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Calibration and performance assessment of the TOF-Wall detector of the FOOT experiment

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Abstract

In this contribution we discuss the calibration and performance of the TOF-Wall detector of the Fragmentation-Of-Target (FOOT) experiment. A thin carbon target was irradiated with carbon ions of several energies ranging from 150 to 400 MeV/u. The charge spectra of the produced fragments were used to calibrate the energy response. The energy resolution for a single bar was about 6%. The time resolution between the two layers ranged from 42 (150 MeV/u) to 62 ps (400 MeV/u).

Keywords: particle detectors, particle therapy, plastic scintillator, silicon photomultiplier

Introduction

The goal of the FOOT (FragmentatiOn Of Target) experiment [1] is the measurement of the differential and double-differential cross-section of the interactions of light projectiles (up to oxygen) with the main constituents of biological tissue, mainly carbon and oxygen, in the energy range of 200 MeV/u - 800 MeV/u. The proposed measurements are fundamental to quantify the dose released during hadron therapy treatments by fragmentation of the tissue and of the primary beams and to correctly assess the radiobiological risk in long space travels, where astronauts have prolonged exposure to Galactic Cosmic Rays and potentially to Solar Particle Events [2]. One of the two setups used for the measurements consists of several detectors aiming at tracking each fragment and measuring its charge, mass and direction. In particular the system is made of a beam monitor, a magnetic spectrometer, a Time of Flight (TOF) apparatus and a BGO calorimeter.

The TOF system [3] is composed of a thin plastic scintillator (start counter detector), positioned in the upstream region of the experiment, and a TOF-Wall detector positioned at about 2-meter distance. The TOF-Wall consists of two layers with 20 + 20 plastic scintillator bars, arranged orthogonally and covering an active area of 40 cm x 40 cm. Both detectors are coupled to silicon photomultipliers, whose analog signals are digitized by the WaveDAQ system [4]. The TOF system allows the identification of the charge of each fragment by measuring the energy deposited in the TOF-Wall and the TOF between the two detectors [5]. To calibrate and characterize the TOF-Wall detector, several irradiations with different beams were carried out and full scans of its active area were performed in different accelerator facilities. We report here the results obtained by irradiating the detector with carbon ion beams with four different energies, from 150 MeV/u up to 400 MeV/u, at the Centro nazionale di Adroterapia Oncologica (CNAO - Pavia, Italy). As an example, the energy calibration, energy resolution and time resolution are reported in detail for one bar of the detector.

1. Materials and Methods

The TOF-Wall detector [6, 7] is composed of plastic scintillator bars (EJ200, Eljen Technology, Sweetwater, Texas) with dimensions of 44 cm × 2 cm × 0.3 cm. The lateral sides of the bars are wrapped with enhanced specular reflector (ESR), while each end is read-out by an array of four silicon-photomultipliers (SiPM), with 3 mm × 3 mm active area, and connected as the parallel of two series, so to readout their signals with a single analog channel. The active area of the TOF-Wall detector ensures an angular coverage of the fragments produced in the target of about 10° in the final configuration of the system. A picture of the TOF-Wall detector is shown in Fig. 1. The arrangement of the scintillator bars in two orthogonal layers allows for the identification of the interaction position of the fragment in the detector with a 2 cm granularity. In case of multiple fragments interacting at the same time in the TOF-Wall, the time

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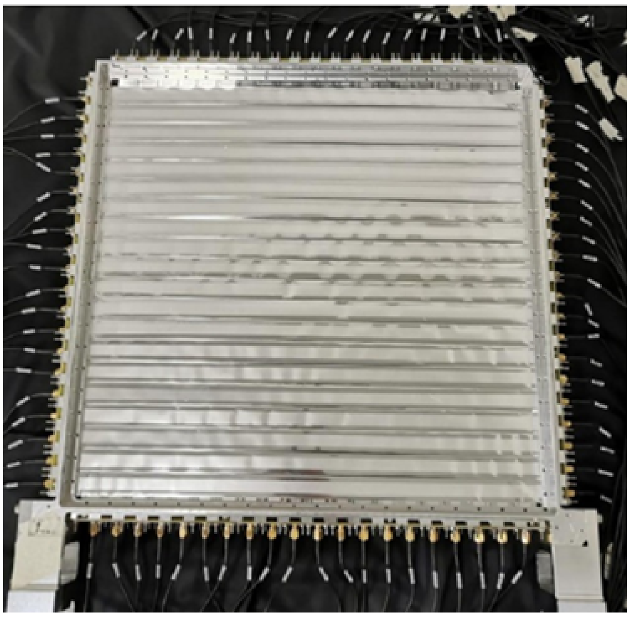

Figure 1: Picture of the TOF-Wall detector.

difference of the signal at the two sides of each triggered bar can be used to identify the intersection between the two layers where the event occurred. The 80 channels of the TOF-Wall detector are digitized by means of the WaveDAQ system. The DAQ allows to digitize each triggered channel with a sampling rate between 1 and 5 GSample/s by means of the Domino Ring Samplers (DRS4 chips) and manage the global trigger of the system. The same DAQ is used also for the readout of the start counter detector and of the calorimeter. To allow the complete calibration of the detector and the alignment with the beam, the TOF-Wall can be installed on a set of stages that enable the movement on the two directions orthogonal to the beam axis. In this way the entire sensitive area can be irradiated with a fixed pencil beam.

In this work, the detector was irradiated using carbon beams with energy of 400 MeV/u, 300 MeV/u, 200 MeV/u and 150 MeV/u. A 5 mm graphite target was positioned before the TOF-Wall so to irradiate the detector also with fragments with different charge. A picture of the setup is shown in Fig. 2. The energy spectrum of the generated fragments was evaluated by simulating the whole experiment in FLUKA [8, 9]. Events were acquired with a maximum data rate of 10^3 events/s with a sampling rate of 3 GSample/s. To maximize the collection of fragmentation events, a trigger that rejects a fraction of primary particles interacting in the TOF-Wall was implemented. The charge collected by each triggered bar was obtained as the square root of the product of the area of the signals collected at the two ends of the bar, while the timestamp corresponding to the trigger time of the bar was calculated as the average of the two timestamps obtained at the two sides using the constant fraction discriminator method on the digitized waveform.

The energy calibration of one bar was performed using the collected charge and the expected released energy for all the different fragments and for the four beam energies. The collected charge was then converted to energy by inverting the previous relation, and the energy resolution of the bar was evaluated for the four primary beams.

Figure 2: Picture of the setup used at the CNAO facility for the TOF-Wall irradiation.

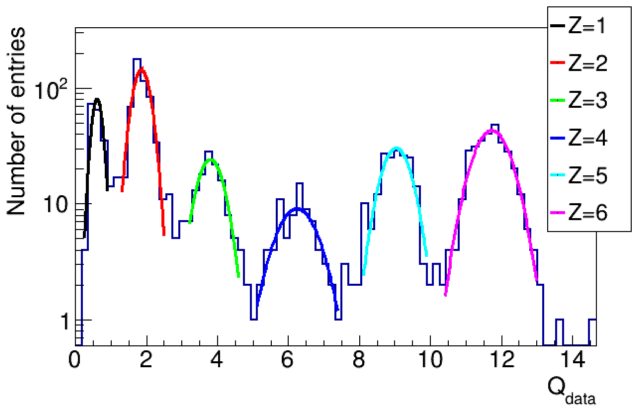

Figure 3: Charge collected in the analyzed bar for the 300 MeV/u carbon beam on graphite target.

2. Results

Fig. 3 represents the charge collected on one bar of the TOF-Wall detector. A Gaussian fit for each one of the six peaks corresponding to the six possible charges of the fragments is also represented. For the same bar, the expected released energy evaluated with the FLUKA simulation is also reported in Fig. 4. The discrepancy between the number of detected hydrogen fragments and the expected one can be due to a reduction in the detector sensitivity for Z=1 fragments, for which the TOF-Wall was not optimized in this data taking. Moreover the beam position was not accurately modelled.

The relation between the expected collected energy and the measured charge is reported in Fig. 5, where the data for all fragments were fitted according to Birks' law. The peaks corresponding to hydrogen ions were not used in the plot since

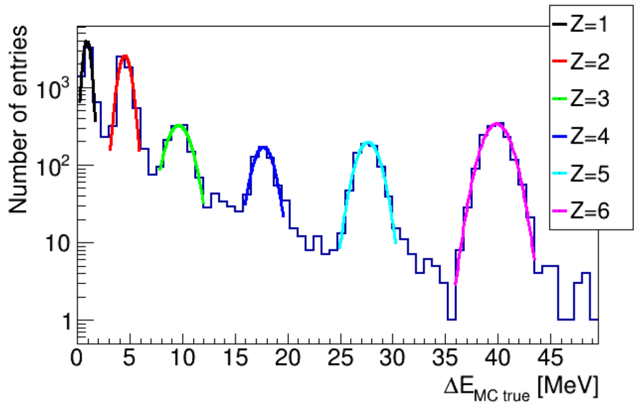

Figure 4: Simulated energy released in the analyzed bar for the 300 MeV/u carbon beam on graphite target.

Table 1: Energy resolution σ_E and time resolution between the two layers σ_{TW}, obtained for one bar of the detector with carbon ions at the four different energies.

Carbon energy	$\sigma_E/E(\%)$	σ_{TW} (ps)
400 MeV/u	6.3 ± 0.3	62 ± 2
300 MeV/u	6.4 ± 0.3	49 ± 2
200 MeV/u	6.1 ± 0.2	47 ± 1
150 MeV/u	6.1 ± 0.1	42 ± 1

their position in the collected charge spectrum could be affected by the above-mentioned sensitivity reduction. The same Birks' function was used for all the fragments, although slight differences can be expected, especially at kinetic energies lower than the ones of our study [10].

The energy resolutions obtained for the four carbon energies are reported in Tab. 1, as a function of the mean released energy in one bar. A resolution of about 6% was found for the four ions. It has to be noted that the overall resolution of the detector is a factor $1/\sqrt{2}$ better (then close to 4 percent for carbon ions) since the information of both layers is combined. We show only the resolution obtained with the primary beams since the energy distribution of the fragments depends also on the fragmentation process and does not correspond to a monochromatic particle beam. The time resolution between the investigated bar and the bars of the second layer are also reported in table.

3. Conclusions

The calibration of the TOF-Wall detector was performed by irradiating a graphite target with four carbon ion beams with energy ranging from 150 MeV/u to 400 MeV/u, and with the support of dedicated simulations. The energy and time resolution were evaluated with carbon ions. The results reported here for one bar of the detector demonstrate that an energy resolution of about 6% was achieved and a time resolution between 42 ps and 62 ps was obtained in coincidence with the bars of the second layer. These results correspond to an energy resolution of the TOF-Wall detector of about 4.3% and to a time resolution between 20 ps and 30 ps when both layers are used. Therefore, the performance of the TOF-Wall detector is compatible with the requirements of the FOOT experiment.

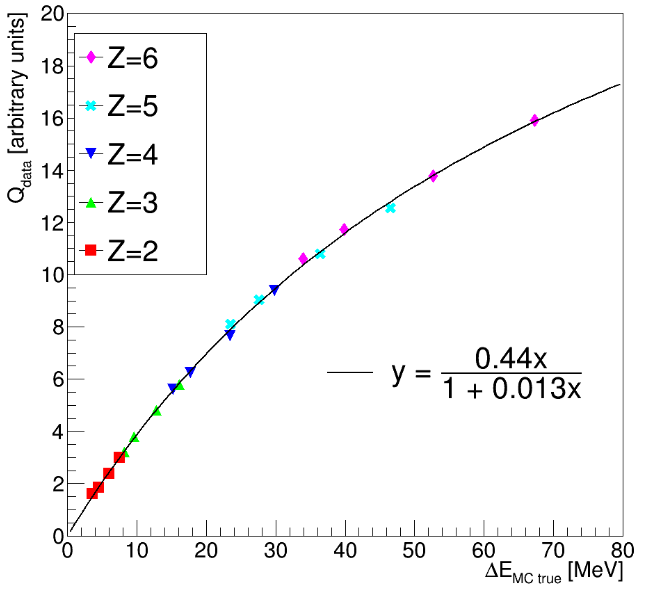

Figure 5: Collected charge as a function of the mean released energy estimated by the simulation for the particles from Z=2 up to Z=6 in the analyzed bar. The Birks' function fit is also reported.

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