Equalizing the response of the FOOT calorimeter as a function of the ion energy and charge

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Abstract.
The precision of clinical treatment planning systems for particle therapy is limited (among other reasons) by the absence of measurements on the differential fragmentation cross sections generated during interactions between light ions (such as C and O) and hydrogen-enriched targets. To address this issue, the FOOT experiment has been designed to take data for beam energies up to 400 MeV/u using an inverse kinematics approach. By extending the energy range to 800 MeV/u, FOOT will also collect valuable data to optimize the design of spacecraft shielding [1]. The experiment aims at identifying fragments by measuring their momentum, kinetic energy, and time of flight with high resolution: 5%, 2% and <100 ps respectively. A calorimeter detector made of 320 BGO crystals coupled to SiPM photodetectors, covering a dynamic range from tens of MeVs to about 10 GeV, measures the kinetic energy. A series of data taking campaigns aiming at characterizing, optimizing and equalizing the crystals response have been conducted at HIT (Heidelberg, Germany) and CNAO (Pavia, Italy). The measurements confirm an integral energy resolution well below the goal of 2%. The modified Birks-energy-response-function shows an excellent agreement with the response of the crystals between 50 and 430 MeV/u for all the ions, although a dependence of the parameters on Z is observed. In this work, the equalization strategy needed to properly measure the fragments kinetic energy and masses in combination with the ToF detectors will be presented.

1 Introduction

The growing number of cancer patients treated with Charged Particle Therapy (CPT) [2] demonstrates its effectiveness, especially for deep-seated solid tumors. Charged hadrons deposit most of their energy in the Bragg Peak—a narrow region at the end of their range—thereby minimizing damage to healthy tissues. However, CPT faces challenges related to a lack of information about the cross sections of fragments produced by beam-tissue nuclear interactions in the entrance channel, which affects the precision of clinical treatment planning systems. Fragmentation Of Target (FOOT) is a nuclear physics experiment that measures fragmentation cross sections induced by carbon beams on hydrogen-enriched/carbon targets, using an inverse kinematics approach [3]. Fragment identification is achieved by measuring their momentum, energy, and time of flight with resolutions of 5%, 2%, and less than 100 ps, respectively. The final goal is to achieve charge and mass identification at 2% and 5% accuracy enabling the calculation of fragmentation cross sections with a precision better than 5% [3].

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2 Calorimeter: Performance and Calibration

The calorimeter is composed of 320 truncated pyramid shape BGO crystals, 240 mm long with a front face of 20x20 mm^2 and a rear face of 30x30 mm^2, grouped in 3x3 modules. Modules are then deployed in a square shape centered on the experiment beam axis. BGO is an ideal material to measure the fragments kinetic energy thanks to its high density (ρ = 7.13 g/cm^3) and high atomic number (A_{Bi} = 83) which results in high stopping power. Crystals are coupled with an array of Silicon Photon Multipliers (SiPMs) each, which allow a compact design. Signals produced by each array are summed and the resulting pulse is sampled by a digitizer module to allow advanced pulse-shape analysis. The final design has been defined thanks to several optimization test runs performed at CNAO (Pavia, Italy) resulting in a SiPM tile geometry which features a 5x5 square array with 22x23 mm^2 dimension. To avoid saturation, microcells with a pitch of 15 μm were chosen, extending the energy range up to 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]. The crystal response was measured with different ions (p, He, C, O) at HIT (Heidelberg, Germany). Fig. 1 shows the energy resolution as a function of the beam energy for one crystal, proving consistency with the design requirement. During the same campaign, the crystal energy response curve has been measured and the calibration has been performed using the same four low-intensity-ion-beams (104 Hz) with energy ranging from 50 and 430 MeV/u. Fig. 2 shows the amplitude (mV) measured by the readout chain during the calibration runs. The four different sets of points obtained can be described by the same calibration function that is referred as "Modified-Birks function" (MBF):

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

where E is the beam energy and A the amplitude readout value, which depends on three parameters (P_0, P_1, P_2) that are different per different ions. A strong dependence on the particle charge can be seen due to the Birks effect [5]. To equalize the ions response, and intercalibrate all the crystals, a strategy based on a fit with a modified Birks function has been developed.

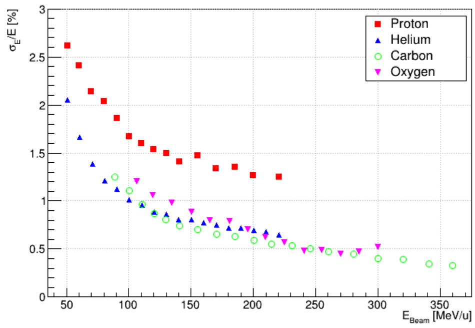

Figure 1. Energy resolution versus beam energy evaluated with HIT test beam data.

3 Intercalibration Strategy

The MBF is also a good function to perform crystals intercalibration and measure the overall resolution of the detector. Thanks to the support of the CNAO accelerator team it was possible to develop a different kind of beam delivering routine: by modifying the current in the scanning magnet, the beam was able to sweep all the installed crystals following a line-by-line path. This procedure significantly reduces the time needed to collect enough statistics on all the crystals (from days to hours) with respect to re-centering the beam on each crystal individually. The collection of multiple energy points, provides MBF for each crystal. To evaluate the resolution of the whole detector, the parameters obtained during these runs were employed to convert the SiPMs' responses into energy values. Fig. 3 shows the integral energy distribution of the calorimeter: each histogram represents the sum of all the single crystals energy measurements after the inverse MBF has been applied. By fitting these distributions with a Crystal Ball function, it is possible to obtain the overall resolution of the detector for each energy, which is well below the 2% design threshold, as shown in Fig. 4.

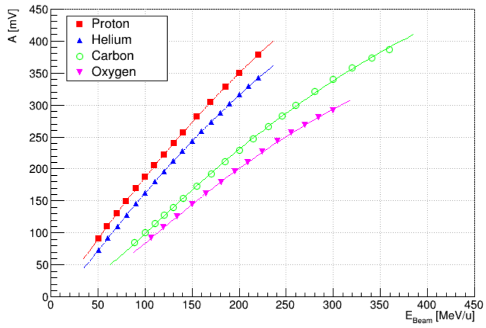

Figure 2. Amplitude response versus beam energy measured with HIT test beam data with MBF fit.

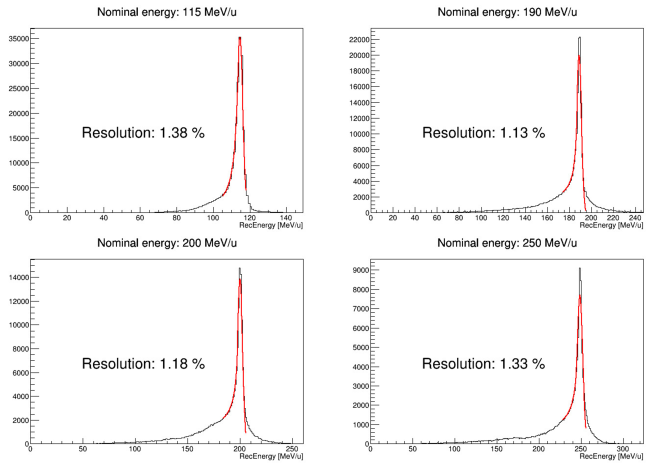

Figure 3. Integral energy distribution measured at CNAO for C after calibration with MBF. Resolution values are reported in each histogram.

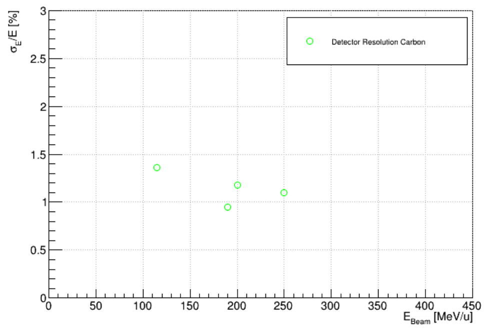

Figure 4. Total energy resolution of the calorimeter for C ions measured at CNAO test beam.

3.1 Charge Number Dependace

Although MBF is a very good calibration function, its strong dependence on the fragment charge requires calibration measurements using all ions from H to O to correctly evaluate its parameters. However, as shown in Fig. 5, it is possible to observe three negative power law trends between the function parameters and the ion charge.

Each parameter has been normalized to the corresponding parameter of the reference ion (in this case C) and can be described by the function:

$$\frac{P_x}{P_{x,C}} = a_0 e^{\frac{-Z}{a_1}} \quad (2)$$

enabling us to calculate the MBF parameters for any possible ion or fragments by knowing its charge Z, which is measured by the FOOT Time of Flight detector (ToF) [6].

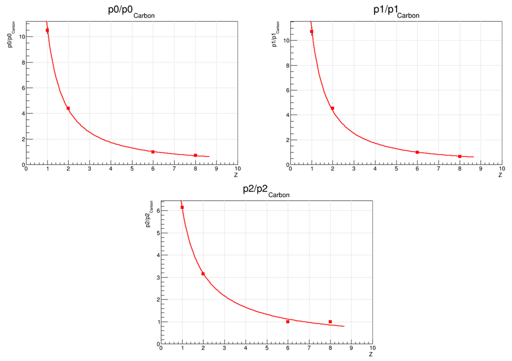

Figure 5. Ratio between MBF parameters of HIT measured particles and reference ion (C).

3.2 Ion Equalization Response

In order to test the performance of this ion-response-equalization strategy the p, He and O calibration point series have been reconstructed using (2) and the MBF parameter calculated from the C calibration point. Using the appropriate charge number (1, 2, 8), the parameters P_0, P_1, P_2, have been evaluated from (2) and used to extrapolate the amplitude values at HIT beam energies. Fig. 6 shows the comparison between measured and reconstructed point series. The equalization strategy shows good performance using four ions, however, due to constraints on beam time at HIT, performing a full detector calibration was not possible. CNAO, on the other hand, allows for longer data acquisition campaign but only provides H and C ions beam so it is important to verify how the equalization strategy performs in this conditions. Fig. 7 shows the power law function calculated with CNAO constraints while Fig. 8 shows the reconstructed point series with the new power law function. A slight worsening in the O reconstruction performance is observed and must be investigated.

4 Conclusion

The results of beam tests at CNAO and HIT were essential in finalizing the strategy for calibrating the FOOT calorimeter. Implementing the line-by-line sweep method significantly reduced the time required for calibration. Having achieved a detector resolution better than design requirement and found a strategy to correctly evaluate the crystal response as a function of the energy, the next step is now to conduct a full detector calibration which is necessary to perform fragments mass measurement in combination with ToF.

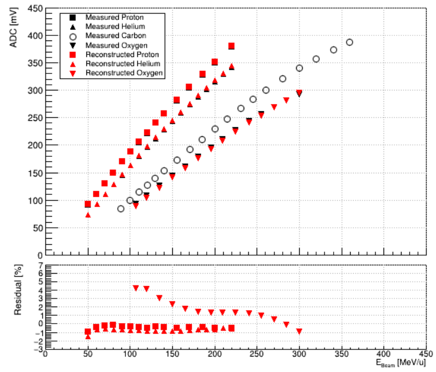

Figure 6. Comparison between reconstructed HIT points using power laws from Fig. 5 and measured points. Residuals are reported below.

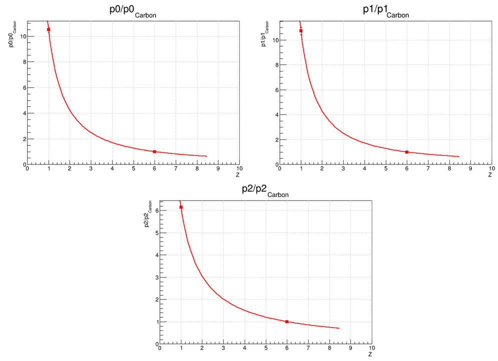

Figure 7. Ratio between MBF parameters of HIT measured particles and reference ion (C) using only p and C.

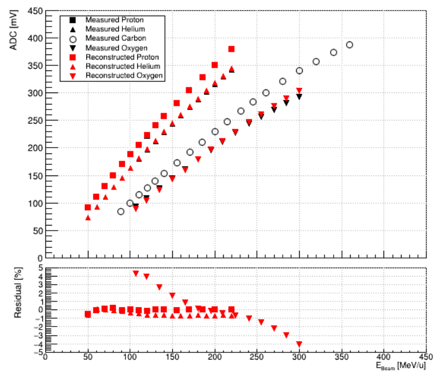

Figure 8. Comparison between reconstructed HIT points using power laws from Fig. 7 and measured points. Residuals are reported below.

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