# The FOOT FragmentatiOn Of Target Experiment

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**Abstract**

In proton-therapy clinical practice a constant RBE equal to 1.1 is adopted, regardless of the demonstrated RBE variations, which depends on physical and biological parameters. Among other mechanisms, nuclear interactions might influence the proton-RBE due to secondary heavier particles produced by target fragmentation that can significantly contribute to the total dose: an unwanted and undetermined increase of normal tissues complications probability may occur. The FOOT experiment is designed to study these processes. Target ($^{16}O$,$^{12}C$) fragmentation induced by $150 - 250\ MeV$ proton beam will be studied via inverse kinematic approach, where $^{16}O$ and $^{12}C$ therapeutic beams, with the same kinetic energy per nucleon of the proton, collide on graphite and hydrocarbons target to provide the cross section on Hydrogen (to explore also the projectile fragmentation). The detector design, the performances and expected resolution results obtained form Monte Carlo study, based on the FLUKA code will be presented.

## Introduction

Particle Therapy (PT) uses protons and light ions beams for the treatment of deep-seated solid tumours. Due to the features of energy deposition of charged particles a small amount of dose is released to the healthy tissue in the beam entrance region, while the maximum of the dose is released to the tumour at the end of the beam range, in the Bragg peak region. Nowadays the efficacy of particle therapy is well established [1, 2] and the national social security services are increasingly heading towards the coverage of medical expenses related to PT treatments (e.g. Italy [3]). Many new centres are under construction: in Europe 11 new centres are expected to be running in $2017 - 2019$ and in the next few years Europe is going to host about $30\%$ of the world PT centres. About $80\%$ of the particle therapy centres (about 70 centres in operation, from ptcog.ch, 4/2017) exploit proton beams.

Despite the large advantage of particle therapy treatments in sparing dose to the healthy tissues, nuclear interactions between beam and patients induce fragmentation both of projectile and target and must be carefully taken into account. The projectile fragmentation contributes mainly to the dose release after the Bragg Peak while the target fragmentation, characterised by particles that have on average a small velocity, changes the radiation Relative Biological Effectiveness (RBE), along its path inside the body. In the current clinical practice, when planning patient treatments, the proton RBE is assumed to be constant and equal to 1.1. There are, however, grown and solid evidences [4] that a non-constant effectiveness should be used to account for the ion slowing down and secondary target fragments production. The authors of [4] suggest that about $10\%$ of the biological effect induced in the entrance channel of the beam in the patient might be associated with target fragments. At the same time, due to the slowing down of primary protons energy, this contribution is reduced to about $2\%$ when approaching the Bragg

peak.

A more accurate description of the RBE in the entrance region would allow for a better definition of the peak-to-entrance RBE ratio, which largely characterises the therapeutic advantage of proton therapy. The deposition of dose associated with target fragmentation, even though low if considered in absolute terms, could be relevant concerning the risk assessment for secondary cancer induction. This is true in particular considering the high LET associated with those fragments [4].

Those aspects impact not only in medical application (proton/particle therapy), but also for the space research: astronauts are exposed to galactic cosmic rays, consisting of accelerated charged particles in the range from protons to iron ions, thus the knowledge of the released dose associated to the high LET fragments is crucial to their healthy. The measurement of the effective flux and spectra of the fragments produced by target fragmentation represents an experimental challenge due to the very short range of the produced particles. This issue will be addressed by the FOOT experiment [5].

## 1 FragmentatiOn Of Target

When performing the target fragmentation measurements, one has to account for the extremely small range of the secondary products, immediately re-absorbed in the target itself. By pursuing an **inverse kinematic** approach is it possibile to gain experimental access to the secondary production cross sections. Obviously, this requires fragment direction and incoming projectile particle four-momentum to be well measured in the laboratory frame to obtain the correct energy in the patient frame. The inverse kinematic approach lead to the use of Carbon ion (and hopefully Oxygen) beams on H target, however a pure H target is a very challenging and expensive. The FOOT strategy is to use double layers of pure C (Graphite) and $C_bH_a$ (Plastic Scintillators) targets. The cross sections on C and H are therefore evaluated exploiting the relation:

$$\frac{d\sigma}{dE_{kin}}(H) = \frac{1}{a} \cdot [\frac{d\sigma}{dE_{kin}}(C_bH_a) - b \cdot \frac{d\sigma}{dE_{kin}}(C)] \tag{1}$$

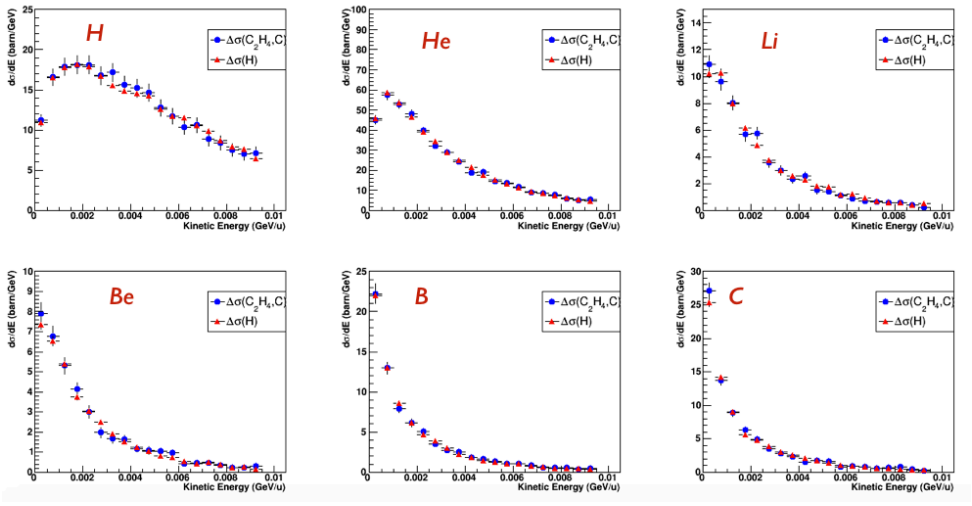


**Fig. 1:** FLUKA proton fragmentation via inverse kinematic. Check of the validity of the target cross sections combination method.

To check the validity of the cross sections measured with the method of combination of targets we evaluated from the simulation data both the cross section on hydrogen target and the cross section obtained from the difference method. The Fig. 1 shows the energy differential cross-section of $^{12}$C beam (200 $MeV/u$) on hydrogen target obtained in inverse kinematics for different produced fragments.

The estimations performed with the $\Delta\sigma(C_2H_4,C)$ and $\sigma(H)$ methods are reported as blue dots and red triangles, respectively and confirm the validity of the method. Similarly, with $C_bH_a$, PMMA ($C_5H_8O2$) and C targets it is possible to measure the cross sections on C, O and H.

### 1.1 FOOT Detector

The FOOT detector has been optimised to study the forward target fragment production ($Z \geq 3$ contained within a cone of $10^o$) with plastic scintillators detectors, trackers and a calorimeter able to stop the heavier fragments produced, in order to provide:

- the charge $Z$ and mass $A$ fragments identification;
- the fragments energy spectra;
- the different fragments production cross sections.

A dedicated emulsion chamber apparatus will characterise the light fragment production scattered at larger angles (see section1.3).

The forward detector includes a magnetic spectrometer for the momentum determination based on silicon pixel and strip detector, a plastic scintillator for the deposit energy and the ToF and a calorimeter for the kinetic energy measurement necessary for the particle identification (Figure 2. The detector has been designed to measure precisely the production cross sections of the fragments. FOOT results will impact on the biological dose evaluation. The radiobiology goal is to improve the NTCP (Normal Tissue Complication Probability) model precision using data from p+C and p+O collisions in the energy range of $[200; 400\ MeV/n]$. The FOOT goal is to obtain a $d\sigma/dE$ and $d\sigma/d\theta$ with a $5\%$ precision, for all the fragments in inverse and direct kinematics with p, C, O, He beams in the $[200 - 400]\ MeV/n$ energy range. In order to reach the needed resolutions on cross sections the detector has been designed to achieve the following experimental resolutions:

- $\Delta p/p \sim 4\%$
- ToF $\sim 70\ ps$
- $\Delta(dE)/dE \sim 3 - 10\%$ depending of Z
- $\Delta Ekin/Ekin \sim 1.5\%$

The experiment is being planned as a *table-top* experiment in order to cope with the small dimensions of the experimental halls of the CNAO and HIT treatment centres and GSI, where the data taking is foreseen in the next years. The experimental setup is shown in Figure 2.

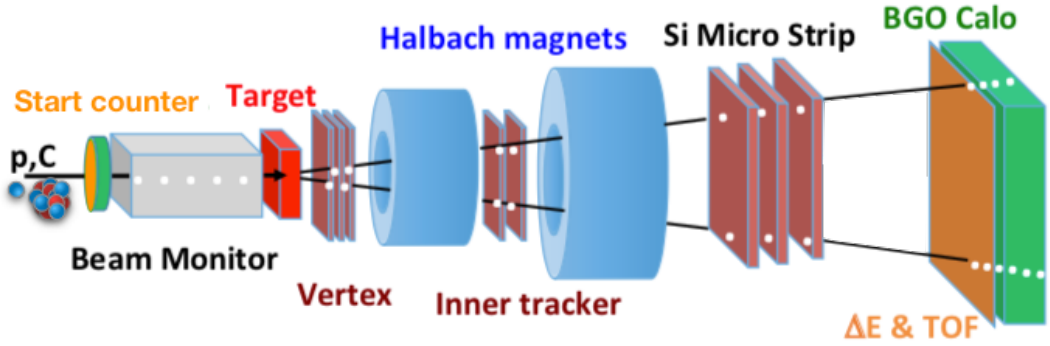


**Fig. 2:** The FOOT experimental setup is shown in this scratch.

A work of data-model verification will be done in synergy with the MC community and the correlation between the measured cross section and the biological uncertainty will be calculated. More details

on the different detectors can be found in [5] and on the experiment website[2].

### 1.2 Expected Performances

In order to evaluate the detector performance, thus the resolution on charge and mass of the fragments, a Monte Carlo Study has been realised. The full experimental setup has been simulated in FLUKA [6].

The fragments energy loss ($dE/dx$) is related to their charge by the well know equation (2):

$$-\frac{dE}{dx} = (\frac{\rho \cdot Z}{A})_{target} \frac{4\pi N_A m_e c^2}{M_U} (\frac{e^2}{4\pi\epsilon_0 m_e c^2})^2 (\frac{z^2}{\beta^2}) [ln(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}) - \beta^2]. \quad (2)$$

#### *1.2.1 Fragment Charge*

In FOOT the energy loss is therefore measured with thin plastic scintillators, exploiting ToF information to measure the $\beta$ of the fragments it is possible to reconstruct their charge.

**Table 1:** True and reconstructed $Z$ values of the selected fragments obtained for a 200 $MeV$ $^{16}O$ ion beam impinging on a 2 $mm$ thick $C_2H_4$ targets.

| Frag. | $^{7}$Li | $^{9}$Be | $^{11}$B | $^{12}$C | $^{14}$N |
|---|---|---|---|---|---|
| $Z$ | 3 | 4 | 5 | 6 | 7 |
| $Z_{rec}$ | $3.03 \pm 0.08$ | $4.05 \pm 0.09$ | $5.06 \pm 0.10$ | $6.09 \pm 0.12$ | $7.11 \pm 0.14$ |

The reconstructed $Z$ values are presented along with their resolutions in Tab. 1 for some selected fragments ($^{7}Li$, $^{9}Be$, $^{11}B$, $^{12}C$ and $^{14}N$); these values were obtained applying a $\Delta E$ resolution parametrised as a function on the deposited energy.

#### *1.2.2 Fragment Mass*

The fragments mass $A$ can be retrieved by coupling two of the three measured quantities $E_k$, $ToF$ and $p$ for each fragment, exploiting equations 3.

$$\begin{aligned} A_1 &= \frac{m}{U} = \frac{p}{U\beta\gamma} \\ A_2 &= \frac{m}{U} = \frac{E_{kin}}{U(\gamma-1)} \\ A_3 &= \frac{m}{U} = \frac{p^2 - E_{kin}^2}{2\,U E_{kin}} \end{aligned} \quad (3)$$

Moreover, to improve the resolution, a global fit with the Augmented Lagrangian Method (ALM [7]) using $E_k$ and $ToF$ and $p$ simultaneously has been implemented; as an example, in the left (right) panel of Fig. 3 it is reported the Helium mass with the ALM method (with a $\chi^2$ cut).

The achievable resolutions on mass determination for the fragments $^{7}Li$, $^{9}Be$, $^{11}B$, $^{12}C$ and $^{14}N$ are reported in Tab. 2.

The values and the plots of Fig. 3 are obtained assuming the following resolutions: $dp/p = 4\%$, $ToF = 70\ (140)\ ps$ for heavy (light) fragments and $dE_{kin}/E_{kin} = 1.5\%$.

[2] $https://web.infn.it/f00t/index.php/it$

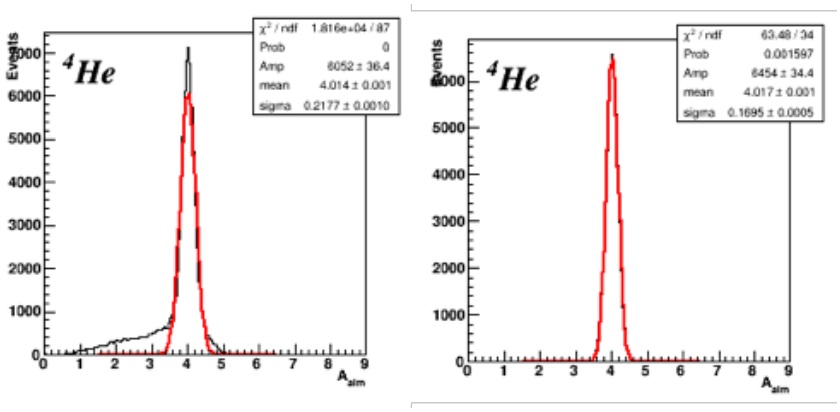


**Fig. 3:** As an example of the mass reconstruction method (a global fit obtained with the Augmented Lagrangian Method (ALM)) is shown for the $^4He$ fragment (left). A tail for neutron emission in the calorimeter detector is present. An appropriated cut on $\chi^2$ removes the tail (right).

**Table 2:** True and reconstructed A values of the selected fragments obtained for a 200 $MeV$ $^{16}O$ ion beam impinging on a 2 $mm$ thick $C_2H_4$ targets.

| Frag. | $^7$Li | $^9$Be | $^{11}$B | $^{12}$C | $^{14}$N |
|---|---|---|---|---|---|
| $A$ | 7 | 9 | 11 | 12 | 14 |
| $A_{\chi^2}$ | $7.00 \pm 0.31$ | $8.99 \pm 0.34$ | $10.99 \pm 0.44$ | $11.99 \pm 0.43$ | $14.00 \pm 0.48$ |
| $A_{alm}$ | $7.00 \pm 0.31$ | $8.98 \pm 0.33$ | $10.98 \pm 0.44$ | $11.98 \pm 0.43$ | $13.99 \pm 0.48$ |

### 1.3 Emulsion spectrometer

Complementary light fragments ($Z \leq 3$) measurements will be achieved by means of an emulsion chamber [8]. This dedicated setup is shown in Figure. 4. In this setup both target and detector are

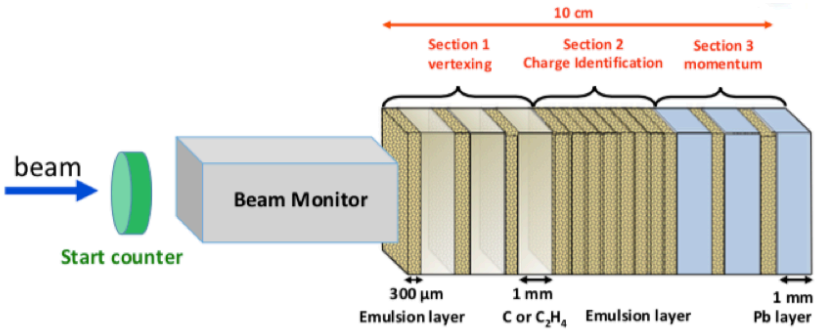


**Fig. 4:** Scheme of the emulsion spectrometer detector.

integrated in a very compact setup allowing for a very accurate reconstruction of the interactions inside the target, with a sub-micrometric resolution. It will provide measurements of fragments emitted in a cone with semi-aperture up to $70^o$, which are mainly protons, deuterons, tritons, Helium and Lithium ions. The pre-target region of the electronic setup will be employed to monitor the incoming primary beam, while the emulsion chamber will act both as target and fragments detector: in the first section target layers (C or $C_2H_4$) are alternated with emulsion films to reconstruct the interaction vertex, the second one will be made only by emulsion films to provide charge reconstruction, while in the last one the emulsion films are interleaved with Lead layers to measure fragments energy and momentum. The fragments charge will be assessed with an expected efficiency better than $99\%$.

## 2 Timeschedule

The construction of different part of the detectors is already started and some preliminary results show the effective feasibility of the experiment. A calorimeter prototype made of $145$ BGO crystal has already been tested with different particles (H, He and C) in a large energy range in HIT experimental room. The energy resolution has been measured to be about $1 - 2\%$. The full calorimeter exploits the $24\ cm$ long BGO crystal of L3 [3] and will be available in about an year. Its new readout system is under optimisation. Preliminary and very encouraging measurement with the ToF detector, bars of plastic scintillators instrumented with SiPM readout with a dedicated electronic system, has been performed with protons and carbon ions. A time resolution of $100 - 180\ ps$ and $\sim 50\ ps$ respectively for p and C ions has been obtained. The energy resolution on $dE/dx$ measurement with the ToF detectors is about $5 - 12\%$ for protons and about the $7\%$ for carbon ions.
The construction of the start detector is also started: $250\ \mu m$ plastic scintillator read out by $48$ SiPM $(12/\text{side})$ readout by the same ToF detector system.
FOOT experiment is advancing as expected: data taking will start in 2019 with the emulsions setup and in 2020 the full setup will be operational.

## Conclusions

The FOOT experiment is the dedicated to the characterisation of the target fragmentation production cross sections. This will improve the modelling of the true RBE of protons, thus PT treatment quality. To this aim an inverse kinematics strategy will be exploited and two experimental setups, one for light and an other one for heavy fragments, are currently under development. A full detectors MonteCarlo FLUKA simulations has been developed in order to optimise the experimental setups and to evaluate the expected performances of the FOOT experiment. Besides target fragmentation, the experiment will also provide projectile cross sections measurements which are crucial in ion therapy. In addition, by considering the application to the radio-protection framework, the operation of FOOT at higher energies would allows to achieve important contributions to the planning of long duration and far from earth space missions. A resolution of about $2\%$ and $3 - 4\%$ is obtained for the charge Z and number of mass A determination respectively.

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