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Design and performance of the Calorimeter for the FOOT experiment

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Summary. — Hadrotherapy is a highly effective method for treating deep-seated tumours. However, the lack of information about cross sections for fragments produced by beam-tissue nuclear interactions limits the precision of clinical treatment planning systems. The FOOT Collaboration is building a detector optimized for the identification of heavy fragments in a reverse-kinematics configuration, through the measurement of their momentum, energy and time of flight. The energy will be measured with a calorimeter composed by 320 BGO crystals coupled with SiPM arrays, which will allow a compact design. Design and performance of the calorimeter tested at the facilities of CNAO will be presented.

1. – Introduction

In the past decade a continuous increase in the number of cancer patients treated with Charged Particle Therapy (mainly protons and carbon ions) has been registered, thanks to its effectiveness in the treatment of deep-seated solid tumors [1]. The typical energy range for therapeutic applications is 50–250 MeV for protons and 50–400 MeV/n for carbon ions. The main advantage of this approach derives from the depth-dose profile of charged particles, characterized by an entrance channel where a low dose is released, followed by a narrow region, the Bragg Peak (BP), where the maximum of the dose is deposited. In biophysics the Relative Biological Effectiveness (RBE), ratio of photon to charged particle dose producing the same biological effect, quantifies the radiation effectiveness. In clinical practice a constant RBE value equal to 1.1 is assigned to protons, but radiobiological measurements show an increase in RBE. This discrepancy is explained by the target fragmentation that generates a spectrum of low energy heavy particles with range of the order of 10–100 μm [2]. Experimental data on the differential cross sections of secondary particle production are still missing. Some experiments studied projectile fragmentation for ^{12}C ions, but only a few energy points have been investigated [3, 4]. FragmentatiOn Of Target (FOOT) is a nuclear physics experiment under construction which aims to fill the gap in experimental data on the differential cross section for the production of secondary fragments induced by proton and ion beam interactions. FOOT is an international collaboration comprising more than 100 members including 10 INFN sections, 5 laboratories from Italy (including Frascati, CNAO and TIFPA), Germany (GSI), France (IPHC) and more than 14 universities in Italy (12), Japan (Nagoya) and Germany (Aachen). The experiment can also address other topics, such as the radioprotection in space. Indeed there is a growing interest in understanding fragmentation processes, related to the design of spacecraft shielding dedicated to long duration space missions. Target fragmentation studies using a ^{4}He beam with energy reaching 700 MeV/n are also programmed.

2. – The FOOT experiment

The goal of the FOOT experiment is to measure the fragment production cross sections with a resolution better than 5%. In order to achieve these results, the fragments charge and mass must be identified with high resolution (2–3% and 5%, respectively). The challenge is associated to the fact that: the fragments created in the target cross a short range (a few tens of microns) and they cannot be detected with a standard approach. To overcome this difficulty, FOOT will adopt the inverse kinematic approach: instead of studying beams of protons impinging on a target with a composition equivalent to human tissue (98% C, O and H nuclei), ion beams (^{12}C and ^{16}O) will hit a hydrogen enriched target. In order to avoid gas targets with low density and low interacting probability, to calculate the cross section of heavy ions on protons, the subtraction of data measured by using a pure C and C_2H_4 target will be performed:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{kin}}(\mathrm{H}) = \frac{1}{4}\cdot\left(\frac{\mathrm{d}\sigma}{\mathrm{d}E_{kin}}(\mathrm{C_2H_4}) - 2\frac{\mathrm{d}\sigma}{\mathrm{d}E_{kin}}(\mathrm{C})\right). \tag{1}$$

In the inverse reference frame, fragments have a boost in energy and thicker targets can be used. The incident beam flux will be set so as the projectile rate will be low enough (few kHz) to have one particle at a time crossing the system. Data will be collected with ^{12}C and ^{16}O beams on C and C_2H_4 targets. From these measurements, we will obtain the fragmentation cross section of ^{12}C (^{16}O) on C and H. Simulations based on the FLUKA Monte Carlo program [5], have shown that the light fragments ($Z < 3$) have a wide emission angle (up to 90°) while heavier fragments are forward peaked within a polar angle of about 10°. Taking into account these remarks and the need to build a "portable" experimental setup fitting in experimental rooms of different facilities, the FOOT experiment was designed in two parts: the "electronic setup" and the "emulsion setup". The first will measure fragments heavier than ^{4}He ($Z > 3$), covering a polar angle of ±10° with respect to the beam axis; the second will allow to measure light fragments emitted at an angle up to about 70°. The FOOT electronic setup is schematically shown in fig. 1. The beam enters from the left, then the apparatus is composed by:

1) Start Counter (SC), a plastic scintillator read by Silicon PhotoMultipliers (SiPMs) that provides the trigger information and the first timestamp of the time-of-flight (TOF) measurement [6];

2) Beam Monitor (BM), a drift chamber (80% Ar, 20% CO_2) that tracks the direction and the position of the beam particles on the target, necessary for an inverse kinematic approach;

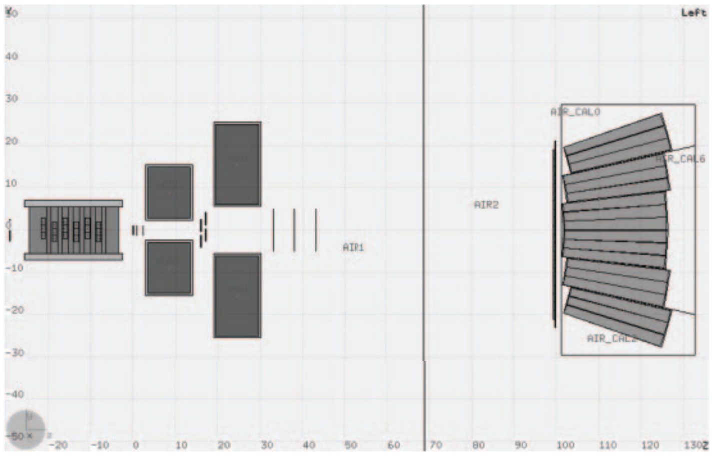
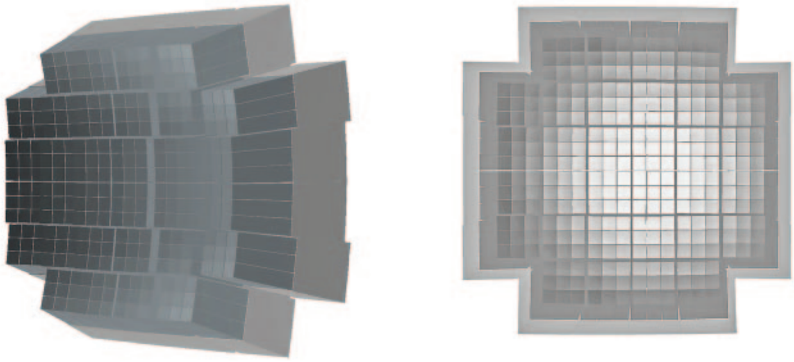


Fig. 1. – Schematic view of the electronic setup of the FOOT experiment.

3) trajectory and momentum of the fragments are measured after the target by a tracking system composed of a series of silicon detectors around and inside a dedicated magnetic spectrometer (magnetic field up to 1.4 T):
   - 4 layers of Si pixel detectors (20 μm pitch) before the first magnet;
   - 2 layers of Si pixel detectors (20 μm pitch) between the two magnets;
   - 2 layers of Si strip detectors (120 μm pitch) after the second magnet;
4) TOF-ΔE, composed of two orthogonal planes of plastic scintillator rods, provides the stop signal for the TOF and the measurement of the energy loss;
5) calorimeter, that provides the measurement of the fragments kinetic energy.

3. – Calorimeter design

The construction and commissioning of the calorimeter is the primary task at INFN Torino [7]. The calorimeter will be composed of 320 $B_4Ge_3O_{12}$ (BGO) crystals positioned with an approximately spherical arrangement ($\sim$20 cm radius), as shown in fig. 2. The high density of this material ($\rho = 7.13\,g/cm^3$) and the high atomic number ($Z_{Bi} = 83$) will guarantee high stopping power. The crystals have a truncated pyramid shape with a front face of about $2\times 2\,cm^2$, a back one of about $3\times 3\,cm^2$ and a length of 24 cm. In order to facilitate the management of a very heavy detector, the calorimeter will be divided in sub-structures called *Modules*, matrices of 3×3 crystals. The fragments that enter the calorimeter lose their energy mostly through electromagnetic effects and photons will be emitted. The amount of emitted light will be directly proportional to the initial energy of the fragments and it will be collected with photodetectors. Silicon Photon Multipliers (SiPM) were chosen because they guarantee a more compact design and lower voltage than other options like PhotoMultiplier Tubes (PMTs). Moreover to further simplify the construction of the calorimeter the electronic readout board was specifically designed to match dimensions of the SiPMs as shown in fig. 3. Several test beams were and will be performed in order to choose the optimal combination of SiPM array, digitizer and BGO wrappings for achieving the required performance from the calorimeter.

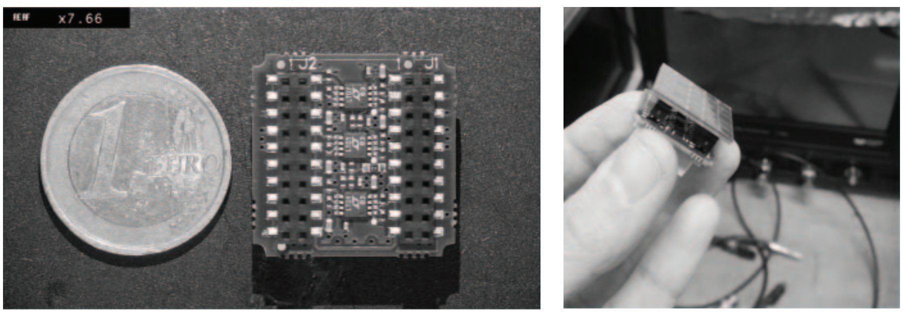


(a) FOOT calorimeter lateral view. (b) FOOT calorimeter front view.

Fig. 2. – Geometry simulation of the whole calorimeter.

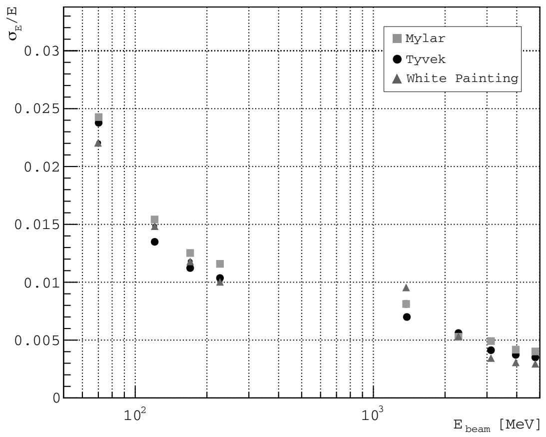
4. – Preliminary tests of BGO crystals

In October 2019 three BGO crystals with different wrappings (tyvek, white painting and mylar) were tested at Centro Nazionale Adroterapia Oncologia (CNAO) of Pavia, performing two energy scans with proton and carbon beams. Each BGO crystal was equipped with a 25 SiPMs matrix with an active surface of $2\times2\,\mathrm{cm}^2$, where each microcell had a pitch of $15\,\mu$m. The energies used (70, 120, 170, 220 MeV for proton and 120, 190, 260, 330, 400 MeV/n for carbon) allowed to verify the calorimeter capability to cover the full energy range foreseen by the FOOT experiment, avoiding optical saturation, and to achieve the required energy resolution. In fig. 4 the points in the first plot represent the ratio between the FWHM and the mean of the Gaussian peak of the charge distributions of the signals for a specific energy. For the three wrappings, energy resolutions below 2.5% are obtained as required by the design of the experiment. In fig. 4(b) the average charge *vs.* the beam energy for the three wrappings shows that the full energy range is covered without saturation effects.

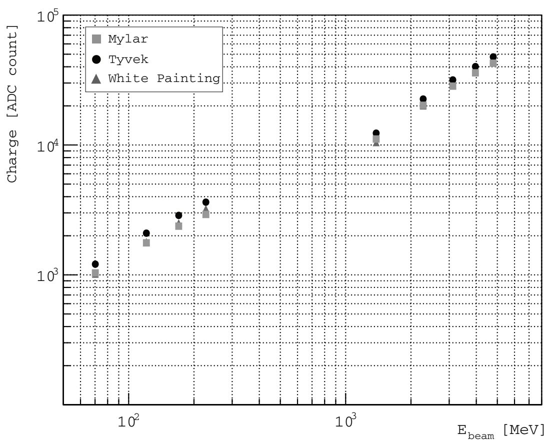


(a) Electronic readout board. (b) SiPM array coupled to the electronic readout board.

Fig. 3. – Scheme of the calorimeter readout (photodetector and board).



(a) Energy resolution *vs*. beam energy for the three wrappings.



(b) Linearity for the three wrappings.

Fig. 4. – Energy resolution (a) and linearity (b) of three single crystals with different wrappings.

5. – First module

In November 2019 the first module prototype (3×3 crystals) of the calorimeter was assembled and tested at CNAO. This test has allowed to measure fragments that crossed more than one crystal. A 3D printed case held the nine crystals together without any additional material in the first half of the crystal. The SiPM arrays were not glued but they were kept coupled to the BGOs through a stopper on the back side of the crystals. A photo of the setup is shown in fig. 5.

In the first part of the test beam campaign energy scans with proton and carbon beams parallel to the module were performed. In the second part the module was rotated with an angle of 30°. The goal was to study the energy resolution summing the light released in more than one crystal. Since all BGOs were different an energy equalisation was needed. From the linearity curves of each crystal, calculated in the first step, the equalisation

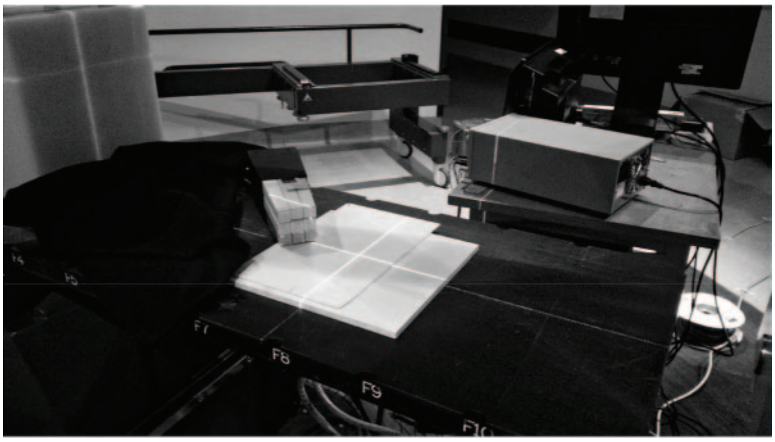


Fig. 5. – Setup of module prototype test beam in a treatment room of CNAO.

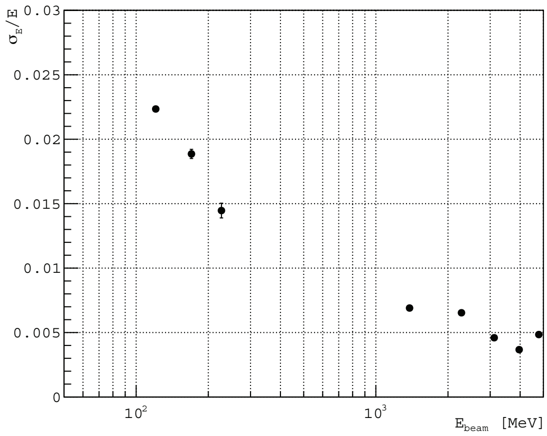


Fig. 6. – Energy resolution *vs.* beam energy of the module prototype rotated by 30°.

factors were estimated and taken into account in the total energy calculations. The points reported in fig. 6 are related to the following beam energies starting from the left: 120, 170, 220 MeV (proton) and 120, 190, 260, 330, 400 MeV/n (^{12}C). Despite the suboptimal coupling of the SiPMs to the crystals the energy resolution found summing the light produced in the crystals close together is very encouraging (<2.5% for all energies).

6. – Conclusion

FOOT will provide high-precision measurements of fragmentation cross sections that are particularly relevant for target fragmentation in hadron therapy and radioprotection in space. The preliminary tests on the calorimeter hint to a performance that exceeds the design requirements. They have shown that BGO crystals coupled to SiPM arrays with 15 μm microcell pitch provide sufficient dynamic range to cover all fragment energies foreseen by the FOOT experiment and are capable of maintaining the required energy resolution below 2.5% over the whole energy range. The test on the first module prototype of the calorimeter shows that the energy reconstruction of fragments that cross more than one crystal is possibile with very good resolution (<2.5% for the lowest energies). The full calorimeter implementation still requires: an optimisation of the design and mechanics, designing the cooling system to keep the temperature of the SiPMs stable and the choice of the digitizer.

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