FramentatiOn
Of Target

Istituto Nazionale di Fisica Nucleare

Nuclear fragmentation measurements for hadron therapy with the FOOT experiment

Aafke Kraan for the FOOT collaboration

INFN Pisa

14-09-2021

Outline

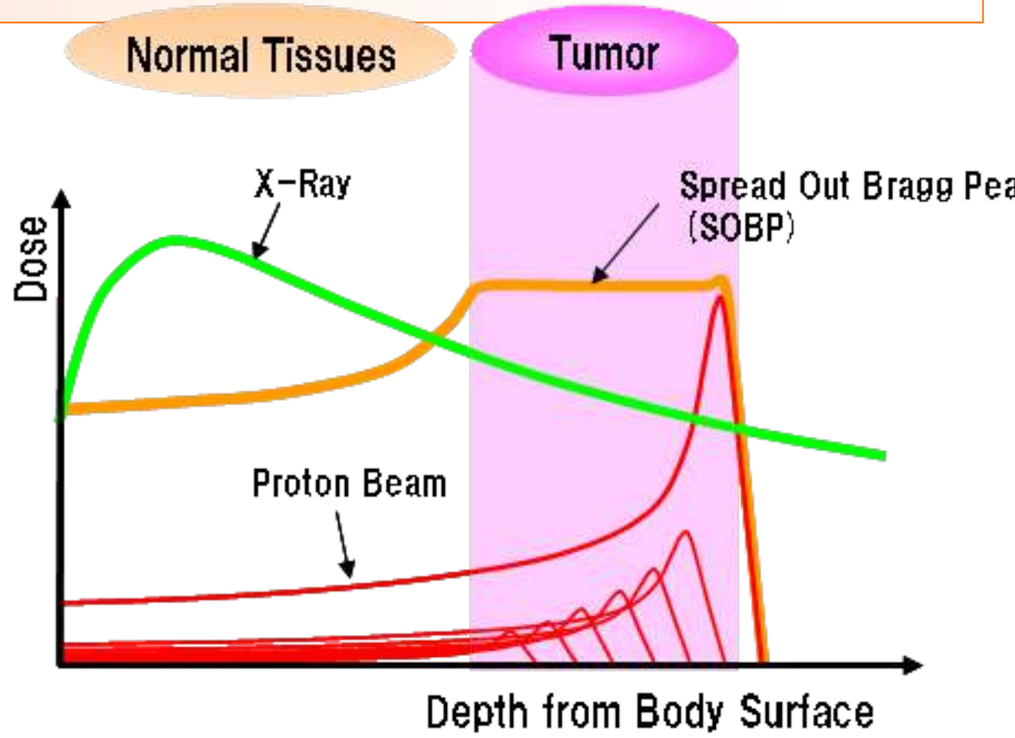
- Introduction:
  - Motivations of FOOT
- FOOT experiment:
  - Organization
  - Measurement strategy
  - Detector: the 2 setups
- Recent results
- Outlook and conclusions

Hadron therapy

- FOOT is an applied nuclear physics experiment for hadron therapy (slides 2-6) and radioprotection in space (see slide 6)
- In Italy, every day 1000 people receive the diagnosis of cancer and 485 persons die per day.
- About half of all patients receives radiotherapy (tumor irradiation)
- Small fraction of them receives hadron therapy (particle therapy)= Tumor irradiation with p or ^{12}C beams
- 3 centers in Italy: Catania, CNAO, Trento
- Beam energy up to 250 MeV (p) or 400 MeV/u (^{12}C)

From: http://www.salute.gov.it

- Pencil beam technique: delivered dose results from combining thousands of ion beams
- Very favorable depth-dose curve: very accurate!



Uncertainties

- However, the key of treatment accuracy is to predict *and deliver* a given dose in a patient in a given volume
- Many uncertainties:
  - Patient 3-D knowledge
  - Setup uncertainties
  - Anatomical (tumor changes, movement, etc)
  - Radiobiology
  - **Effect of nuclear physics interactions in human body**
    - Fragmentation of target
    - Fragmentation of projectile

FOOT
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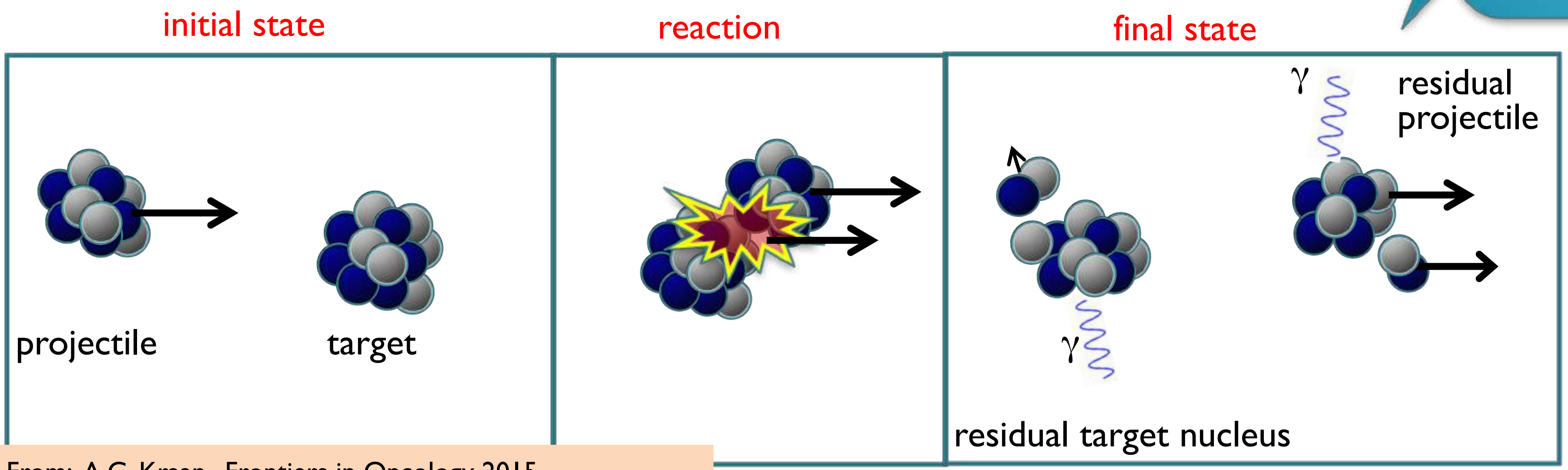
Who?
How many?
Which direction?
Which energies?



From: A.C. Kraan, Frontiers in Oncology 2015

Effects of nuclear fragmentation in the human body

- Primary beam: beam attenuation (on average about 40% of carbon ions undergoes inelastic interaction)

Durante, Paganetti: Rep. on Prog. Physics, 79 (9), 2016

- Secondary particle production
  - Different secondaries cause different density of ionization tracks (on DNA/cell scale) → different biological impact.
  - Understanding yields, angles etc is important:

Well understood	More knowlegde needed
Physics of carbon ions, protons	Physics of 'new' beams like Helium and Oxygen
Physical dose in patient for most projectiles	Biological dose effects
Total cross sections for light targets and projectiles	Differential and double differential cross section measurements in angle and kinetic energy, for light targets and projectiles (old, non-exisiting large errors)
Fragment measurements at small emission angles	Fragment measurements at large emission angles

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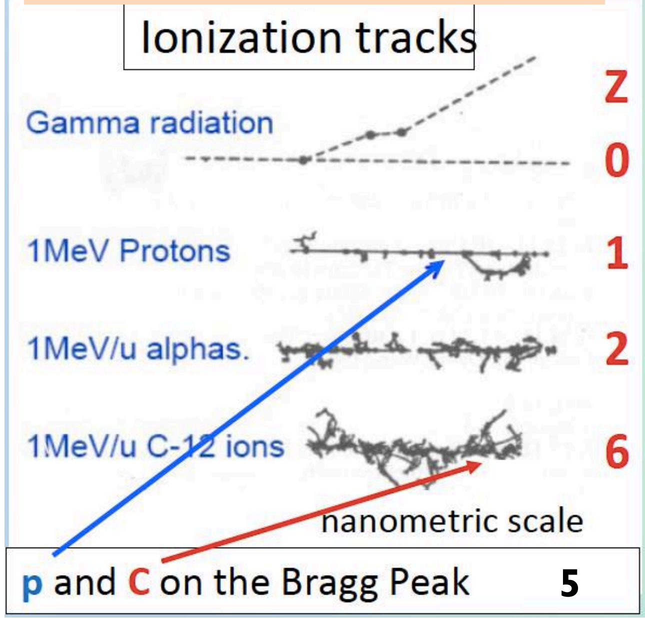
From R. Spighi, presentation EuNPC2018



W. J. Norbury et al, Frontier in Physics 2020

S. Muraro, G. Battistoni, A.C. Kraan, Frontiers in Physics 2020

F. Luoni et al, arXiv:2105.11981

Are the current models not good enough?

Particle therapy is not new… Are the nuclear interaction models still not satisfactory today??

- Yes, for physical dose they are good enough
  - Perfect depth-dose curves can be predicted!
- No, for biological dose they are far from being fully satisfactory, and this is the quantity that is of clinical interest!

Multi-disciplinary

RBE= Relative Biological Effectiveness, complex function depending on several parameters

- Physical: irradiation type, energy, LET, dose
- Chemical: e.g. oxygen concentration
- Biological: radio sensitivity of tissue, cell cycle phase, ...

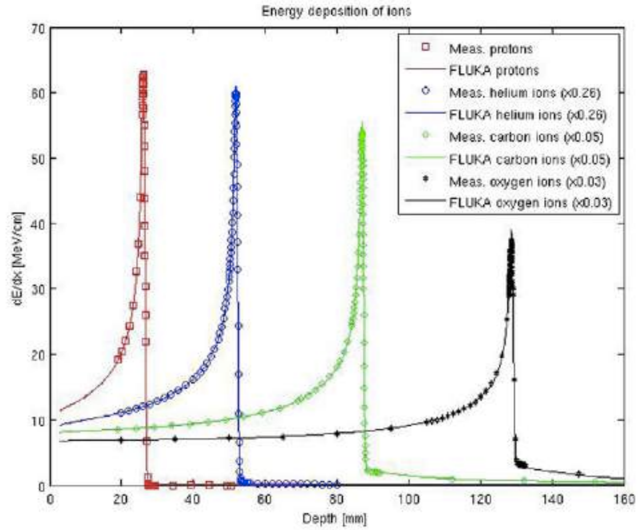
$$RBE = \frac{D_X}{D_R}$$

ref

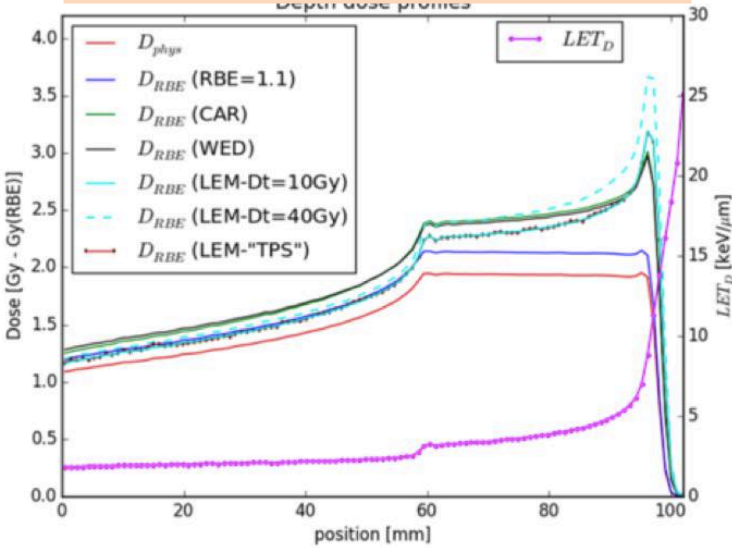
particle

FOOT: new nuclear fragmentation cross sections to improve accuracy of RBE needed to improve treatment accuracy. Especially debated in proton therapy.

G. Battistoni et. al., Frontiers in Oncology 2016



Chaudhary et al.,(2014) Int J. Radiation Oncol Biol Phys, 90:27-35



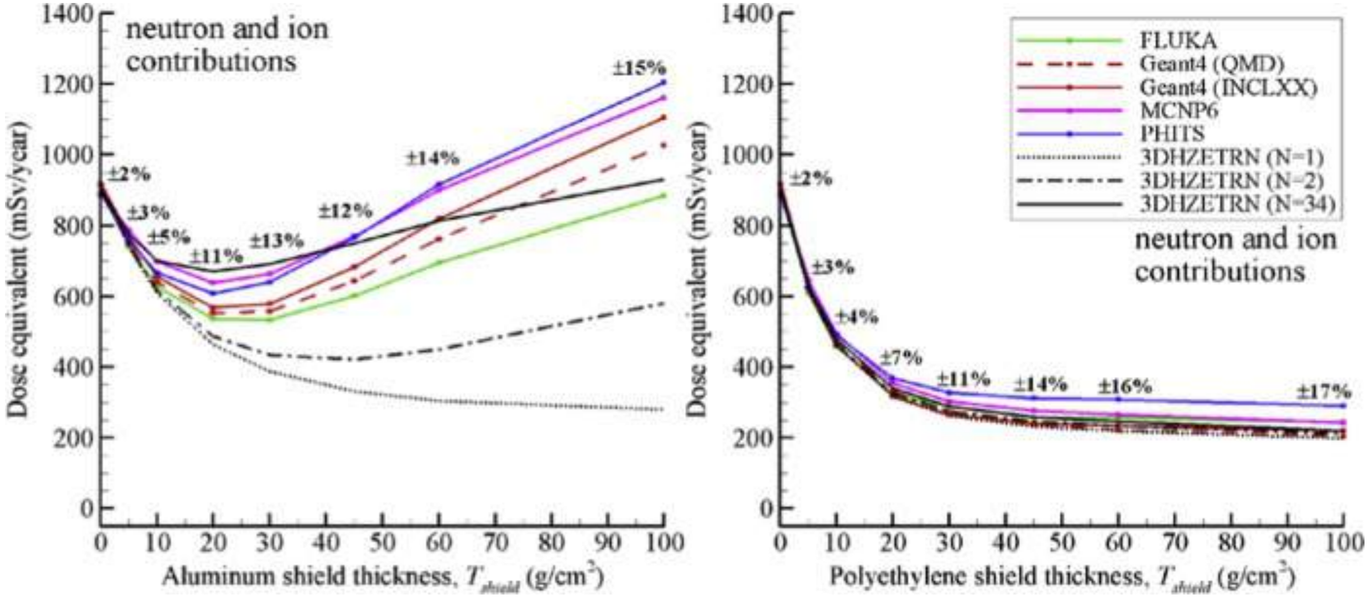
Radiation protection in space

Besides particle therapy, another field of interest of FOOT is radiation protection in space

- Dose calculations (see before)
- Shielding materials for long-term space missions
    - Example: Mars: no natural protection from radiation (CBR + SPE)
    - The role of neutrons is particularly important

Maximum of flux of GCR is around 800-1000 MeV/u (^{12}C)

C. Slaba et al Life Sciences in Space Research Volume 12, 2017, Pages 1-15



The FOOT collaboration

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FOOT approved by the INFN on September 2017 (CSN3)

- Italy: 10 INFN sections/labs, CNAO
- Germany: GSI, Aachen University
- France: IPHC Strasbourg
- Japan: Nagoya University
- ~90 researchers 34 FTE, tecnologi 3 FTE

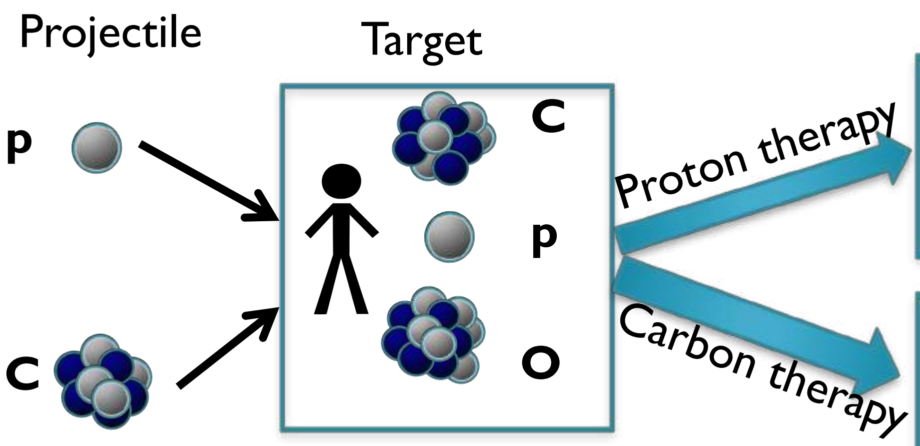
Fixed target experiment, physics program:

- Hadron therapy:
  - Nuclear fragmentation @ 200 - 400 MeV/u **TODAY**
- Radioprotection in Space:
  - Nuclear fragmentation up to 800 MeV/u

Web site: https://web.infn.it/f00t/index.php/en/

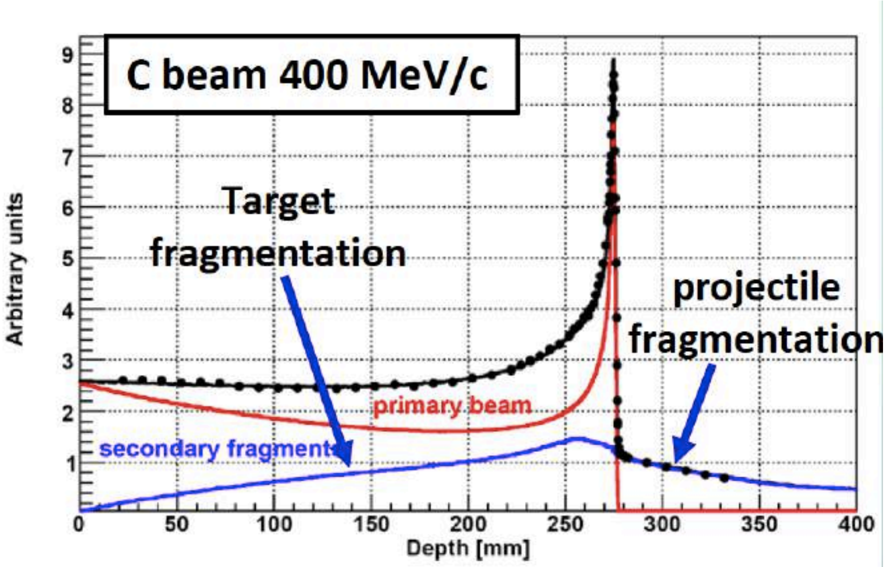
The FOOT collaboration

How to measure the fragmentation spectrum?



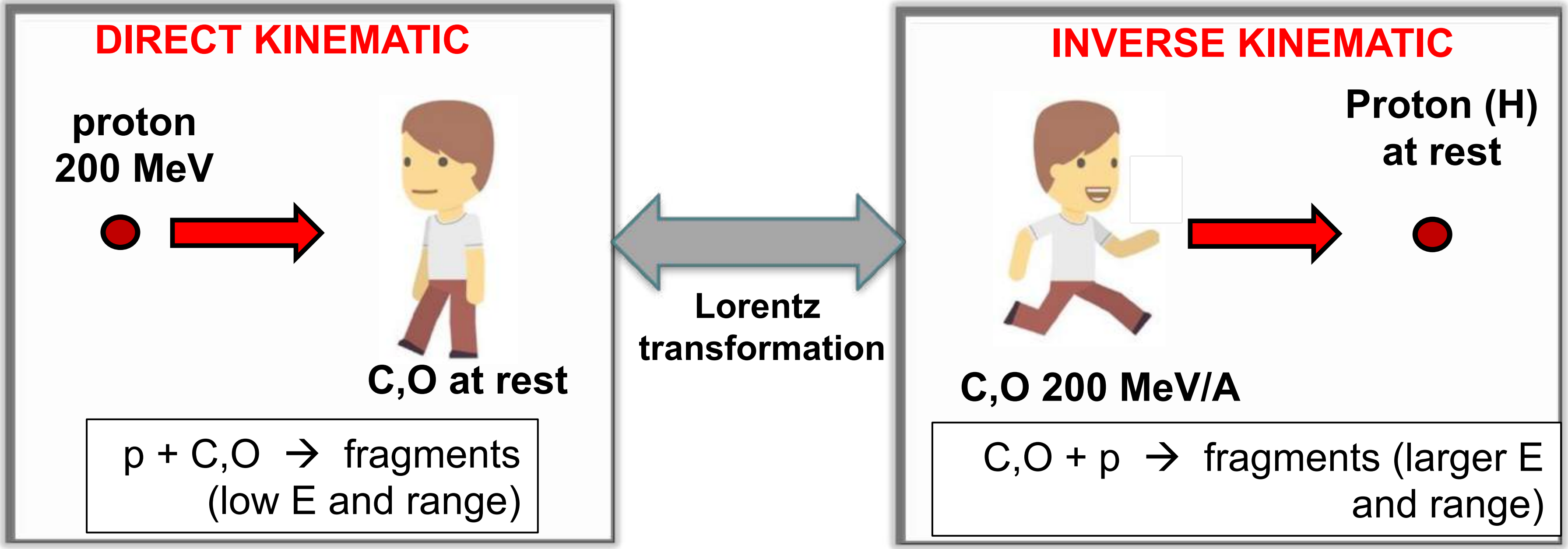
	Who fragments?	Range
p+p →	none	
p+C,O →	target	Short (μm)
C+p →	projectile	Long (> few cm)
C+C,O →	target	Short (μm)
	projectile	Long (> few cm)

- Projectile fragmentation: long range fragments can be measured directly
- Target fragmentation: how to measure short range fragments?
  - Difficult to directly detect them, would need very very thin target



Inverse kinematics approach

Target fragmentation



Target can be as thick as a few mm (range of fragments is or order ~ few cm)

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

Webber et al, Phys Rev C (1990) 41(2); 520
Dudouet et al, Phys Rev C (2013) 88(2):064615

Experimental setups

See: G. Battistoni, M. Toppi, V. Patera. Front. Phys., February 2021

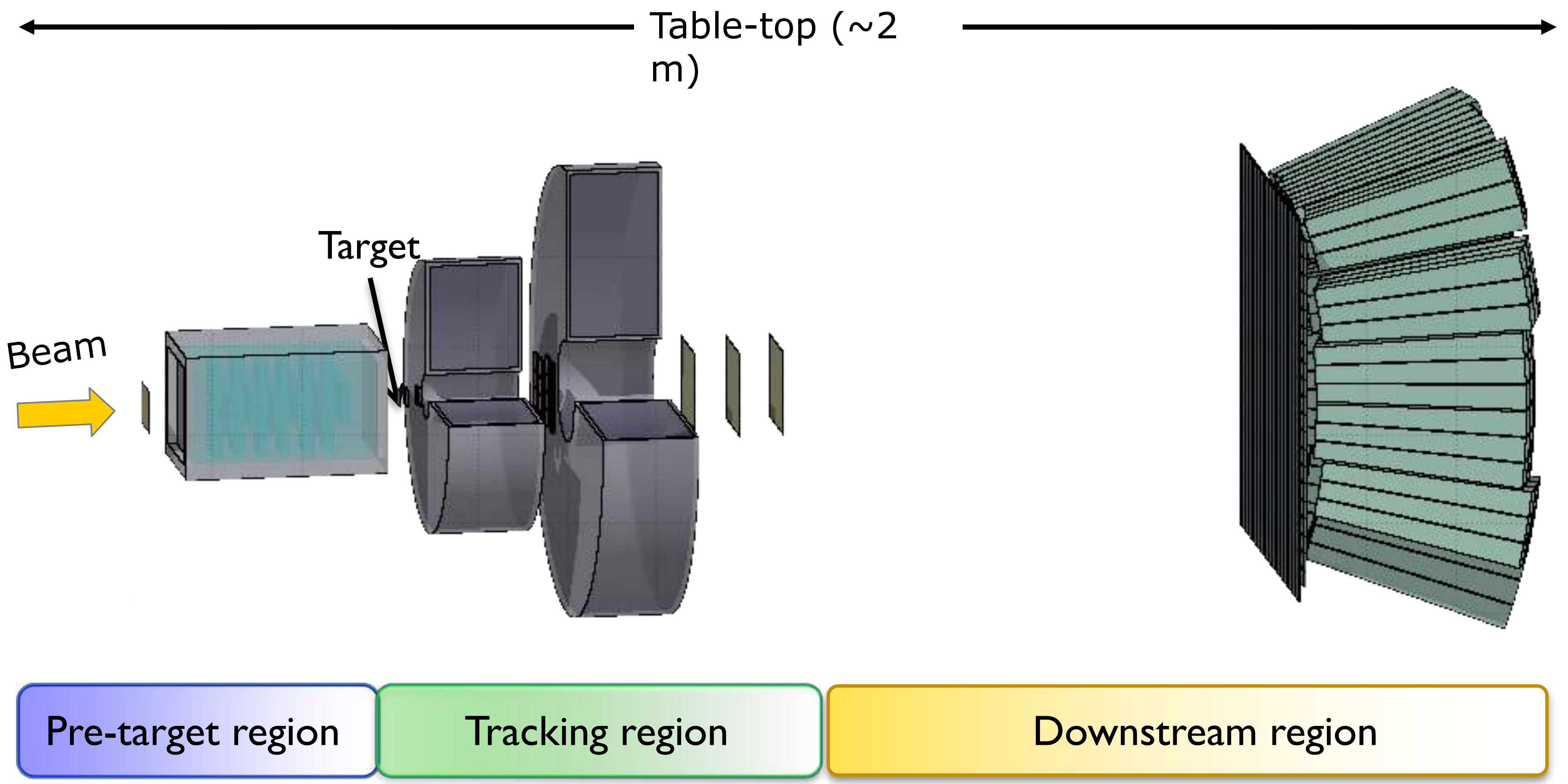
Design constraints

- Required accuracy from 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%
- Moveable, compact

- 2 different setups:
  - 'Electronic' setup: for measurements with heavy fragments (Z>2), emitted at small angles (setup covering up to 10°)

  - Emulsions: for measuring lighter fragments (Z<3), emitted at larger angles (setup covering up to 70°)

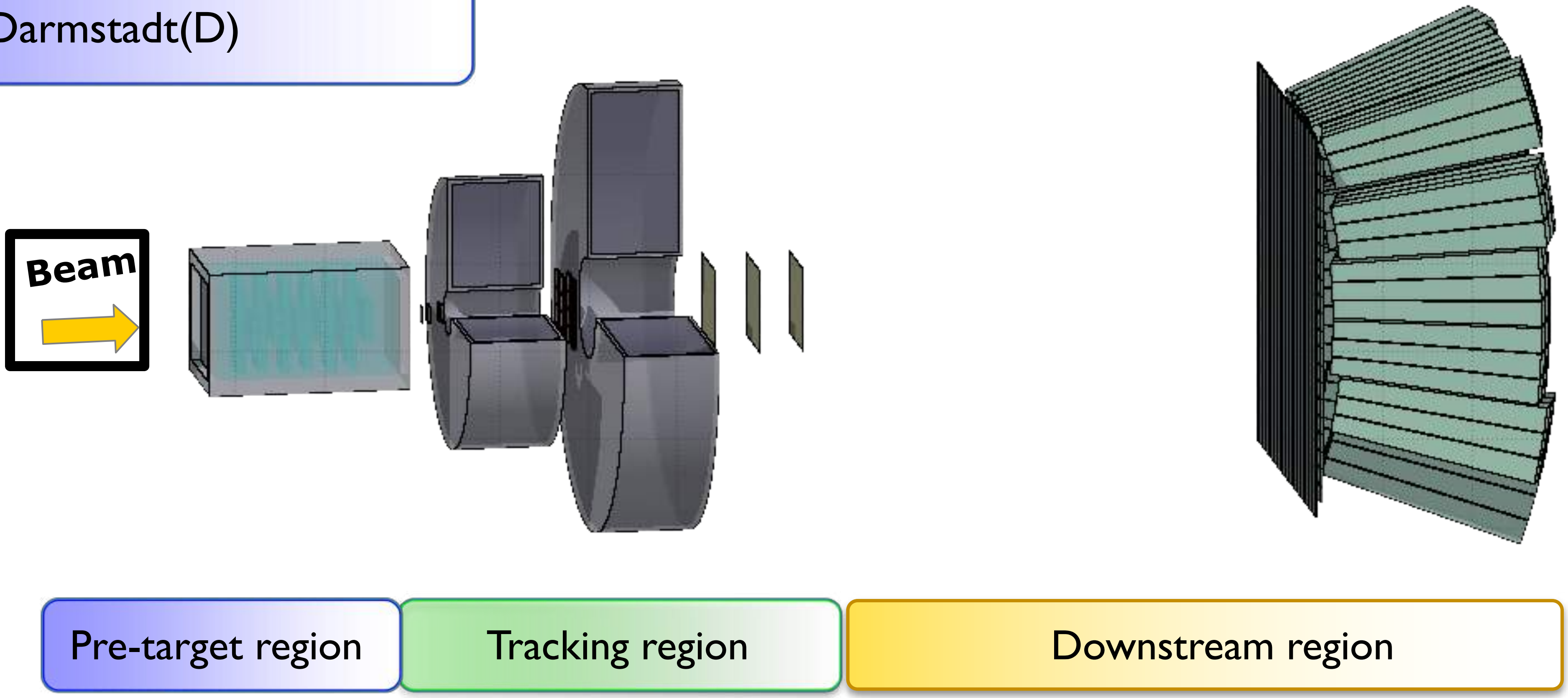
Electronic setup of FOOT



Electronic setup of FOOT

UNDER CONSTRUCTION

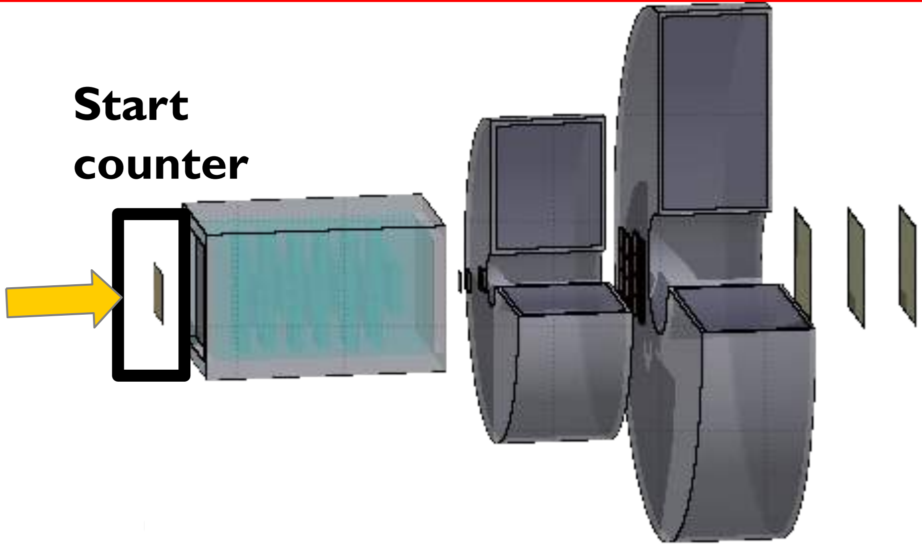
- Protons, Helium, Carbon. Oxygen
- Test at
  - CNAO, Pavia (IT)
  - HIT, Heidelberg (D)
  - GSI, Darmstadt(D)

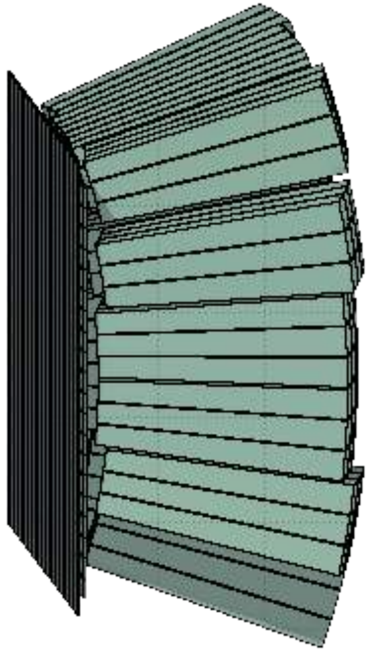


Electronic setup of FOOT

- Very thin (250 μm) plastic scintillator
- Beam **counter**
- Trigger and first time stamp of Time-Of-Flight (**TOF**)

Status: ready and already used for data acquisition



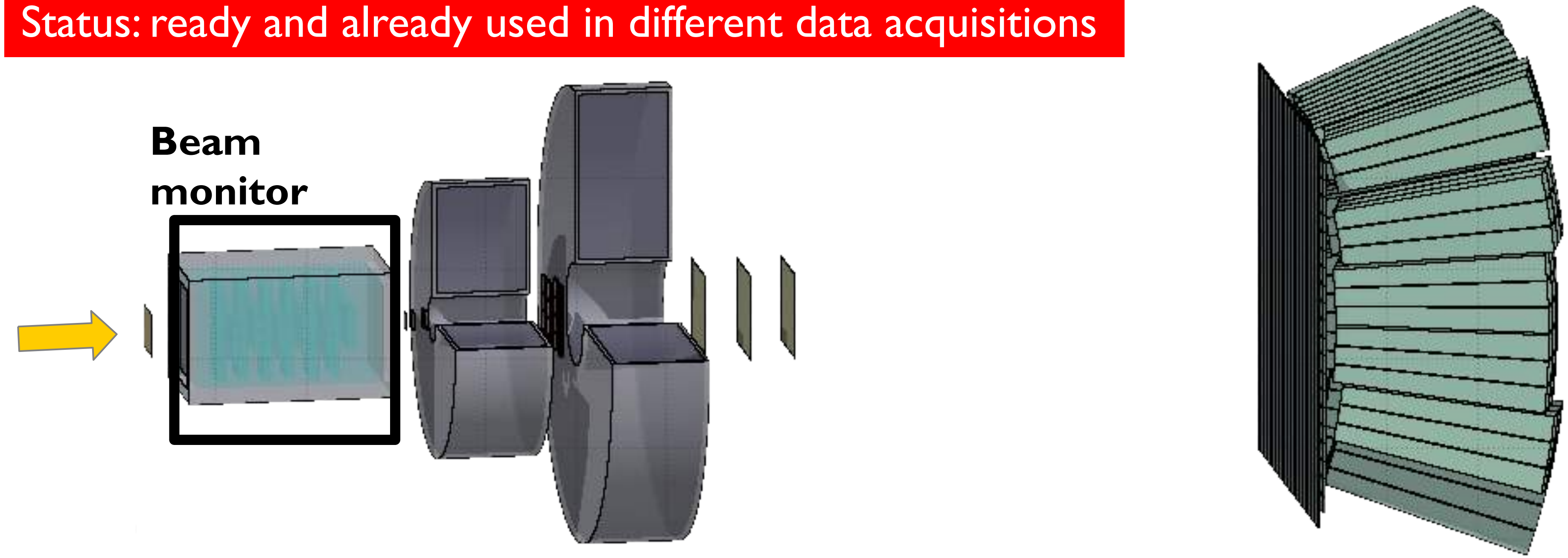


Pre-target region | Tracking region | Downstream region

Electronic setup of FOOT

- Drift chamber, from FIRST experiment
- **Position and direction** of particles
- Identifies possible interactions in the Start Counter

Status: ready and already used in different data acquisitions



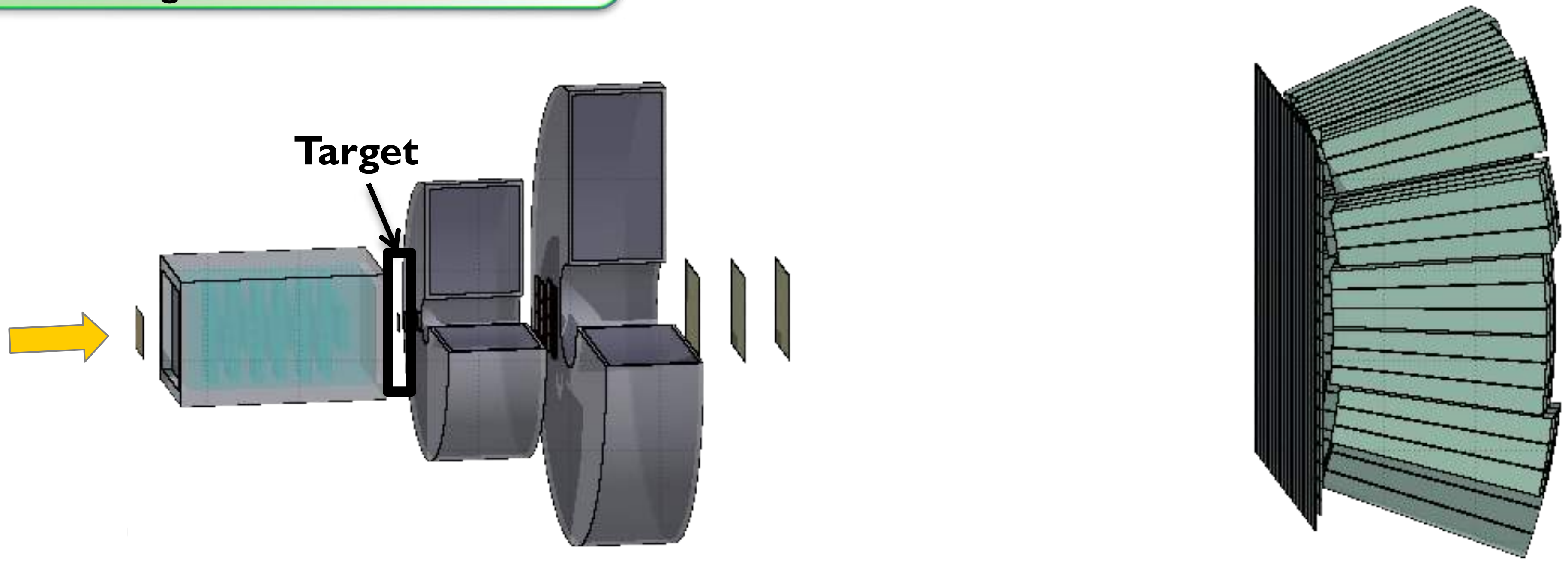
Pre-target region | Tracking region | Downstream region

Electronic setup of FOOT

Basic choice:

- Polyethylene (C_2H_4), graphite (C) target
- 2-5-10 mm thick

In the future other targets can be considered

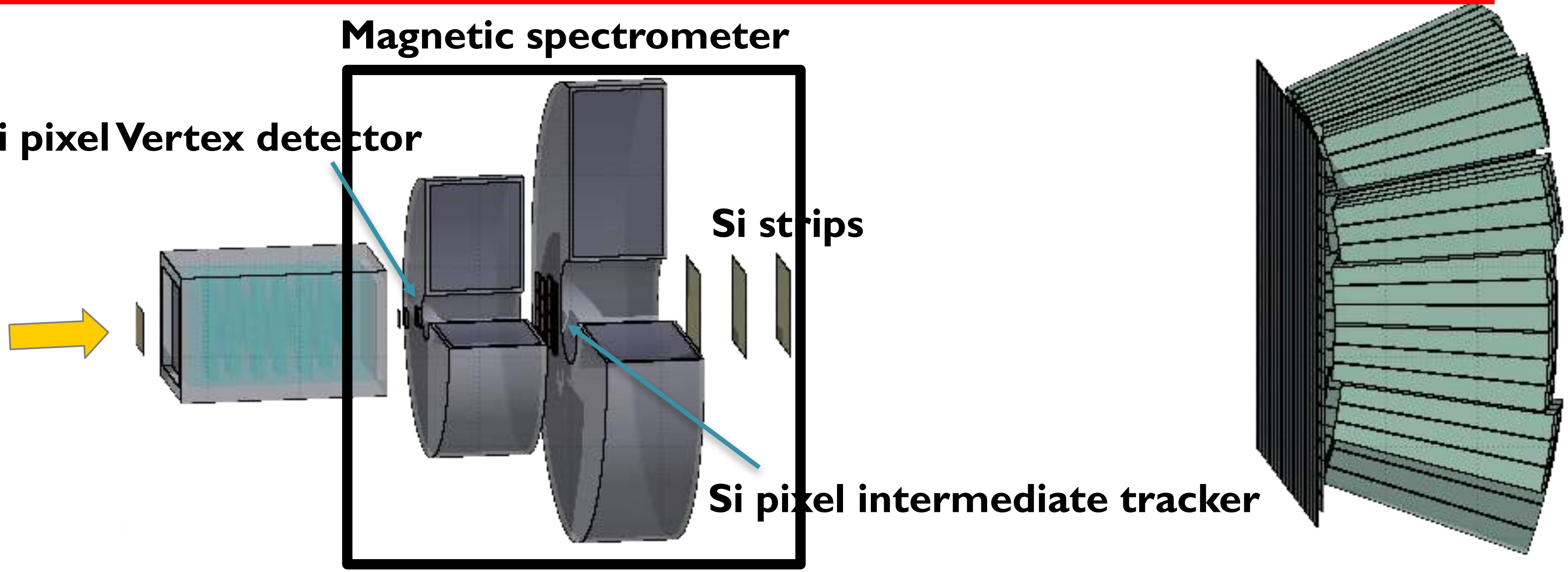


Pre-target region | Tracking region | Downstream region

Electronic setup of FOOT

- silicon trackers alternated to 2 magnets 0.9 and 1.4 T max B
- **Momentum** of the fragments and the **dE/dx** in the last silicon station :

Status: magnet now in production, silicon pixel vertex detector tested and operational, intermediate pixel detector under production, silicon strips tested last July,

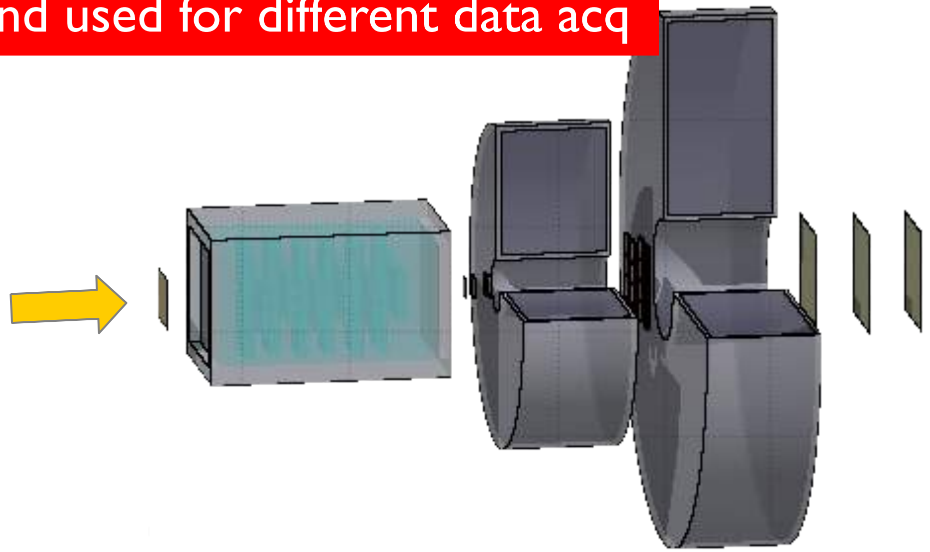


Pre-target region | Tracking region | Downstream region

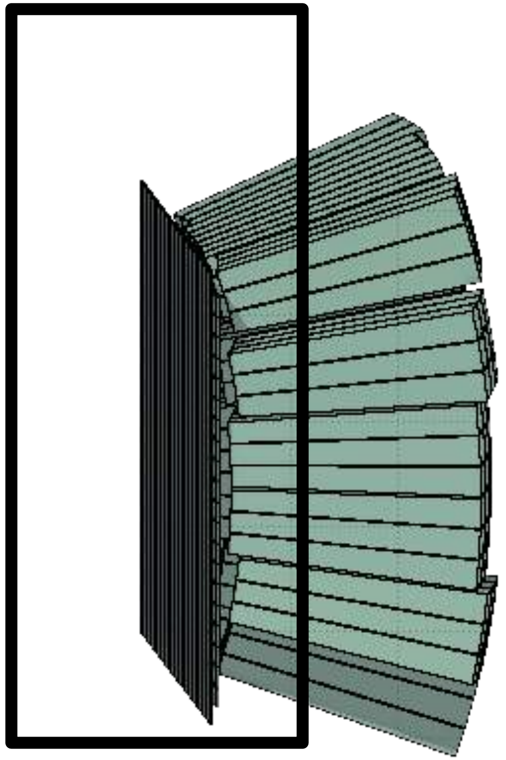
Electronic setup of FOOT

- TOF-Wall: thin (3 mm) plastic scintillator bars
- 2 orthogonal layers of bars: 20+20 bars
- TOF Wall measures:
  - **Energy deposited** in the scintillator (ΔE)
  - **Second time stamp for TOF**

Status: ready and used for different data acq



TOF Wall

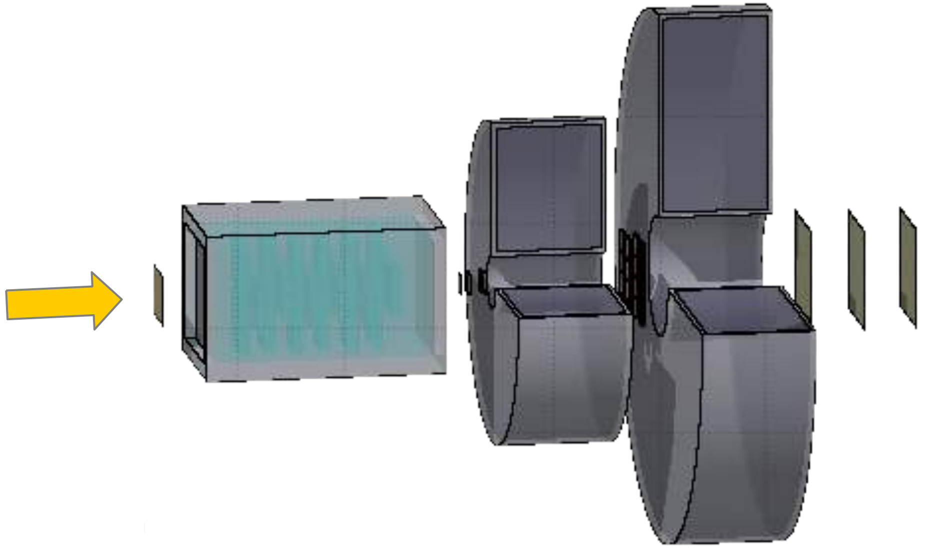


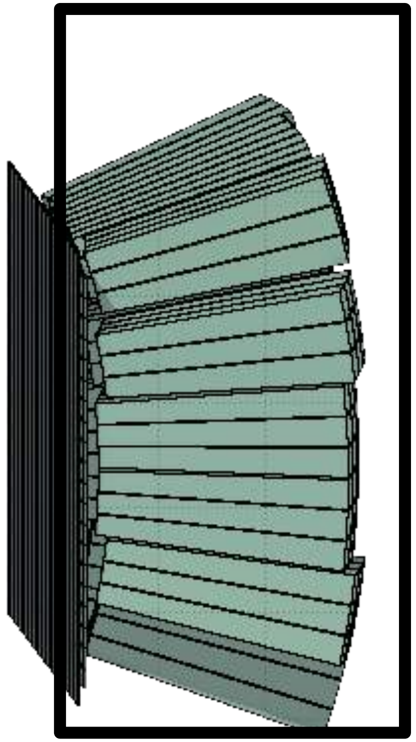
Pre-target region | Tracking region | Downstream region

Electronic setup of FOOT

- Thick BGO crystal
- **Kinetic energy** of the fragments

Status: first module ready and tested at GSI (July 2021)





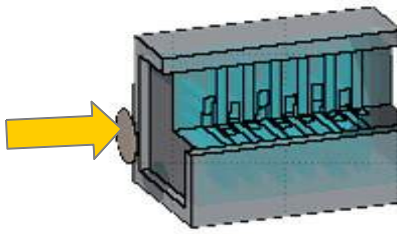
Pre-target region | Tracking region | Downstream region

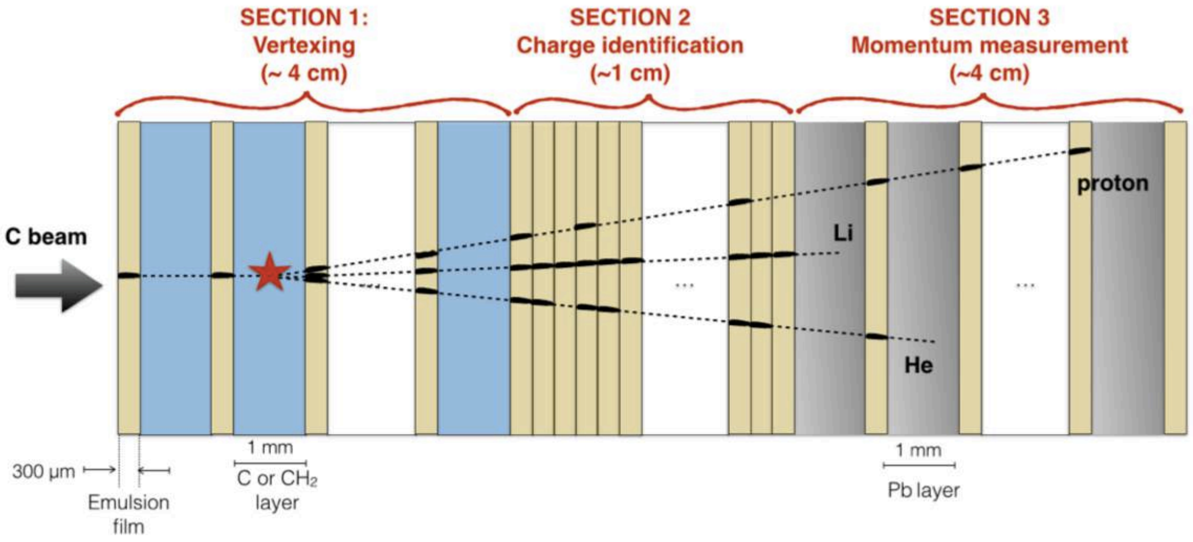
Emulsion setup of FOOT

Emulsion chamber setup

- Lighter fragments (**Z <= 3**) have wider angular aperture

Status: ready, first data taken



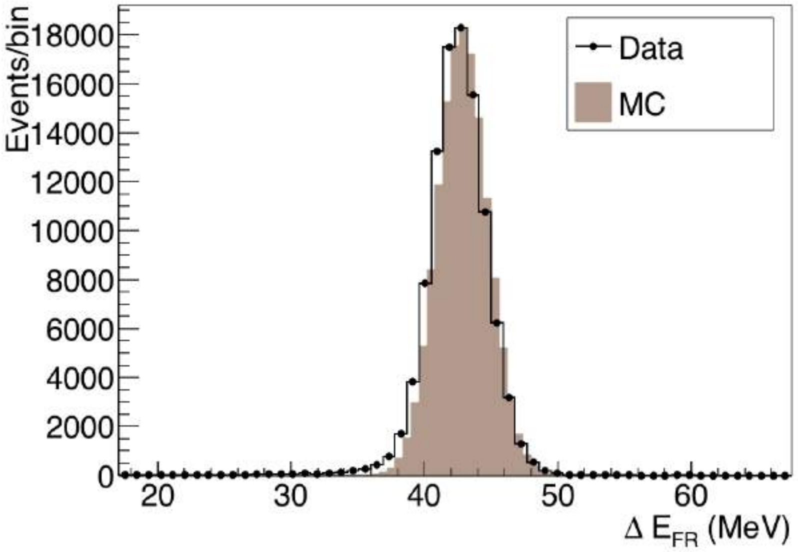


Pre-target region

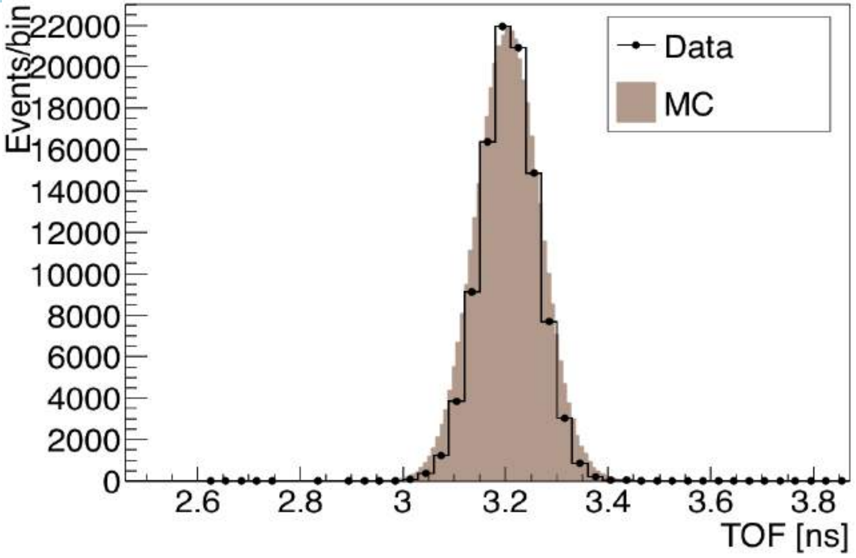
Recent results of electronic setup

2019 data, only TOF-wall and start counter

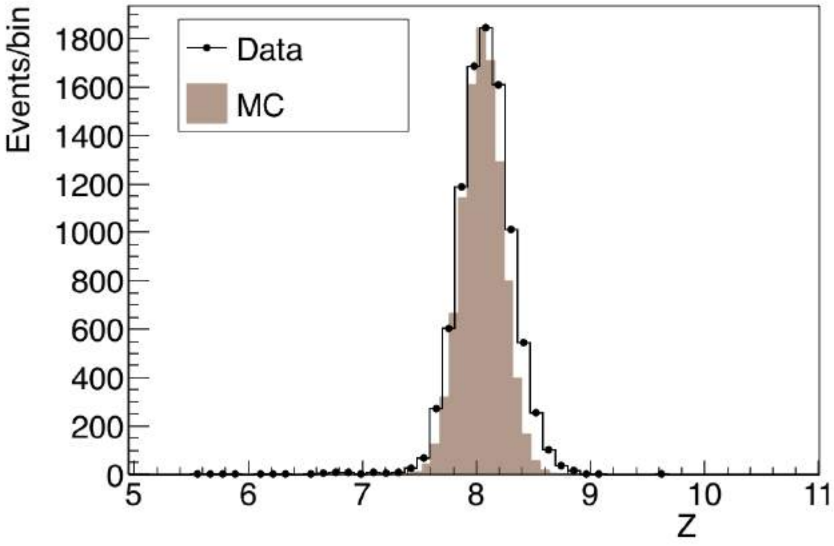
ΔE spectrum ^{12}C 260 MeV/u



TOF spectrum ^{12}C 115 MeV/u



Z spectrum ^{12}C 115 MeV/u



σ(ΔE)/ΔE
4 – 5.2% for C/O
5.7% for protons

+

σ(TOF)
54 - 84 ps for C/O
260 ps for protons

⇒

σ(Z)
2.5 - 4% for C/O
6.2% for protons

A. C. Kraan et. al., NIMA 2021: 1001(9):165206

Recent results of electronic setup

Results for the charge-changing cross section for the interaction of a beam of ^{16}O at 400 MeV/u on a 0.5 cm carbon target:

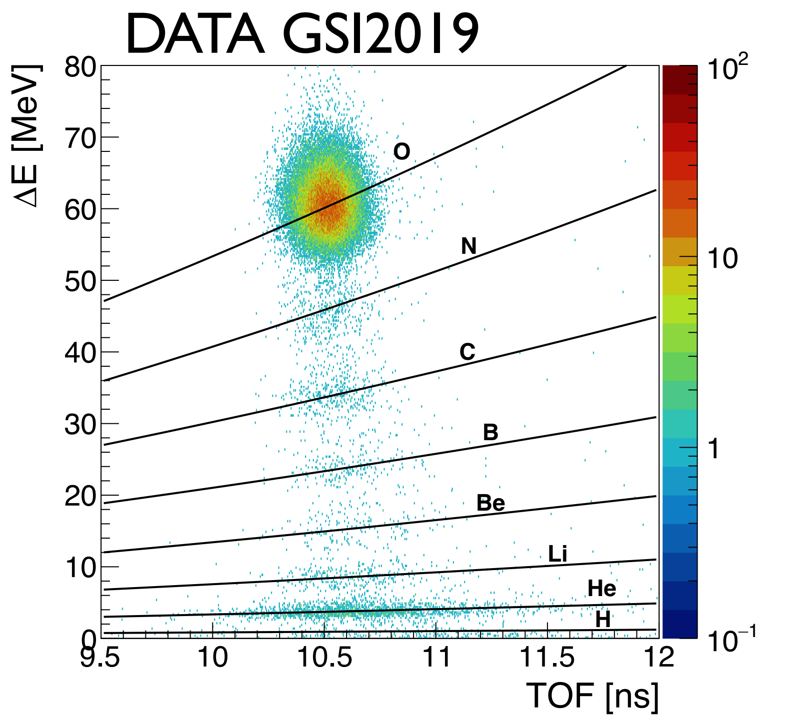
$$\sigma(Z) = \int_{E_{min}}^{E_{max}} \int_0^{\Delta\theta} \left(\frac{\partial^2\sigma}{\partial\theta\partial E_{kin}}\right) d\theta dE_{kin} = \frac{N_{frag}(Z)}{N_{prim} \cdot N_{TG} \cdot \epsilon(Z)}$$

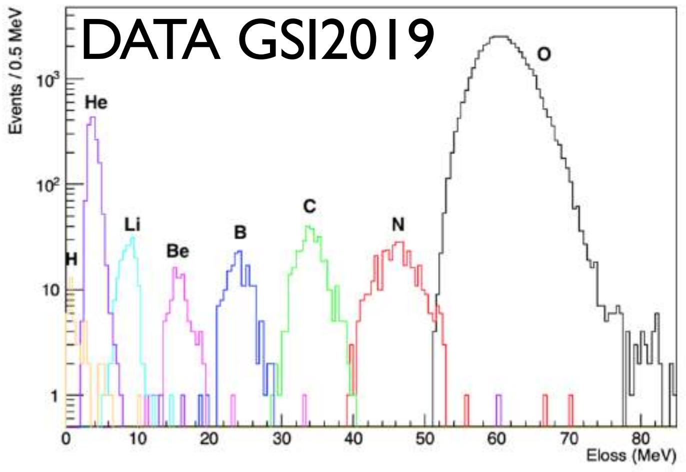
$$N_{TG} = \frac{\rho \cdot dx \cdot N_A}{A}$$

[cm^{-2}]

$$\begin{cases} \rho = 1.83 \text{ g/cm}^3 \\ dx = 0.5 \text{ cm} \\ A = 12.0107 \end{cases}$$

Element	$\sigma_{frag} \pm \Delta_{stat} \pm \Delta_{sys} [mbarn]$	$\Delta_{stat}/\sigma_{frag}$	$\Delta_{sys}/\sigma_{frag}$	$\sigma_{MC} [mbarn]$
He	$625 \pm 22 \pm 21$	3.6%	3.6%	621
Li	$85 \pm 10 \pm 5$	11.9%	5.6%	67
Be	$31 \pm 10 \pm 3$	31.8%	8.8%	33
B	$70 \pm 10 \pm 5$	14.9%	7.3%	38
C	$113 \pm 12 \pm 3$	10.9%	2.7%	81
N	$101 \pm 14 \pm 5$	13.7%	4.8%	105



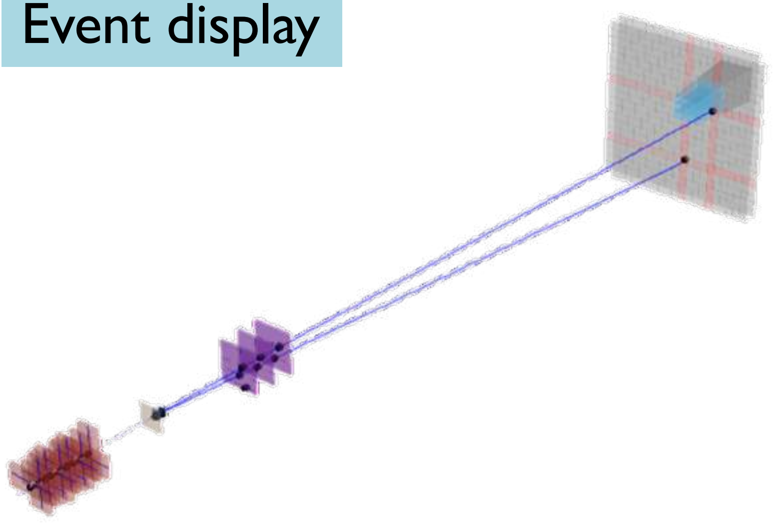


Recent results of electronic setup

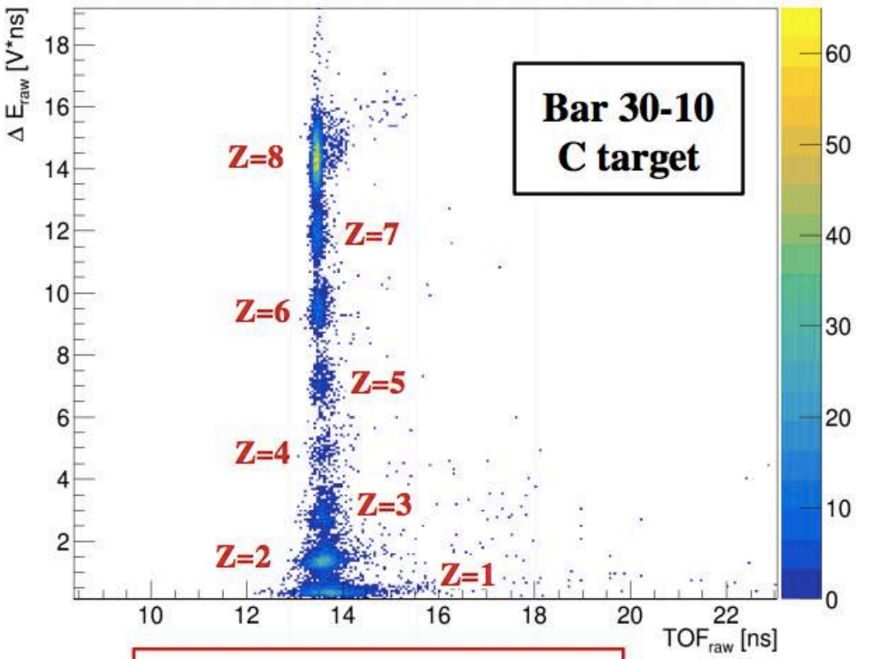
GSI July 2021 part of the electronic FOOT setup was brought to GSI

- ✓ Tested various subdetectors
- ✓ DAQ working well, all detectors integrated
- ✓ Software (SHOE) handles DAQ, data and MC decoding, processing and full event reconstruction.
- ✓ Event display working
- ✓ Subdetectors working

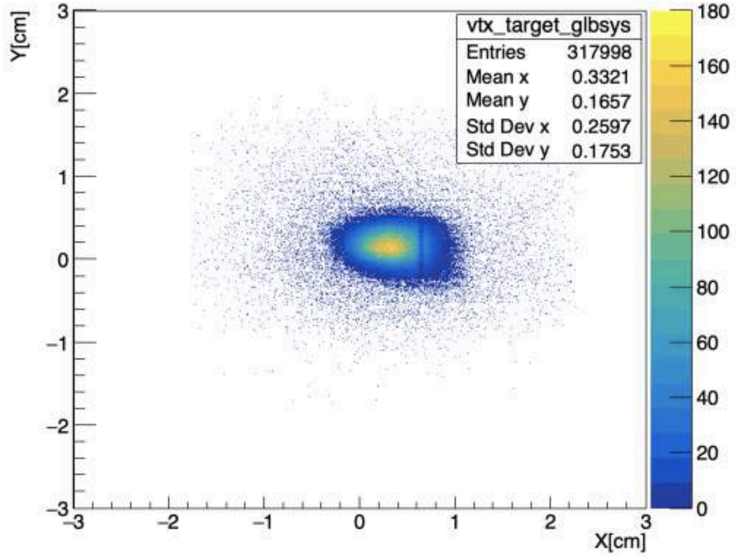
Event display



TOF-Wall+ start counter



Beam profile as seen by beam monitor+vertex detector



Recent results of emulsion setup

- Oxygen Beam @200 MeV and 400 MeV/u on C and C_2H_4 targets (2019)
- Carbon Beam @200 MeV and 400 MeV/u on C and C_2H_4 targets (2020)
- Identification of Z≤2 fragments with a cut-based analysis (provide also cosmic rays selection)
- Identification of Z ≥2 fragments with the Principal Component Analysis

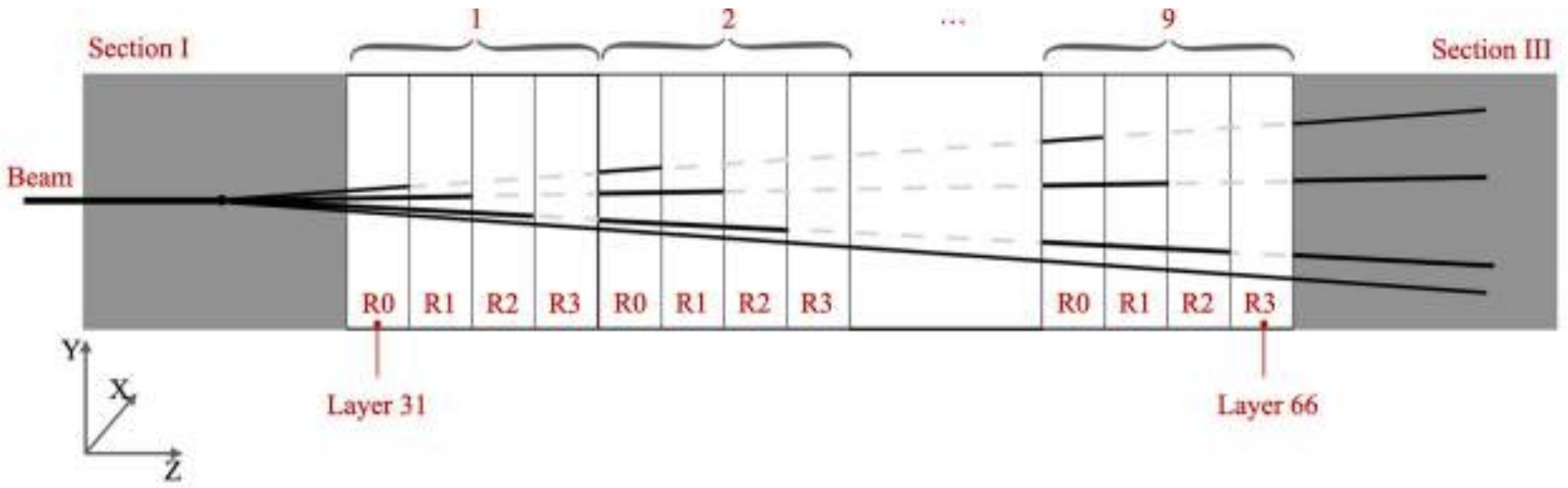
Measure light (Z≤3) fragments emitted within an angular acceptance up to 70°

Charge identification analysis

First analysis (Oxygen data): G. Galati et. al., Open Physics 2021; 19: 383–394

Method:

- Section II is divided into nine cells, each one consisting of four emulsion films that underwent different thermal treatments.
- The more base-tracks survive to thermal treatments, the higher the particle's Z.

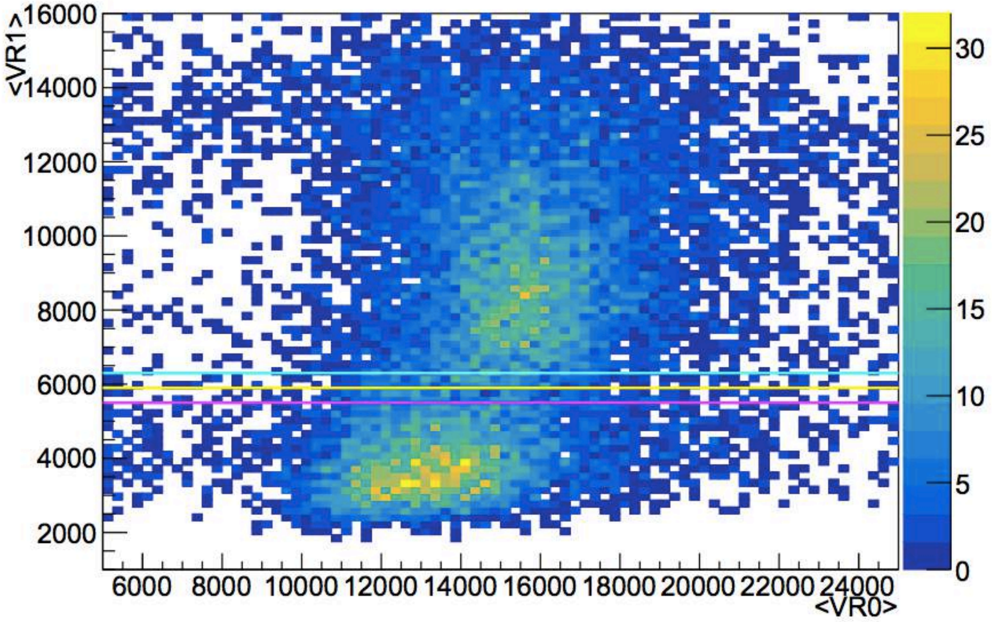


Recent results of emulsion setup

Result of charge identification analysis

- Volume Refreshing (VR) parameters are an estimate of the ionization (V) produced in the nuclear emulsions after two different thermal treatments (VR1 and VR2).

G. Galati et. al., Open Physics 2021; 19: 383–394



Separation between two different populations of ions (Z=1 and Z>2)

Z	Fragments classification					
	CB	PCA	Total	%	Syst. Err. (%)	Stat. Err. (%)
1	21,199	/	21,199	70	5	0.7
2	1,438	3,506	4,943	16	2	1.4
3	/	2,915	2,915	10	2	1.9
≥4	/	1,108	1,108	4	1	3.0
[illegible]	[illegible]	[illegible]	[illegible]			

Future

GSI

- Data analysis

CNAO

- New measurements planned in November 2021 and later in 2022

HIT Heidelberger Ionenstrahl-Therapiezentrum

- New measurements will be requested in 2022 (He beam)

FOOT FramentatiOn Of Target

- Complete detector
- Faster start counter
- Extension of FOOT to implement neutron detection. Two PRINs submitted
  - FOOTPRINT (principal investigator V. Patera): BGO calorimeter readout
  - RIPTIDE (principal investigator M. Villa): double n scattering with organic scintillators

Conclusions

- FOOT designed for fragmentation cross section measurements for particle therapy and radiation protection in space.
- 2 setups:
  - Emulsions: completed
  - Electronic setup: almost completed
- Preliminary cross section measurement of 400 MeV/u ^{16}O beam with a partial setup
- New data available ready to be analysed!
- New data takings soon at CNAO
- Multi-disciplinary context: physics, radiobiology, medicine, …
- National and international collaborations