frontiers in Physics

ORIGINAL RESEARCH
published: 19 November 2020
doi: 10.3389/fphy.2020.567990

The MONDO Tracker: Characterisation and Study of Secondary Ultrafast Neutrons Production in Carbon Ion Radiotherapy

Marco Toppi[1,2], Giuseppe Battistoni[3], Alessandro Bochetti[4,5,6], Patrizia De Maria[7], Micol De Simoni[4,6], Yunsheng Dong[3,8], Marta Fischetti[1,6], Gaia Franciosini[4,6], Leonardo Gasparini[9], Marco Magi[1,6], Enrico Manuzzato[9], Ilaria Mattei[3], Riccardo Mirabelli[4,5,6], Silvia Muraro[3], Luca Parmesan[9], Vincenzo Patera[1,5,6], Matteo Perenzoni[9], Alessio Sarti[1,5,6], Angelo Schiavi[1,6], Adalberto Sciubba[1,5,6], Giacomo Traini[5,6], Serena Marta Valle[3] and Michela Marafini[5,6]*

[1]Dipartimento di Scienze di Base e Applicate per l'Ingegneria, "Sapienza" Università di Roma, Rome, Italy, [2]Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Frascati, Italy, [3]Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Milan, Italy, [4]Dipartimento di Fisica, "Sapienza" Università di Roma, Rome, Italy, [5]Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Rome, Italy, [6]Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Rome, Italy, [7]Scuola di Specializzazione in Fisica Medica, "Sapienza" Università di Roma, Rome, Italy, [8]Dipartimento di Fisica, Università degli Studi di Milano, Milan, Italy, [9]Integrated Radiation and Image Sensors (IRIS), Fondazione Bruno Kessler, Trento, Italy

Edited by:
Laurent Ottaviani, Aix-Marseille Université, France

Reviewed by:
Peter R. Hobson, Queen Mary University of London, United Kingdom
David Christian, Fermilab (DOE), United States

***Correspondence:**
Riccardo Mirabelli
riccardo.mirabelli@roma1.infn.it

Specialty section:
This article was submitted to Radiation Detectors and Imaging, a section of the journal Frontiers in Physics

Received: 23 June 2020
Accepted: 16 October 2020
Published: 19 November 2020

Citation:
Toppi M, Battistoni G, Bochetti A, De Maria P, De Simoni M, Dong Y, Fischetti M, Franciosini G, Gasparini L, Magi M, Manuzzato E, Mattei I, Mirabelli R, Muraro S, Parmesan L, Patera V, Perenzoni M, Sarti A, Schiavi A, Sciubba A, Traini G, Valle SM and Marafini M (2020) The MONDO Tracker: Characterisation and Study of Secondary Ultrafast Neutrons Production in Carbon Ion Radiotherapy. Front. Phys. 8:567990. doi: 10.3389/fphy.2020.567990

Secondary neutrons produced in particle therapy (PT) treatments are responsible for the delivery of a large fraction of the out-of-target dose as they feebly interact with the patient body. To properly account for their contribution to the total dose delivered to the patient, a high precision experimental characterisation of their production energy and angular distributions is eagerly needed. The experimental challenge posed by the detection and tracking of such neutrons will be addressed by the MONDO tracker: a compact scintillating fiber detector exploiting single and double elastic scattering interactions allowing for a complete neutron four-momentum reconstruction. To achieve a high detection efficiency while matching the fiber (squared, 250 μm side) high granularity, a single photon sensitive readout has been developed using the CMOS-based SPAD technology. The readout sensor, with pixels of $125 \times 250\ \mu m^2$ size, will be organised in tiles covering the full detector surface and will implement an autotrigger strategy to identify the events of interest. The expected detector performance in the context of neutron component characterisation in PT treatments delivered using carbon ions has been evaluated using a Monte Carlo simulation accounting for the detector response and the neutrons production spectra.

Keywords: neutron tracking, particle therapy, carbon ions radiotherapy, secondary radiation monitoring, SPAD technology

1 INTRODUCTION

Particle therapy (PT) is a modern technique of solid tumor treatment that exploits the energy deposit of charged light ion beams, highly localised in the target region defined as "Bragg-Peak," to preserve the healthy tissues. The interaction of therapeutic beams with the patient, besides releasing the dose necessary to induce the tumor cells apoptosis, produces secondary particles (neutral and charged radiation and beam fragments) whose contribution to the total dose is generally negligible. However, secondary neutrons can deposit an absolute nonnegligible energy in and out of field even far away from the target volume (voxel) as they are weakly interacting with the patient's body [1 2]. Their contribution has hence to be taken into account with the highest possible precision when performing the treatment plan optimisation and evaluating the dose absorbed by the organs at risk. To this aim, a high precision experimental characterisation of the secondary neutron spectra and fluxes is eagerly needed.

So far, the experimental attempts have been focused on measuring the total neutron production yields and energies, regardless of their production points summing up all the contributions coming from different production processes. To separate the secondary neutrons, produced directly from the beam interactions with the patient, from the ternary neutral component generated in the iterative interactions of fragmentation products with the treatment room and the patient itself, a tracking detector would hence be needed. Tracking the primary neutrons produced by the PT beam interactions with the patient tissues, which have energies of hundreds of MeV, is extremely challenging from the experimental point of view.

The MONDO tracker [3, 4] was designed, as a primary goal, to provide such capability for these ultrafast neutrons and to this aim exploits the detection single (SES) and double (DES) (consecutive) elastic scattering interactions. The detector is made out of a compact matrix of thin plastic scintillating fibers, assembled in orthogonally oriented layers, and has a total size of $16 \times 16 \times 20\ \mathrm{cm}^3$.

The tracker layout has been optimised to ensure a detection efficiency of the order of 10^{-1} and 10^{-3} for SES and DES events, respectively. The details on the fiber choice (squared fibers with 250 μm side), the implemented layout, and the related readout performed using the SPAD technology have been already presented elsewhere [5]. The final tracker will be realised with the same technique previously described by means of a constant step motorized system able to weave a single plane of fibers. Fibers of the same layers are then glued together, dropping a small quantity of glue in fiber interspace. Between each plane, a 5 μm aluminized Mylar foil will be placed in order to prevent the intralayer crosstalk.

The readout sensor will be able to cover the full detector area, providing the necessary spatial resolution (matching the fiber granularity) and detection efficiency. An autotrigger algorithm will be implemented using a two-level strategy (at pixel and chip level), allowing a significant combinatorial background reduction, while keeping a very high efficiency for signal events [6].

The strategy to evaluate the tracker's expected performance when detecting monoenergetic neutrons originating from a point-like source has already been discussed in detail elsewhere [7]. In this contribution, we present the evaluation of the expected performance using a detailed MC simulation of the neutrons production during a carbon ion PT treatment. The MC simulation was implemented using an accurate description of the detector geometry and accounted also for the trigger strategy.

The pixel size has been chosen in order to oversample the fiber; however, a fiber-pixel coupling is not expected to be possible, as the size of the fibers can range with a tolerance of about 6%. Calibration would be performed before operating the final detector. In order to take into account the nonperfect match between pixel and fibers, a fiber/pixel misalignment of 1 μm in both directions has been introduced in the simulation.

At present time, the Mylar foils and the glue are not included in the MC simulation.

The simulation was used as the basis for the background rejection algorithm development and to evaluate the performance of the fragment energy measurement strategies (for both partially and fully contained tracks). In this work, the elastic scattering event selection was performed exploiting MC truth information: protons emitted from single and double elastic scattering are selected using an *elastic* flag that identified the events. The secondary neutron spectra expected from a carbon ion beam impinging on a PMMA target have been used to evaluate the detector neutron tracking performance in a PT case scenario.

In the following, we present the simulation details, and we report the expected detector performance, in terms of both back-pointing resolution and efficiency.

2 MATERIALS AND METHODS

To evaluate the expected performance of the MONDO neutron tracker in a clinical environment, an MC simulation has been used. In the following, we describe the procedure used to evaluate the detector performance and the details about the simulation configuration.

The MC simulation studies discussed in this manuscript, used to evaluate the expected performance of the MONDO tracker in the context of PT applications, are based on the FLUKA code (FLUKA 2011.2c) [8, 9]. In particular, the study presented hereafter aimed at the evaluation of the detector backtracking efficiency and energy resolution.

The back-pointing performance is crucial in order to discriminate the scattered neutrons coming from the target and the ones produced by subsequent interactions with the treatment room environment. The latter contribution is an unavoidable background when using traditional, nontracking, neutron detectors. In this case, only the overall neutron production can be measured. Instead, by using a tracking detector like MONDO, it is possible to measure the neutron flux disentangling the different components. The precision achievable on the neutron production point plays a crucial role in this task. For this reason, an MC simulation has been set up to evaluate the MONDO potential in detecting the emission point of the neutrons produced by PT hadron beams (e.g., p or ^{12}C). The neutron production induced by a hadron beam is represented schematically in **Figure 1**. MONDO is a compact, movable detector and can be placed in different positions and at different angles with respect to the neutron production point. In this way, it is possible to reconstruct neutron production fluxes as a function of the emission angles. Moreover, the irreducible background of ternary neutrons produced from secondary interactions with patients and with the treatment room can be identified and rejected, thanks to the tracking capability of

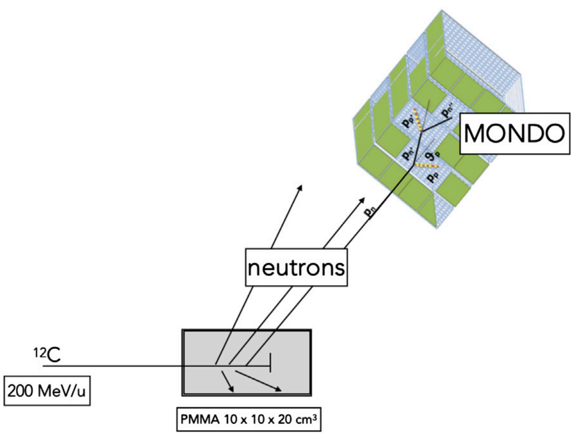

FIGURE 1 | Schematic representation of the detection of a DES event in MONDO for a neutron produced in a target by a particle therapy beam. The beam (p or ^{12}C) interacts with the target (e.g., patient tissues or material placed on the beamline) producing neutrons detectable in MONDO. The neutron emission point can be measured once the neutron four-momentum reconstruction is performed and the relative position of the detector and the target is known.

the detector. The distance between detector and neutrons production source (e.g., the fraction of solid angle) will be adapted to the specific treatment room and chosen beam rate. Assuming that the tracker is used to study the neutron production induced by PT beams, different strategies in the data analysis can be pursued depending on the experimental conditions. It is possible to exploit the reconstruction of single elastic scattering events (SES), assuming that the production point is known when studying the beam interactions with a thin target. Whenever the production point is not known (as in the case of PT applications), it is however possible to perform the full reconstruction of double elastic scattering events (DES) and measure the neutron four-momentum disentangling the primary and secondary radiation components. In **Figure 1**, a schematic representation of a DES event reconstruction is shown, showing the principle behind the neutron emission point measurement.

A detailed description of the detection strategy of how SES and DES can be used to measure the neutron characteristic is discussed elsewhere [4, 10]. In the following, the two-step approach adopted in the simulation to specifically reproduce the conditions expected in the PT environment is discussed.

Firstly, the expected neutron spectra, produced in PT treatments, have been obtained by means of a dedicated MC simulation. The energy of the neutrons produced by the interactions of ^{12}C ions of 200 MeV/u energy with a PMMA phantom (volume: $10 \times 10 \times 20\,\text{cm}^3$) has been obtained. The primary ions were shot at the center of the entrance phantom face (x and y planes), along the z-axis.

The second step has been the study of the interaction of such neutrons with the detector in a simplified setup: neutrons with the proper energy spectra (obtained in the previous step) have been generated, assuming a point-like source placed 20 cm away from the detector. The neutrons were shot along the z-axis in the detector center, while the entrance face of MONDO lies in the x and y planes.

The MONDO tracker layout used for the simulation has been optimised for the reconstruction of neutrons produced in PT applications [4]. The simulated detector has 800 layers of $16\,\text{cm} \times 16\,\text{cm} \times 250\,\mu\text{m}$ fibers made of plastic scintillating material, x-y oriented, for a total size of $16 \times 16 \times 20\,\text{cm}^3$.

The response of the MONDO detector has been carefully included in the simulation to evaluate the resolution on the neutron energy and direction reconstruction, for both SES and DES events. The interactions of all the particles with the fiber matrix have been recorded by FLUKA and the details in the conversion of the collected light, at the fiber output, and the number of pixels that had an over threshold signal have been obtained.

The SPAD-based readout, described in Ref. 5, has been implemented in the simulation allowing us to test the reconstruction algorithms starting from the information provided in terms of pixels that have a signal over the threshold when a particle interacts with the corresponding fiber. The readout response has been simulated in an external dedicated code that uses as input the energy release in the fibers and processes this information following the measured performances [6]. When a scintillating fiber is crossed by a particle, it releases a dE fraction of its energy. Pixels associated with fibers are generated matching the fiber coordinates with the pixel one. Since fibers and pixels have different dimensions (and the mismatch between fiber matrix and sensor tiles is simulated with the introduction of a difference of $1\,\mu$m in both pixel dimensions), each generated pixel can be associated with two or more contiguous fibers. The dE released in the fiber has been converted in terms of photoelectrons detected by a single pixel. The energy release dE is first converted into scintillating photons considering the fiber light yield and the trapping efficiency. Conversion from scintillating photons to detected photoelectrons has obtained considering the pixel Fill Factor (FF 30%), the photon detection probability (PDP 33%), and the maximum number of SPADs in one pixel (30 SPAD). Fill Factor has been introduced considering that the active area is limited to the high part of the pixel; thus, only photons produced in correspondence with the area covered by SPADs can be considered in the conversion. To obtain the number of activated SPAD in a single pixel, all the photons produced from the fibers overlying the active area of the considered pixel have been considered. Since a SPAD can convert only one photon in photoelectron for each event, the formula

$$N^{n}_{SPAD} = PDP \times \frac{SPAD - N^{n-1}_{SPAD}}{SPAD} + N^{n-1}_{SPAD} \quad (1)$$

must be applied to all the considered photons impinging on the considered pixel. N^{n}_{SPAD} represents the number of occupied SPADs when the $n-$th photon is impinging on pixel and $SPAD$ is the number of total SPADs in one pixel.

The noise of the detector (dark current) has been included in the simulation of the detector but in this study, this contribution has not been taken into account and only the physical interactions of the particles with the detector have been considered. A more detailed experimental characterisation of the sensor is needed in order to implement reasonable values and obtain a realistic tracking evaluation.

The detector performance has been studied using different energy spectra as input: either monochromatic or following the expected energy dependence in case of a PT application scenario. The obtained results are shown in the following section.

3 RESULTS

3.1 Monochromatic Beams

The kinetic energy of the recoil protons produced via elastic scattering interaction is calculated via range measurements in the MONDO baseline approach. Therefore, full containment of the proton tracks in the detector is required. To study the impact on the efficiency achievable in the neutron tracking, monoenergetic neutron beams in the range between 30 and 300 MeV have been studied. Neutrons undergoing both SES and DES were reconstructed applying the full containment constraint to the scattered protons and the obtained results were presented in Ref. 11. The expected DES (SES) interactions range from 10^{-3} (10^{-1}) to 10^{-4} (10^{-2}) as a function of the neutron energy. The proton containment in the MONDO detector, due to the need for computing kinetic energy via range, impacts strongly for neutrons above 100 MeV and in particular for DES events where the detection probability drops exponentially after 100 MeV.

For this reason, a different and complementary strategy has been developed in order to recover some of the events that were not totally contained inside the detector. In order to compute the proton kinetic energy, the deposited energy in each fiber and the timing of the scintillation photons have been studied. The proton *dE*/*dx* has been studied as a function of the track length and particle depth with respect to its production point along its direction. Monoenergetic neutrons have been used also to evaluate the achievable detector energy resolution. For all the reconstructed neutrons, the difference between the production and detected energy has been studied and the RMS of the resulting distribution, normalized to incoming neutron energy, has been used to compute the relative energy resolution.

For all the events with proton crossing at least 10 fibers, the length of the particle tracks inside the detector has been reconstructed for both contained and noncontained protons and the value of the energy loss in the single fibers provided from the FLUKA simulation has been collected for the first 40% of the total number of fibers composing the track. The choice of 40% allows us to consider only the initial flat part of the energy release distribution as a function of the particle path, excluding the Bragg-Peak area. The β value associated with the computed mean energy loss has been evaluated from the Bethe-Bloch equation. The initial proton kinetic energy

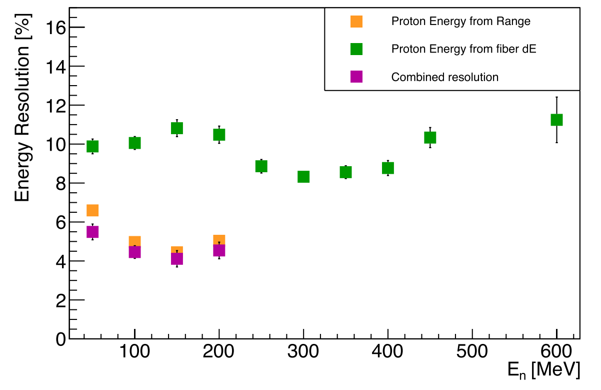

FIGURE 2 | Energy resolution for DES events as a function of the incoming neutron kinetic energy. Orange squares represent the energy resolution obtained via energy-range measurements while the green squares show resolution obtained from the *dE*/*dx* measurement. Violet squares represent the resolution obtained from the combination of the two methods.

that will be used from the reconstruction of the incoming neutron energy and direction can be computed from the obtained β.

The results are shown in **Figure 2** both for the neutron four-momentum reconstruction performed using the range (fully contained events, shown in orange) and for the energy loss inside the fibers for partially contained events (shown in green). While for neutron incoming energies below 200 MeV, the dominant contribution to the resolution is clearly the one that comes from the range measurements, while above 200 MeV, the full containment requirement is not fulfilled by most of the tracks, and hence the energy loss method is the only viable one.

While the energy resolution achievable with the range method is more performing (3% vs. 6%), the kinetic energy measurement via the energy loss detection inside the fibers allows reconstructing events above 200 MeV, providing a neutron full four-momentum measurement.

The monoenergetic beams have been used to study the back-pointing resolution as a function of the incoming neutron energy. The event reconstruction proceeds as detailed in Ref. 10: DES events are flagged and selected by means of MC truth information, the events are processed, and the production point is obtained, backtracking the reconstructed neutron in the plane that contains the point-like source. The distribution in the *x* and *y* planes for neutrons with incoming energy of 100 MeV is shown in the left picture of **Figure 3**.

The projections along the *x* and *y* directions can be obtained and a Gaussian fit can be performed in order to extract the single neutron reconstruction emission point resolution. The results for the projections in the *x* direction are shown in **Figure 3** (right, full markers) as a function of the neutron energies. In order to evaluate the intrinsic resolution on the neutron production point related to the uncertainty on the production angles and energy loss in the fibers, the back-pointing has been computed exploiting the MC truth kinetic

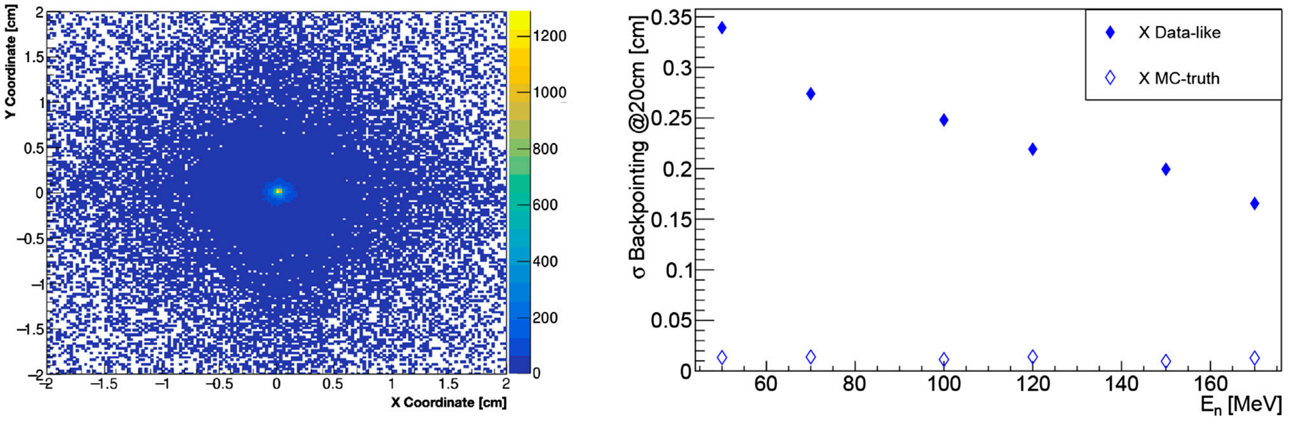

FIGURE 3 | (Left) Two-dimensional reconstructed emission point at 20 cm from MONDO detector. The distribution is symmetric for both *x* and *y* planes. **(Right)** Back-pointing resolution for the X-projection as a function of the neutron kinetic energy. Emission point at 20 cm from MONDO detector is assumed. The resolutions obtained from MC truth proton energy and direction are also shown. The error bars correspond to the statistical contribution in the back-pointing resolution measurement.

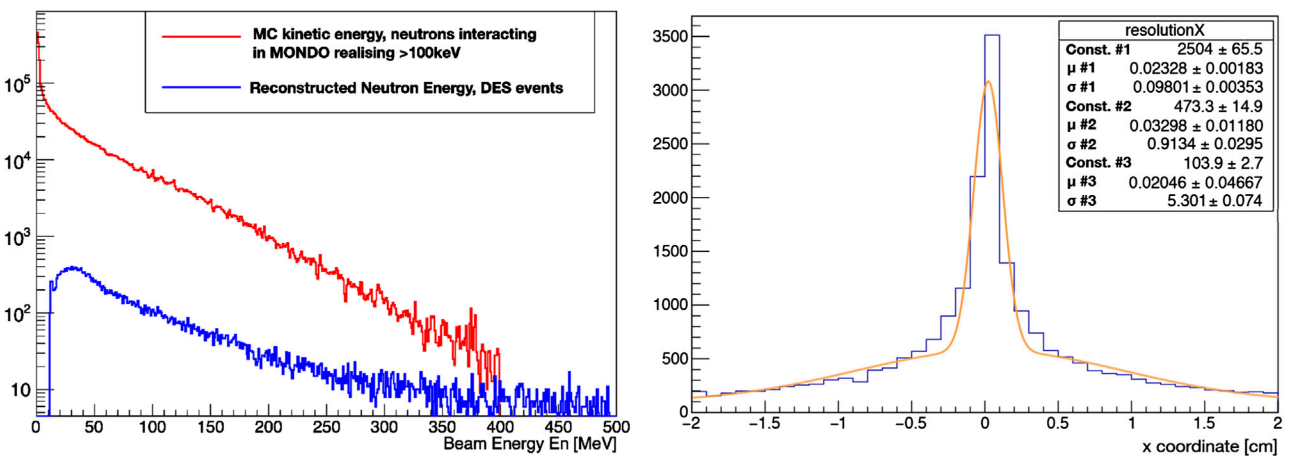

FIGURE 4 | (Left) Comparison between the simulated neutron spectrum generated from a 200 MeV ^{12}C ion beam on a PMMA target and the spectrum reconstructed by MONDO. **(Right)** Profile of the reconstructed emission point at 20 cm from MONDO detector. The distribution is symmetric for both *x* and *y* planes. Only the *x* plane is shown.

energy of the protons; thus, the empty markers show the resolution obtained in backtracking the neutron on its production plane. As can be seen, such contribution is nearly negligible and confirms the observation that the dominant contribution to the neutron tracking resolution in DES events is related to the error in reconstructing the protons angle and energy. The achievable resolution is below ~ 3.5 mm in the full explored energy range (above 70 MeV) and improves with the neutron energy as the proton multiple scattering decreases allowing a more precise reconstruction of the protons' direction and hence of the scattering angles. It has to be stressed that this back-pointing resolution fulfills the MONDO requirement of separating the ternary neutron component, coming from the treatment room, from the secondary one produced in the patient.

3.2 PT-Like Beams

The energy spectra of the neutrons produced in the interactions of carbon ions of 200 MeV/*u* with a PMMA target have been used to generate neutrons in a PT-like scenario, as represented in **Figure 1**. In **Figure 4** (left), the spectra of the neutron generated in the PMMA impinging on the MONDO detector depositing at least 100 keV in one fiber are shown in red. The blue spectra show the reconstructed energy of the neutrons interacting in MONDO via DES. As well as in the previous study, the MC truth has been exploited to select the DES events; thus, no inelastic contamination is included here.

For all the reconstructed events, a production point distribution in the plane containing the point-like source has been obtained. In **Figure 4** (right), the profile along the *x*-axis of the reconstructed point is shown. A similar symmetric behavior in the x and y projections is observed as in the case of monoenergetic beams. A fit with a function implementing three Gaussian components is performed in order to account for the different contributions to the tracking resolution and the impact of a tail at large values: an overall resolution of ~ 3 mm is obtained as the weighted average of the three measured σ values.

4 DISCUSSION

The potential of the MONDO tracker in characterising the neutrons produced in a PT treatment with carbon ions has been explored using neutrons from a point-like source placed 20 cm from the detector face, according to the energy spectrum of neutrons produced in PT conditions (from FLUKA simulation). For this initial study, the neutrons have been produced with only a specific angle of impact in the center of the detector (zero neutron angles). Future developments foresee the study of achievable detection efficiency and resolution with more realistic scenarios in which neutrons have a widespread spatial emission and direction distributions.

While the geometry and readout structure have been implemented in the MC simulation, the detector electronic noise and the fiber crosstalk have not yet been introduced in the analysis of the MC-data events, as an experimental and complete characterisation of the readout sensor coupled with the scintillating fibers is still ongoing.

A preliminary event reconstruction software for which the full simulation chain is accounted, starting from the particles' interactions with the MONDO fibers up to the signal collection (readout response in terms of pixels with signals over threshold), has been implemented and DES events have been reconstructed and used to evaluate the detector performance.

Results have been obtained for monoenergetic beams and for neutrons generated with the energy spectrum expected in PT applications. In that condition, an energy resolution of $\sim 3-6\%$ has been evaluated for DES events, while the expected back-pointing resolution is below 3.5 mm (for a neutron source placed 20 cm from the detector surface).

The preliminary results presented hereafter fully support the capability of MONDO to monitor the neutrons produced in PT treatments with the required precision needed to disentangle the secondary and ternary neutron components, thus the direct production of beam interactions with the patient tissues from the neutrons produced by interactions with the surrounding environment.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All the authors contributed to the MONDO detector conception and development. MT contributed to the prototype test and readout characterisation. GB developed the MC code of the detector and participated in the prototype test beams. AB and GT contributed to the prototype readout characterisation and to the mechanical assembly of prototypes. MD, PD and YD contributed to the prototype test beams and to the MC development. MF and GF contributed to the readout characterisation and MC development. RM contributed to the prototype test characterisation, to the readout conception and test, to the MC development, and to the mechanical definition of the assembly strategy. MaM contributed to the mechanical definition and assembly procedure definition of the detector and its prototype. IM, SM, and AnS developed the MC framework for the carbon on target simulation. AdS, AlS, and VP developed the MC code of the detector, contributed to the readout conception, and participated in the test and characterisation of the detector prototypes and in the mechanical definition of the assembly strategy. LG, EM, and LP developed the innovative readout sensor SBAM. MiM supervised, coordinated, and contributed to the full system development and implementation, to the detector characterisation, and to the MC framework development.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.