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The FOOT (Fragmentation Of Target) Experiment

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Particle therapy uses protons or ^{12}C beams for the treatment of deep-seated solid tumors. Due to the features of the energy deposition of charged particles in matter, a limited amount of dose is released to the healthy tissue in the beam entrance region, while the maximum of the dose is released to the tumor at the end of the beam range, in the Bragg peak region. However nuclear interactions between beam and patient tissues induce fragmentation both of projectile and target. This has to be carefully taken into account since different ions have different effectiveness in producing a biological damage.
In ^{12}C treatments the main concern are long range forward emitted secondary ions produced in projectile fragmentation that release dose in the healthy tissue after the tumor. Instead, in a proton treatment, the target fragmentation produces low energy, short range fragments along all the beam range.
The FOOT experiment (FragmentatiOn Of Target) is designed to study these processes. Target nuclei (^{16}O,^{12}C) fragmentation induced by 150-250 MeV proton beam will be studied by means of the inverse kinematic approach. ^{16}O,^{12}C therapeutic beams, at the quoted kinetic energy per nucleon, collide on graphite and hydrocarbons target. The cross section on Hydrogen can be then extracted by subtraction. This configuration explores also the projectile fragmentation of these ^{16}O,^{12}C beams, or other ions of therapeutic interest, such as ^{4}He for instance.
The detector includes a magnetic spectrometer based on silicon pixel and strip detectors, a scintillating crystal calorimeter able to stop the heavier produced fragments, and a ΔE detector, with TOF capability, to achieve the needed energy resolution and particle identification.
In addition to the electronic apparatus, an alternative setup based on the concept of the "Emulsion Cloud Chamber", coupled with the interaction region of the electronic FOOT setup, will provide the measurement of lighter charged fragments: protons, deuterons, tritons and Helium nuclei.
The FOOT data taking is foreseen in the available experimental rooms existing in the presently operational charged particle therapy facilities in Europe, and possibly at GSI. An initial phase with the emulsion setup will start in early 2018, while the complete electronic detector will take data starting in 2019.

In this work a general description of the FOOT experiment and of its expected performances is presented.

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1. Introduction

In the last decade a continuous increase in the number of cancer patients treated with Charged Particle Therapy (CPT) [1] has been registered, due to its effectiveness in the treatment of deep-seated solid tumors [2]. The main advantage of this approach derives from the depth-dose profile of charged particles. This is characterized by an entrance channel where a low amount of dose is released, followed by a narrow region, the Bragg Peak (BP), where the maximum of the dose is deposited and that is usually seated on the cancer region, allowing to spare healthy tissues. Furthermore 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. In biophysics the Relative Biological Effectiveness (RBE), ratio of photon to charged particle dose producing the same biological effect, quantifies this effectiveness. Even though track structure also plays a role, as a general approximation, high LET corresponds to high RBE. This effect is particularly important for ions like ^{12}C, since their LET exhibit significant variations in the proximity of the Bragg Peak region.

In proton treatment, due to the to high energy of the proton beam in the entrance channel and to the low and slowly varying LET, a RBE close to one would be expected. A constant RBE value equal to 1.1 is currently assigned to protons in clinical practice. However, radiobiological measurements show a significant increase in RBE above 1.1 [3] and the topic of RBE variability in protontherapy is being widely debated in recent years. In particular, as shown in ref. [4], the increase of RBE can give rise to a biological range extension after BP or to an increase of biological damage in the entrance channel (plateau region in the Bragg curve), i.e. in the region of healthy tissues. In fact it emerges that using a constant RBE=1.1 can lead to an underestimation of the dose in the healthy tissue region.

An hypothesis proposed in ref. [4] is that particles produced in target fragmentation could be one of the causes contributing to the increase of proton RBE. When crossing the patient, nuclear interactions occur between the beam and the patient tissues. In the case of proton beams, only target fragmentation occurs, generating a spectrum of low energy heavy recoils that depends on beam energy and target materials. These secondary charged particles have short range (e.g. order of 10÷100 μm), very high LET and then high RBE. In proton therapy this process can have an impact in particular in the entrance channel.

The determination of the RBE of fragments by means of radiobiological experiments is difficult and there is lack cross section data for the production of heavy recoils after proton irradiation in the energy range of interest (up to 250 MeV for protons and 400 MeV/u for carbon ions). In recent years some experiments have been dedicated to the study of projectile fragmentation for ^{12}C ions, however this program was carried out only for a few energies [6, 7]. On the other hand the process of target fragmentation, which is the only relevant process of this kind in proton therapy, so far has been almost completely neglected. Actually there are some measurements of light fragment (Z<3) production, but there is a total lack of data for larger A values. The new experiment FOOT (**F**ragmentati**O**n **O**f **T**arget) has therefore been proposed.

2. The FOOT experiment

The main experimental difficulty in the measurement of the target fragmentation induced by proton beams is due to the short range of produced fragments that have low probability to escape the target: their range is confined to tens of microns and even a very thin solid target can badly spoil the fragment energy measurement. A possible workaround can be envisaged in the use of gaseous target but an inverse kinematic approach can be pursued, studying the fragmentation of different ions beams (C, O, Ca, etc.) onto hydrogen enriched target, such as CH_2, as already adopted in ref.[8, 6]. Secondary fragments will have boosted energy and longer range, making the detection easier. The authors of ref. [6] have already shown that the cross section on H can be extracted by subtraction from the coupled data obtained using both CH_2 and pure C target.

The final goal of the experiment would be to measure the heavy fragment (Z>2) cross section with maximum uncertainty of 5% and the fragment energy spectrum (in the "patient" reference frame) with an energy resolution of the order of 1-2 MeV/u, in order to contribute to a better radiobiological characterization of protons. The charge and isotopic identification (at the level of 2-3% and 5% respectively) are also important goals of this measurement. Montecarlo calculations based on the FLUKA code [9] predict that the heavier fragments ($Z>2$) are forward peaked within a polar angle of $\simeq 10^\circ$ and with a kinetic energy per nucleon peaked around the corresponding value of the primary beam, while the light fragments have wider angular and kinetic energy distribution. Due to the particular interest on the heavier fragments, the experiment is focused on the detection of secondary production in a narrow cone ($\simeq 10^\circ$) around the beam direction.

Furthermore, beyond the analysis in terms of direct kinematics, one can also extend and complete the measurements of projectile fragmentation cross sections induced by C and O beams. Such measurements are needed to improve the projectile fragmentation description of these beams in ion therapy and their specific Treatment Planning Systems.

The adoption of the inverse kinematics approach asks not only for a few % level of accuracy on the energy and momenta of the produced fragments, but also for a resolution on the emission angle with respect to the beam direction of the order of few mrad. To achieve such an angular resolution, both the beam particles direction before the target and the fragment emission angle after the target must be tracked with an angular accuracy at the mrad level. Furthermore the multiple scattering angle of beam+fragment couple inside the target must be kept below the mrad as well. This sets a severe limit on the allowed thickness of the target (of the order of $2 \div 4$ g/cm^2) and limits accordingly the probability of the fragmentation events to order of 10^{-2}.

The general idea is to design an experimental setup which can be easily movable ("table top") and fit the space limitations set by the different experimental and treatment rooms where ion beams of therapeutic energies are available. A good balancing between the detector cost, its portability and the quest for the largest possible geometrical acceptance for the heavy-forward fragments reconstruction can be found by using a magnetic spectrometer composed by a permanent magnet and high precision tracking detectors. However, the experience from previous experiments about nuclear fragmentation, together with the study of the relevant physics process by means of Montecarlo simulations, show that it's hard to achieve the desired acceptance for all secondary fragments with an apparatus of limited size. The main reason comes from the fact that lower mass fragments ($Z<3$) can be emitted within a wider angular aperture with respect to heavier nuclei. Therefore the necessary size, and weight, of a magnetic apparatus would become impracticable in view of a table top setup design. Therefore, the FOOT experiment will consider two alternative setups:

1. a setup based on electronic detectors and a magnetic spectrometer, aiming to the identification and measurement of fragments heavier than the ^{4}He, covering an angular acceptance up to 10÷20 degrees with respect to the beam axis;

2. a setup exploiting the emulsion chamber capabilities. As already tested in the FIRST experiment[7], a specific emulsion chamber will be coupled with the pre-target devices of the FOOT setup to measure the production in target fragmentation of light charged fragments as protons, deuterons, tritons and Helium nuclei. The emulsion spectrometer supplies complementary measurements for fragments emitted at large angle with respect to the electronic detector, extending the angular acceptance up to about 70°.

3. The Electronic Detector Setup

The FOOT detector is designed to achieve a robust charge and isotopic identification of the produced fragments. Therefore the setup needs to measure the following quantities of the fragments produced: momentum, kinetic energy, Time Of Flight (TOF). The fragment dE/dx is measured through the ΔE released in a thin slab of material. To fulfill the requirements it is necessary to achieve the following resolutions: i) momentum resolution $\sigma(p)/p$ at level of 4%; ii) time of flight (TOF) resolution at level of 100 ps; iii) $\sigma(E)/(E)$ at level of 1÷2%; iv) $\sigma(\Delta E)/(\Delta E)$ at level of few %. The fragment charge can be identified by correlating the ΔE measurement with TOF or kinetic energy, while the mass can be extracted by means of the three kinematic constraints:

$$p = mc\beta\gamma \qquad E_{kin} = mc^2(\gamma - 1) \qquad E_{kin} = \sqrt{p^2c^2 + m^2c^4} - mc^2 \tag{3.1}$$

where $\beta = \frac{v}{c}$ and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ are derived by the TOF of the fragment.

The fragmentation contribution due to detector material must be kept as low as possible and eventually subtracted.

The design of the detector was optimized by means of a FLUKA simulation of the fragmentation processes. The experience of the FIRST experiment at GSI[7] was also exploited. The detector geometry is driven by two main factors: the emission angle of the (heavy) fragments and the angular separation between two fragments emitted in the same events. The first item decides the angular acceptance while the second rules the granularity.

The apparatus can be divided in three different regions along the beam direction: the upstream/target region, the magnetic tracking region and the calorimeter region. A schematic view of the detector is shown in Fig. 1.

1. The upstream/target region. Here the beam crosses a thin plastic scintillator counter (250 μm) that provides trigger information and the start of the TOF. Then a drift chamber acts as beam monitor and tracks the direction and the position of the beam. The target is the last element of this region.

2. The vertex region. A telescope of pixel trackers provides the vertex reconstruction and the initial tracking of the produced fragments.

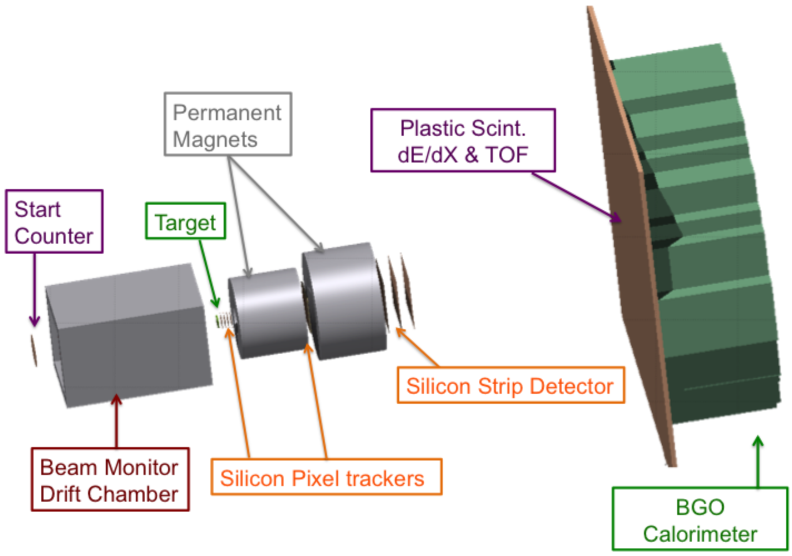

Figure 1: Schematic view of the FOOT apparatus.

3. The magnetic region. After the production in the target and the vertex detector, the fragments enter in a magnetic region. The magnetic field is provided by two permanent dipole magnets (Halbach geometry). Between the two magnets, the fragment direction is measured by two additional layers of silicon pixel trackers. At the exit of the magnet system, a telescope of silicon microstrips provides a further precision tracking. All these tracking elements allow the measurement of the fragment momentum.

4. The calorimeter region. After the magnetic region the fragments travel $\sim$1 m to reach a ΔE and TOF detector made of two orthogonal planes of 3mm thick, 40 cm long plastic scintillator rods. Finally the fragments kinetic energy is measured in a calorimeter made of an array of thick BGO crystals.

The Start Counter (SC), already used in the FIRST experiment[7], is made by a 250μm thick scintillator disk with a radius of 26 mm. The light produced in the scintillator is collected radially by 160 optical fibers grouped in four bundles and read by fast PMT Hamamatsu H10721-210 with 40% of quantum efficiency. The thickness of the scintillator was minimized to reduce the pre-target particle interaction probability, that is less than 5% with respect to the on-target one, assuming a 2 mm thick graphite target. The SC provides the trigger signal to the whole experiment and the measurement of the total number of ions used for the cross section measurement. A time resolution of the order of σ_t = 100 ps has been measured using only one of the four channels of the device, thus fulfilling the design criteria for the experiment.

The Beam Monitor (BM) is a drift chamber, operated with an Ar/CO2 80/20 gas mixture, with twelve layers of wires oriented along the x-axis and the y-axis alternatively, in such a way to reconstruct both the orthogonal profiles of the beam (on z axis). There are three drift cells per layers and the cell shape is rectangular (16$\times$10 mm^2) with the long side orthogonal to the beam. The twelve planes provide tracking redundancy and ensure a high tracking efficiency and an excellent spatial resolution. The BM detector will be placed between the SC and the target and will be used to measure the direction and impinging point of the ion beam on the target, a crucial information needed to address the pile-up ambiguity in the vertex detector. The BM efficiency is measured to be close to unity for carbon ion beam and the mean track spatial resolution was measured to be order of the order of $\simeq 140\ \mu$m [11, 12].

The magnetic spectrometer is based on the use of permanent magnets that could allow the needed $B * L$ in a limited dimension and weight. A preliminary feasibility study has been done to evaluate the performances achievable by means of magnets built in the Halbach configuration [14]. There the dipolar magnetic field is obtained with a cylindrical geometry where the internal cylindrical hole is the region where a magnetic field, smoothly varying in space, is obtained. A maximum field of 0.8 Tesla can be reached with such a configuration.

The overall tracking system and magnetic momentum measurement of FOOT is organized in three measuring stations.

1. The Vertex detector will be implemented in a similar manner like in the FIRST experiment [10], immediately after the target at about 5 mm of distance. It will consist of a stack of four layers of pixel sensors using as sensing element the M28 chip, from the family of CMOS Monolithic Active Pixel Sensors, implemented by the Strasbourg CNRS PICSEL group [13]. All four M28 sensors are thinned to 50 μm, with an overall material budget for the entire Vertex tracker of 200 μm.

2. The Inner Tracking station in between the two permanent magnets foresees two additional planes of M28 pixel sensors, covering an area of about 8×8 cm^2, to measure both the position of the track in the plane orthogonal to the beam axis and the direction of the track itself. The sensors will be implemented in a structure composed by ladders similar to the ones implemented in the PLUME project [15], a a project started at IPHC Strasbourg in collaboration with the University of Bristol and DESY in Hamburg.

3. The outer tracker station, right at the end of the magnetic volume, will consist of three double x-y planes of silicon microstrip sensors. Each double plane is made out by two 70 μm thick silicon modules, with the strips oriented orthogonally to measure independently the x and y coordinates. The strip pitch will be 125 μm and they will be read analogically, in order to reach an intrinsic spatial, resolution in both coordinates better than 35 μm. The total covered area would be 9x9 cm^2 and the number of readout channels would be 4320. Modules of this kind, 10 cm long and thinned to 50 μm, have already been produced [16] and tested, albeit in experiments devoted to Minimum Ionizing Particle (MIP) detection. In the configuration for FOOT we aim to cover an energy deposition ranging from 3 to 300 MIPs, to be able to identify heavy fragments. To such a purpose, being the thickness of the sensors reduced, the LGAD mechanism will be implemented in order to recover the loss of signal [17].

3.1 ΔE and TOF Detector

This detector will provide the stop to the TOF measurement and the measurement of the energy release in a thin slab of material (dE/dx) that will identify the charge of the crossing fragment. The

dE/dx measurement should achieve accuracy of the order of $2-3\%$ while a 70 ps time resolution should be achieved on the heavy fragments (C,O) at 200 MeV/u, to fulfill the 100 ps requirements on TOF resolution.

The ΔE/TOF detector is made of two orthogonal layers of 20 plastic scintillator rods, each one 3 mm thick, 2 cm large and 40 cm long. The 40×40 cm^2 area matches the fragments aperture at 1 m distance form the target. The 2 cm granularity matches the 2×2 cm^2 traversal surface of the calorimeter units and is enough to keep the occurrence of double fragments in the same rod below the % level. The chosen thickness is a trade off between two opposite trend: a thicker rod will integrate more energy release and more emitted light, so improving the resolution on both ΔE and TOF, but on the other hand a re-fragmentation inside of thick plastic rod would spoil the dE/dx measurement. The scintillator bars will be read-out at both ends by means of silicon photomultipliers

3.2 Calorimeter

The FOOT calorimeter is designed to measure the energy of projectile fragments exiting the target volume, after they are bent by the magnetic field and cross the silicon tracker and the fast scintillator for dE/dx measurement. The upper bound of the fragments energy range is defined by the beam energy, while the lower bound is set by the intensity of the magnetic field. FOOT will operate in a range in which fragments are below the energy threshold that triggers a shower in a calorimeter. Therefore, the mechanisms for energy loss will be driven by the electromagnetic interaction, with a competing effect of nuclear interactions, which, through the production of neutrons that can escape the calorimeter undetected, can cause a fraction of the fragment initial energy to escape the calorimeter and determine a systematic underestimation of the initial energy.

The calorimeter will be composed by an array of 350 BGO crystals with 2x2 cm^2 transverse size. The crystal thickness is still an open parameter, which will range between 7 cm and 21 cm: the optimal value will be defined as a trade off between performance on one side, mechanical constraints and cost on the other. An early test with 7 cm thick BGO crystals was already run with proton beams in the 125-228 MeV range. The measured energy release for 228 MeV protons is remarkably good: $\Delta E/E$ 2%.

4. The FOOT Emulsion Spectrometer

An emulsion spectrometer (ES) is foreseen in order to measure the low Z fragments. The use of emulsions is coupled to the achievements in the developments of automated scanning system. The last generation microscopes recently developed allow very fast scanning with wide angular acceptances (more than 70°) and real-time analysis of huge data sets, about one order of magnitude faster than those used for the OPERA experiment [18, 19]. An emulsion detector (made of nuclear emulsion films [20] alternated to lexan plates to simulate the human tissue) was exposed to a beam of ^{12}C nuclei with an energy of 400 MeV/u to identify the nuclei due to the fragmentation of carbon in the target [21, 22]. By analyzing the grain density along the particle track, it was possible to assign the charge to these fragments with very high efficiency (larger than 99%). The separation of hydrogen, helium, lithium, beryllium, boron and carbon can be achieved at two standard deviations, or considerably more [21]. Emulsion detectors were then adopted in the FIRST experiment to study the large angle fragments produced by ^{12}C ions beam (400 MeV/u) impinging on a composite target [23]. The kinematical properties of protons emitted with angles up to 80° with respect to incident beam axis could be measured.

The ES, based on the concept of Emulsion Cloud Chamber (ECC) [24], will be designed with passive material as carbon target alternated to nuclear emulsions films, acting as both high-resolution tracking devices and ionization detectors. It is planned to be made of three sections (Fig. 2): vertex and tracking detector, ionization detector for charge identification and tracking detector for momentum measurements.

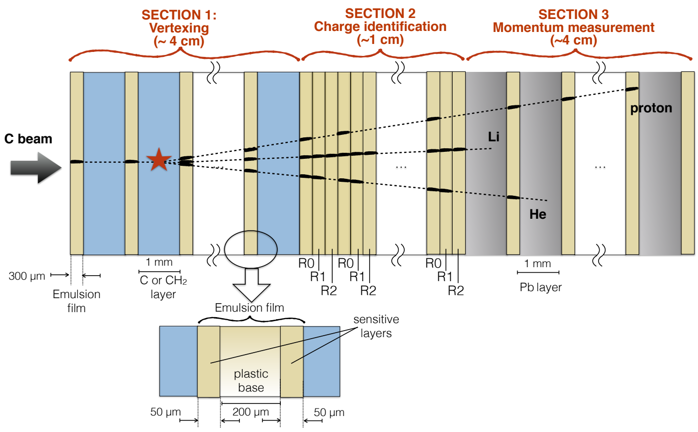

Figure 2: Scheme of the emulsion spectrometer (ES).

The nuclear emulsion films consist of two 50 μm thick sensitive emulsion layers deposited on both sides of a plastic base, 200 μm thick, resulting in a total thickness of 300 μm. The sensitive emulsion layers are made of AgBr crystal scattered in a gelatine binder. The crystals have a diameter of 0.2 μm and are sensitive to MIPs. The trajectory of a MIP is recorded by a series of sensitized AgBr crystals along its path acting as latent image centers. After the chemical process of development, silver clusters grains can be seen with an optical microscope. The emulsion will be scanned by an automated system and the image is then analyzed by a dedicated software in order to recognize aligned clusters of dark pixels produced by the penetrating particle.

5. Conclusion and future schedule

The FOOT collaboration is designing a detector to measure both target fragmentation in proton therapy and projectile fragmentation in carbon therapy. The R&D for experiment during has been approved and funded by INFN, with the contribution of the Centro Fermi Institute. Final approval for the 2018-2021 period is expected in june 2017.

The data taking will take place mainly using C,O beams in the 150-400 MeV/u energy range. Further important features of the experimental site could be the possibility to mount and calibrate the experimental setup before data taking for long time (1-2 week), beam time availability in the week range. The preferred site is the experimental hall of the CNAO center in Pavia, Italy and a possible data for the first data taking is late 2018 for the emulsion setup, while late 2019 is the target data taking for the complete setup.

The measurements performed with the proposed experiment could be also interesting for other applications, like radioprotection in space. NASA and other space agencies have started since several years the study of the risk assessment for astronauts in view of long duration space missions, such for instance the travel to Mars [25]. The design and optimization of spacecraft shielding requires a detailed knowledge of fragmentation processes.

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