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

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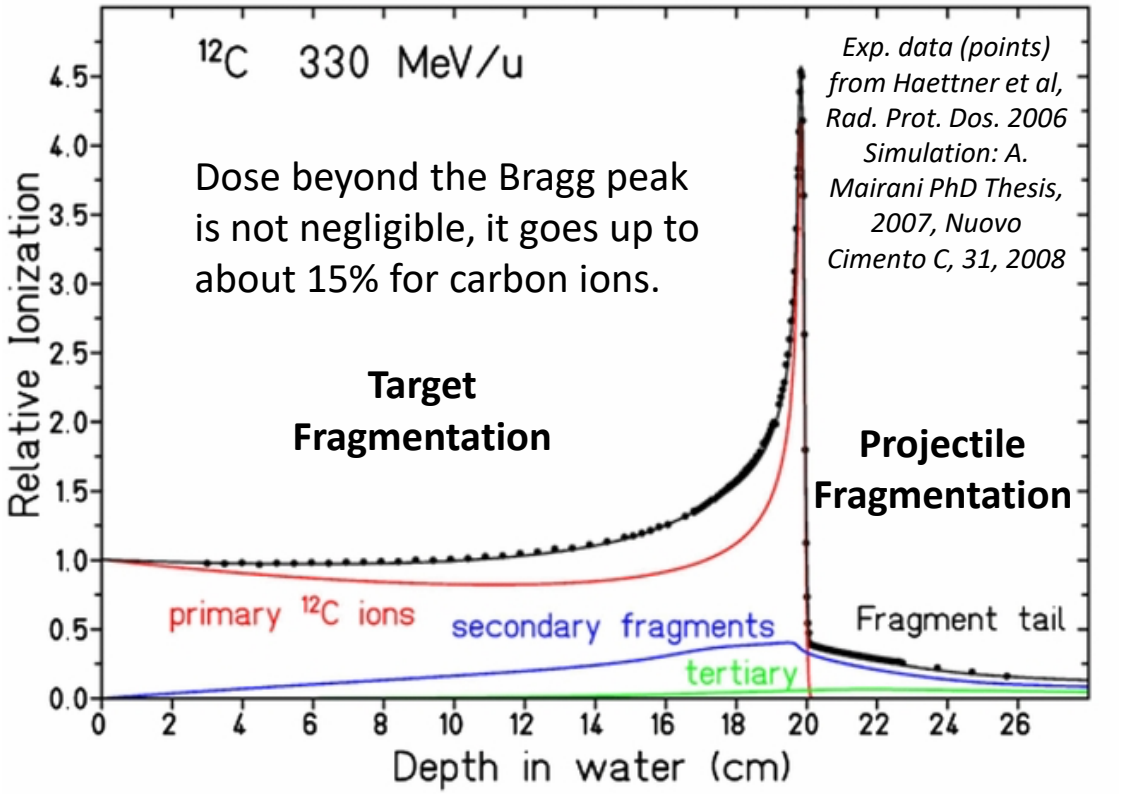
On behalf of the FOOT collaboration

The FOOT experiment

FOOT is an applied nuclear physics experiment that aims at measuring the fragmentation cross-section for ions and energies of interest for hadron therapy and radioprotection in space

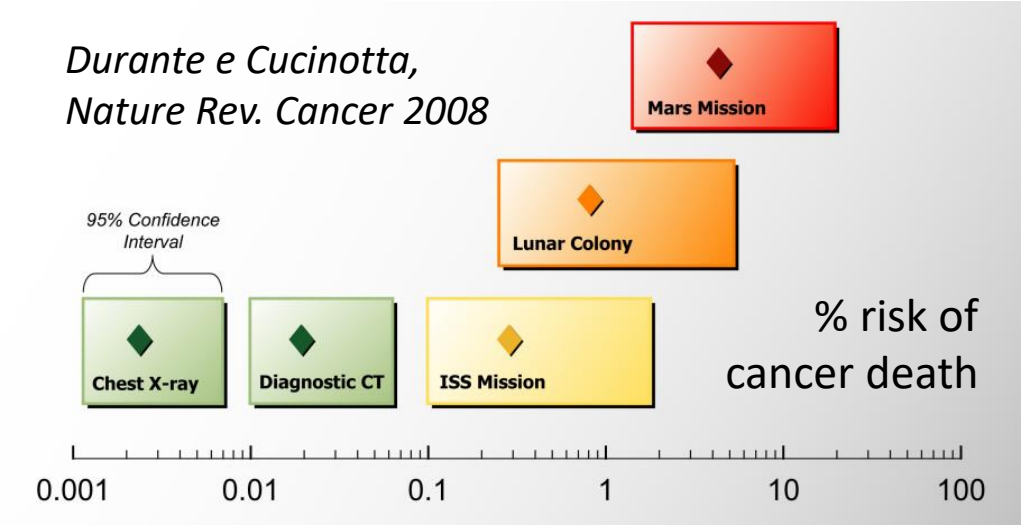


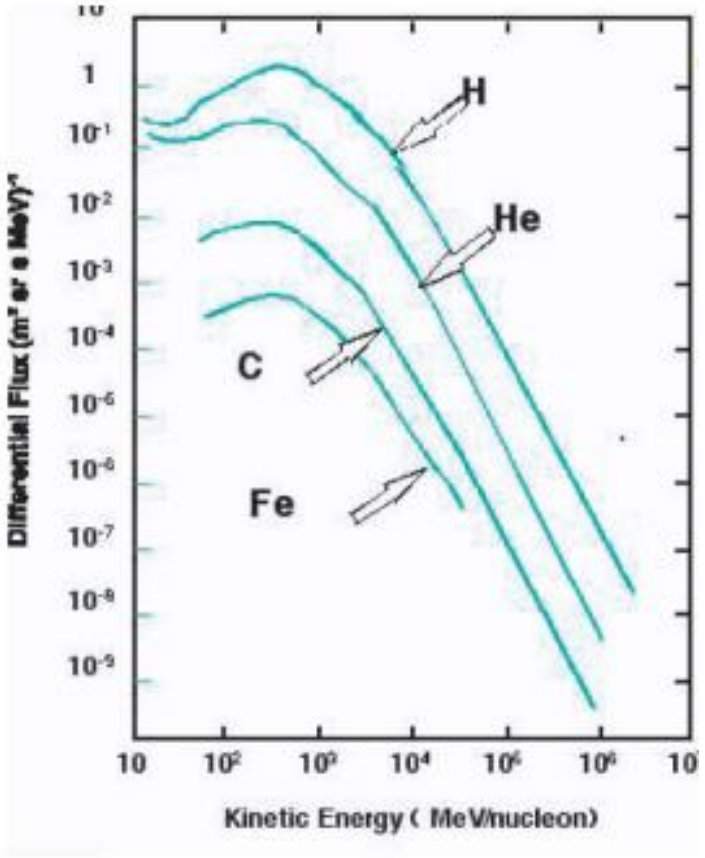
- **Target fragmentation** causes the generation of ions in the entrance channel with very low range and high RBE
- **Projectile fragmentation** causes the generation of ions that may travel beyond the Bragg peak, irradiating healthy tissues

A full knowledge of differential and double differential cross section measurements (in angle and kinetic energy), for light targets and projectiles is still missing.

The FOOT experiment

- **Solar particle events**: protons (GeV)
- **Galactic cosmic rays**: mainly high energy protons and Helium nuclei (MeV-TeV)
- **Geomagnetically trapped particles**: protons (hundreds of MeV) and e (hundreds of keV)





Galactic cosmic rays

- 87% protons
- 12% helium
- 1% heavier ions

~1 mSv/day

As a reference:

- 1 chest X-ray – 0.1 mSv
- 1 brain CT – 1.6 mSv

Need for optimal shielding and accurate modeling of their interactions with particles.

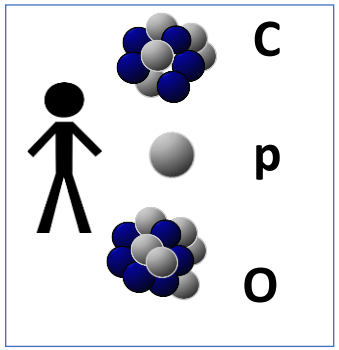
FOOT expected measurements

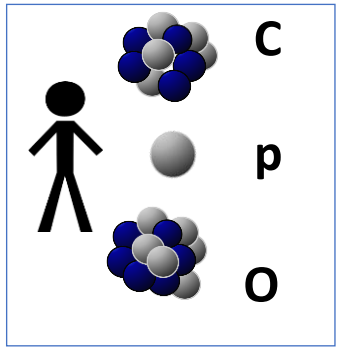
Projectile **Target**

p → Proton therapy (up to 200 MeV)

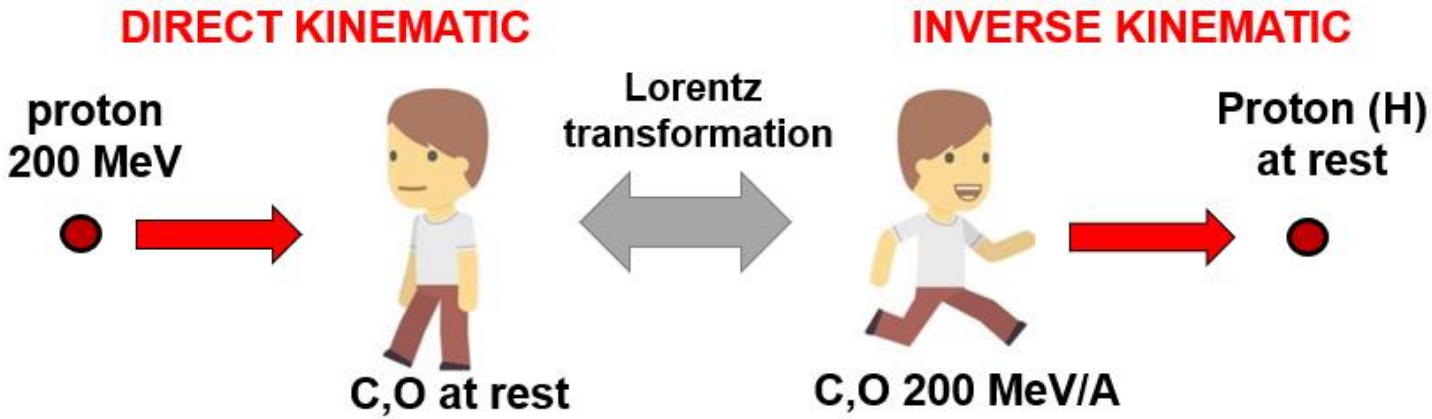
C → Carbon therapy (up to 400 MeV/u)

Space (~800 MeV)





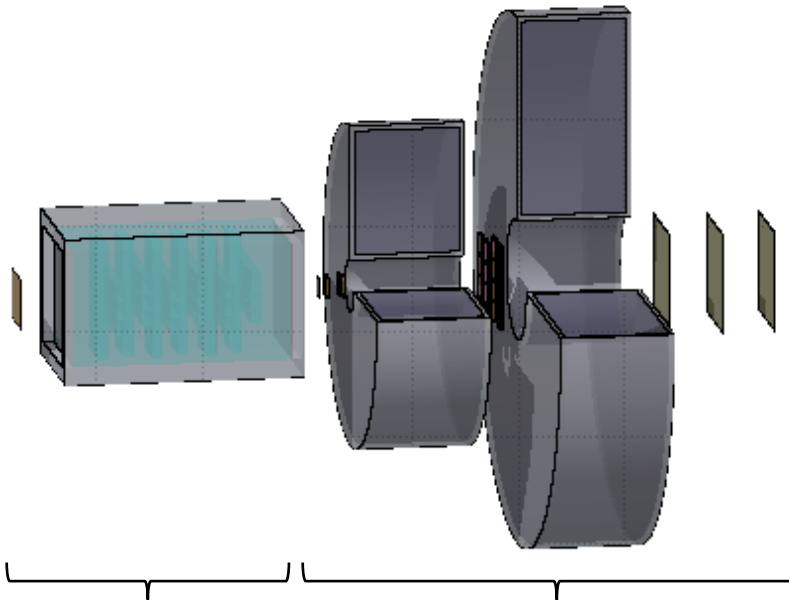
In the case of a proton projectile, the target fragmentation can be studied using an inverse kinematic approach, so to have fragments with high kinetic energy.



Thin targets (few mm) of C and C_2H_4, PMMA

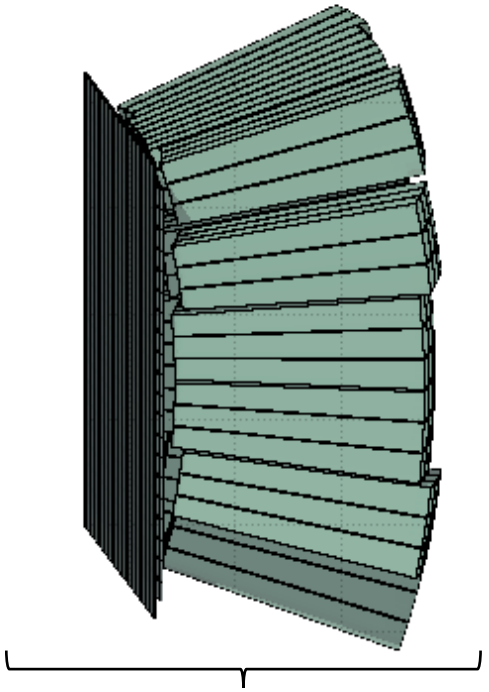
$$\frac{d\sigma}{dE_{kin}}(H) = \frac{1}{4}\left(\frac{d\sigma}{dE_{kin}}(C_2H_4) - 2\frac{d\sigma}{dE_{kin}}(C)\right)$$

The Electronic set-up



Upstream region

Tracking region



Downstream region

~ 2 meters

- ~10° angular acceptance
- Mainly focused on heavier ions (Z > 2)
- 1 kHz acquisition event rate
- Usable in different accelerator facilities (CNAO, GSI, HIT)
- A, Z, θ, E identification of each fragment

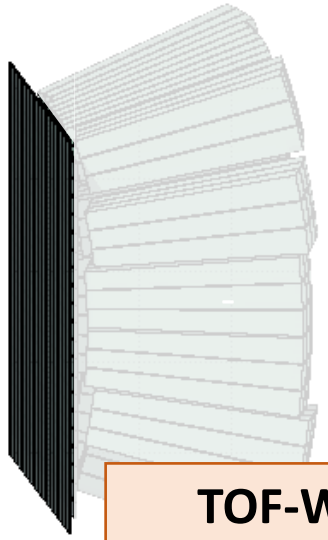
The TOF apparatus

START COUNTER

EJ-228 plastic scintillator layer of 250 μm thickness with 4 x 4 cm^2 active area read out by 8 groups of 6 SiPMs connected in series.

Requirements:

- Time resolution σ < 100 ps
- Energy resolution σ/μ ~5% (depending on the fragment energy)



Charge of the fragment reconstructed using the Bethe-Bloch equation:

$$\left\langle \frac{dE}{dx} \right\rangle_{coll} = K \frac{\rho_t Z_t}{A_t} \frac{Z^2}{\beta^2} \left[\frac{1}{2} \log \left(\frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I_t^2} \right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right]$$

dE/dx from TOF-WALL

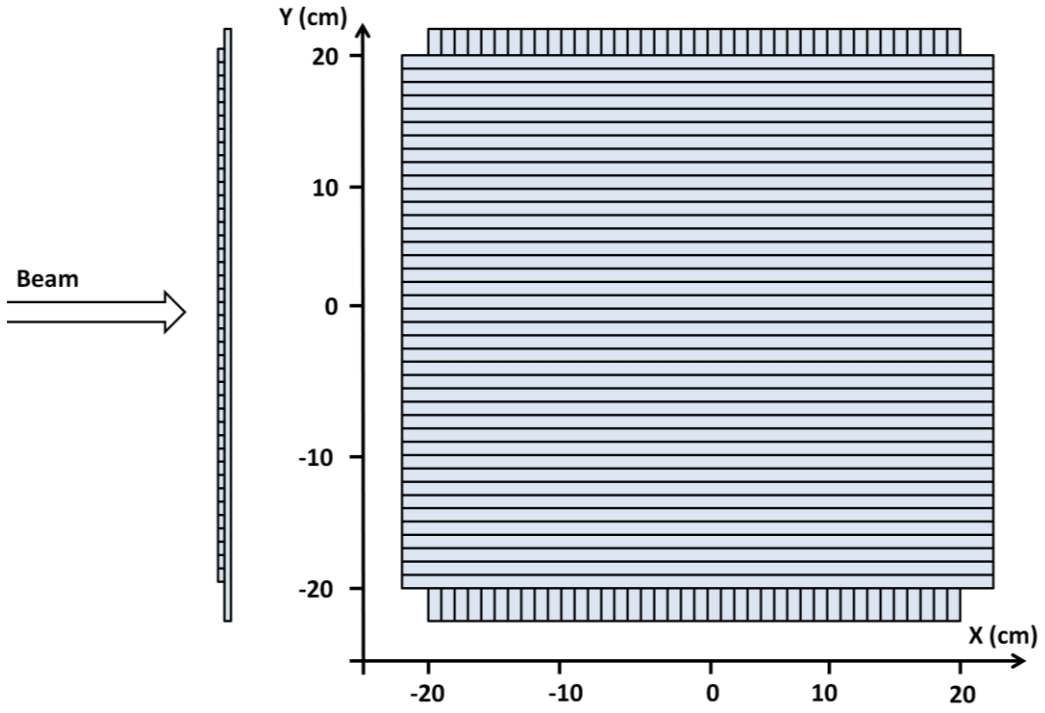
TOF

TOF-WALL DETECTOR

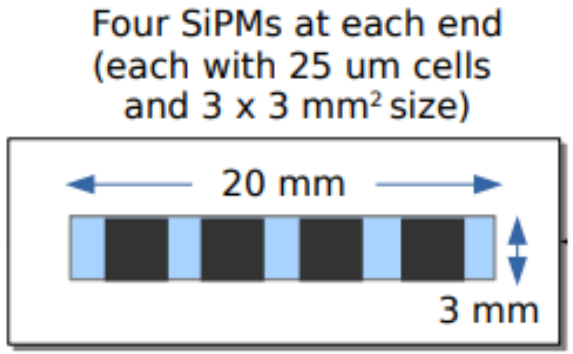
Two layers of EJ-200 plastic scintillator bars arranged orthogonally.

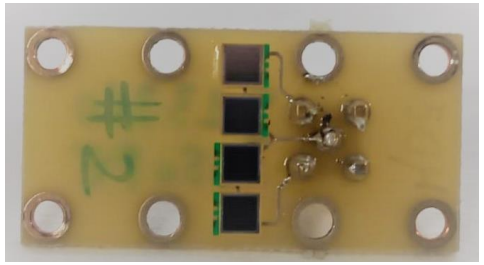
The TOF-Wall detector

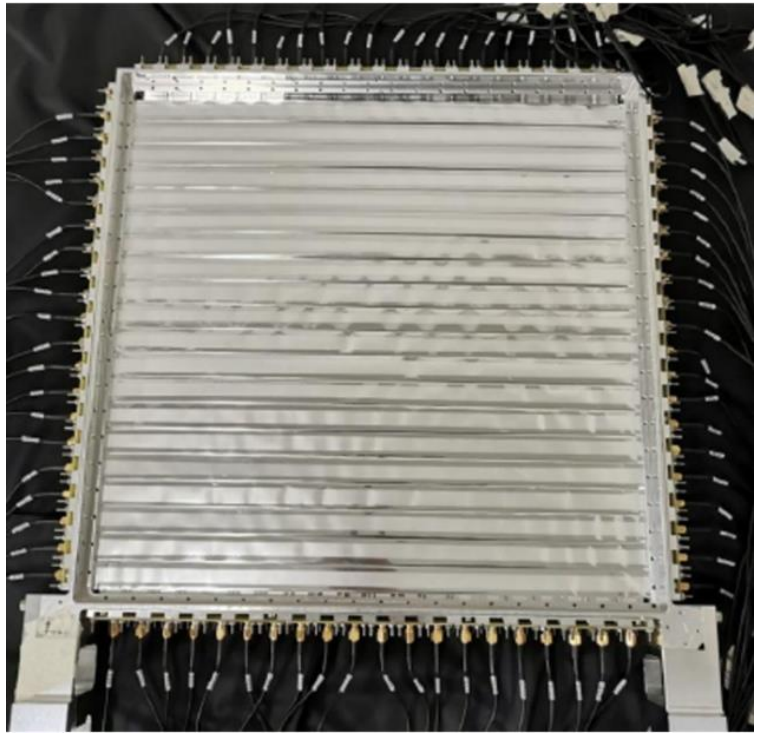
Composed of 20 + 20 plastic scintillating bars
Each one with size 440 mm x 20 mm x 3 mm



- Active area of 40 x 40 cm^2
- 80 analog channels



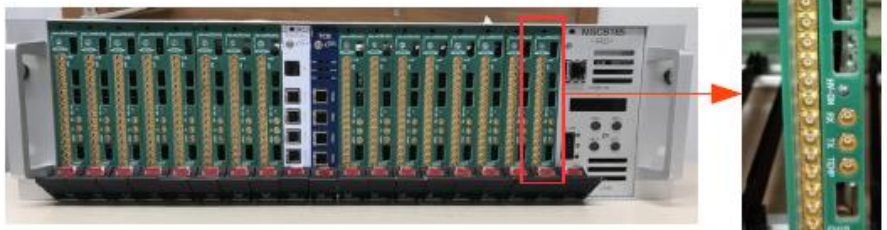




Data acquisition and analysis

The signals are acquired and digitized with DRS4 using the WaveDAQ system

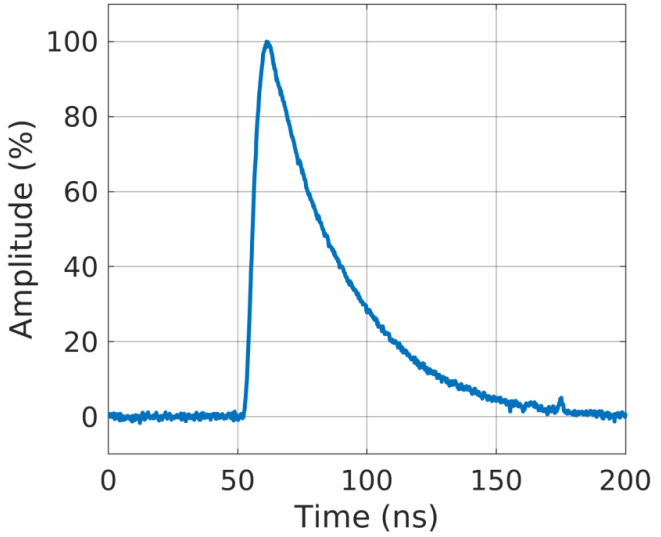
* L. Galli et al., WaveDAQ: An highly integrated trigger and data acquisition system, NIM-A 2018



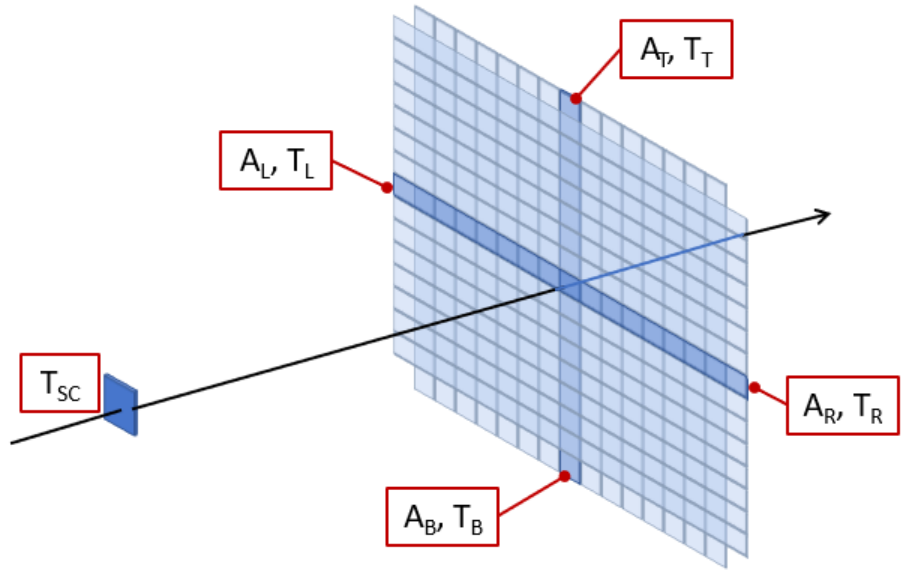
Bias, trigger & DAQ
WaveDAQ (PSI & INFN)

More on WaveDAQ in Ritt et al., Poster ID 6

More on FOOT trigger in Galli et al., Poster ID 49



Waveforms of both start counter and triggered channels of TOF-Wall are stored and analyzed off-line



$$T_H = \frac{T_L + T_R}{2} \qquad T_{TW} = \frac{T_H + T_V}{2}$$

$$T_V = \frac{T_B + T_T}{2} \qquad TOF = T_{TW} - T_{SC}$$

Measurement set-up

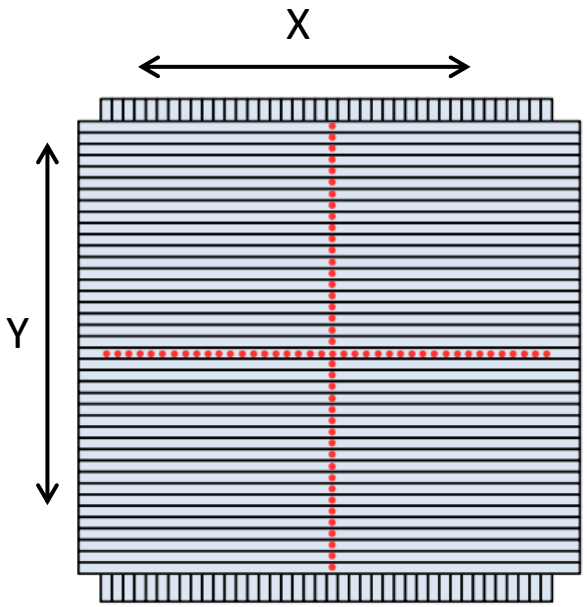
GOALS
Time and energy resolution
Uniformity of the response
Z reconstruction capability

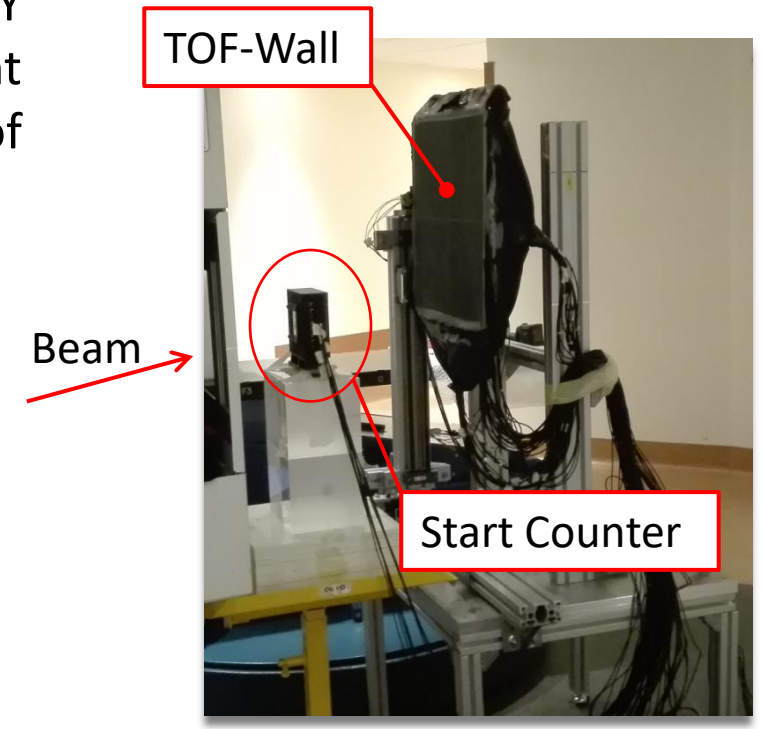
Data taken at:

Centro Nazionale di Adroterapia Oncologica (CNAO - Pavia, IT)

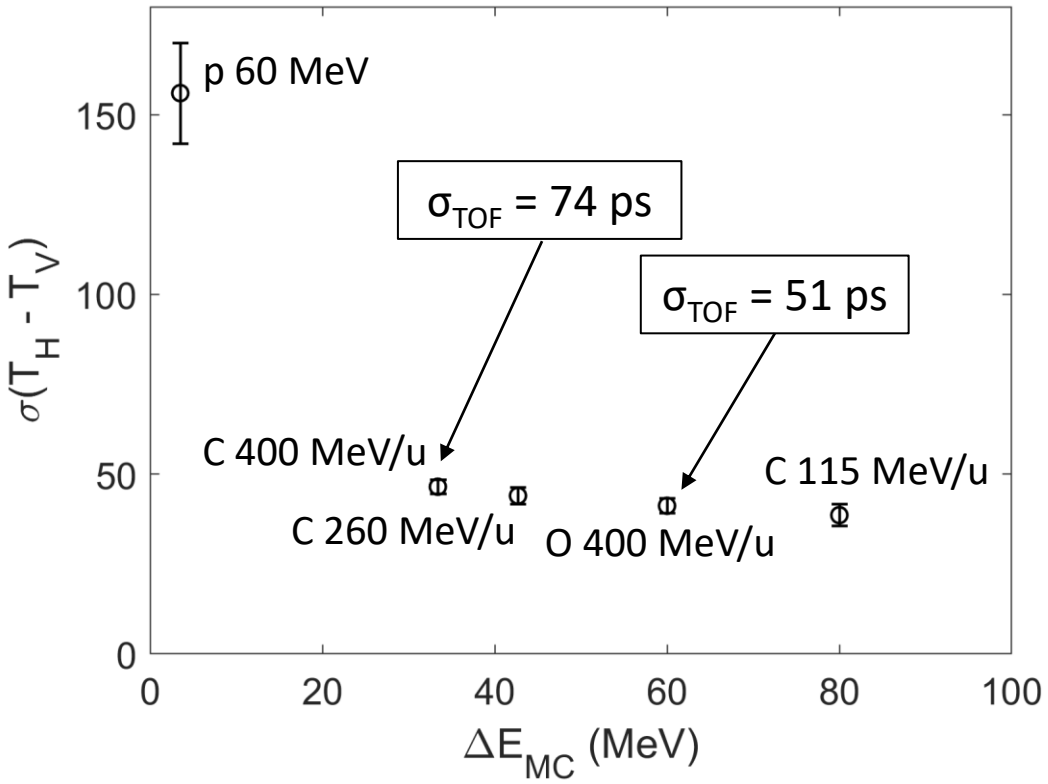
Helmholtzzentrum für Schwerionenforschung (GSI – Darmstadt - DE)

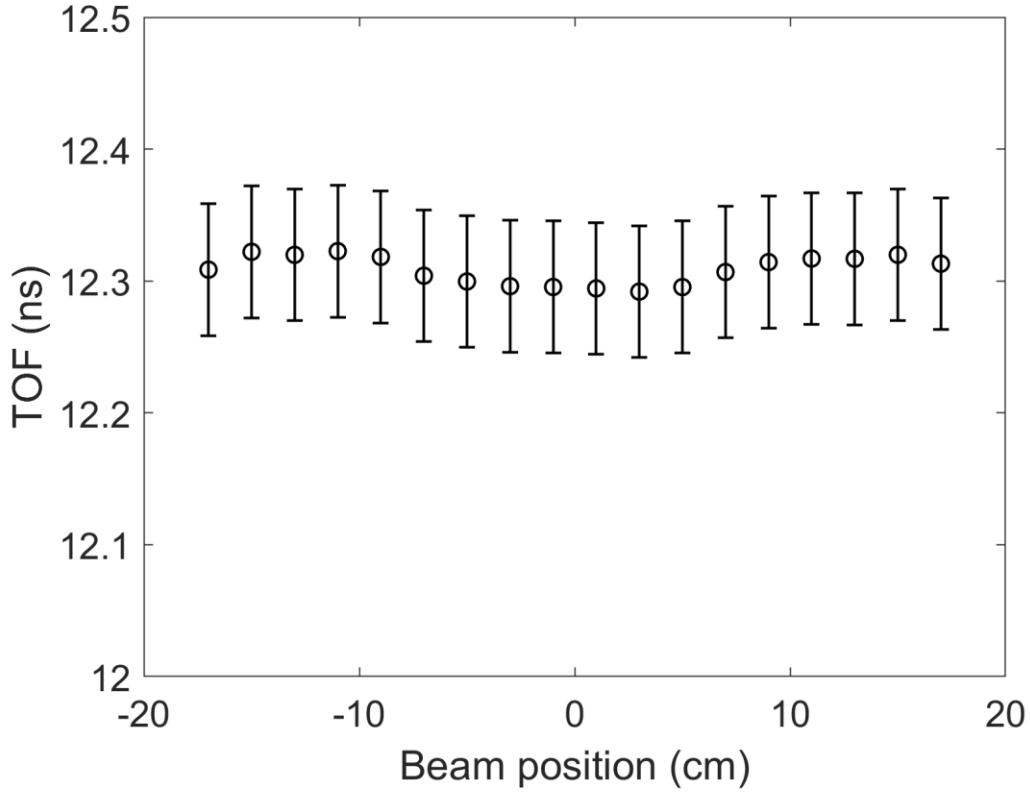
The TOF-Wall was moved on X and Y directions in order to irradiate different parts of the detector with beams of proton, carbon, oxygen





TOF-Wall - Time resolution



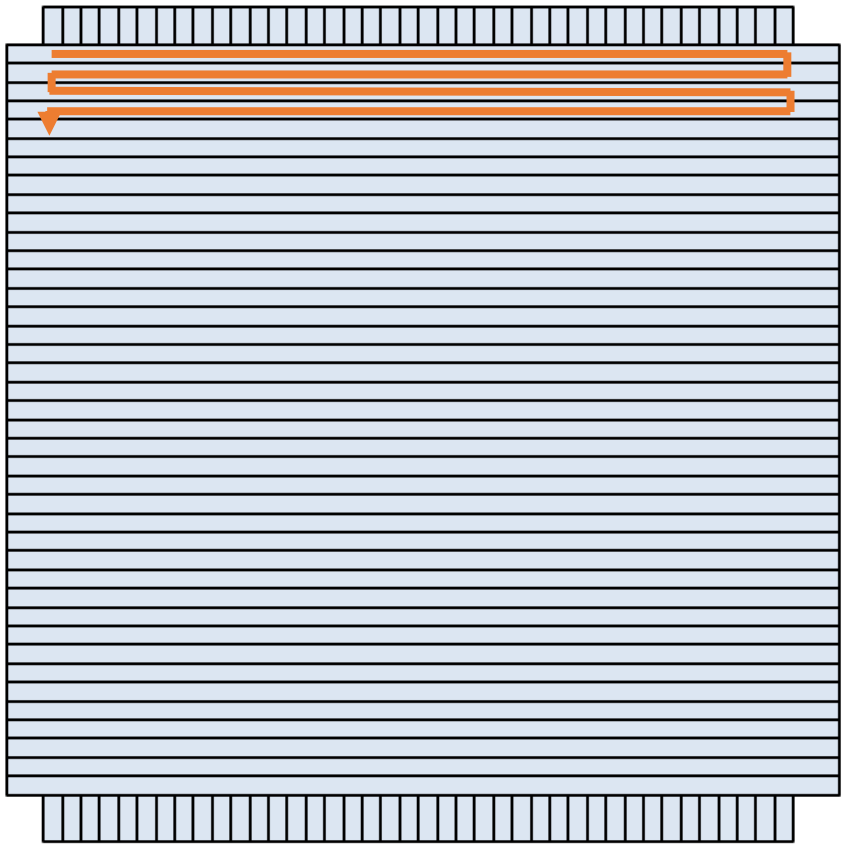


TOF-Wall time resolution is half of the reported value, since the timestamp is the average of T_H and T_V

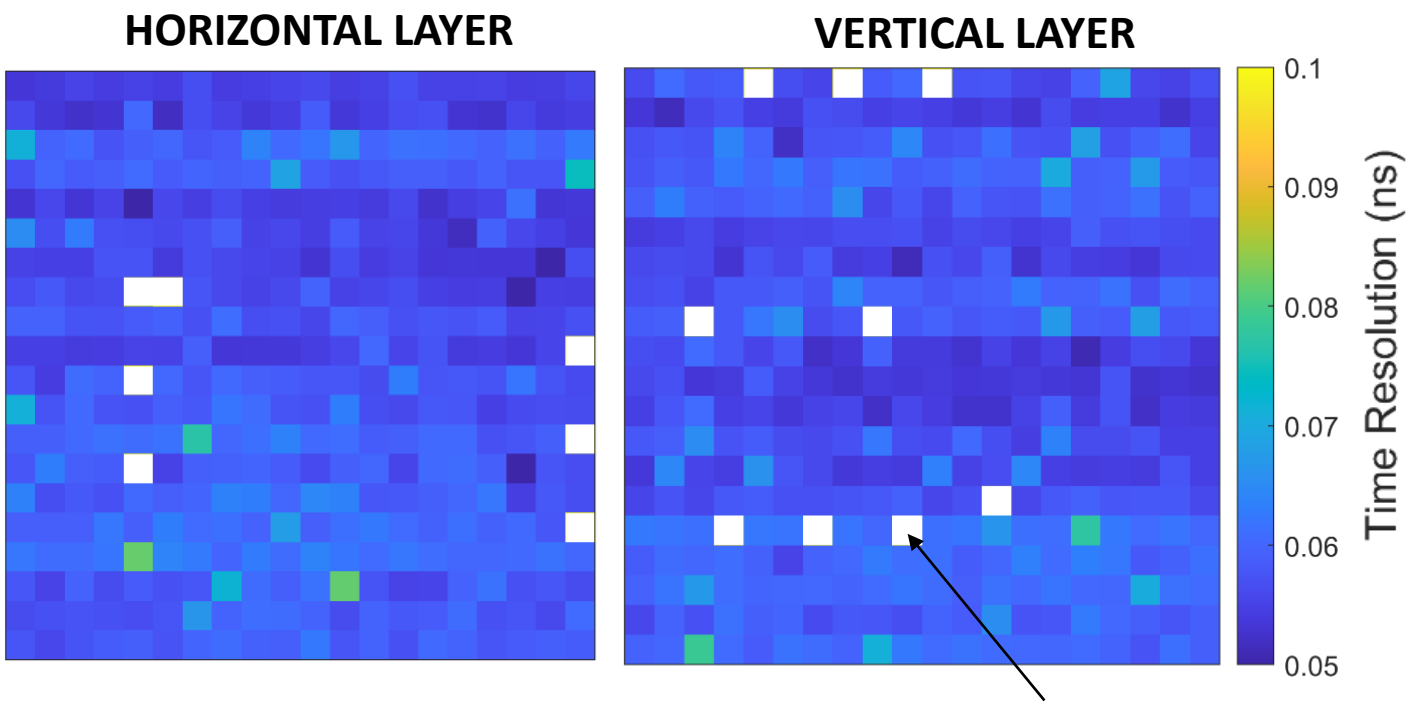
Time response is uniform along the bar within the resolution of the detector

TOF resolution uniformity

Full scan of the active area of the detector using 400 MeV/u oxygen beam



TOF resolution is uniform in the whole area of the detector



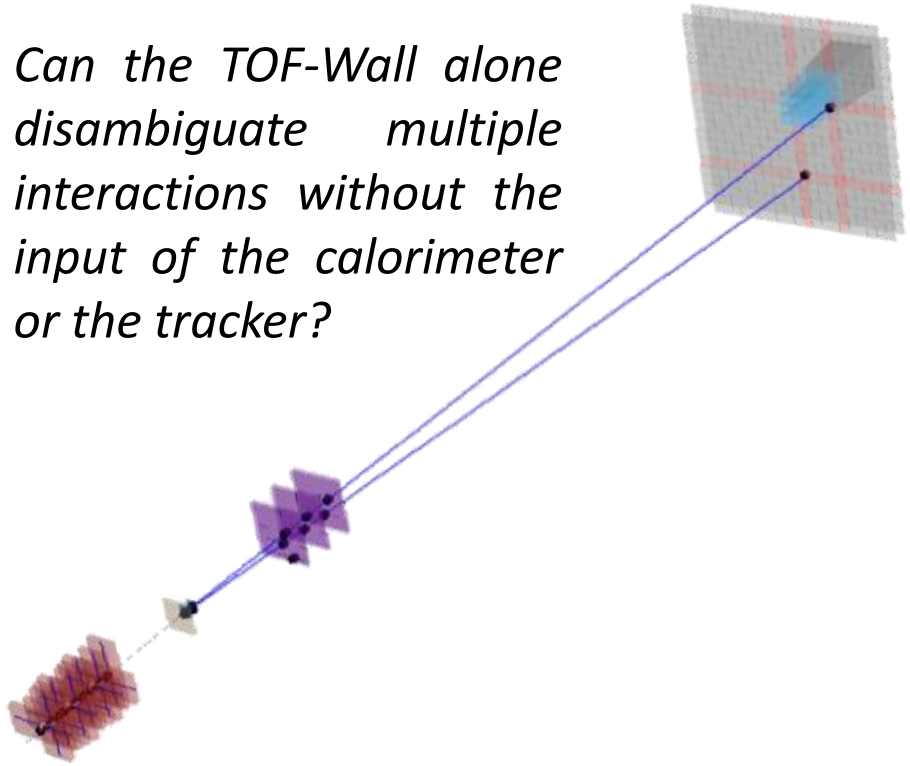
TOF resolution obtained with a single layer in coincidence with the Start Counter detector.

Some positions have low statistics due to the beam duty cycle

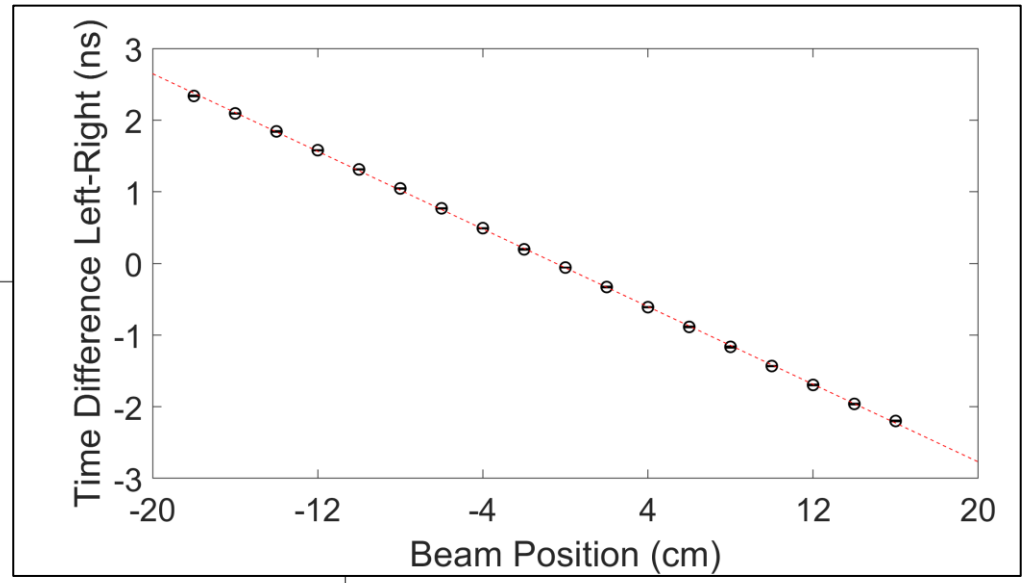
Interaction position determination

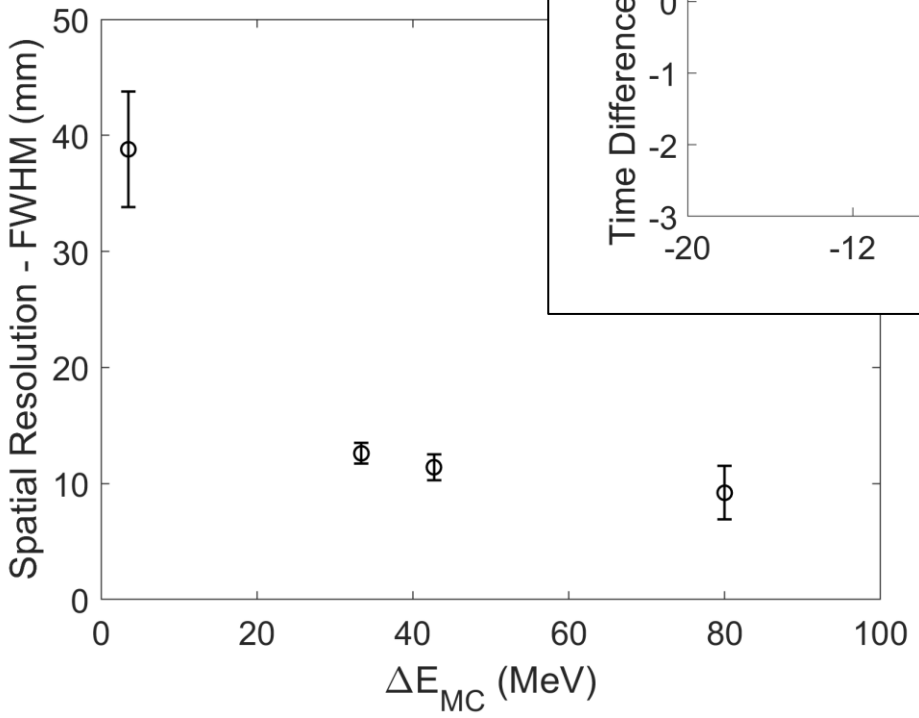
Need to identify the interaction position of each fragment in case of multiple interactions in the detectors.

Can the TOF-Wall alone disambiguate multiple interactions without the input of the calorimeter or the tracker?

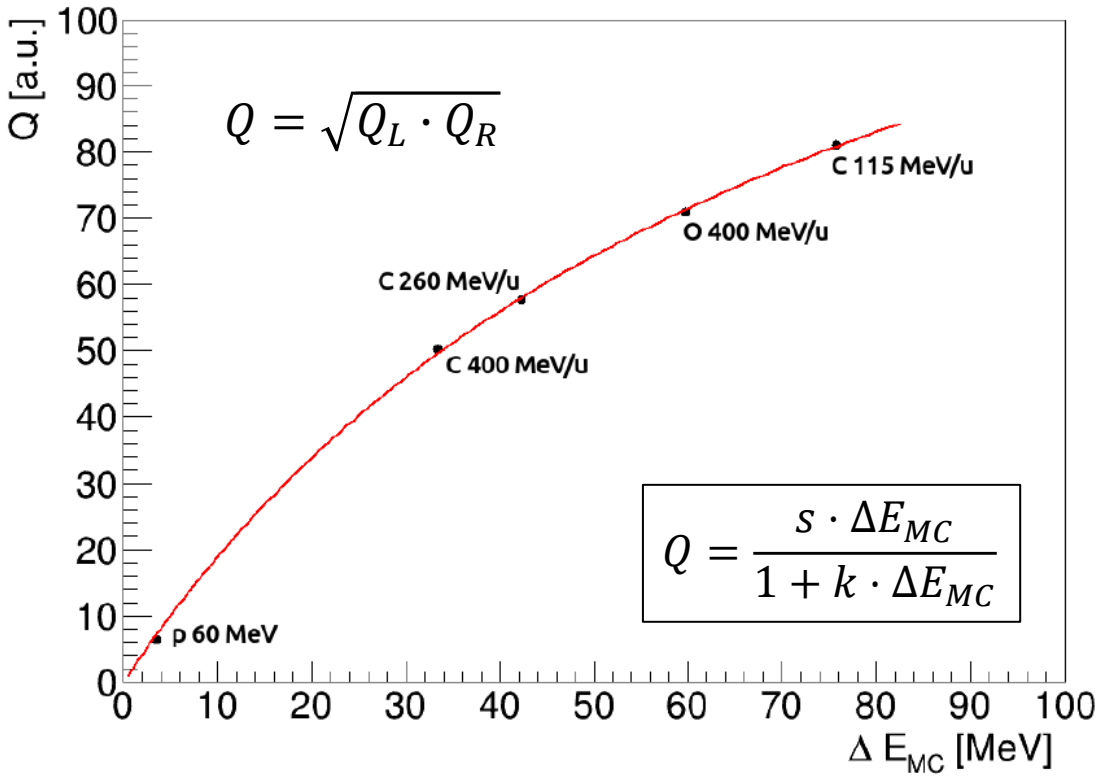


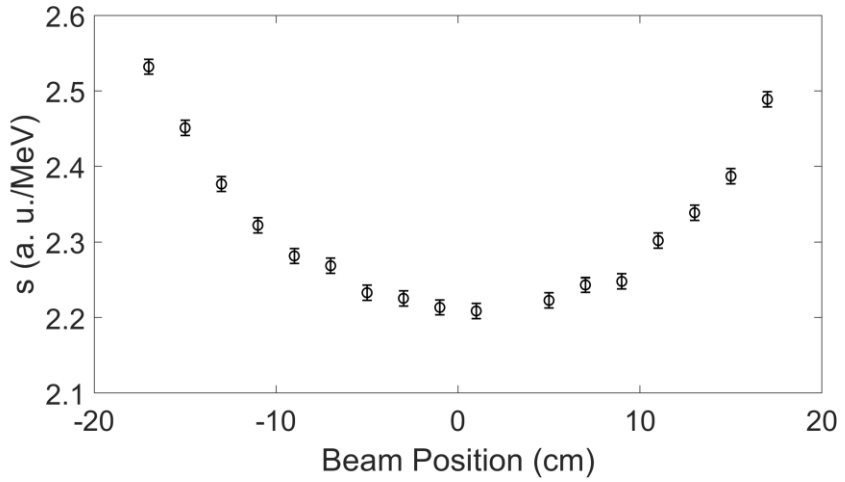
Comparison of the two timestamps in the bar



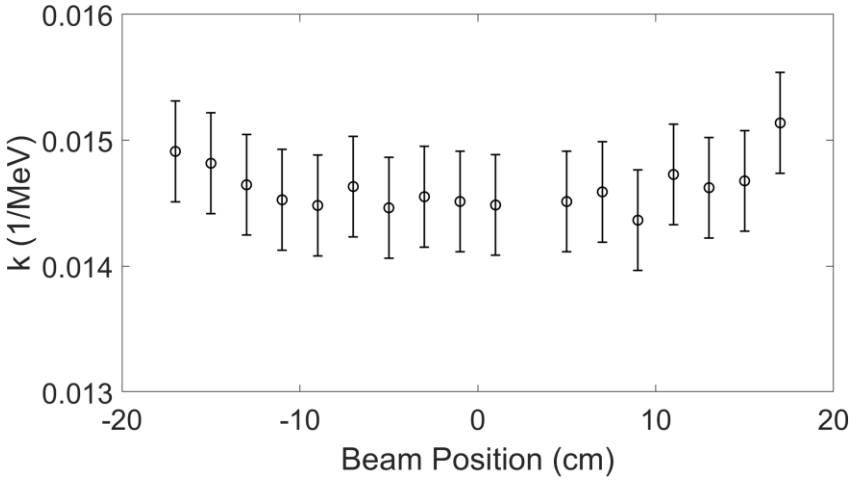


Energy calibration





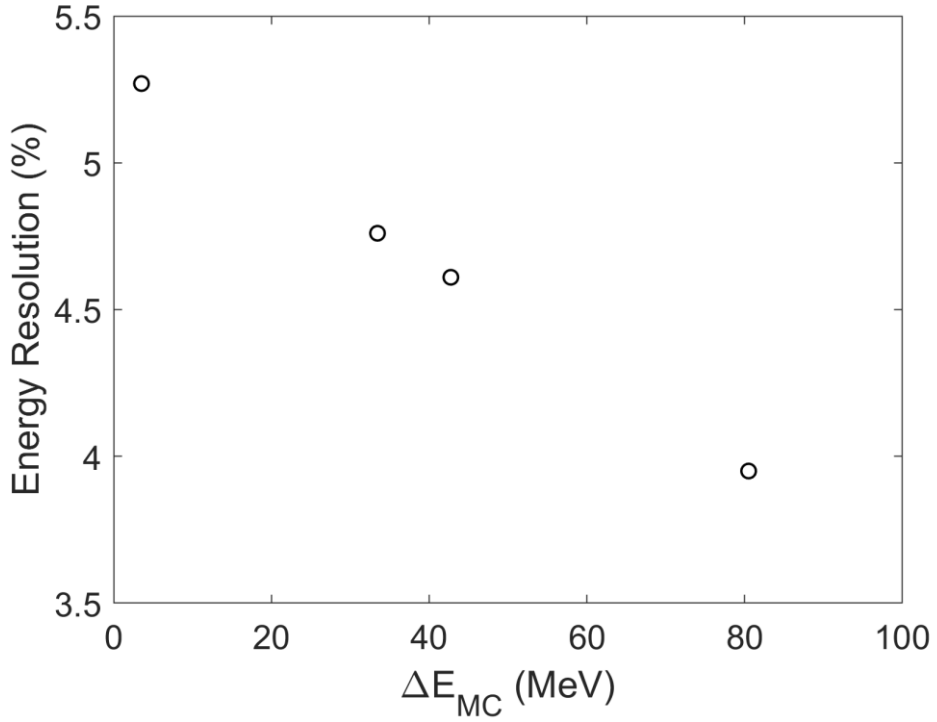
The value of *s* depends on the interaction position, less signal is collected at the center of the bar. Need for a correction



The value of *k* is almost uniform along the bar, as expected.

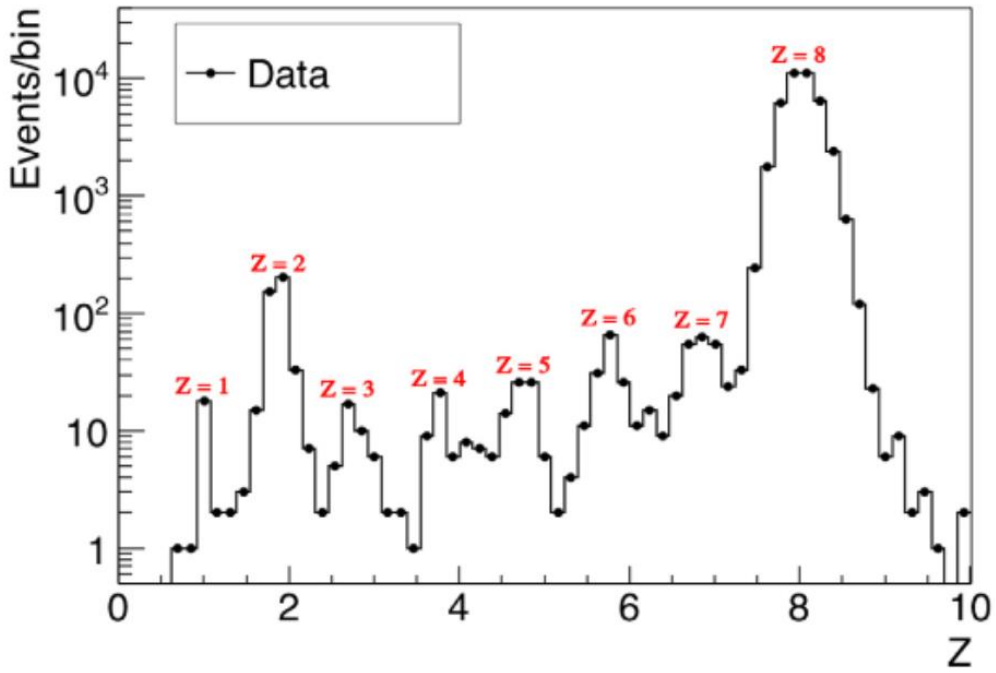
Energy resolution and Z reconstruction

After the conversion from collected signal to MeV, the energy resolution of the detector can be evaluated.



Morrocchi et al., IEEE TNS 60(5) 2021

By inverting the Bethe-Bloch, the Z can be reconstructed. A resolution of 2.7% and 3.9% in Z was obtained for O@400 MeV/u and C@400 MeV/u, respectively.



Kraan, Zarrella et al., NIM-A 1001, 2021

Conclusions

- The TOF-Wall detector of the FOOT experiment was tested with different ion beams
- The time resolution between the two layers was in the range σ = 50 - 35 ps for carbon ions
- The energy resolution was 4-5% for carbon ions, and about 5.5% for 60 MeV protons
- A time resolution σ = 51 ps and σ = 74 ps was obtained for O@400 MeV/u and C@400 MeV/u, respectively
- A resolution of 2.7% and 3.9% in Z was obtained for O@400 MeV/u and C@400 MeV/u, respectively

Thank you!

The FOOT collaboration

- Italy: 10 INFN sections/labs, CNAO
- Germany: GSI, Aachen University
- France: IPHC Strasbourg
- Japan: Nagoya University
- ~90 researchers