



Istituto Nazionale di Fisica Nucleare



# Particle tracking in the FOOT experiment

R. Zarrella on behalf of the FOOT collaboration



# FOOT (FragmentatiOn Of Target) goals

## Hadrontherapy

### Target and Projectile fragmentation

- $d\sigma/dE$  and  $d\sigma/d\Omega$  with 5% precision of fragment production cross sections in direct/inverse kinematics
- p, C, O beams @ 200-400 MeV/u



**Radiobiology request:** to have a more precise Treatment Planning System (TPS)

## Radioprotection in space

Detailed knowledge of fragmentation processes to **optimize the spacecraft shielding** (long term mission)

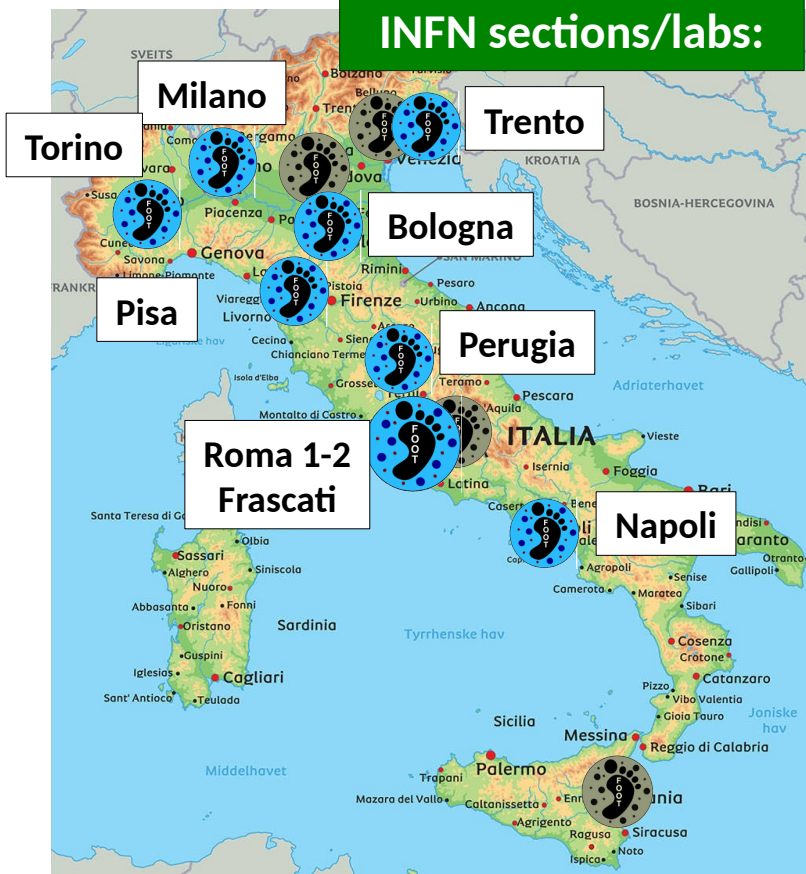


- $d\sigma/dE$  and  $d\sigma/d\Omega$  with 5% precision of the fragment production cross sections in direct/inverse kinematics
- p, He, Li, C, O beams @ 700-800 MeV/u

# FOOT Collaboration



## INFN sections/labs:



FOOT approved by the INFN on September 2017 (CSN3)

~ 100 members:

- 10 INFN sections
- 5 laboratories: Frascati, CNAO, Trento, GSI, IPHS (Strasbourg)
- 12 Italian Universities
- 2 foreign Universities: Aachen, Nagoya
- Centro Fermi

Physics program:

- Hadrontherapy:
  - Nuclear fragmentation @ 200 MeV/u
- Radioprotection in space:
  - Nuclear fragmentation @ 700 MeV/u

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

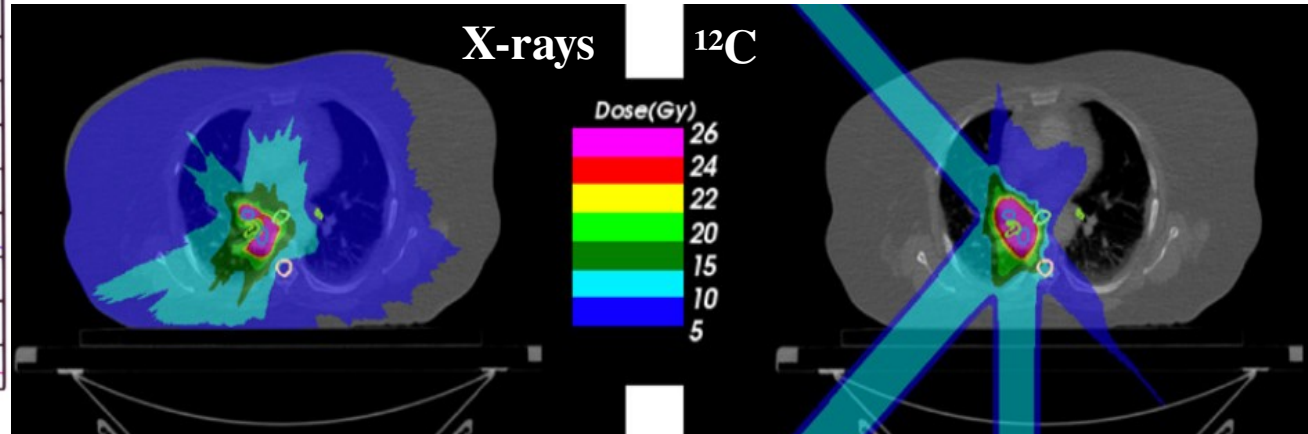
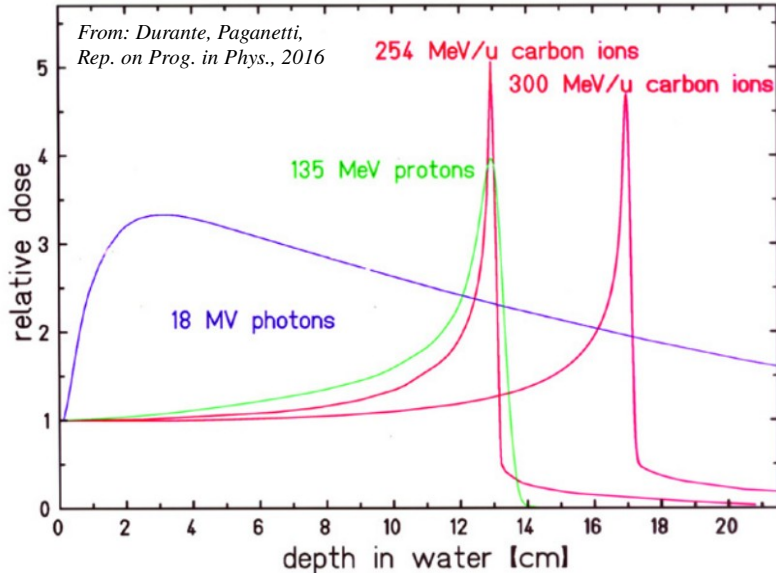
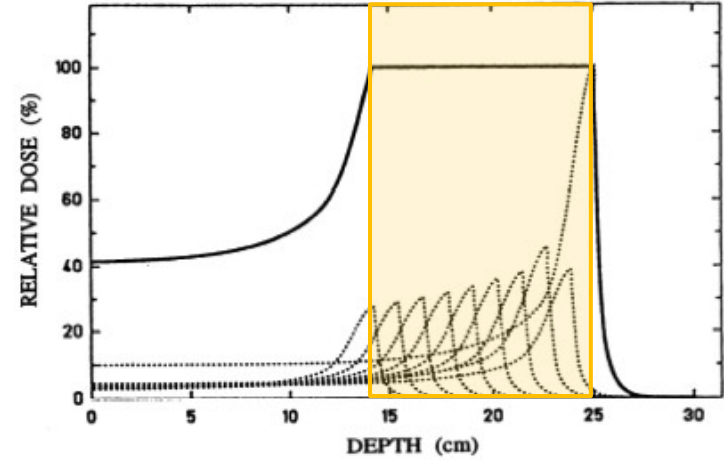
FOOT papers: <https://web.infn.it/foot/en/docs-links-eng/>



# Hadrontherapy vs Radiotherapy

- ✓ Favorable depth-dose profile (Bragg curve)
- ✓ Penetration depends on energy
- ✓ Lower dose/damage outside the tumor

- ✗ MORE expensive than X-rays
- ✗ Nuclear fragmentation

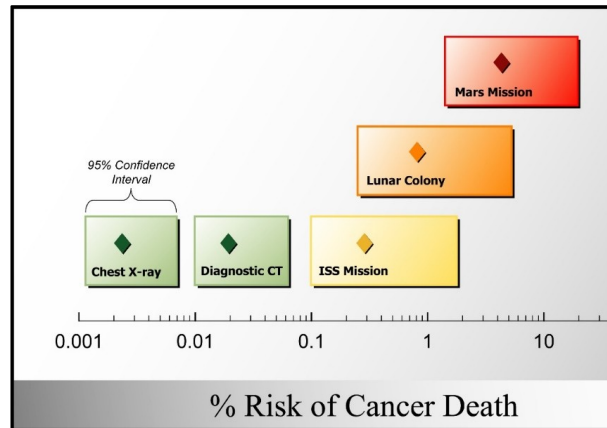


# Radioprotection in Space

## Mission to Mars!

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

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

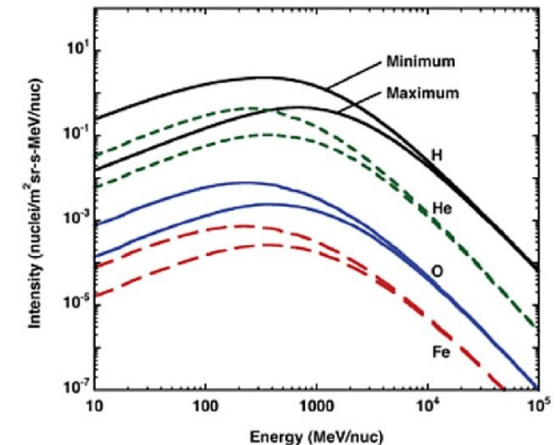


Mars mission radiation:  
 → Travel: 1.8 mSv/day  
 → On Mars: 0.64 mSv/day  
 On Earth: 2.64 mSv/year



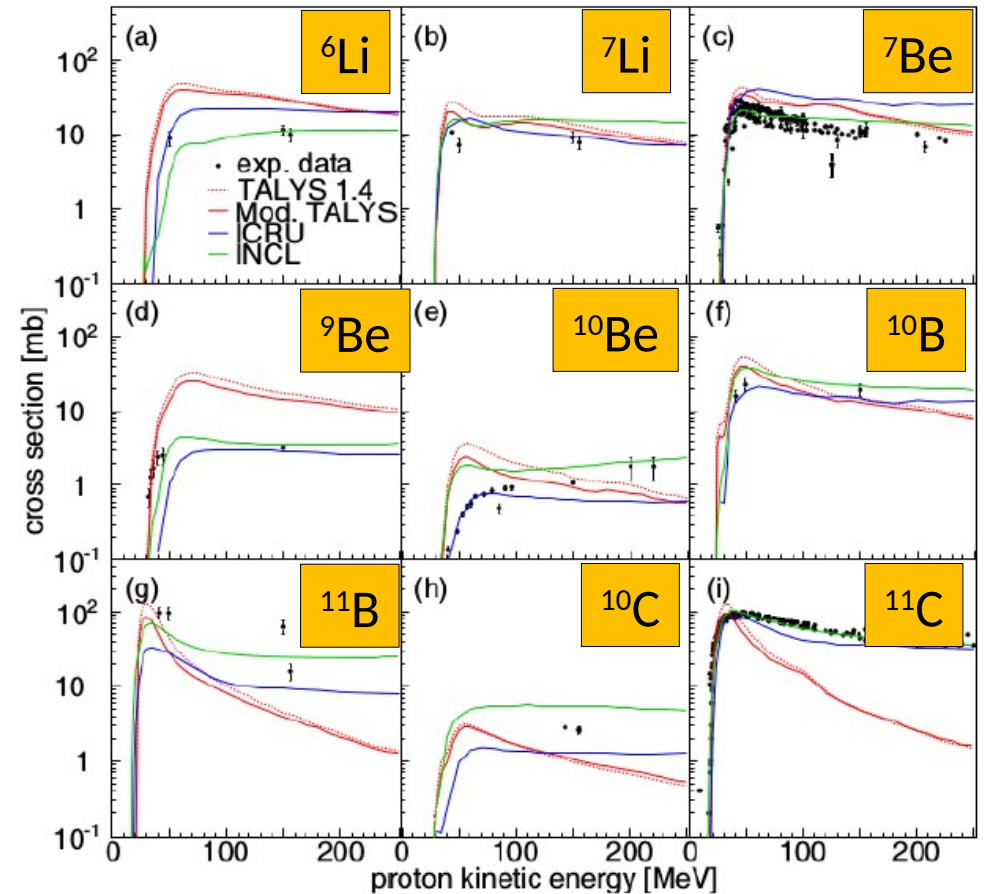
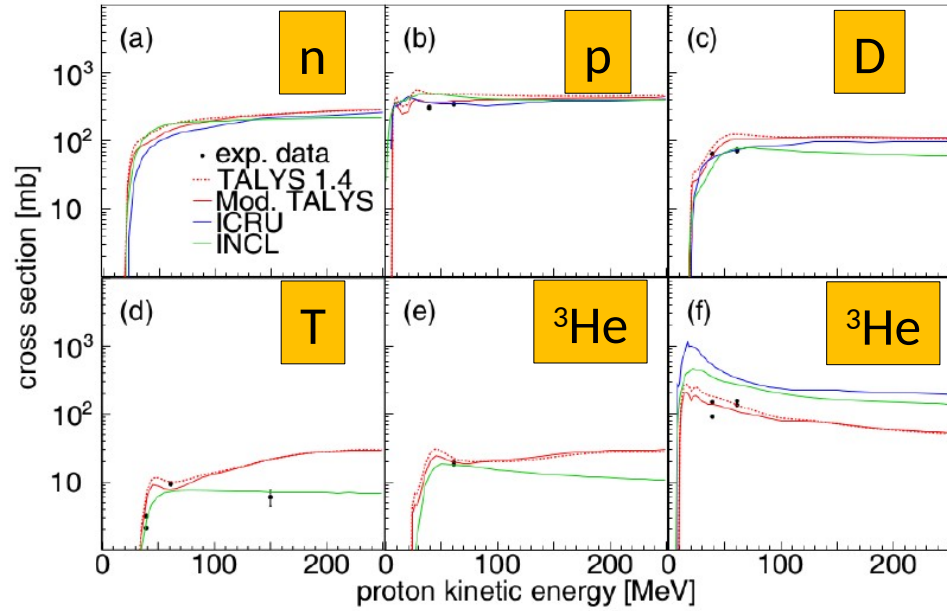
**Astronauts need effective shielding!!**

$Rad_{Mars} / Rad_{Earth} = 280$   
 1 Sv ~ 3% increase in cancer probability





# Target fragmentation in proton therapy



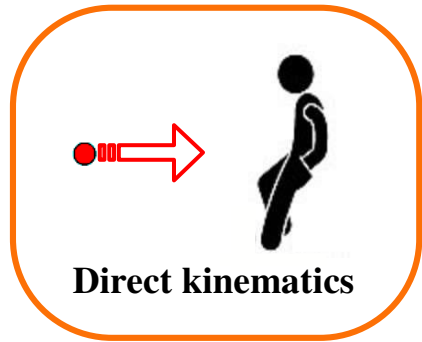
**Missing data  
in literature!!**



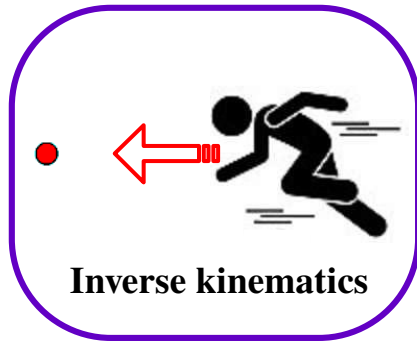
# Target fragmentation in proton therapy

**Problem:** Fragments have very short range ( $\sim 10\text{-}100 \mu\text{m}$ )

**Solution:** Reference frame back-transformation



Direct kinematics



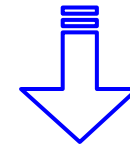
Inverse kinematics

Lorentz boost  $\longrightarrow$  Subtract projectile momentum

**Problem:** Very difficult to handle an hydrogen target

**Solution:** Composite targets

Polyethylene ( $\text{C}_2\text{H}_4$ ) - Graphite (C)



$$\frac{d\sigma}{dE_k}(H) = \frac{1}{4} \left[ \frac{d\sigma}{dE_k}(\text{C}_2\text{H}_4) - 2 \frac{d\sigma}{dE_k}(\text{C}) \right]$$

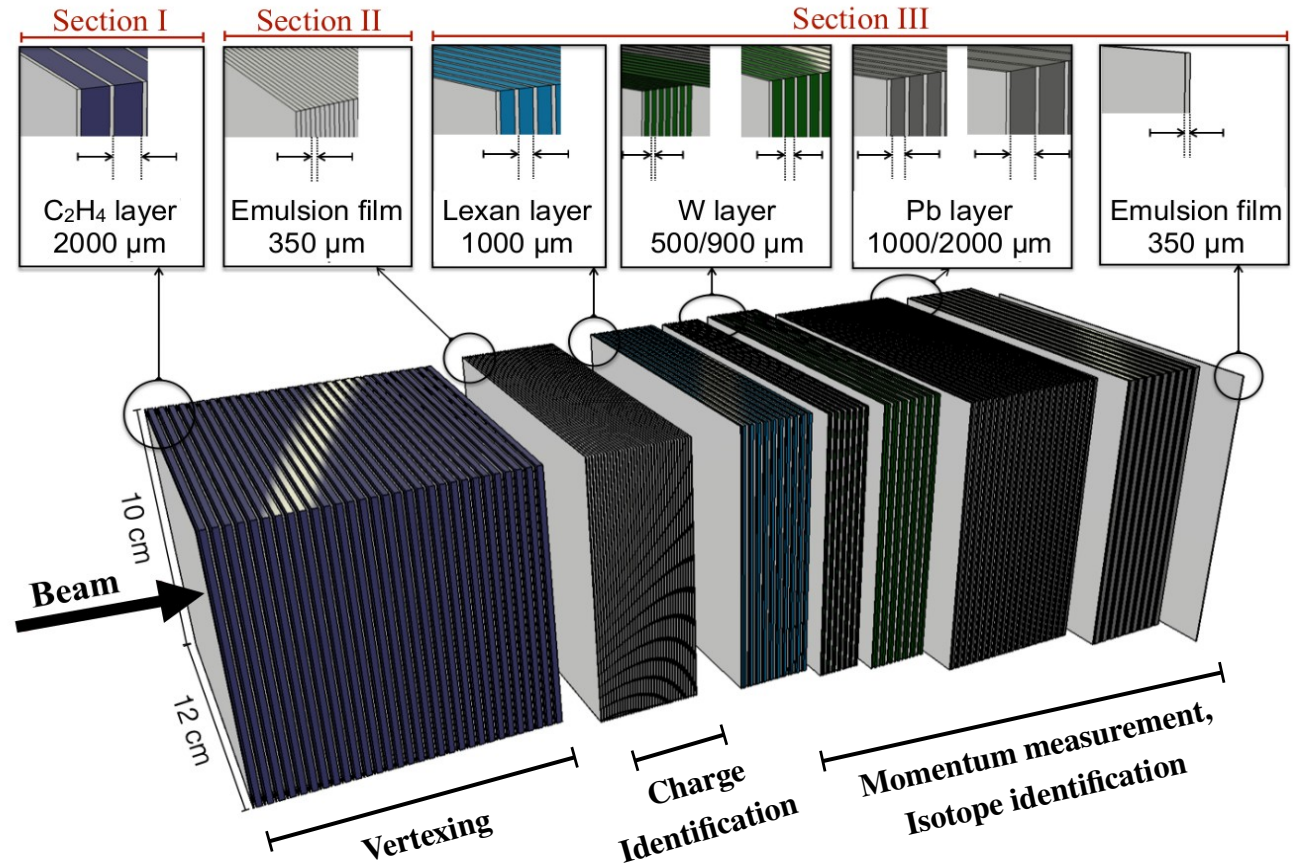
**Very high precision measurements needed!!!**



# FOOT apparatus: emulsion setup

## Emulsion Chamber Setup

- Light fragments  $Z \leq 3$
  - Angular aperture  $\pm 70^\circ$
  - Sections:
    - I. Emulsions + target
    - II. Emulsion layers
    - III. Emulsion + passive material
- Ready and acquiring data





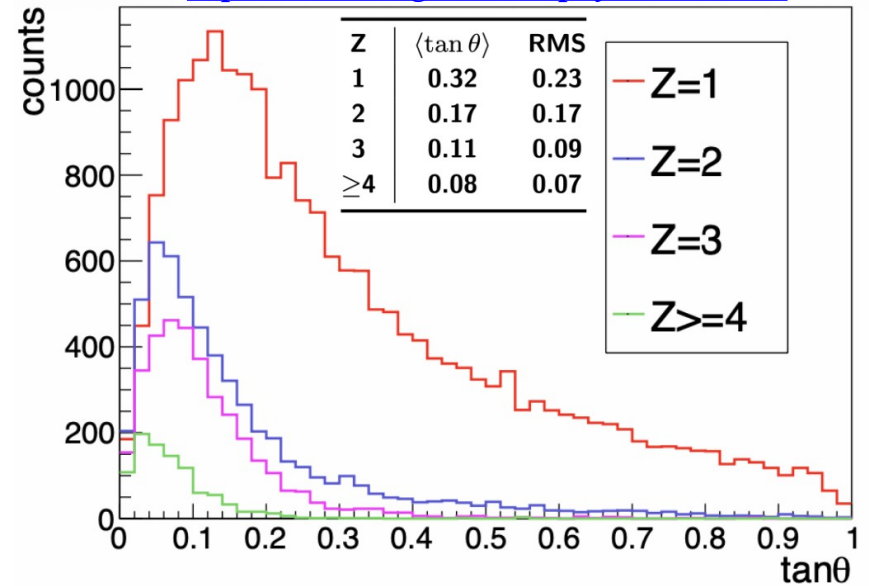


# FOOT apparatus: emulsion setup acquisitions

- Two data acquisition campaigns at GSI
- Emulsion scan w/ thermal treatment completed
- Alignment:
  - Completed for GSI1, 2 and 3
  - Partial for GSI4
- Data for Section II of GSI2 have been analyzed

TARGET	BEAM	2019		2020
		Oxygen 200 MeV/n	Oxygen 400 MeV/n	Carbon 700MeV/n
Carbon		GSI1	GSI3	GSI5
Polyethylene		GSI2	GSI4	GSI6

<https://dx.doi.org/10.1515/phys-2021-0032>



GSI2



Z assigned to  
98.3% of tracks



Others

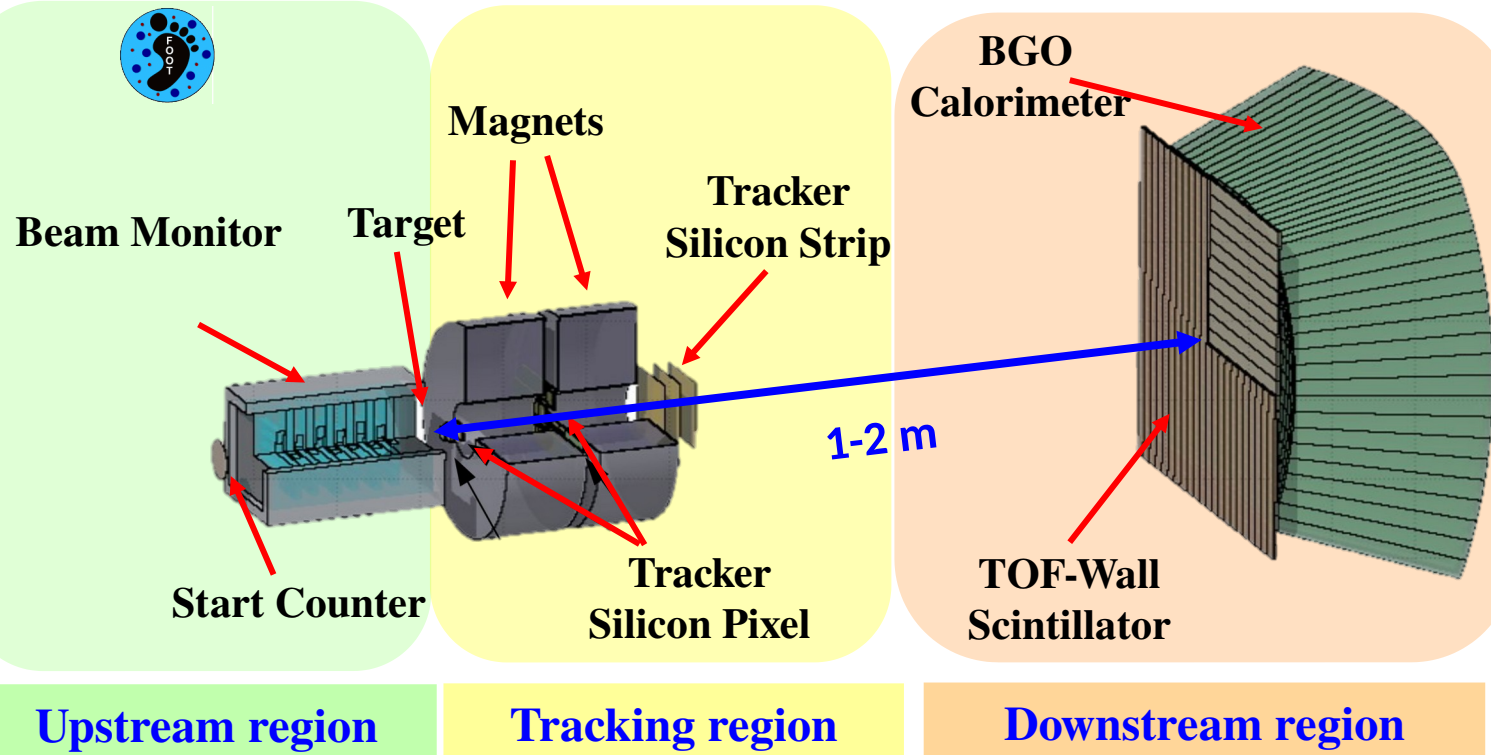


Ongoing analysis



# FOOT apparatus: electronic setup

## Electronic Setup



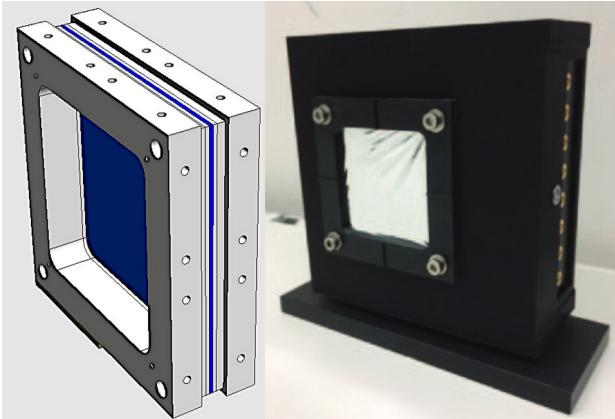
- **Heavy fragments**  
 $Z \geq 3$
- **Angular aperture**  
 $\pm 10^\circ$
- **In construction**





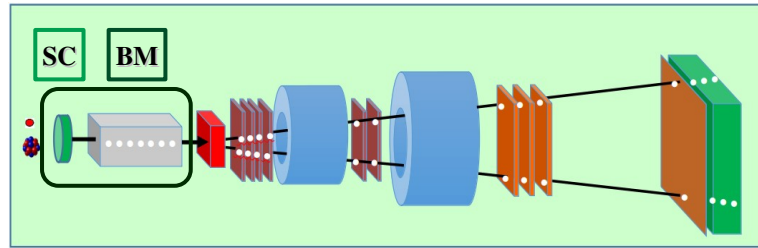
# Electronic setup: Upstream region

## Start Counter (SC)



### Trigger and TOF start

250  $\mu\text{m}$  – 1 mm thick plastic scintillator  
5x5 cm<sup>2</sup> active area  
48 SiPMs, 8 channels readout

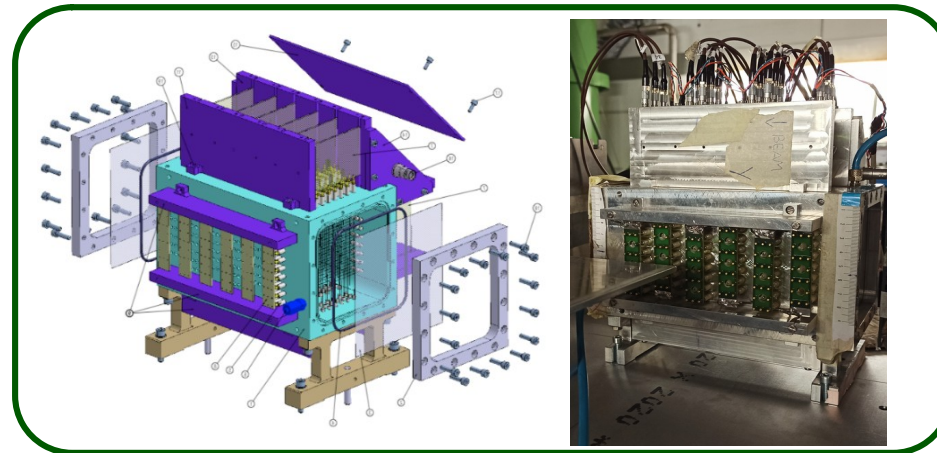


*Pre-target*



*beam characterization*

## Beam Monitor (BM)



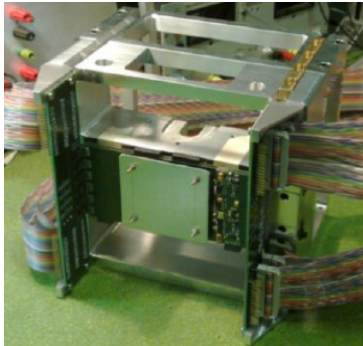
**Beam momentum  
& direction**

Drift chamber  
Gas: Ar/CO<sub>2</sub> (80/20%)  
12 layers w/ 3 cells each  
Fragmentation in SC



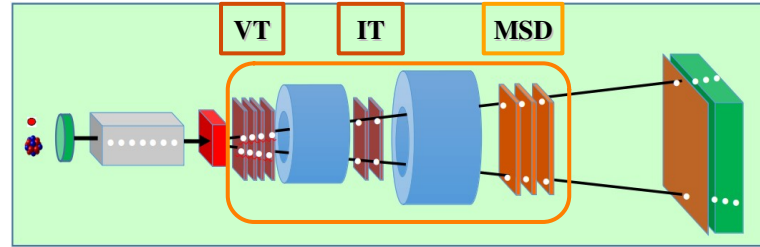
# Electronic setup: Tracking region

## Vertex (VT) & Inner Tracker (IT)

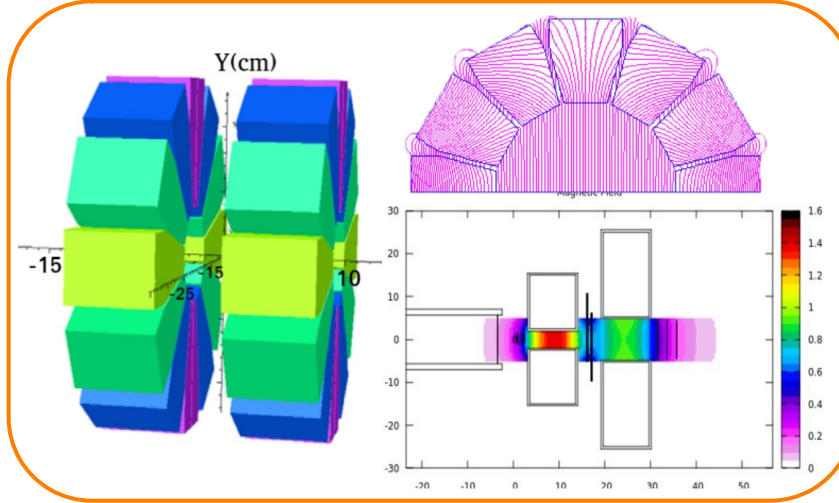


VT: 4 layers Si pixel ( $20 \times 20 \mu\text{m}$ )

IT: 2 layers Si pixel ( $20 \times 20 \mu\text{m}$ )



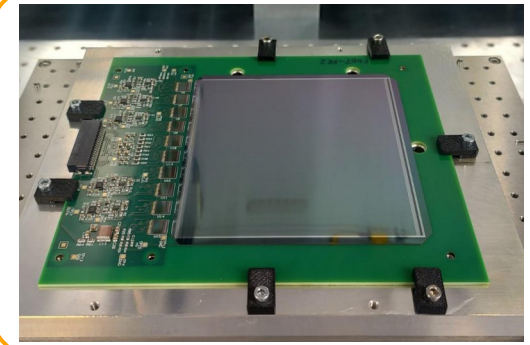
## Magnets



2 permanent Hallbach magnets

B field in y axis (max 0.9 and 1.1 T)

## Micro Strip Detector (MSD)



3 couples of orthogonal layers

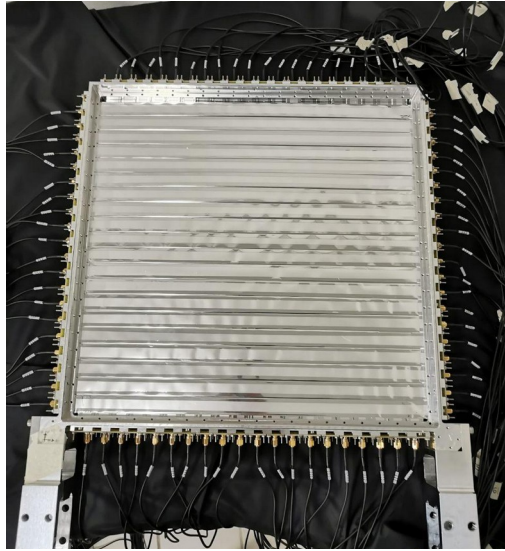
$120 \mu\text{m} \times 9 \text{ cm}$  Si strips

Fragment tracking  
and momentum



# Electronic setup: Downstream region

## TOF-Wall (TW)

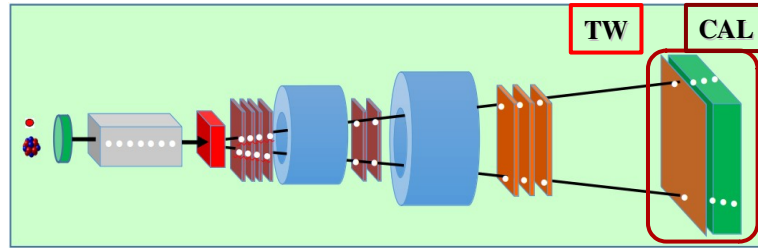


### $\Delta E - TOF$

44x2 cm<sup>2</sup> plastic scintillator bars  
3 mm thickness  
2 layers of 20 bars  
SiPM readout

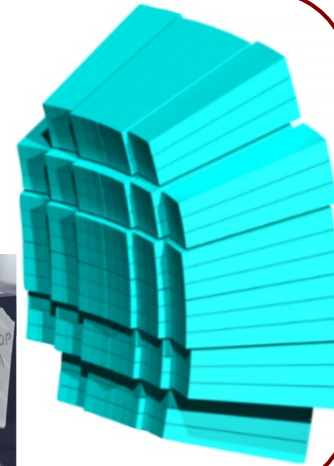
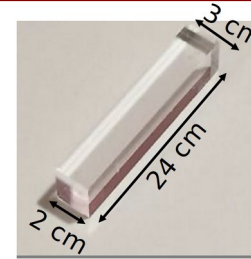
### Kinetic Energy

BGO – inorganic scintillator  
288 crystals – 3x3 modules  
330 kg total weight  
Geometry pointing to the target



## Fragment Identification

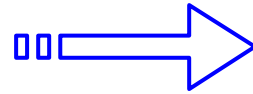
### Calorimeter (CAL)





# Particle identification in FOOT

Why?



Fundamental for differential cross section measurement

## Charge identification

$$\left. \begin{array}{l} * \sigma(\Delta E)/\Delta E \sim 4-5\% \\ * \sigma(\text{TOF}) < 100 \text{ ps} \end{array} \right\} \sigma(Z)/Z \sim 2-6\%$$

- Measured by SC and TW
- Performances in line with requirements!  
( <https://doi.org/10.1016/j.nima.2021.165206> )

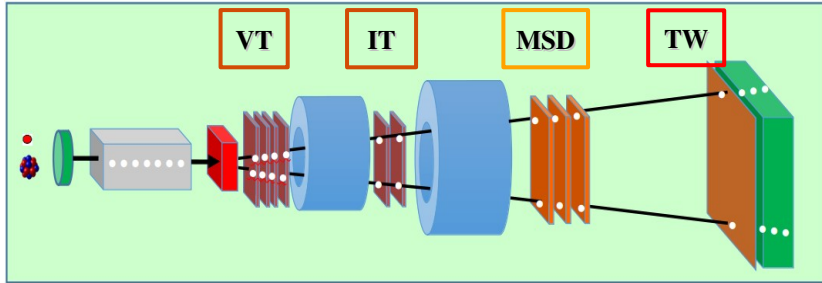
## Mass identification

$$\left. \begin{array}{l} * \sigma(\text{TOF}) < 100 \text{ ps} \\ * \sigma(E_k)/E_k \sim 1-2\% \\ * \sigma(p)/p \sim 4-5\% \end{array} \right\} \sigma(A)/A \sim 3-5\%$$

- TOF from SC and TW
- $E_k$  from CALO
- $p$  from trackers (VT, IT, MSD) and TW



# Particle tracking

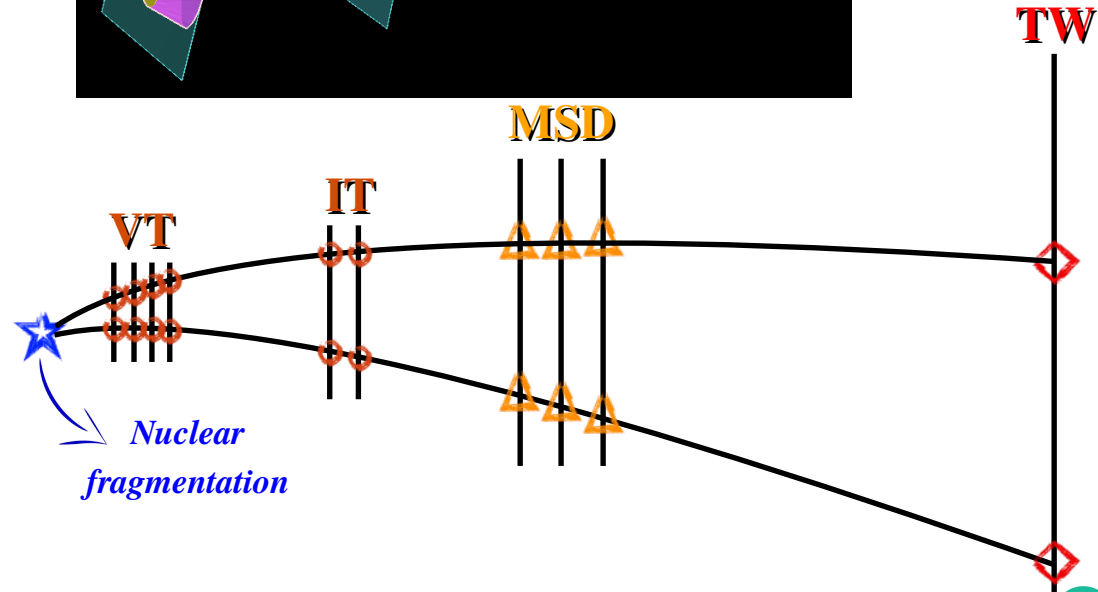
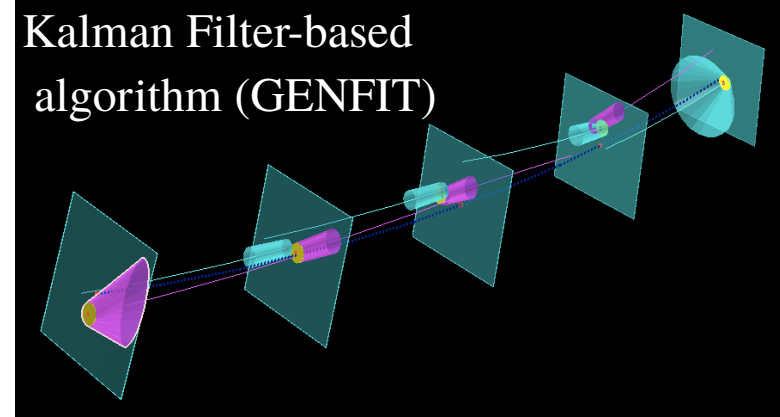


- Use information from:  
trackers (VT, IT, MSD)  
TW



- Only quantity measured indirectly

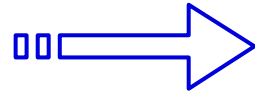
**Reconstruction of fragment trajectory  
and momentum measurement**





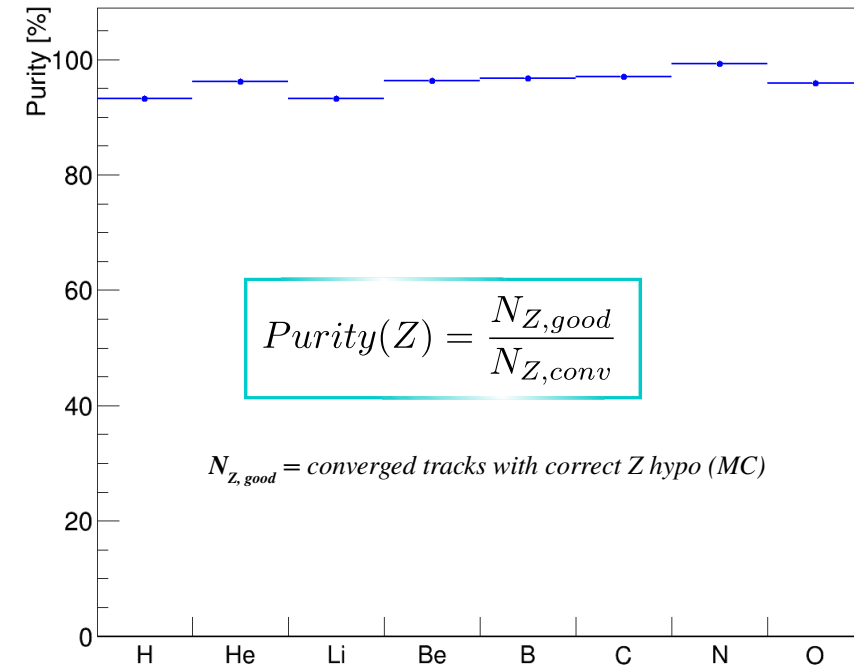
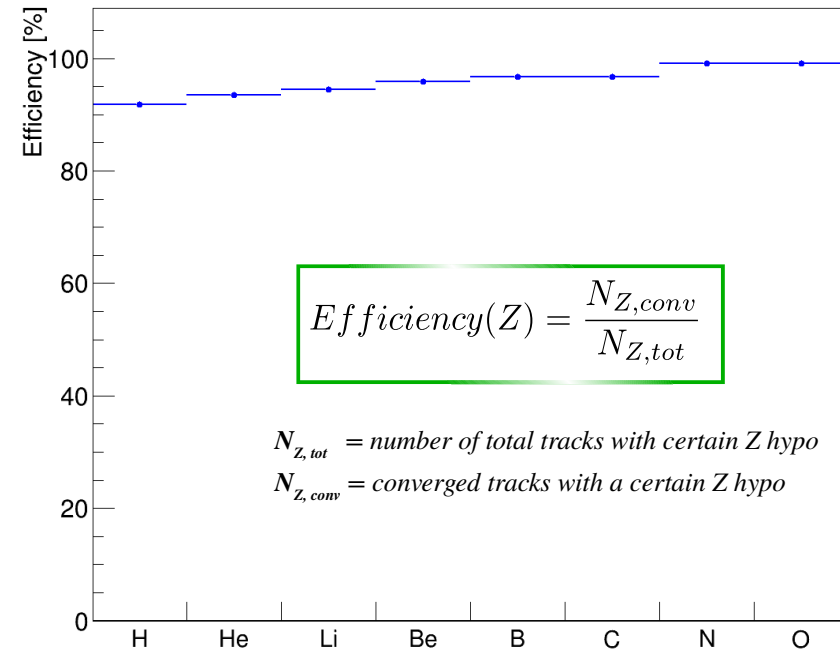
# Performance – Efficiency and Purity

Track reconstruction  
algorithm tested on  
MC simulations



Selection &  
Fitting

**Both efficiency and purity  
> 90% for all fragments!**

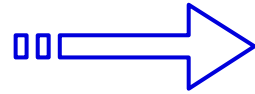






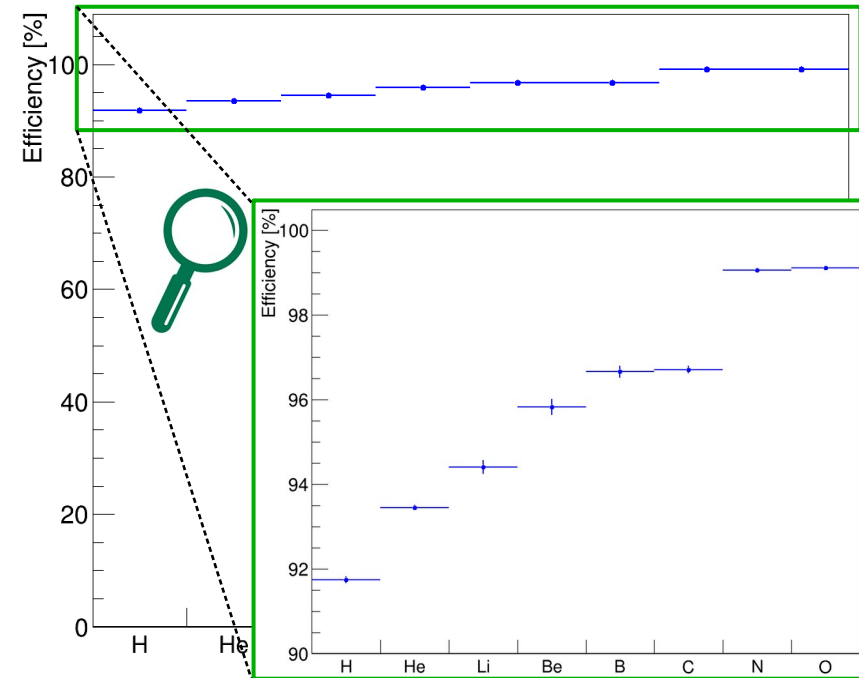
# Performance – Efficiency and Purity

Track reconstruction algorithm tested on MC simulations



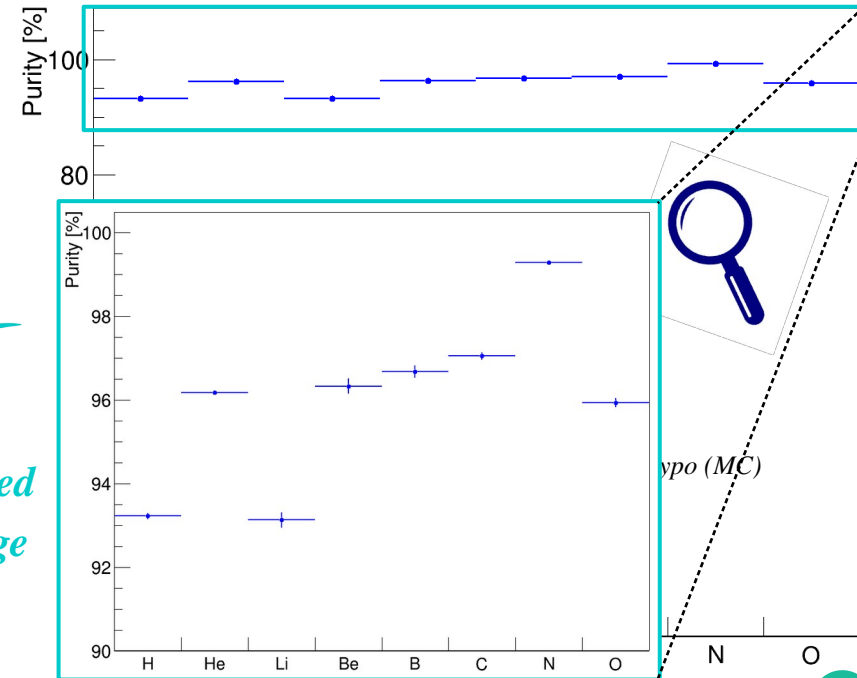
Selection & Fitting

Both efficiency and purity > 90% for all fragments!



Track reconstruction mostly successful

Fragments associated with the right charge

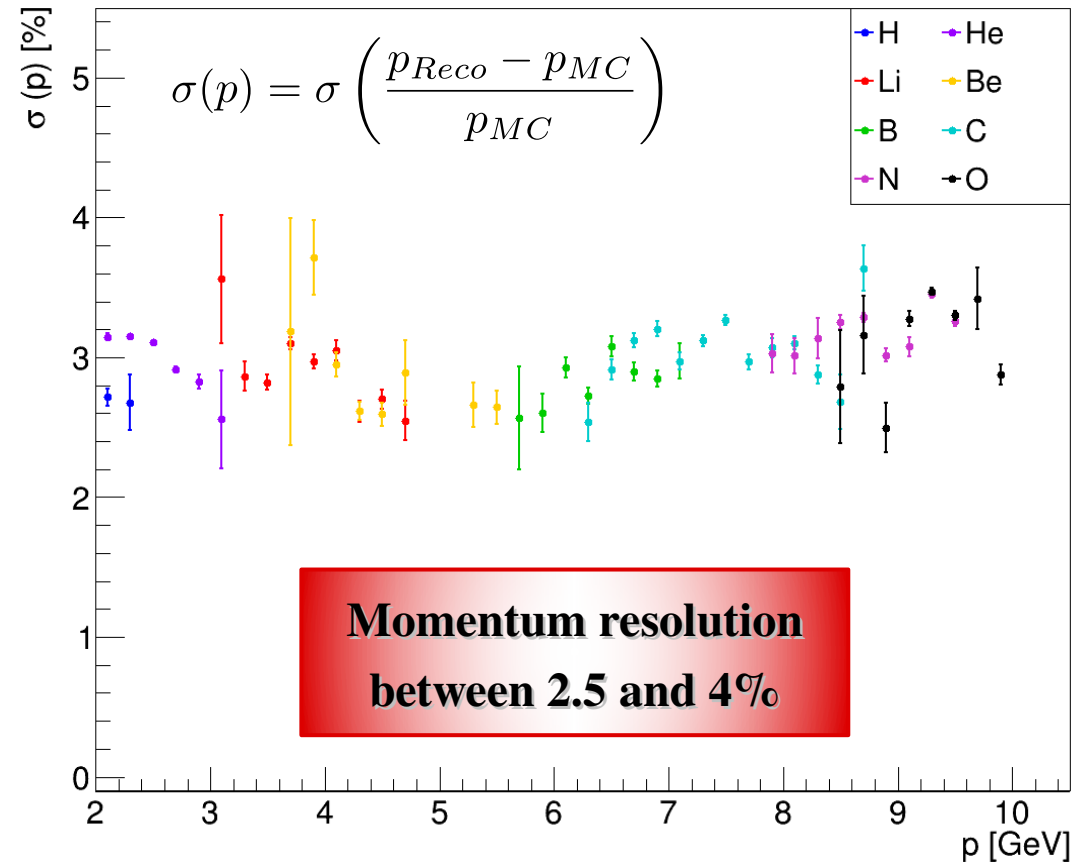
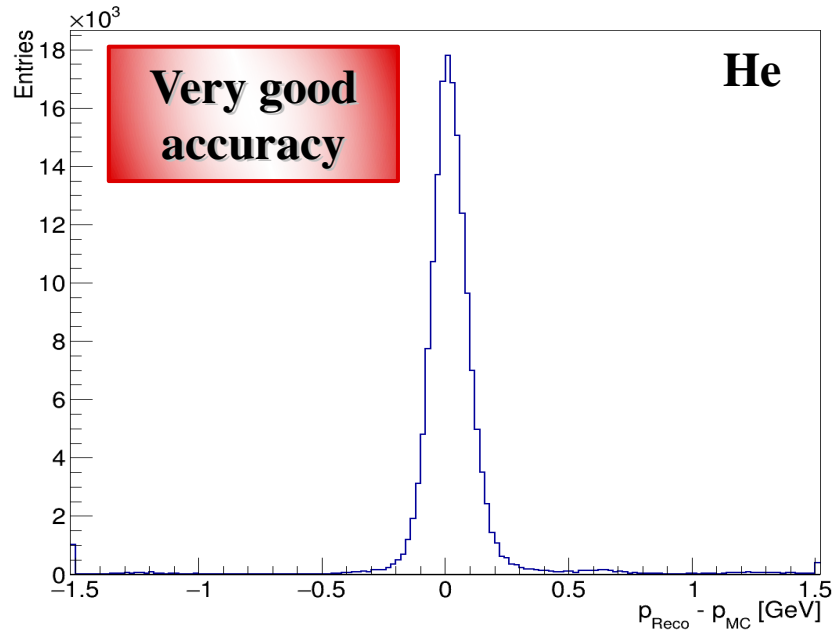




# Performance – Momentum

## Momentum at the target:

- Extracted from track fit
- Checked with MC

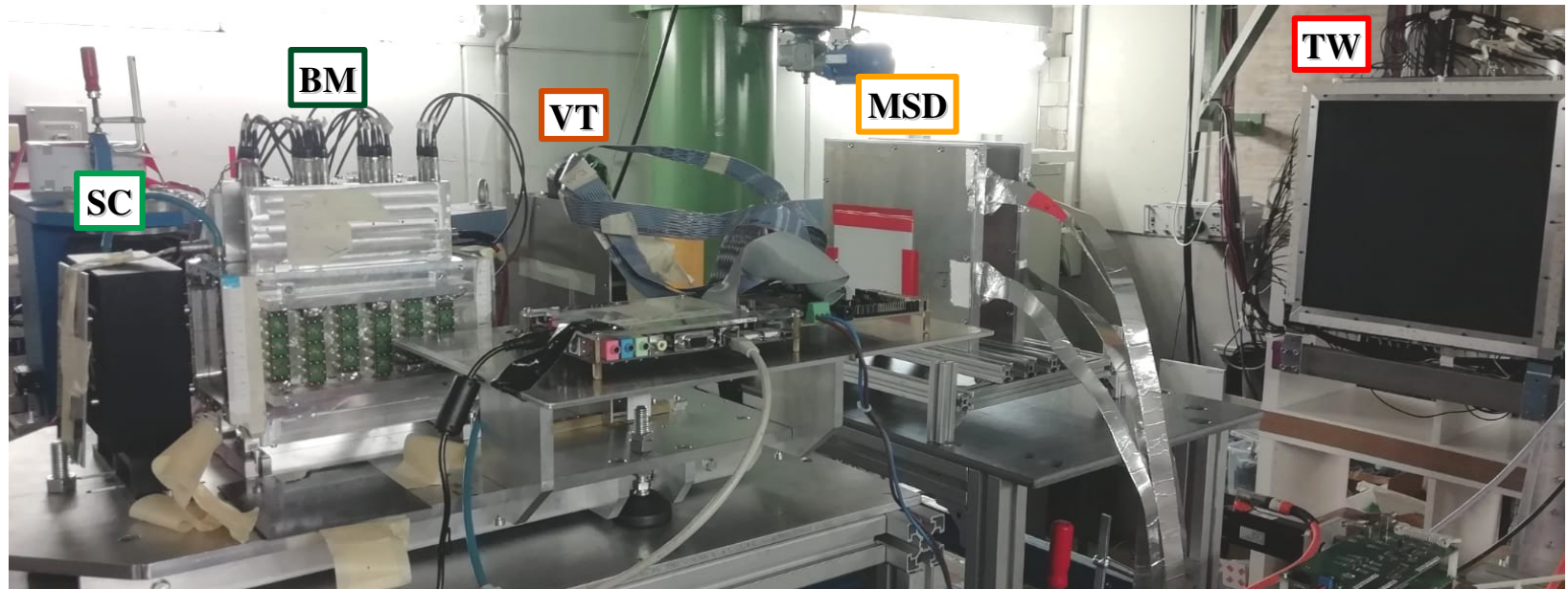


# GSI 2021 campaign - July 2021

## Setup:

- ✓ SC + BM
- ✓ VT + MSD
- ✓ TW
- ✓ 1 CALO module

*Magnets, IT and CALO still under construction!*



- $^{16}\text{O}$  beams at 200 and 400 MeV/u
- C (5 mm) and  $\text{C}_2\text{H}_4$  (5-10 mm) targets
- 42M events acquired



**First data acquisition  
in 2 years!!**

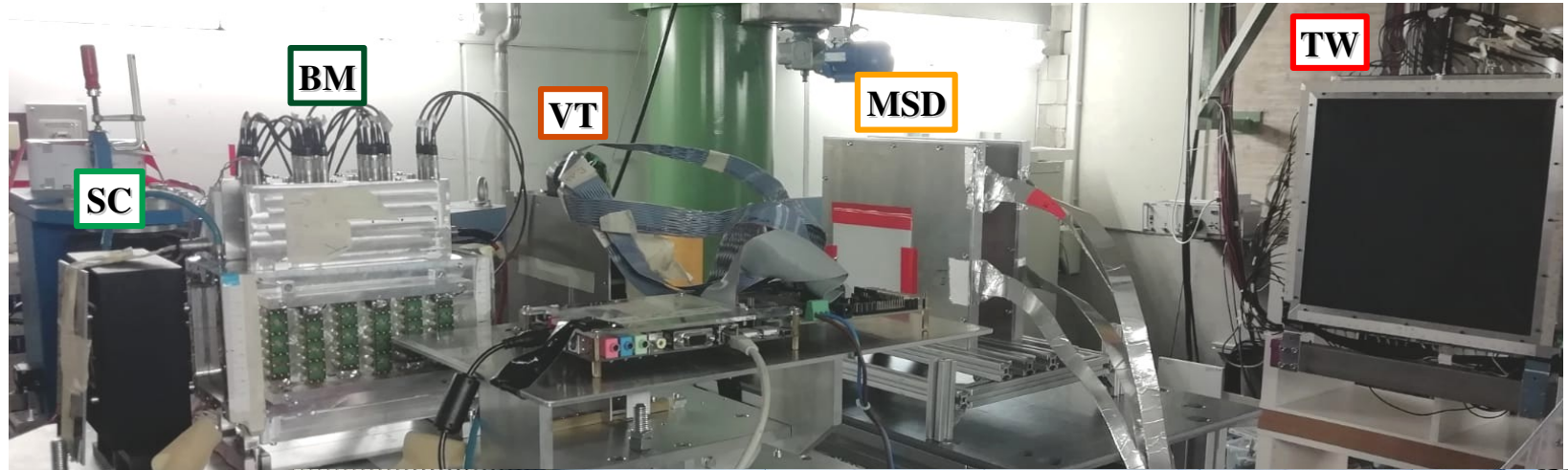


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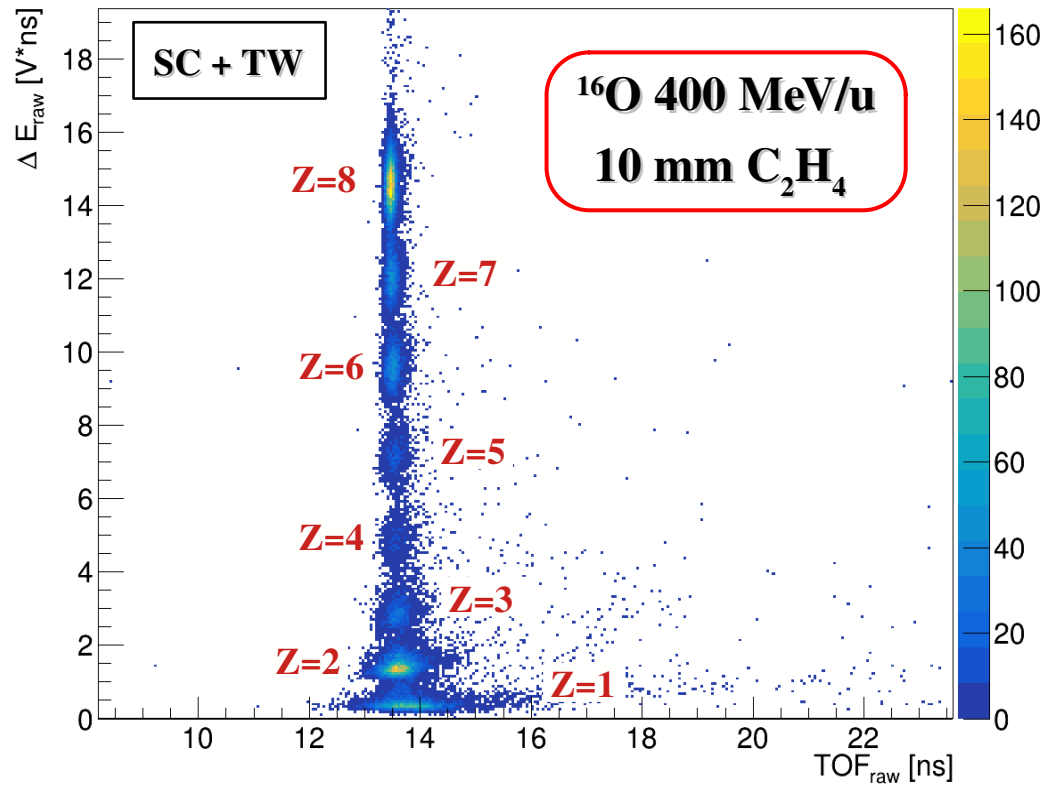
- $^{16}\text{O}$  beams at 200 and 400 MeV
- C (5 mm) and  $\text{C}_2\text{H}_4$  (5-10 mm)
- 42M events acquired



# GSI 2021 campaign – Preliminary results



## Particle charge identification



- ✓ Good energy ( $\Delta E$ ) resolution
- ✓ TOF resolution  $\sim 45\text{-}50$  ps
- ✓ Good efficiency on protons



**Very good charge separation!**

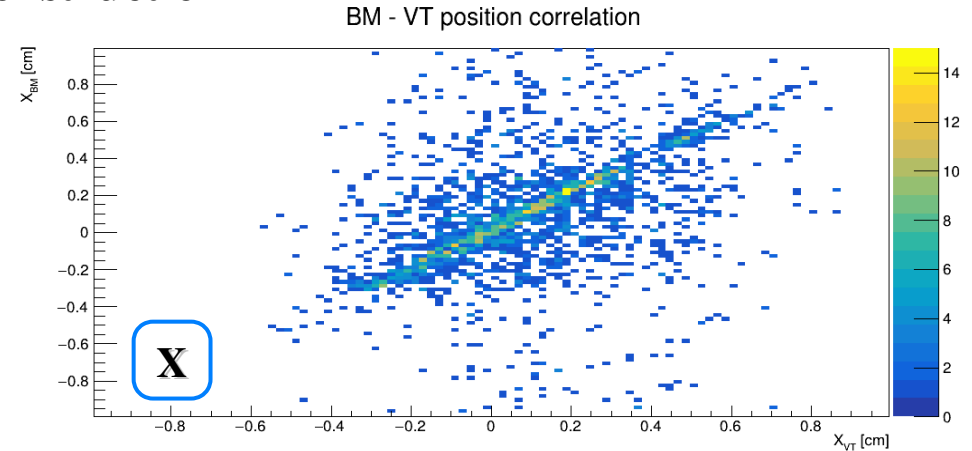
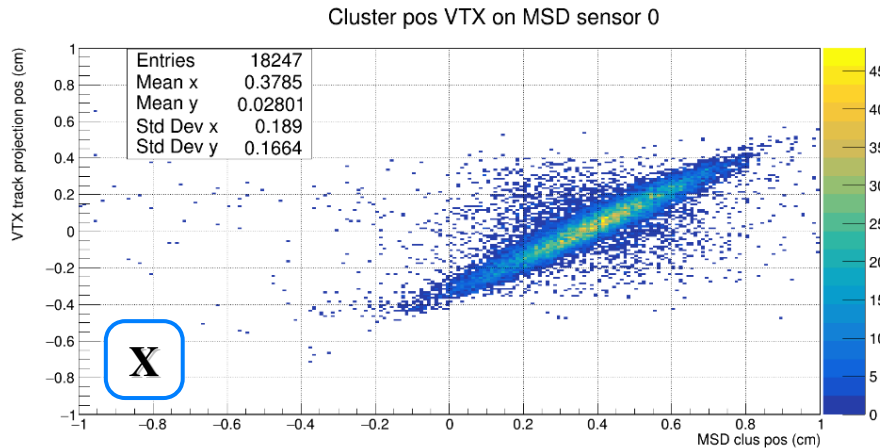
*however*

ⓘ **Detector calibration needed!**



# GSI 2021 campaign – Preliminary results

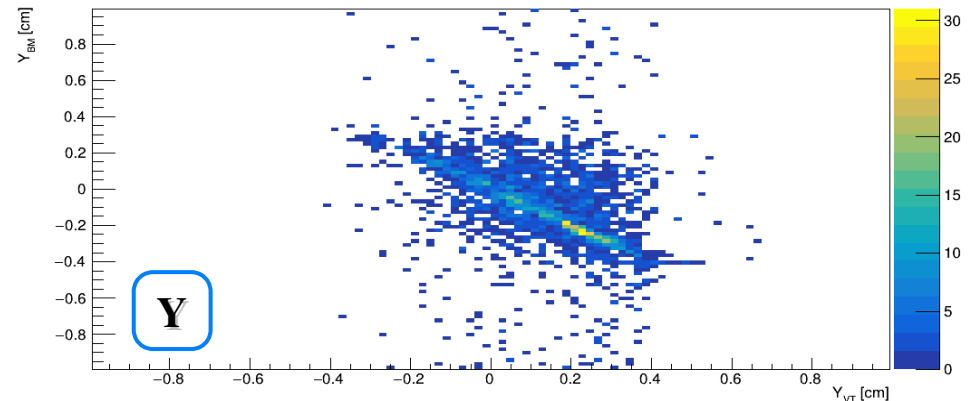
## Position reconstruction



- ✓ **BM - VT correlation**
- ✓ **VT - MSD correlation**



⚠ **Detector alignment to be completed!**





# Conclusions and Future

Particle tracking performances in line with requirements:

- ✓ MC: Very high efficiency and purity → solid particle identification
- ✓ MC: Extracted momentum resolution ~ 2.5-4%
- ✓ Promising results from first look @ GSI data

Future developments:

- 💡 Complete GSI 2021 data analysis → cross section
- 💡 Completion of the electronic setup (IT, Magnets, CALO) + neutrons
- 💡 More acquisitions w/ Emulsion Chamber Setup



*Thank you for  
your attention*

