



The FOOT Experiment: Nuclear Fragmentation Cross Section Measurements for Particle Therapy and Space Radiation Protection

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59th Zakopane Conference on Nuclear Physics, 30/08-06/09/2026

Hadrontherapy

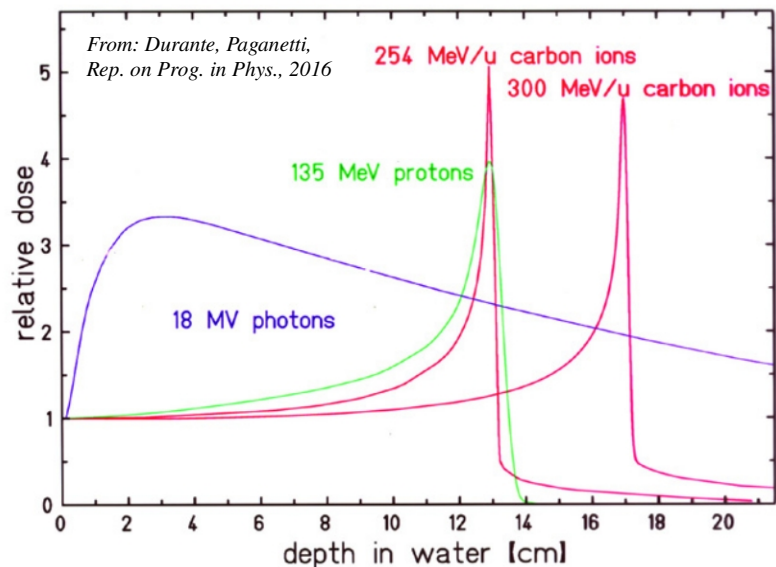
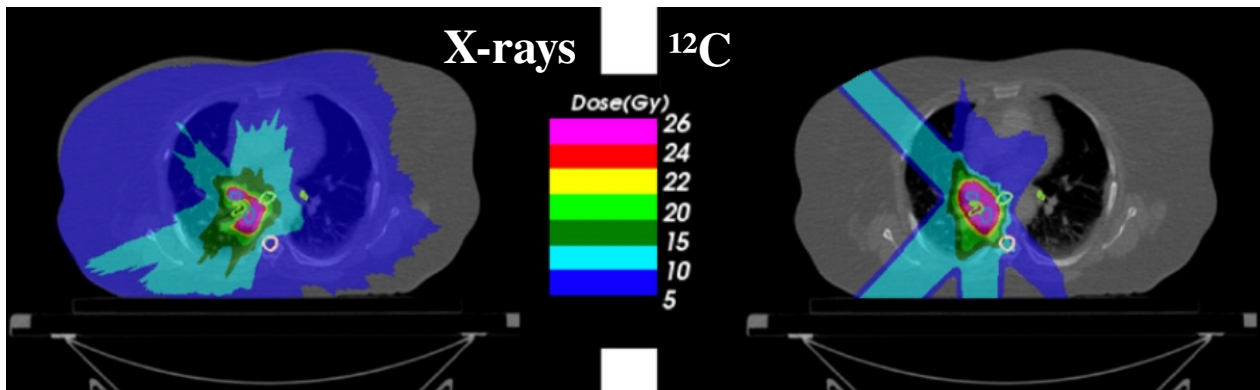


Therapeutic particle beams

- p , ${}^4\text{He}$, ${}^{12}\text{C}$, ${}^{16}\text{O}$ @ 100-400 MeV/u

Radiobiology request:

- More precise Treatment Planning System (TPS)
- Minimize damage to healthy tissues



- ✓ Favorable depth-dose profile (Bragg curve)
- ✓ Penetration depends on energy
- ✓ Enhanced biological effectiveness
- ✓ Lower dose/damage outside the tumor
- ✗ More complex infrastructures (accelerators)
- ✗ Cost and Availability
- ✗ Nuclear fragmentation

Radiation Protection in Space



Space radiation environment

- Light ions (p-O), peak @ 700-1500 MeV/u



Mission to Mars!

- Long cruise (~180 days each way)
- Thin atmosphere
- No magnetosphere

No natural protection from radiation!! (GCR + SPE)

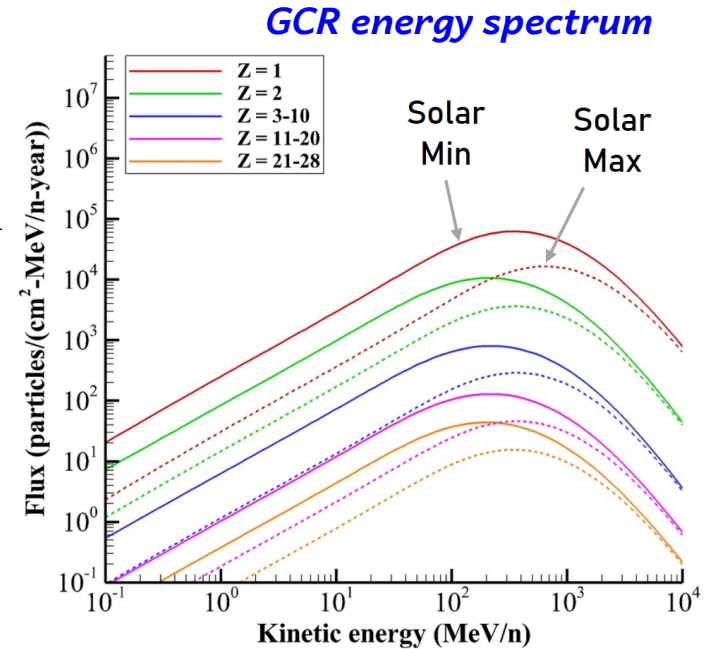
Mars mission radiation:

- Travel: 1.8 mSv/day
- On Mars: 0.64 mSv/day

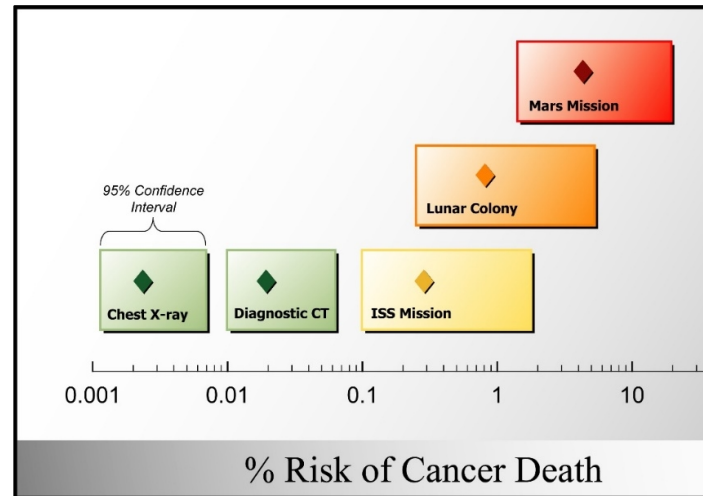
On Earth: 2.64 mSv/year



$$\frac{Rad_{Mars}}{Rad_{Earth}} \sim 280$$



Detailed knowledge of fragmentation processes to **optimize spacecraft shielding** (long term human missions)



FOOT (FragmentatiOn Of Target)



International Collaboration → 99 authors, 35 institutions, 6 countries

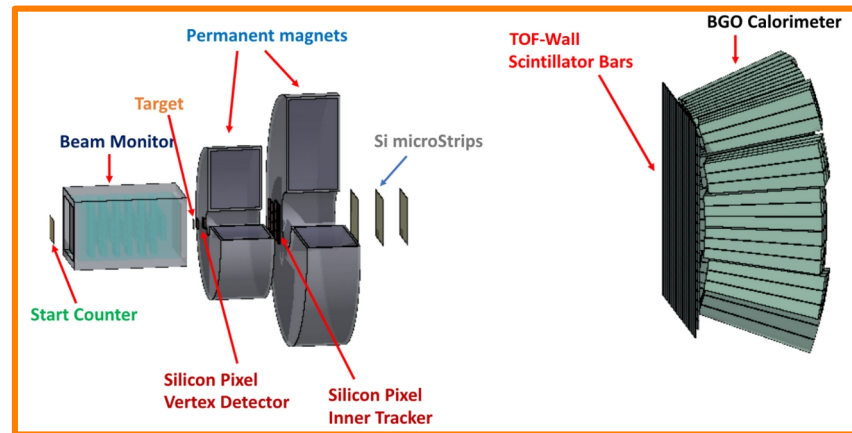
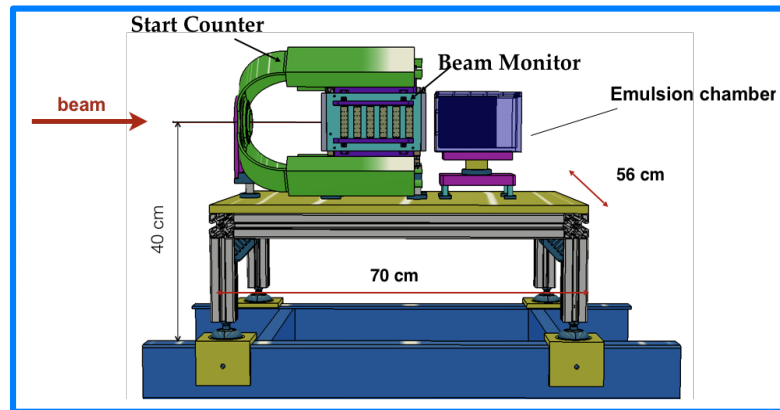
$d^2\sigma/dEd\Omega$ for nuclear fragmentation with 5% uncertainty in direct and inverse kinematics

Light projectiles ($A < 20$) at 150-1500 MeV/u on therapy/space targets

- Beam in different facilities → “portable”
- 2 complementary setups:
 - Emulsion Cloud Chamber ($Z \leq 3$)
 - Electronic detectors Setup ($Z \geq 2$)

FOOT core physics program

Fragmentation	Research Field	Beam	Energy [MeV/u]	Target	Kinematics
Projectile	Therapy	^4He	150-400	C, C ₂ H ₄ , PMMA	direct
Projectile	Therapy	^{12}C	200-400	C, C ₂ H ₄ , PMMA	direct
Projectile	Therapy	^{16}O	200-500	C, C ₂ H ₄ , PMMA	direct
Projectile	Space	^4He , ^{12}C , ^{16}O	700-1500	C, C ₂ H ₄ , PMMA, Al	direct
Target	Therapy	^{12}C , ^{16}O	200	C, C ₂ H ₄	inverse
Target	Therapy	p	100-220	C	direct

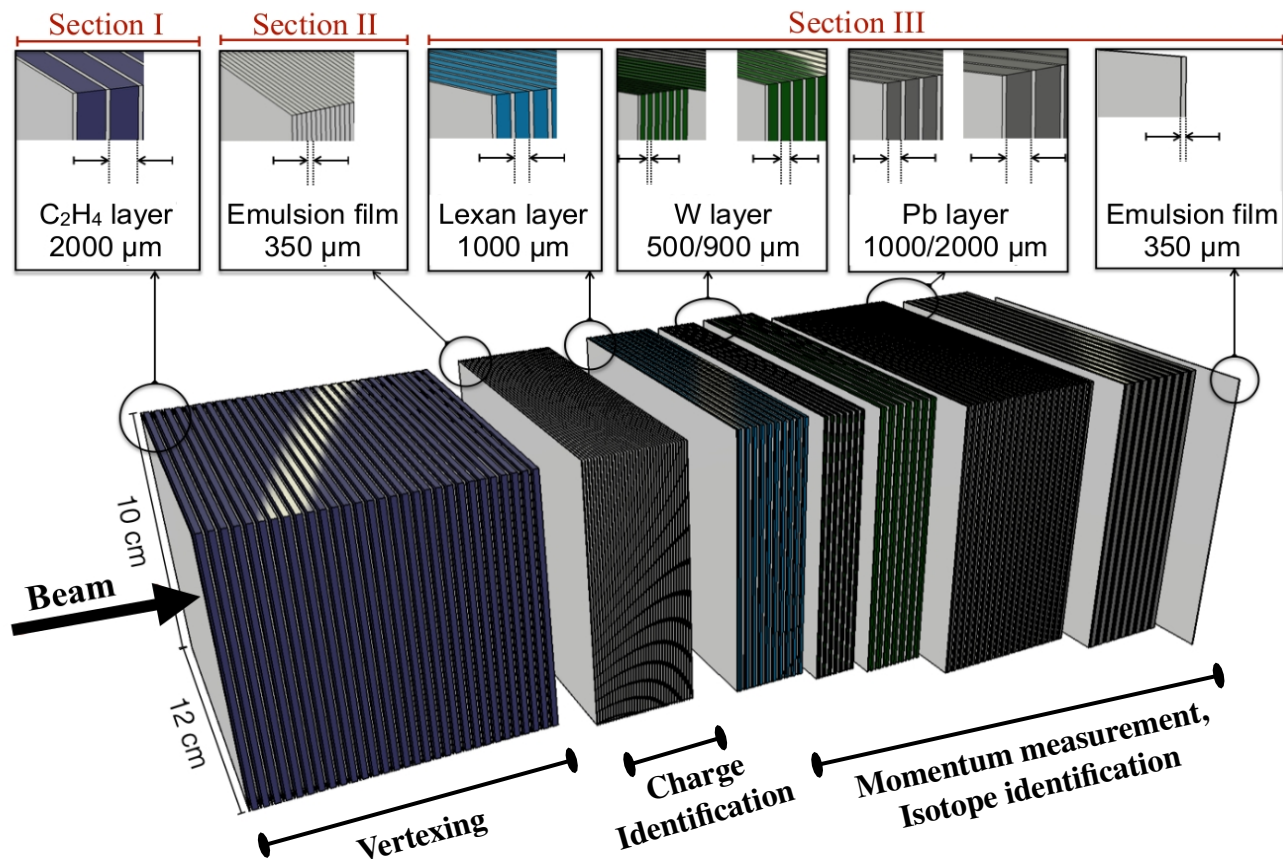


FOOT apparatus: emulsion setup

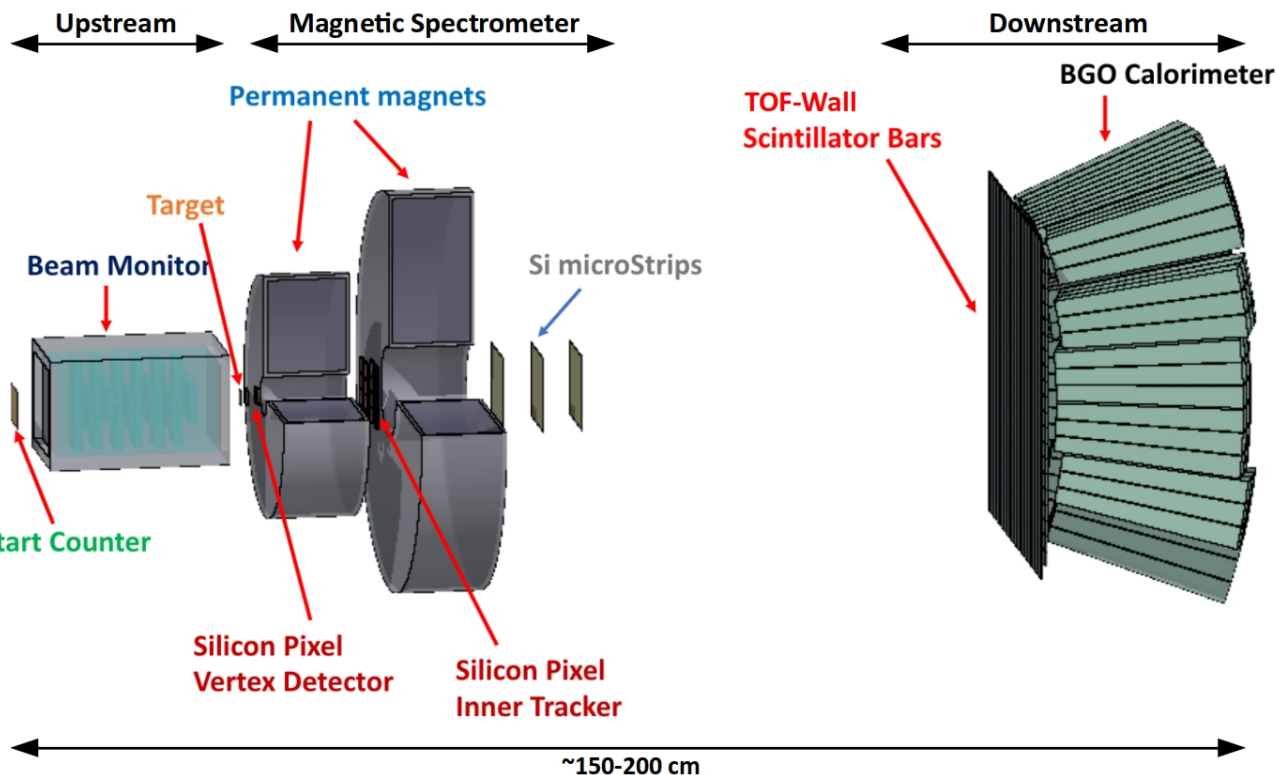


Emulsion Cloud Chamber Setup

- Light fragments $Z \leq 3$
 - Angular aperture of 45°
 - Sections:
 - I. Emulsions + target
 - II. Emulsion layers
 - III. Emulsion + passive material
 - Different beam energies with single irradiation
- Ready and acquiring data



FOOT apparatus: electronic setup



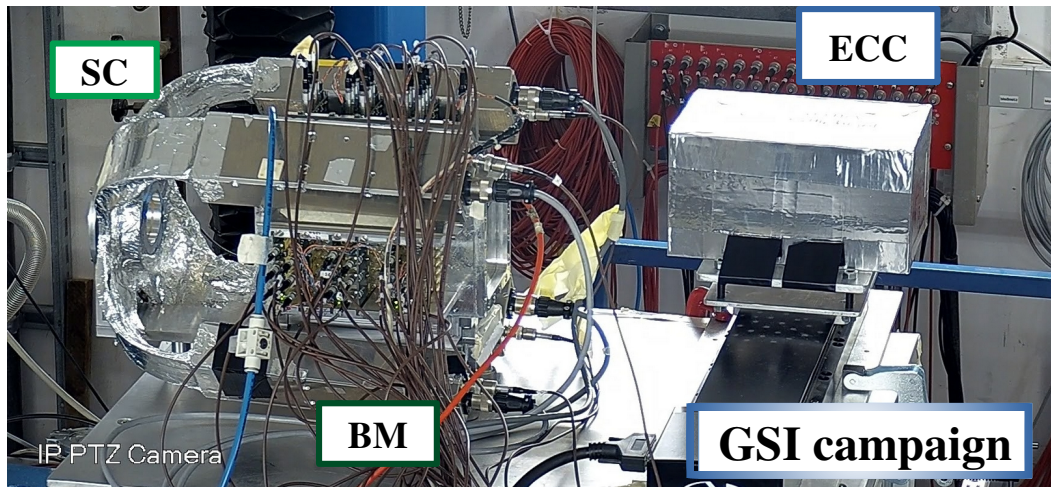
Electronic Setup

- “Heavier” fragments $3 \leq Z \leq 8$
- Angular aperture 10°
- 2-3 m in total
(~ beam energy)
- Characterize both primary beam and fragments
- 3 main sections
 - Upstream: **Trigger + beam**
 - Spectrometer: **Tracking + Rigidity**
 - Downstream: **Charge + TOF + E_{kin}**
- **Ready and acquiring data**

Emulsion setup: first results



$^{16}\text{O} + \text{C}/\text{C}_2\text{H}_4 @ 200/400 \text{ MeV/u}$

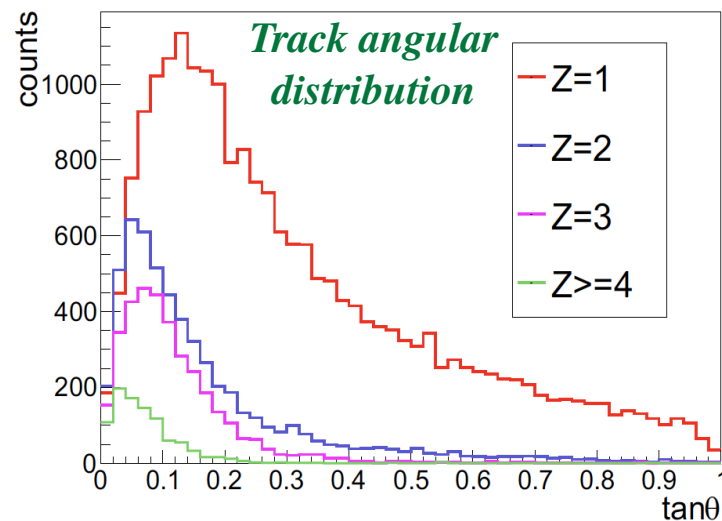
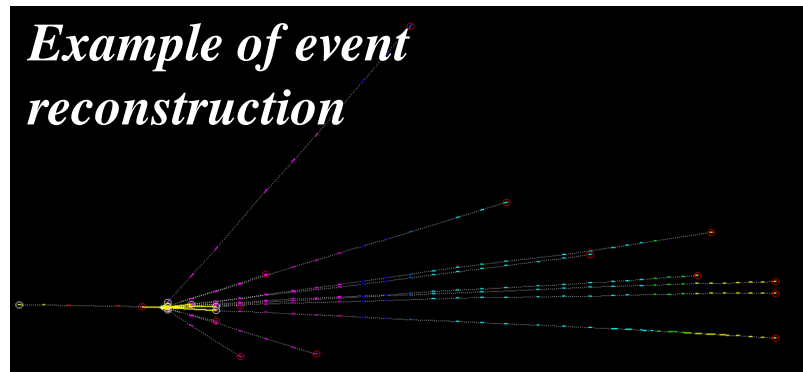


- Data acquisitions started in 2019
- SC + BM for primary beam monitoring
- Vertexing (Section1) + Charge identification (Section2)

Track reconstruction

Thermal treatment +
Principal Component Analysis

Example of event reconstruction



Emulsion setup: first results



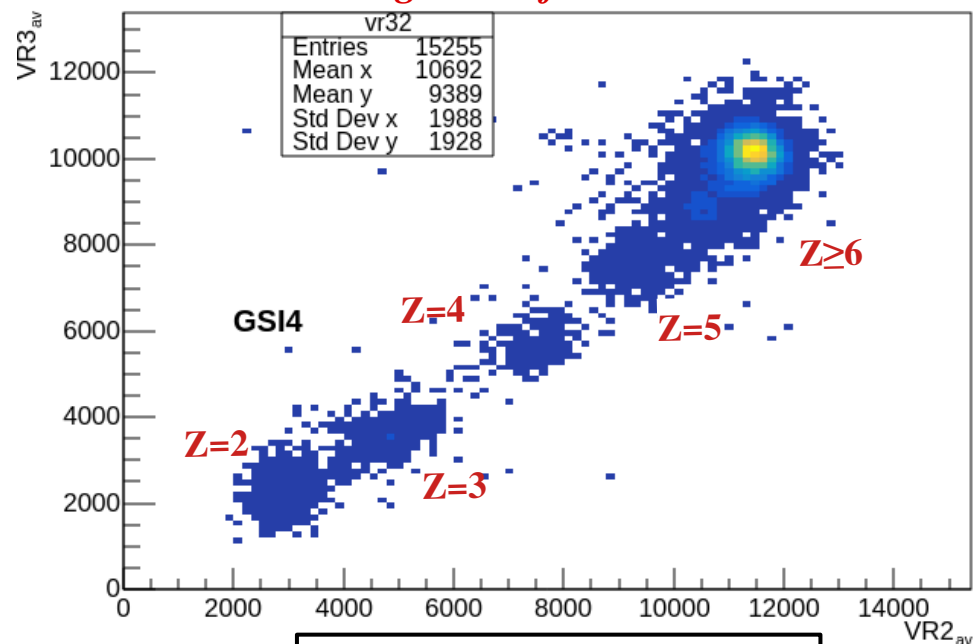
Charge identification published in two works!

- doi.org/10.1515/phys-2021-0032
- doi.org/10.1016/j.nima.2005.08.109

Currently working on

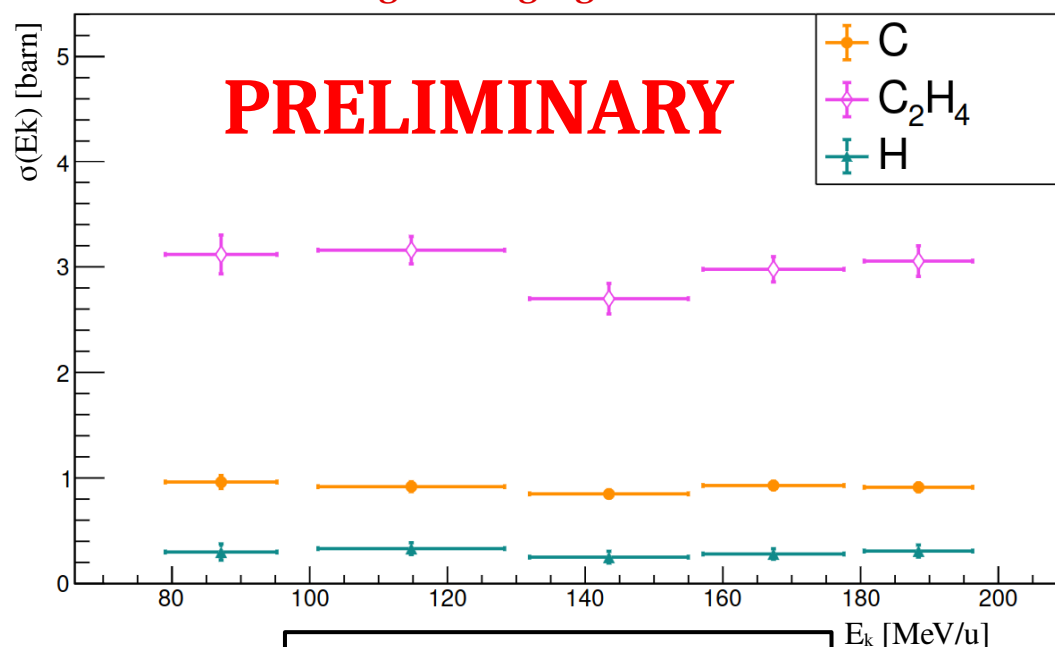
- Momentum and energy reconstruction
- **Cross section (*in submission!*)**

Charge identification



^{16}O @ 400 MeV/u + C_2H_4

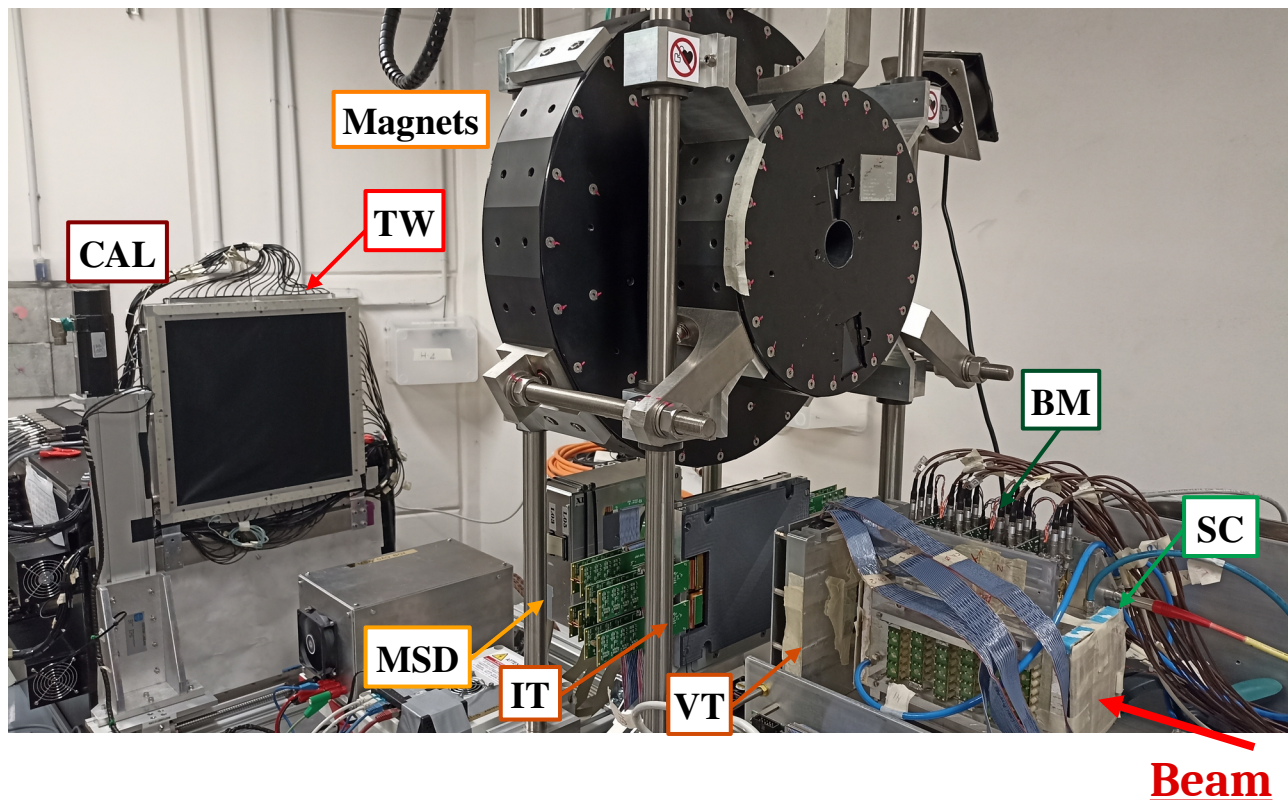
Charge-changing cross section



^{16}O @ 200 MeV/u + C/ C_2H_4

Electronic setup: first results

- Many data acquisitions with partial and full setup
- Solid charge identification from TW (soon also MSD)
- Analysis with SC + BM + TW finished!
- **First differential cross sections!**
- Mass identification capabilities under study (CAL + Tracking)



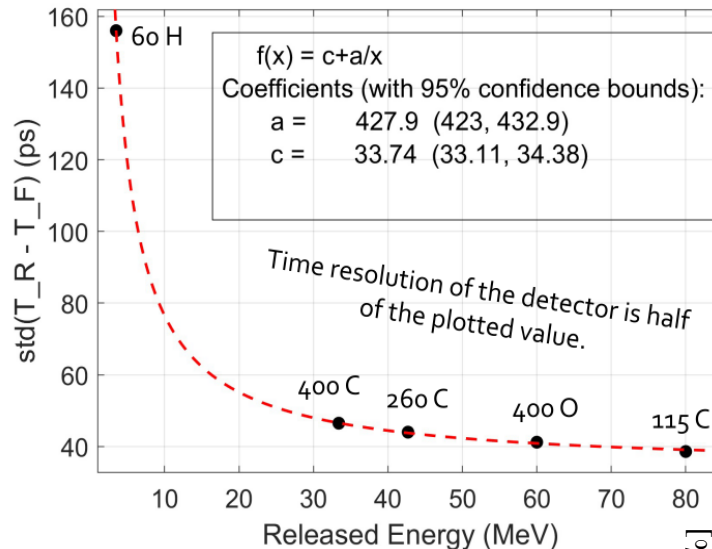
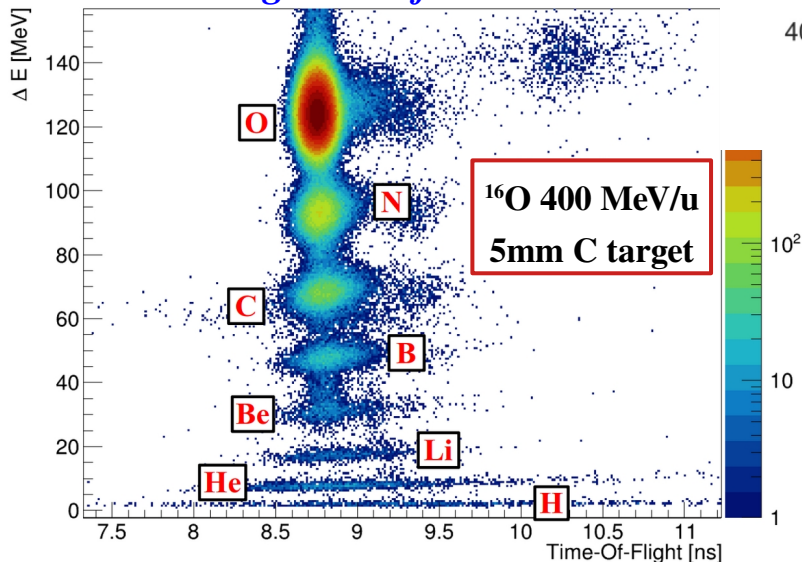
Full setup first mounted in late 2023!

Electronic setup: first results



- ✓ Good energy (ΔE) resolution
- ✓ TOF resolution ~ 45-50 ps
- ✓ Very good charge separation

Charge Identification



TOF-Wall time resolution

- ✓ Kinetic energy resolution 0.4-2%
- ✓ Isotopic identification possible!

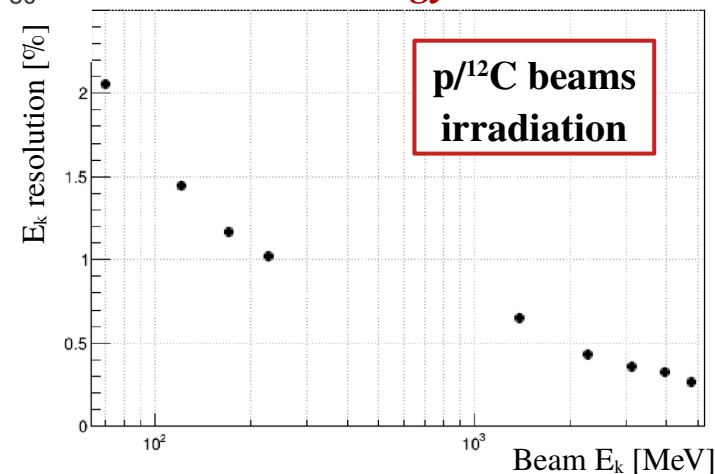
Calorimeter performance paper:

doi.org/10.1088/1748-0221/20/03/P03021

ΔE -TOF performance papers:

- doi.org/10.1016/j.nima.2021.165206
- doi.org/10.1016/j.nima.2022.167615

Kinetic Energy Resolution



Electronic setup: first results

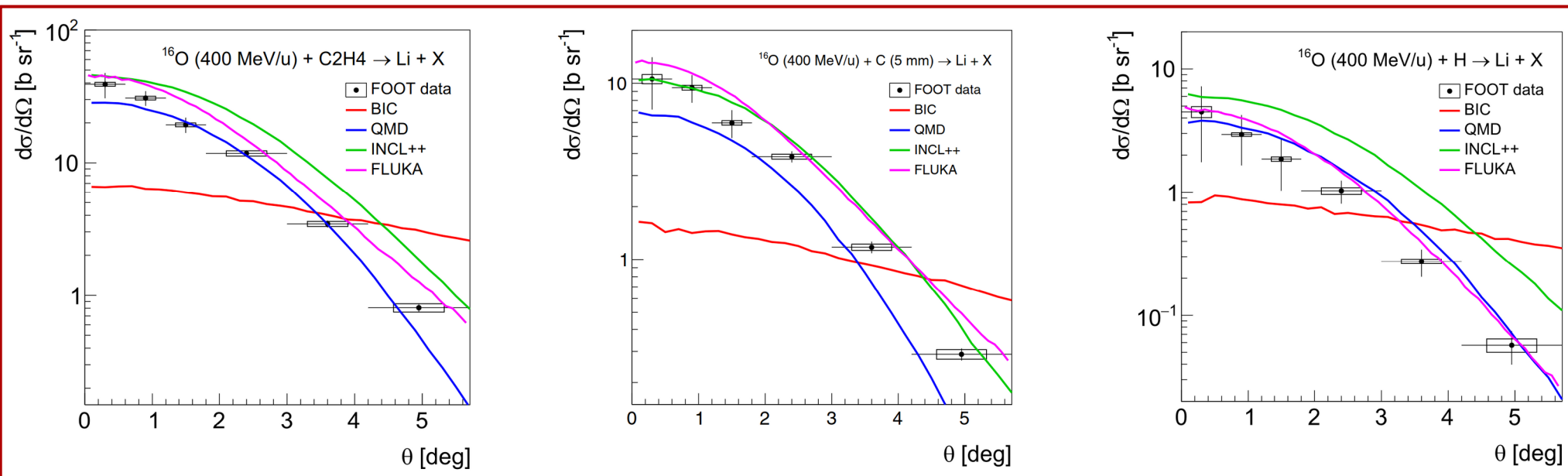


$$\frac{d\sigma}{d\Omega} [H] = \frac{1}{4} \left(\frac{d\sigma}{d\Omega} [C_2H_4] - 2 \frac{d\sigma}{d\Omega} [C] \right)$$

Experimental campaigns with C and C₂H₄ targets

- doi.org/10.1103/nmw9-ldrm
- doi.org/10.1103/17nq-3ddt

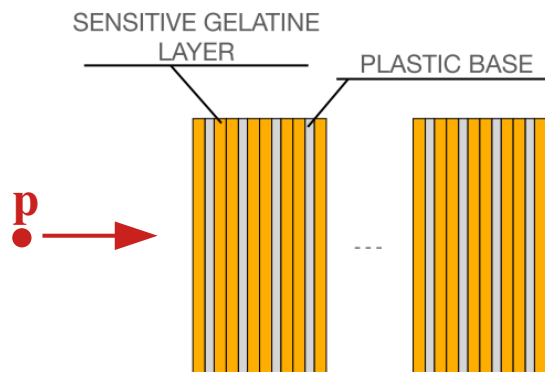
First elemental + angular differential cross section measurements!



FOOT future developments: Emulsion setup

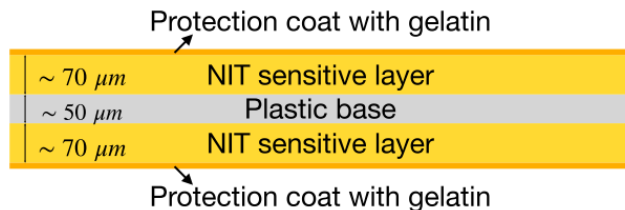


Nano Imaging Trackers

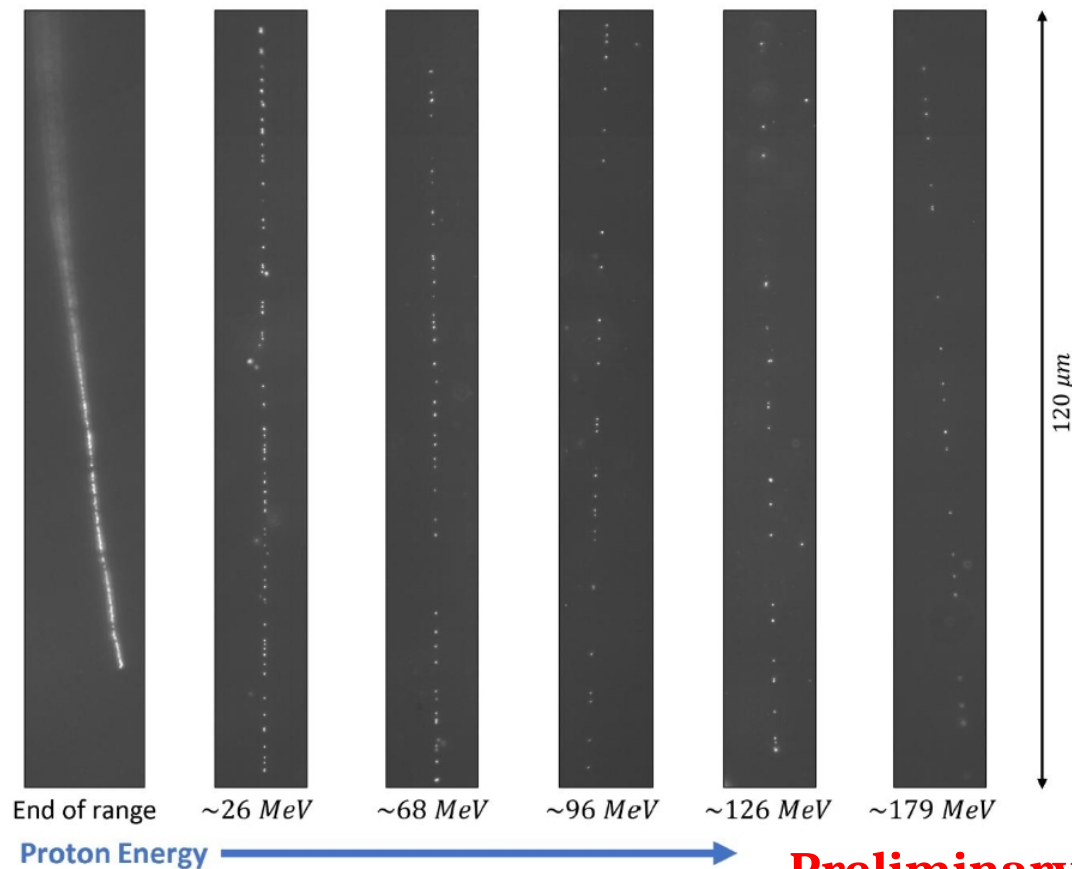


- Very thin emulsion layers
- Sensitive to 100 μm tracks
- Not sensitive to MIPs
- **R&D ongoing!**

**Direct target
fragmentation
measurements**



Test @ Nagoya Proton Therapy Center



Preliminary

FOOT future developments: Electronic setup

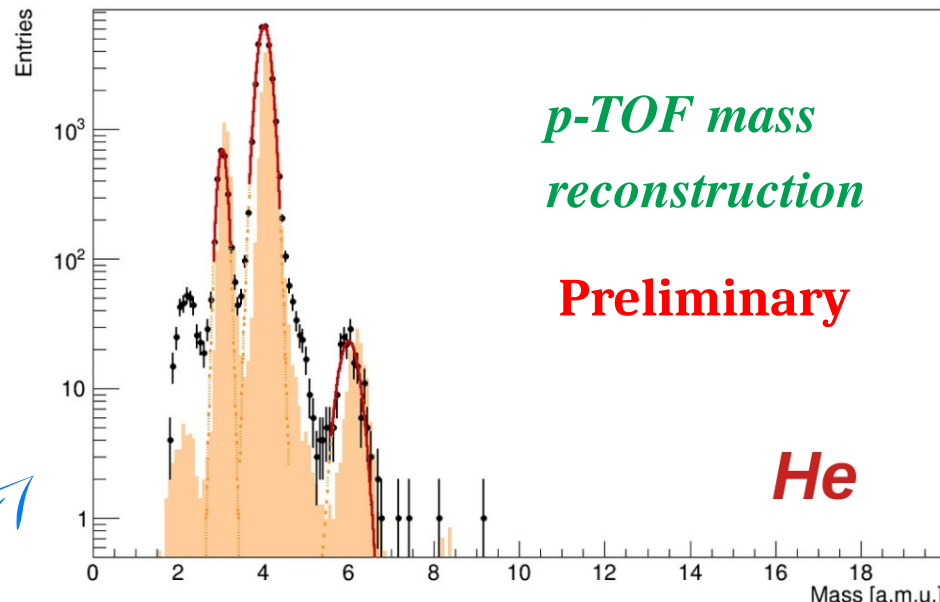
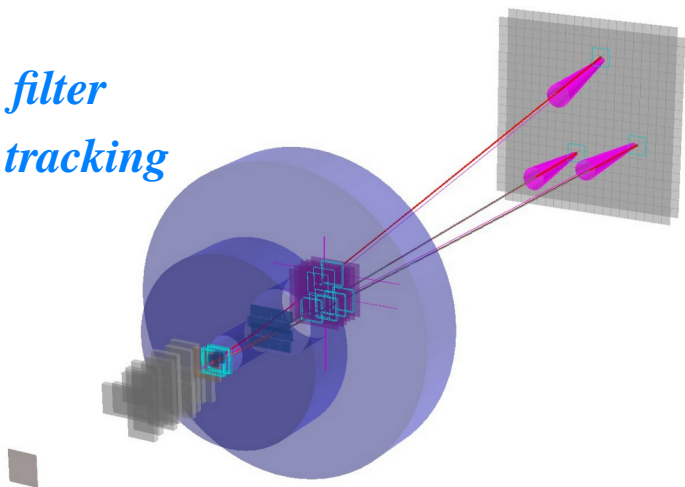


Full Event Reconstruction

Exploit full FOOT setup capabilities

- Particle tracking + calorimetry
 - Redundant particle identification (Z , A)
 - Isotopic double differential (Ω , E_k) cross sections
 - α -clustering in projectile fragmentation
 - Inverse kinematics measurements ($H/O + X$)

Kalman filter
particle tracking



Upgrades

- Detector developments (Tracker + TOF-Wall)
- Neutron detection
- ...

Conclusions

FOOT website: <https://web.infn.it/foot/en/home/>

FOOT papers: <https://web.infn.it/foot/en/docs-links-eng/>



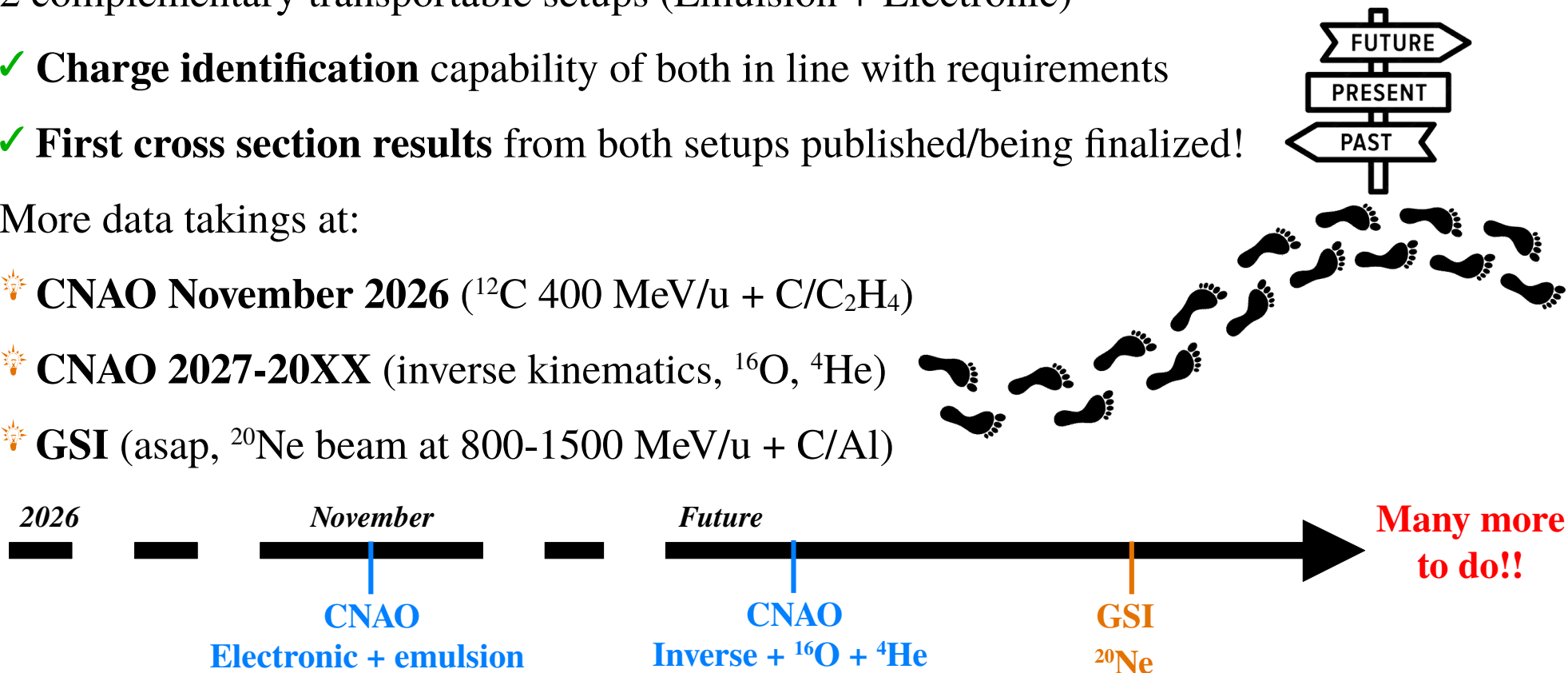
Nuclear fragmentation measurements with FOOT ongoing:

- 2 complementary transportable setups (Emulsion + Electronic)
- ✓ **Charge identification** capability of both in line with requirements
- ✓ **First cross section results** from both setups published/being finalized!
- More data takings at:

💡 **CNAO November 2026** (^{12}C 400 MeV/u + C/C₂H₄)

💡 **CNAO 2027-20XX** (inverse kinematics, ^{16}O , ^4He)

💡 **GSI** (asap, ^{20}Ne beam at 800-1500 MeV/u + C/Al)



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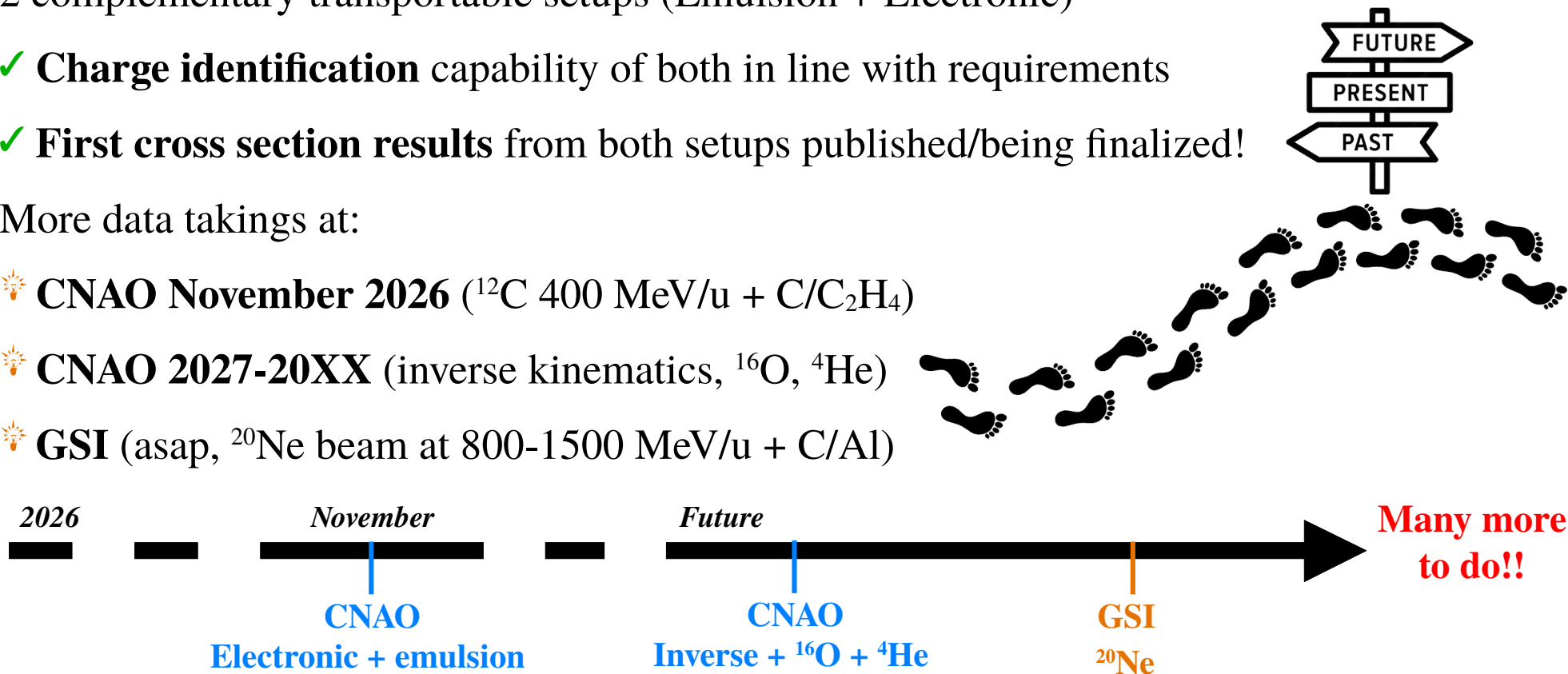
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Nuclear fragmentation measurements with FOOT ongoing:

Thank you for your attention

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**Many more
to do!!**