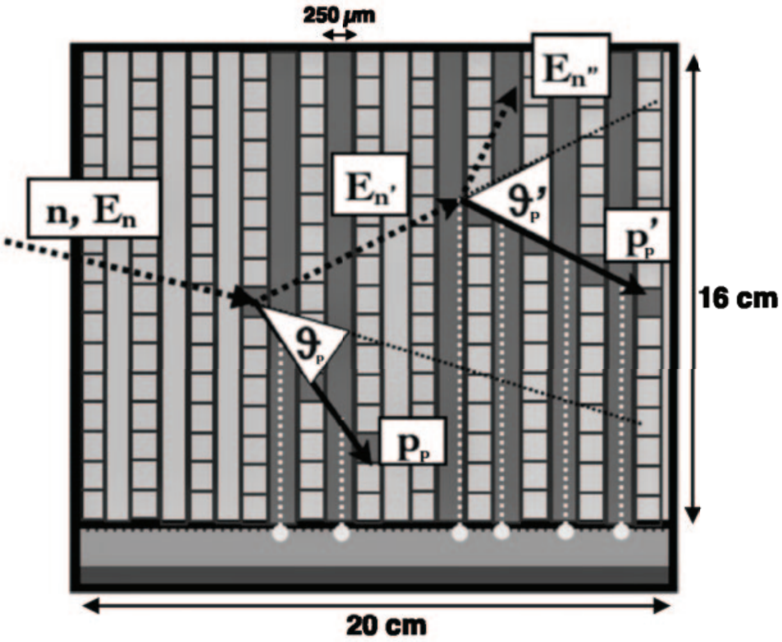

Fig. 1. – The MONDO tracker design with a double elastic scattering event producing a scintillation signal.

the recoiled proton in a single interaction. In order to maximize the probability of DES events with protons, a highly hydrogenated material is chosen for both target and active medium in the MONDO tracker.

In principle (fig. 1), if the neutron initial direction is known, a single elastic scattering is sufficient to close the kinematic of the process and determine the value of its energy by measuring the proton momentum from an energy/range relation. In formulas, calling $(E_n, \vec{p_n})$ and $(E_p, \vec{p_p})$ the four-momenta of the incoming neutron and recoiled proton, m_n and m_p their masses, and θ_p the angle in the three-dimensional space between their directions:

$$(1a)\qquad \vec{p_n} = \vec{p_p}\,\frac{1+m_n/m_p}{2\cos\theta_p} \simeq \frac{\vec{p_p}}{\cos\theta_p}, \quad \text{because } m_n \simeq m_p;$$

$$(1b)\qquad E_n = \frac{2E_p m_p}{\cos^2\theta_p(E_p + 2m_p + E_p/\cos^2\theta_p)} \simeq \frac{E_p}{\cos^2\theta_p}, \quad \text{if } E_n \ll m_n.$$

When the incident neutron has unknown direction (*i.e.*, θ_p to be determined), eq. (1), applied to two consecutive interactions in a DES event contained inside the detector, allows to reconstruct the four-momentum by the following steps: a) $\vec{p_p}'$ and $\vec{p_p}$ are measured; b) θ'_p is the angle between $\vec{p_p}'$ and the line connecting the two interaction vertices; c) $\vec{p_n}'$ is uniquely determined through eq. (1a); d) $\vec{p_n}$ is computed through momentum conservation; e) finally, θ_p is determined using eq. (1a) once again.

2˙2. *MONDO project*. – The detector, as sketched in fig. 1, is based on a compact matrix of layers of squared plastic scintillating fibers (thickness 250 μm) arranged in orthogonally oriented planes. The dimensions of fibers have been chosen in order to have a good granularity on proton tracks, so to maximize the achievable spatial resolution and reduce threshold on signals from low-energy protons, set at $E_p \sim 12$ MeV, corresponding to the request of having no less than 3 fibers crossed, minimum number for 3D track reconstruction. The final detector will be realized by weaving singularly planes of fibers with a constant-step motorized system, and then fixing them together with a small quantity of glue in the space between. In order to prevent intra-layers cross-talk, an aluminized Mylar foil (thickness 5 μm) will be placed between each plane.

For the readout system, the requirement of a fast readout, handling a large number ($\sim 10^5$) of tightly assembled channels with high resolution, has driven the choice towards the CMOS-based Single-Photon Avalanche Diode (SPAD) technology. The sensor, built up from an array of SPADs, has been designed and produced specifically for MONDO in collaboration with Fondazione Bruno Kessler (FBK); the first chip has been produced and tested at FBK and SBAI Department of "La Sapienza" University of Rome. The main characteristics of the SPAD-Based Acquisition for the MONDO experiment (SBAM) are: pixel size of 125×250 μm^2, matching the granularity of fibers; suitability to arrange chips in tiles covering the whole detector external surface; time resolution of 100 ps; quantum efficiency (QE) $\sim 40\%$; fill factor $\sim 30\%$; possibility to individually turn off noisy SPAD (reduction of Dark Current contribution); two level trigger logic (at pixel and chip level) tuned for fast scintillation light signals ($\sim$ 5–10 ns) and a dark count rate (DCR) of about 1 kHz [9].

The number of expected photoelectrons produced inside a fiber, using the deposit energy of protons produced at initial E_p of 100 MeV, has been evaluated assuming a light yield of 8000 photons/ MeV and a trapping efficiency of 7.3% (double cladding, manufactured by Saint-Gobain(1)) and 4.2% (single cladding, by Kuraray(2)) fibers. The results are presented in table I [8,9].

The table shows that the average number of photoelectrons expected to be detected by a single fiber is 13 and 6 for, respectively, double cladding and single cladding types. For this reason, the readout sensor model has been optimized for the detection of few photons per incident particle.

3. – MC simulation

For estimates on MONDO expected performances, a dedicated Monte Carlo (MC) simulation based on the FLUKA code [10] was written to model the detector structural and technological features. The geometry used as starting point is the optimized configuration for the reconstruction of neutrons produced in PT applications [8], which is that of 800 layers of fibers of area 16×16 cm^2 and thickness 250 μm, with a total size of $16 \times 16 \times 20$ cm^3. At present time, the intra-layer materials (glue and Mylar foils) are not included in the MC simulation. Mono-energetic neutrons have been generated by a point-like source placed 20 cm away from the tracker volume, along an axis passing through the center of the fibers planes. As they encounter the hydrogenated material, FLUKA saves information about the type of interaction, particles produced, scintillation light output and activated pixels.

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(1) `https://www.crystals.saint-gobain.com/products/scintillating-fiber`
(2) `https://www.kuraray.com/products/psf`

Table I. – *MONDO project fibers characteristics.*

<table>
<tr><th>Fiber</th><th>S.Gobain d. clad.</th><th>Kuraray s. clad.</th></tr>
<tr><td>thickness</td><td>SQ 250 μm</td><td>SQ 200 μm</td></tr>
<tr><td>deposit energy (proton 100 MeV)</td><td>180 keV</td><td>145 keV</td></tr>
<tr><td>fiber light yield</td><td colspan="2">8000 ph/ MeV</td></tr>
<tr><td>trapping eff.</td><td>7.3%</td><td>4.2%</td></tr>
<tr><td>No. ph.</td><td>105</td><td>48</td></tr>
<tr><td>SBAM QE</td><td colspan="2">40%</td></tr>
<tr><td>SBAM fill factor</td><td colspan="2">33%</td></tr>
<tr><td>SBAM SPADs on</td><td colspan="2">90%</td></tr>
<tr><td>number of ph.el.</td><td>13</td><td>6</td></tr>
</table>

Taking advantage of the first sensor characterization, it was possible to include a wide range of hardware parameters inside the simulation; besides the trigger structure and values of QE and fill factor, the fact that a perfect fiber-pixel coupling is not considered possible, since the tolerance on fibers size is about 6%, was taken into consideration and implemented in the code, establishing a value of fiber/pixel misalignment of 1 μm in both directions. The intrinsic noise of the apparatus, the dark current rate (DCR), has also been inserted in the simulation, and its effect on reconstruction has received a first qualitative estimate.

The most recent studies of MONDO by means of the FLUKA code were conducted specifically with the aim of evaluating its performances in a clinical environment, so, in particular, its detection efficiency for DES events, backpointing rejection capability and energy resolution. The software framework served as basis to test an event reconstruction algorithm which, for the first time, did not exploit MC-truth information about the particle producing a signal inside the detector, but instead worked only with the simulated readout information, taking advantage of the full optimized sensor model without making additional requests on the observed particle. Therefore, the algorithm requires an additional strategy to identify a DES event from the hardware signal.

In order to properly make use of the readout signal, activated pixels are first grouped in 2D clusters which are then conglomerated in a 3D object by a track reconstruction method, which works by analysis of the event topology at pixels level. To make the results as clean and straightforward as possible, particles fully contained inside the detector and with minimum range of 3 fibers crossed were considered, a condition used also in previous studies [9, 11].

Figure 2 shows an example of event display at pixel level before and after cluster reconstruction: in this case, the event involves two protons each leaving a cluster of activated pixels. Some pixels are also randomly activated by FLUKA, simulating the background due to a DCR at 90%. From this crude event, the algorithm task is to extract the cluster structure that contains the information about the proton four-momentum, separating it from the spurious signal. As can be seen, the algorithm recognizes the cluster structure due to the proton passage with a generated DCR up to 90%, correctly discriminating the two contributions.

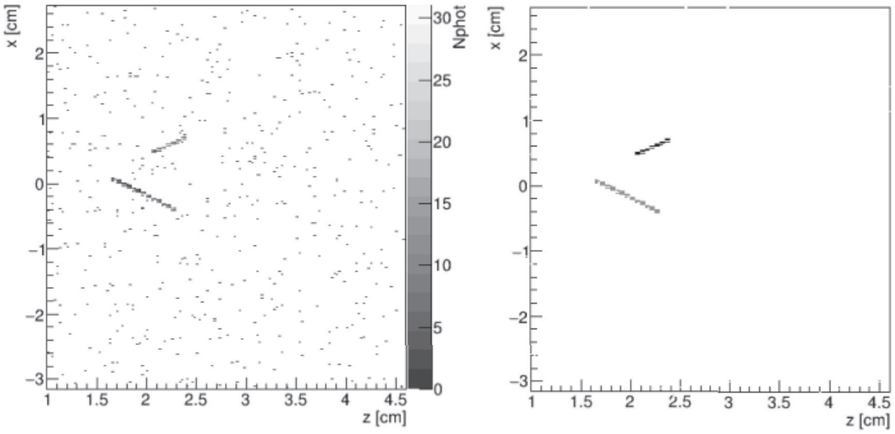


Fig. 2. – Left: example of event readout display with DCR at 90%. Right: reconstructed clusters.

3˙1. *Background evaluation.* – Observing the output signal generated in the simulation, events can be classified based on the number of tracks generated by the algorithm. DES events, which allows MONDO to close the kinematics if the direction is unknown and whose reconstruction is vital for backpointing rejection capability, are to be searched among events with 2 tracks, corresponding to two recoiled protons. The task of comparing the number of reconstructed elastic interactions with the background of inelastic events can be achieved referring to MC-truth.

The number of double-track scattering events per primary neutron in the tracker is plotted in fig. 3 as a function of the incoming neutron kinetic energy (E_n), chosen in the

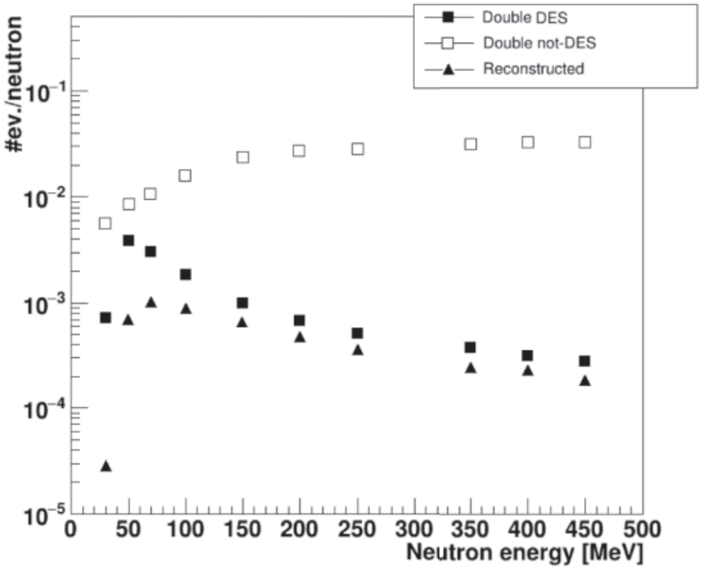


Fig. 3. – Rate of double-track contained events as a function of E_n.

interval $[30, 450]$ MeV, corresponding to the expected energy range of secondary products in PT treatments. Events represented with squares are those expected to produce 2 tracks based on MC, whilst triangles stand for events effectively reconstructed by the algorithm, using the hardware constraints mirroring the MC-truth used in previous analysis [7, 11]; these have been set as a particle activating at least 29 pixels in both planes (corresponding to a 2 mm range in the fiber volume) and track fully contained inside a confidence volume (particle containment). Purely DES events (black squares) reach a peak at 70 MeV and are quickly overshadowed by other types of spurious interactions (white squares), either purely inelastic or mixed elastic-inelastic.

Reconstructed events with no additional constraints show an expected sizable contamination of non-DES events. An additional algorithm request was made to further select interesting events: since elastic scattering kinematics fixes the 3D angle between secondaries at the interaction vertex at 90 degrees, the event is considered eligible for four-momentum reconstruction if the angle between the first proton track and the scattered neutron range (derived from the observed distance between the two vertices) is measured to be 90 degrees. As the angle between particle directions is computed by means of linear fits to the recoiled proton and scattered neutron tracks, this is still a measurable quantity that can be legitimately used to estimate the algorithm performance.

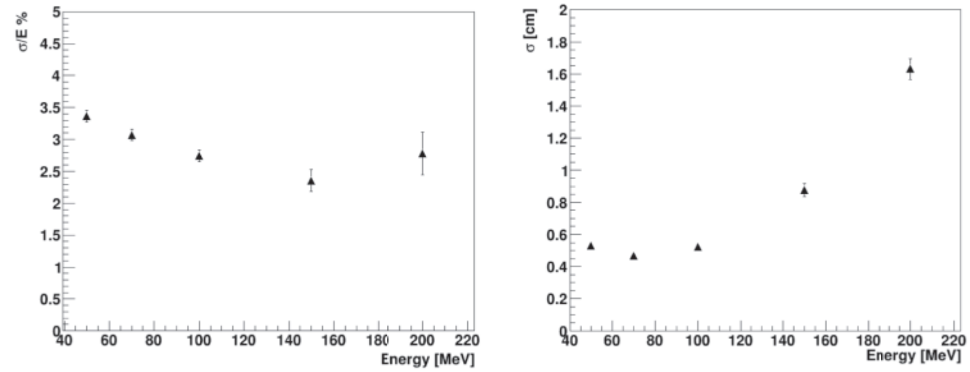
The resulting events (black triangles) have been used to evaluate the energy resolution and backpointing rejection capability of the detector. The total neutron rate can be extracted from the number of detected DES events, a dedicated calibration will be performed at neutron beam facilities at different energies. As can be seen from fig. 3, the detection capability for DES events is quite small (10^{-3}–10^{-4}, scaling with energy). This is due to the strict conditions that have been applied to cut spurious events and maximize the chances of picking DES events. For E_n lower than 50 MeV, there are considerably fewer events than expected from MC because of the requirement that recoiled protons produce tracks of enough length to determine with high precision the particle four-momentum, to benefit the energy and position resolution. Because less energetic protons produce shorter tracks, the number of events picked by the algorithm is limited. Further implementations will be considered to increase the number of reconstructed neutron interactions.

3·2. *Energy resolution.*

– The reconstructed energy resolution for secondary neutrons has been evaluated. The proton kinetic energy has been computed by using the energy-range relation proposed by Bortfeld and Schlegel [12] and using the extrapolated range fitting the reconstructed 3D track with a linear function.

The energy resolution for neutron four-momentum computed via double-track events with containment and elastic scattering assured by measuring the angle at the first vertex (equal to 90 degrees), was found out to be less than 4% (fig. 4(a)). At neutron energies lower than 50 MeV, the statistics was too limited by the requirement that protons have enough energy to cross at least 3 fibers, whilst at energies higher than 200 MeV, events contained were too few to reasonably reconstruct E_n.

An alternative method to compute proton energies is to exploit the Bethe-Bloch relation describing the mean energy loss per distance travelled $\mathrm{d}E/\mathrm{d}x$. This allows the analysis to move beyond the containment request and compute energy resolution at initial neutron kinetic energies higher than 200 MeV. The results are expected to be strongly dependent on the sensor characteristics (as is the implementation of cross-talk between pixels), so the study is close to be completed given the most recent production and characterization of SBAM [11].



(a) **(b)**

Fig. 4. – Resolution values computed in the energy interval $[30, 200]$ MeV. (a) Energy resolution as a function of E_n. (b) Backpointing resolution for the x component of the neutron direction as a function of E_n.

3·3. *Backpointing rejection capability.* – As previously mentioned, the backpointing rejection performance is a fundamental characteristic of the MONDO project; it is prerogative of the tracker to be able to discriminate scattered neutrons coming from the patient from the ternary background produced in iterative interactions with the environment. It has been evaluated as the precision of the algorithm in reconstructing the neutron origin, which in the considered simulation is a fixed point-like source. The position is computed with a method of Closest Point of Approach (CPA): given the first vertex of interaction and the reconstructed scattered particles directions, the primary neutron direction is extracted; then another line is traced, passing through the origin. The CPA between the reconstructed neutron direction and the line across the origin is taken as the computed emission point.

Resolution is obtained performing a Gaussian fit on the coordinates. The result for the x coordinate is shown in fig. 4(b). Like previously said for the energy, containment reduces the rate of useful events, and above 200 MeV many proton tracks escape the detector. Nevertheless, the procedure estimates a backpointing resolution of ~ 1 cm for E_n up to 150 MeV and still lower than 2 cm for higher energies, suggesting that the algorithm is already quite effective for discrimination of the primary neutron from moderation background, and can be enhanced by improving angular measurements and implementing a more comprehensive sensor characterization.

4. – Conclusions

MONDO is dedicated to the development of a tracker for the characterization of secondary neutrons produced in PT, studying their impact on treatment quality by computing their contribution to the total dose inside the patient. The project also opens up the possibility to implement the detector in other applications of radiation physics involving neutron dosimetry and high-precision cross-section measurements on tissue-equivalent compounds. The detector design consists of a compact matrix of plastic scintillating fibers, coupled with a custom made readout system (SBAM sensor), and its strategy is to reconstruct the neutron four-momentum by measuring energy and direction of recoil protons produced from two consecutive (n, p) elastic scattering events.

The algorithm for event reconstruction based on measurable quantities from the signal collected by the MONDO readout system has been developed, and has given preliminary results on fundamental parameters such as detection efficiency, energy resolution and backpointing rejection capability. For the next future, work is expected to particularly improve the rate of events useful for reconstruction by implementing methods for computing the recoiled proton energy without using the containment request. The simulation will be completed with a thorough implementation of pixel cross-talk, as soon as tests on the sensor are run, and will also perform a study on the tracker response with non-monochromatic beams of neutrons, better approximating MONDO usage in a clinical environment.

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