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The magnetic spectrometer of the FOOT experiment

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Summary. — 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 a light ion beam, such as proton, helium, carbon, and different targets (proton, carbon, oxygen). Two important fields can benefit from these kinds of measurements: firstly, in the 150–400 MeV/nucleon beam energy range, the data will be used to evaluate the nuclear fragmentation occurring in a standard hadrontherapy treatment and thus to estimate potential secondary effects. Secondly, in the 700–1000 MeV/nucleon 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 and it is currently in its data taking phase. A description of the magnetic spectrometer of the experiment and a first approach to the track reconstruction of detected fragments will be presented.

1. – Introduction

Hadrontherapy, or Charged Particle Therapy, CPT, is an external radiotherapy technique in which protons and carbon ions are used to treat deep-seated solid tumours. This technique offers a lot of advantages with respect to conventional Radiation Therapy (RT). In particular, the dose-depth profile of charged particles shows a sharp rise, the Bragg peak, beyond which the dose falls fast to zero while it stays low in the entrance channel where healthy tissues are located. This allows to treat tumours near organs at risk with a reduced risk of secondary cancers [1]. Some problems have still to be addressed: among them, nuclear fragmentation of both the beam and the target should be characterised well in order to evaluate the dose correctly [2, 3].

Moreover, the hazard of radiation in space represents one of the major challenges for manned space missions beyond LEO (Low Earth Orbit) or even a potential showstopper. Indeed, it is necessary to shield astronauts from SPEs (Solar Particle Events) and GCR (Galactic Cosmic Radiation), so the shielding effectiveness of different materials in terms of nuclear fragmentation has to be studied [4].

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2. – The FOOT experiment

The FOOT (FragmentatiOn Of Target) experiment aims at measuring the double-differential cross-sections of fragmentation reactions between ion beams and different targets for hadrontherapy and radioprotection in space. In particular, FOOT will measure both target fragmentation occurring in proton therapy treatments and projectile fragmentation, which is of interest in both hadrontherapy and radioprotection in space. The former measurement is very challenging because of the short range of produced fragments preventing them from escaping the target. For this reason, an inverse kinematics approach will be used together with a cross-section subtraction technique to overcome the difficulty in handling some targets, such as hydrogen.

The electronic setup of the FOOT experiment is designed for $Z \geq 3$ fragments. It consists of several subdetectors devoted to the measure of different quantities in order to recognise the charge and the mass of fragments generated in the target. In particular, the momentum of the fragments is measured using the FOOT magnetic spectrometer composed by the Vertex Detector, the magnetic system, the Inner Tracker, the Micro Strip Detector.

The Vertex Detector consists of 4 layers of silicon pixel sensors with a total active area of $8 \times 8\,\mathrm{cm}^2$. The MIMOSA-28 technology has been chosen for both this detector and the Inner Tracker, with a pitch of $20.7\,\mu$m allowing to reach a $5\,\mu$m spatial resolution [5].

The magnetic system is necessary to bend the fragments produced in the target, thus providing a useful tool to evaluate their momentum. The need to keep the size of the detector small and to have a high bending power requires the use of two permanent magnets in Halbach configuration: this setup will allow to reach a maximum magnetic field of 1.4 T.

The last tracking station after the magnetic field is composed by 3 x-y layers of a microstrip sensor with a $9.6 \times 9.3\,\mathrm{cm}^2$ active area. The huge number of strips allows to have a spatial resolution well below $40\,\mu$m and to match the hits among different detectors even in multi-fragment events. In order to fulfill FOOT requirements, the resolution in momentum $\sigma(p)/p$ must be at the level of 5%. A schematic view of the FOOT electronic setup is shown in fig. 1.

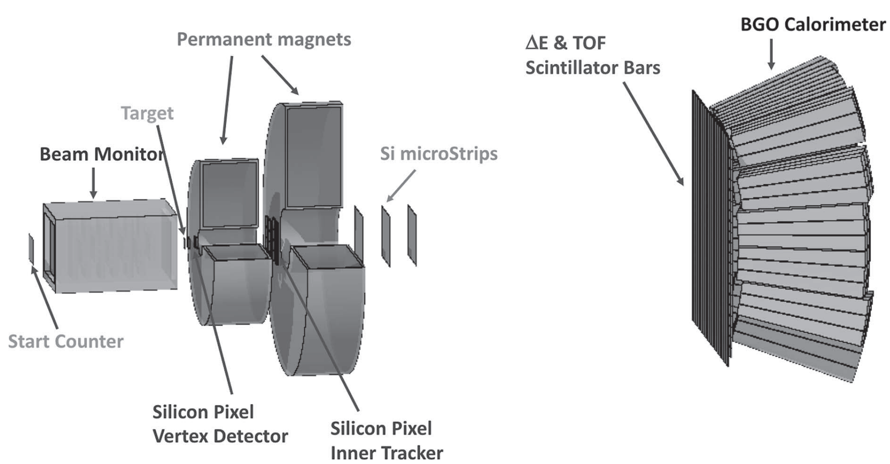

Fig. 1. – Schematic view of the FOOT electronic setup.

3. – Software

In the software developed for the FOOT experiment, a general-purpose open-source toolkit for track reconstruction, called GENFIT, is included.

GENFIT is designed to handle measurements from different detectors (for instance, 1D measurements for strip detectors, 2D for pixel detectors), to provide track models and fitting algorithms [6]. Among them, the Kalman filter is an efficient recursive algorithm which finds the best estimate for the kinematic state of a dynamic system, *e.g.*, fragments. Instead of taking the information all at once as global methods do, the Kalman filter proceeds from one measurement in a detector plane to the next improving the knowledge as it goes forward [7].

However, before performing the final fit to extract the track parameters, namely the momentum, it is necessary to select the hits belonging to a track candidate.

4. – Track reconstruction strategy

The preliminary track reconstruction strategy developed for the FOOT experiment combines information from tracking stations and the ToF wall [8]. Track candidates in the Vertex Detector and the charge of fragments passing through the ToF wall are provided by pre-existing algorithms.

As a first step in each event, the charge of fragments seen by the ToF wall is retrieved. This is useful to build track models, thus making a guess on nuclei produced in the collision. Then, every track found in the Vertex Detector, within the angular acceptance of the setup, is projected to the Inner Tracker positions: this projection is purely geometric and it is made only on the non-bending y-z view.

After the selection of the closest hits to the projection it is possible to extrapolate the track candidate to the Micro Strip stations. This time a 4th-order Runge-Kutta extrapolator implemented in GENFIT is used to take into account energy loss, scattering and the deflection due to the magnetic field.

After the selection of Micro Strip hits the last extrapolation to the ToF wall is performed. The track model is updated with the charge measured by the latter and the full fit is made again from the beginning using the selected hit collections. Only one track model for each element is developed, *i.e.*, the one describing the isotope with $A = 2 \cdot Z$ with the exception of lighter fragments (H, He) for which every possible isotope is listed.

5. – Results

In order to assess the track finding efficiency it is mandatory to define a *reference set*, *i.e.*, a set of tracks that a perfect algorithm should find [7]. This task can be carried out using Monte Carlo simulation provided by FLUKA code [9]. As a reference set, all tracks originated in the target reaching the ToF wall regardless on the number of hits in tracking detectors have been chosen. The *reconstruction efficiency* is then defined as

$$\varepsilon_{reco} = \frac{N_{ref}^{reco}}{N_{ref}}, \tag{1}$$

where N_{ref}^{reco} is the number of fragments reconstructed by at least one track and N_{ref} is the number of reference tracks as defined above.

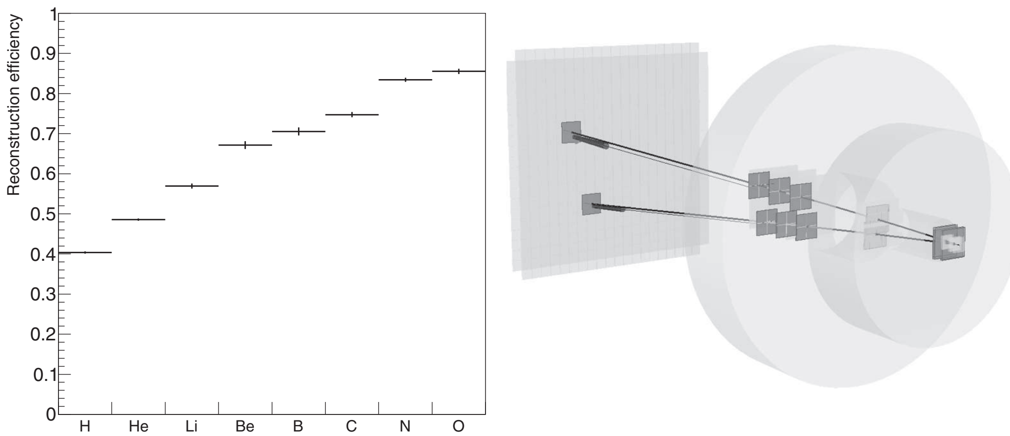

Fig. 2. – Reconstruction efficiency of the algorithm for 40 k fragmentation events of a 200 MeV/nucleon ^{16}O beam on a carbon target (left). Event display with two reconstructed fragments in the FOOT detector (right).

The *purity*, or hit matching efficiency, *i.e.*, the percentage of hits correctly assigned to a given track, is nearly 98% for every fragment type. The reconstruction efficiency for each element and an example of the FOOT event display are reported in fig. 2.

6. – Conclusions

The preliminary track reconstruction strategy for the FOOT experiment was presented. The results show that the reconstruction efficiency depends on the fragment, ranging from 40% to 85%. Several improvements in the algorithm are currently underway, both on the track finding and on the track fitting, since it is crucial to fulfill FOOT requirements on momentum resolution in order to be able to disentangle among different isotopes.

REFERENCES

[1] Schardt D., Elsässer T. and Schulz-Ertner D., *Rev. Mod. Phys.*, **82** (2010) 383.
[2] Durante M. and Paganetti H., *Rep. Prog. Phys.*, **79** (2016) 096702.
[3] Tommasino F. and Durante M., *Cancers*, **7** (2015) 353.
[4] Durante M. and Cucinotta F. A., *Rev. Mod. Phys.*, **83** (2011) 1245.
[5] Valin I. *et al.*, *JINST*, **7** (2012) C01102.
[6] Höppner C. *et al.*, *Nucl. Instrum. Methods A*, **620** (2010) 518.
[7] Mankel R., *Rep. Prog. Phys.*, **67** (2004) 553.
[8] Morrocchi M., Ciarrocchi E. *et al.*, *Nucl. Instrum. Methods A*, **916** (2019) 116.
[9] Ferrari A. *et al.*, CERN-2005-10, INFN/TC-05/11, SLAC-R-773 (2005).