PROCEEDINGS OF SCIENCE

Energy response function and calibration of the FOOT calorimeter

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The FOOT experiment aims at measuring the differential cross sections for the production of secondary fragments in interactions between light ions (C, O) and hydrogen-enriched targets, with beam energies of up to 400 MeV/u, a topic relevant for the optimization of particle therapy treatments, which can only be addressed in inverse kinematics. By extending the energy range up to 800 MeV/u, the experiment will also collect valuable data for understanding fragmentation processes relevant for the design of spacecraft shielding.
The experiment, whose construction is almost completed, aims at identifying heavy fragments by measuring their momentum, kinetic energy, and time of flight with high resolution: 5%, 2% and <100 ps respectively. The kinetic energy will be measured with a calorimeter detector made of 320 BGO crystals coupled to SiPM photodetectors, covering a dynamic range from tens of MeVs to about 10 GeV.
Data takings, aiming at measuring the response function for different ions and at optimizing crystal intercalibration, have been conducted at HIT (Heidelberg, Germany), and at CNAO (Pavia, Italy), using 12 modules of 3x3 crystals each. The energy response between 50 and 430 MeV/u is consistent with a modified Birks function for all the ions, although the parameters depend on Z. The dependence of the parameters on Z has been measured, allowing to reconstruct the fragment energy. The integrated system resolution is, as expected, well below 2% over the 100-300 MeV/u range.

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1. Introduction

The increasing number of cancer patients treated with Charged Particle Therapy (CPT) [1] attest its effectiveness, particularly in the treatment of deep-seated solid tumors. Charged hadrons deposit most of their energy in the Bragg Peak, the narrow region at the end of range, thus minimizing the damage to healthy tissues. CPT reliability can be further improved with precise measurement of cross section fragment production due to beam-tissue nuclear interactions in the entrance channel. FragmentatiOn Of Target (FOOT) is a nuclear physics experiment which measures fragmentation cross sections induced by carbon beams on hydrogen-enriched/carbon targets, taking advantage of the reverse kinematics approach [2]. Beam energies up to 400 MeV/u are employed for CPT optimization but the experimental setup is also capable to measure fragments produced by beam up to 800 MeV/u which are relevant for space radio protection purpose. Fragment identification will be conducted by measuring their momentum, energy and time of flight with resolutions of 5%, 2%, and <100 ps respectively, allowing to calculate fragmentation cross sections with a precision better than 5%.

2. Experimental setup

According to simulations performed in the design phase, the angular distribution of fragments varies widely. For this reason the FOOT experiment has been designed with two distinct experimental setups: the Emulsion Cloud Chamber (ECC) to measure the differential cross section of light fragments ($Z < 3$) and the Electronic Spectrometer for the heavier ones ($Z \geq 3$).

2.1 Emulsion setup

Nuclear emulsion detectors achieve the highest spatial resolution among the tracking devices for ionizing particles. Emulsion chambers integrate target and detector in a compact setup, providing an accurate reconstruction of the interactions occurring inside the target. This, coupled with the fact that no power supply or readout electronics is required, achieves an angular accetpance up to 70°. Moreover, last generation microscopes allow very fast scanning with wide angular acceptances and real time analysis of huge data sets, Based on the Emulsion Cloud Chamber concept [3], the emulsion spectrometer for the FOOT experiment is designed with passive materials alternated to nuclear emulsions films acting as both high-resolution tracking devices and ionization detectors. The Emulsion Cloud Chamber is composed of three sections:

- *Target and vertexing section*: the first section is composed of emulsion films alternated with layers of C or C2H4 target material. The emulsion films operate as vertex detector to reconstruct the charged fragments tracks.
- *Charge identification section*: the central section is completely composed of emulsion films, aiming to measure the fragments charge.
- *Momentum measurement and isotope identification section*: the last section is composed of emulsion films interleaved with passive high-Z absorber layers. Particle momentum and mass can be evaluated by measuring the length of the entire track and the angles between the base-tracks caused by the multiple coloumb scattering.

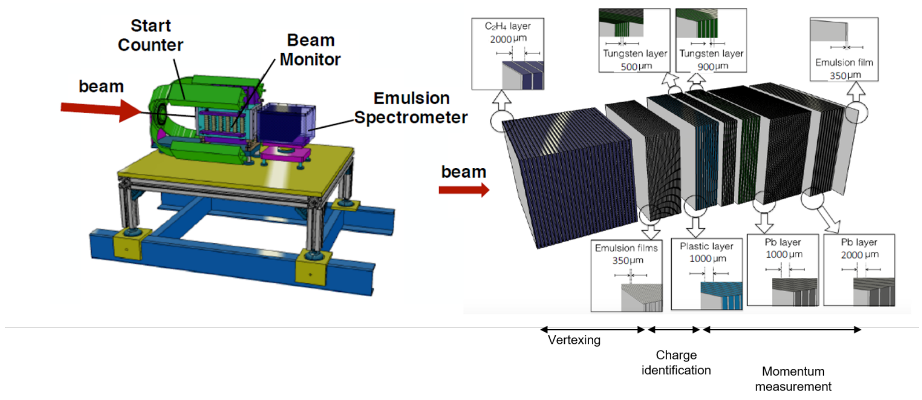

Figure 1: Schematic view of the emulsion setup with details of the emulsion spectrometer

2.2 Electronic setup

The FOOT electronic spectrometer has been designed to detect the fragments with Z ≥ 3 and with an angular acceptance up to about 10°. The layout can be divided in three parts:

- *Upstream region*: it is the region before the target, composed of a plastic scintillator and a drift chamber, called Start Counter (SC) and Beam Monitor (BM), respectively. These detectors are used in the event trigger system, in order to provide the "start signal" for the Time Of Flight (TOF) measurement, necessary for the measurement of the fragments velocity, and to reconstruct the incoming primary particle trajectory.
- *Magnetic Spectrometer region*: it is composed by two permanent magnets and a set of silicon tracking detectors placed beyond the target: Vertex (VTX) detector, Inner Tracker (ITR) and Micro Strip Detector (MSD). This region aims to reconstruct the tracks and momenta of the fragments.
- *Downstream region*: it is composed of a plastic scintillator called Tof-Wall (TW) and a Calorimeter (CAL). The former provides the fragment energy loss dE/dx and the "stop" of the TOF, the latter measures the kinetic energy of charged fragments.

3. Calorimeter

The calorimeter is composed of 320 truncated pyramid shape BGO crystals, 240 mm long with a front face of 20×20 mm^2 and a rear face of 30×30 mm^2, grouped in 3x3 modules. Modules are then deployed in a square shape centered on the experiment beam axis. The combination of BGO high density (ρ = 7.13 g/cm^3) and high atomic number (A$_{Bi}$ = 83) results in a high stopping power, which makes BGO an ideal material to measure fragments kinetic energy. Each crystal is coupled with an array of Silicon Photon Multipliers (SiPMs), which eliminate the need for high voltage and allow a compact design, to collect the scintillation light emitted by particles during the ionization process. Signals produced by each array are summed and the resulting pulse is sampled

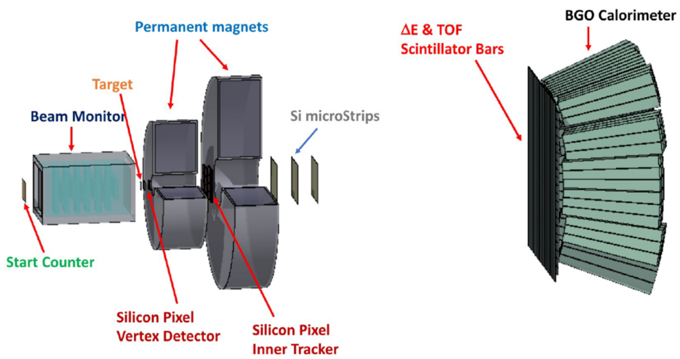

Figure 2: Schematic view of the electronic setup. From left to right: Upstream region, Magnetic Spectrometer region, Downstream region.

by a digitizer module to allow advanced pulse-shape analysis. After several optimization test runs performed at CNAO (Pavia, Italy) the final design had been defined. This results in a SiPM tile geometry which features a 5x5 square array with 22x23 mm^2 dimension. Microcells have a pitch of 15 μm which, after multiple tests, confirmed to avoid saturation up to energies of 800 MeV/u. A custom readout board was designed to match the tile size, while the crystals were enveloped in a Tyvek reflective sheet to maximize the light yield.

4. Calibration

In order to calibrate and study strategies for crystal equalization two beam tests have been conducted at HIT (Heidelberg, Germany), and at CNAO (Pavia, Italy) with a partially assembled calorimeter.

4.1 Crystal response study

The crystal response was measured with different ions (p, He, C, O) in an energy range from 50 MeV/u to 430 MeV/u. The setup consisted of a single full assembled module without other detectors along the beam line. The beam was focused on the central crystal while the lateral ones were used as veto in order to remove events with energy deposition in more than one crystal. Figure 3 shows the energy resolution as a function of the beam energy for the central crystal: its value, being well below the 2% threshold, is consistent with the design requirement. During the same campaign, the crystal energy response curve has been measured. Figure 4 shows that its linearity is affected by the Birks effect [4]

$$\frac{\mathrm{d}S}{\mathrm{d}x} = \frac{A\frac{\mathrm{d}E}{\mathrm{d}x}}{1 + KB\frac{\mathrm{d}E}{\mathrm{d}x}}$$

which introduces a strong dependence on the particle charge. In order to fit the response curve, a three-parameter modified Birks function has been used

$$ADC(E) = \frac{P_0 E^2}{1 + P_1 E + P_2 E^2}$$

where E is the beam energy and ADC the readout value. The parameters are different for each ions but overall a very good approximation of the collected data is achieved. To address the Z dependence it is possible to observe a negative exponential trends between the function parameters and the ion charge. Each of these trends, as shown in Figure 5, has been normalized to a reference ion (in this case carbon) and is described by the function:

$$\frac{P_x}{P_{x,ion}} = a_0 + a_1 e^{\frac{-Z}{a_2}}$$

that allows to extract the Birks parameters for any possible ion by knowing its charge Z, which is measured by the FOOT Time of Flight detector (ToF). In this way, it is possible to equalize the ADC response for different ions as shown in Figure 6

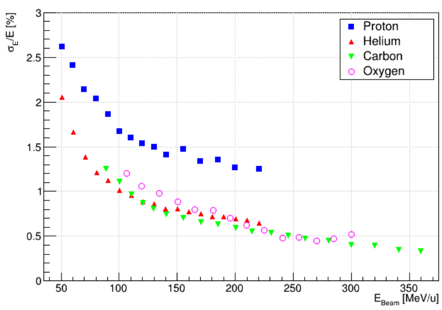

Figure 3: Energy resolution versus beam energy evaluated with HIT test beam data.

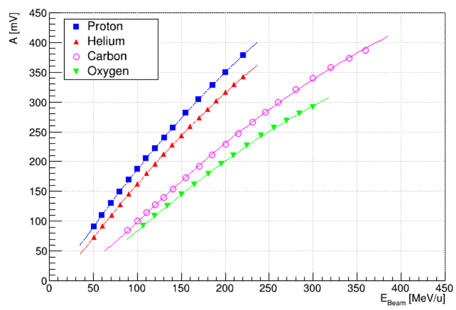

Figure 4: Amplitude response versus beam energy measured with HIT test beam data with “Modified-Birks” fit

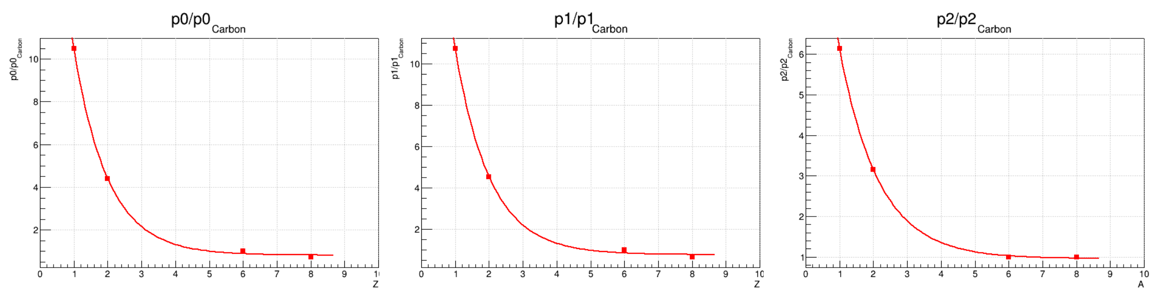

Figure 5: Ratio between “Modified-Birks” parameters of HIT measured particles and reference ion (Carbon)

4.2 Equalization study

The modified Birks function is also a powerful tool to perform the crystals equalization. At CNAO, two different strategies have been tested using data collected with 12 fully assembled modules. The first one relied on the definition of single equalization factor while the second one on the direct calibration of the crystals. Both methods are possible thanks to the efforts of the CNAO accelerator team which developed a new kind of beam delivering routine. By modifying the amount of current in the scanning magnet, the beam was able to sweep all the installed crystals following

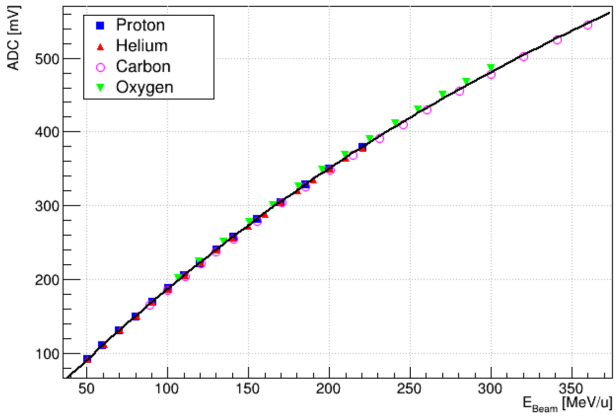

Figure 6: Energy amplitude response distribution after ions equalization has been applied.

a line-by-line path. This procedure significantly decreases the amount of time needed to collect enough statistics on all the interested crystals (from days to hours) with respect to re-centering the beam on each crystal individually. These premises allow the collection of multiple C energy points (115 MeV/u, 200 MeV/u and 300 MeV/u) which are then used to calculate the parameters of the Birks function for each crystal.

- *Single factor equalization*: This equalization strategy revolves around the definition of a reference crystal which is fitted with the modified Birks function. Parameters P_1 and P_2 evaluated in this way are subsequently used as fixed parameter in fitting all the other crystals. The ratio between P_0 of the reference crystal and P_0 of all the other crystals is the chosen intercalibration factor and it is used to scale the amplitude value collected in the beam test accordingly.

- *Direct calibration*: This equalization strategy directly use collected energy point to perform a modified Birks function fit on all the crystals. Parameters evaluated in this way are then used in the inverse modified Birks function to retrieve the corresponding value.

4.3 Calorimeter Resolution

In order to test the performance of the intercalibration strategies, the amplitude and energy distributions for the full calorimeter have been calculated. Figure 7 shows six distributions, one for each energy point and strategy. Each distribution is obtained as the sum of all the single crystals corresponding distributions after the chosen equalization strategy is applied. By fitting these distributions with a crystalball function, it is possible to obtain the overall resolution of the detector. Resolution values obtained from the amplitude distribution can be compared with those obtained from energy spectra, amplitude - energy conversion performed with the modified Birks function virtually conserve this quantity. The results show that direct calibration achieves better resolutions: for 115 MeV/u C resolution improves from 1.95% to 1.01%, for 200 MeV/u C resolution improves from 1.75% to 1.16% and for 300 MeV/u C resolution improves from 2.39% to 1.40%. Direct calibration satisfy the experimental resolution requirement.

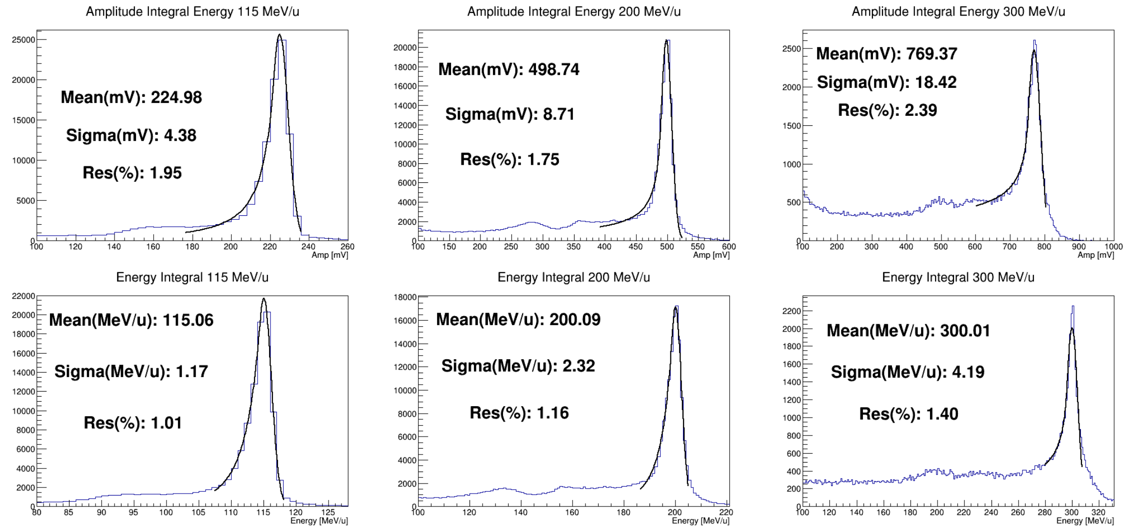

Figure 7: Integral amplitude (top) and energy (bottom) distribution measured at CNAO for carbon. Resolution values are reported in each histogram.

5. Conclusion

The results of beam tests at CNAO and HIT were crucial for finalizing the beam delivery needed to perform the FOOT calorimeter calibration. The use of the line-by-line sweep significantly reduced the amount of time required for calibration, which is then repeated for each data acquisition campaign. Having achieved a detector resolution better than expected and developed a strategy to accurately measure the particles kinetic energy, the team will now focus on mass measurement, by combining the TOF and energy measurements.

References

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