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Study of the performance of the FOOT experiment

Y.Dong[1*], on behalf of the FOOT collaboration
[1] *Università degli studi di Milano, INFN sezione di Milano*, Italy.
**yunsheng.dong@mi.infn.it*

Abstract

In the last decade a continuous increase in the number of cancer patients treated with Particle Therapy (CPT) has been registered. CPT is still a discipline where the contribution coming from research in physics plays an important role. For example, different studies have shown that in proton therapy nuclear inelastic interactions of the incident beam with the patient tissues may lead to the fragmentation of the target nuclei producing a non negligible amount of target fragments, which may alter the estimated local dose deposition, especially in the entrance region. On the other hand, in heavy ion treatments, the main effect of nuclear inelastic interactions results in the break up of the incident ion instead of the target nuclei. The produced fragments have a longer range than the projectile, leading to an undesirable dose deposition beyond the Bragg peak. At present there is still a lack of complete and reliable experimental measurements of nuclear reaction cross sections for fragments produced in the interaction with tissues nuclei (H, C, Ca, O, N) of 60-250 MeV protons and 100-400 MeV/u carbon ions, which are the typical energies adopted in CPT treatments. These data will be important to develop a new generation of high quality treatment planning systems for CPT.

The FOOT (FragmentatiOn Of Target) experiment aims to fill the gap, performing a set of measurements of nuclear fragmentation cross sections relevant for CPT. As far the study of target fragmentation is concerned, the FOOT experiment will adopt an inverse kinematic approach to overcome the difficulties related to the short fragments range (~μm). In order to bypass the difficulties to manage a pure hydrogen target, it has been chosen a strategy of a double target separately made of C and C_2H_4 and the final cross section on Hydrogen will be obtained by subtraction. Further interest in this type of measurements comes from the issue of radioprotection in space missions, where the energy to be considered is higher and close to 1 GeV/u. FOOT consists of two different setups depending on the detection of heavy and light fragments: the heavy fragments are detected by a high precision tracking system in magnetic field, a time of flight measurement system and a calorimeter, while the lighter ones by a separated emulsion chamber. The optimization and the performance analysis of the setup have studied by means of the FLUKA Monte Carlo code and different detectors have been tested [1,2,3].

In this work, an overview of the FOOT experiment and a report on the study of the detector performances will be presented.

Keywords: Hadrontherapy, Cross Section Measurement, Nuclear Fragmentation, Radioprotection

1. INTRODUCTION

In recent years, the development of new technologies and the evolution in radiation oncology techniques has led to the establishment of an alternative technique with respect to conventional radiotherapy based on charged particle beams: Charged Particle Therapy (CPT). CPT exploits accelerated charged hadrons, such as protons and heavier ions, for the treatment of deep seated solid tumours. The main advantage in the adoption of charged particles resides in their depth-dose profile distribution. This is characterized by an entrance channel with a low dose deposition, followed by a narrow region, the Bragg Peak (BP), where the maximum of the dose is deposited. This property allows to reach a high irradiation accuracy over the tumour volume, minimizing collateral effects on surrounding healthy tissues and organs at risk. Furthermore, for the heavy ion therapy, as expressed by the higher values of the Relative Biological Effectiveness (RBE), the increase in Linear Energy Transfer (LET) in the BP region produces an enhanced biological effectiveness in cell killing as compared to conventional photon radiation [4].

However, the state of the art in CPT indicates the need of knowledge of the dose deposition due to the nuclear interactions of the charged particles in the human tissues. Indeed, they are a source of inaccuracy in the Treatment Planning System (TPS), varying the estimated RBE value and being a source of side effects in the region outside the tumour volume. The most relevant nuclear process, at the CPT energies, is the fragmentation of the incident particles in the heavy ion therapy and of the target tissues in the proton therapy. In the former case, the projectile fragments are produced mostly with the same velocity and the same direction with respect to the primary particle. However, given their lower masses, the fragments have a longer range than the projectile, leading to an unwanted dose deposition beyond the BP [5]. In the latter case, the target tissues fragments are produced almost at rest. They are characterized by a very low range (tens of μm), that results in an undesirable dose deposition in the entrance channel, before the BP [6]. In both cases, in order to take into account the effects of nuclear interactions in the current TPS, data on the nuclear reaction cross sections are fundamental.

2. THE FOOT EXPERIMENT GOALS AND MEASUREMENT STRATEGY

The FOOT experiment aims to measure the target and projectile fragmentation differential cross sections (with respect to kinetic energies and direction) relevant for CPT with a precision of 5% given by the radiobiological desiderata. To reach this goal the charge and isotopic identification have to be at the level of 2-3% and 5% respectively, while the particle energy resolution has to be of the order of 1-2 MeV/u. Furthermore, the FOOT experiment will perform measurements of interest for the radioprotection in space purpose. Indeed, the exposure to Galactic Cosmic Radiation (GCR) in long term missions far from the Earth requires the measurement of the differential cross section of nuclear interaction between the GCR and different materials suitable for the spacecraft shields. The GCR are mainly composed of proton (90%), helium (9%) and heavy ion (1%), thus the involved particles are mainly the same adopted in CPT. The energy range of the GCR particles that will be measured by the FOOT experiment is 700-1000 MeV/u.

In order to perform the measurement for the target fragmentation, the FOOT experiment adopts an inverse kinematic approach, studying the nuclear inelastic interaction of ^{12}C and ^{16}O beam on a proton target. This is mandatory to overcome the difficulties related to the short fragment range (~μm) that, otherwise, confines the particles inside the target, making their detection impossible. However, the adoption of a pure hydrogen target would drastically reduce the interaction probability and increase the difficulties related to the management of an inflammable and instable gas. Thus, the p-N data are obtained by subtraction of cross sections on C and C_2H_4 targets, as already performed in the Ganil experiment [7]. The measurements regarding the projectile and the GCR fragmentation will be performed in a direct kinematic approach, using targets of C and C_2H_4.

3. EXPERIMENTAL SETUP

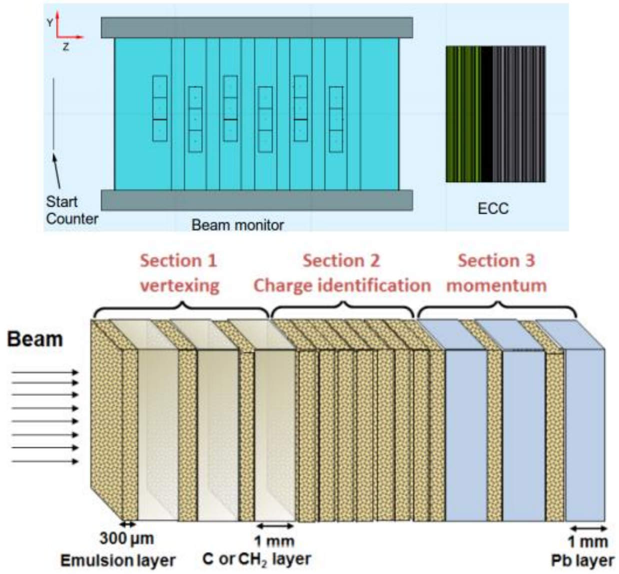

Figure 1. The nuclear emulsion cloud chamber setup. Top: the complete experimental setup with the start counter, the beam monitor and the ECC detectors. Bottom: ECC sections.

The FOOT experiment has two different detector setups optimized to detect the light ($Z \leq 3$) and heavy ($Z \geq 3$) fragments. In the former case, the particles are produced in a wide opening angle and they are detected by a setup of nuclear emulsions assembled in the Emulsion Cloud Chamber detector (ECC), as illustrated in Fig. 1 [8]. While in the latter case, the heavy ion fragments are produced in a narrow cone (~10°) around the beam direction. As shown in Fig. 1, the ECC setup consists of a pre-target region made up of a plastic scintillator (Start Counter) adopted as counter and trigger, and a drift chamber (Beam Monitor) employed for the beam profile measurement. The ECC is composed of three different sections:

- the first section consists of layers of passive target material (C and CH_2) interleaved with nuclear emulsion films, adopted with vertexing purpose;
- the second section is entirely composed of layers of nuclear emulsion films to identify the fragments charge;
- the last section is made of layers of absorbing material (Pb) alternated with layers of nuclear emulsion films for the particle momentum measurement.

The first test of the ECC setup has been performed in Chiba (Japan) at the HIMAC accelerator with a beam of ^{12}C at 400 MeV/u. The resulting charge identification efficiency has been found to be of 99%, fulfilling the radiobiological desiderata [8]. In 2017 the ECC has been tested at LNS with proton, deuteron, helium and carbon ion beam at 80 MeV/u, and at Trento with proton beam at 50, 80 and 200 MeV. The preliminary results confirm the previous charge measurement performances, while the isotope identification is still under study. For the high energy beam measurements, the ECC setup will have different geometry in the layer distribution, maintaining the same structure for the sections. In particular, in order to include the fragments with higher energies, the number of absorbing material layers in the last section will be increased.

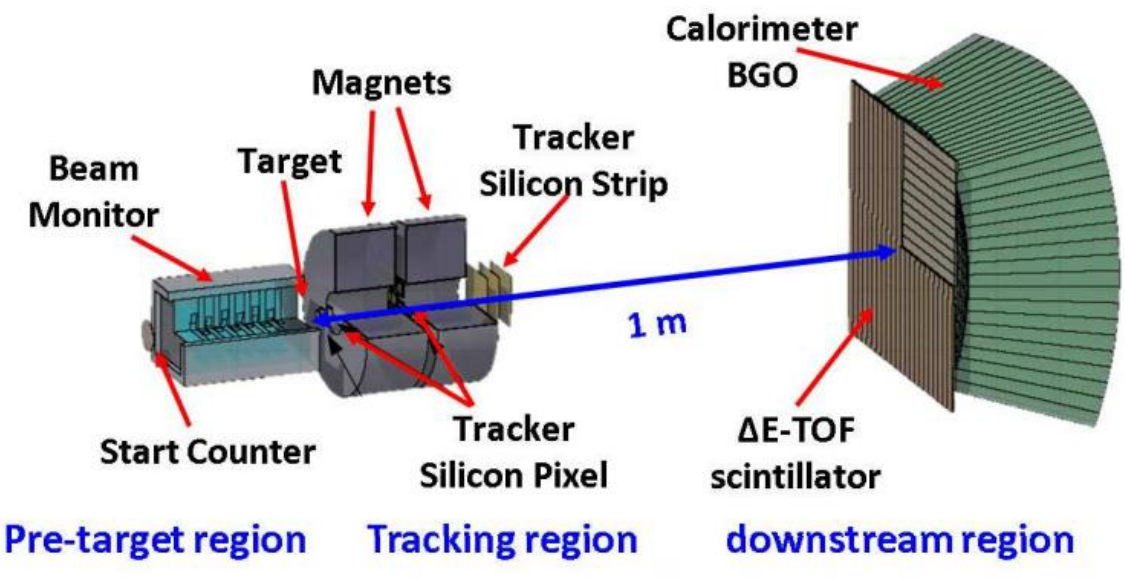

Figure 2. The FOOT electronic experimental setup

The electronic setup of the FOOT experiment (Fig. 2) consists of three different regions:

- pre-target region: it is composed of the Start Counter and the Beam Monitor, as in the ECC setup. The former is adopted as the trigger for the DAQ and to provide the start time of the Time Of Flight (TOF) measurement. The latter is used to measure the beam direction and to reject the events in which the primary ion has fragmented before the target;
- tracking region: four layers of silicon pixeled detector placed beyond the target are exploited for vertexing purpose. Other two layers of silicon pixel are settled between the two permanent magnets, that are arranged in a Halbach geometry providing a maximum of 0.8T magnetic field in the direction orthogonal with respect to the incident beam. Just beyond the magnets other three layers of silicon strip detector complete the tracking detectors, which are exploited to reconstruct the fragments tracks and evaluate their momentum;
- Downstream region: composed of two planes of orthogonal plastic scintillator bars exploited to measure the $\Delta E/\Delta x$ and the end time of the TOF. Finally, 145 crystals of BGO inorganic scintillator are used for the kinetic energy measurement.

Since the data tacking is foreseen to be performed in 2020 in different CPT treatment centres (CNAO, Trento, LNS, GSI and HIT), the whole experimental setup has been designed to fit the dimensions of the treatment rooms. However, in the case of GCR fragmentation measurements, the space between the tracking system detectors has to be increased to improve the momentum resolution, increasing the arm of the magnetic field (B·dl). Furthermore, the downstream detectors will be shifted from the target of about 3 m instead of 1 m, to maintain the same TOF resolution. Different detectors have already been tested to evaluate their performances. In details, the downstream scintillator has been tested at CNAO and the measured TOF resolution is 40-50 ps for carbon ions and 100-150 ps for protons [9]. Assuming similar performances for the Start Counter time resolution, the final TOF measurement accuracy for the heavy ion fragments is about 70 ps. The measured $\Delta E/\Delta x$ precision of the scintillator is 3-10% varying from carbon to proton. The calorimeter performance has been preliminarily measured at HIT with proton, helium and carbon ion beam at different energies, showing an energy resolution of 1.5% for heavy ion fragments. The performances of the tracking detectors have been studied by means of FLUKA MC simulation code and the momentum resolution of the fragments has been evaluated to be about 4% constant in all momentum range.

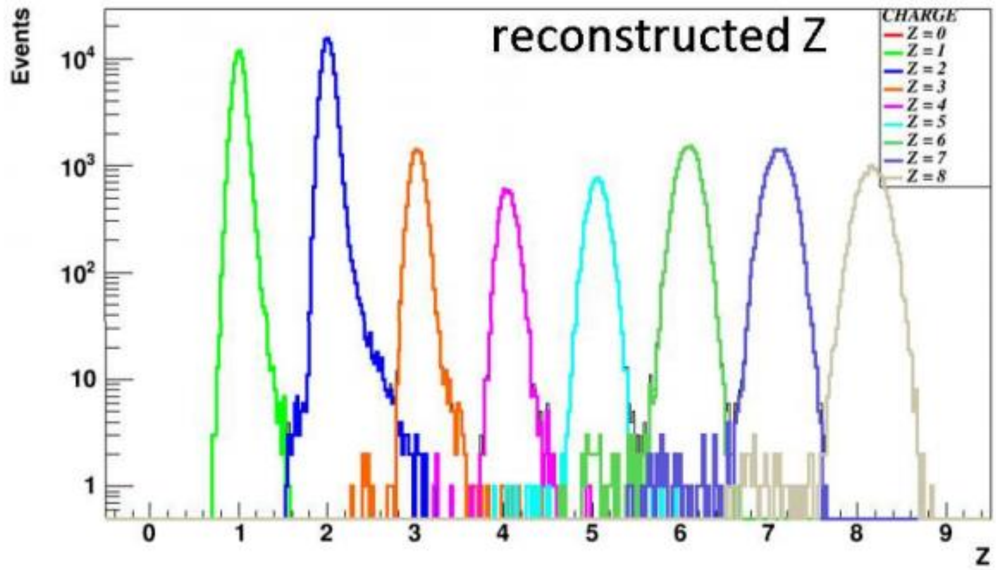

Figure 3. Charge reconstruction distribution for fragments produced by ^{16}O beam at 220 MeV/u on a target of C_2H_4, (FLUKA simulation)

4. CHARGE AND MASS IDENTIFICATION IN THE ELECTRONIC SETUP

Given the $\Delta E/\Delta x$ measurement of the downstream scintillator and the TOF estimation from the time measurements of the same scintillator and the Start Counter, it is possible to evaluate the charge of the fragments inverting the Bethe-Block formula, since the particle velocity (β) can be calculated from the TOF measurement as in Eq. 1, where L is the particle covered distance and c is the speed of light.

$$\beta = \frac{1}{c}\frac{L}{TOF} \tag{1}$$

The fragments separation has been evaluated by means of FLUKA MC simulations and the results are shown in Fig. 3. The resolution of the charge identification is about 2% for heavy fragments ($Z \geq 3$) and the charge misidentification is below 1%. Similar results have been obtained for the GCR particles, by means of FLUKA simulation with 16O beam at 700 MeV/u on C_2H_4 target.

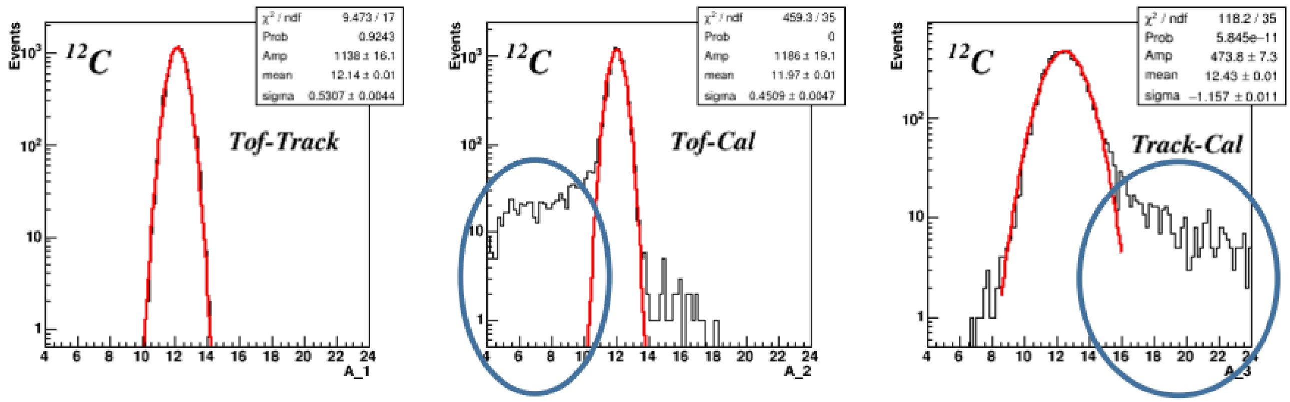

Figure 4. A_1, A_2 and A_3 mass reconstruction distributions for carbon ion produced by ^{16}O beam at 200 MeV/u on C_2H_4 target, by means of FLUKA simulation. The two blobs in the second and third plots point out the distribution tails given by the loss of energy measurement of the neutrons in the calorimeter.

The mass identification of the fragments is performed combining the measurement of the particle momentum (P), velocity (β) and kinetic energy (E_{kin}) in three different redundant ways. As shown in Eq.2, where u is the atomic mass unit and γ is the Lorentz factor, the three mass evaluations, A_1, A_2 and A_3, are calculated respectively from the TOF and P, Ekin and TOF, P and E_{kin} measurements.

$$A_1 = \frac{P}{u\beta\gamma}; \qquad A_2 = \frac{E_{kin}}{u(\gamma-1)}; \qquad A_3 = \frac{P^2 - E_{kin}^2}{2uE_{kin}} \tag{2}$$

The reconstructed mass distribution for the A_1, A_2 and A_3 methods are shown in Fig. 4. The best reconstruction method is A_1, since in the other cases the tail in the energy measurement of the calorimeter, gives rise also to a tail in the mass distribution.

The three estimated values for the fragment mass are then merged with an Augmented Lagrangian Method (ALM) fit and a standard chi square (χ2) fit [10]. The results of the two fitting procedures are shown in the first two plots of Fig. 5.

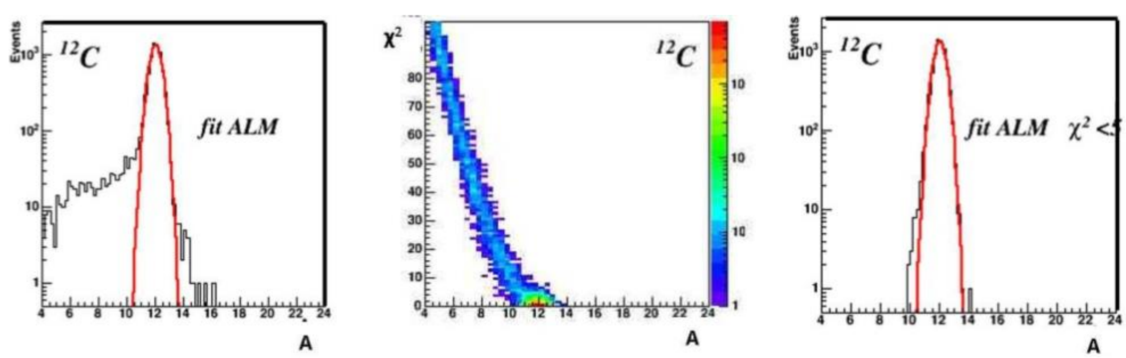

Figure 5. Mass identification with the χ2 and the ALM method for carbon ion produced by ^{16}O beam at 200 MeV/u on C_2H_4 target, by means of FLUKA simulation. From left to right: the first plot is the mass reconstruction performed with ALM method; the secondo plot is the mass calculated with the χ2 technique; the last plot is the final mass reconstruction with the ALM method and χ2<5

Combining the ALM and the $\chi2$ procedure results by applying a $\chi2$ cut ($\chi2<5$), it is possible to reject the tail in the ALM mass distribution given by the missing neutron energy measurement, as shown in the last plot of Fig. 5. Since in the 17% of the events the fragments interact with the calorimeter material producing neutrons, the efficiency of the mass identification is about 0.87 and the overall mass resolution is about 3% for carbon ion.

5. CONCLUSION

The main goal of the FOOT experiment is to measure the differential cross sections for nuclear interactions relevant for CPT and radioprotection in space, with the final aim to improve the current TPS and to optimize the shielding of the spacecrafts for long term missions. Different detectors of the electronic experimental setup have been tested showing satisfying results. The overall charge and mass identification performances have been studied by means of FLUKA simulations demonstrating the feasibility of the experiment. The ECC setup has been extensively tested providing good results that fulfill the radiobiological desiderata.

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