Status of the FOOT experiment: the measurement of fragmentation of light ions in the 200-700 MeV/u energy range

Silvia Muraro (INFN Milano)
on behalf of the FOOT collaboration

FragmentatiOn Of Target (FOOT) experiment

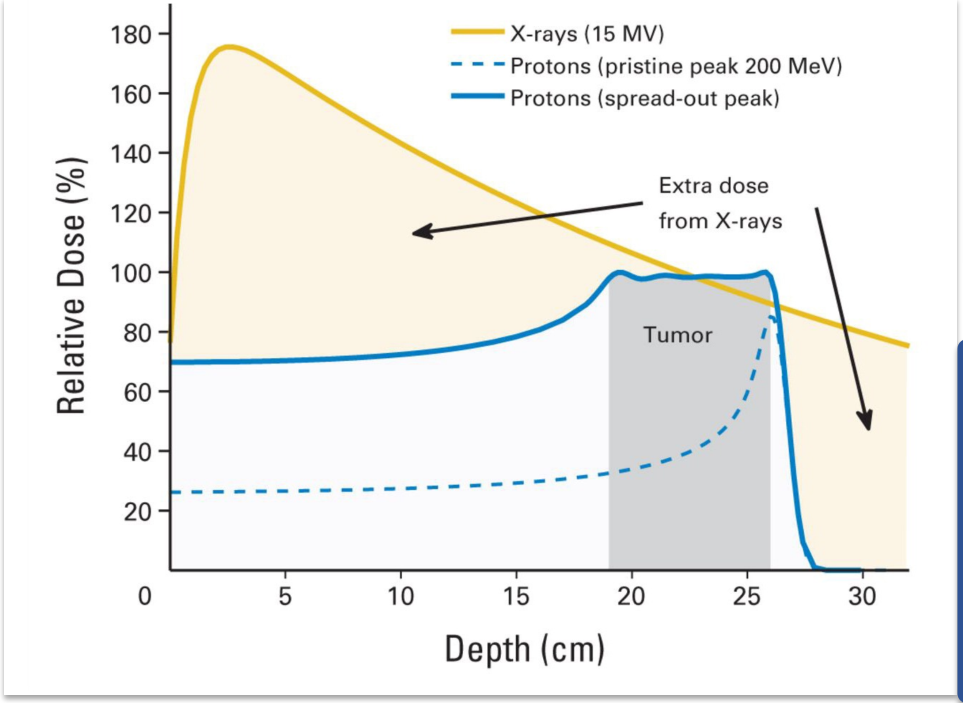
Purposes:

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

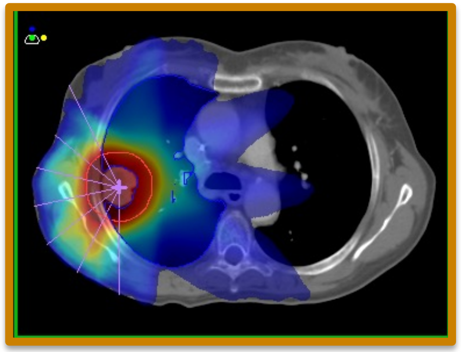
p + C + He + O +	C, O, H, (Si, Al)	$$\frac{d^2\sigma}{d\Omega\, dE_{\mathrm{kin}}}$$

Goal accuracy <5%

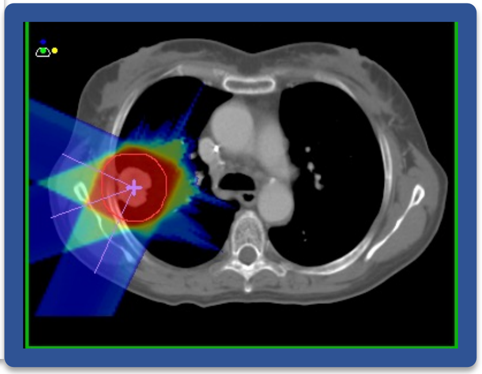
$$60\ \mathrm{MeV}/u < E_{kin} < 400\ \mathrm{MeV/u}$$



Traditional radiotherapy



Particle therapy



Particle Therapy

Limited dose in entrance channel, max dose release in the Bragg peak -> Better dose conformation

Fragmentation of projectile (if Z>1) and of target nuclei in tissues leads to production of Z>1 secondaries -> high relative biological effectiveness

There not enough experimental data in the relevant energy region to benchmark calculation models

FragmentatiOn Of Target (FOOT) experiment

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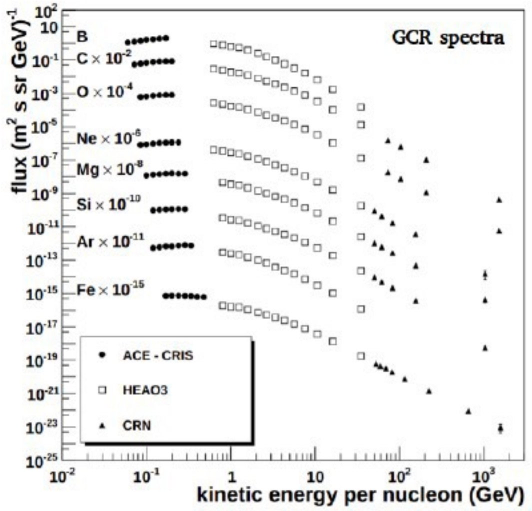
FOOT is an applied nuclear physics experiment that aims at measuring the double differential nuclear fragmentation cross-section for ions at energies of interest for **particle therapy** and **radioprotection in space**

p + | C + | He + | O + → C, O, H, (Si, Al)

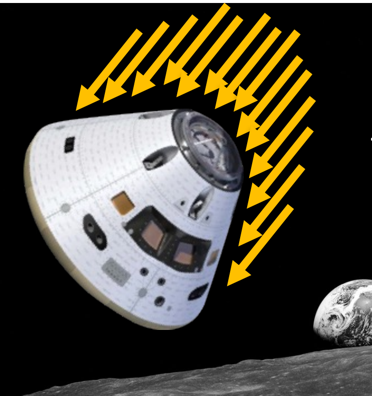
$$\frac{d^2\sigma}{d\Omega\, dE_{kin}}$$

Goal accuracy <5%

$$E_{kin} > 0.5\ \mathrm{GeV/u}$$



Mirko Boezio and Emiliano Mocchiutti. Chemical composition of galactic cosmic rays with space experiments. *Astroparticle Physics*, s 39–40, 08 2012.



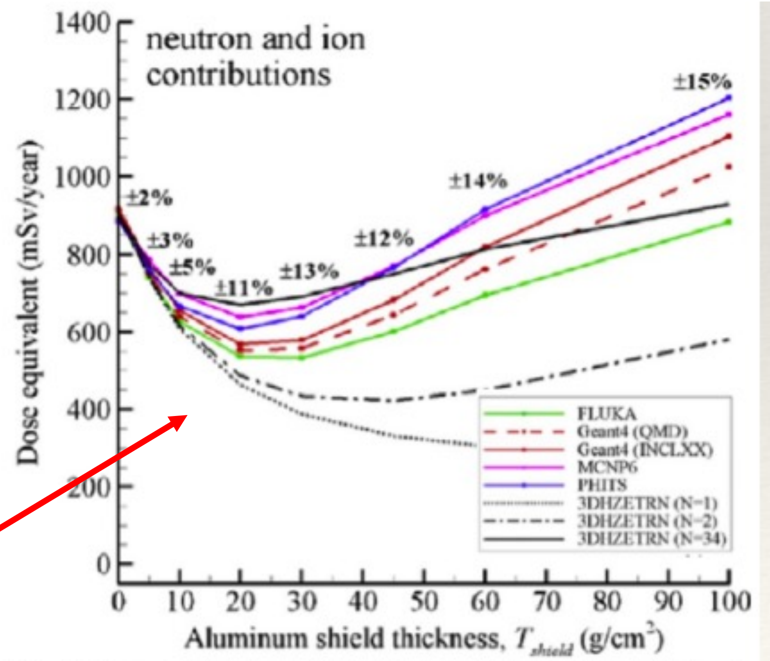
Humans to Mars and on the lunar base

Spacecraft shielding and radioprotection in space

Radiation hazards in space from GCR and SPE is one of the obstacles for missions

In the case of GCR, high contribution to the equivalent dose from primary light ions (mainly p and ^{4}He) and HZE fragments (high energy heavy ions)

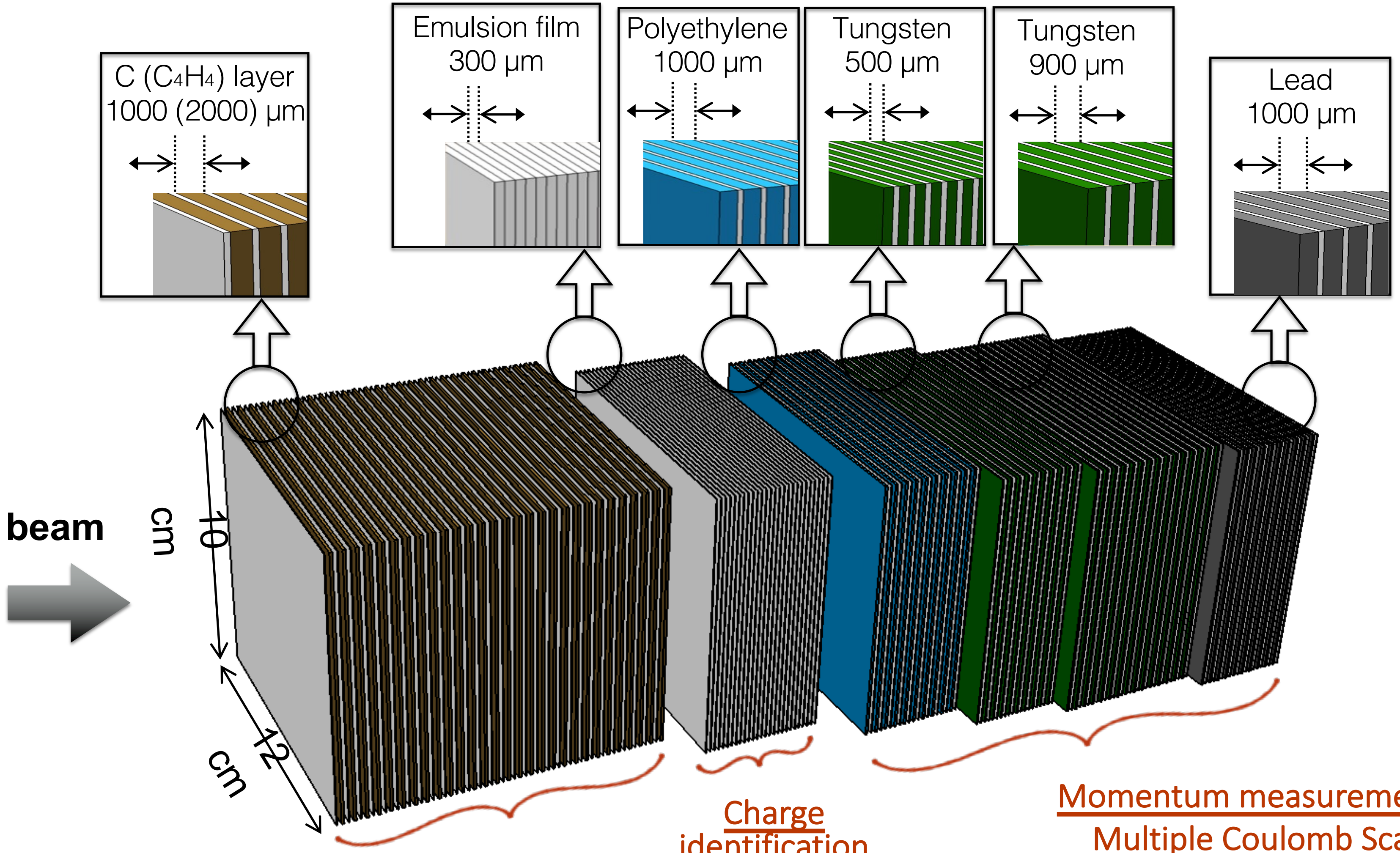
Large discrepancies among transport codes



Slaba TC, Bahadori AA, Reddell BD, Singleterry RC, Clowdsley MS, Blattnig SR. Optimal shielding thickness for galactic cosmic ray environments. *Life Sci Space Res.* (2017) 12: 1–15. doi:10.1016/j.lssr.2016.12.003.

The FOOT experiment: the emulsion spectrometer

Z ≤ 3
Wide angular acceptance



Vertex detector
Tracking of all charged particles
alternated layers of emulsions and target (C or C_2H_4)

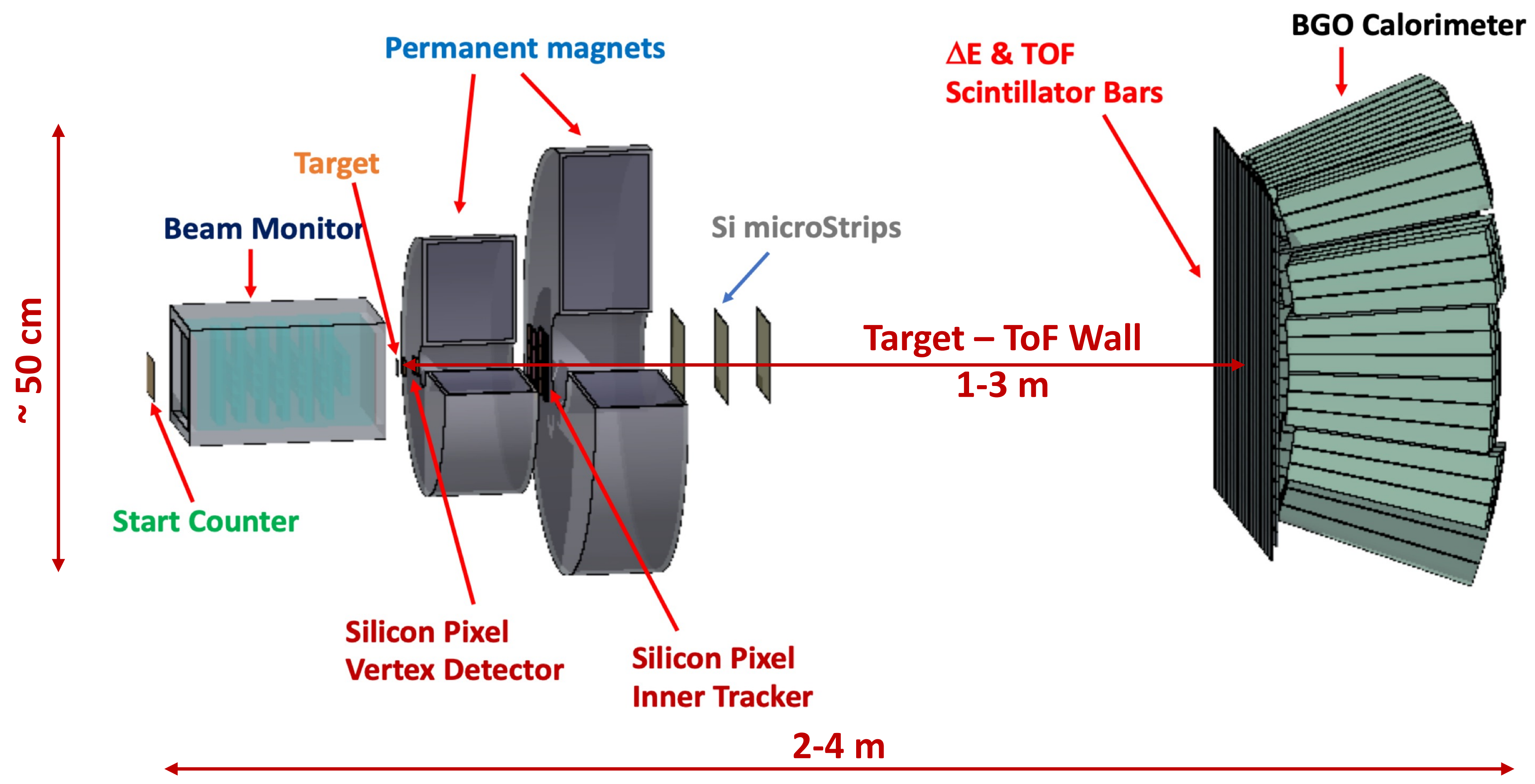
Charge identification
only emulsion layers

Momentum measurement by range and Multiple Coulomb Scattering (MCS) and isotope identification
alternated layers of emulsions and passive material (plastic, tungsten and lead)

The FOOT experiment: the electronic spectrometer

The FOOT detector dimensions are limited to fit the experimental rooms of different PT treatment centers / experimental facility (CNAO, HIT - Heidelberg, GSI) with ion beams.

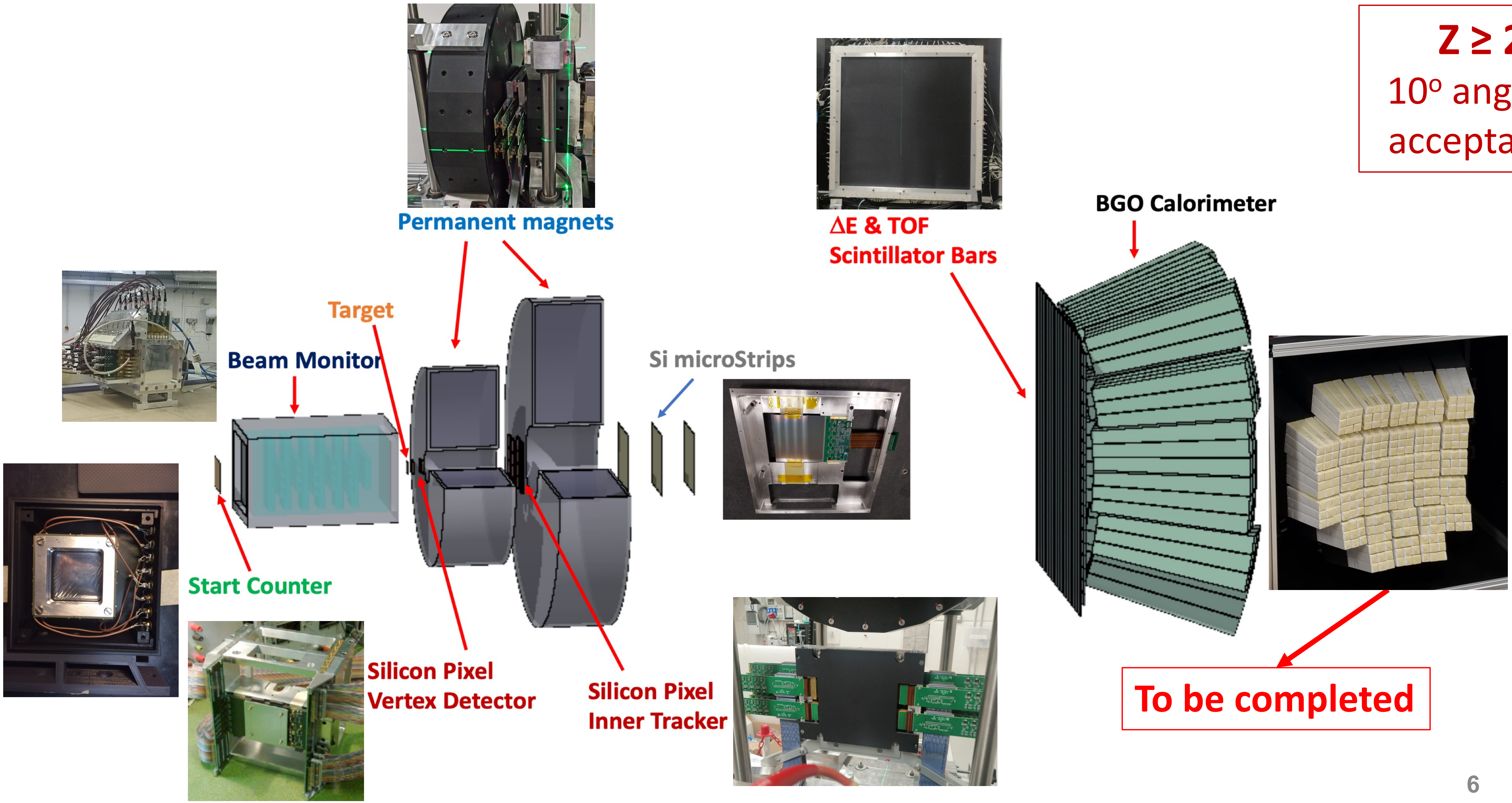
$Z \geq 2$
10^o angular acceptance



The FOOT experiment: the electronic spectrometer

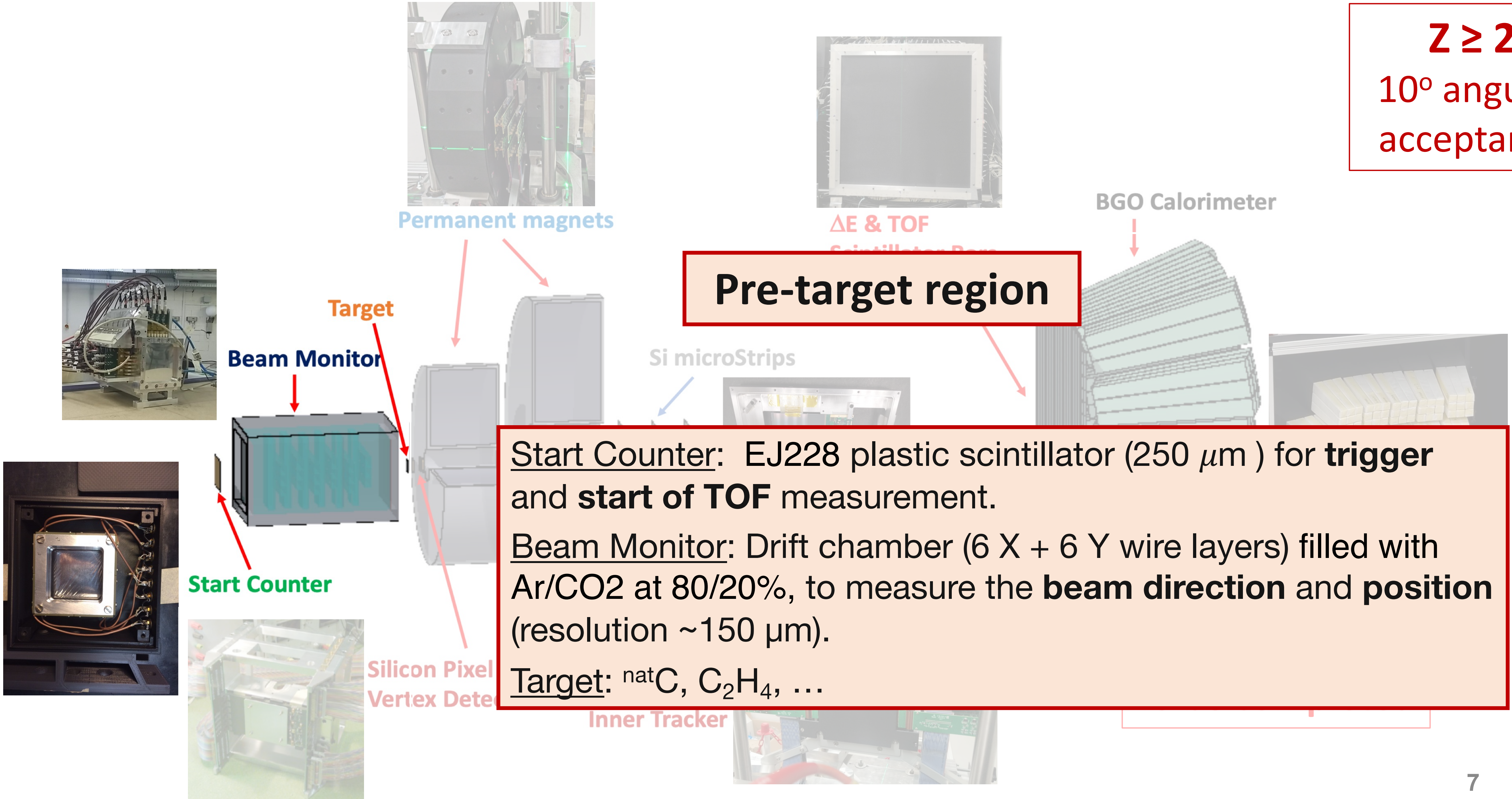
$Z \geq 2$

10^{o} angular acceptance



The FOOT experiment: the electronic spectrometer

Z ≥ 2
10^o angular acceptance



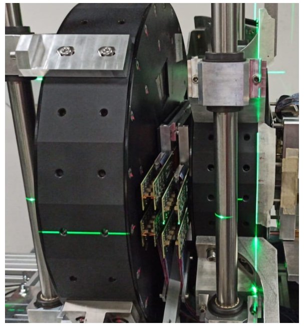
Start Counter: EJ228 plastic scintillator (250 μm) for **trigger** and **start of TOF** measurement.

Beam Monitor: Drift chamber (6 X + 6 Y wire layers) filled with Ar/CO2 at 80/20%, to measure the **beam direction** and **position** (resolution ~150 μm).

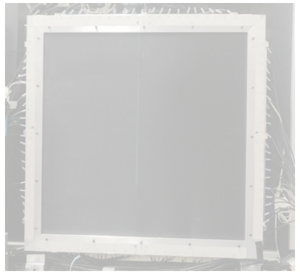
Target: ^{nat}C, C_2H_4, …

The FOOT experiment: the electronic spectrometer

Tracking and magnetic region



Permanent magnets

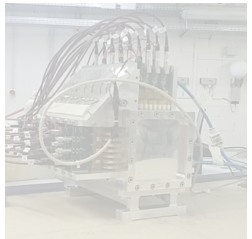


ΔE & TOF Scintillator Bars

BGO Calorimeter

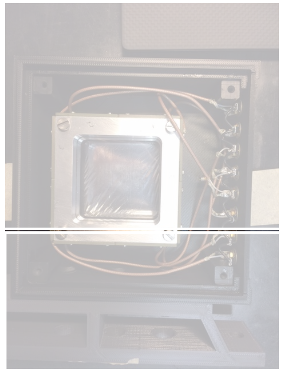
Z ≥ 2

10^{o} angular acceptance

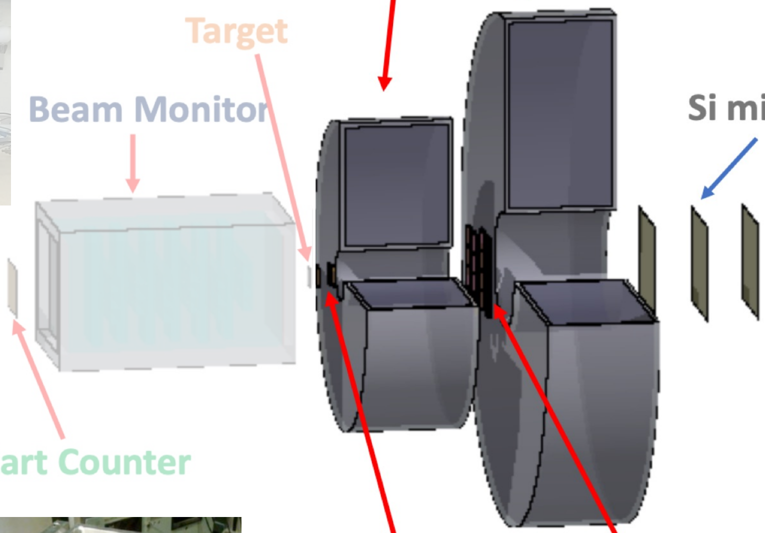


Target

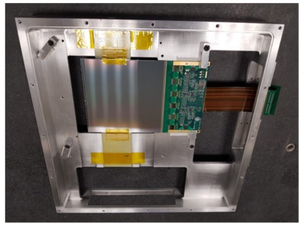
Beam Monitor

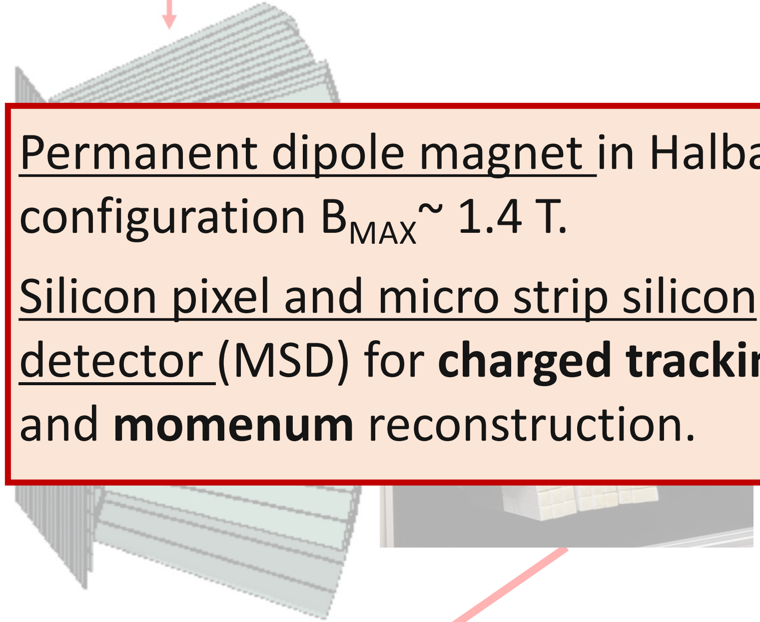


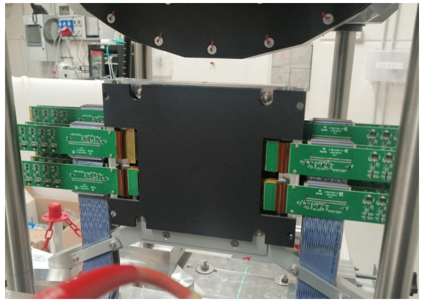
Start Counter



Si microStrips







Silicon Pixel Vertex Detector

Silicon Pixel Inner Tracker

Permanent dipole magnet in Halbach configuration B_{MAX}~ 1.4 T.

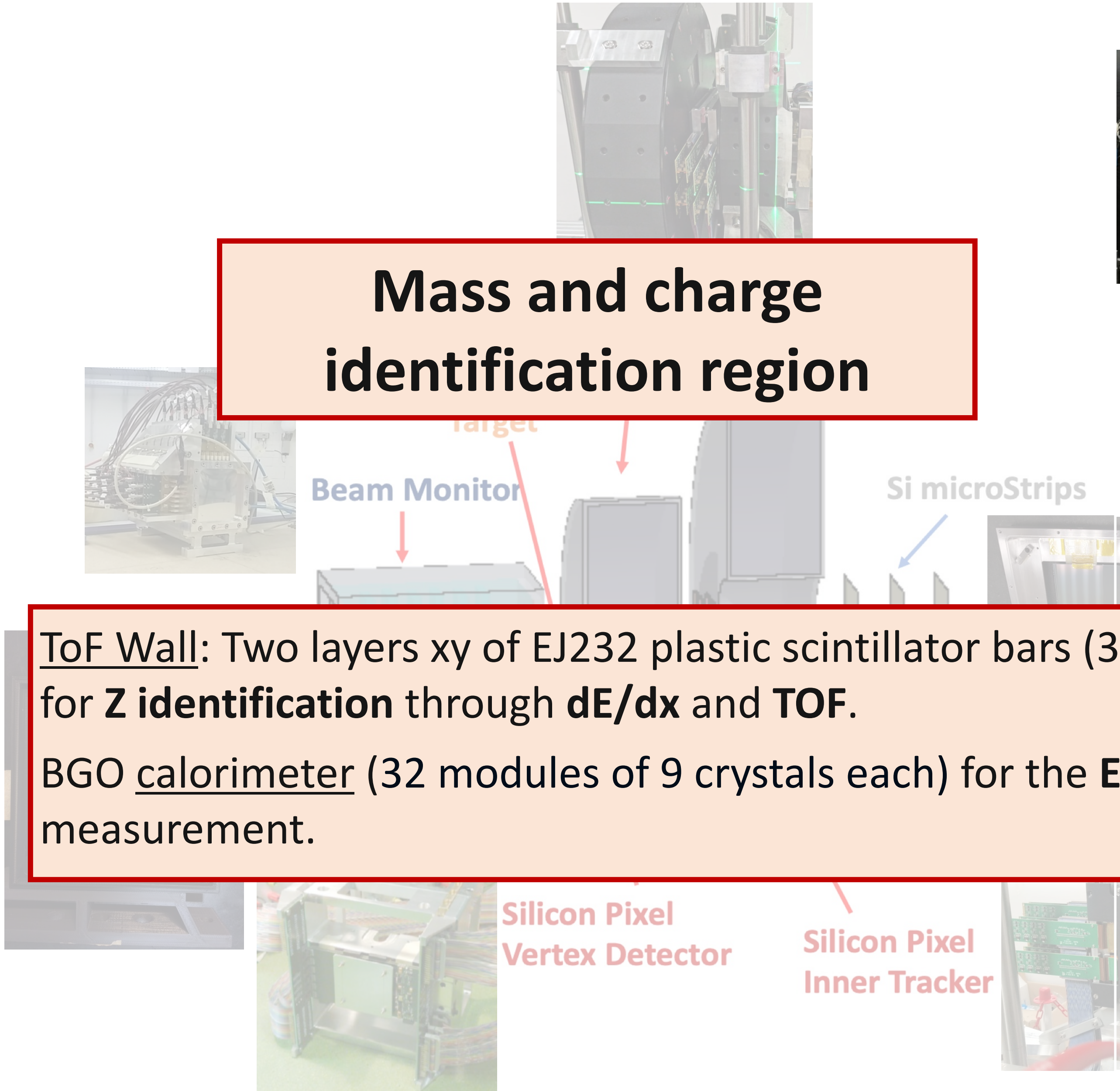
Silicon pixel and micro strip silicon detector (MSD) for **charged tracking** and **momenum** reconstruction.

To be completed

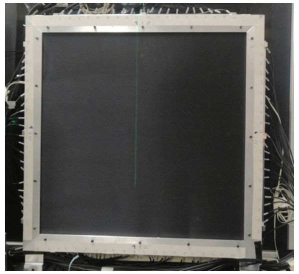
The FOOT experiment: the electronic spectrometer

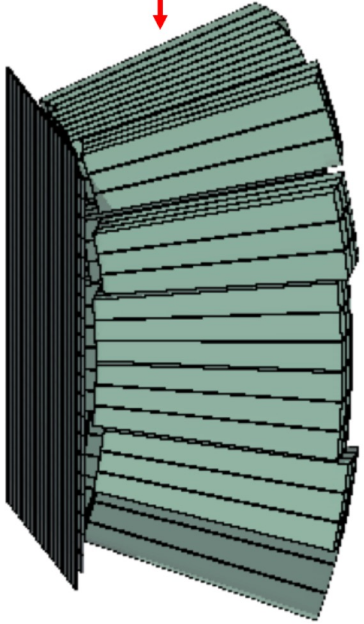
$Z \geq 2$

10^{o} angular acceptance



Mass and charge identification region





To be completed

ToF Wall: Two layers xy of EJ232 plastic scintillator bars (3 mm thick) for **Z identification** through **dE/dx** and **TOF**.

BGO calorimeter (32 modules of 9 crystals each) for the $\mathbf{E_{kin}}$ measurement.

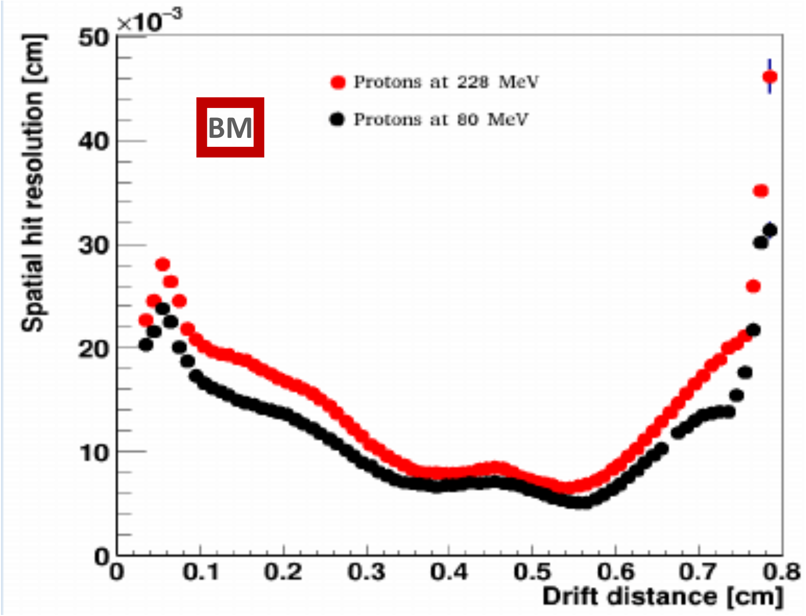
The FOOT Priority Physics Program

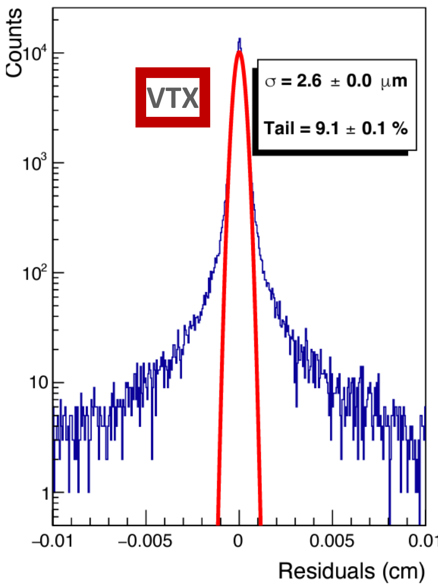
Specific measurements related with Particle Therapy & Radioprotection in Space

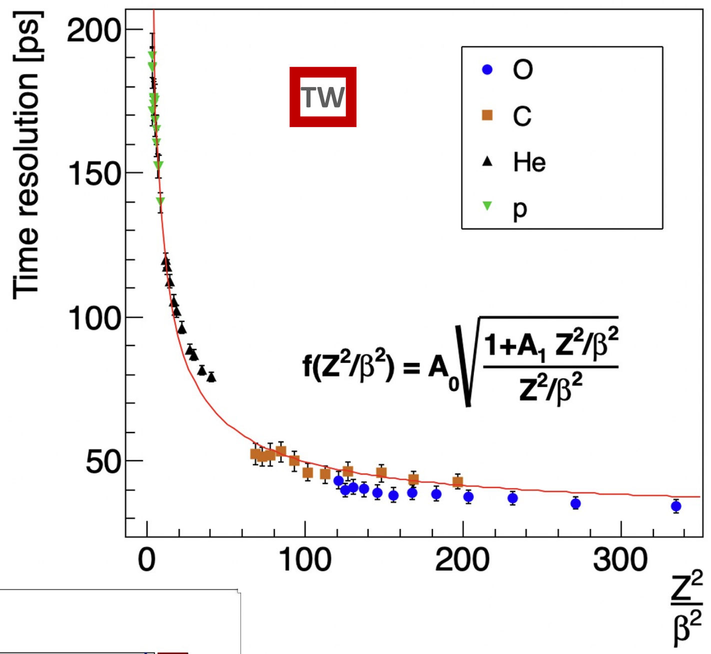
target C, C_2H_4, PMMA ($C_5O_2H_8$) ➔ cross sections on C, O and H

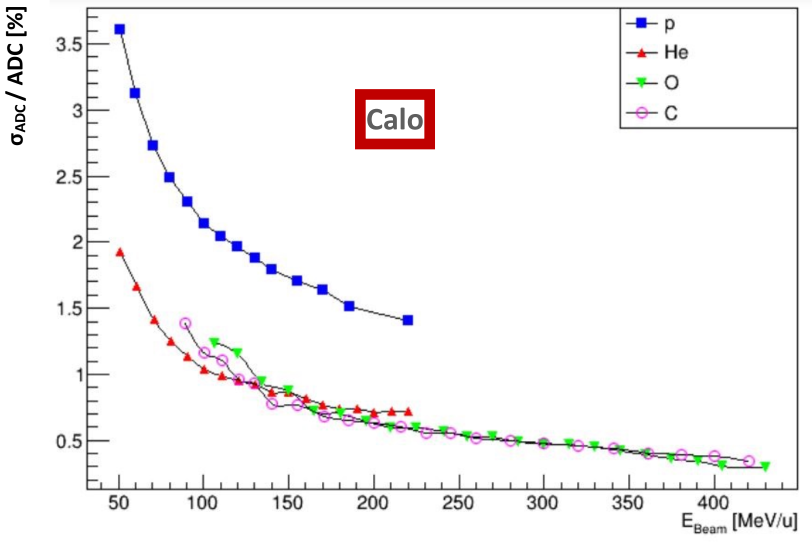
Phys	Beam	Target	Energy (MeV/u)	Inv/direct kinematics
Target Frag. PT	^{12}C	C, C_2H_4	200	inv
Target Frag. PT	^{16}O	C, C_2H_4	200	inv
Beam Frag. PT	^{12}C	C, C_2H_4, PMMA	200-400	dir
Beam Frag. PT	^{16}O	C, C_2H_4, PMMA	200-400	dir
Beam Frag. PT	^{4}He	C, C_2H_4, PMMA	100-250	dir
Rad. Prot.space	^{4}He	C, C_2H_4, PMMA	500-1000	dir
Rad. Prot.space	^{12}C	C, C_2H_4, PMMA	500-1000	dir
Rad. Prot.space	^{16}O	C, C_2H_4, PMMA	500-1000	dir

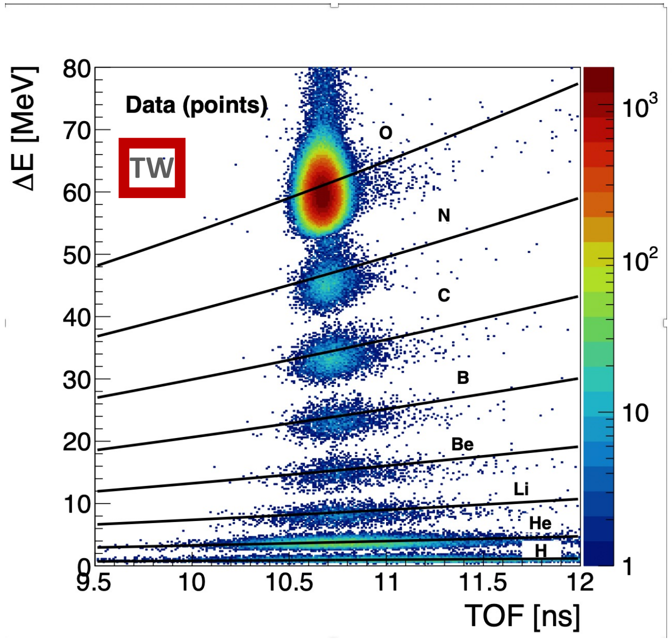
FOOT performances and status











FOOT performances:

$\sigma(E_{kin})/E_{kin} < 3\%$

$\sigma(TOF) \sim 50$ ps ($Z>2$)

$\sigma(\Delta E)/\Delta E \sim 4\text{-}5\%$

$\sigma(p)/p < 5\%$

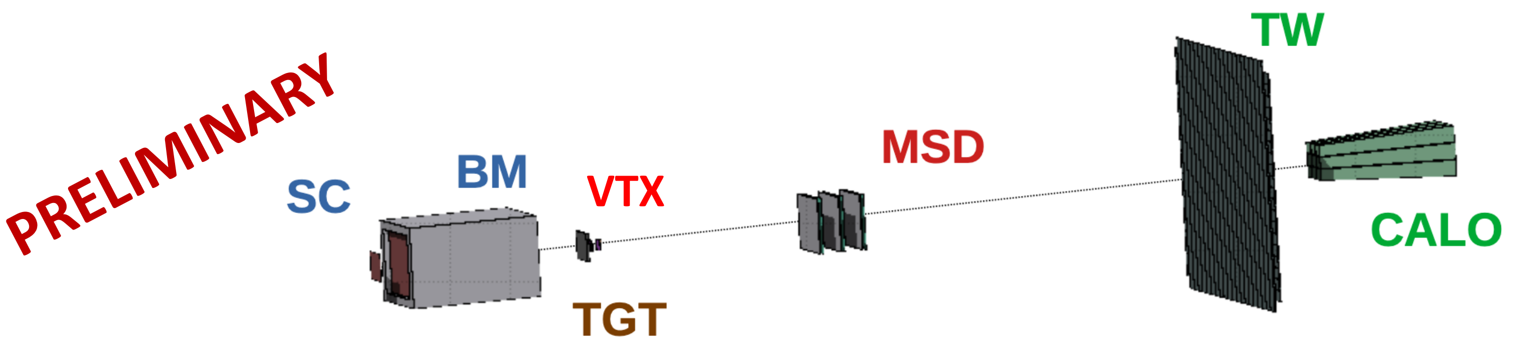
Detectors status:

- The setup is almost completed
- Different detectors already characterized: TOF system, Drift chamber, Vertex
- Characterization of trackers (IT and MSD) and calorimeter ongoing

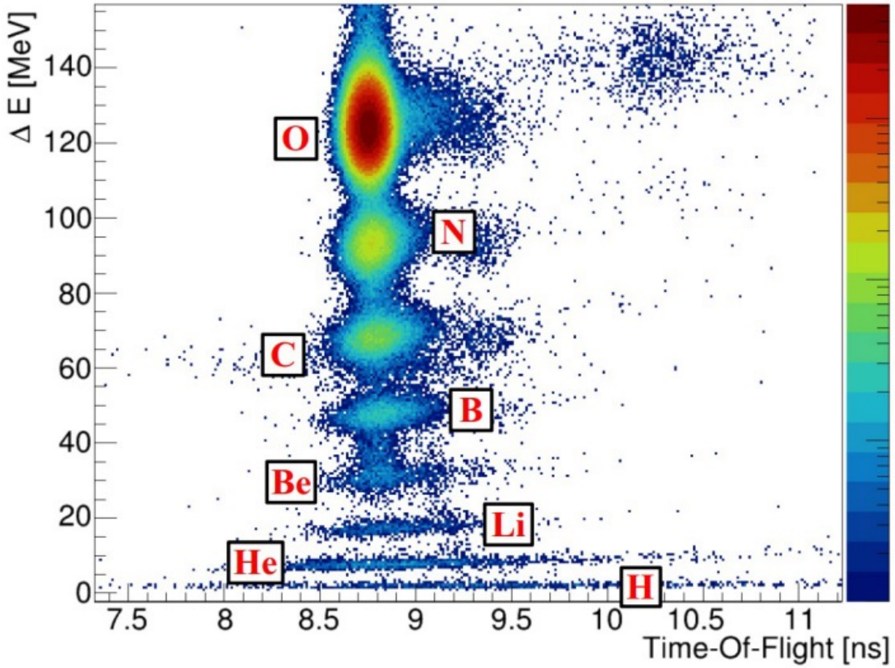
Some results from GSI 2021 data (engineering run)

Measurements at GSI, Beam: ^{16}**O**, **400 MeV/n**, Target: ^{nat}**C**

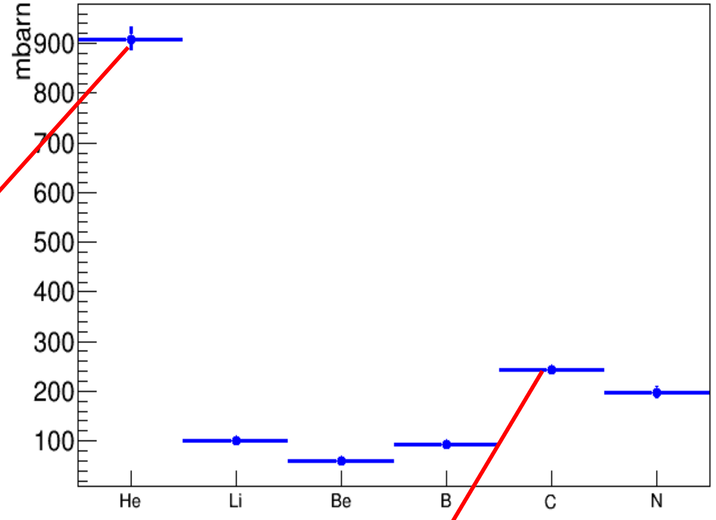
No magnet. One calorimeter module only (not used for analysis).



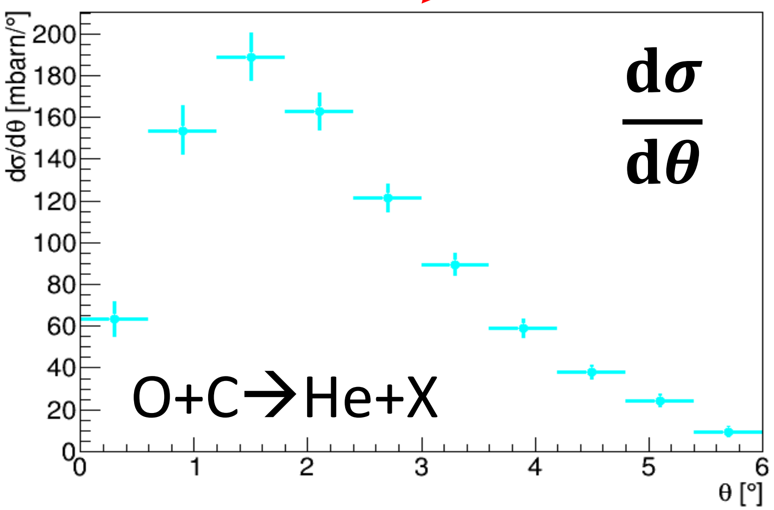
Particle Z identification

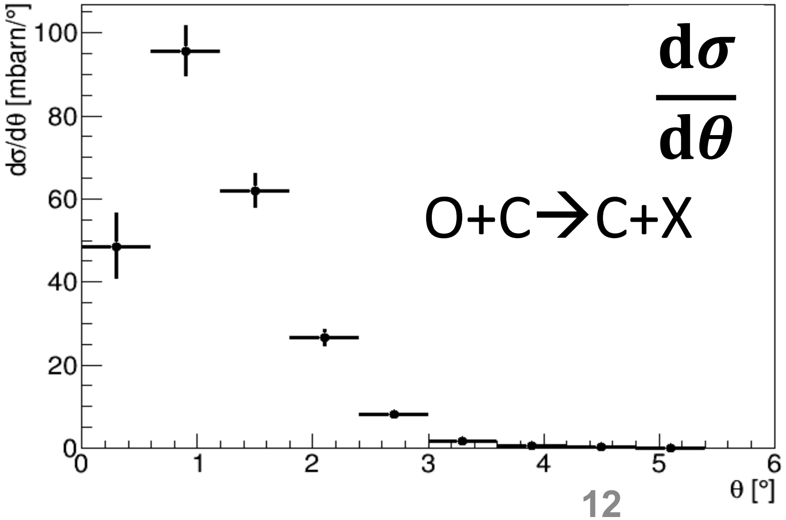


Production cross section for specific elements



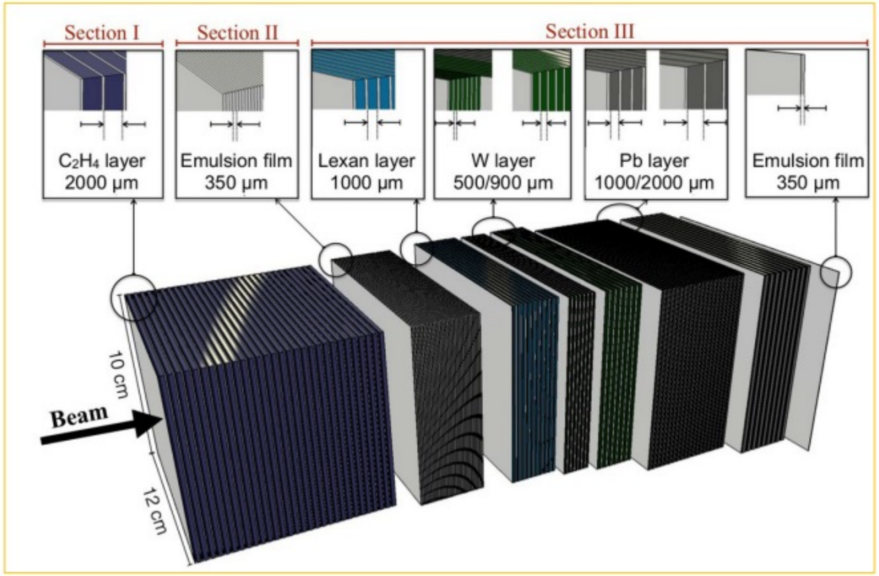
First angular cross section measurements





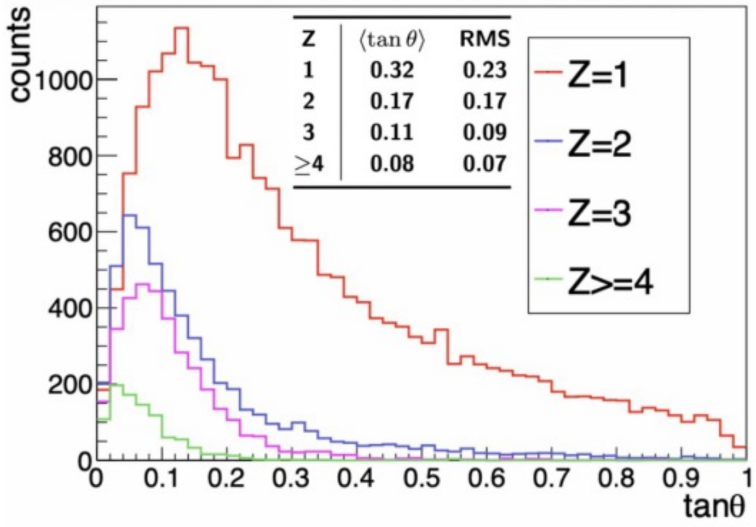
Emulsion results, GSI 2019/21 data

Charge identification of fragments with the emulsion spectrometer of the FOOT experiment; G. Galati et al., Open Physics 2021; 19: 383–394



Beam: ^{16}O, 200 MeV/u

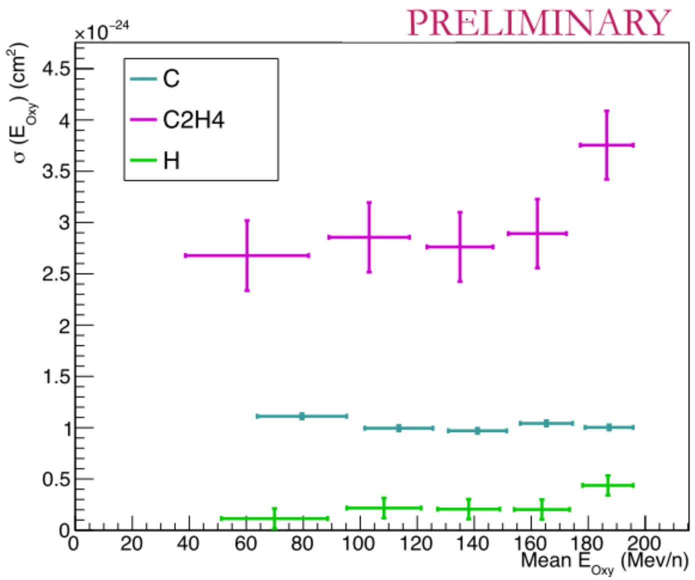
Target: ^{nat}C, C_2H_4



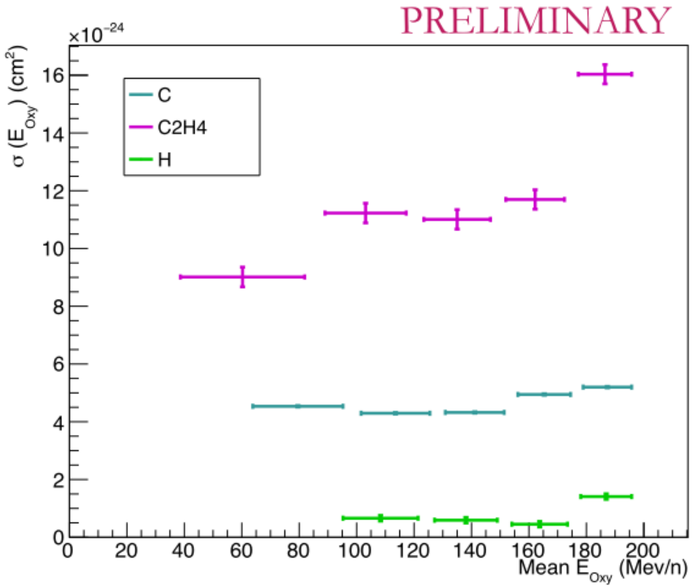
Two target technique to extract cross sections on H

$$\sigma|_H = \frac{1}{4}(\sigma|_{C_2H_4} - 2\sigma|_C)$$

Total reaction cross section



Total charged production cross section



Summary of preliminary data takings campaigns

First publication on physics results with the electronic set-up:
Elemental fragmentation cross sections for a 16O beam of 400 MeV/u kinetic energy interacting with a graphite target using the FOOT ΔE-TOF detectors;
M.Toppi et al.; Frontiers in Physics, 10, 2022.
Related to the 2019 campaign at GSI, with TOF and dE/dx for charge identification

Electronic set-up:

GSI	2019-2021	($^{16}O + {}^{nat}C$, 200-400 MeV/u)
HIT	2022	($^{4}He + {}^{nat}C$, 100-220 MeV/u)
CNAO	2022	($^{12}C + {}^{nat}C$, 200 MeV/u)
CNAO	2023	($^{12}C + {}^{nat}C$ and C_2H_4, 200 MeV/u)

Emulsions:

GSI	2019	($^{16}O + {}^{nat}C$ and C_2H_4, 200-400 MeV/u)
GSI	2020	($^{12}C + {}^{nat}C$ and C_2H_4, 700 MeV/u)
CNAO	2023	($^{12}C + {}^{nat}C$ and C_2H_4, 200 MeV/u)

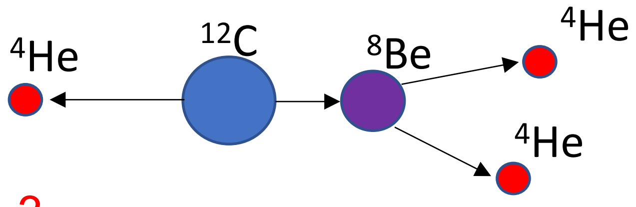
Further possible measurements in nuclear physics: α-clustering at intermediate energies

There exist a lot of data about clustering phenomenology at Coulomb barrier and Fermi energies, but not enough at 200 MeV/u and beyond, where the mechanism of nuclear reactions becomes more and more dominated by nucleon-nucleon collisions

We plan to start an analysis of FOOT data in terms of **α-clustering.**
We shall first investigate the exclusive channels $^{12}C \rightarrow 3\,\alpha$; $^{16}O \rightarrow 4\,\alpha$.

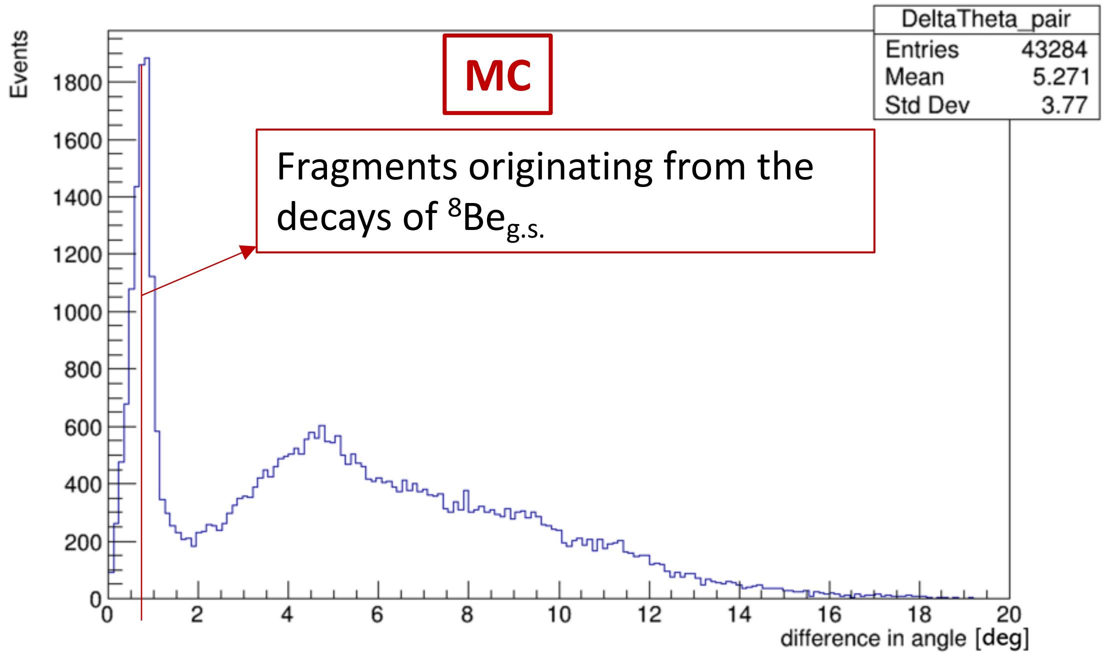
Poster session:
Analysis of the -clustering phenomena in the fragmentation of 12C and 16O ions at 200 MeV/u in the FOOT experiment.
Y. Dong, A. Caglioni, G. Battistoni, S. Muraro, I. Mattei

MC study shows that FOOT is able to identifiy intermediate states by studing angular correlation between α pairs.



For example:
$^{12}C \rightarrow {}^{8}Be + \alpha \rightarrow 3\,\alpha$

Kinematic reconstruction allow the measurement of the excitation energy of intermediate states



Conclusions

We are on the edge of completing the electronic detector.

Detector comprehension is constantly increasing.

Some physics results published, other almost ready to be published.

2019-2022: preliminary test runs with emulsion setup and incomplete electronic detector

Dec 2023: first «engineering run» with full detector at CNAO

For the **future** we are looking forward to perform fragmentation cross section measurements with different beams, targets and energies, both for electronic and emulsion set-up.

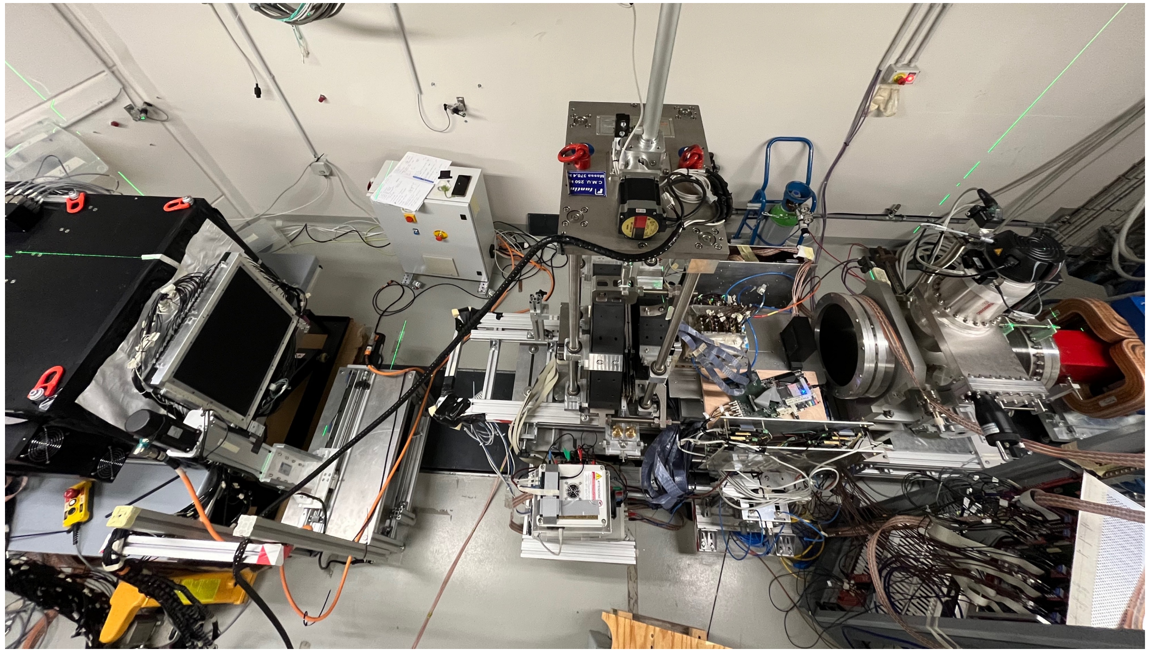
In 2024: first true physics run at CNAO with ^{12}C beam (mainly 200 MeV/u)

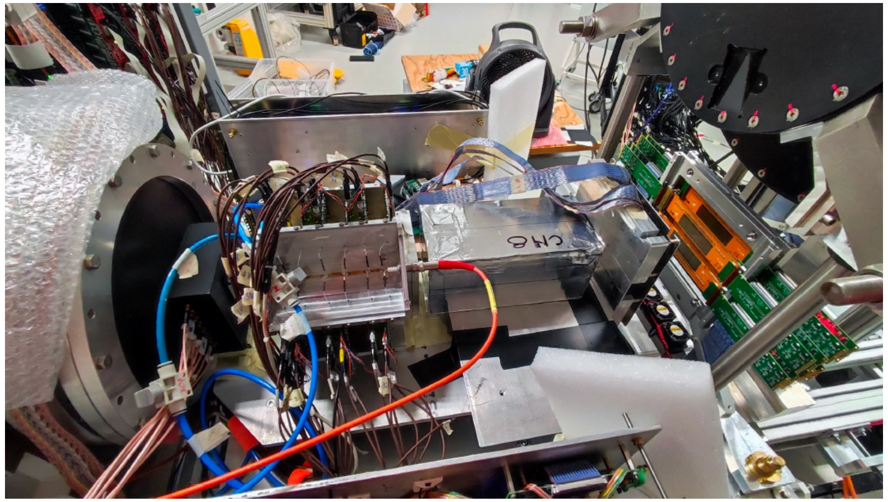
2024-2025: measurements at GSI with ^{16}O beams (E>400 MeV/u)

We are also considering other nuclear physics measurements: α-clustering is a possibility

Measuring the Impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT Experiment.
Battistoni G, Toppi M, Patera V and The FOOT Collaboration (2021). Front. Phys. 8:568242. doi: 10.3389/fphy.2020.568242

Thank you for the attention





Back up

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

TOF Wall: TOF + dE/dx
TRACKER: p
CALORIMETER: E_{kin}

Three different methods to reconstruct the **mass number** of the fragments:

$$A_1 = \frac{p}{u\,\beta\,\gamma}$$

TOF + dE/dx and TRACKER

$$A_2 = \frac{E_{kin}}{u\,(\gamma - 1)}$$

TOF + dE/dx and CALORIMETER

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

TRACKER and CALORIMETER

where ***u*** is the atomic mass unit

Expected average physical parameters for target fragments produced in water by a 180 MeV proton beam

Fragment	E (MeV)	LET (keV/μm)	Range (μm)
^{15}O	1.0	983	2.3
^{15}N	1.0	925	2.5
^{14}N	2.0	1137	3.6
^{13}C	3.0	951	5.4
^{12}C	3.8	912	6.2
^{11}C	4.6	878	7.0
^{10}B	5.4	643	9.9
^{8}Be	6.4	400	15.7
^{6}Li	6.8	215	26.7
^{4}He	6.0	77	48.5
^{3}He	4.7	89	38.8
^{2}H	2.5	14	68.9

GoodHead D.T., Radiation protection dosimetry, 122, 2006

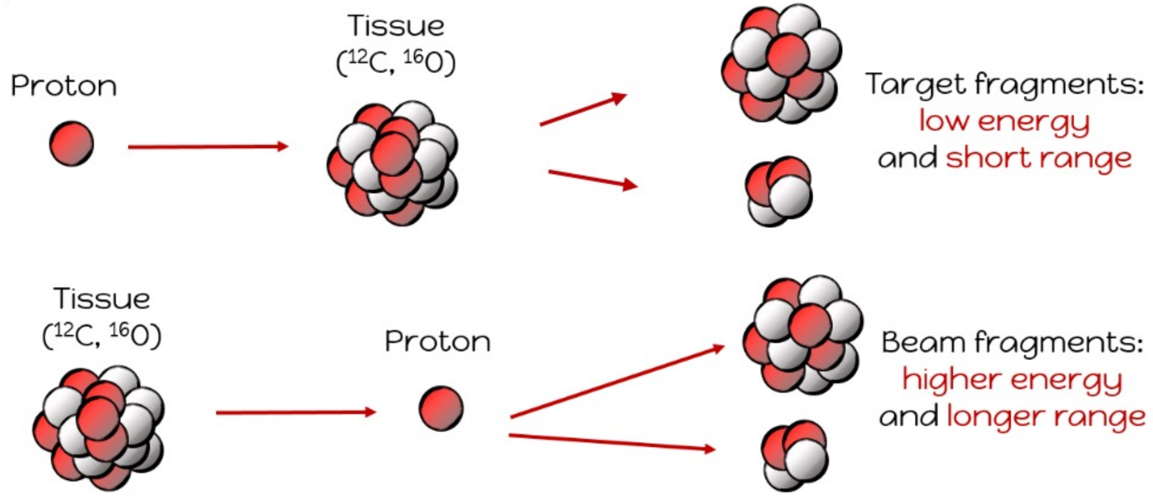
Strategy for target fragmentation measurement

Target fragments have a very **low energy** and so a very **low range** that make the detection really difficult.

By applying a Lorentz boost it is possible to switch from the laboratory frame to the "patient frame"

DIRECT KINEMATIC

INVERSE KINEMATIC



Needed high resolution in quantities entering in Lorentz Boost (p, E, ToF, θ) for **indirect kinematic approach** for proton beams induced target fragmentation

With this strategy the fragmentation of **tissue-like ion beams** (mainly C and O) impinging on a **hydrogen enriched target** are studied **moving from the challenging measurement of target fragmentation to the easier case of projectile fragmentation**

Angular and kinetic energy distributions of different fragments
200 MeV/nucleon ^{16}O beam on a C_2H_4 target

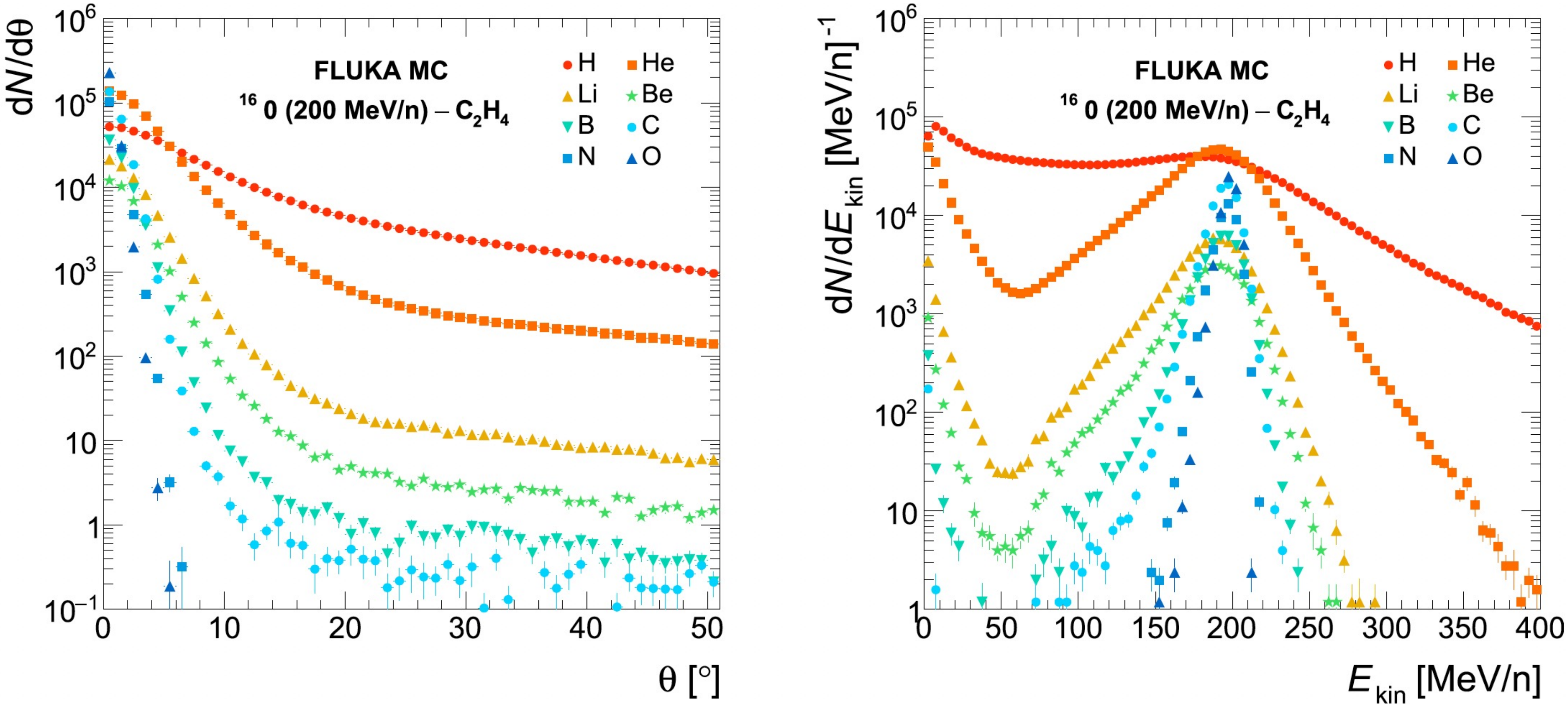


FIGURE 1 | MC calculation [33, 34] of the angular **(Left)** and kinetic energy **(Right)** distributions of different fragments produced by a 200 MeV/nucleon ^{16}O beam impinging on a C_2H_4 target.

Measuring the Impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT Experiment.
Battistoni G, Toppi M, Patera V and The FOOT Collaboration (2021). Front. Phys. 8:568242. doi: 10.3389/fphy.2020.568242

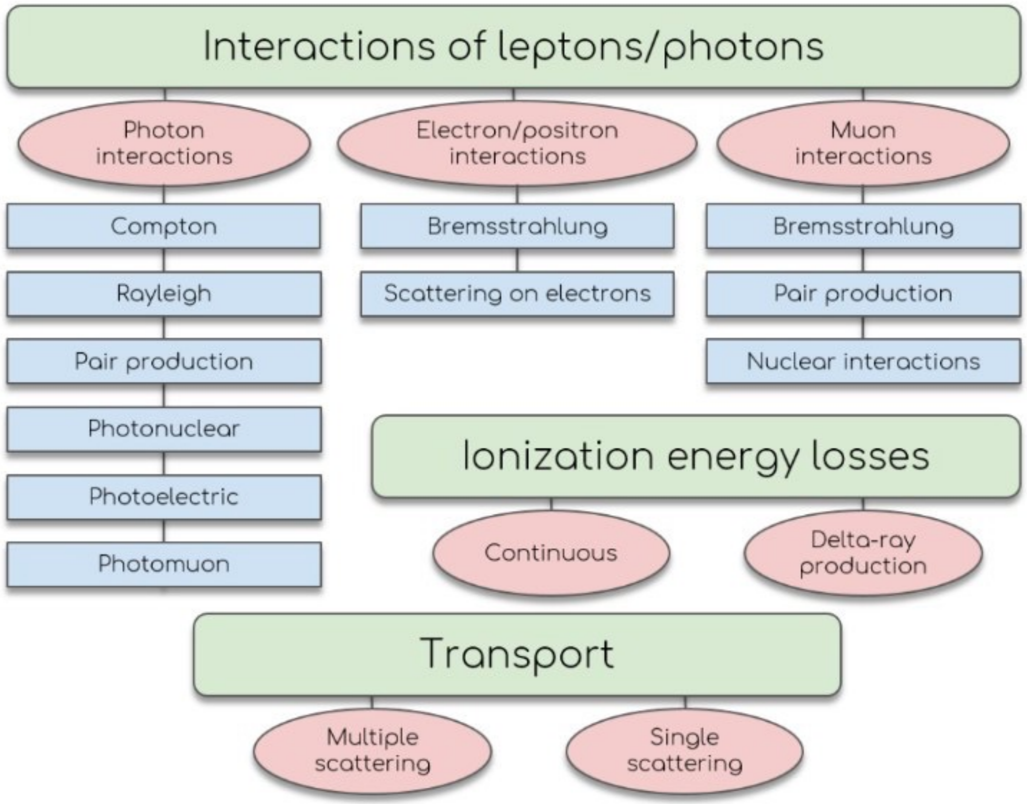
TOF Wall

PROPERTIES	EJ-232	EJ-232Q (% Benzophenone)				
		0.5	1.0	2.0	3.0	5.0
Light Output (% Anthracene)	55	19	11	5	4	3
Scintillation Efficiency (photons/1 MeV e^-)	8,400	2,900	1,700	770	610	460
Wavelength of Maximum Emission (nm)	370	370	370	370	370	370
Rise Time (ps)	350	110	105	100	100	100
Decay Time (ps)	1600	700	700	700	700	700
Pulse Width, FWHM (ps)	1300	360	290	260	240	220
No. of H Atoms per cm^3 ($x10^{22}$)	5.13	5.12	5.12	5.12	5.12	5.12
No. of C Atoms per cm^3 ($x10^{22}$)	4.66	4.66	4.66	4.66	4.66	4.66
No. of Electrons per cm^3 ($x10^{23}$)	3.30	3.38	3.38	3.38	3.38	3.38
Density (g/cm^3)	1.023	1.023	1.023	1.023	1.023	1.023
Polymer Base	Polyvinyltoluene					
Refractive Index	1.58					
Softening Point	75°C					
Vapor Pressure	Vacuum-compatible					
Coefficient of Linear Expansion	7.8×10^{-5} below 67°C					
Light Output vs. Temperature	At 60°C, L.O. = 95% of that at 20°C. No change from 20°C to -60°C.					
Temperature Range	-20°C to 60°C					

Start Counter

PROPERTIES	EJ-232	EJ-232Q (% Benzophenone)				
		0.5	1.0	2.0	3.0	5.0
Light Output (% Anthracene)	55	19	11	5	4	3
Scintillation Efficiency (photons/1 MeV e^-)	8,400	2,900	1,700	770	610	460
Wavelength of Maximum Emission (nm)	370	370	370	370	370	370
Rise Time (ps)	350	110	105	100	100	100
Decay Time (ps)	1600	700	700	700	700	700
Pulse Width, FWHM (ps)	1300	360	290	260	240	220
No. of H Atoms per cm^3 ($x10^{22}$)	5.13	5.12	5.12	5.12	5.12	5.12
No. of C Atoms per cm^3 ($x10^{22}$)	4.66	4.66	4.66	4.66	4.66	4.66
No. of Electrons per cm^3 ($x10^{23}$)	3.30	3.38	3.38	3.38	3.38	3.38
Density (g/cm^3)	1.023	1.023	1.023	1.023	1.023	1.023
Polymer Base	Polyvinyltoluene					
Refractive Index	1.58					
Softening Point	75°C					
Vapor Pressure	Vacuum-compatible					
Coefficient of Linear Expansion	7.8×10^{-5} below 67°C					
Light Output vs. Temperature	At 60°C, L.O. = 95% of that at 20°C. No change from 20°C to -60°C.					
Temperature Range	-20°C to 60°C					

FLUKA Monte Carlo models of interest for FOOT



Electromagnetic interactions models in FLUKA

Handron-nucleus interactions:

- PreEquilibrium Approach to NUclear Thermalization (PEANUT) model for particles with P<3-5 GeV/c based on Generalized Intra-Nuclear Cascade (GINC) model
- Pre-equilibrium emission of light nuclei (A<5)
- Evaporation, Fission, Fragmentation and γ de-excitation

Nucleus-nucleus interactions

- Boltzmann-Master Equation model (E<100 MeV/u): Thermalization of composite nuclei by means of two-body interactions and secondary particles emissions
- Relative Quantum Molecular Dynamics (0.1 - 5 GeV/u): Collision simulated minimizing the Hamiltonian equation of motion considering the Gaussian wave functions of all the nucleons in the nucleus overlapping region