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Calibration and performances of the full-scale ΔE-TOF prototype of the FOOT experiment

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Summary. — FOOT (FragmentatiOn Of Target) is an applied nuclear physics experiment aiming to perform cross section measurements for nuclear fragmentation reactions of interest in particle therapy and radioprotection in space. An important component of the apparatus is the ΔE-TOF system, composed of two scintillation detectors and dedicated to the charge identification of nuclear fragments. The first full-scale prototype of this system was tested in 2019 at CNAO (Pavia, Italy) with protons and ^{12}C ions and at GSI (Darmstadt, Germany) with ^{16}O beams. We developed a calibration procedure for the detectors and validated it with Monte Carlo simulations. As a result the system showed promising performances, reaching energy and time resolutions of 3.9–5% and 50–84 ps for ^{12}C and ^{16}O beams, respectively. The ΔE-TOF was then employed for the first time to identify the charge of nuclear fragments produced by a 400 MeV/u ^{16}O beam impinging on a 5 mm thick graphite target.

1. – Introduction

The increasing number of patients treated with Charged Particle Therapy (CPT) is a consequence of its effectiveness against deep-seated solid tumors. The favorable depth-dose profile (Bragg curve) of ions makes it possible to spare healthy tissues in a much more efficient way with respect to conventional X-rays [1].

The advantage of more conformal dose distributions comes with the drawback of nuclear fragmentations. Both target and projectile fragmentation increase the amount of dose deposited in healthy tissue around the tumor. Target fragmentation is the main issue in protontherapy, where short-range heavy fragments produced in the entrance channel of the beam can damage the tissue in front of the tumor. For ion beams such as ^{12}C or ^{16}O, projectile fragmentation is also relevant, since long-range energetic fragments

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produce dose tails behind the tumor. The exact impact of these processes in CPT sessions is difficult to determine since cross section measurements for fragmentation reactions are scarce at therapeutic energies (up to 250 MeV for protons and 400 MeV/u for ^{12}C ions). An in-depth knowledge of such processes could lead to a significant improvement in the accuracy of state-of-the-art treatment planning systems [2, 3].

The topic of nuclear fragmentation is of great interest also in the field of radioprotection in space (RS). Spacecrafts and astronauts are continuously exposed to a wide variety of ionizing radiation, mainly composed of high-energy protons and ^{4}He ions. Risk assessment for radiation damage is fundamental to plan long-duration far-from-Earth missions, such as a travel to Mars.

The main source of radiation in interplanetary space are Galactic Cosmic Rays (GCRs), which have an energy spectrum ranging from MeV to TeV that peaks around 100–800 MeV/u. These particles can damage both crew members and electronic instrumentation through direct interactions or through secondary fragments produced in the spacecraft. An accurate modeling of these processes stems from the availability of cross section data, which are only partially present in the literature, introducing a non-negligible uncertainty in the Monte Carlo (MC) transport codes currently used in risk assessment. Additional measurements are thus needed to perform efficient predictions on dose exposure and improve radiation shielding in spacecrafts [4].

In this context, the aim of the FOOT (FragmentatiOn Of Target) experiment is to provide the missing data by performing a wide range of cross section measurements for nuclear fragmentation processes of interest in both CPT and RS. The final objective is a resolution of 5% or better on double differential cross sections with respect to kinetic energy and angle of emission, which would lead to a significant improvement in MC models employed in CPT treatment plans and RS risk assessment. The FOOT project has been approved and funded by INFN (Istituto Nazionale di Fisica Nucleare, Italy) in 2017 and the collaboration currently counts around 100 members from 6 countries (Cuba, France, Germany, Italy, Japan and Russia) [5].

2. – The FOOT experiment and the ΔE-TOF system

FOOT has been designed as a fixed-target experiment. Data acquisition campaigns will employ low-rate (1–10 kHz) beams of ^{4}He, ^{12}C or ^{16}O ions impinging on thin C or hydrogen-enriched targets with chemical composition similar to human tissues. The apparatus will then detect and characterize the produced nuclear fragments and extract their production cross section as a function of kinetic energy and direction of emission. To ensure the requested accuracy on cross section measurements, FOOT will need to have solid particle identification capabilities in terms of both charge Z (from 2% for heavy ions to 6% for lighter fragments) and mass A (at the level of 3–6%) [5].

Since different primary beams will be available in different facilities, the system needs to be limited in size (2–3 m) while also keeping a good angular acceptance. Following a series of preliminary studies performed on MC simulations, FOOT envisages two setups with complementary purposes:

- an emulsion chamber spectrometer, dedicated to the identification of light fragments ($Z \leq 3$) and with an angular acceptance of ~ 70 degrees from the beam axis;
- a setup composed of electronic detectors coupled with a magnetic spectrometer, dedicated to heavy-fragment ($Z \geq 3$) identification and with angular acceptance of about 10 degrees.

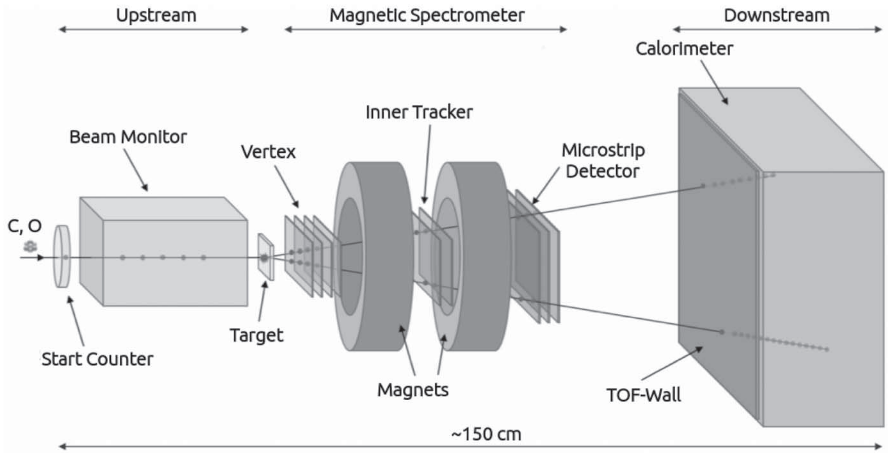


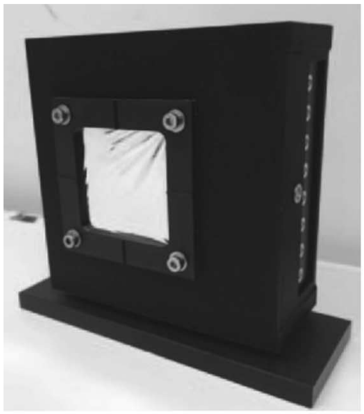
Fig. 1. – Schematic view of the electronic setup of FOOT and its sections: the *upstream* region, dedicated to primary beam monitoring; the *magnetic spectrometer*, which performs particle tracking and momentum evaluation; the *downstream* region, dedicated to energy and TOF measurements.

Both setups will include an *upstream* region, composed of pre-target detectors and dedicated to the characterization of the primary beam, followed by a region where fragment tracking and identification are performed. The electronic setup is shown in fig. 1, where the different regions and their functions are highlighted. The setup is still under development and the first acquisition with the full apparatus and DAQ system is planned for the late 2021. Most of the detectors have already been built and are currently undergoing preliminary tests and calibration procedures.

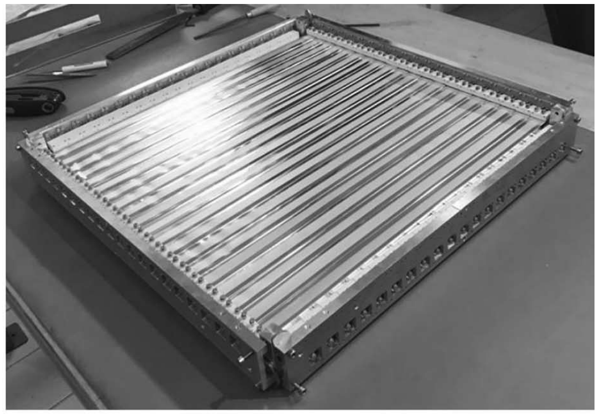
An important component of the electronic setup of FOOT is the ΔE-TOF system, dedicated to the charge identification of fragments. The ΔE-TOF is made of two scintillation detectors, which will measure the energy loss (ΔE) and the Time Of Flight (TOF) of ions. These quantities can then be used to retrieve the charge of impinging fragments through the Bethe-Bloch formula. To fulfill the requirements of the experiment, the ΔE-TOF should be capable of measuring these two quantities with a resolution at a level of 4–5% for ΔE and below 100 ps for TOF, respectively. These performances would ensure the precision on charge measurement requested by the experiment.

2˙1. *Start counter*. – The first component of the ΔE-TOF is the Start Counter (SC). It is a 250 μm thick plastic scintillator (EJ-228) foil with an active area of 5×5 cm^2. The light produced in the foil is read out by eight groups of 6 SiPMs (ASD-NUV3S-P) with 25 μm microcell pitch. The purpose of this detector in the final setup is to provide the rate of primaries, measure the start time of TOF and generate a trigger signal for all the other components of FOOT. The thickness of the material has been optimized to have a low impact on primaries while keeping a good time resolution and detection efficiency at the chosen beam rates [6]. A picture of the SC is shown in fig. 2(a).

2˙2. *TOF-Wall*. – The second detector of the ΔE-TOF is the TOF-Wall (TW). This is made of 40 bars of plastic scintillator (EJ-200) arranged in two orthogonal layers (horizontal the first, vertical the second). Each bar has a surface of 2×44 cm^2, is 3 mm



(a) Start counter.



(b) TOF-Wall.

Fig. 2. – Components of the ΔE-TOF system.

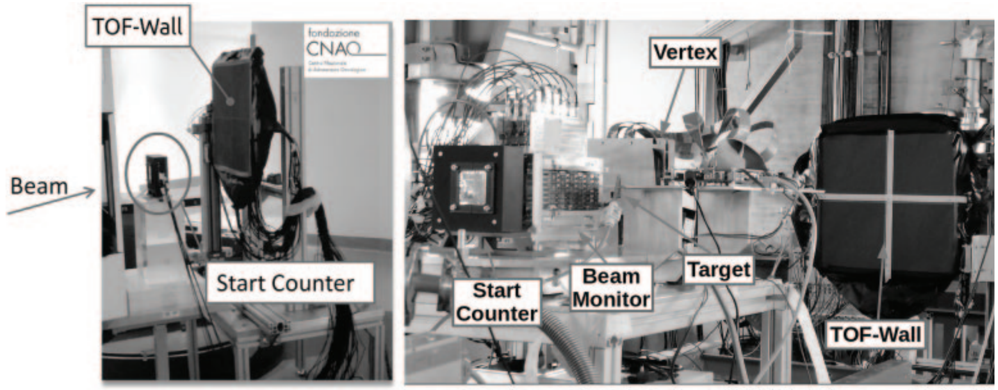
thick and is wrapped with darkening tape and reflective aluminum. The two layers of the TW overlap over a total area of 40×40 cm^2. The signals produced by particles crossing the TW are read out at each bar end by a group of 4 SiPMs (Hamamatsu S13360-3025PE) with 25 μm microcell pitch. The main purpose of the TW is to measure the energy loss (ΔE) of the particles in a thin scintillator and provide the stop time for TOF calculations. The thickness of the bars has been optimized to ensure good energy and time resolution, while also keeping the probability of secondary fragmentations as low as possible [7]. A picture of the TW is reported in fig. 2(b).

The signals produced in the SiPMs of both SC and TW are acquired through the WaveDAQ system, which employs DRS4 chips in combination with fast digitizers [8]. The WaveDAQ handles all the 88 channels utilized for the read-out of the ΔE-TOF (8 for the SC, 80 for the TW) and allows for sampling frequencies in the range 0.5–5 Gsamples/s. The data reported in this work have been acquired using a sampling frequency of 4 Gsamples/s.

3. – Beam tests at CNAO and GSI

The first full-scale prototype of the system was built in 2019 and was tested in two consecutive campaigns. The first one was carried out in March at the CNAO (Pavia, Italy) facility with the aim of acquiring calibration data for the ΔE-TOF. The setup was composed only of the SC and TW at a fixed distance of ~ 42 cm. In this case the beams employed were protons at 60 MeV and ^{12}C ions at 115, 260 and 400 MeV/u. A picture of the setup (as well as the direction of the primary beam) is shown in fig. 3(a).

The second beam test was performed in April at the GSI (Darmstadt, Germany) facility. The setup chosen for the acquisition can be seen in fig. 3(b). In this case, the SC and TW were placed at a fixed distance of ~ 2.20 m and part of the tracking system was included. The GSI campaign aimed at acquiring calibration and fragmentation data with ^{16}O ion beams, while also testing the global DAQ system of FOOT for the first time. All the acquisitions were performed with 400 MeV/u beams and, for the fragmentation run, a 5 mm thick graphite target was chosen.



(a) CNAO. (b) GSI.

Fig. 3. – Setups utilized for the beam tests of the ΔE-TOF detector.

Concerning the ΔE-TOF system, the data acquired during the CNAO and GSI campaigns have been utilized to develop the energy and time calibration procedures needed to reconstruct the charge of impinging particles. Both procedures are based on the ΔE and TOF values expected from the MC simulations we performed in the FLUKA framework by accurately reproducing the setups depicted above. In particular, the energy calibration was carried out using the Birks model [9], which describes the light output of organic scintillators as a function of the energy loss:

$$Q = \frac{p_0 \Delta E}{1 + p_1 \Delta E}. \tag{1}$$

The quantity Q in the above expression is the *total collected charge* in a TW bar and it is proportional to the number of photons produced in the bar by the passage of a particle. The parameters p_0 and p_1 represent a gain factor and a saturation parameter accounting for the non-linearity of plastic scintillators response. The TOF calibration was instead performed by simply matching the experimental mean raw TOF to MC values for each beam considered. The resulting calibration was then applied to fragmentation data for the first time to obtain the Z spectrum of the produced fragments.

4. – Results

4˙1. *Calibration.* – An example of the energy calibration curve obtained with the Birks model is reported in fig. 4. Here, the parameters of the model were extracted by inserting the energy loss expected from MC simulations in eq. (1) and fitting the experimental Q data collected in the TW. As can be seen from the graph, the light output of the scintillator is not directly proportional to the energy deposited by particles, which is typical for plastic scintillating materials. However, fig. 4 shows clearly that the Birks model reproduces the response of the TW with good accuracy, meaning that it can be used to extract calibrated ΔE values from raw data.

Applying this procedure to each of the calibration runs, we obtained an energy resolution ranging from 3.9 to 5% for ^{12}C and ^{16}O ions and of 5.3% for the proton beam. This

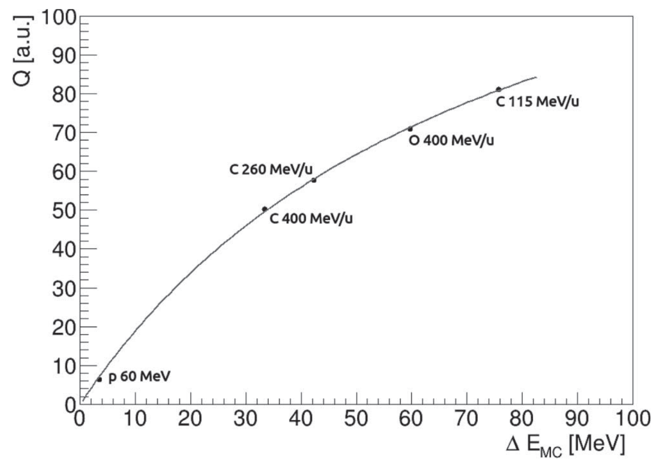
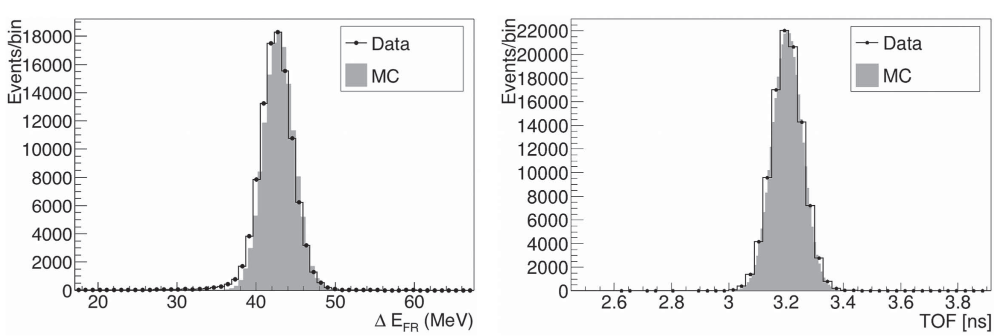


Fig. 4. – Energy calibration curve obtained with the Birks model. The points shown in the graph are labeled with the corresponding beam. Errors on experimental data are shown but too small to be appreciated.

means that the performances of the prototype are compatible with the overall requirements of FOOT. An example of a calibrated energy distribution is reported in fig. 5(a), where the corresponding MC distribution is also shown. Note that, to account for detector resolution, a Gaussian smearing has been applied to the MC distribution. The spread applied to simulation results was determined by modeling the energy resolution of the TW $\sigma(\Delta E)/\Delta E$ as a constant over the energy loss range explored in the acquisitions. The final value used for the smearing was $\sigma(\Delta E)/\Delta E = 4.77\%$.

Concerning the TOF calibration, for each of the beams considered, we calculated the difference between the mean TOF value obtained from data and simulations. Then, this offset was subtracted from raw data in order to extract the calibrated TOF. As an example, a calibrated TOF spectrum is reported in fig. 5(b). The resolution we obtained



(a) ΔE spectrum for ^{12}C at 260 MeV/u. (b) TOF spectrum for ^{12}C at 115 MeV/u.

Fig. 5. – Examples of calibrated spectra and MC distributions for ΔE and TOF for two of the ^{12}C beams employed at CNAO. Both the ΔE and TOF displayed here have been obtained as the mean of the measurements performed by the two TW layers in each event. Note that the MC distributions have been smeared according to the described models.

for calibrated TOF measurements was 54–72 ps for ^{12}C ions, 84 ps for the ^{16}O beam and $\sim$ 260 ps for the protons. Again, the performances shown by the ΔE-TOF are compatible with the requirements of the experiment.

Note that fig. 5(b) also contains the distribution obtained from MC simulations, which was again smeared with a Gaussian to account for detector resolution. This was necessary to perform an accurate MC-data comparison, since the intrinsic spread of TOF distributions obtained from the simulations was well below 1 ps. In the case of TOF, we decided to include the response of the system by modeling the experimental resolution σ(TOF) as a function of the energy loss with the function,

$$\sigma(\mathrm{TOF}) = \sqrt{\frac{A}{\Delta E} + B}, \tag{2}$$

where A and B are free parameters. The final result of this procedure is reported in fig. 6. As one can see in the graph, the point (squared) obtained from the calibration run at GSI does not really align with the behavior expected from the model. This slight worsening of the time resolution at GSI is still being investigated, but it was likely caused by a change in the experimental conditions between the two acquisitions. In fact, the ΔE-TOF system had to be completely disassembled for transport and then re-built, partially with different cables. Because of this, we chose to model the TOF resolution of the system using only CNAO data.

4·2. *Charge identification.* – The calibrated data were then utilized to check if the charge Z of primary beams in the calibration runs could be reconstructed accurately. Thus, we applied the Bethe-Bloch formula to retrieve the charge spectrum of each acquisition. Figure 7 shows the final Z distribution obtained for the ^{16}O beam at GSI, together with the spectrum obtained from MC simulations. The reported example shows that the procedure we developed is indeed accurate and the charge of impinging particles

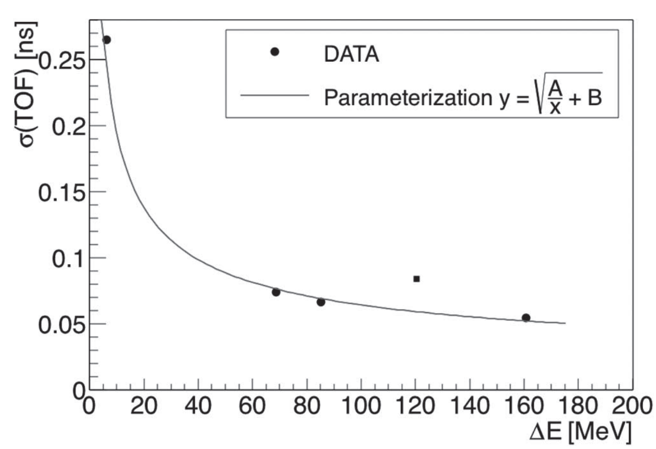


Fig. 6. – TOF resolution as a function of the mean energy loss and model used for the parameterization of detector response in the MC simulations. Each point represents a calibration run and the ΔE reported on the x-axis is the sum of the energy deposited by ions in the two layers of the TW. Errors on single TOF resolutions are displayed but too small to be appreciated in the graph.

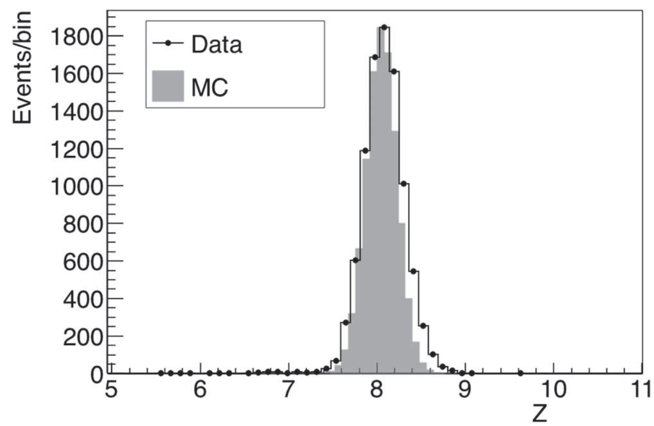


Fig. 7. – Example of reconstructed charge spectra: comparison of real data and MC simulations (with Gaussian smearing) for the ^{16}O at 400 MeV/u calibration run at GSI.

is extracted correctly. Note also that the MC distribution is narrower than data in this case, as expected from the model shown in fig. 6 and the already mentioned worsening of TOF resolution at GSI.

The final Z resolution obtained for calibration runs ranged from 2.5 to 3.9% for the three ^{12}C beams and was equal to 2.7% for ^{16}O ions and 6.1% for protons. As expected from the performances shown on energy and time measurements, the ΔE-TOF prototype matched the requirements of FOOT also in terms of Z resolution.

The calibration parameters extracted from previous runs were then applied to the fragmentation data obtained at GSI with ^{16}O ions impinging on a 5 mm thick graphite target. Figure 8 shows the final Z spectrum of the acquisition. As is clearly visible in the graph, the ΔE-TOF was able to discriminate well the differently charged particles.

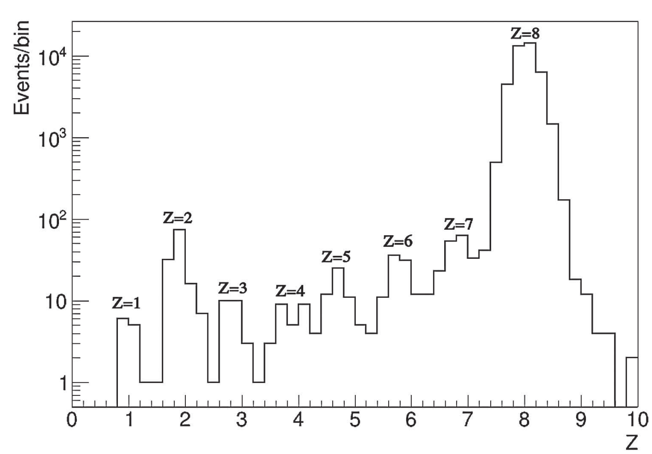


Fig. 8. – Charge spectra of the fragmentation run performed at GSI with ^{16}O ions on graphite.

5. – Discussion

The result shown in fig. 8 is really promising in view of future acquisitions with the full FOOT apparatus. A solid charge discrimination is in fact crucial for the correct identification and tracking of the fragments produced in the target. The very good time resolution obtained is also really important for isotopic identification, since the TOF will be used to calculate the mass of ions traveling through FOOT.

Moreover, both components of the ΔE-TOF are still being developed, which means that the performances of the system could still improve. As an example, a set of measurements performed with a newer version of the SC in 2020 showed a significant increase in the precision of time measurements. Concerning the TW, the detector has just been mounted in its new mechanical frame, which will improve both the stability of the system and the optical isolation between different bars. During 2021, the performances of both detectors will be assessed again and the FOOT Collaboration is planning an acquisition with the full setup at the end of the year.

6. – Conclusions

The first prototype of the full ΔE-TOF system has been tested. The results show that the calibration procedure we developed leads to performances compatible with the overall requirements of the experiment in terms of both ΔE and TOF resolution. The procedure was also applied for the first time to a fragmentation acquisition, showing that the ΔE-TOF is currently able to discriminate the charge of nuclear fragments with good accuracy.

REFERENCES

[1] Durante M. and Paganetti H., *Rep. Prog. Phys.*, **79** (2016) 9.
[2] Tommasino F. and Durante M., *Cancers*, **7** (2015) 353.
[3] Osama M. *et al.*, *Cancers*, **9** (2017) 66.
[4] Durante M., *Life Sci. Space Res.*, **1** (2014) 2.
[5] Battistoni G., Toppi M. *et al.*, *Front. Phys.*, **8** (2021) 568242.
[6] Traini G. *et al.*, *Nuovo Cimento C*, **43** (2020) 16.
[7] Morrocchi M. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **916** (2019) 116.
[8] Galli L. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **936** (2019) 399.
[9] Birks J. B., *The Theory and Practice of Scintillation Counting*, in *International Series of Monograms and Instrumentation*, Vol. **7** (Pergamon Press) 1964.