The FOOT experiment

Riccardo Ridolfi on behalf of the FOOT collaboration
1 Department of Physics and Astronomy, University of Bologna, Bologna, IT
2 INFN, Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Bologna, IT
E-mail: riccardo.ridolfi@bo.infn.it

Abstract. The main goal of the FOOT (FragmentatiOn Of Target) experiment is the measurement of the differential cross sections with respect to the energy and angle of the produced fragments in nuclear interactions between an ion beam, such as proton, Helium, Carbon, and different targets (proton, Carbon, Oxygen). Two important fields can benefit from these kind of measurements: firstly, in the 150 – 400 MeV/u beam energy range, the data will be used to evaluate the nuclear fragmentation occurring in a standard hadrontherapy treatment and thus potential side effects. Secondly, in the 700 – 1000 MeV/u beam energy range, the FOOT experiment aims at studying novel shields for spacecrafts involved in long term missions within the Solar System. The experiment has been funded by INFN since September 2017 and it is currently in its construction phase while the first data taking is scheduled by the end of 2020. A description of the experiment and a overview of expected performances and test beam results will be presented.

1. Introduction

Hadrontherapy (or Particle Therapy, PT) is a external radiation therapy technique in which protons and heavier ions (mainly Carbon) are used to treat deep tumours. The main advantage of PT with respect to conventional radiation therapy with photons is the characteristic energy deposit of heavy charged particles in a medium. Indeed, their energy release in depth is characterized by a low value in the entrance channel and by a sharp peak (the so-called Bragg peak) near the end of their path. The depth of the Bragg peak depends on beam energy so it can be tuned to cover the whole tumour volume [1]. The high precision of this kind of treatment allows to target tumours located near critical structures, such as brain stem or spinal cord, without affecting normal tissues. Moreover, heavier ions such as carbon can be used to treat also hypoxic tumours (i.e. tumours with a low oxygen concentration) thanks to their high Linear Energy Transfer (LET).

A major drawback of PT is the nuclear fragmentation of the target and of the projectile nuclei. While the latter is under study since several years, the former is currently neglected by Treatment Planning Systems (TPS) because of the lack of cross section experimental data in hadrontherapy energy range (150 – 400 MeV/u). However, the Relative Biological Effectiveness (RBE) of nuclear fragments from the target nuclei can be high and it should be taken into account in order to evaluate the correct dose depositions and potential side effects. In order to get these data, FOOT will measure the differential (with respect to the kinetic energy and direction) cross section of each produced fragment with a precision of the order of 5% so that nuclear fragmentation could be included in next-generation TPS fulfilling radiobiological constraints [2].
Figure 1. The FOOT detector: the emulsion setup (top) and the electronic setup (bottom).

Thanks to the flexibility of the FOOT experiment, the experimental programme could be extended also to higher energies (700−1000 MeV/u) typical of the Galactic Cosmic Rays (GCR). This kind of data are extremely useful to spaceship shielding design and to prevent health risks for astronauts in a future deeper exploration of the Solar System that will involve long term missions as the expedition to Mars [3]. Considering that the GCR are composed of 90% of proton, 9% helium and the rest heavy nuclei, experimental strategies and analysis methods can be shared between the two purposes taking into account the different energy range.

2. The FOOT Detector
In order to cover the full charge spectrum of the fragments coming from nuclear interaction, two different configurations of the FOOT detector are planned. Nuclear fragmentation products are both light and heavy fragments with different angular distributions. While the first are produced in a wide opening angle, the second travel close to the beam direction. The two setups of the FOOT experiment are shown in figure 1.

2.1. The emulsion setup
The Emulsion Cloud Chamber setup (ECC) is designed for light fragments (Z ≤ 3) and to reconstruct large angle particles detected above 70° with respect to the incident angle. The ECC is made of a sequence of nuclear emulsion films interleaved with passive material. It can be divided into three different sections, each one with a specific purpose:
• the vertex and tracking section is made of elementary cells of Carbon or $C_2H_4$ layers (as target) alternated with emulsion film (300 $\mu$m) to track the secondary fragments and reconstruct the vertex position;

• the charge identification section is composed of elementary cells, each containing three emulsion films treated at different temperatures after radiation exposure in order to separate low Z fragments (H, He, Li) with the same technique used in the OPERA experiment [4];

• the last section is dedicated to energy and momentum measurements using emulsion films of 300 $\mu$m thickness interleaved with lead plates of 1 mm as passive material. By using two independent methods for the energy and momentum estimate (range measurement and multiple Coulomb scattering) the isotopic identification of the fragments can be achieved.

2.2. The electronic setup

The charge and isotopic identification for heavy fragments ($Z \geq 3$) in the FOOT experiment is performed by the electronic setup whose angular acceptance will be up to ±10°. This setup is composed by several subdetectors and three different regions can be identified:

• the pre-target region consists of a thin plastic scintillator counter that provides trigger information and the start of time of flight (TOF) measurement, while a drift chamber acts as beam monitor in order to accurately measure the beam direction and position and to reject potential fragmentations before the target which is located immediately after the beam monitor;

• the tracking region is a magnetic spectrometer composed by three tracking stations and two cylindrical permanent magnets in Halbach configuration. The first station (vertex detector) is composed by four layers of silicon pixel placed just after the target and it allows to reconstruct the interaction point. Two additional layers of silicon pixel trackers (inner tracker) and a telescope of three layers of orthogonally oriented silicon microstrips are placed between and beyond the magnets respectively.

• the downstream region consists of two orthogonal planes of 3 mm thick scintillator bars measuring $\Delta E$ and TOF, moreover the kinetic energy measurement is provided by a calorimeter made of 320 BGO crystals.

Several test beam were carried out in order to check detector performances. For the emulsion setup, the performances show a very good efficiency (>99%) in charge separation [5]. Concerning the electronic setup, the plastic scintillator was tested at CNAO with proton and Carbon beams at various energies: the observed time resolution was around 50 ps for Carbon and 100 ps for proton while the energy resolution lies in the [5 − 10]% range from Carbon to proton [6]. Some calorimeter crystals were tested at CNAO too resulting in a energy resolution for heavy fragments of about 1.5%. The tracking system has yet to be tested and in the following results from FLUKA [7] simulation data will be used: the momentum resolution is around 3.5 − 4%.

3. Experimental strategy

The main experimental difficulty in such an experiment is to measure fragments produced in the target due to their low range (tens of $\mu$m, i.e. few cell diameters). These fragments would never be able to escape from the target, preventing any measurement. The FOOT experiment overcomes this issue using a inverse kinematics approach: instead of shooting protons against a target made of human body nuclei, tissue-like nuclei (mainly Carbon and Oxygen since protons do not fragment at these energies) are shot against a proton target. These fragments have a higher energy and, thus, a longer range. After that, it is possible to apply a Lorentz transformation to come back to the patient frame because cross sections are invariant, provided the beam energy per nucleon is fixed. However, pure Hydrogen targets are not allowed in all
experimental rooms and they would have a very low interaction probability with the beam due to their gaseous state. To overcome all these issues, in the FOOT experiment two targets will be used: a pure Carbon (graphite) target and a $C_2H_4$ target. Differential cross sections on Hydrogen can be extracted by subtraction from the data obtained from the two targets [8].

4. FOOT performances

In order to identify a fragment, the charge ($Z$) and the mass ($A$) have to be measured. The charge is measured by inverting the Bethe-Bloch formula using the information provided by the scintillator, i.e. the deposited energy per unit length ($\Delta E/\Delta x$) and the TOF system. The energy released in the scintillator and the reconstructed charge of the fragments for 200 MeV/u $^{16}O$ ions impinging on a $C_2H_4$ target are reported in figure 2. The obtained resolution on the charge determination is at level of 2% for heavy fragments ($Z \geq 3$) so that the wrong charge assignment is below 1%. Similar performance has been obtained at higher energy (700 MeV/u).

Concerning the mass identification, the redundancy of the FOOT apparatus allows to reconstruct it in three different correlated ways:

$$A_1 = \frac{p}{u\beta\gamma}, \quad A_2 = \frac{E_{\text{kin}}}{u(\gamma - 1)}, \quad A_3 = \frac{p^2 - E_{\text{kin}}^2}{2uE_{\text{kin}}}$$ (1)

where $u$ is the atomic mass unit, $\beta$ is the relative velocity of the fragment with respect to the speed of light, $\gamma$ is the Lorentz factor, $p$ is the momentum of the fragment, $E_{\text{kin}}$ is the kinetic energy and $A_1$, $A_2$, $A_3$ are the mass number from TOF and tracking system, TOF and calorimeter, tracking system and calorimeter, respectively. A better result on mass number can be achieved combining all these measurements at the same time. Two different fit strategies are used: a standard $\chi^2$ minimization approach and a Augmented Lagrangian Method (ALM) fit [9]. In figure 3, left, the fit of the $^{12}C$ fragments using ALM is shown while on the right all reconstructed Carbon isotopes are reported. As it can be seen, with these analysis methods it is possible to disentangle different isotopes also for heavier fragments.

Similar results are obtained with higher energies but the analysis strategy is not the same. Indeed, at higher energies the FOOT setup has to be enlarged in order to achieve the same resolution on the time of flight and, due to the huge number of fragmentation in the calorimeter, it is not possible to use $A_2$ and $A_3$ quantities in equation 1 anymore. For this reason, the analysis at space radioprotection energies is carried out relying on the tracking system and the TOF measurement. However, thanks to the better resolution of the magnetic spectrometer, it is still possible to disentangle isotopes despite the calorimeter cannot be used in the majority of events.

Figure 2. Energy released in the scintillator (left) and reconstructed charge of the fragments (right).
Figure 3. Example of $^{12}$C fragments generated by FLUKA simulation: evaluation of mass by applying both the ALM fit and a $\chi^2$ cut (left) and production of Carbon isotopes reconstructed with ALM with $\chi^2 < 5$ (right).

5. Conclusions
The FOOT experiment main goal is to measure target and projectile fragmentation cross section as a function of the angles and the kinetic energy of the produced fragments. The measurements will be performed at two different energy ranges (150 – 400 and 700 – 1000 MeV/u) in order to improve the accuracy of next-generation Treatment Planning System for hadrontherapy treatment and to optimize the shielding of the spacecrafts for long term missions. In order to achieve this purpose, an inverse kinematics strategy will be adopted and two experimental setups, an electronic setup for heavier fragments measurement and an emulsion cloud chamber for the lighter, are currently under development. Optimization and performances of the detectors are currently studied by means of FLUKA simulations and the outcomes are promising.

References
[1] Schardt D, Elsässer T and Schulz-Ertner D 2010 Rev. Mod. Phys. 82(1) 383–425
[2] Patera V et al. 2017 Proceedings of Science vol 281
[3] Durante M and Cucinotta F A 2011 Rev. Mod. Phys. 83(4) 1245–1281
[4] Nakamura T et al. 2006 Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 556 80 – 86
[5] Montesi M et al. 2019 Open Physics 17 233–240
[6] Morrocchi M et al. 2019 Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 916 116 – 124
[7] Böhlen T T et al. 2014 Nuclear Data Sheets 120 211–214
[8] Dudouet J et al. 2015 Phys. Rev. C 86(2) 024606
[9] Cho W S et al. 2016 JHEP 01 026 (Preprint 1508.00589)