The FOOT (Fragmentation of Target) experiment: an overview and first results

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on behalf of the FOOT collaboration

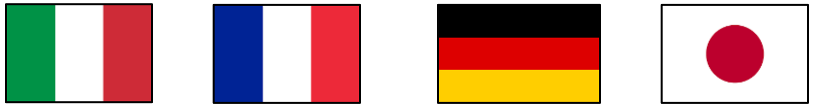
Quinto Incontro Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso
9-11/05/2022

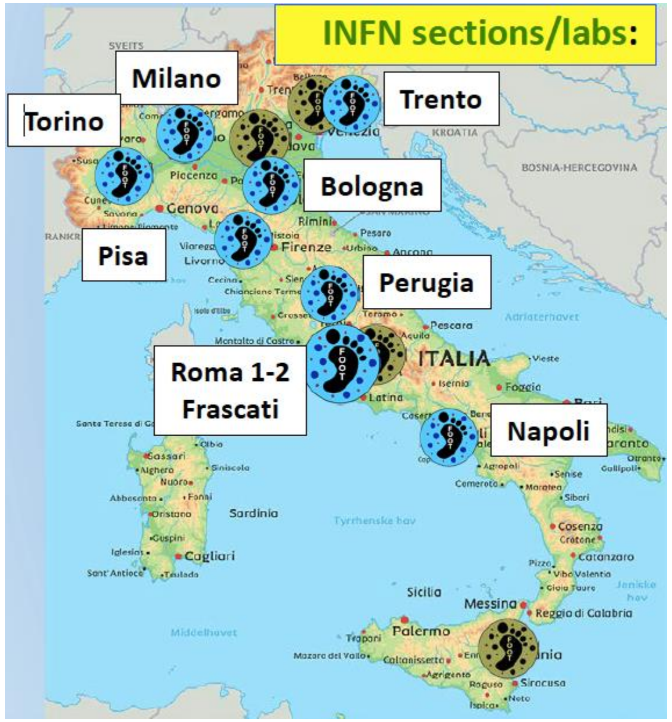
Goal

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

Study of nuclear physics interactions in the elements that mainly constitute the human body for a precise dosimetric evaluation in two different contexts

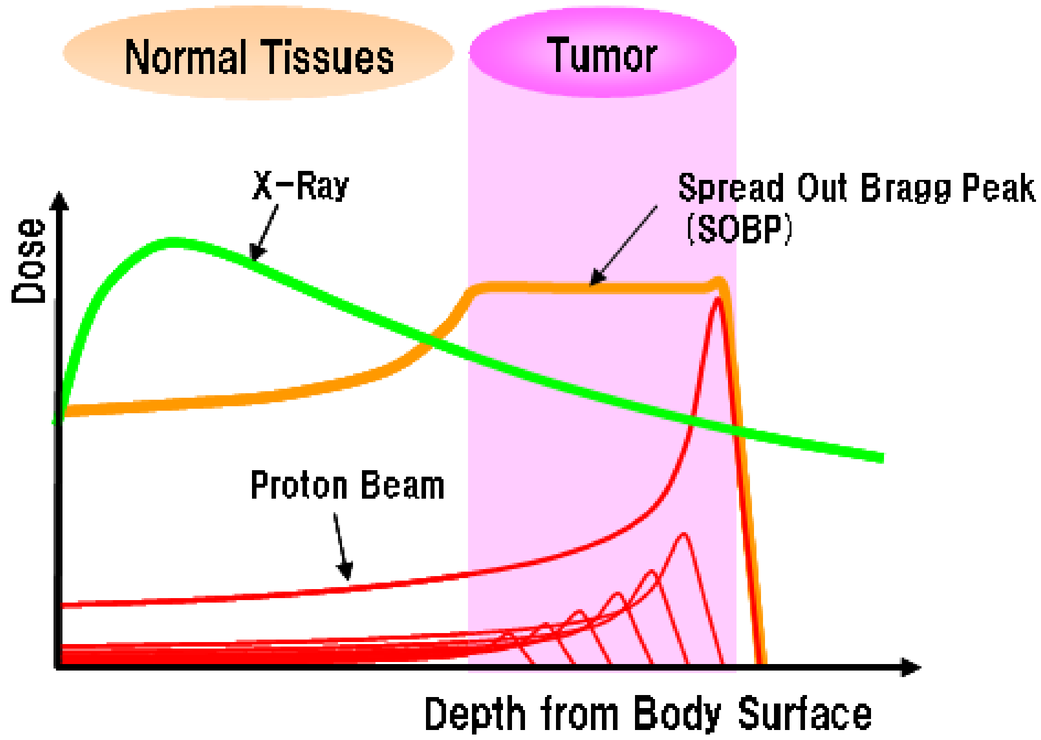
- Italy: 10 INFN sections/labs, CNAO
- Germany: GSI, Aachen University
- France: IPHC Strasbourg
- Japan: Nagoya University
- ~90 researchers





Motivation: hadron therapy

The Bragg peak allows the confinement of the dose deposition in a narrow and tunable region (especially favourable for deep-seated tumour), but dose delivery needs a very accurate prediction

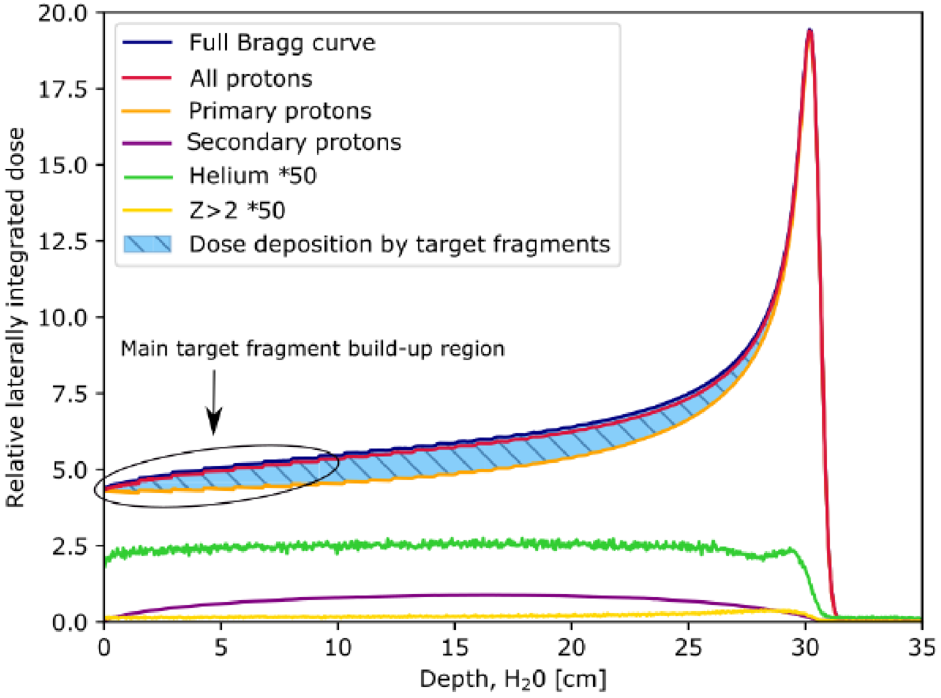


Fragmentation of tissues (and also of projectile for Z>1) needs to be considered in the treatment planning:

- Higher dose released out of the Bragg peak
- Higher RBE (relative biological effectiveness) of the fragments compared to the primary beam

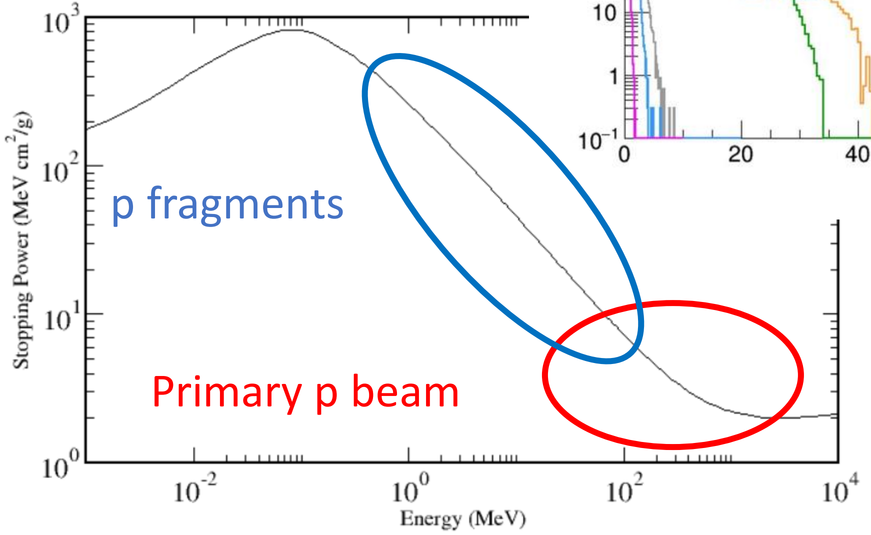
A full knowledge of differential and double differential cross section measurements (in angle and kinetic energy), for light targets and projectiles is still missing.

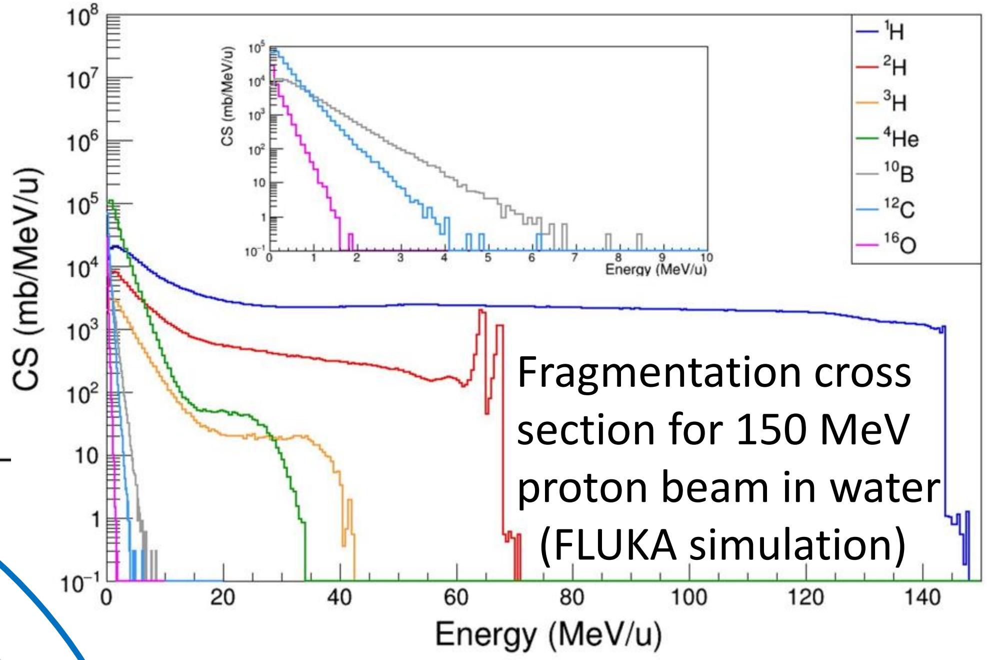
Motivation: proton therapy



Pfuhl et al, PMB 63(17) 2018

Fragments with lower energy compared to the primary beam have a higher LET

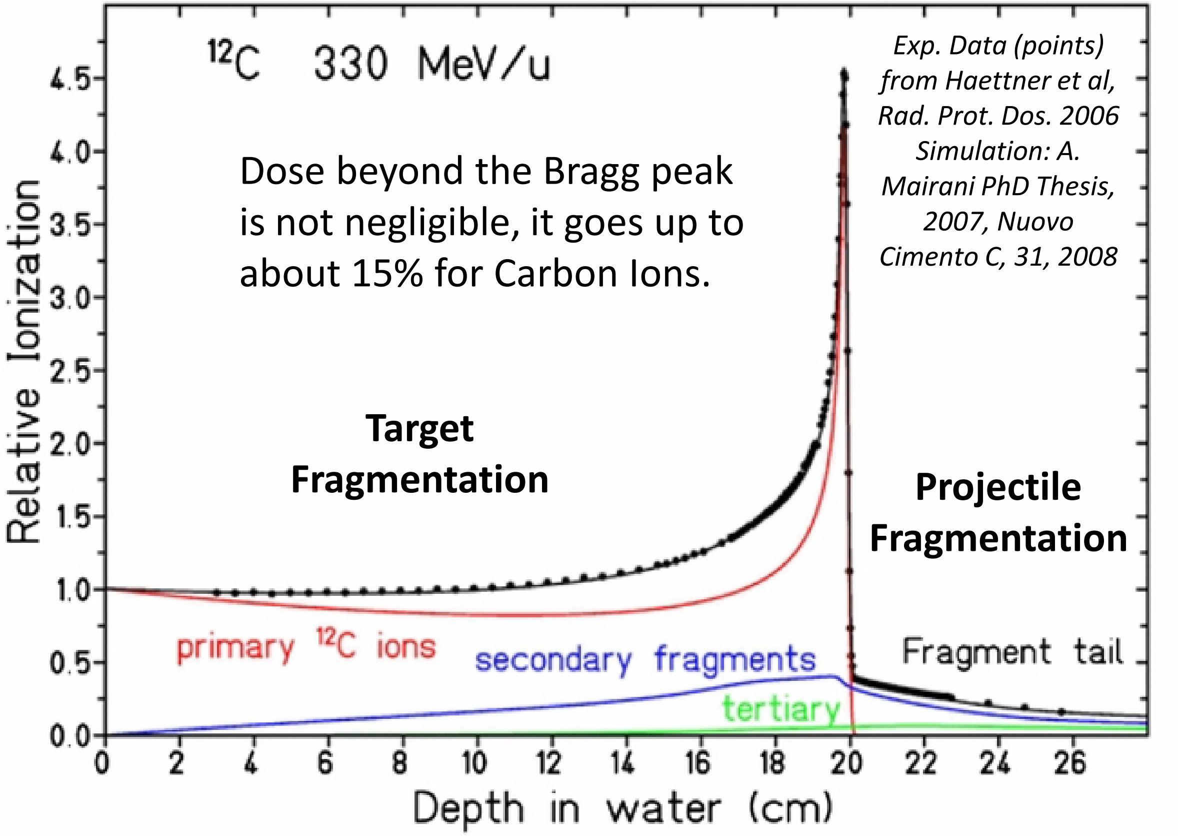




Fragmentation cross section for 150 MeV proton beam in water (FLUKA simulation)

Embriaco et al, EJMP 80 2020

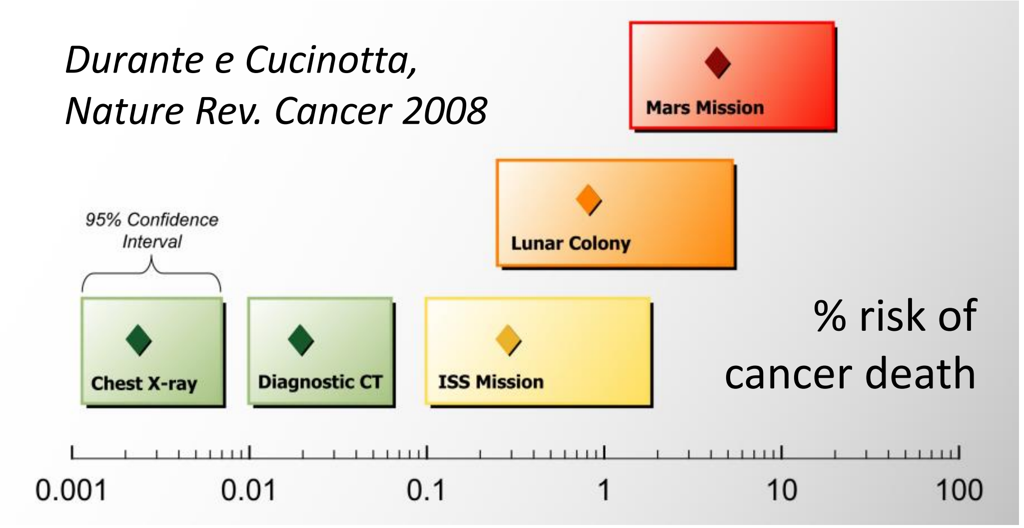
Motivation: carbon therapy

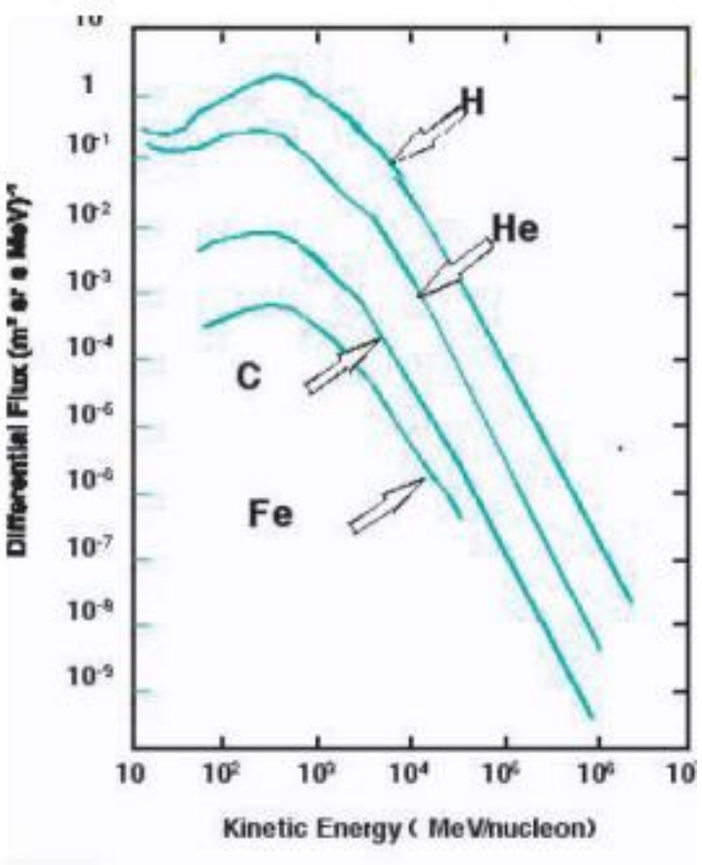


- **Target fragmentation** causes the generation of ions in the entrance channel with very low range and high RBE
- **Projectile fragmentation** causes the generation of ions that may travel beyond the Bragg peak, irradiating healthy tissues

Motivation: radioprotection in space

- **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

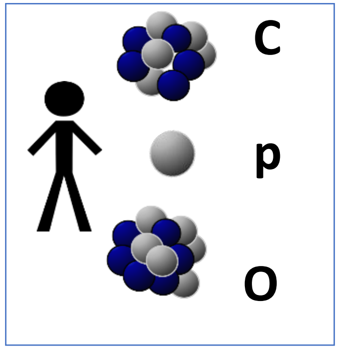
Need for optimal shielding and accurate modeling of their interactions with particles.

Required measurements

Projectile **Target**

p →

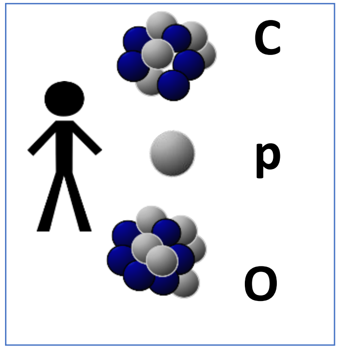
Proton therapy
(up to 200 MeV)
Space
(~800 MeV)



Target fragments
very short range (few um)

C →

Carbon therapy
(up to 400 MeV/u)



Target fragments
very short range (few um)

Projectile fragments
long range (cm)

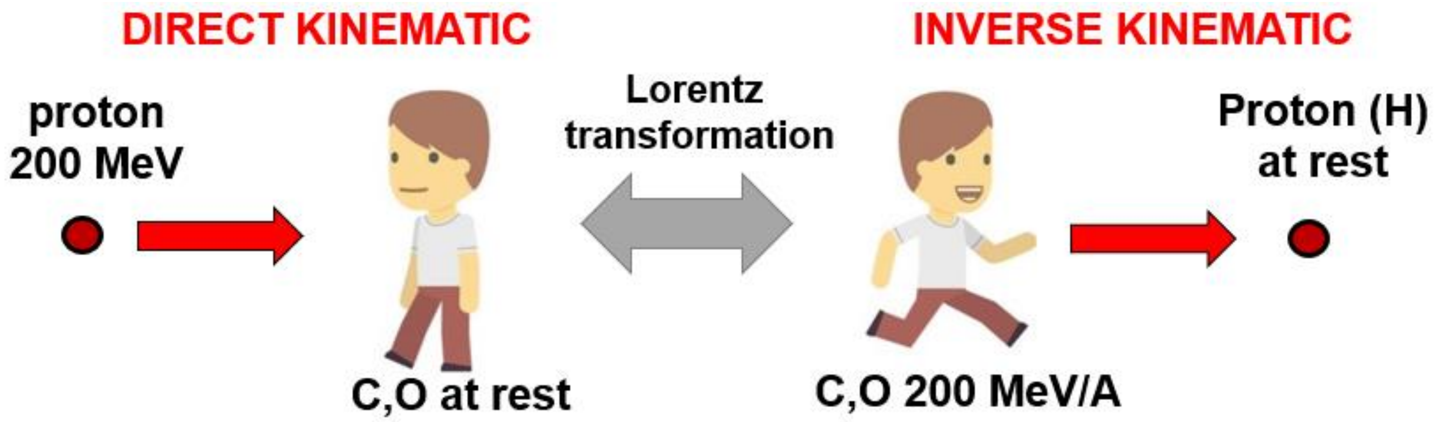
Required accuracy for particle therapy

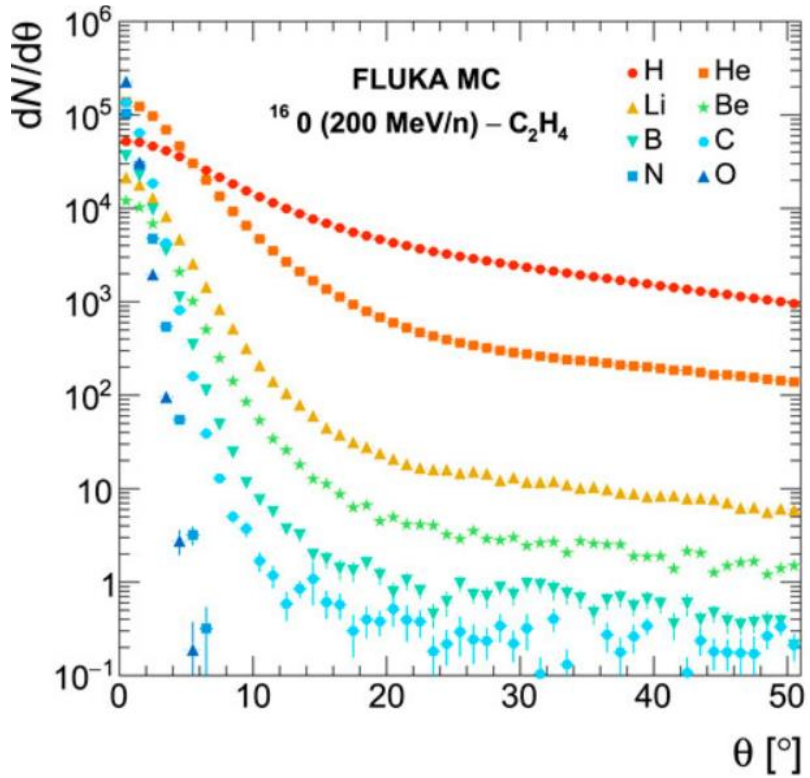
- Target fragmentation accuracy on $d\sigma/dE_{kin}$ better than 10%
- Projectile fragmentation accuracy on $d^2\sigma/(dE_{kin}d\Omega)$ better than 5%
- Charge Z identification ~3%
- Mass A identification ~5%

Need for a moveable and compact system

Inverse kinematic

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.



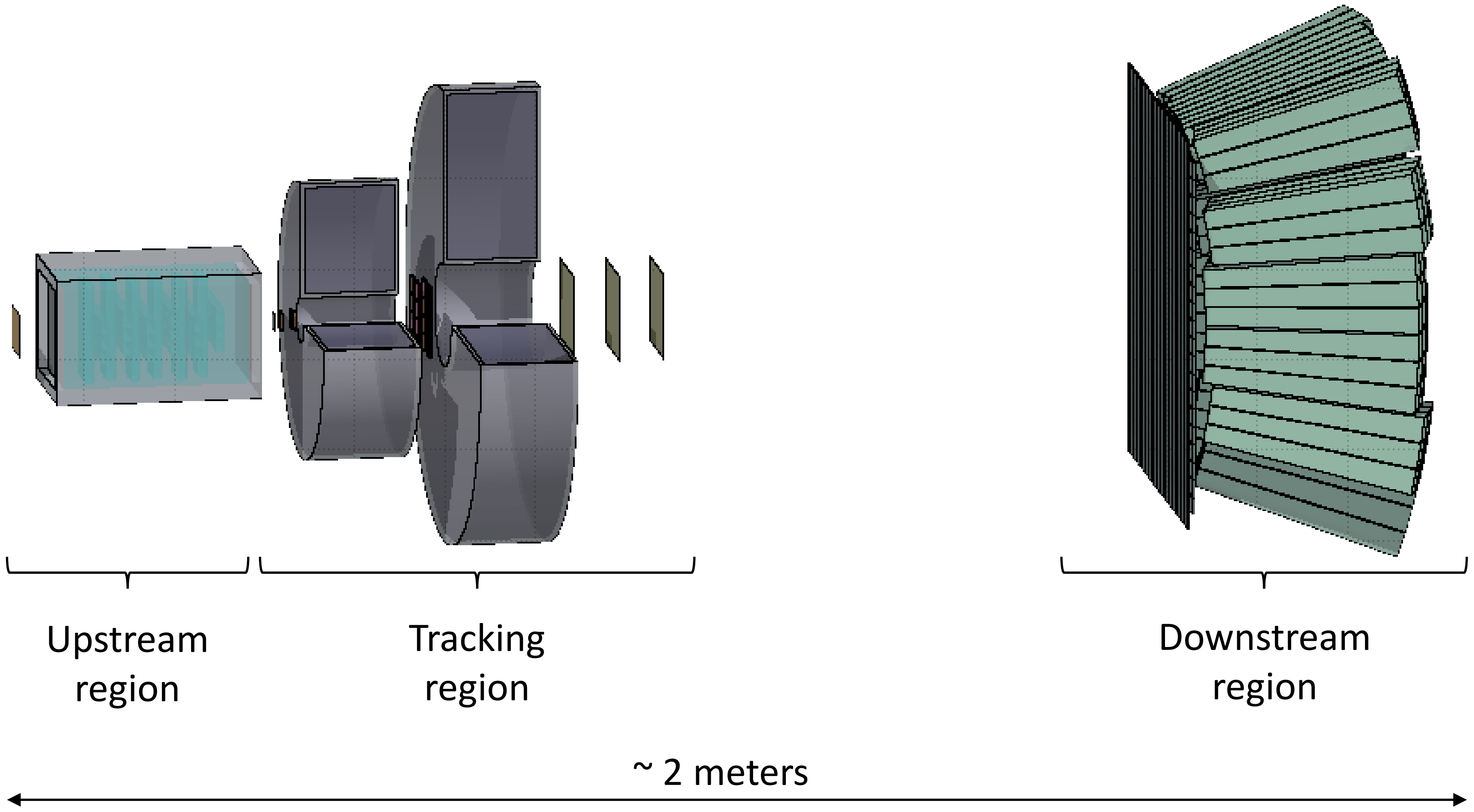


Thin targets (few mm) of C and C_2H_4, PMMA

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

Angular distribution of the fragments depends on Z → Two different experimental setups for lower and higher Z

Electronic setup



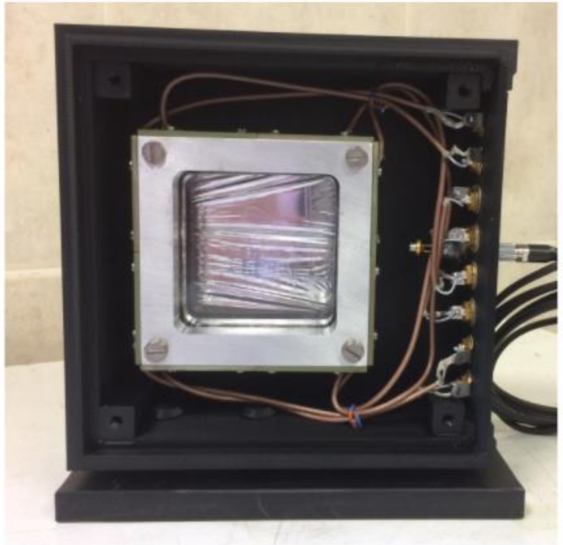
- ~10° angular acceptance
- Mainly focused on heavier ions
- 1 kHz acquisition event rate
- Usable in different accelerator facilities (CNAO, GSI, HIT)
- A, Z, θ, E identification of each fragment

Electronic setup

Start Counter Detector

It provides the first timestamp for the time of flight measurement. It also provides the minimum bias trigger for the data acquisition

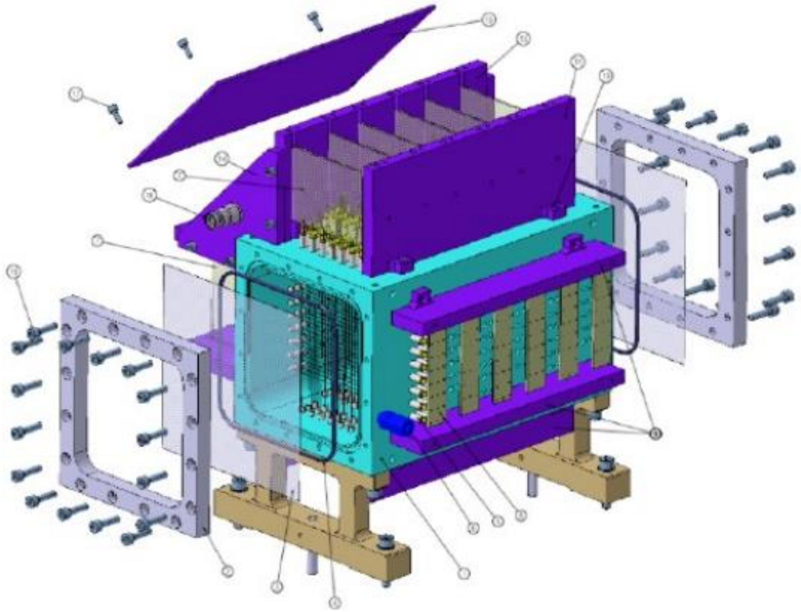
- 250 µm EJ212 plastic scintillator foil
- 8 analog read-out channels
- 6 SiPMs connected in series on each channel



Thickness is minimized to reduce the chance of beam fragmentation before the target.

Electronic setup

Beam Monitoring

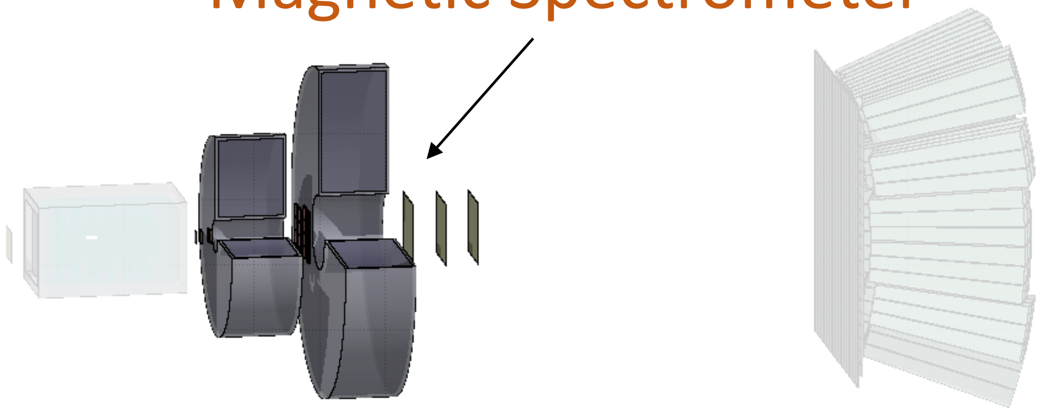


It measures the direction and the impinging position of the beam ions on the target

- Dimensions: 11.2 cm x 11.2 cm x 21 cm
- 6 staggered layers of cells on X and Y view
- 3 rectangular cells (16 x 10 mm^2) on each layer
- Mylar windows at beam entrance and exit
- Filled with Ar/CO_2 at 80/20%

Electronic setup

Magnetic Spectrometer



Three tracking stations plus two permanent magnets.

Information about the particle momentum and the interaction position of the primary particle.

VERTEX

- Four layers of MIMOSA28 chip
- 20.7 um pitch and about 20 x 20 mm^2 sensitive area
- Identification of the vertices of the trajectories

INNER TRACKER

- Two planes of MIMOSA28 chip
- Larger sensitive area compare to the VERTEX

MICROSTRIP DETECTORS

- Last stage for particle tracking
- Provide also dE/dx information
- 10° angular acceptance

Electronic setup

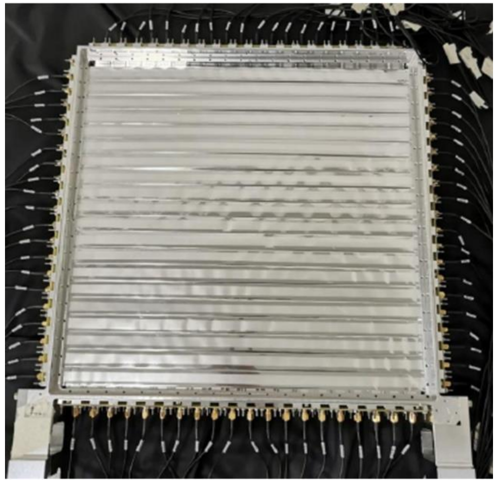
TOF-Wall Detector

Composed of 20 + 20 plastic scintillating bars (EJ200)
Each one with size 440 x 20 x 3 mm^3

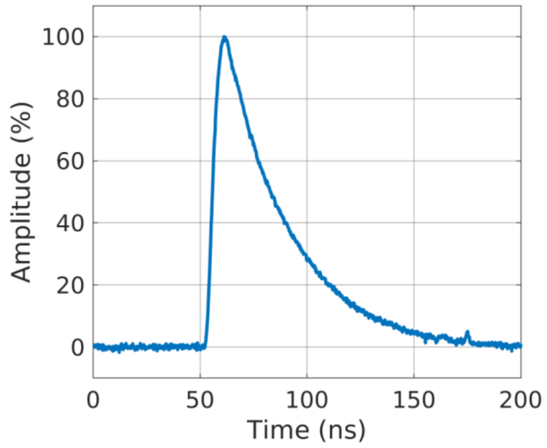
- The two layers are orthogonally arranged to identify the interaction position
- Total active area of 40 x 40 cm^2
- 80 analog channels in total

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

Bias, trigger & DAQ
WaveDAQ (PSI & INFN)

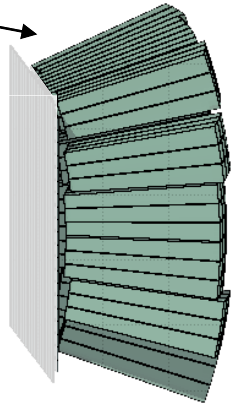


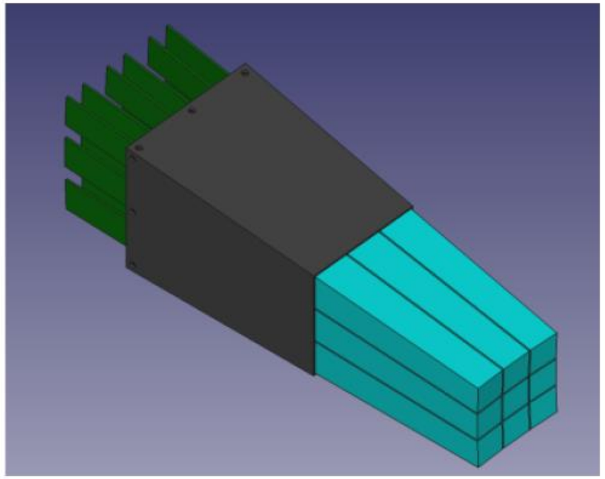
Waveforms of start counter and triggered channels of the TOF-Wall are stored and analyzed off-line

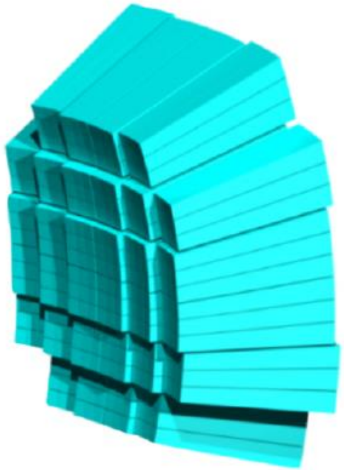


Electronic setup

BGO Calorimeter







- Tapered crystals
- 32 modules composed of 9 crystals each
- Dimension of 2 x 2 cm^2 (front) and 2.9 x 2.9 cm^2 (back), 24 cm length.
- Almost 1-to-1 match between calorimeter pixels and TOF-Wall intersections
- Energy resolution ranging from 1% to 3%

Mass reconstruction

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 or **MICROSTRIP**

TOF

Three different methods to reconstruct the mass of the fragments:

$$A_1 = \frac{p}{U \beta \gamma}$$

TOF+dE/dx and TRACKER

$$A_2 = \frac{E_{\text{kin}}}{U(\gamma - 1)}$$

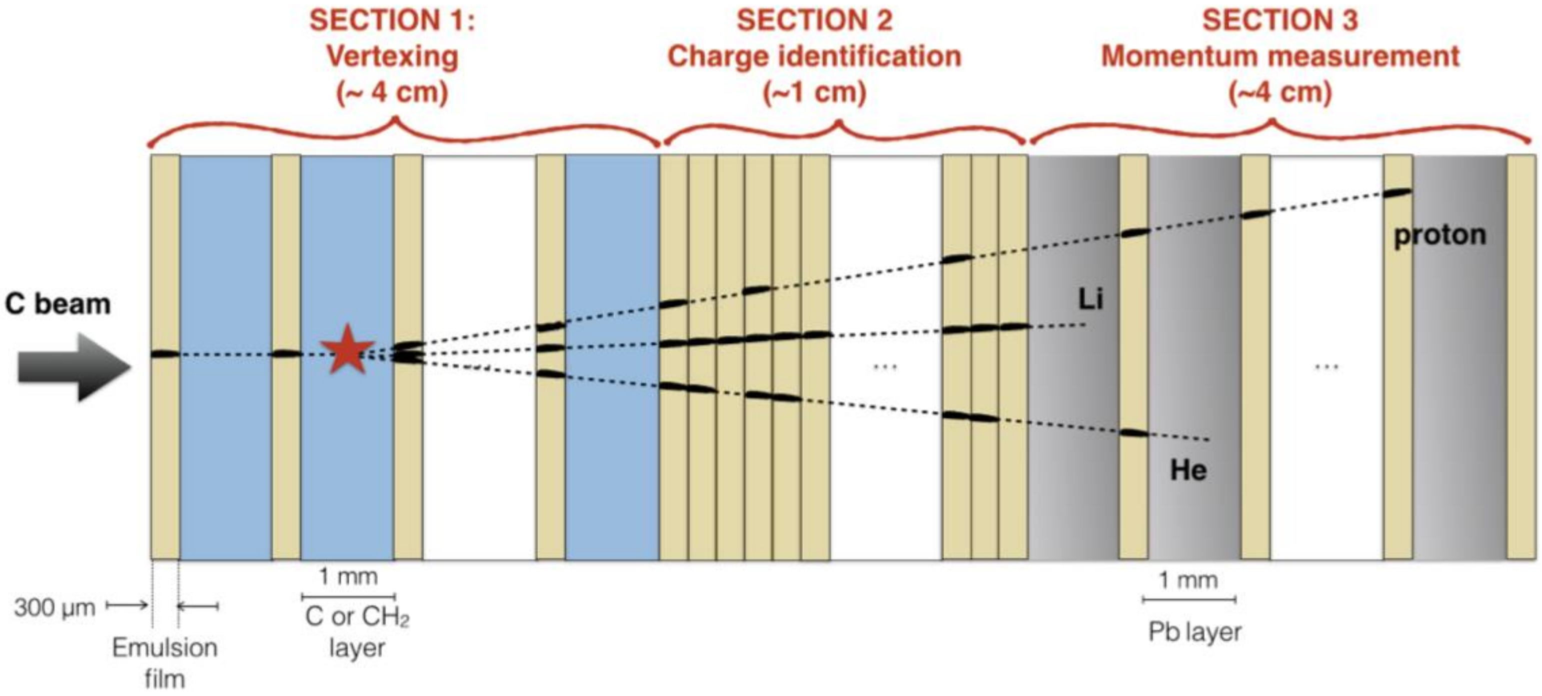
TOF +dE/dx and CALORIMETER

$$A_3 = \frac{p^2 - E_{\text{kin}}^2}{2 E_{\text{kin}}}$$

TRACKER and CALORIMETER

Emulsion setup

- Optimized for Z<3
- Large angle covering



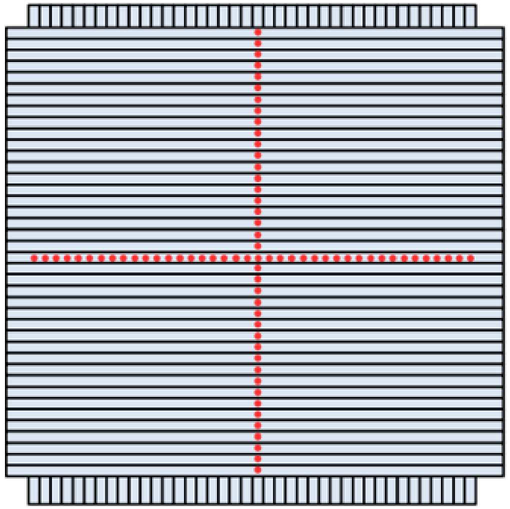
- **vertex detector**: target layers alternated with emulsion films
- **charge identification**: emulsion films only
- **momentum measurement and isotopic ID**: lead planes alternated with emulsion films

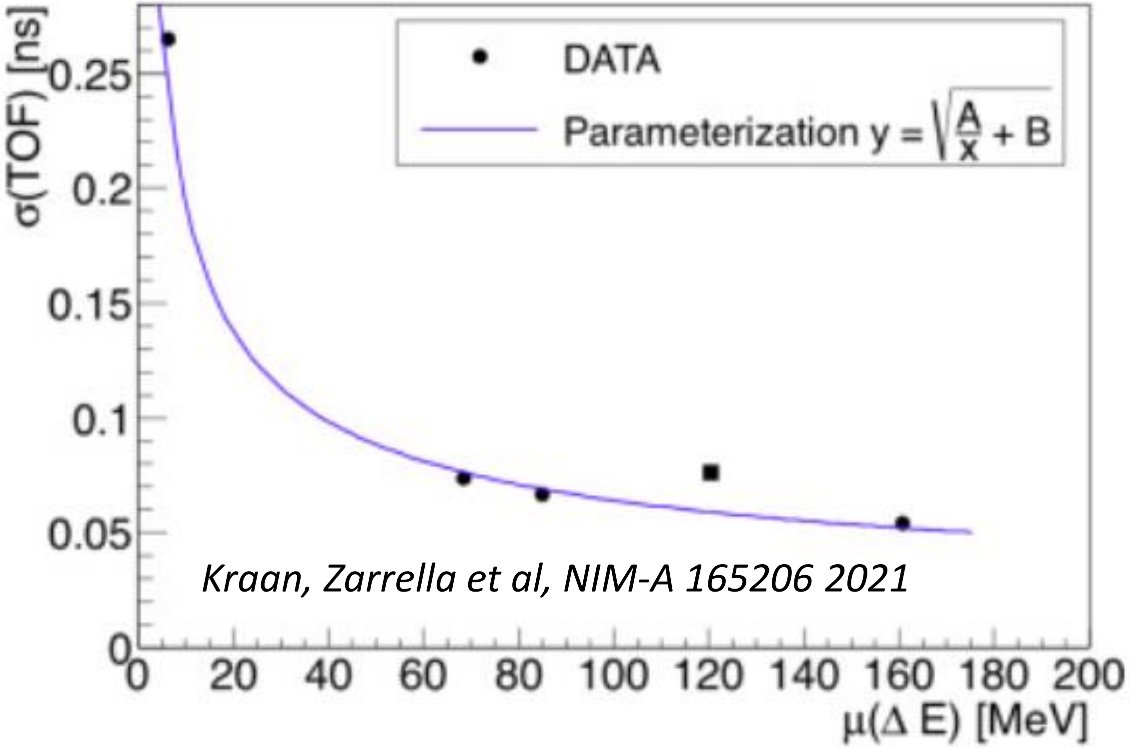
First results with the electronic setup

TOF system tested at CNAO and GSI facilities:

- 60 MeV proton
- 115-260-400 MeV/u carbon
- 400 MeV/u oxygen

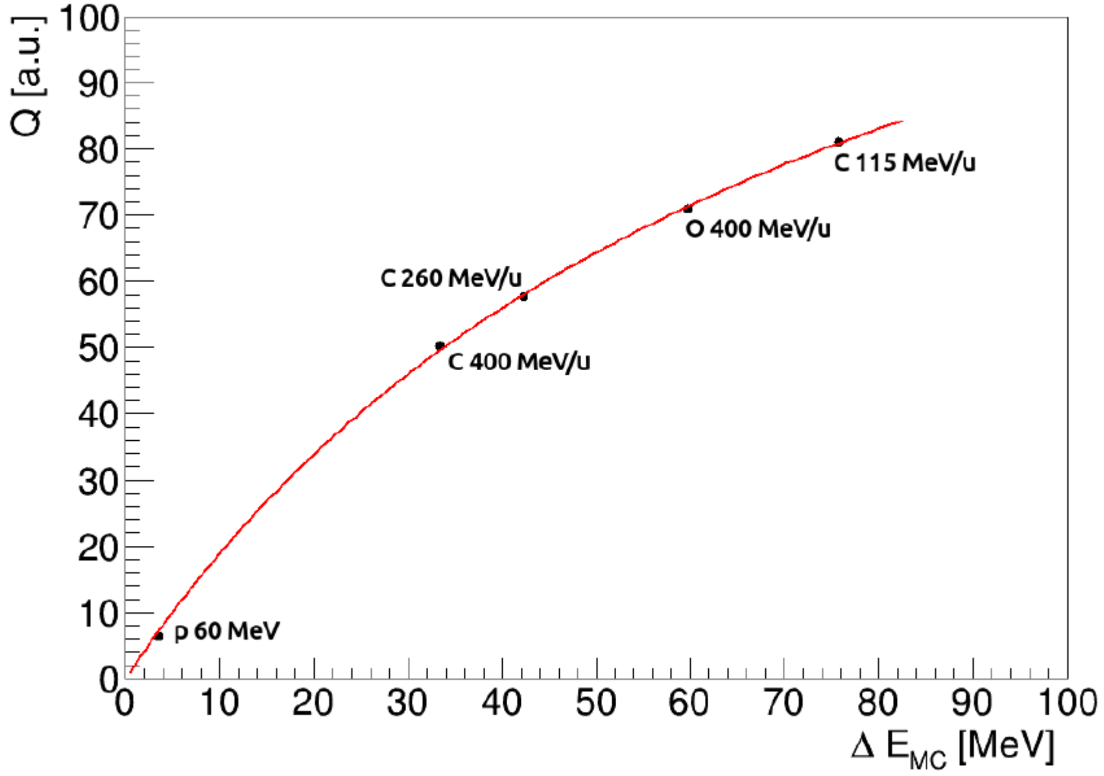
Scan of all the bars of the TOF-Wall detector

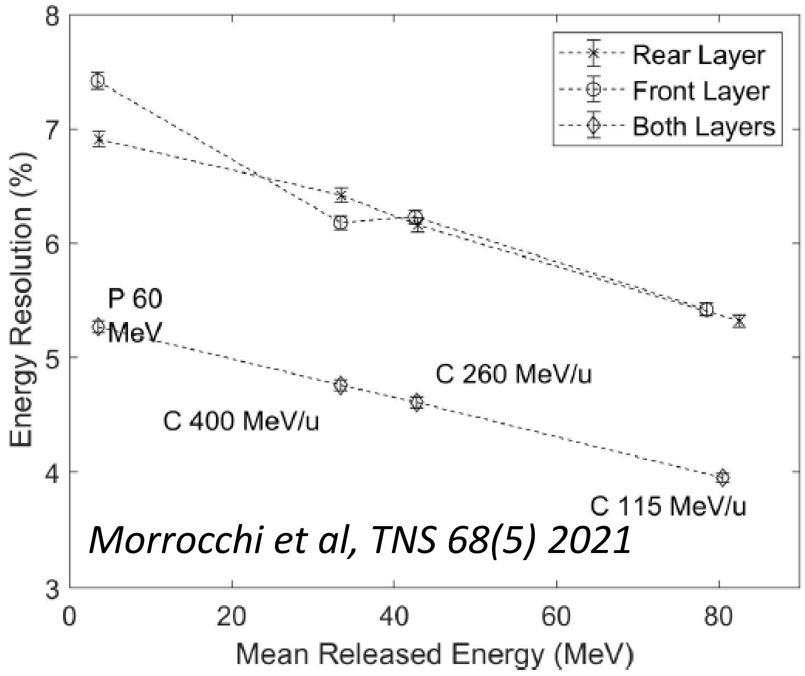




First results with the electronic setup

Energy calibration of the TOF-Wall detector, according to Birk's law

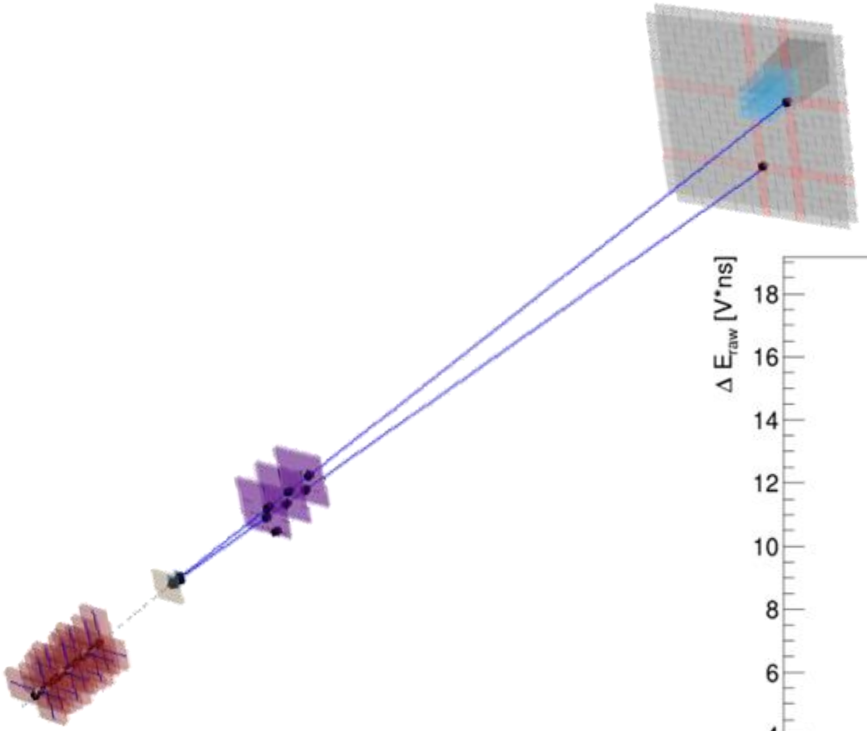


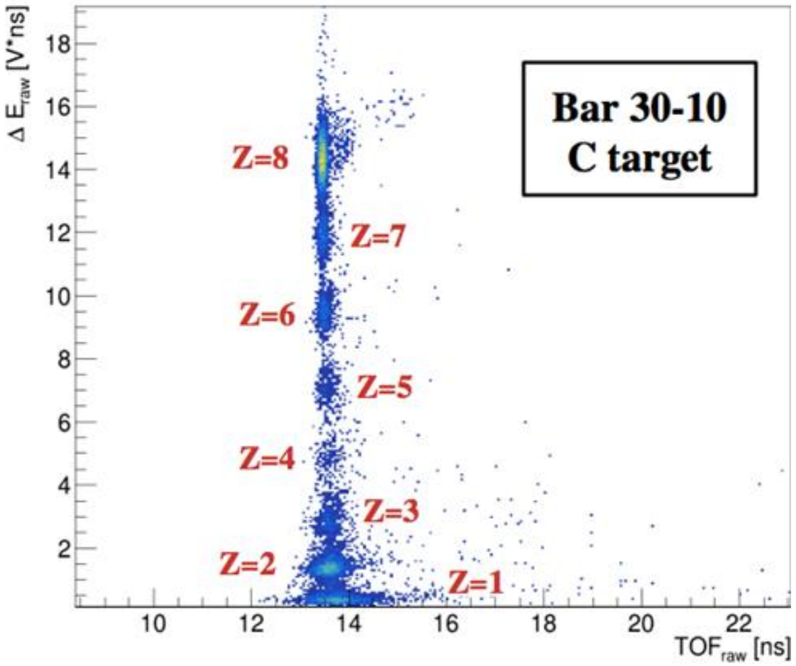


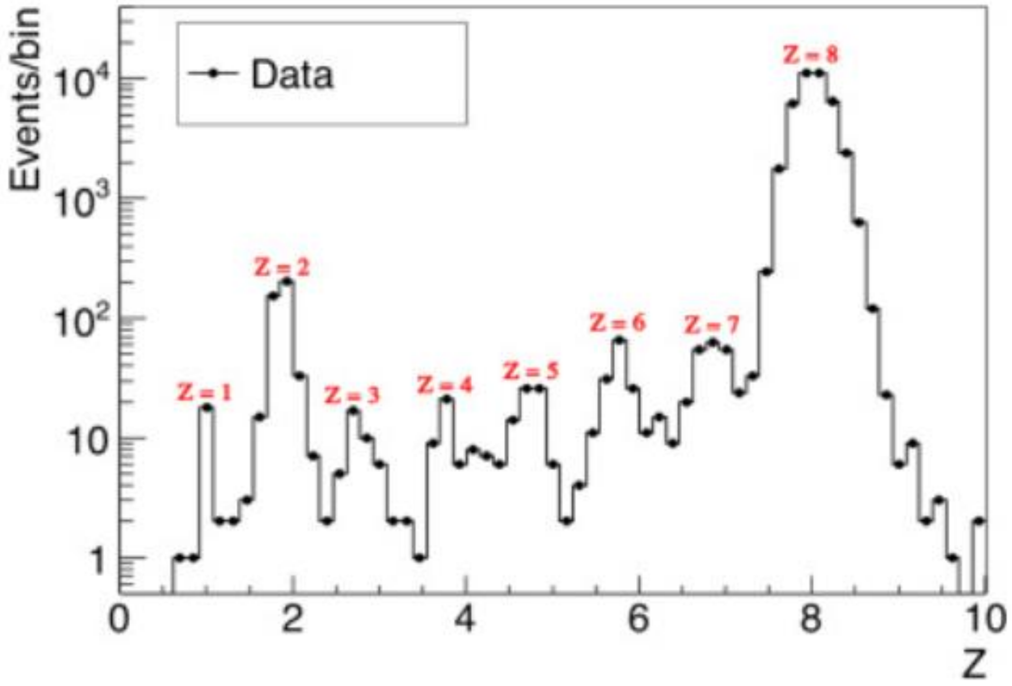
Particle	E_{beam} [MeV/u]	$\mu(Z)$	$\sigma(Z)$	$\sigma(Z)/\mu(Z)$ [%]
p	60	0.96	0.06	6.10 ± 0.02
^{12}C	115	6.17	0.15	2.51 ± 0.01
^{12}C	260	6.01	0.21	3.52 ± 0.01
^{12}C	400	6.07	0.24	3.85 ± 0.01
^{16}O	400	8.07	0.22	2.67 ± 0.02

First results with electronic setup

- Fragmentation studies with oxygen beam and carbon target (GSI)
- Only a subset of the detectors was employed in the data taking







Conclusion

- The FOOT experiment will provide a set of double differential fragmentation cross sections for application in hadron therapy and space dosimetry
- Initial data takings were performed with a subset of detectors
- First results with oxygen beams on C and C_2H_4 targets demonstrate that the fragment charge can be reconstructed with the FOOT electronic setup
- The setup assembly is ongoing and it is expected to be completed by the end of the year
- Next data takings are expected this year (Heidelberg and CNAO)