Nuclear Fragmentation Measurements for Particle Therapy and Beyond

Aafke Kraan
National Institute for Nuclear Physics (INFN), Pisa, Italy

Thanks for the invitation!

Introduction

Physics motivation

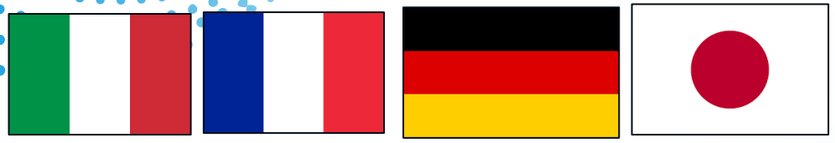
The FOOT experiment

Battistoni et al, Measuring the Impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT Experiment, Front. Phys., 08 February 2021, Sec. Radiation Detectors and Imaging

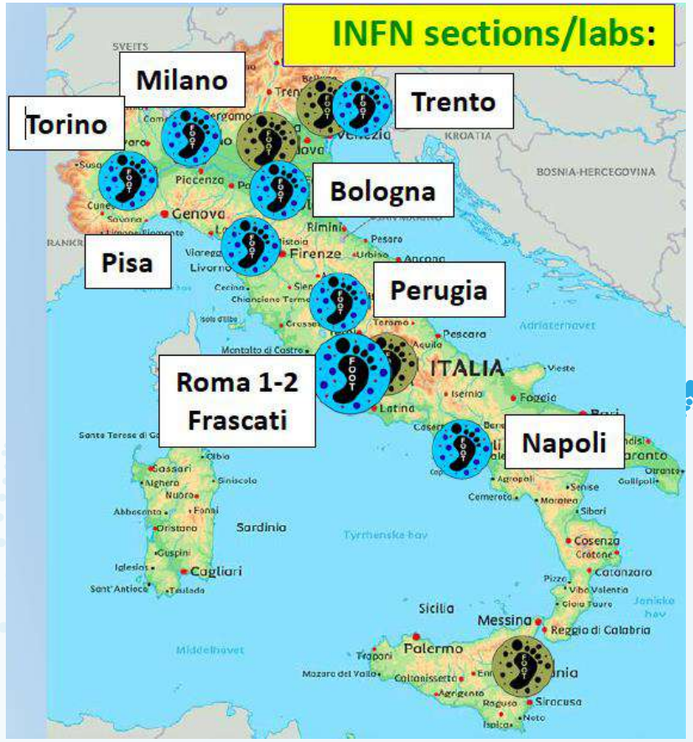
FOOT=FragmentatiOn Of Target

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

- Italy:
  - 10 INFN sections/labs
  - CNAO (Centro Nazionale di Adroterapia Oncologica)
- Germany: GSI
- France: IPHC Strasbourg
- Japan: Nagoya University
- Collaborating since recently with India
- ~95 researchers

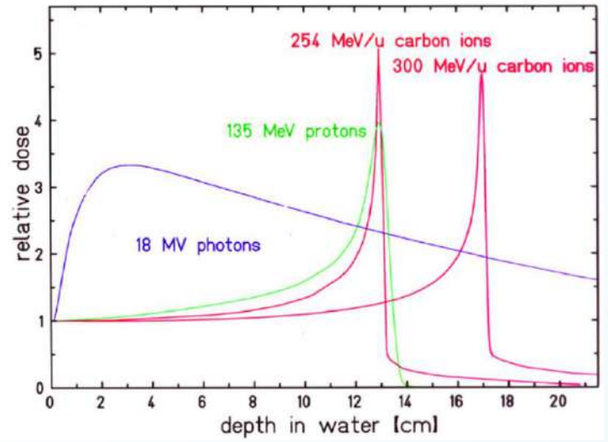


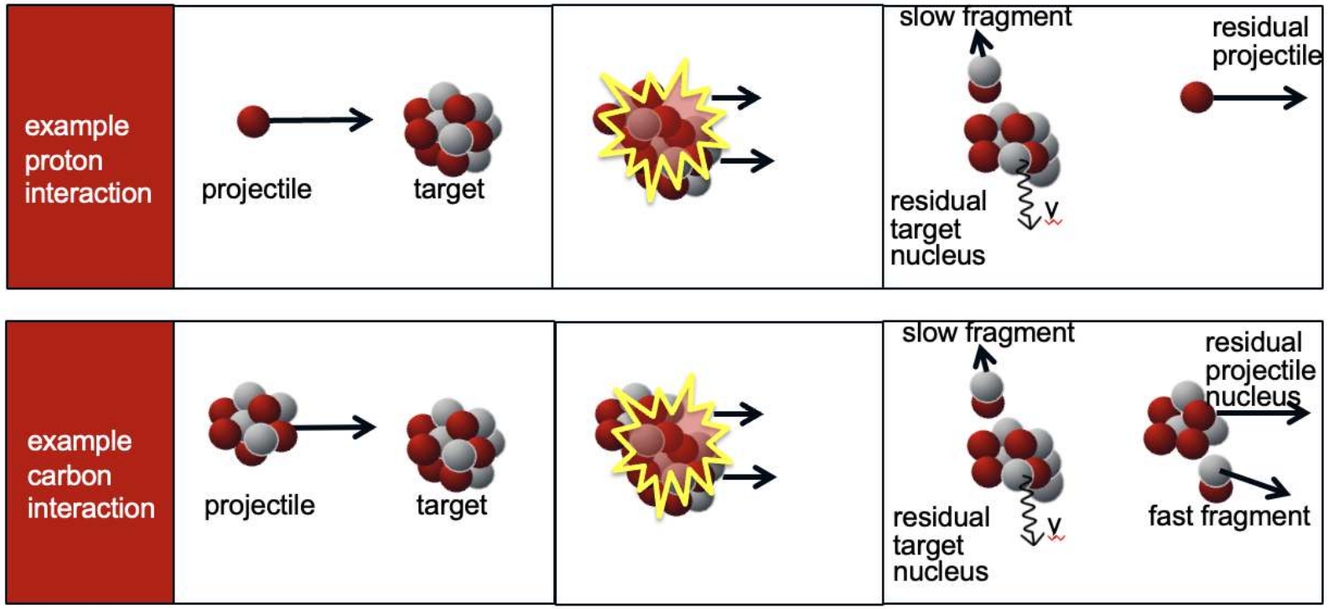
Construction almost completed

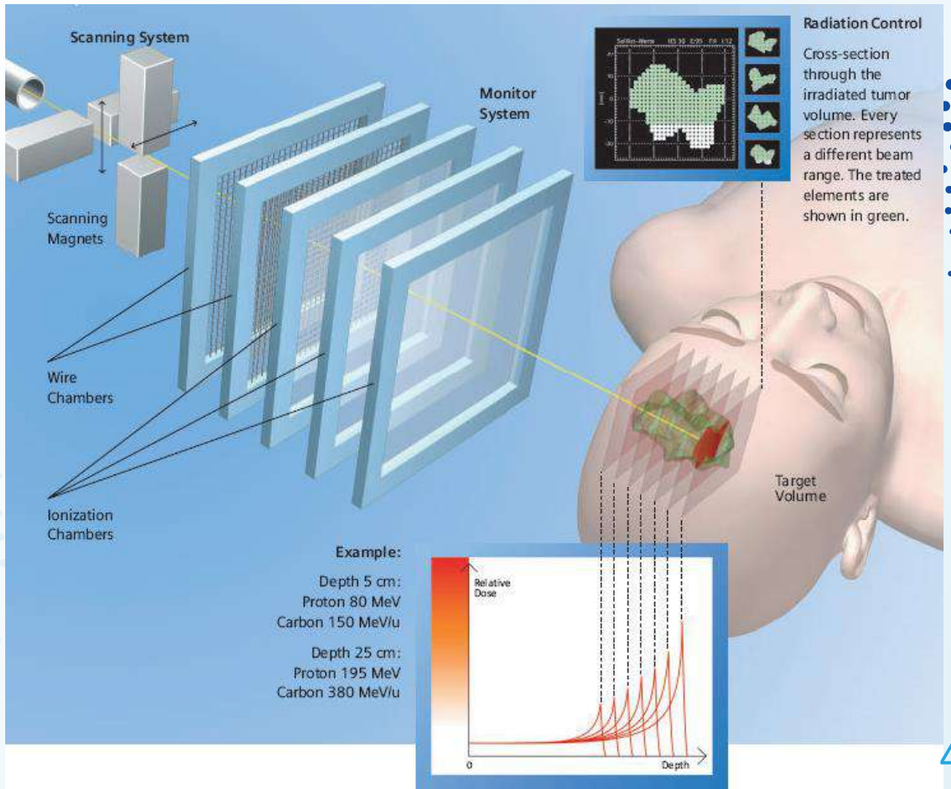


Motivation: particle therapy

- Particle therapy: radiotherapy with charged particles: protons, carbon, but being explored is also helium, oxygen
  - Energy range 50-250 MeV (p), 100- 450 MeV/u (carbon)
- Depth-dose profile distributions of protons and carbon ions are characterized by a small entrance dose and a distinct narrow peak dose (**Bragg peak**)→ precise dose
- The fragmentation of the tissue (and projectile in case of carbon ions) leads to production of secondaries.



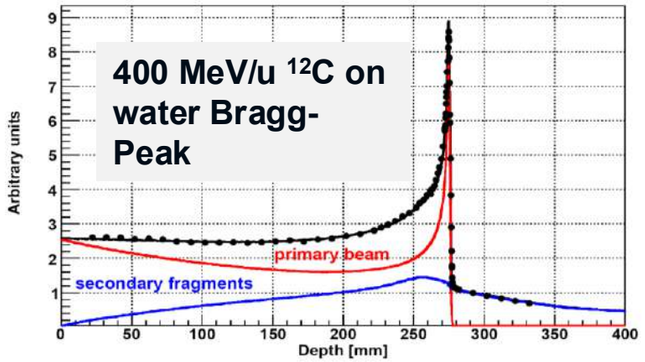




Applications of Radiation Detectors to Society 2023, Springer Proceedings in Physics Advanced Radiation Detector and Instrumentation in Nuclear and Particle Physics, p. 11-19 DOI 10.1007/978-3-031-19268-5_2

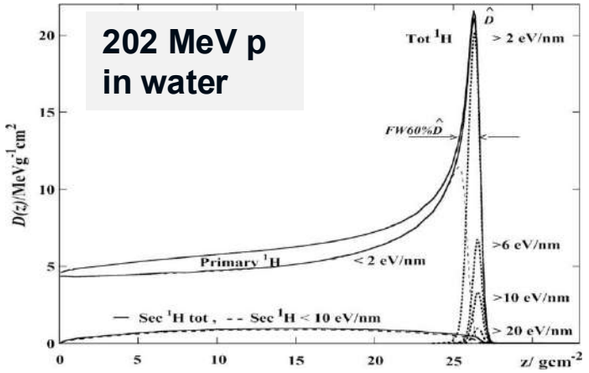
Motivation: particle therapy

Carbon therapy: ~40% of absorbed (physics) dose in entrance channel is due to secondary fragments! *Bohlen, et al, Phys Med Biol.* (2010). **55**:5833–47.



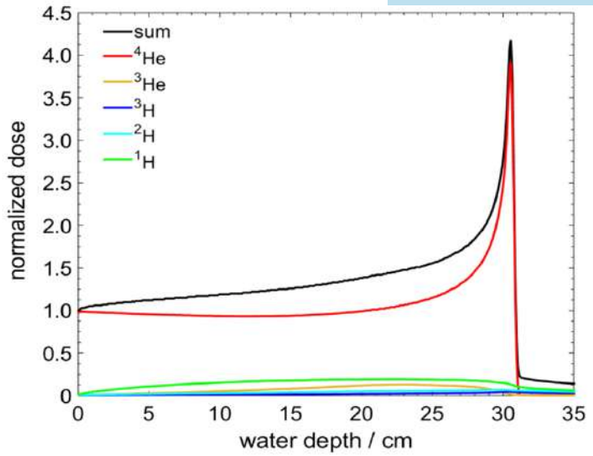
Proton therapy: ~10%

J. Kempe et al, Med. Phys. 34 „1 2007



Helium therapy: ~20%

F.Horst, MCMA2017



- Secondaries have high Linear Energy Transfer (LET) and a high Relative Biological Effectiveness (RBE)
- Thus, **physics dose and RBE-weighted (biological) dose are much different**!
- To better predict **biological dose**, need to know types (Z,A), angles, energies and amounts of secondaries→ cross sections needed, particularly (double) differential (E,Ω)
- Experimental cross section measurements in 10^2 MeV range are sometimes in disagreement, old, or have large errors… especially at large angles! (see slides 13-14)

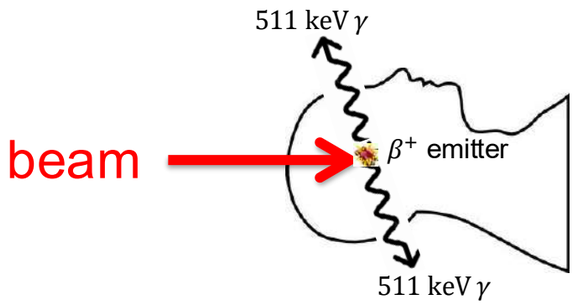
Recent progress for He: Horst F, et al.. *Phys Rev C.* (2019). **99**:014603.

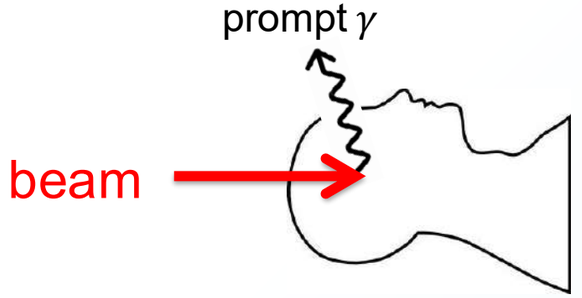
See also "Experimental data of nuclear fragmentation for validating Monte Carlo codes: Present availability and lacks", G. Battistoni, S. Muraro, A. C. Kraan, in: Monte Carlo in Heavy Charged Particle Therapy, Edition1, 2024

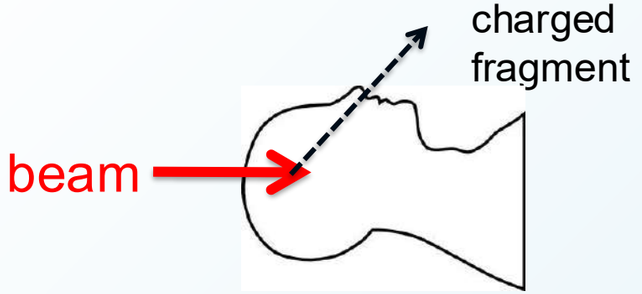
More cross section measurements are needed!

Motivation: particle therapy range monitoring

New cross section measurements could also be extremely useful for **range monitoring**







- Still many uncertainties, particularly regarding charged fragment production
- Some charged fragment measurements for range monitoring done, but only a few angles and energies
- **MC models unreliable at large angles, missing data…**
- New cross section measurements very useful!
- See for instance:

K. Gwosch et. al, Phys. Med. Biol. 58 (2013) 3755–3773

Agodi C, et al flux. Phys. Med. Biol. 57 (2012)5667.

A. Rucinski . Med. Biol.63(2018) 055018.

From: Muraro, Battistoni, Kraan, Front. Phys, 2020 Sec. Medical Physics and Imaging, volume 8 - 2020

TABLE 3 | Summary of measurements in the context of range monitoring studies.

Incident beam	Energy [MeV/u]	Target	Technique	Measurement	Refs.
P	160	PMMA	Prompt γ	Energy spectra and yields at 90°	Smeets et al. [143]
P	230	Water	Prompt γ	Energy spectra and yields at 90°	Verburg et al. [151, 152]
P	48	4 samples with varying amount of O, C, H	Prompt γ	Energy spectra and yields at 90°	Polf et al. [153]
^{12}C	73, 95, and 305	PMMA and water	Prompt γ	Time-of-flight and energy spectra at 90°	Testa et al. [154–156]
^{12}C	220	Polymethyl methacrylate	Prompt γ	Energy spectra and yields at 90°	Vanstalle et al. [157]
^{12}C	95 and 310	PMMA and water	Prompt γ	Energy spectra and yields at 90°	Pinto et al. [144]
^{12}C	80	PMMA	Prompt γ	Energy spectra and yields at 90°	Agodi et al. [158]
^{4}He, ^{12}C, ^{16}O	100 to 300	PMMA	Prompt γ	Yields at 60°, 90°, and 120°	Mattei et al. [159]
^{12}C	80	PMMA	Fast charged hadrons	Proton yields at 60° and 90°	Agodi et al. [160]
^{12}C	220	PMMA	Fast charged hadrons	Fragments with $Z = 1$ at 90°	Piersanti et al. [76], Mattei et al. [161]
^{4}He, ^{12}C	120–220	PMMA	Fast charged hadrons	Secondary protons at 90°	Rucinski et al. [162]
^{16}O	–	PMMA	Fast charged hadrons	Yields of fragments with $Z = 1$ as function of energy and production position at 60° and 90°	Rucinski et al. [163]
^{12}C	400	Composite target	Fast charged hadrons	Secondary fragments for angles 34° to 81°	Alexandrov et al. [164, 165]
p, ^{12}C	40–220(p), 65–430(C)	Graphite and beryllium oxide	β+	Cross section measurements of ^{10}C, ^{11}C, and ^{15}O	Horst et al. [136]
p, ^{12}C	110, 140, 175 (p), 212, 260, and 343 (C)	PMMA	β^+	Absolute activity distributions and total production cross sections of ^{10}C, ^{11}C, and ^{15}O	Pshenichnov et al. [166]
P	55	Water, carbon, phosphorus, nd calcium	β+	Number of short lived β+ emitters	Dendooven et al. [139]
P	10 to 70	Polyethylene and water	β^+	Cross sections of 4 specific reaction channels for production of ^{11}C, ^{15}O, ^{13}N	Akagi et al. [167]
P	10 to 70	Polyethylene	β^+	Cross sections of specific reaction channels for production of ^{11}C and ^{15}O	Matsushita et al. [133]

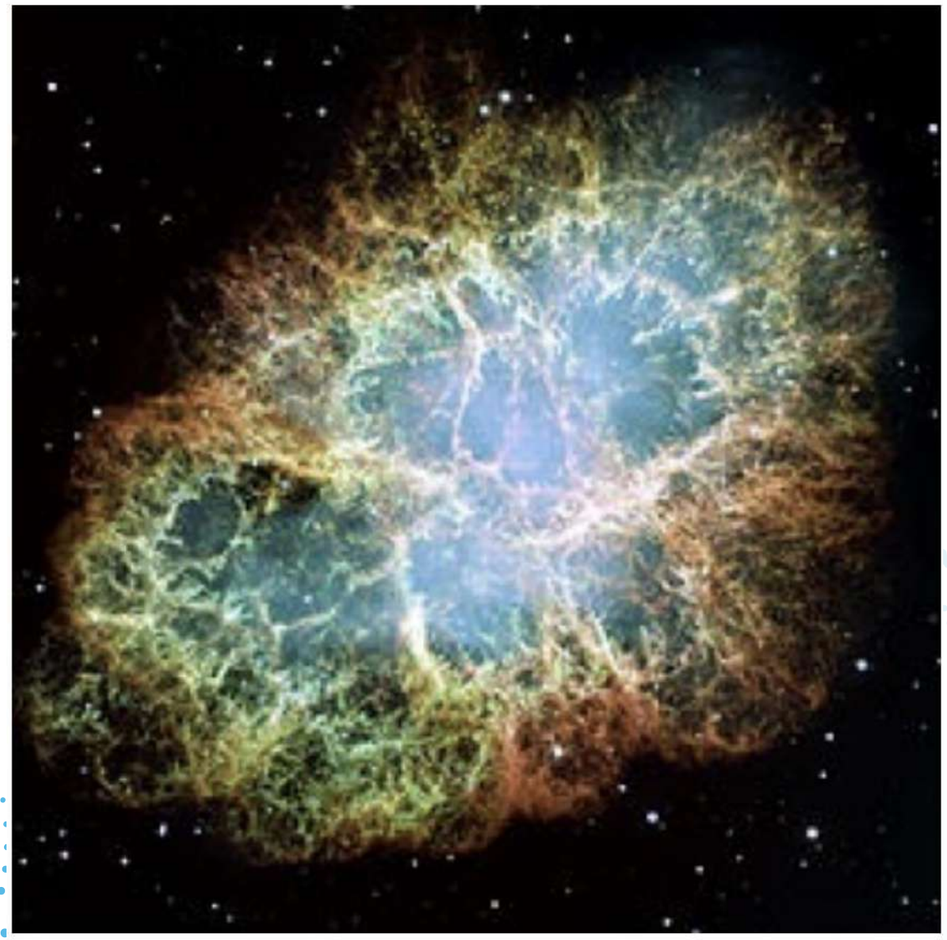
Motivation: radioprotection in space...

https://www.nasa.gov/organizations/ochmo/human-spaceflight-hazards/

Motivation: radioprotection in space…

See Presentation by Norbury et al, Nuclear data needs for protection from space radiation, FOOT-MAECI-MOFFITS meeting, May 2025

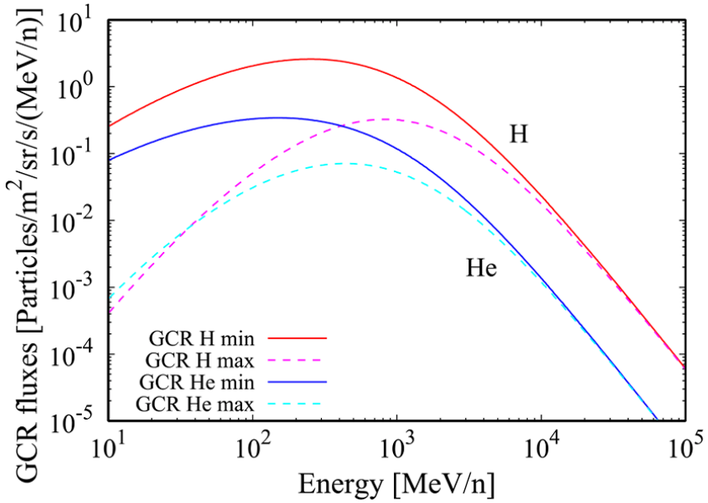
Galactic Cosmic Rays (GCR)



Crab Nebula

Image courtesy of NASA

- Highly penetrating, complex mixed field including protons and heavier nuclei
- Protons (85%), He ions (12%)
- High charge and energy (HZE) ions (1%) (lower flux but biologically significant)
- Energies from MeV to tens of TeV/n
- Chronic low-dose rate exposure that varies with solar cycle
- **Difficult to shield** due to energy and complexity of field
- Biophysical properties of HZE particles differ vastly from terrestrial radiation with adverse biological affects contributing to health risks
- From supernova shock waves



Masayuki et al, Journal of radiological protection. 40. 947-961. 10.1088/1361-6498/abb120.

Motivation: radioprotection in space…

Geomagnetically trapped radiation

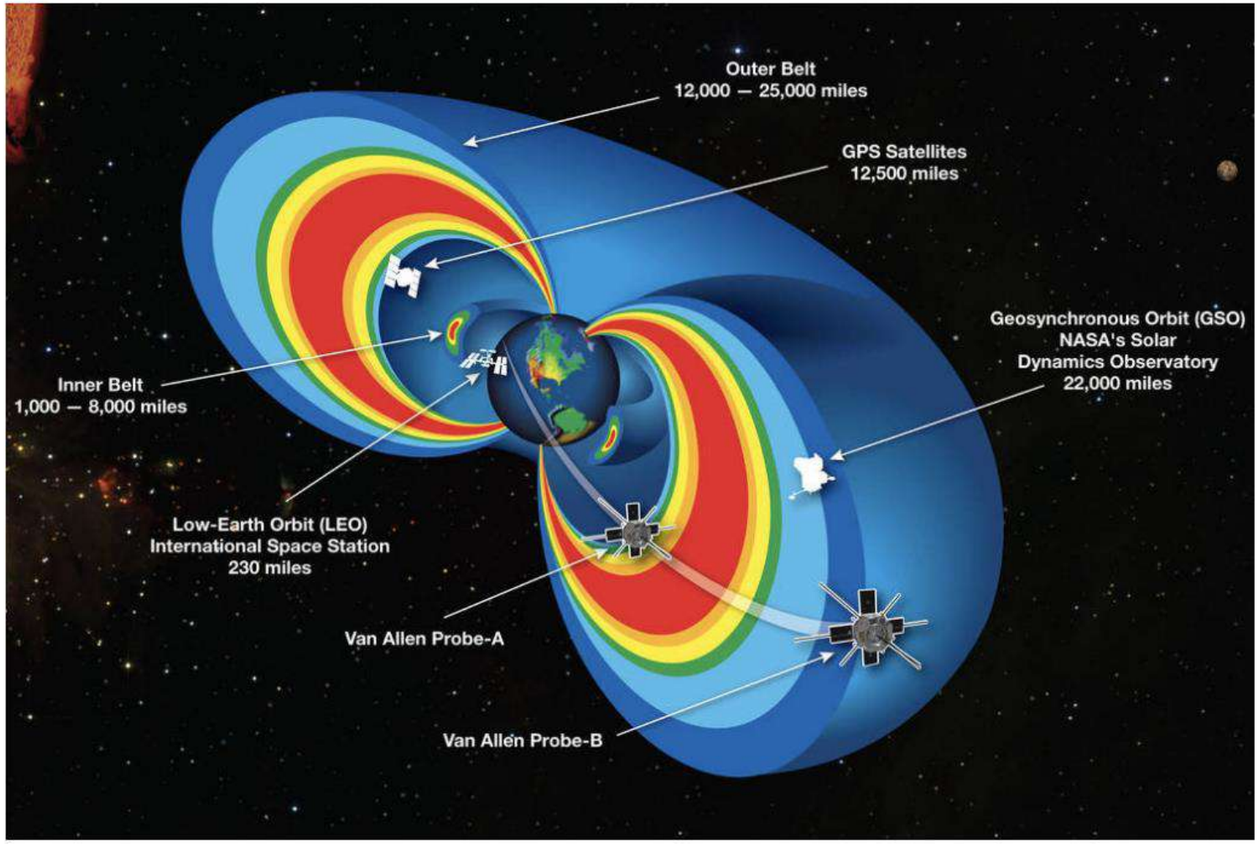


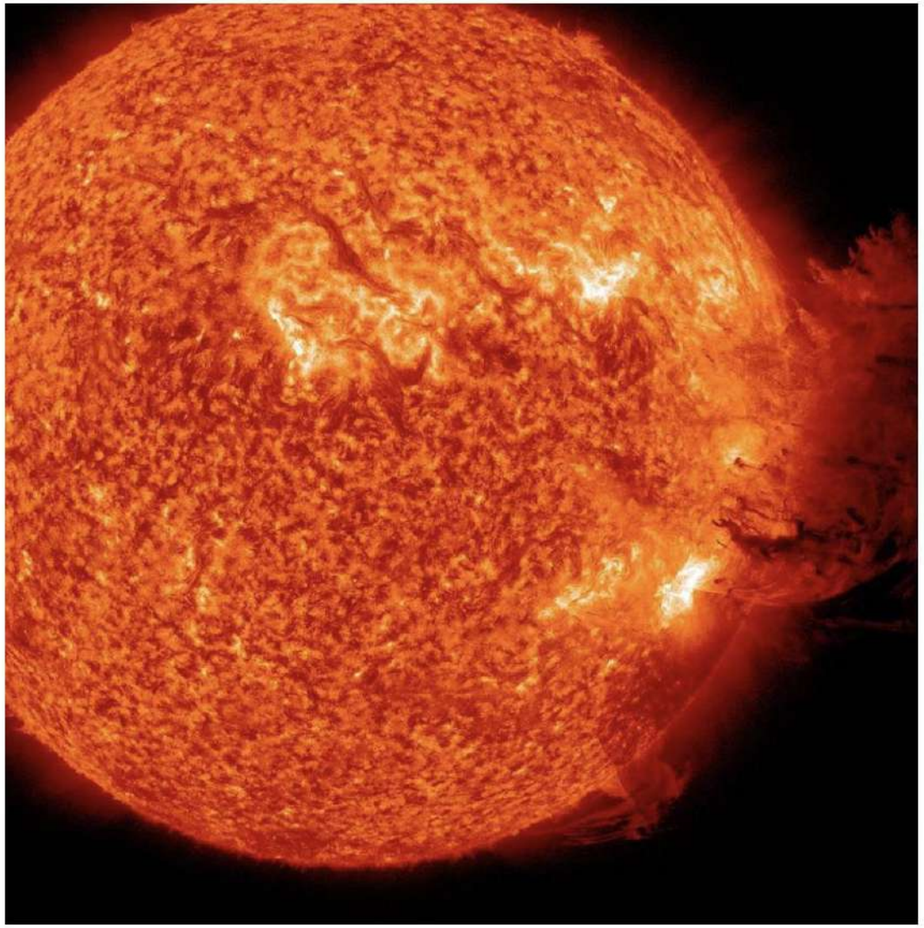
Image courtesy of NASA

- Low energy protons (< 250 MeV) and electrons (< 7 MeV)
- Inner Belt: mostly protons and electrons
- Outer belts: composed of electrons
- Continuous exposure at altitude up to 40,000 km
- **Can be shielded**; mainly relevant to ISS

See Presentation by Norbury et al, Nuclear data needs for protection from space radiation, FOOT-MAECI-MOFFITS meeting, May 2025

Motivation: radioprotection in space…

Solar Particle Events (SPE)



7 June 2011

Image courtesy of NASA

- Medium (keV to 100s MeV) to high energy protons (< 1 GeV) from coronal mass ejection
- Intermittent exposure with peak activity during solar max so kind of predictable
- **Can be effectively shielded** to prevent severe acute radiation syndrome
- Storm shelters minimize exposure risk

See Presentation by Norbury et al, Nuclear data needs for protection from space radiation, FOOT-MAECI-MOFFITS meeting, May 2025

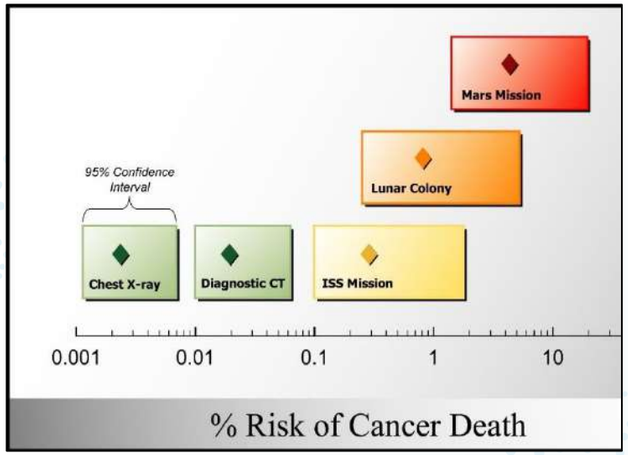
Motivation: radioprotection in space...

- Radiation in space is one of the obstacles for space exploration

Source	Nuclei	Energy
Galactic cosmic rays	mostly p	MeV-TeV
Solar particles	p, α	MeV-GeV
Magnetically trapped particles	p	< 100 MeV

- Dose equivalent in space is high

Where	dose equivalent
On earth	~ 7 µSv/day
Chest x-ray	– 0.1 mSv
Brain CT	~ 1.6 mSv
Space	0.5-2 mS/day
Mars	0.64 mSv/day



- For optimal shielding and accurate (physics and biology) modeling of interactions with human tissue, need MC predictions! Especially differential and double differential cross section measurements needed!
  - Mainly light ions (p, He) with higher energies than particle therapy

Particle therapy and radiation protection have common needs!

Common needs:

- Uncertainty quantification
- Cross section measurements overlap
  - Similar types (double-differential)
  - Similar projectiles (H, He, C, O)
  - Similar projectile energies
  - Similar targets
  - Similar fragments (light ions)
- Nuclear model improvements
- Transport code improvements with improved nuclear models

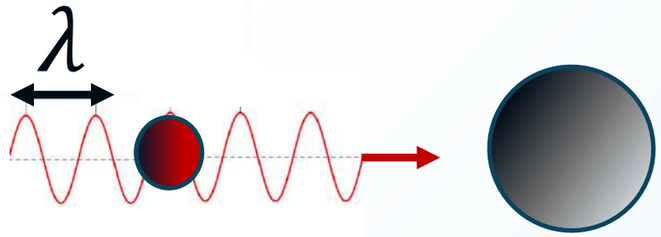
But also differences

	Ion Therapy	Space Radiation
Energy	10s - 100s MeV/n	10s MeV/n – 50 GeV/n
Projectiles	H, He, C, O	H – Ni
Targets - human body	H, C, O, N, Ca, P, S, K, Na, Cl, Mg	H, C, O, N, Ca, P, S, K, Na, Cl, Mg
Targets - materials		C, Al, Cu, Ti

See Presentation by Norbury et al, Nuclear data needs for protection from space radiation, FOOT-MAECI-MOFFITS meeting, May 2025

- **FOOT program: cross sections up to ~800 MeV/u**
- **So far: measurements up to 400 MeV/u**

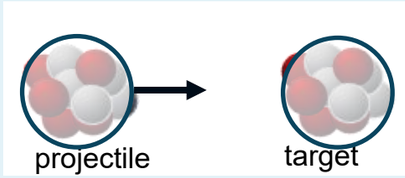
How about Monte Carlo model predictions?



Low energies

The semi-classical approximation : at kinetic energies below ~10 MeV/A

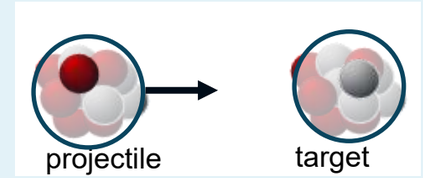
- λ = h/p of incident particle is higher than the nuclear size → nucleons are bound, entire nucleus acts as a single unit, and the interaction is between nuclei (scattering, fusion)



High energies

The single particle approach: at energies well above 1000 MeV/A:

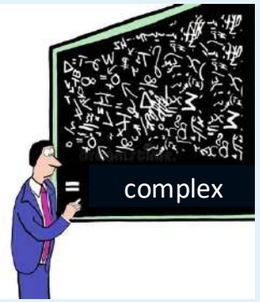
- λ = h/p of incident particle is smaller than the nuclear size and much smaller than the mean free path λ_N inside the nucleus → nucleons in the colliding nucleus are like single (nearly free) particles in vacuum, no nuclear structure
- Perturbative region (if high p transfer), At very large energies: Quark Gluon Plasma



Intermediate energies

Particle therapy and space radioprotection regime: from ~10 to 1000 MeV/A

- No full first principle calculations possible, no perturbative approximations
- Several models exist with different agreement with data: phenomenological models, like Quantum Molecular Dynamic and intranuclear cascade approaches.
- **Essential ingredient to benchmark and validate models for particle therapy and radioprotection in space: cross sections**!

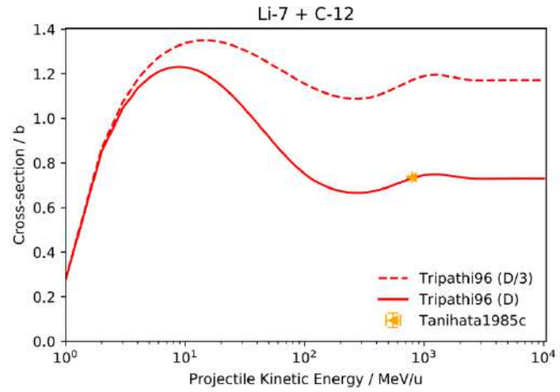


Experimental data of nuclear fragmentation

Available data are not yet fully satisfactory

- Some measurements are quite old
- Some data disagree with each other
- Some data are lacking

But recently **new data** are coming!

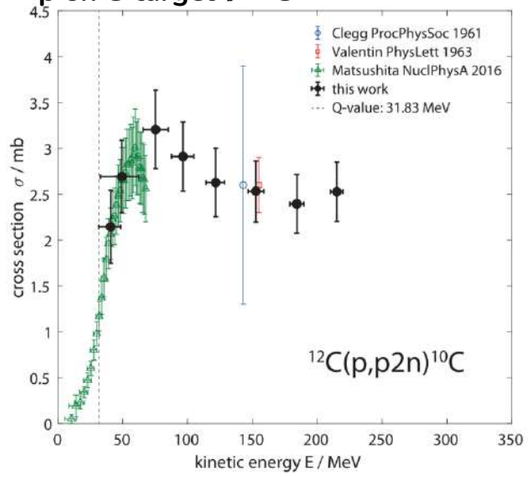


F Luoni *et al* 2021 *New J. Phys.* **23** 101201

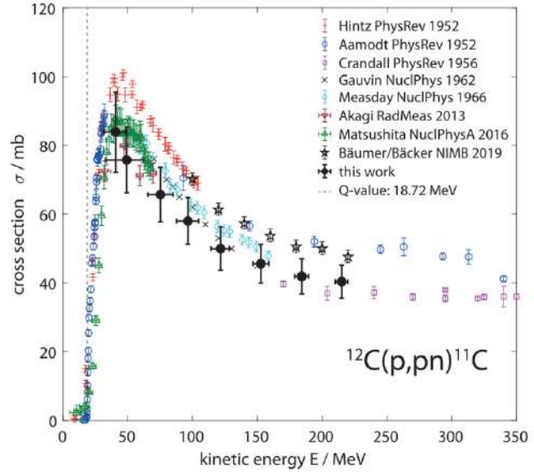
^{7}Li on C target

From: F. Horst et al, Phys. Med. Biol. 64 (2019) 205012 (16pp)

p on C target→ ^{10}C



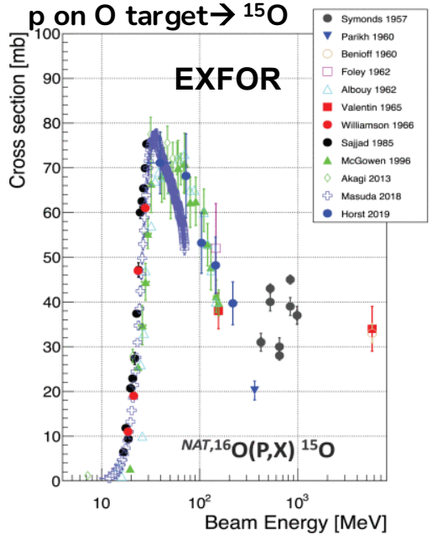
p on C target→ ^{11}C



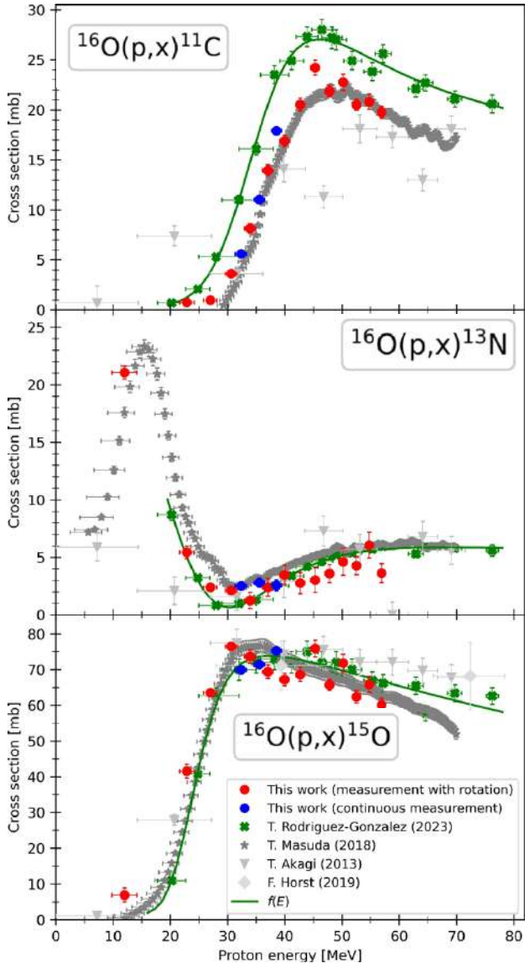
Cross sections for the production of ^{10}C and ^{11}C target fragments by protons on carbon targets as a function of energy,

A. C. Kraan and A. Del Guerra, "Technological Developments and Future Perspectives in Particle Therapy: A Topical Review," in *IEEE-TRPMS*, vol. 8, no. 5, pp. 453-481, 2024

p on O target→ ^{15}O



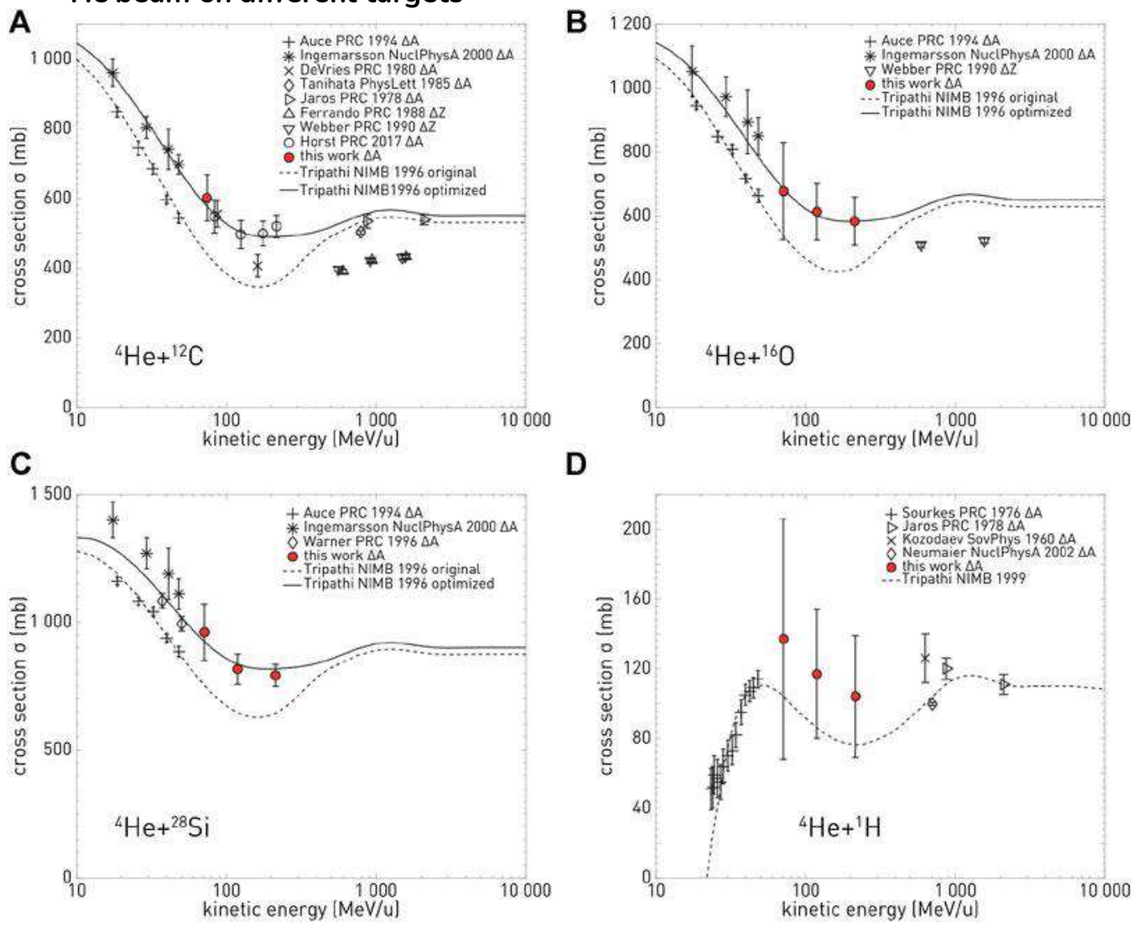
p on oxygen target (SiO_2)



Matulewicz, J., Skwira-Chalot, I., Kusyk, S. *et al.* Measurement of cross section of proton-induced reactions on oxygen with silicon dioxide target. *Eur. Phys. J. A* **60**, 203 (2024).

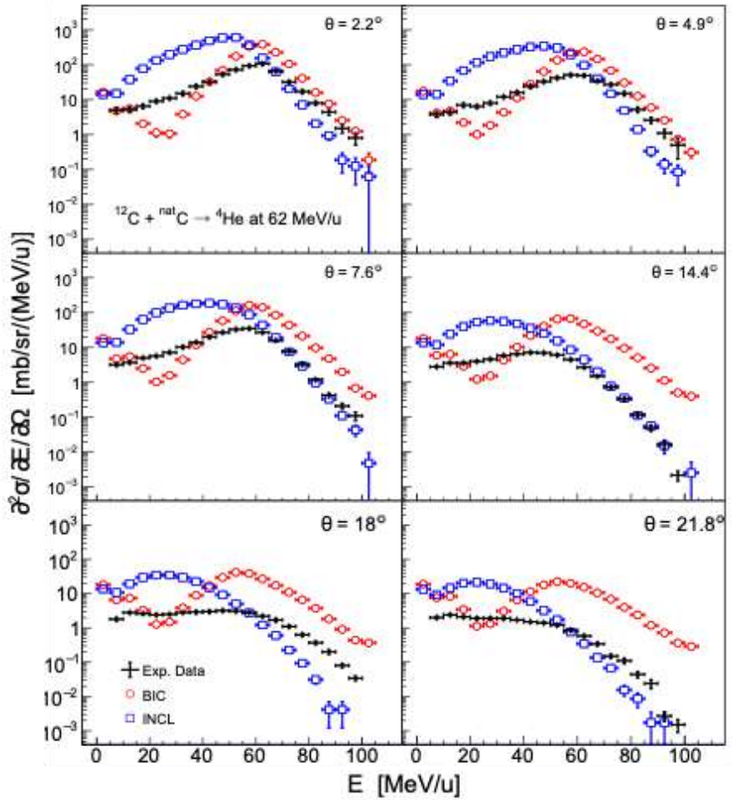
Experimental data of nuclear fragmentation

He beam on different targets



Horst F, et al. Measurements of He charge and mass changing cross sections on H,C, O, and Si targets in the energy range 70-220 MeV/u for radiation transport calculations in ion-beam therapy. *Phys Rev C.* (2019). **99**:014603. doi:10.1103/PhysRevC.99.014603

P. Arce et al (Geant coll), Medical Physics, 48(1):19, 2021.



Double-differential cross sections at different angles of α-particle production interaction of 62 MeV/u ^{12}C beam with a thin C target, as a function of the α-particle kinetic energy. Experimental data from De Napoli et al

See also N. Sakhno et al, ACTA PHYSICA POLONICA A No. 5 Vol. 146 (2024) .

protons on different targets

$^{14}N(p, x)^{10}C$

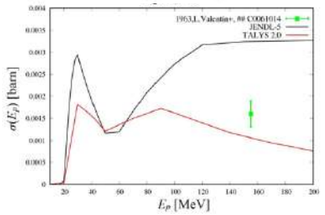


Fig. 4. Calculation results for the $^{14}N(p, x)^{11}C$ nuclear reaction.

$^{16}O(p, x)^{10}C$

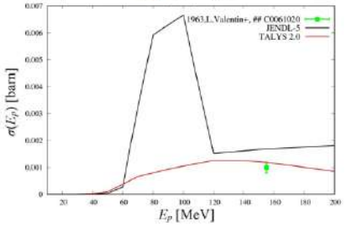
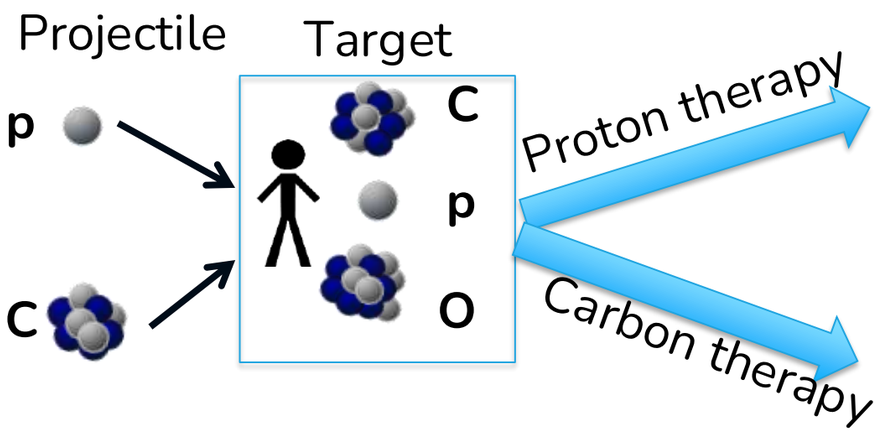


Fig. 5. Calculation results for the $^{16}O(p, x)^{10}C$ nuclear reaction.

More cross section measurements are needed for validating MC codes!

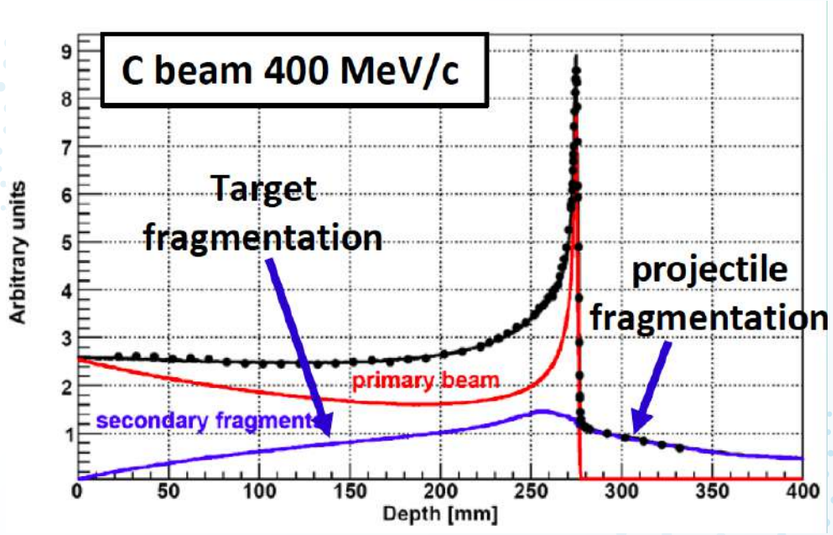
Target and projectile fragmentation

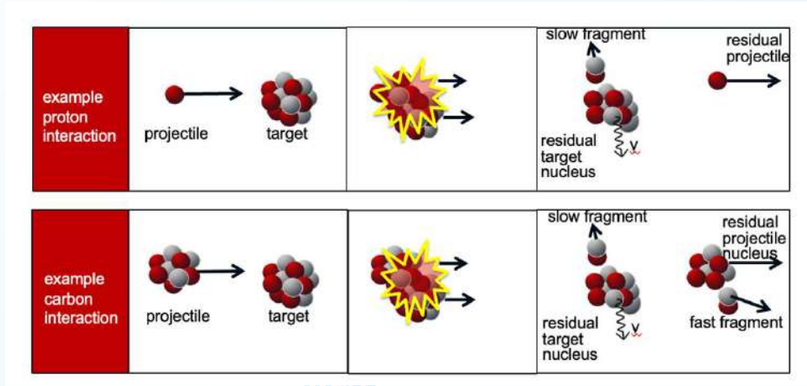


Who fragments? Range

p+p	no	
p+C,O	target	Short (μm)
C+p	projectile	Long (> few cm)
C+C,O	both	Both

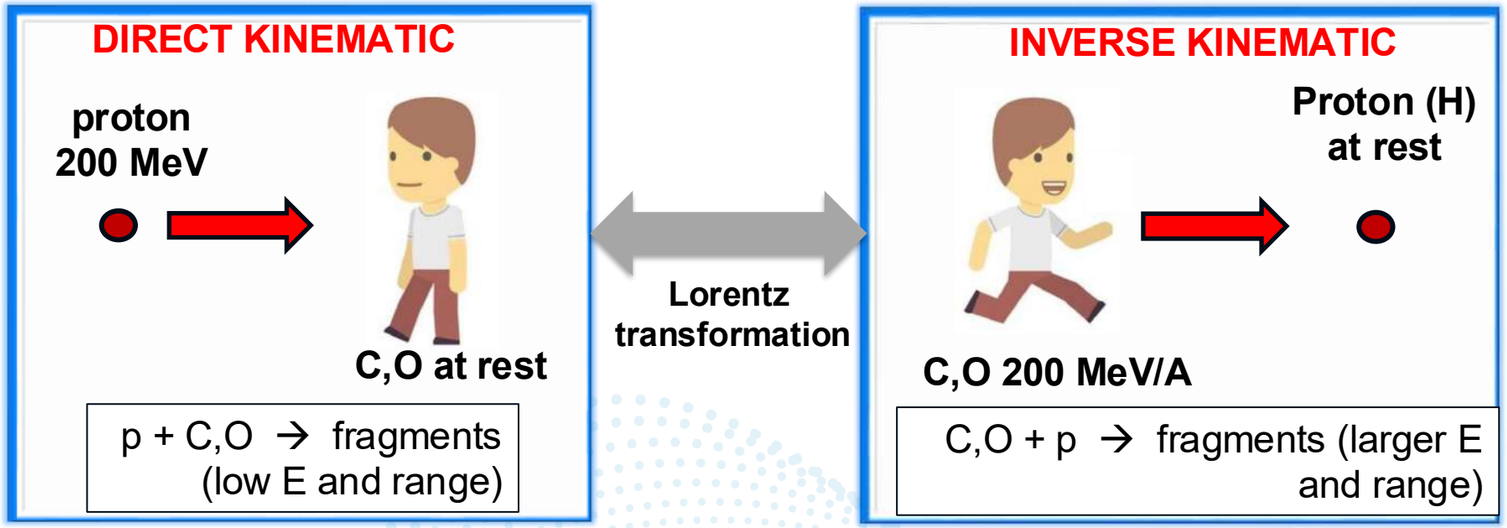
- Long range fragments can be measured directly
- But how to measure short range fragments?
  - Difficult to directly detect them, would need very thin target
  - Such a very thin target produces very few events (+background).
  - Other techniques: difficult/expensive





FOOT strategy: inverse kinematics

Problem with target fragmentation:
target can be as thick as a few mm >> range of fragments, which is of order ~ few μm)



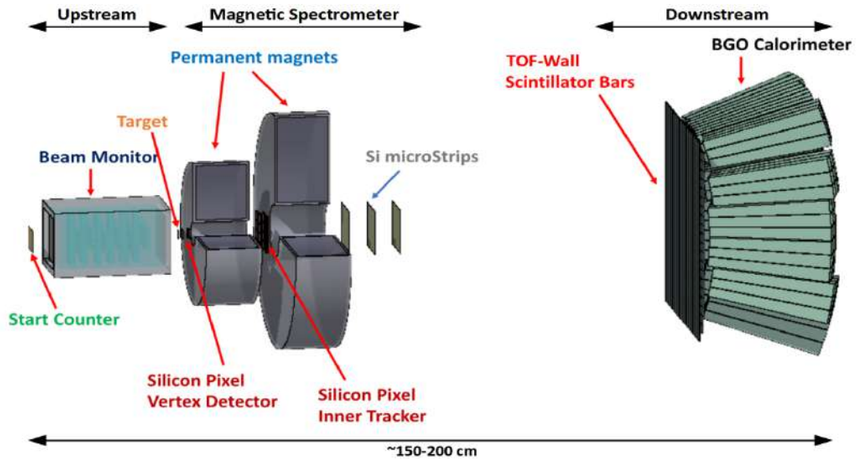
$$\frac{d\sigma}{dE_{kin}}(H) = \frac{1}{4}\left(\frac{d\sigma}{dE_{kin}}(C_2H_4) - 2\frac{d\sigma}{dE_{kin}}(C)\right)$$

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

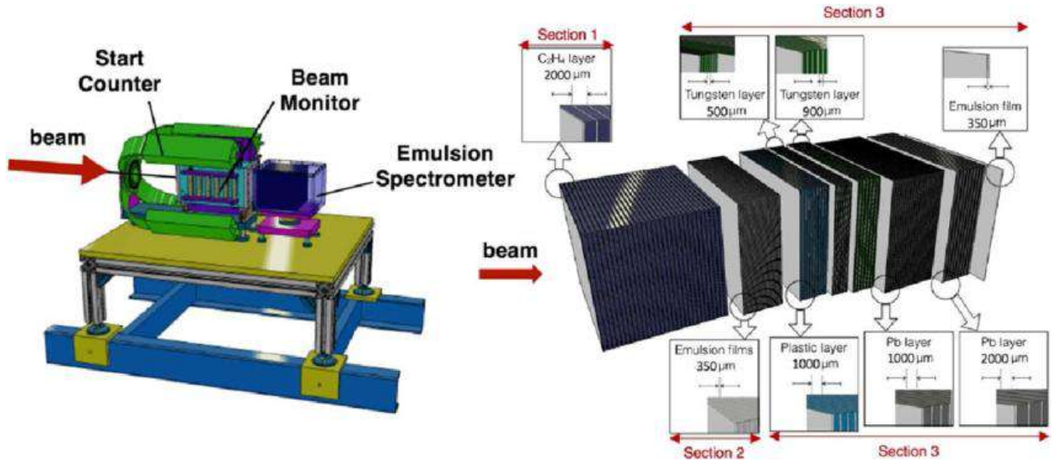
FOOT physics program

- Measure cross sections (double differential, in E and angle)→ measure **A, Z, angle and E of particles**
- Beams of light ions (Z≤ 8) with energies of order of a few 10^2 MeV/u. Available at very few centers in Europe, including
  - CNAO (National Center of Oncological Hadrontherapy) in Pavia
  - HIT (Heidelberger Ionenstrahl-Therapiezentrum) in Heidelberg
  - GSI (Helmholtzzentrum für Schwerionenforschung) in Darmstadt.
- Target: tissue like targets: C, polyethylene
- FOOT data taking typically in treatment room → **need a moveable and compact system**
- Two complementary setups:
  - Electronic detectors setup (Z ≥ 2), up to 10 degrees
  - Emulsion Cloud Chamber (Z ≤ 3), up to 70 degrees

Electronic setup: up to 10 degrees



Emulsion cloud chamber: up to 45 degrees

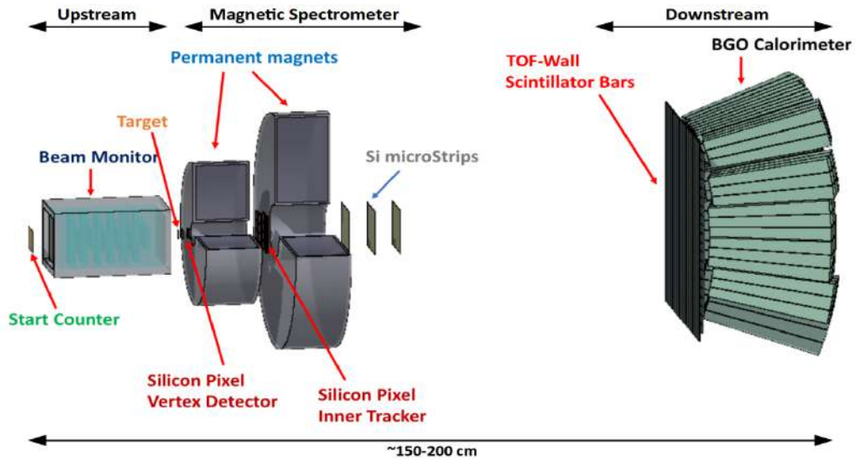


FOOT physics program

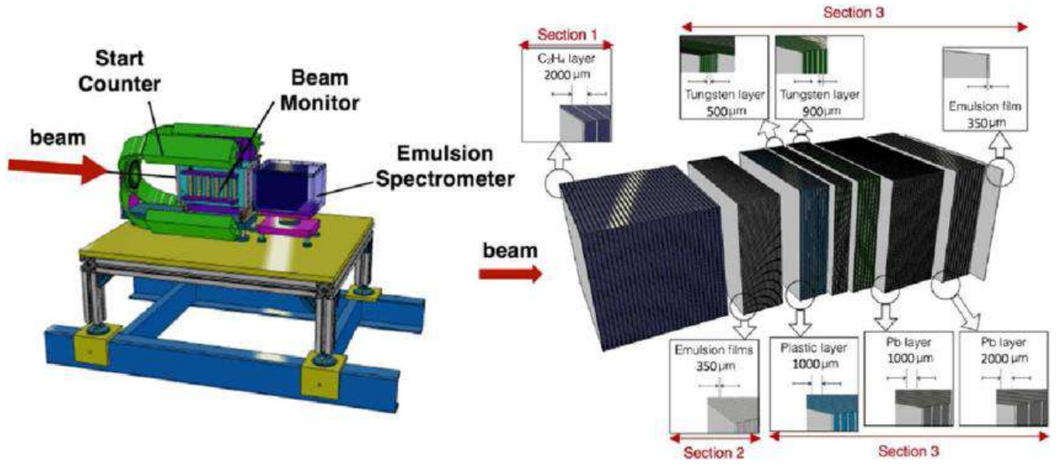
- Measure cross sections (double differential, in E and angle)→ measure **A, Z, angle and E of particles**
- Beams of light ions (Z≤ 8) with energies of order of a few 10^2 MeV/u. Available at very few centers in Europe, including
  - CNAO (National Center of Oncological Hadrontherapy) in Pavia
  - HIT (Heidelberger Ionenstrahl-Therapiezentrum) in Heidelberg
  - GSI (Helmholtzzentrum für Schwerionenforschung) in Darmstadt.
- Target: tissue like targets: C, polyethylene
- FOOT data taking typically in treatment room → **need a moveable and compact system**
- Two complementary setups:
  - Electronic detectors setup (Z ≥ 2), up to 10 degrees
  - Emulsion Cloud Chamber (Z ≤ 3), up to 70 degrees

TODAY

Electronic setup: up to 10 degrees



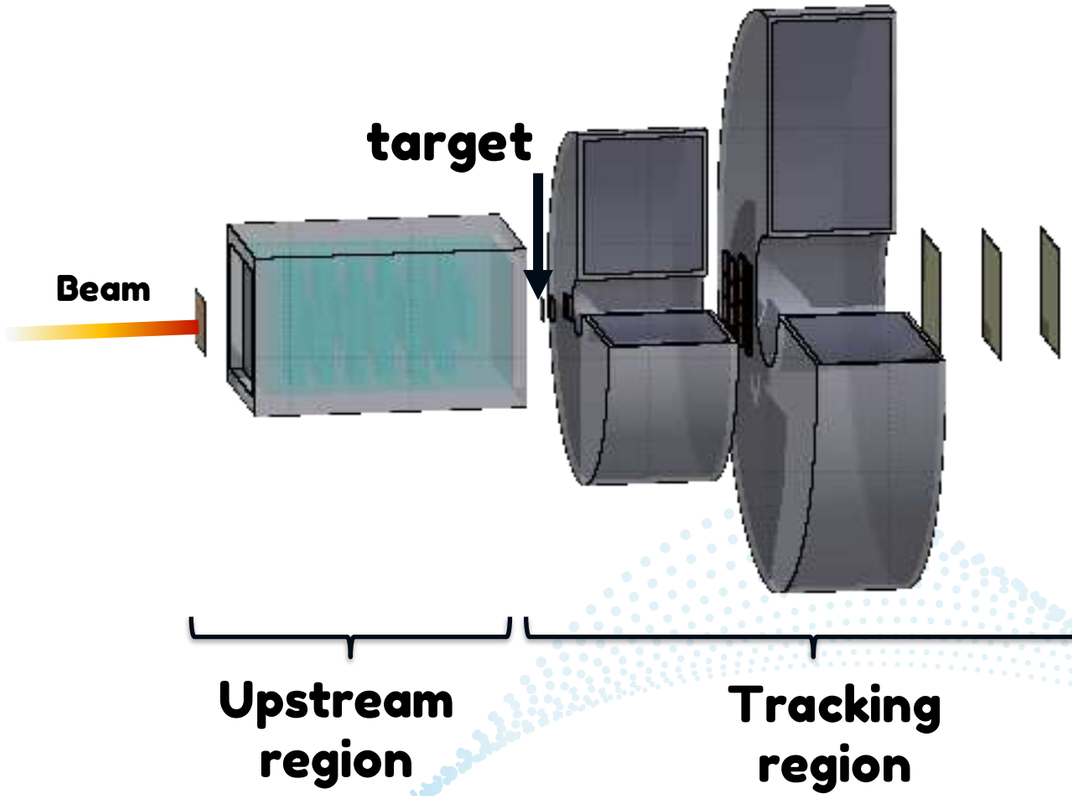
Emulsion cloud chamber: up to 45 degrees

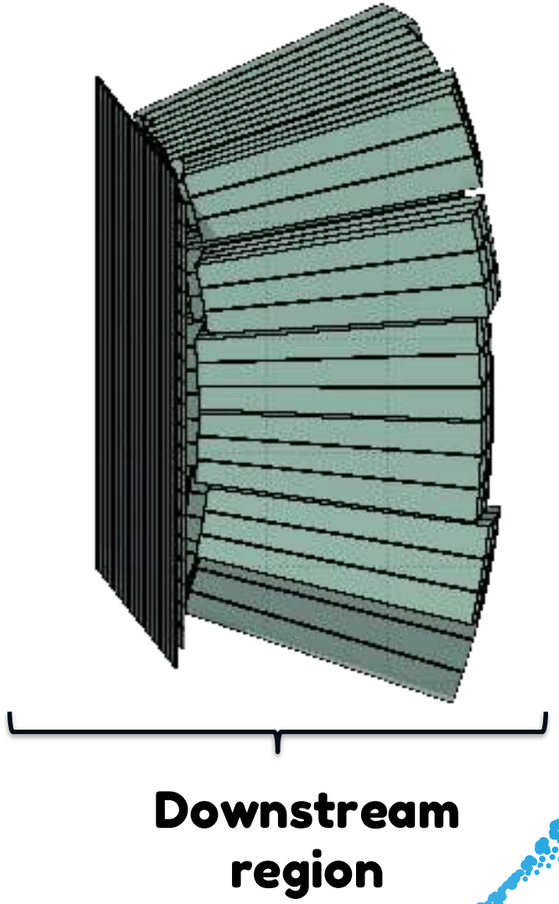


The detector

Electronic setup

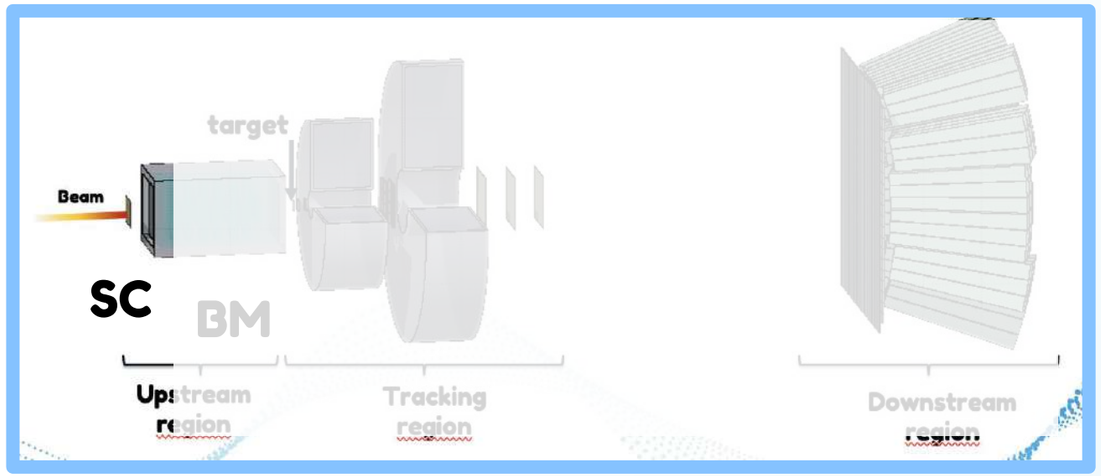
FOOT detector (electronic setup)





- Total length: about 3 meters

FOOT Start Counter detector



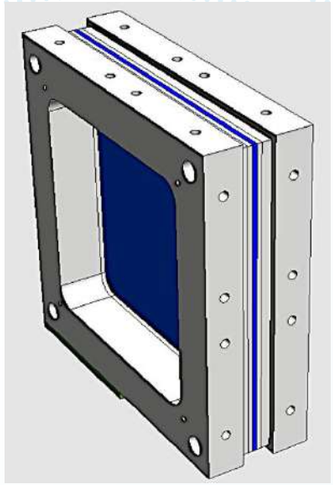
Start Counter (SC):

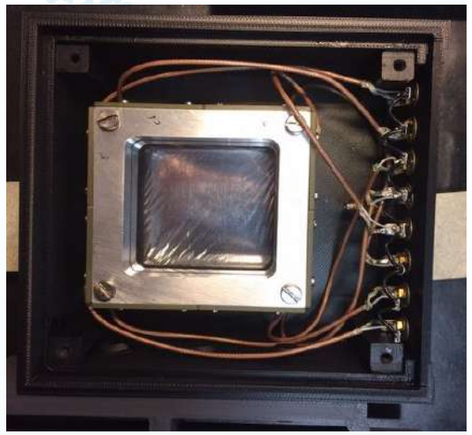
- First detector encountered by beam
- 250 μm thick plastic scintillator
- EJ 228, Eljen Technology
- 5x5 cm² active area
- 48 SiPMs (ASD-NUV3S 3x3mm^2), 8 channels readout
- Closed with a thin layer of 4 μm aluminized mylar
- DAQ system developed at PSI for MEG2
- Channels connected to custom board WaveDREAM
- SC signals from 8 channels summed and the resulting WF is analyzed with a CFD algorithm → T_{SC}

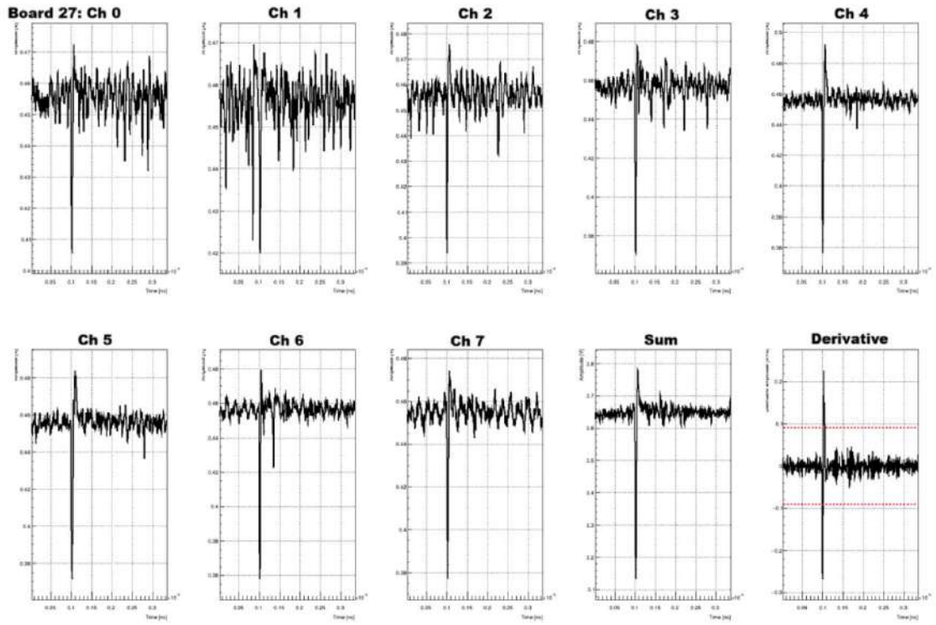
Galli, Francesconi, NIM A 936 (2019) 39

- **Trigger**
- **First time stamp for TOF**

G. Traini, A. Alexandrov, B. Alpat, Il Nuovo Cimento (2020).



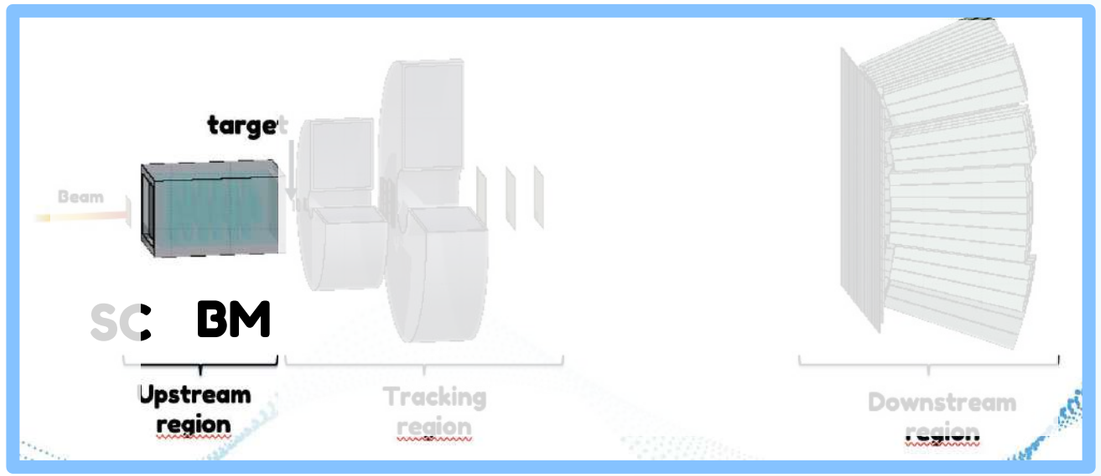


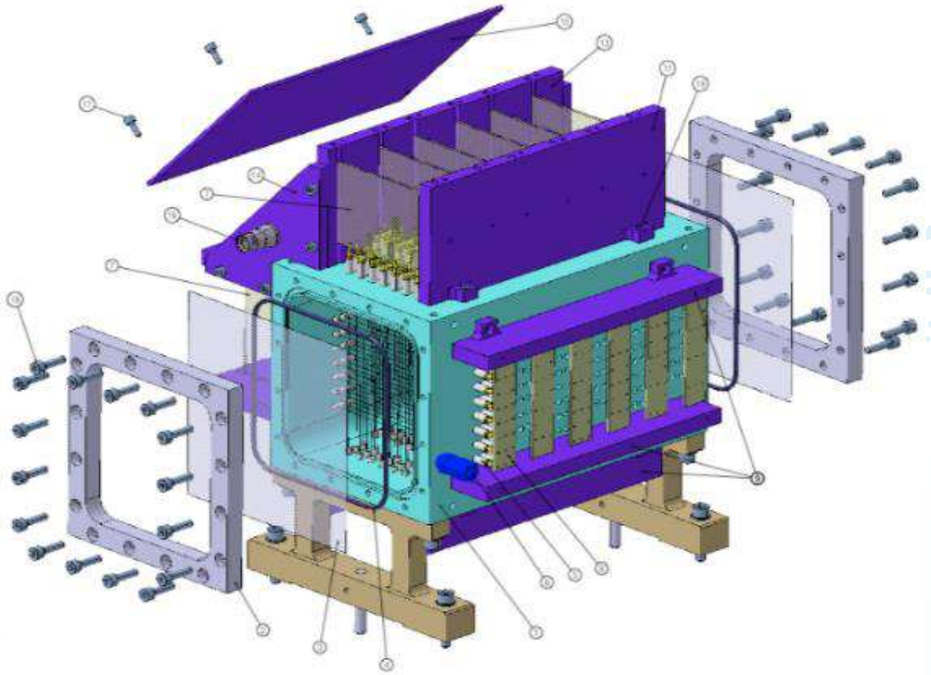


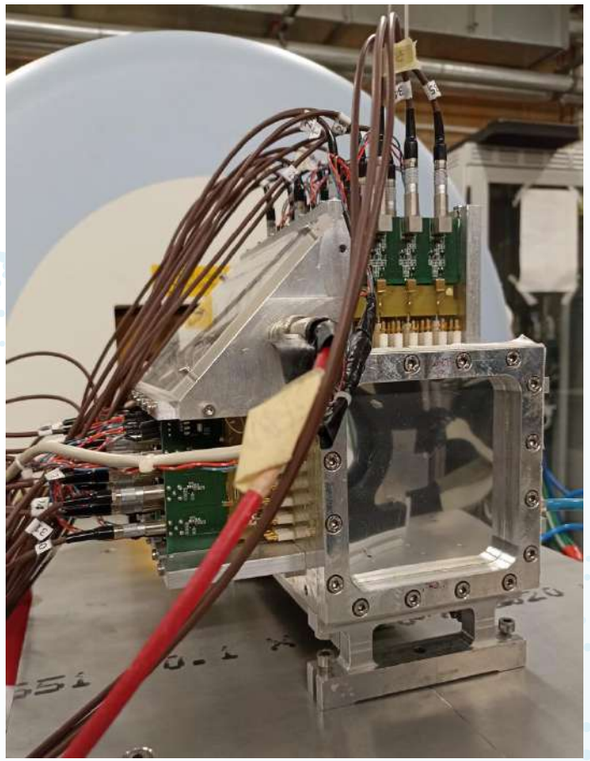
FOOT detector: upstream region

Pre-target region: **beam characterization**

Beam monitor (BM)







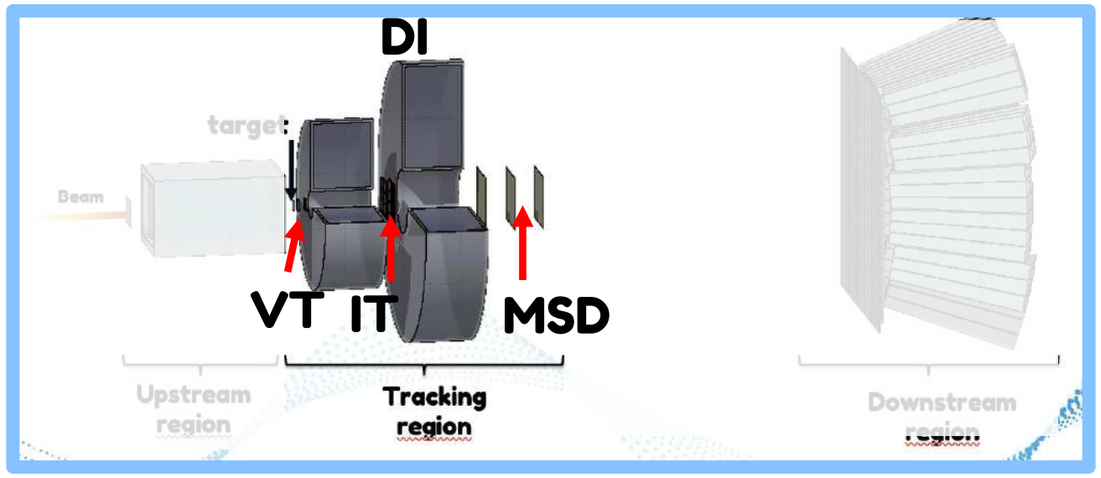
- Drift chamber
- Gas: Ar/CO_2 (80/20%)
- 12 layers, 3 cells each

- **Beam momentum**
- **Direction**

Dong et al., NIMA, 986, 2021, 164756

FOOT detector: tracking region

Tracking region→ **Fragment tracking and momentum**

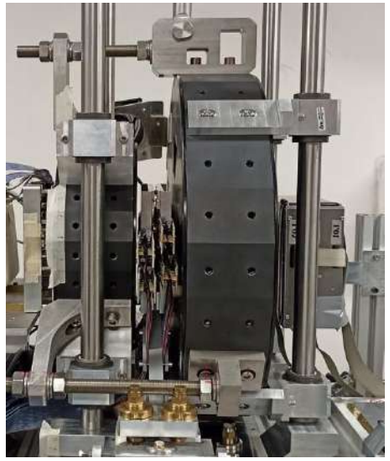


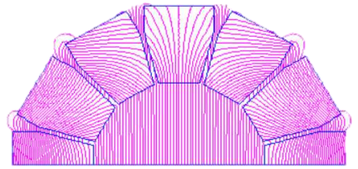
Vertex (VT) & Inner Tracker (IT)

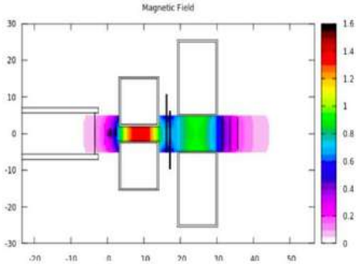
- VT: 4 layers Si pixel (20x20 μm^2), 2x2 cm2 active area
- IT: 2 layers Si pixel (20x20 μm^2) , 8x8 cm^2 total active area

→ **Fragment tracking**

Dipole magnets (DI)



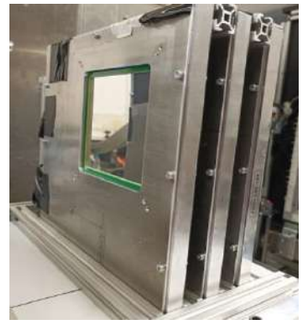




- 2 permanent Hallbach magnets
- B field in y axis (max 0.9 and 1.4 T)

→ **Particle curvature**

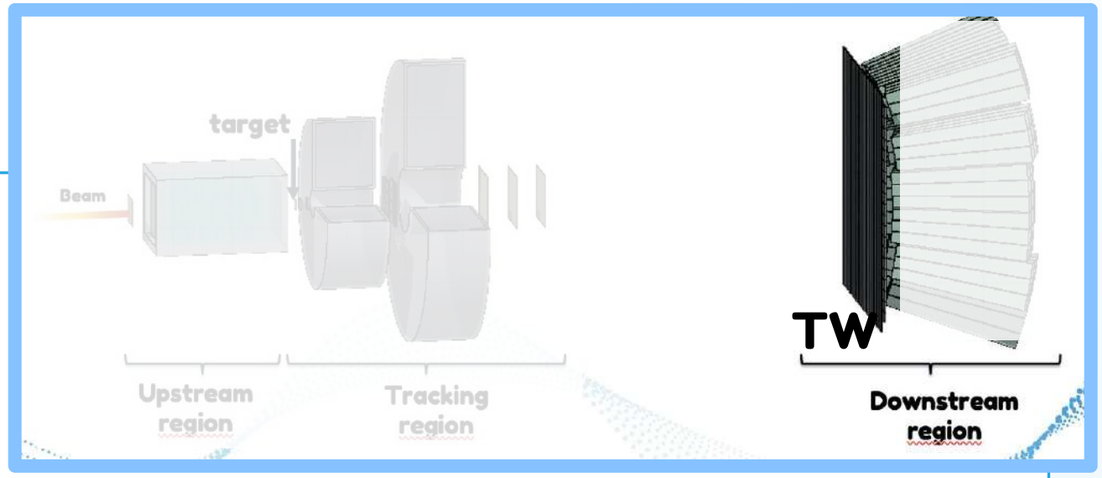
Micro Strip Detector (MSD)



- 3 couples of orthogonal layers
- 9x9 cm^2 active area
- 150 μm thickness
- 50 μm strip implantation pitch

→ **Fragment tracking**

FOOT TOF-Wall detector



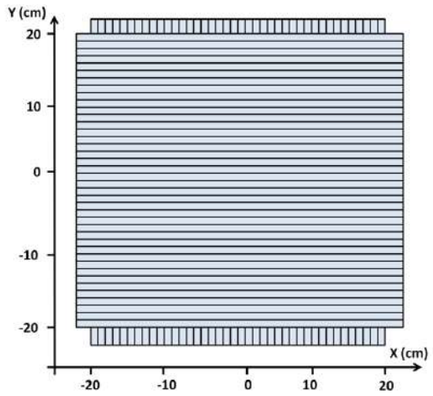
TOF-wall (TW): ΔE and second time stamp for TOF

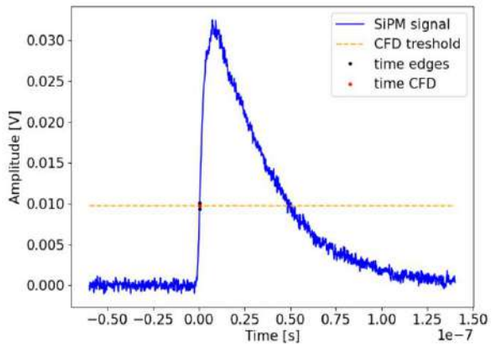
- 2 orthogonal layers of bars: 20+20 bars

Bar: plastic scintillator EJ200, Eljen technology

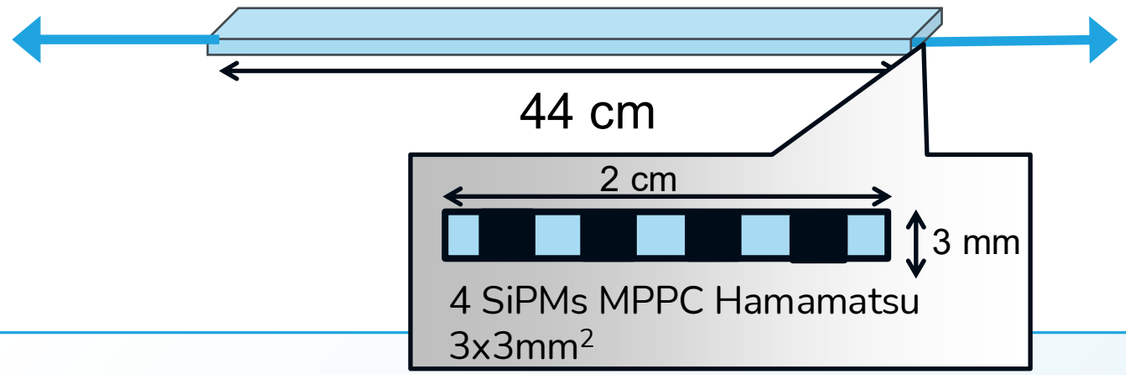
- 44 cm long, 3 mm thick, 2 cm wide
- Each bar side: 4 SiPMs MPPC Hamamatsu 3x3mm^2
- DAQ system developed at PSI for MEG2
- Channels from each bar connected to custom board WaveDREAM
- CFD algorithm to determine time

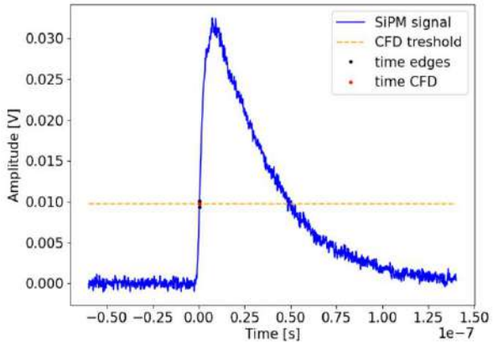
M. Morrocchi, et al, IEEE Trans Nuc Sc 68.5 (2020), pp. 1161–1168





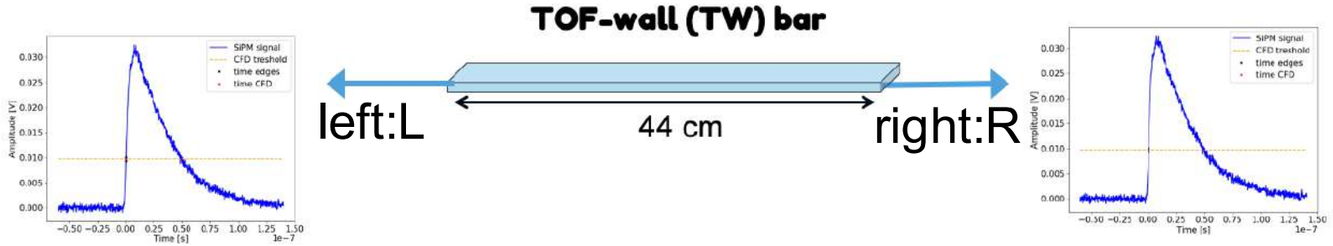
TOF-wall (TW) bar

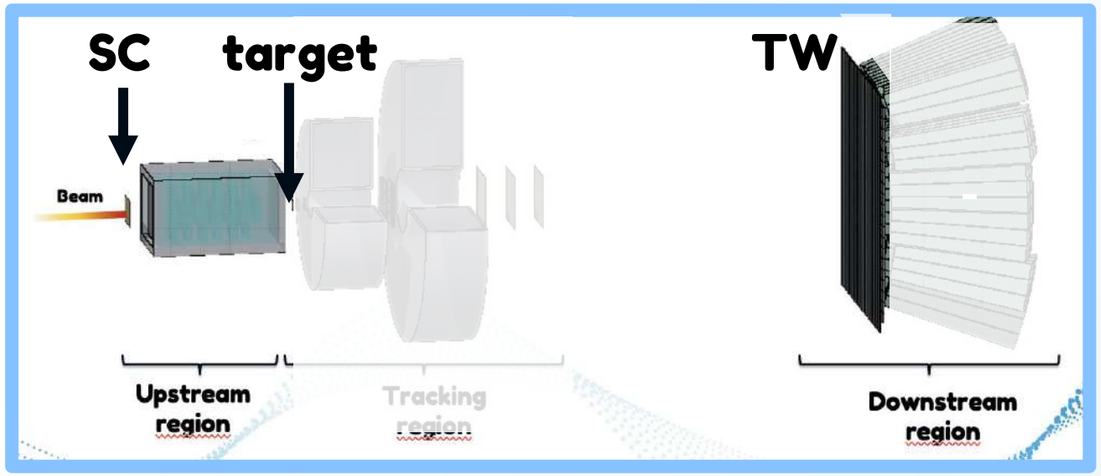




Tof Wall data processing and charge identification

Data processing:





- **Raw charge**
  - Bar: obtain Q_L and Q_R: waveform integrated
  - Total charge in bar: $\boldsymbol{Q_{bar} = \sqrt{Q_L Q_R}}$
  - Calibration by using MC simulations $\rightarrow \boldsymbol{\Delta E}$

- **Raw Time-Of-Flight**
  - $T_{TWbar} = \dfrac{T_L + T_R}{2}$
  - $TOF_{raw} = T_{TWbar} - T_{SC}$
  - Correct for time between SC and target $\rightarrow \boldsymbol{TOF}$

Z by Bethe-Bloch equation

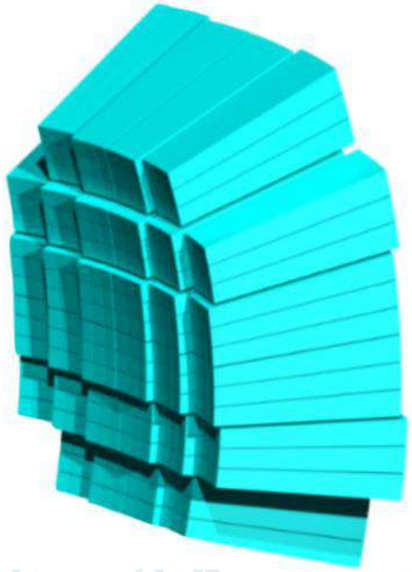
$\boldsymbol{\Delta E}$ → $\left\langle \frac{dE}{dx} \right\rangle_{coll}$ **fragment charge Z** → Z $\boldsymbol{TOF}$ → β

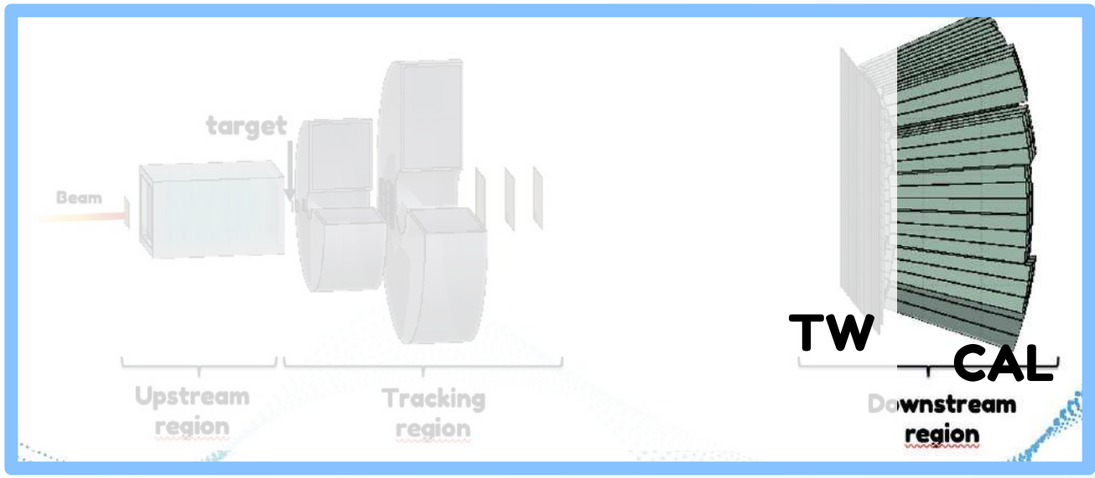
$$\left\langle \frac{dE}{dx} \right\rangle_{coll} = K \frac{\rho_t Z_t}{A_t} \frac{Z^2}{\beta^2} \left[\frac{1}{2} \log \left(\frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I_t^2} \right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right]$$

FOOT detector: downstream region

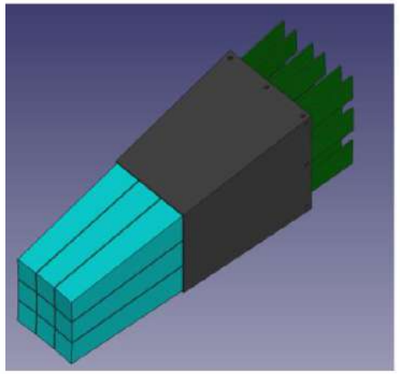
Calorimeter (CAL)

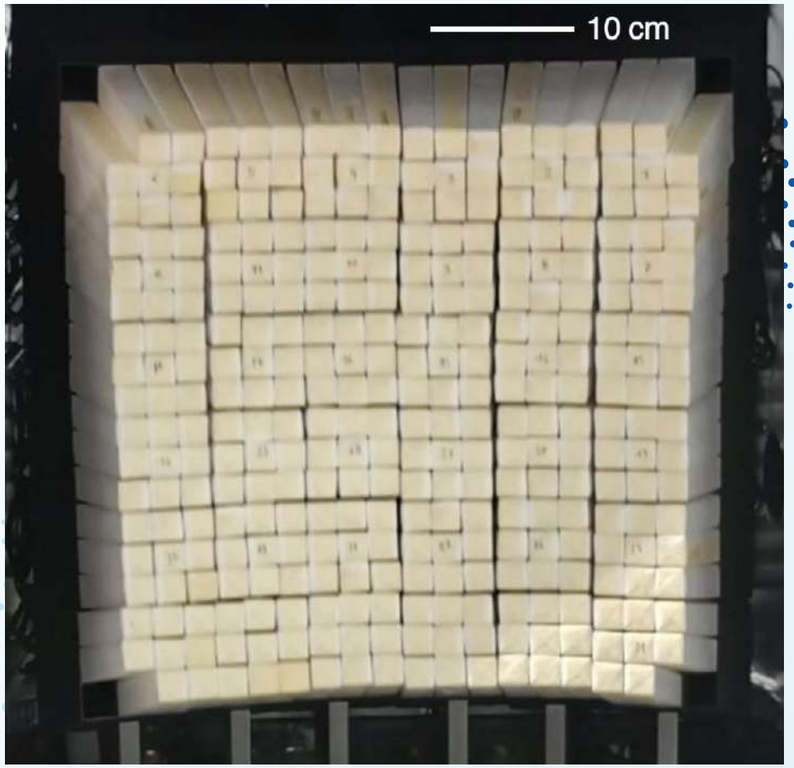
- BGO – inorganic scintillator
- 288 crystals – 330 kg
- 25 SiPMs/crystal
- 1 crystal – 1 channel readout





- **Kinetic energy**
- **Fragment identification (mass)**



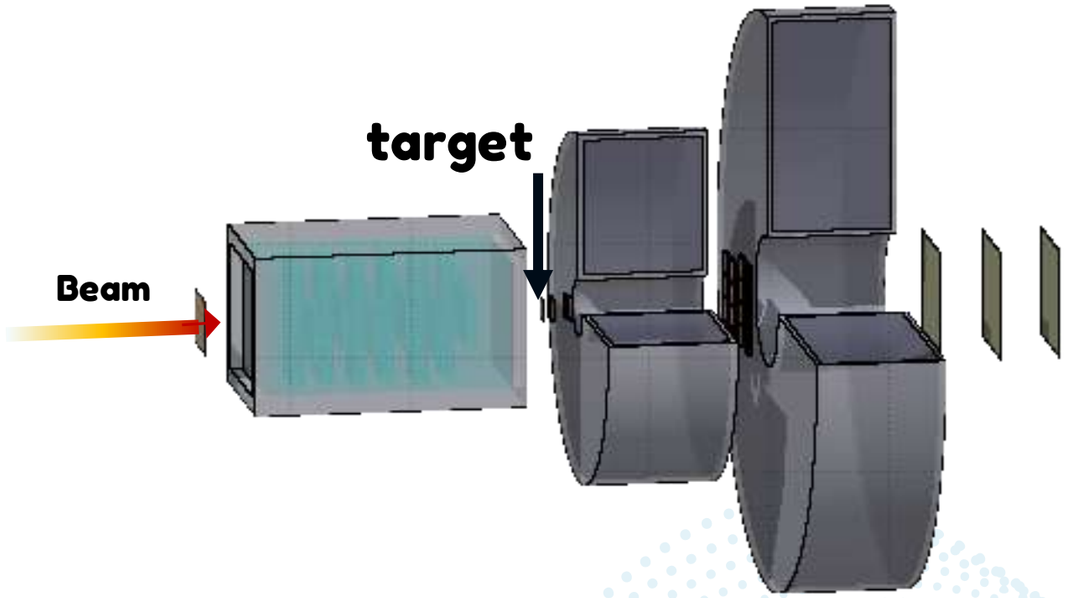


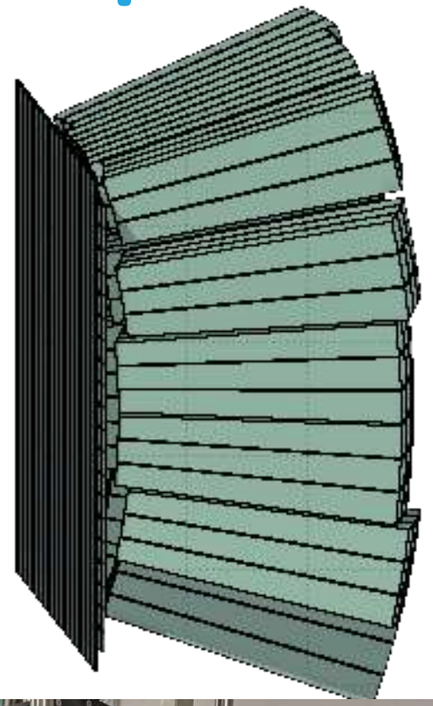
10

Mass identification

- **Mass A** reconstruction: 3 ways
  - TOF & Tracker: $p = mc\beta\gamma$
  - TOF & Calorimeter: $E_{\text{kin}} = mc^2(\gamma - 1)$
  - Tracker & Calorimeter $E_{\text{kin}} = \sqrt{p^2c^2 + m^2c^4} - mc^2$

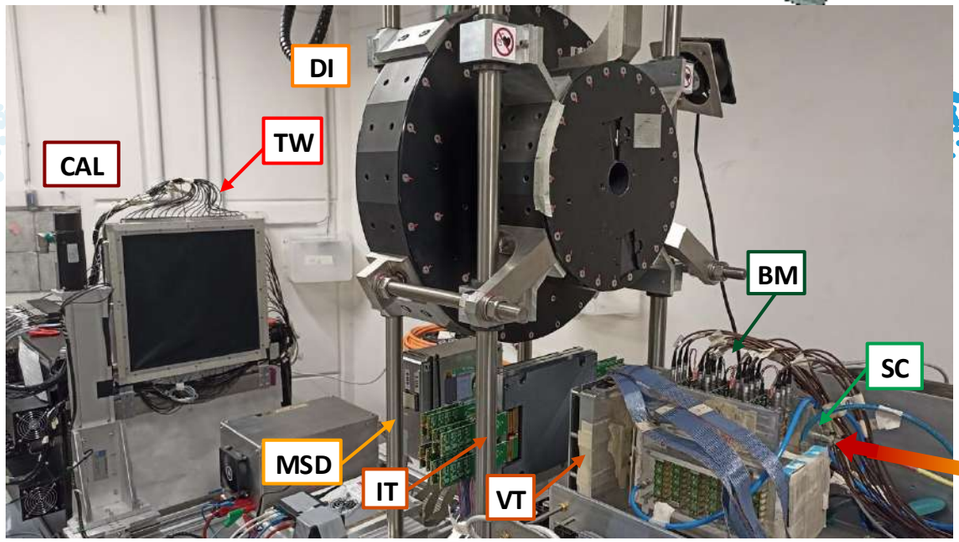
FOOT detector: status 2026 of electronic setup





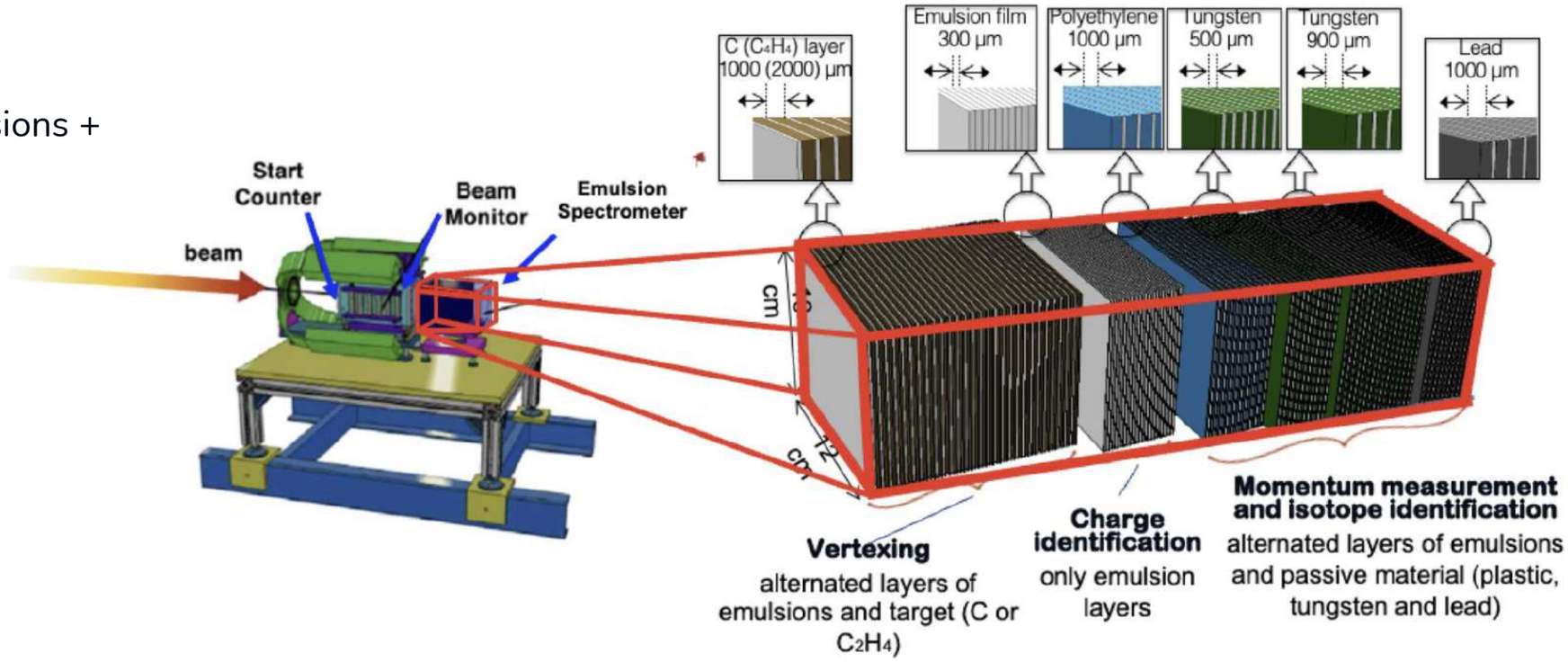
Status March 2026

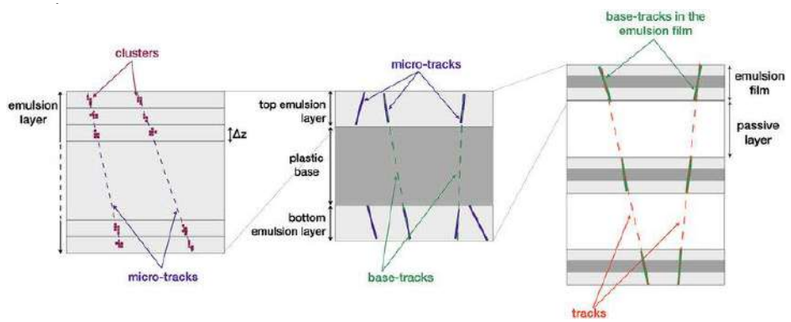
- Start counter: ready and fully tested
- Beam monitor: ready and fully tested
- Magnets: ready and tested
- VTX: ready, being tested
- Inner tracker: test phase
- Microstrip detectors: in advanced test phase
- Tof-Wall: ready and fully tested
- Calorimeter: ready, in advanced test phase



FOOT detector: emulsion spectrometer

- “Light” fragments Z ≤ 3
- Angular coverage of 45°
- Sections:
  - **Vertexing:** emulsions + target
  - **Charge id**: emulsion layers
  - **Momentum and isotope id**: emulsions + passive material
- Different beam energies with single irradiation





Status March 2026

Ready, fully tested, and acquiring data

Recent measurements and results

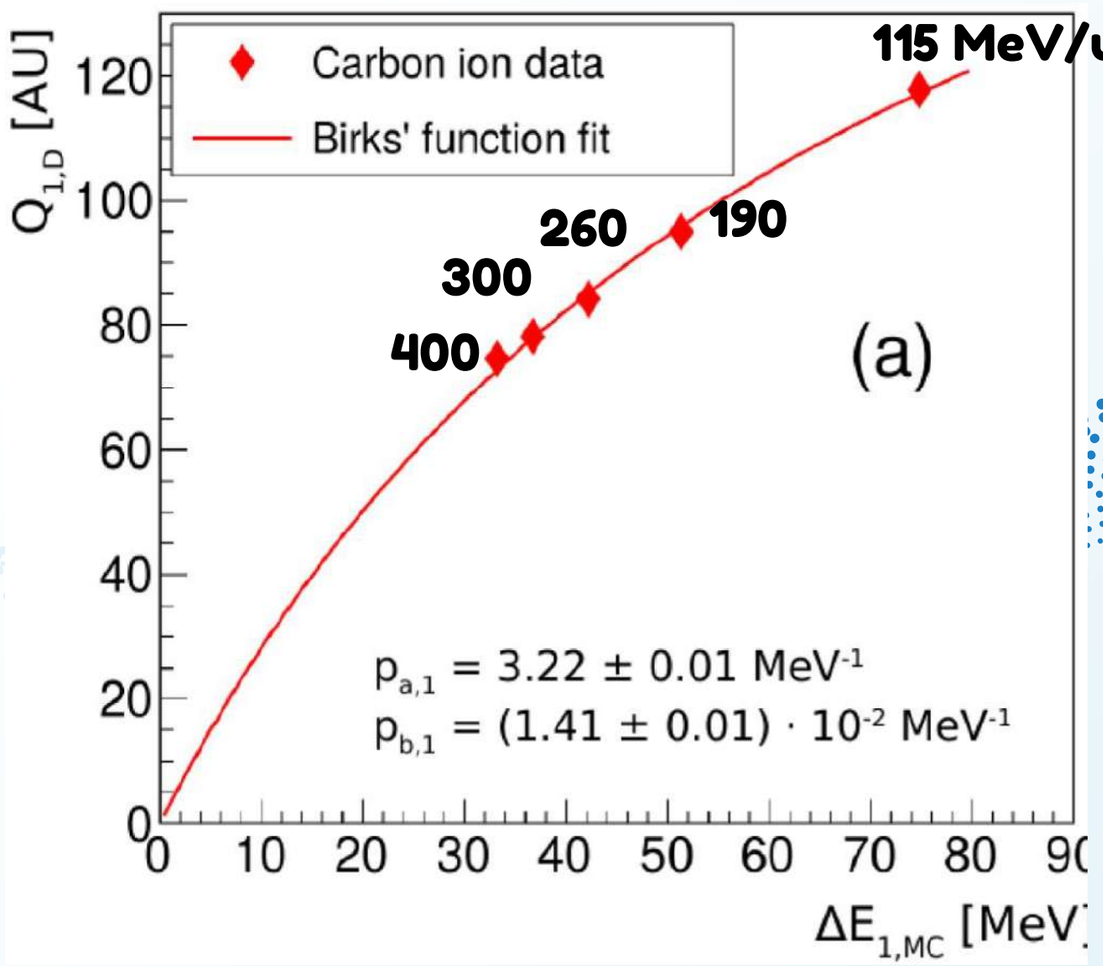
TOF-Wall energy calibration

- Each bar was calibrated by equalizing raw charge with FLUKA Monte Carlo simulations
- Non-linear relationship between energy deposit and detected charge in a bar (**quenching**)
- Not a perfect fit with Birks'

$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

- **What happens if we look at the whole spectrum produced in target fragmentation?**

Carbon ions of various energies, shot directly on scintillator bar

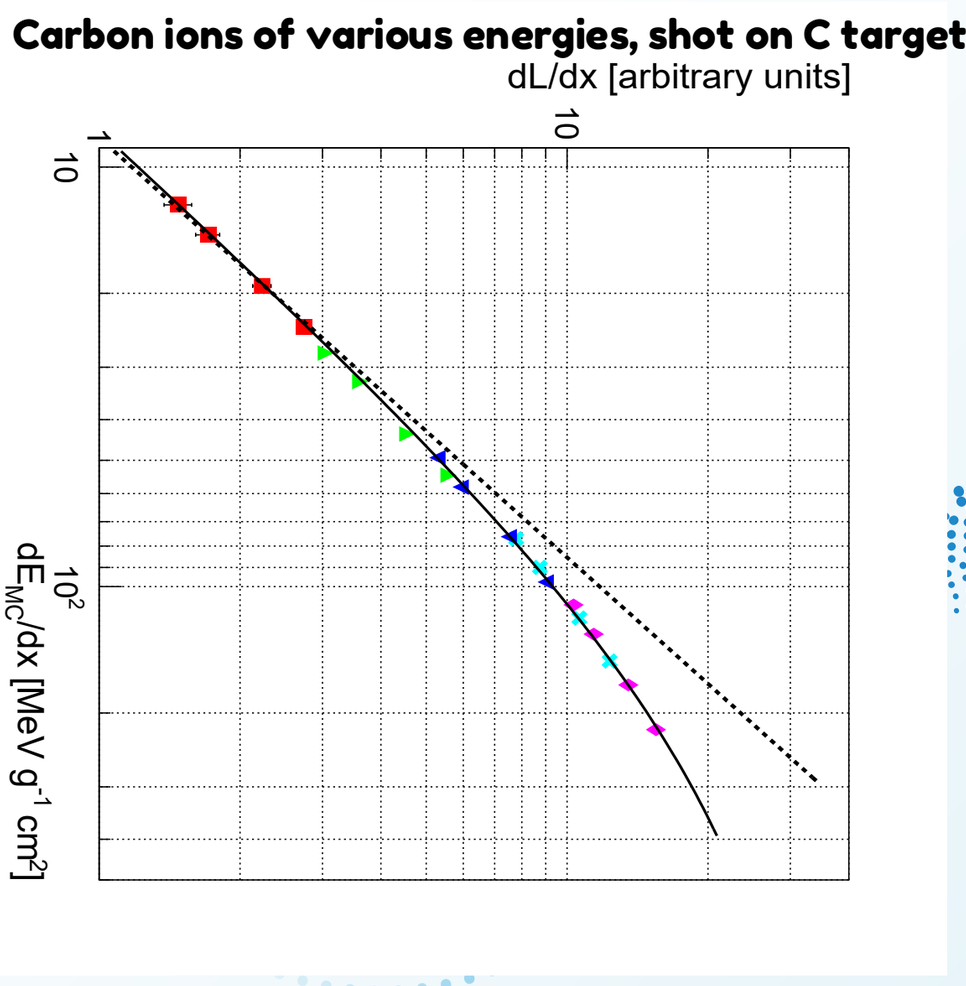


TOF-Wall energy calibration

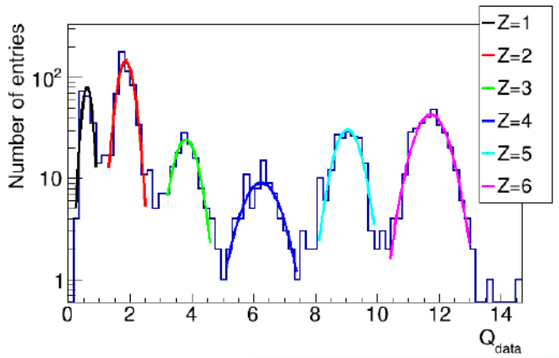
- Calibration by equalizing raw charge with FLUKA Monte Carlo simulations
- Non-linear relationship between energy deposit and detected charge in a bar (**quenching**)
- Not a perfect fit with Birks'

$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

- **What happens if we look at the whole spectrum produced in target fragmentation?**



- Used 5 peaks x 4 energies

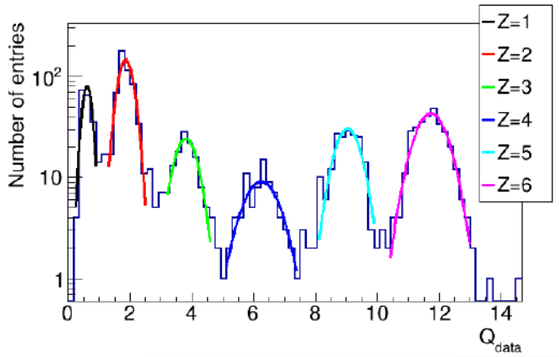


TOF-Wall energy calibration

- Calibration by equalizing raw charge with FLUKA Monte Carlo simulations
- Non-linear relationship between energy deposit and detected charge in a bar (**quenching**)
- Not a perfect fit with Birks'

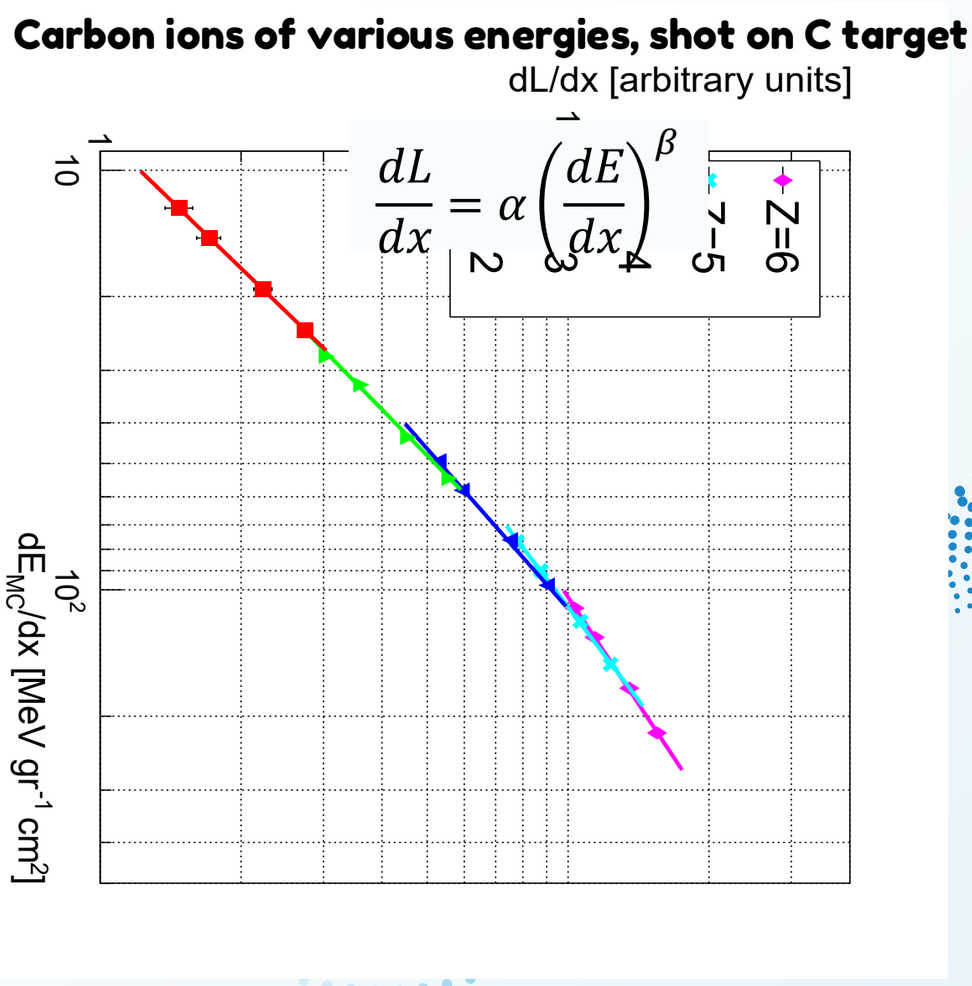
$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

- **What happens if we look at the whole spectrum produced in target fragmentation?**



- Used 5 peaks x 4 energies

Carbon ions of various energies, shot on C target

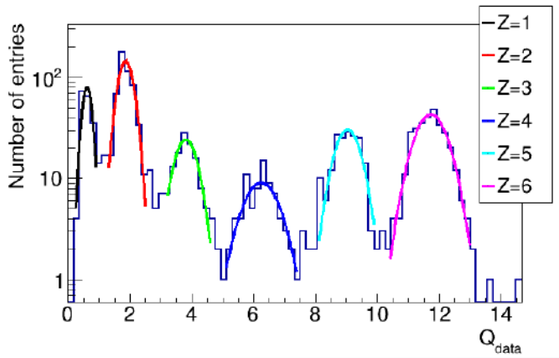


TOF-Wall energy calibration

- Calibration by equalizing raw charge with FLUKA Monte Carlo simulations
- Non-linear relationship between energy deposit and detected charge in a bar (**quenching**)
- Not a perfect fit with Birks'

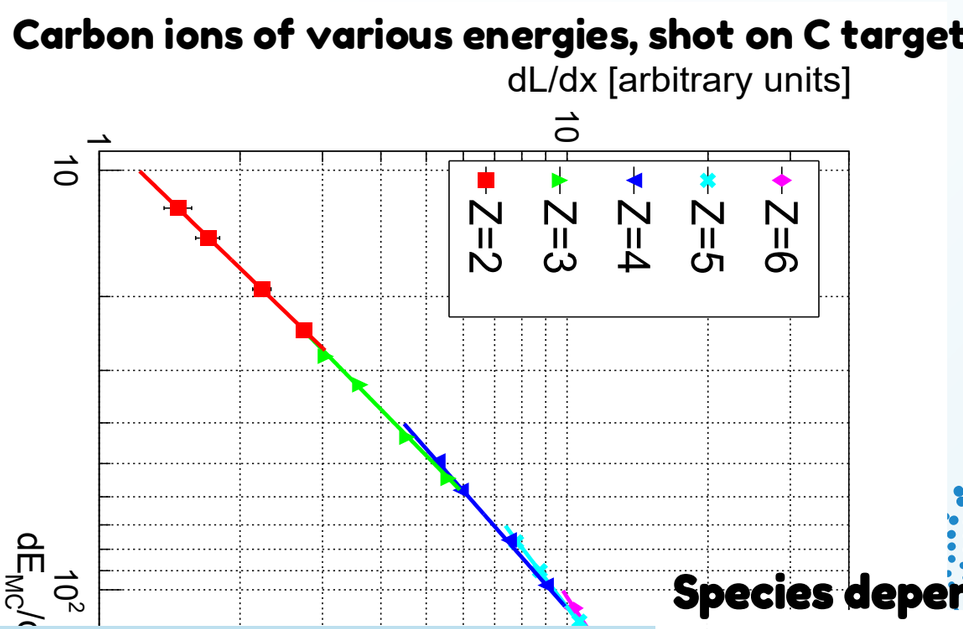
$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

- **What happens if we look at the whole spectrum produced in target fragmentation?**

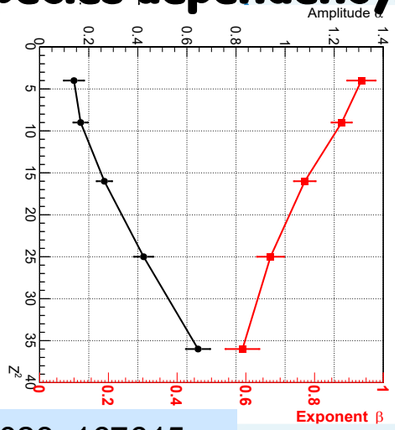


- Used 5 peaks x 4 energies

Carbon ions of various energies, shot on C target



Species dependency:



- Amplitude α: increases for larger Z,
- Exponent β: decreases for larger Z, because of more significant quenching in core for high Z particles (?)
- See Matsufuji et al, NIMA437, 1999

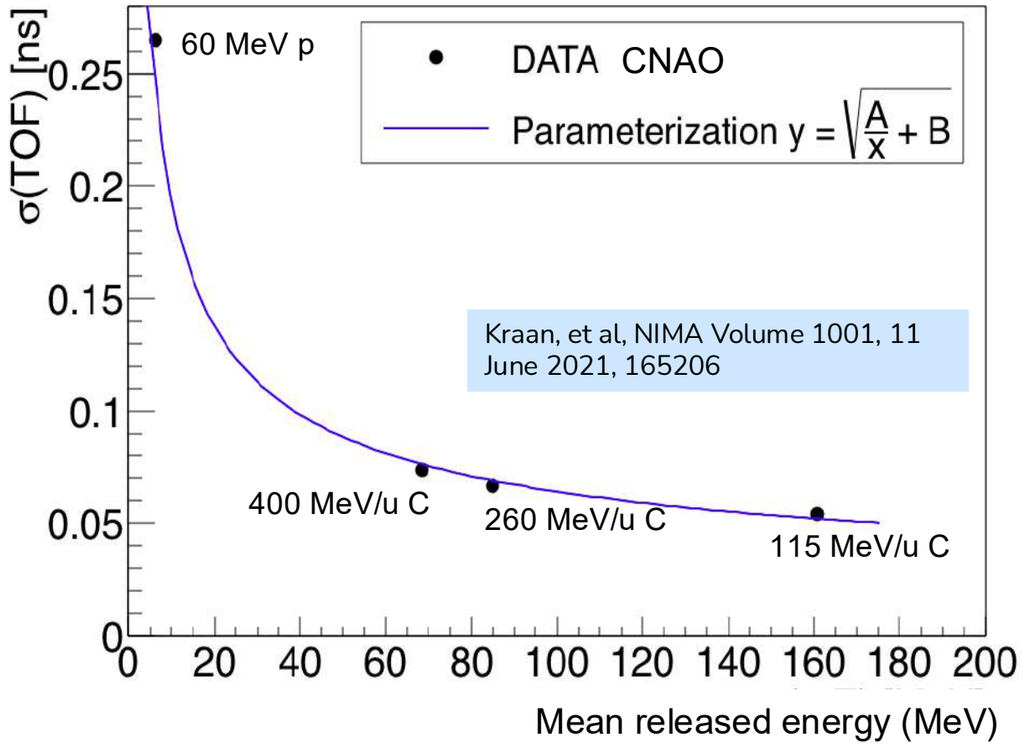
See Kraan, et al, NIMA 1045, 2023, 167615

TOF and Delta-E Resolution

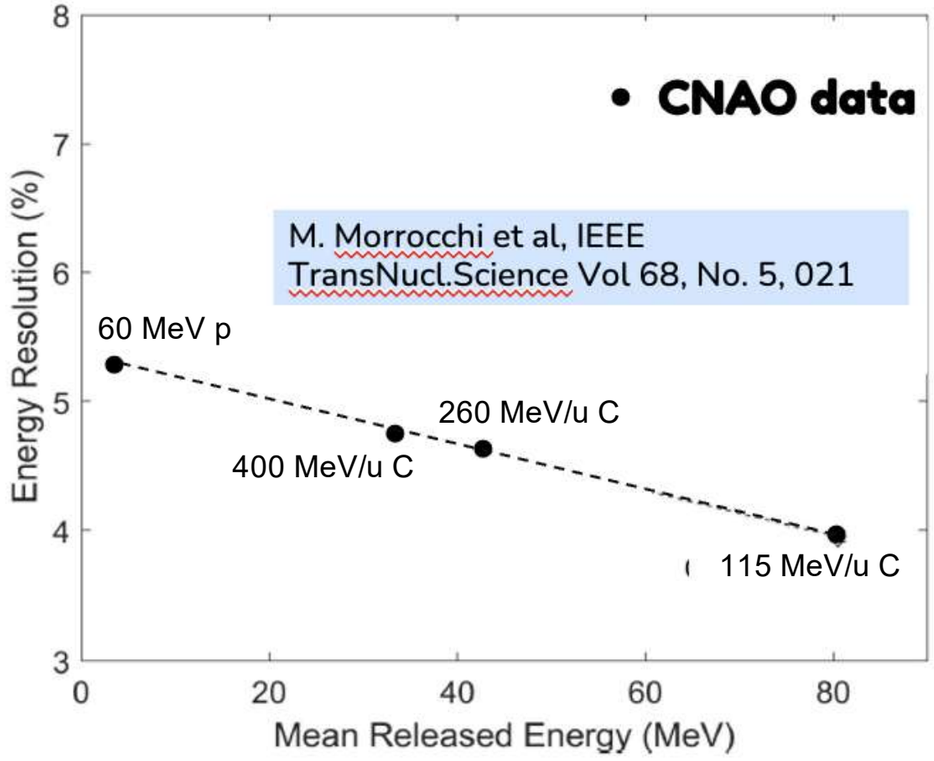
Shot directly on bars, no target

- CNAO=Centro Nazionale di Adroterapia Oncologica

TOF Wall time resolution



TOF Wall energy resolution



Resolution	Protons	Carbon ions
Time-of-flight TOF	265 ps	54 -75 ps

	60 MeV Protons	Carbon ions
Resolution (%)	5.7%	4.0% - 4.7%

Z identification: resolutions

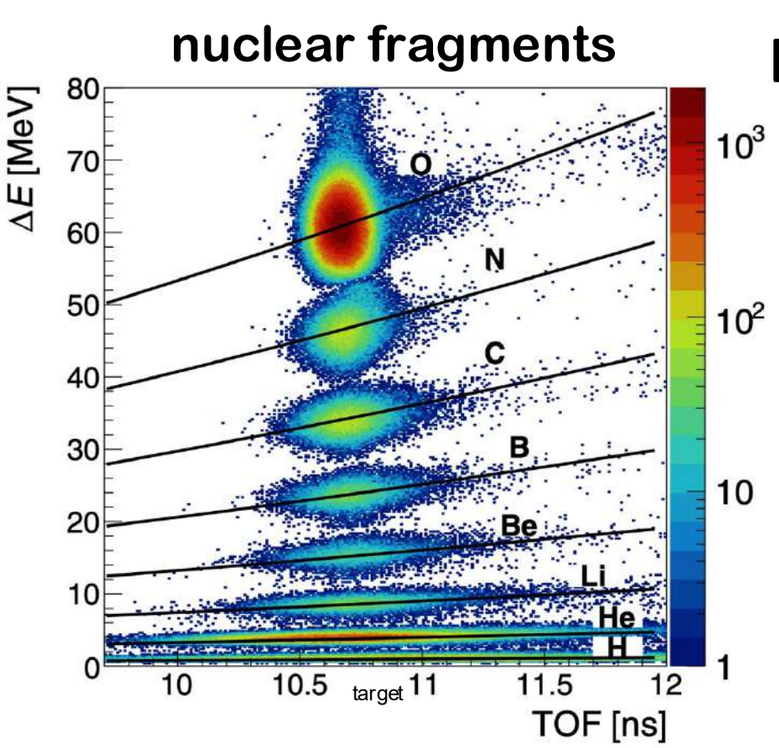
Resolutions determined **without target (different data takings)**

Facility	Particle	Beam energy [MeV/u]	$\mu(Z)$	$\sigma(Z)$	R_Z[%]
CNAO	p	60	0.96	0.06	6.10
HIT	He	100	2.03	0.06	2.72
HIT	He	140	2.04	0.07	3.44
HIT	He	200	2.06	0.09	4.36
HIT	He	220	2.05	0.09	4.51
CNAO	^{12}C	115	6.17	0.15	2.51
CNAO	^{12}C	260	6.01	0.21	3.52
CNAO	^{12}C	400	6.07	0.24	3.85
GSI	^{16}O	400	8.07	0.22	2.67

Z identification with TOF and Delta-E

Example of charge spectrum for 400 MeV/u **oxygen ions on graphite target** at **GSI** Helmholtzzentrum für Schwerionenforschung

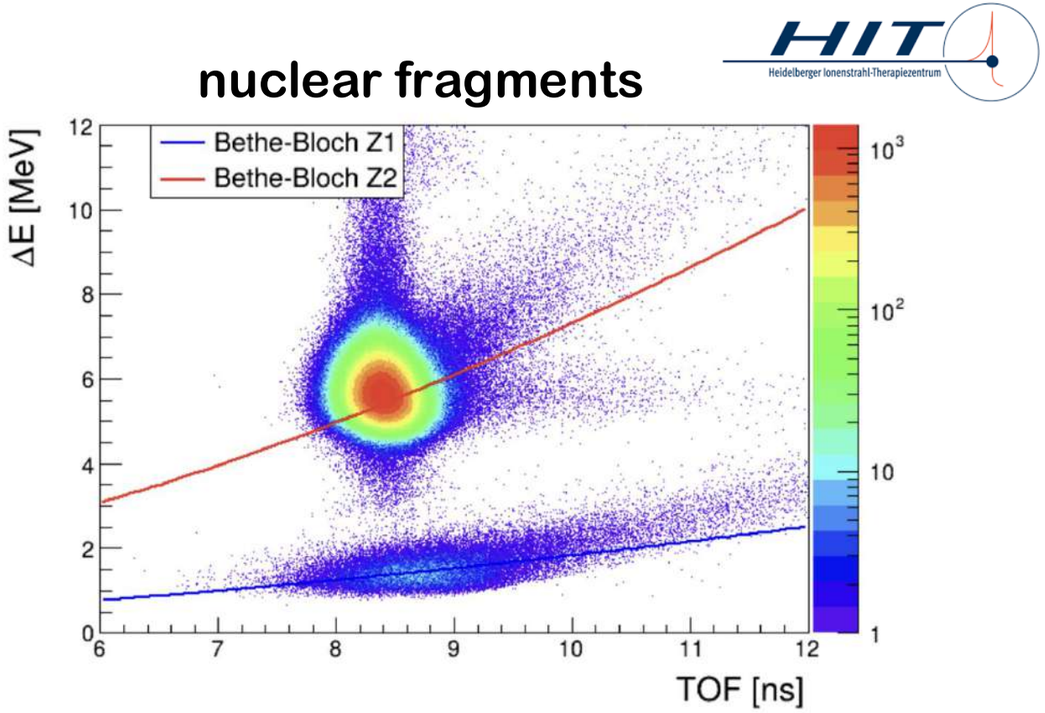
- Partial setup: no magnet, no calorimeter



Ridolfi et al, Phys Rev C 112, 014610 (2025)

Example of charge spectrum for 200 MeV/u **helium ions on graphite target** at Heidelberger Ionenstrahl-Therapiezentrum **HIT**

- Partial setup: no magnet, part of calorimeter

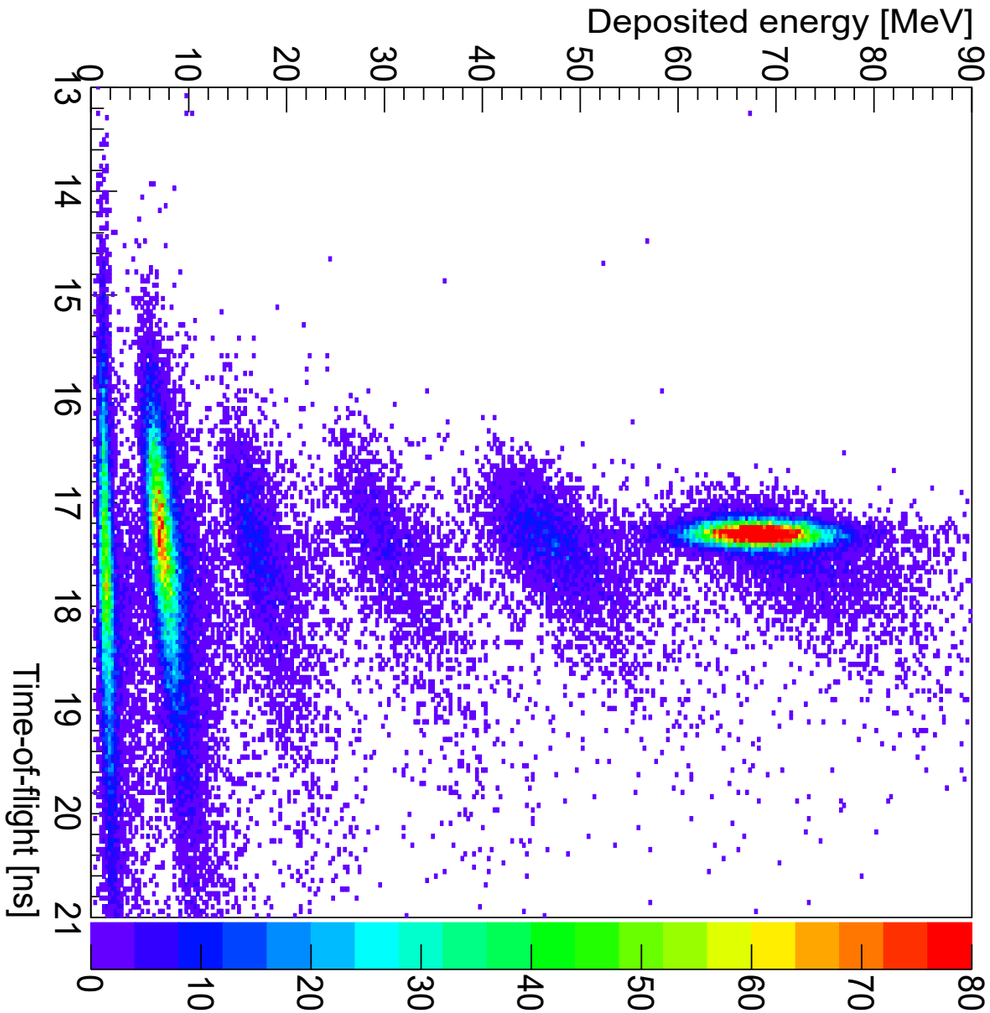


A. C. Kraan, *2025 IEEE NSS MIC RTSD conference*, Yokohama, Japan, 2025

Z identification with TOF and Delta-E

Example of charge spectrum for 150 MeV/u **carbon ions on carbon target** at **CNAO**

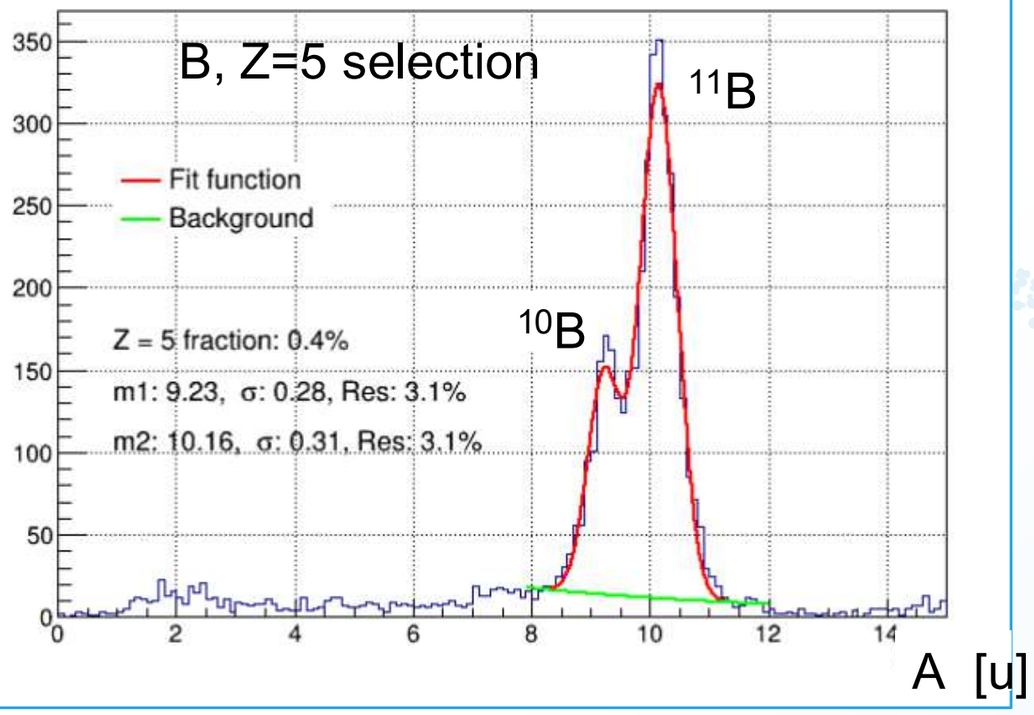
- Partial setup: no magnet, no calorimeter



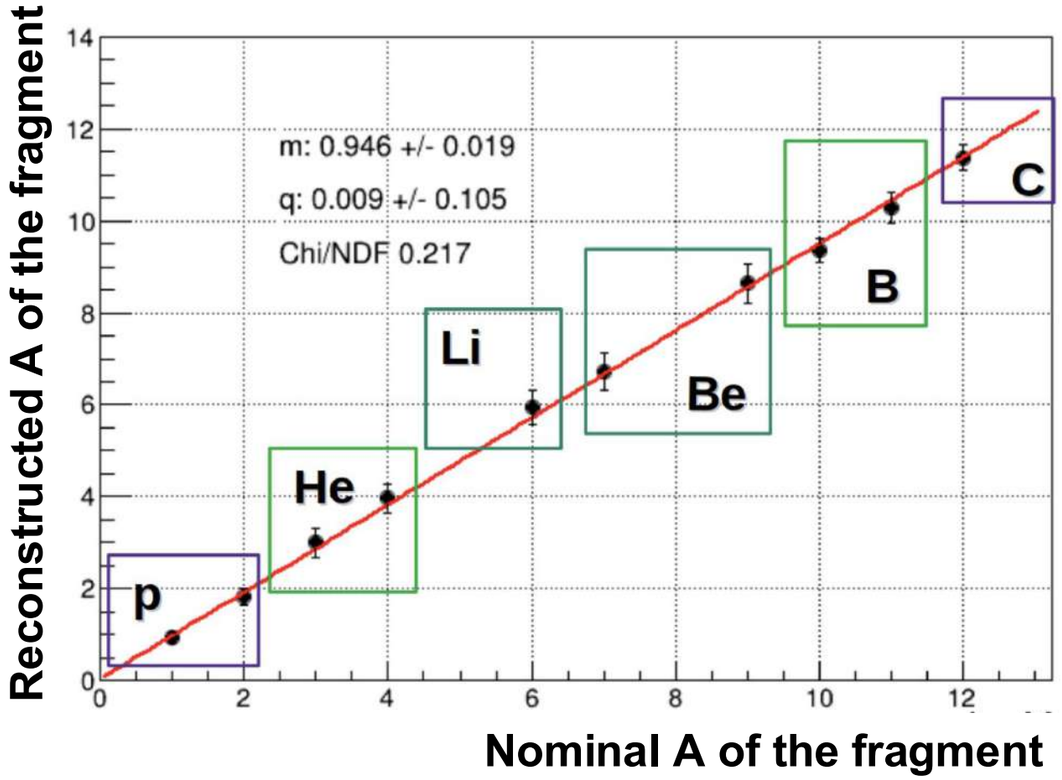
Isotope identification with Calo & TOF

$$A = \frac{E_{kin}[MeV] \cdot u}{0.931494\,MeV \cdot (\gamma - 1)}$$

Reconstructed (FLUKA MC) mass peaks from 200 MeV/u ^{12}C beam on carbon target, at CNAO



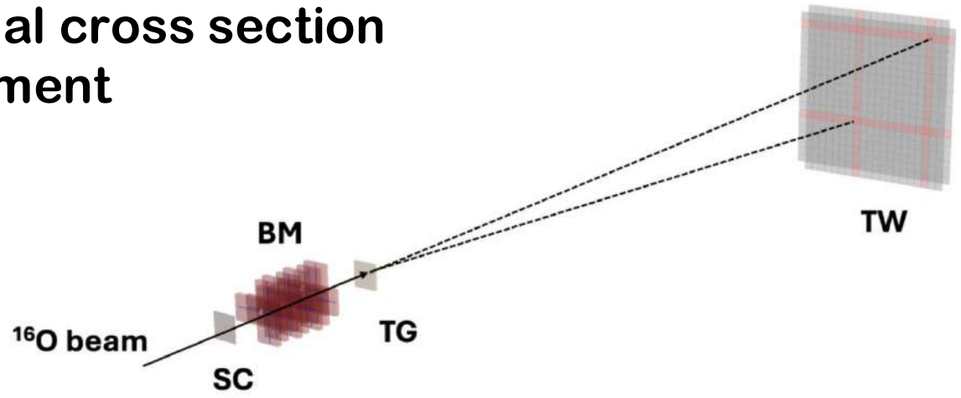
Reconstructed (FLUKA MC) mass vs nominal pass, in 200 MeV/u ^{12}C beam on carbon target, at CNAO



Cross section measurements GSI data

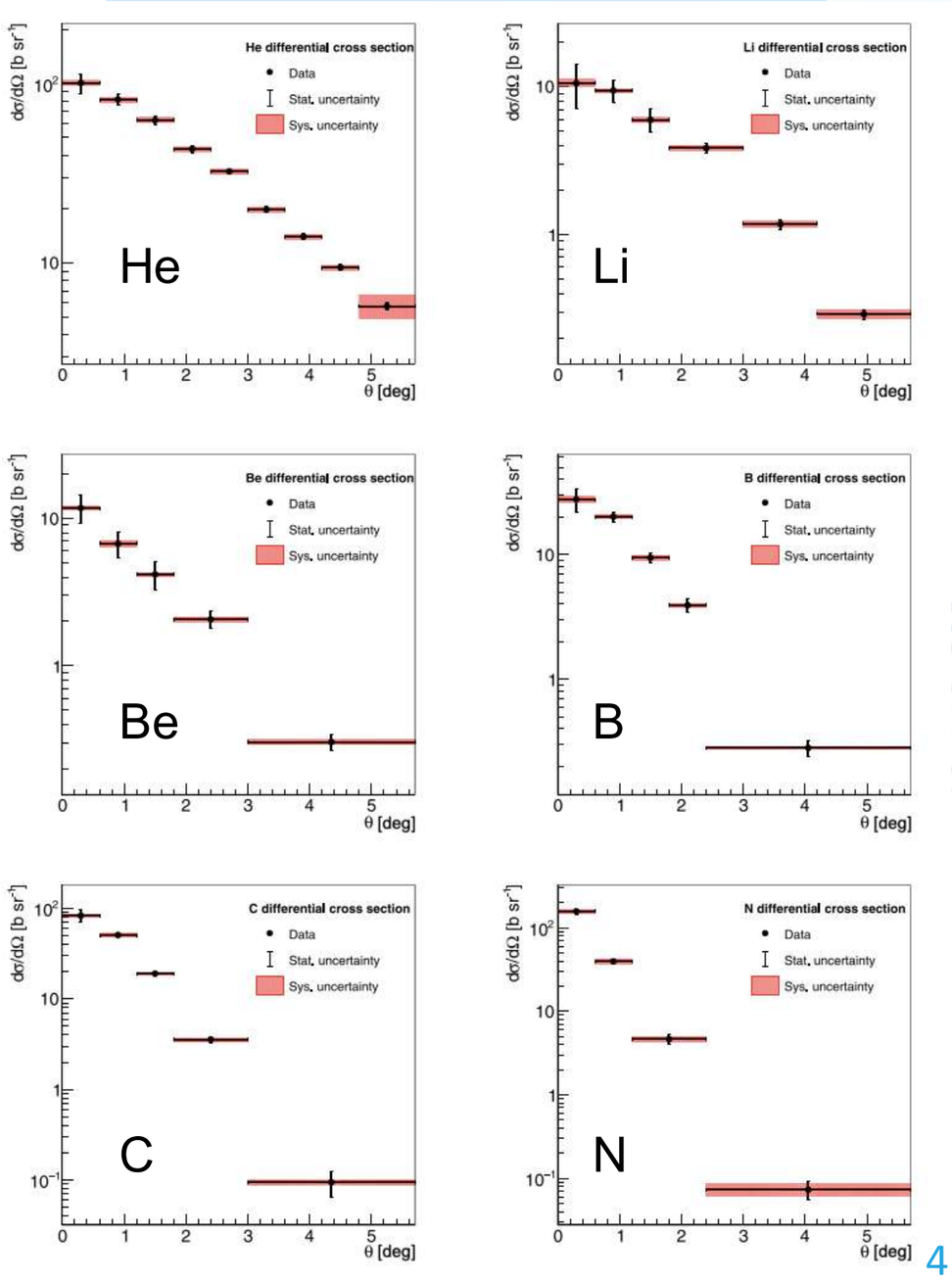
Ridolfi et al., Phys Rev C 112, 014610 (2025)

Differential cross section measurement



$$\frac{d\sigma}{d\Omega}(Z,\theta) = \frac{Y(Z,\theta)}{N_{prim} N_{TG} \varepsilon(Z,\theta)\,\Delta\Omega}$$

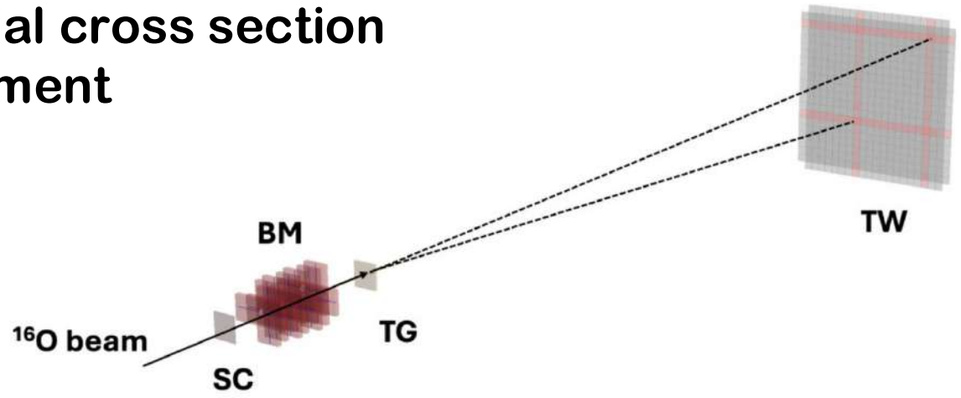
- $Y(Z,\theta)$= selected number of fragments of a **given charge Z** measured by TW at a given angle θ
- N_{prim} = selected number of primaries impinging on the target
- $\varepsilon(Z,\theta)$ = efficiency for a given charge in a given angle
- $\Delta\Omega$ = solid angle bin width
- N_{TG} = number of interaction centers in the target per unit surface $N_{TG} = \frac{\rho d N_A}{A}$



Cross section measurements GSI data

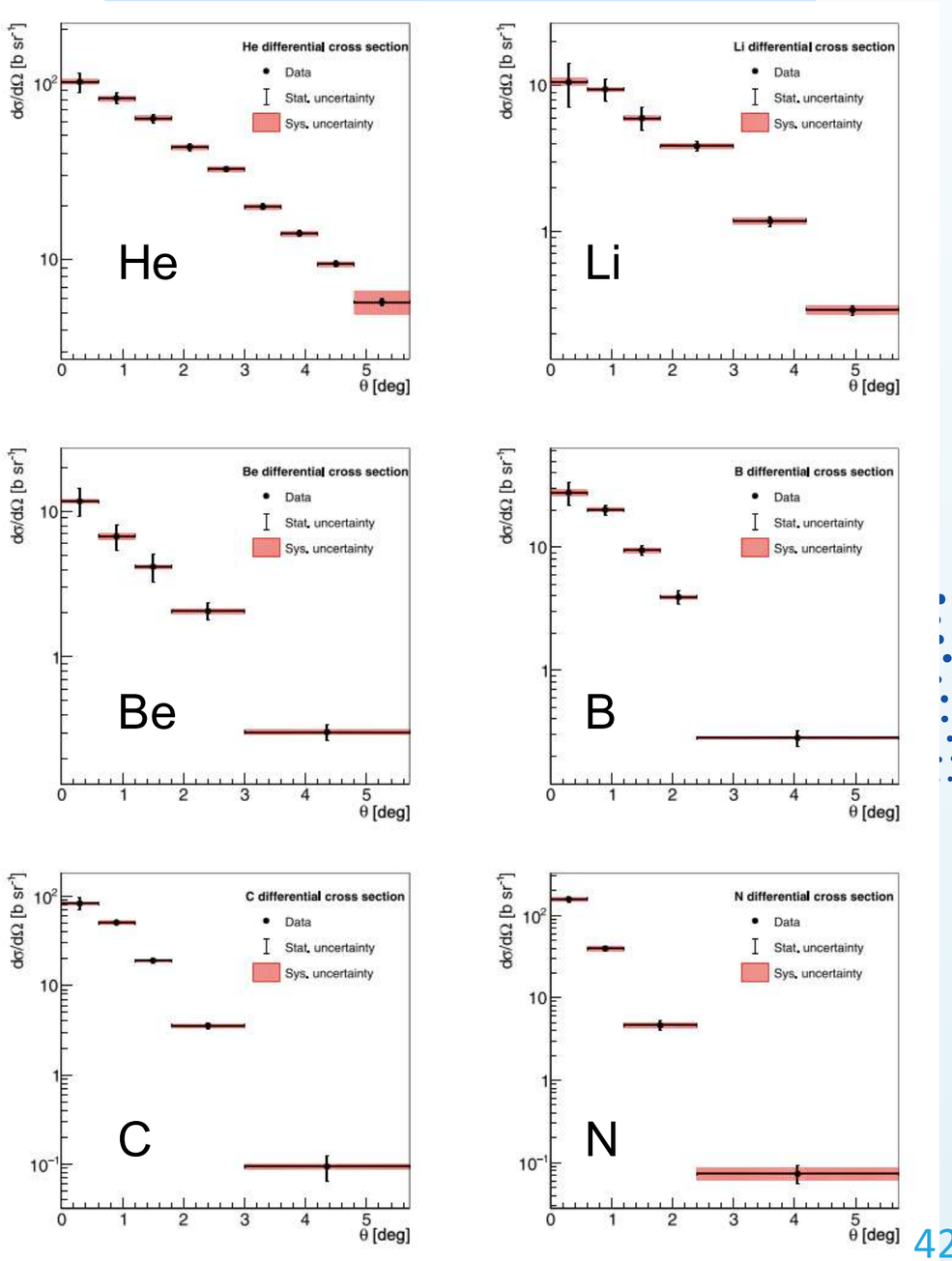
Ridolfi et al., Phys Rev C 112, 014610 (2025)

Differential cross section measurement



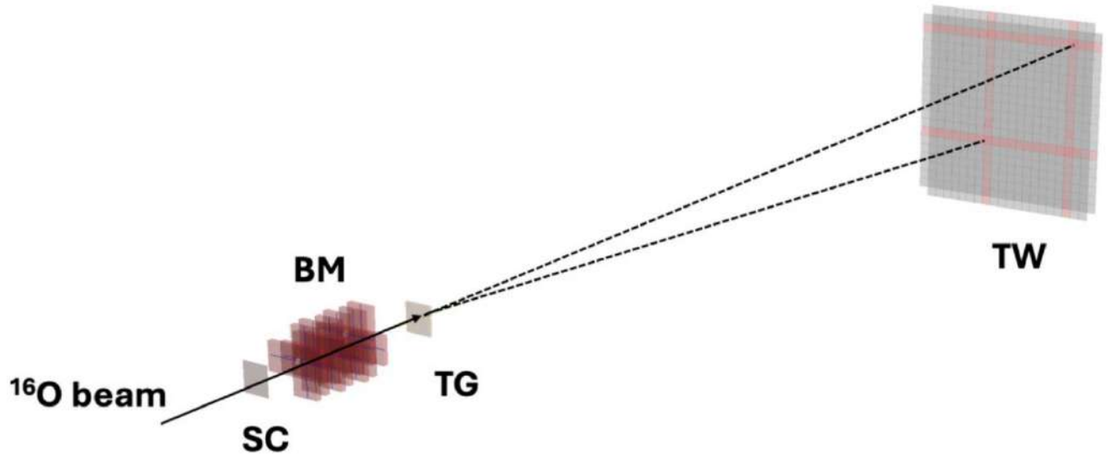
Differential cross section for various charge fragments extracted:

- Measurements up to 5.7 degrees
- Values from about 0.1 up to 10^2 b sr^{-1}



Cross section measurements GSI data

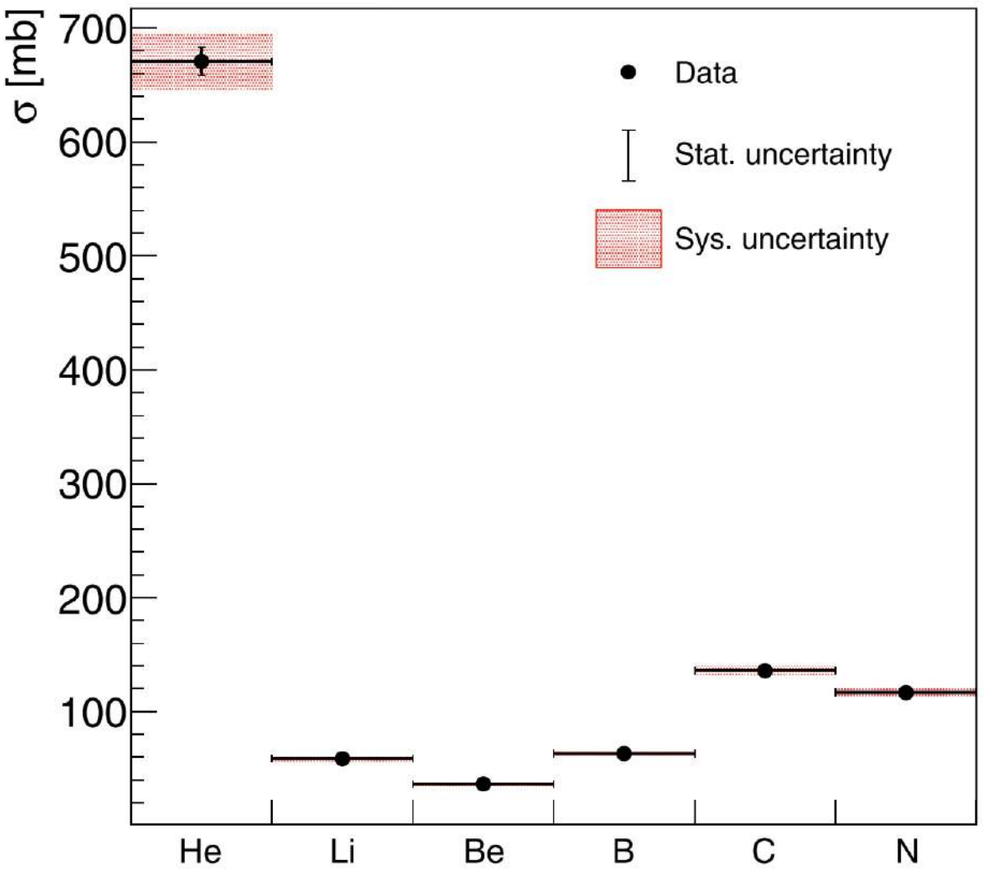
Ridolfi, Phys Rev C 112, 014610 (2025)



Total cross section measurement 400 MeV/nucleon ^{16}O beam on graphite target

Element	$\sigma \pm \Delta_{stat} \pm \Delta_{sys}$ (mb)	Δ_{stat}/σ	Δ_{sys}/σ
He	$671 \pm 12 \pm 25$	1.9%	3.7%
Li	$59 \pm 3 \pm 2$	5.6%	3.5%
Be	$37 \pm 3 \pm 1$	7.8%	3.0%
B	$63 \pm 4 \pm 2$	6%	3%
C	$136 \pm 6 \pm 4$	4.4%	3.1%
N	$117 \pm 6 \pm 4$	5.4%	3.0%

Ridolfi, Phys Rev C 112, 014610 (2025)



Main uncertainties from:

- Statistics
- Systematics: reconstruction, out-of-target fragmentation

Comparison with models

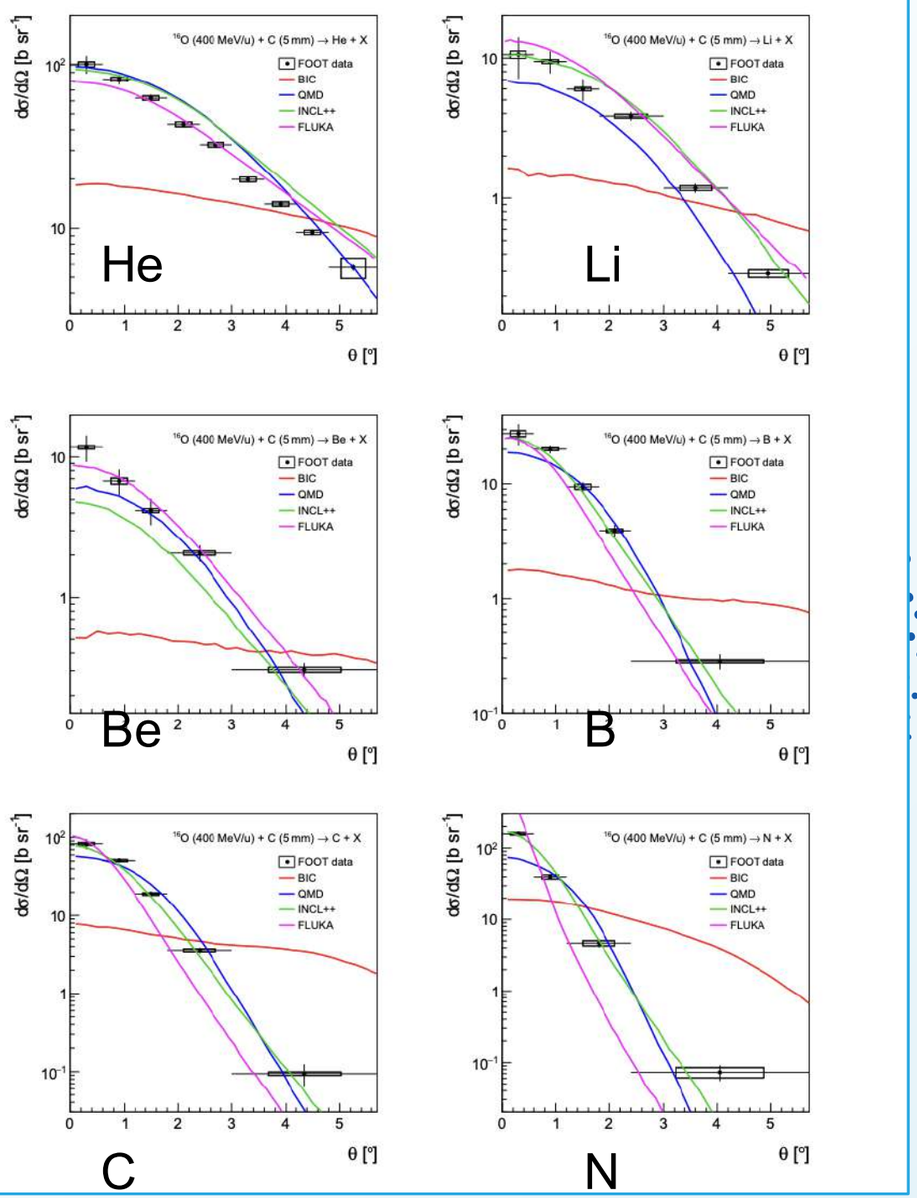
Ridolfi, Phys Rev C 112, 014610 (2025)

Comparison with theoretical predictions from 4 different nuclear interaction models used in MC codes:

- FLUKA MC code
  - relativistic Quantum Molecular Dynamics model: rQMD2.4. (high E, but coupled to PEANUT it's ok for FOOT)
- Geant 4 Binary Ion Cascade (BIC) model: Glauber-Gribov cross sections
- Geant 4 Quantum Molecular Dynamics (QMD): nucleon is treated as wavepacket that evolve according to QMD
- Liège Intranuclear Model (INCL^{++}): nuclear reaction is series of of dependent nucleon-nucleon collisions in target

Difference lay in:

- distinct physical models, such as different approaches to direct reactions, pre-equilibrium reactions, or compound nucleus reactions.
- Underlying Nuclear Data Libraries may differ
- Benchmarking with data differs



Comparison with models

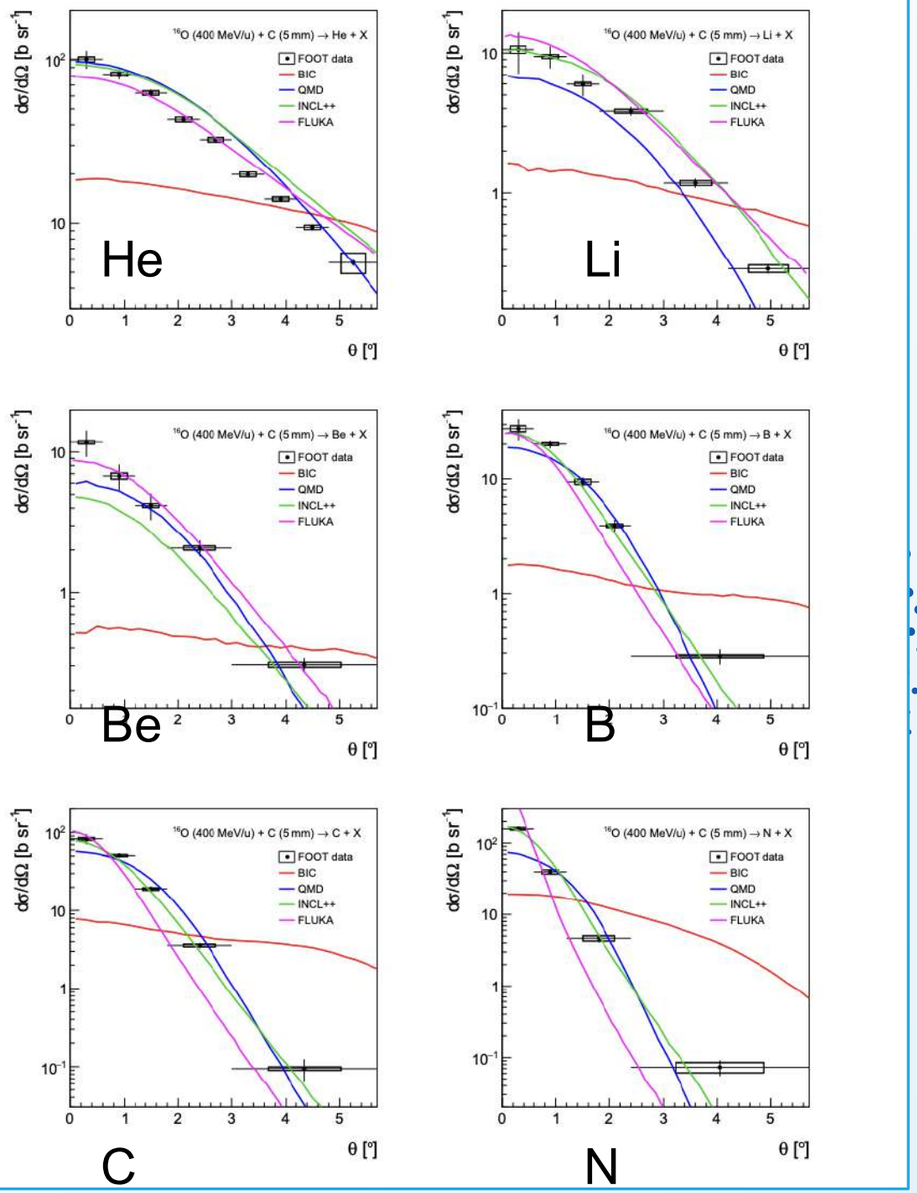
Ridolfi, Phys Rev C 112, 014610 (2025)

Comparison with theoretical predictions from 4 different nuclear interaction models used in MC codes:

- FLUKA MC code
  - relativistic Quantum Molecular Dynamics model: rQMD2.4. (high E, but coupled to PEANUT it's ok for FOOT)
- Geant 4 Binary Ion Cascade (BIC) model: Glaub[illegible]ov cross sections
- Geant 4 Quantum Molecular Dynamics (QMD): nucleon [illegible] treated as wavepacket that evolve according to QMD
- Liège Intranuclear Model (INCL^{++}): nuclear reaction is series of of dependent nucleon-nucleon collision[illegible]get

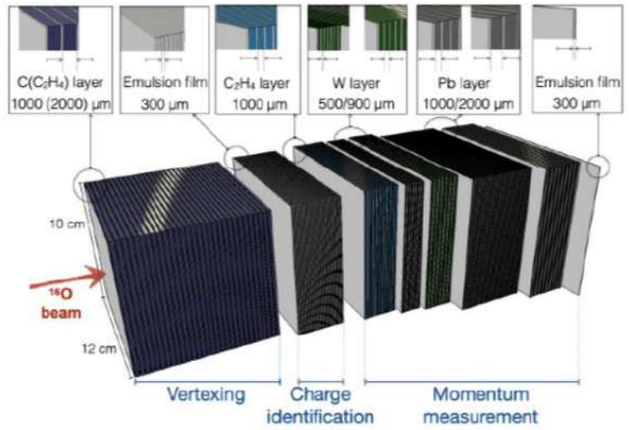
Difference lay in:

- distinct physical models, such as different approaches to direct reactions, pre-equilibrium reactions, or compound nucleus reactions.
- Underlying Nuclear Data Libraries may differ
- Benchmarking with data differs

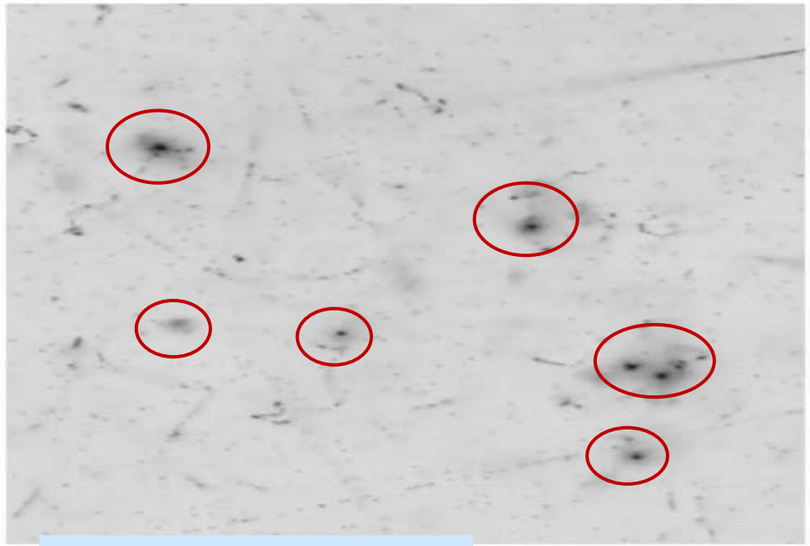


Emulsion spectrometer

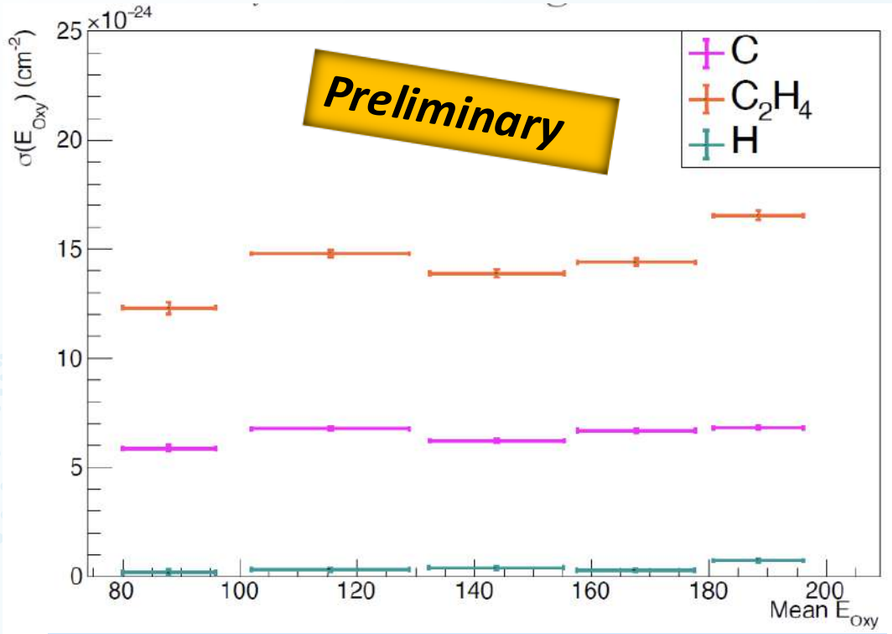
- 200 MeV/u ^{16}O beam delivered on a carbon or polyethylene target embedded between the emulsion films



- Fragments pass through the detector, leaving a track in the emulsion sensitive gelatine
- After a development process and a thermal treatment, a dedicated analysis allows to reconstruct the tracks and charge of the fragments
- Integrated cross section of oxygen on carbon and polyethylene is estimated. The proton production cross section is computed by a linear combination of the two (inverse kinematic approach



Oxygen tracks in the emulsion.



Total reaction cross sections on C, C_2H_4, and H as a function of energy.

Conclusion

- The FOOT experiment has two set-ups for measuring cross sections:
  - Electronic detectors setup ($Z \geq 2$), up to ~10 degrees
  - Emulsion Cloud Chamber ($Z \leq 3$), up to ~70 degrees
- The FOOT experiment will provide a set of double differential fragmentation cross sections. More accurate modelling of fragment productions→ more accurate calculations of biological dose
  - Better treatments!
  - Improving radiation protection in space
- Initial data takings were performed with a subset of detectors
  - Focus here on Tof Wall → resolutions, experimental tests, etc
- Fragment charge can be reconstructed with the FOOT electronic setup
  - Successfully measuring cross sections for fragments and angles with both set-ups
  - Benchmarking with main fragmentation nuclear models
- New! Fragment masses have been reconstructed using Tof-Wall and Start Counter
- More results to come in next years

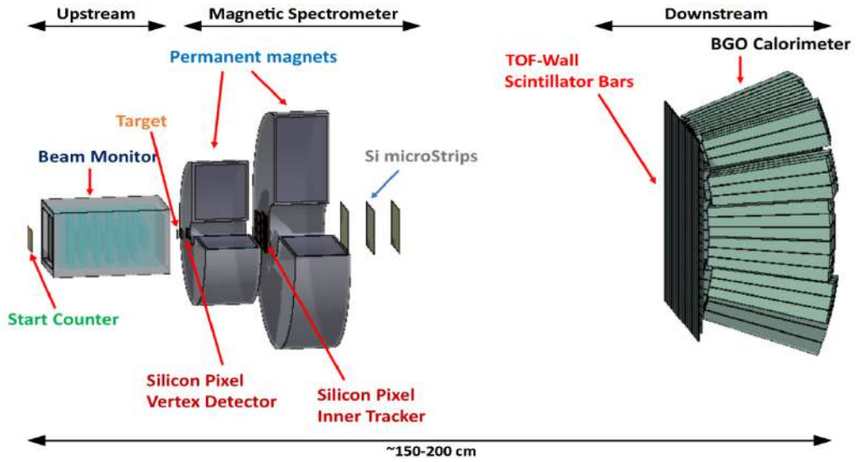
FOOT January 2026

Many thanks to Tomasz Matulewicz for the invitation!

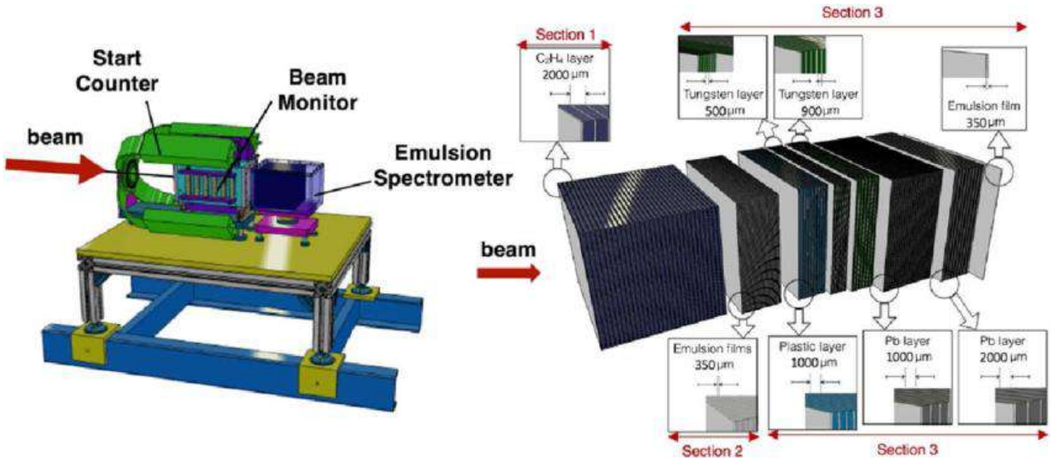
FOOT (FragmentatiOn Of target) detector

- Measure for each fragment: Mass A, Charge Z, Polar angle θ, Kinetic energy E
- Usable in different accelerator facilities: portable design.
- Light projectile and target nuclei at 200-800 MeV/u (protons, helium, carbon, oxygen)
- Characterize primaries and fragments
- Target: Graphite, Polyethylene (thin, typically 5 mm)
- Measurements both in direct and inverse kinematics
- Two complementary setups: Electronic detectors setup (Z ≥ 2) and Emulsion Cloud Chamber (Z ≤ 3)

Electronic setup: up to 10 degrees



Emulsion cloud chamber: up to 45 degrees

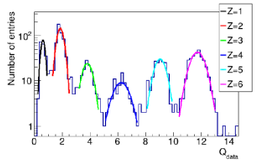


TOF-Wall energy calibration (interesting physics)

- Non-linear relationship between energy deposit and detected charge in a bar (**quenching**)
- Not a perfect fit with Birks'

$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

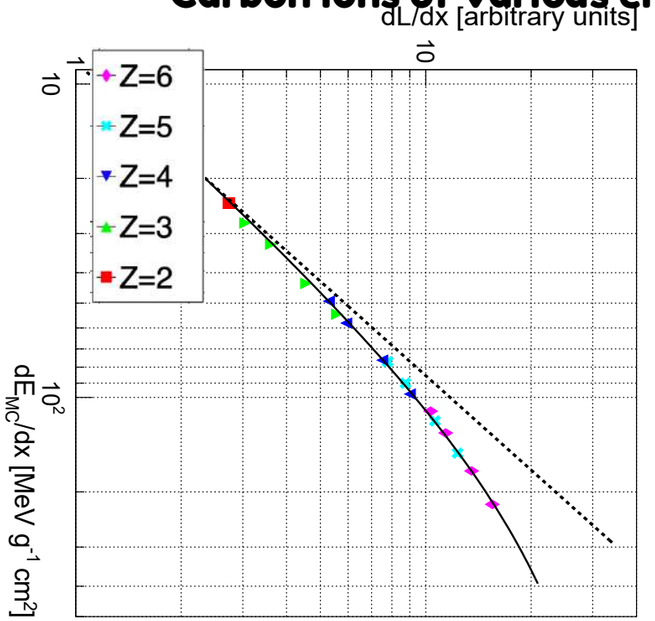
- **What happens if we look at the whole spectrum produced in target fragmentation?**

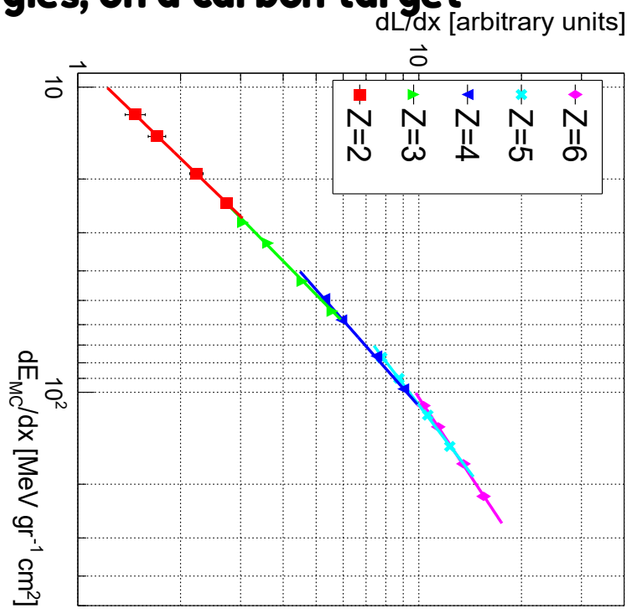


- XX MeV Carbon ions on carbon target
  - 4 energies, 5 Z values → 20 points
  - Fit with 5 different curves (similar to Matsufuji et al, NIMA437, 1999)

$$\frac{dL}{dx} = \alpha\left(\frac{dE}{dx}\right)^{\beta}$$

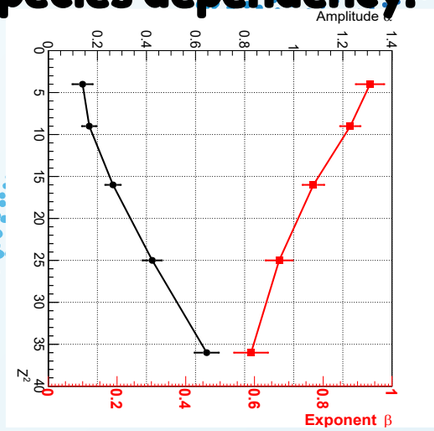
Carbon ions of various energies, on a carbon target





Species dependency:

- Amplitude α: increases for larger Z,
- Exponent β: decreases for larger Z, because of more significant quenching in core for high Z particles (?)



See Kraan, et al, NIMA 1045, 2023, 167615

Z identification: resolutions

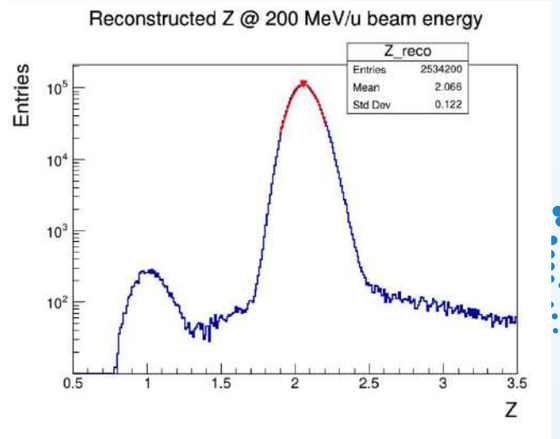
Resolutions determined **without target**

Helium Different particles at different data takings):

- TOF resolution: 116 ps (at 100 MeV/u) to 157 ps (220 MeV/u)
- Energy resolution: 5% (at 100 MeV/u) to 8% (at 220 MeV/u)
- Z identification resolution from 2.7% to 4.5%.

Z resolution compared with previous data takings (settings not identical)

Facility	Particle	Beam energy [MeV/u]	$\mu(Z)$	$\sigma(Z)$	R_Z[%]
CNAO	p	60	0.96	0.06	6.10
HIT	He	100	2.03	0.06	2.72
HIT	He	140	2.04	0.07	3.44
HIT	He	200	2.06	0.09	4.36
HIT	He	220	2.05	0.09	4.51
CNAO	^{12}C	115	6.17	0.15	2.51
CNAO	^{12}C	260	6.01	0.21	3.52
CNAO	^{12}C	400	6.07	0.24	3.85
GSI	^{16}O	400	8.07	0.22	2.67



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