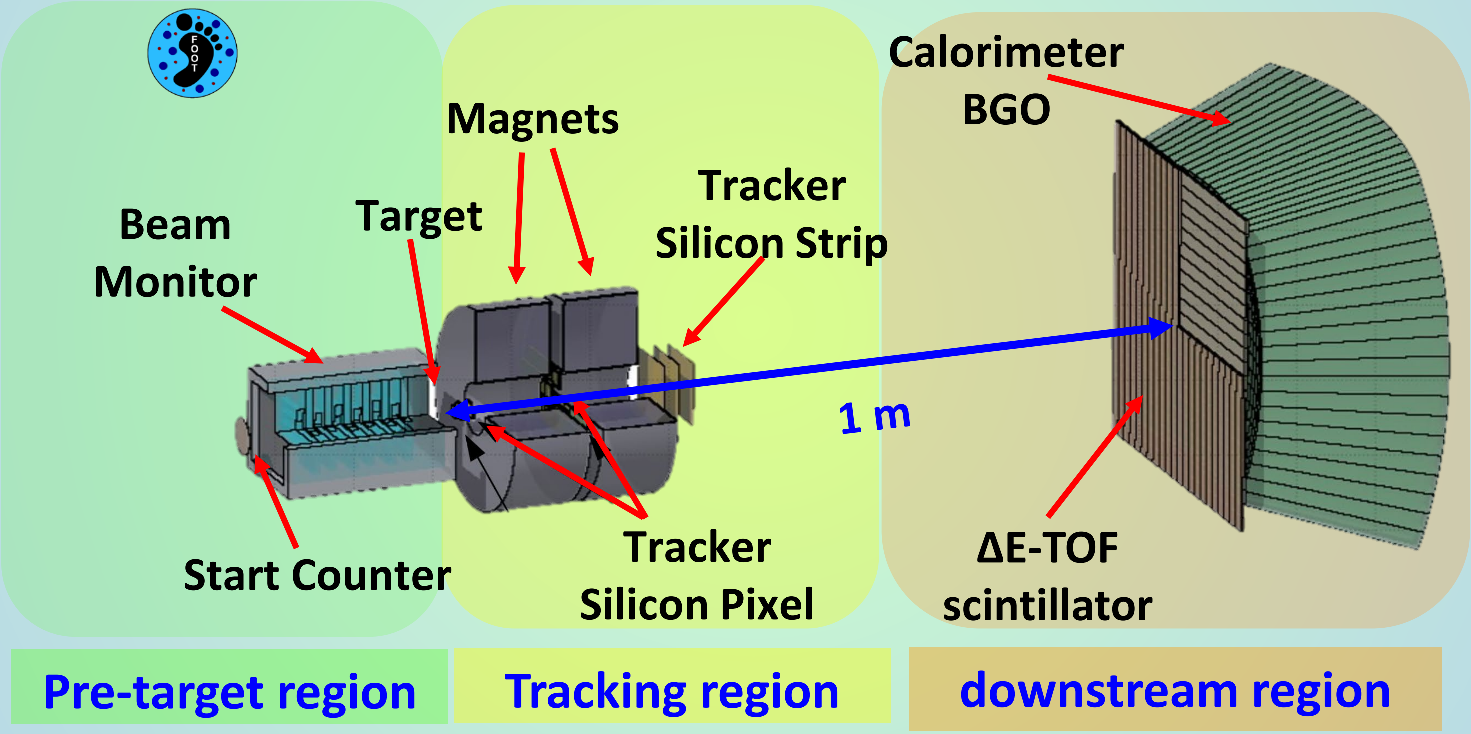
FOOT: FragmentatiOn Of Target Experiment



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FOOT goals

Hadrontherapy

Target fragmentation

- dσ/dE and dσ/dω with 5% precision of the fragment production X sections in inverse kinematics
- p, C, O beams
- Hadrontherapy energies (200-400 *MeV/u*)

Projectile fragmentation

- same but in direct kinematics

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

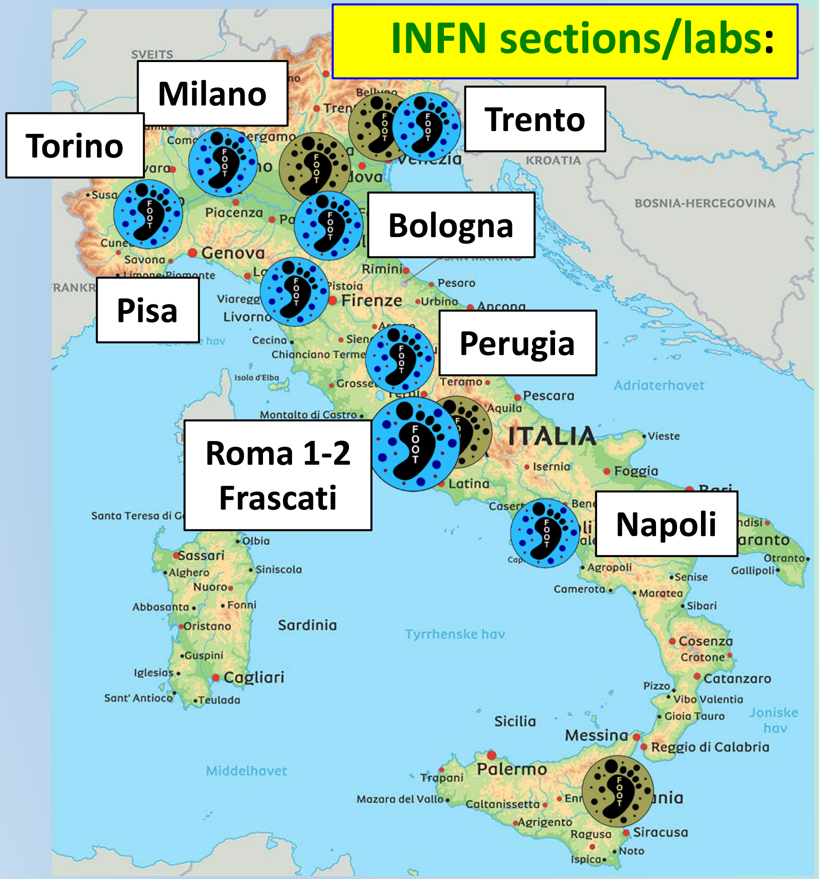
Radioprotection in space

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

- dσ/dE and dσ/dω with 5% precision of the fragment production X sections in direct and inverse kinematics
- p, He, Li, C, O beams (the most common in space)
- Radioprotection energies (around 700 *MeV/u*)

FOOT Collaboration

FOOT approved by the INFN on September 2017 (CSN3)



92 members (60% staff):

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

Physics program:

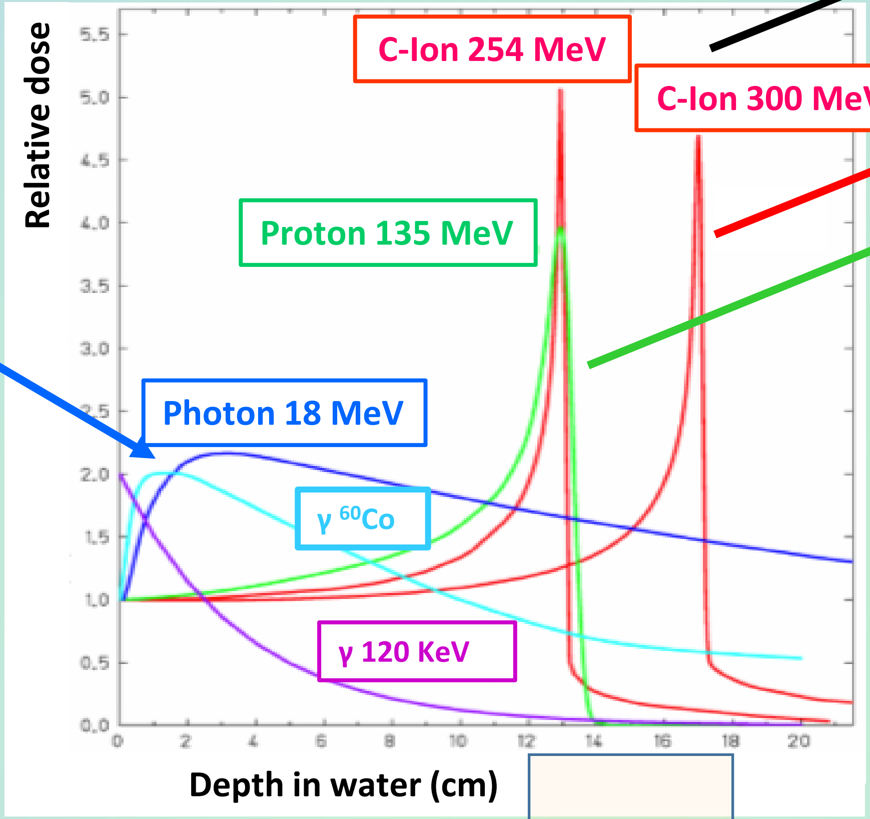
- **Hadrontherapy:**
  - **Nuclear fragmentation @ 200 MeV/u**
- **Radioprotection in Space:**
  - **Nuclear fragmentation @ 700 MeV/u**

Hadrontherapy vs Radiotherapy

Bragg Peak

Gamma

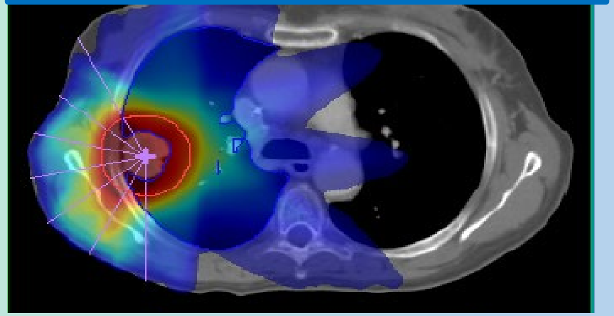
- ❑ Photoelectric ($\sim Z^4/E^3$)
- ❑ Compton ($\sim Z/E$)
- ❑ Pair prod ($\sim Z^2/\ln E$)



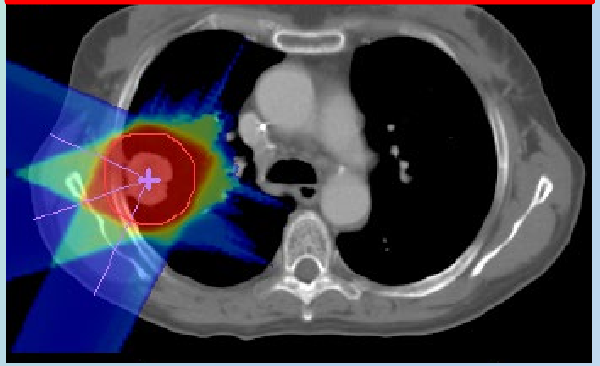
Proton/charged ion

- ❑ Ionization
- ❑ Excitation
- ❑ Bremsstrahlung
- ❑ Fragmentation

Radiotherapy, IMRT 7 fields

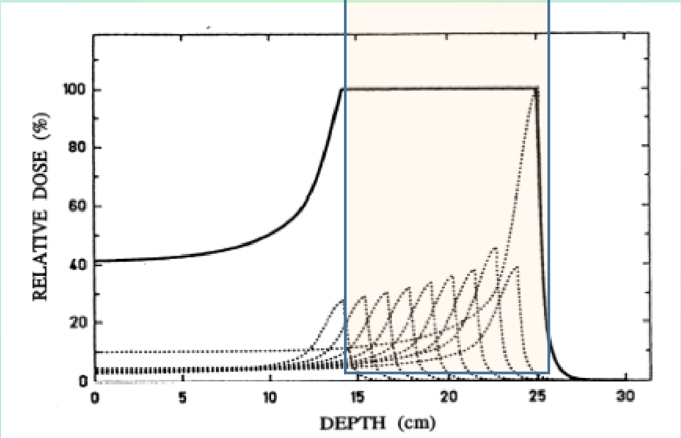


Hadrontherapy, proton



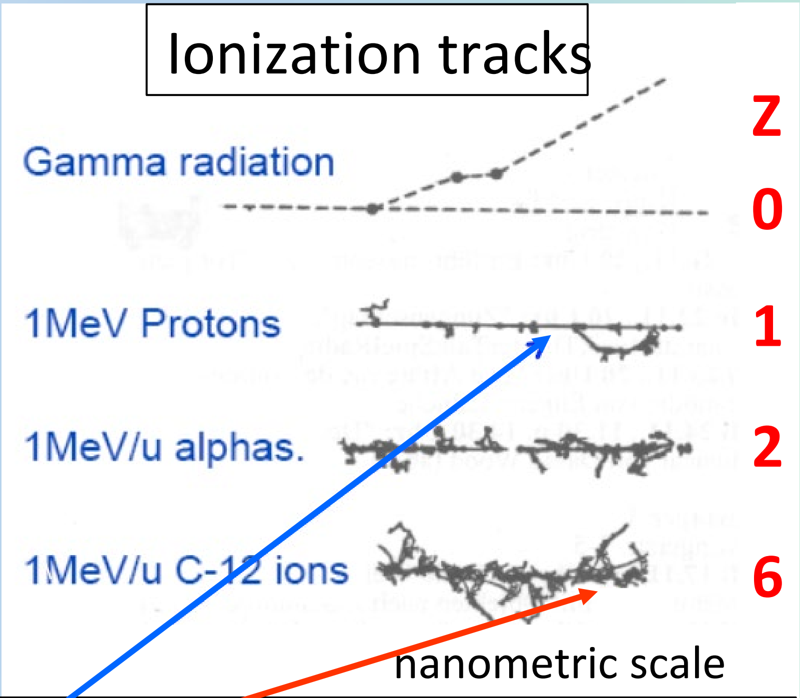
Pros and cons

- ❑ dose release maximum at the end
- ❑ Penetration depends on energy
- ❑ Hadron > efficient than γ
- ❑ Hadron < damage outside tumor
- ❑ MORE expensive than γ



Damage on DNA

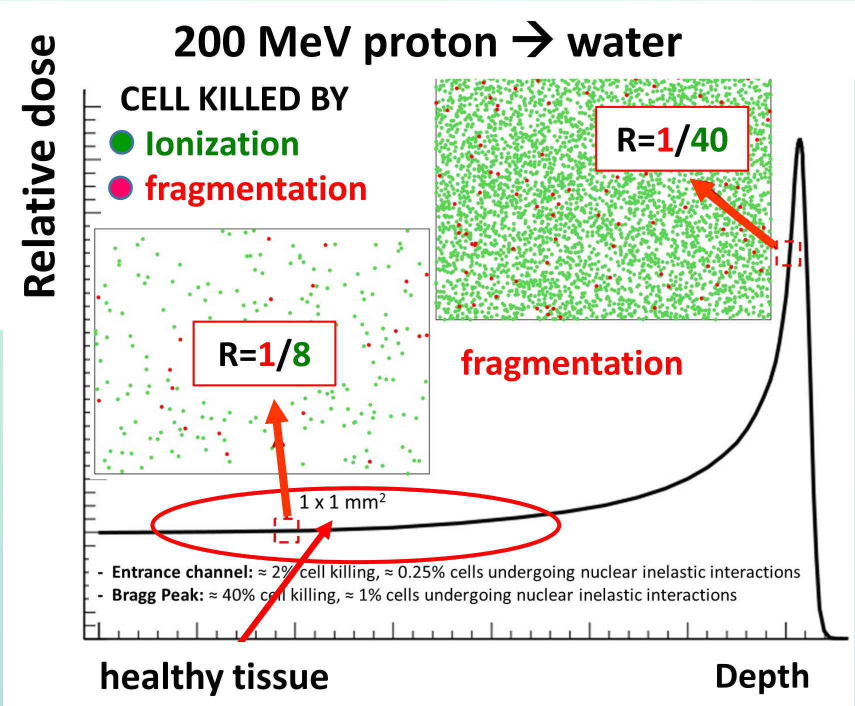
Tumor is a cellular alteration → not controlled proliferation → stop the proliferation → damage on DNA

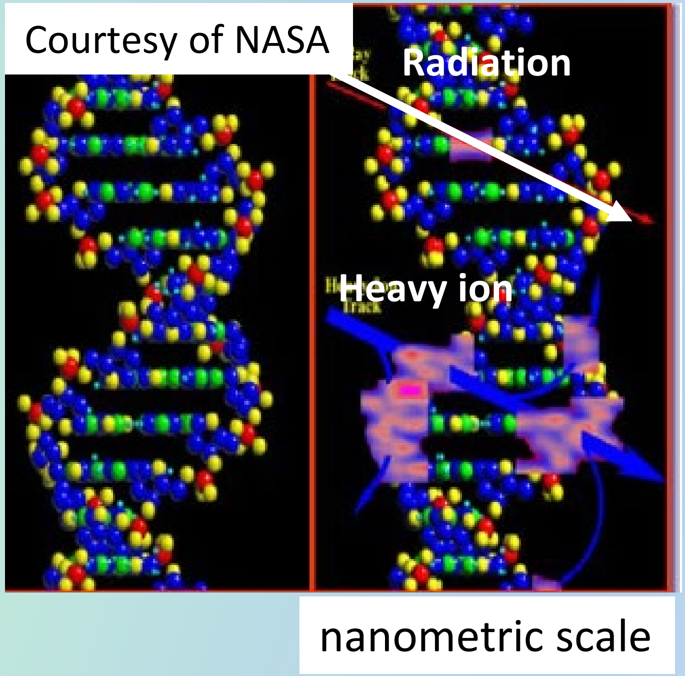


p and C on the Bragg Peak

Higher Z → Higher damage

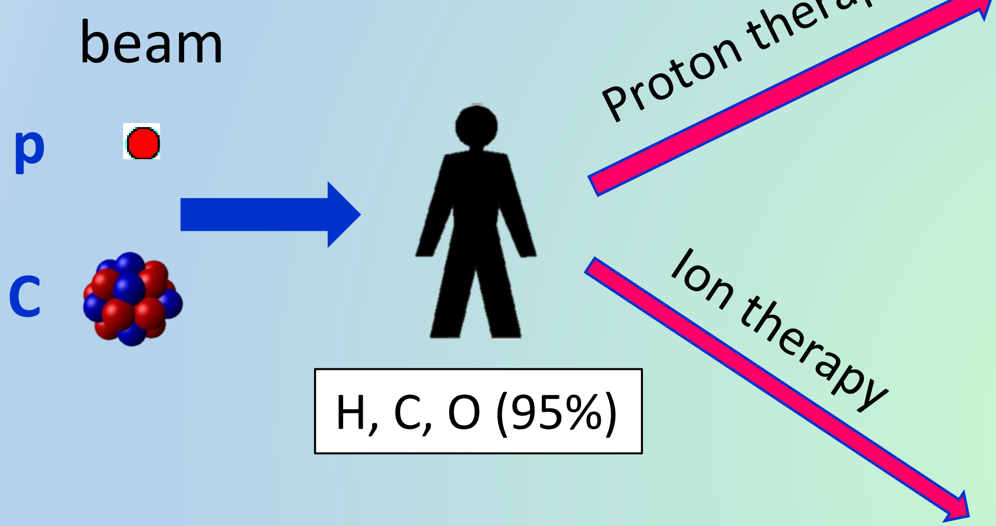
but, necessary to know the
Nuclear fragmentation cross sections





Double strand break → irreparable damage

Target-Projectile fragmentation



p + H

p + C,O → target fragments
low Energy → **low range**

No fragmentation

Target fragmentation

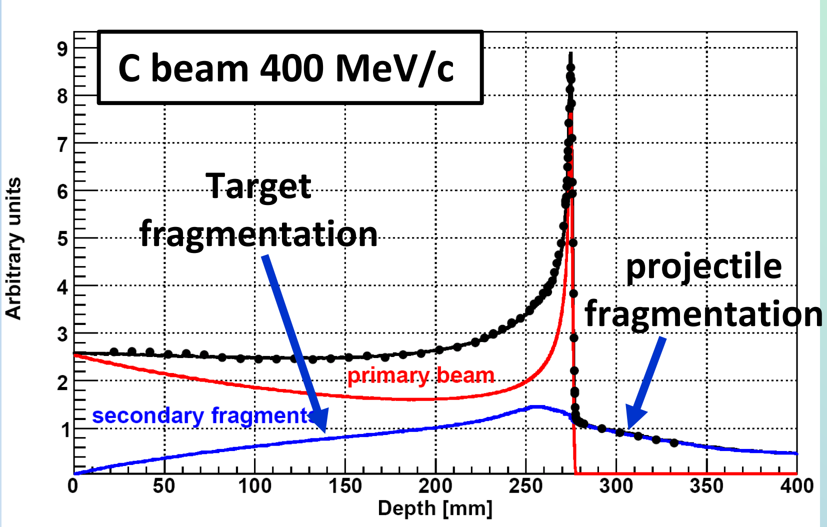
Fragment	E (MeV)	LET (keV/μm)	Range (μm)
^{15}O	1.0	983	2.3
^{15}N	1.0	925	2.5
^{14}N	2.0	1137	3.6
^{13}C	3.0	951	5.4
^{12}C	3.8	912	6.2
^{11}C	4.6	878	7.0
^{10}B	5.4	643	9.9
^{8}Be	6.4	400	15.7
^{6}Li	6.8	215	26.7
^{4}He	6.0	77	48.5
^{3}He	4.7	89	38.8
^{2}H	2.5	14	68.9

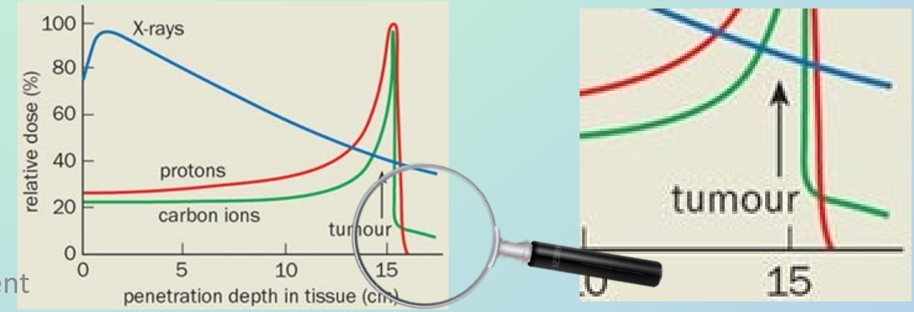
C + H → projectile fragments
High Energy → **Long range**

Projectile fragmentation

C + C,O → target/projectile fragments

both





Tail present only when using Carbon

FOOT MAIN GOAL: *Target fragmentation in proton therapy*

p + C,O → fragments

Target fragments remain in the target

Impossible to detect fragments

DIRECT KINEMATIC

proton
200 MeV

C,O at rest

p + C,O → fragments

INVERSE KINEMATIC

C,O 200 MeV/A

C,O + p → fragments

Proton (H)
at rest

A the end
Lorentz boost

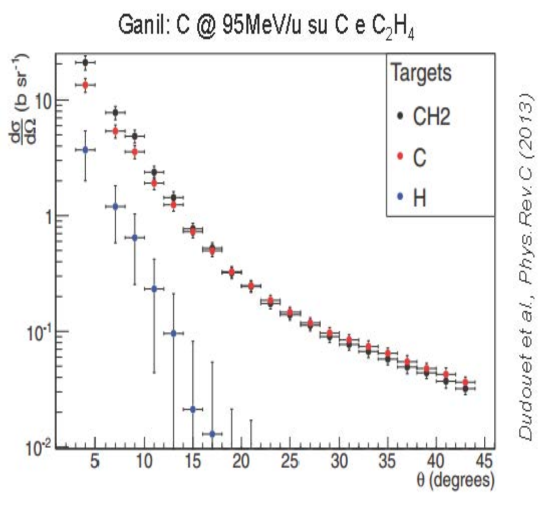
H target

Target (2mm)

C	C_2H_4

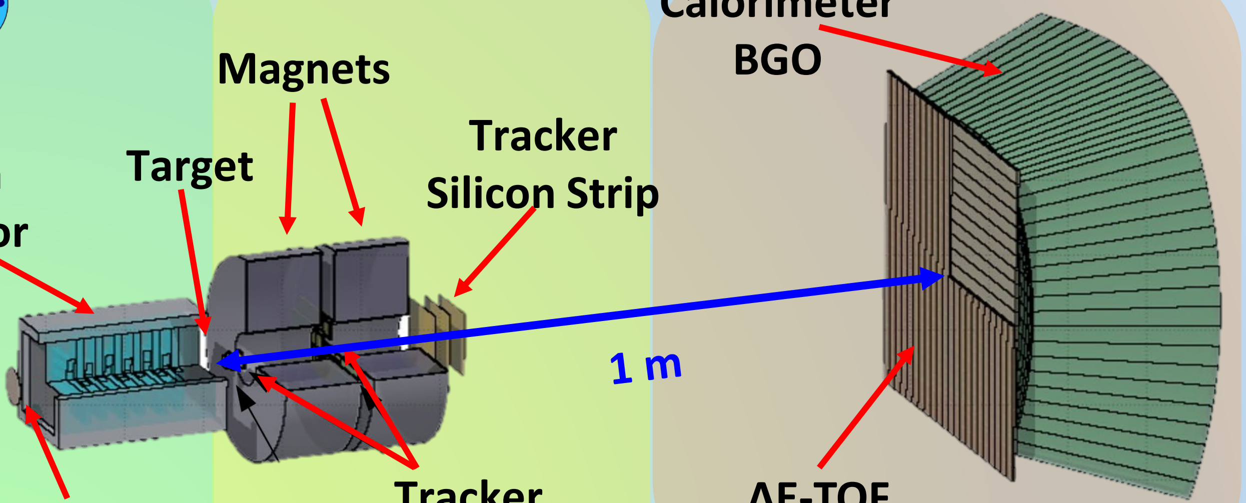
$$\frac{d\sigma}{dE_{kin}}(H) = \frac{1}{4}\left(\frac{d\sigma}{dE_{kin}}(C_2H_4) - 2\frac{d\sigma}{dE_{kin}}(C)\right)$$

Ganil experimental data

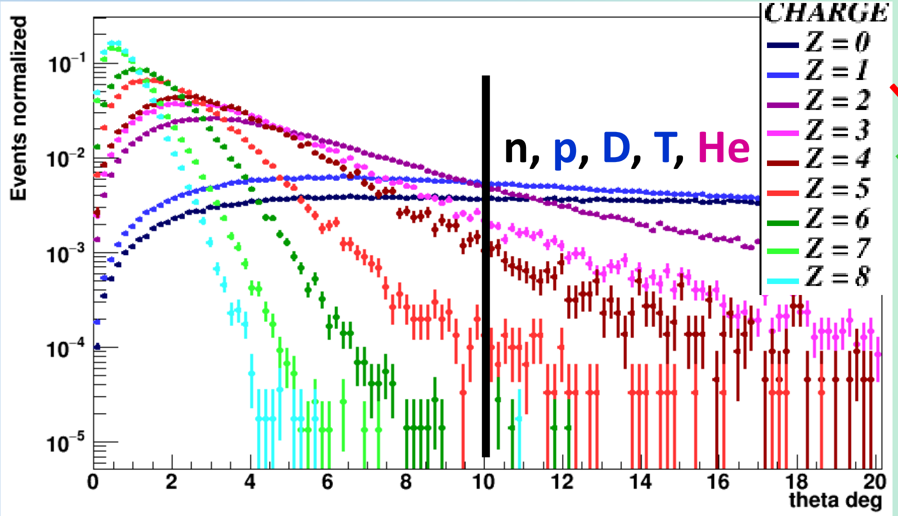


FOOT Detector (in construction)

Electronic Setup



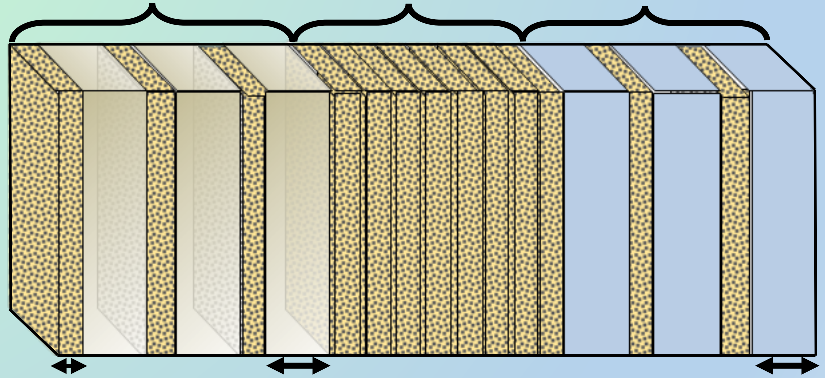
Pre-target region | Tracking region | downstream region



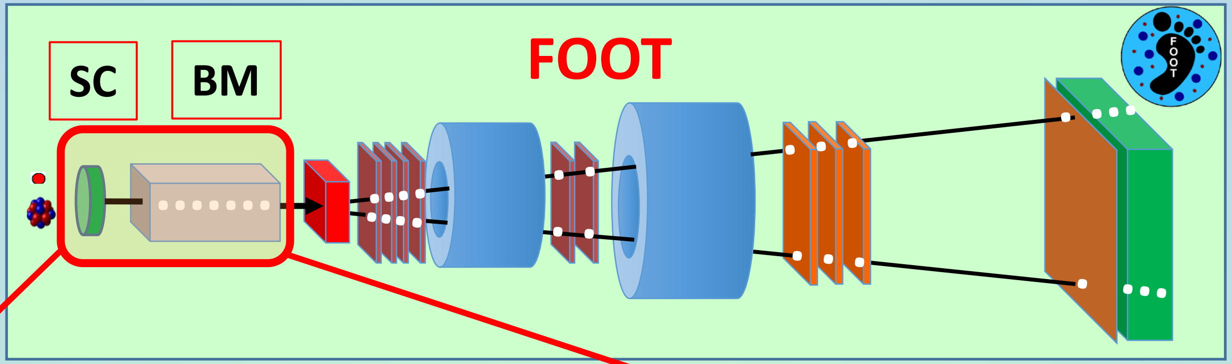
Heavy fragments
Angular open ± 10°

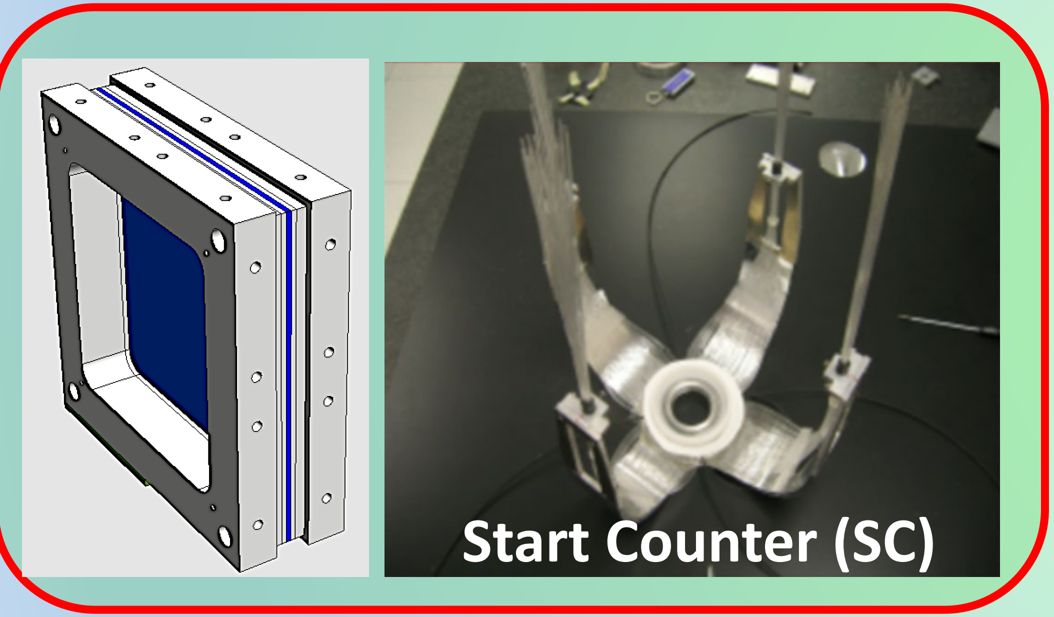
Light fragments
Angular open ± 70°

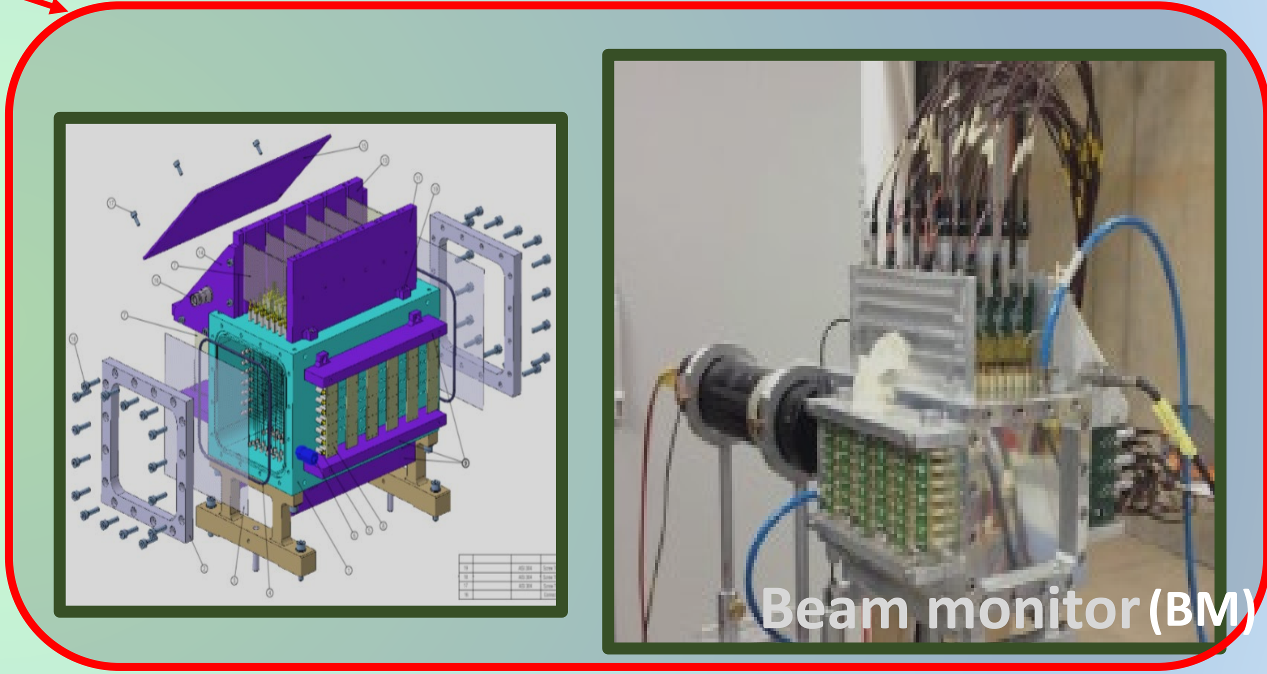
Emulsion Chamber Setup



Pre target region







Trigger and ToF start

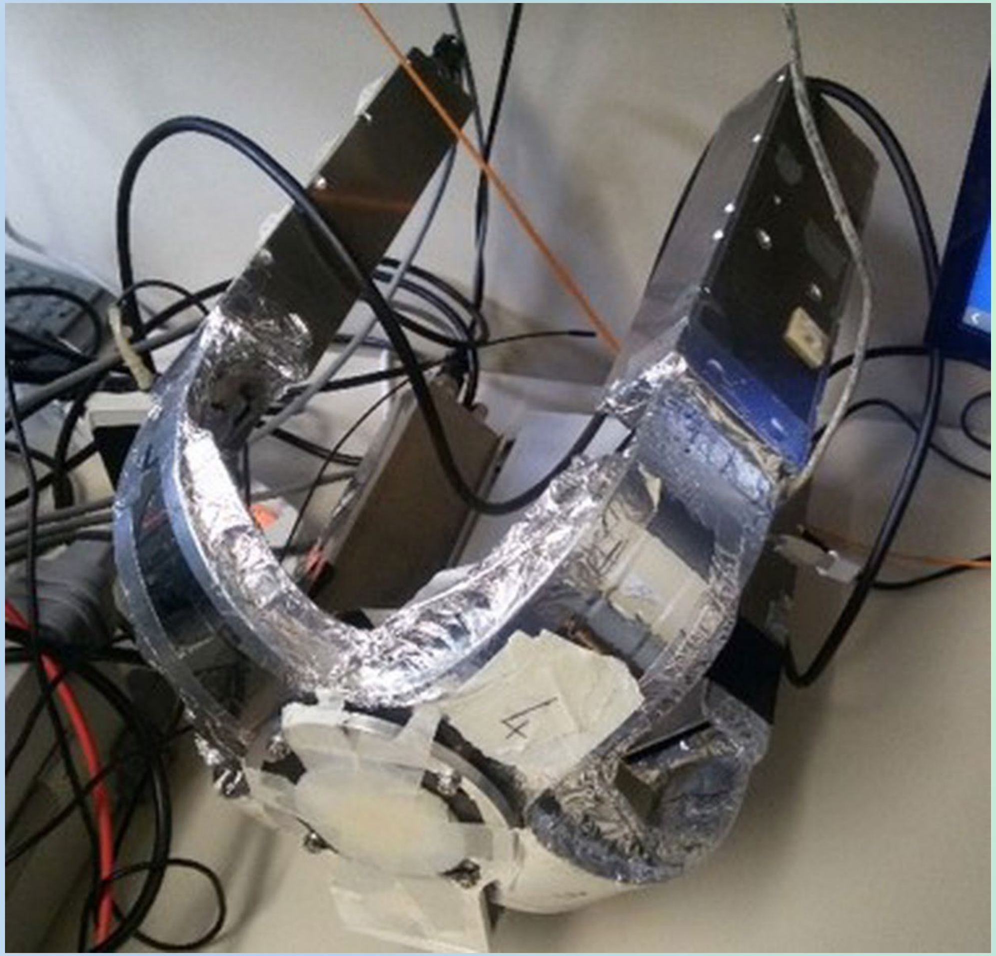
250 µm–1 mm thick plastic scintillator (depending on E beam)
50 mm radius
~ 400 optical fibers → 4 boundles to 4 PMTs
Test beam in september in Trento

Beam momentum/direction & fragmentation in SC

Drift chamber
Gas: Ar/Co_2 (80/20%)
Test beam in september in Trento

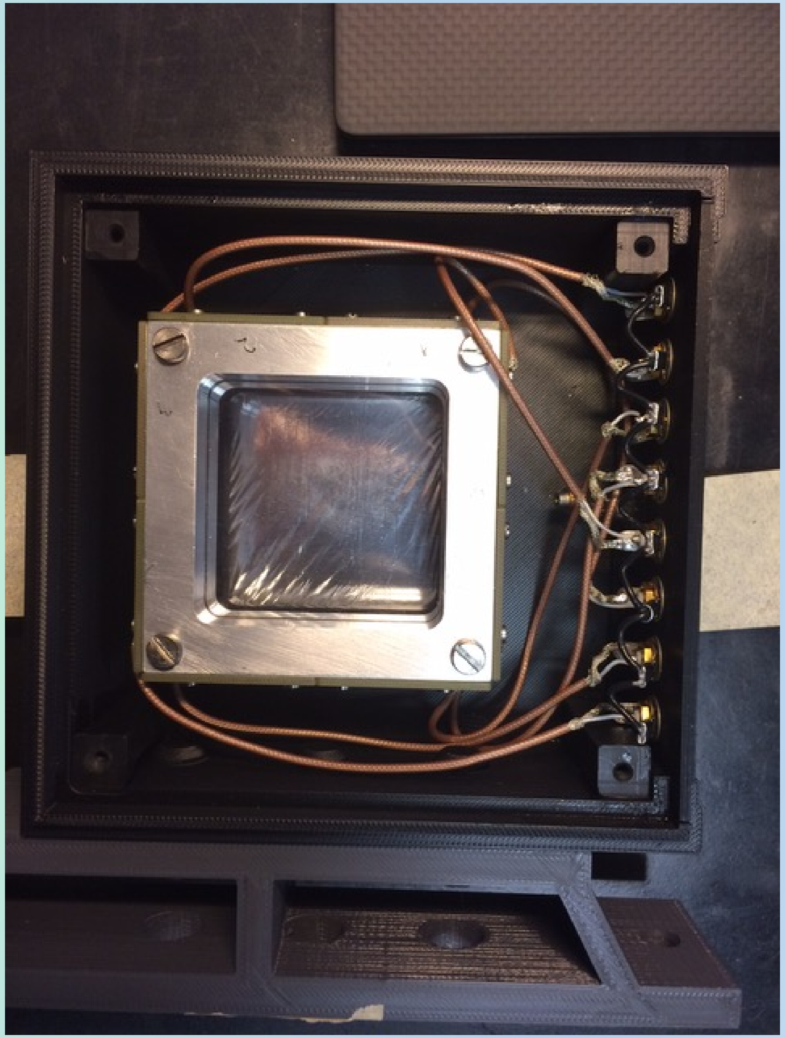
Start Counter

Margherita



SiPM

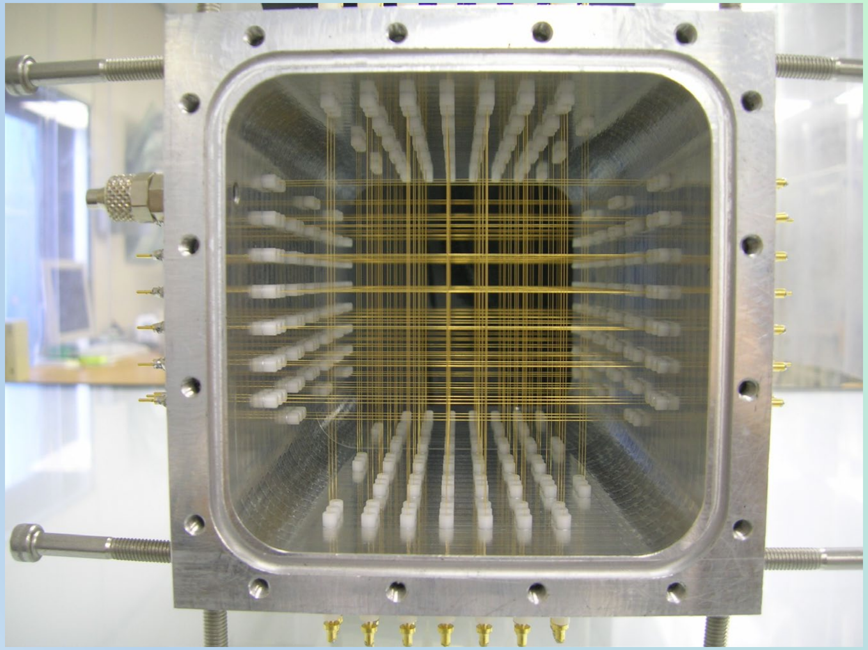
Margarita



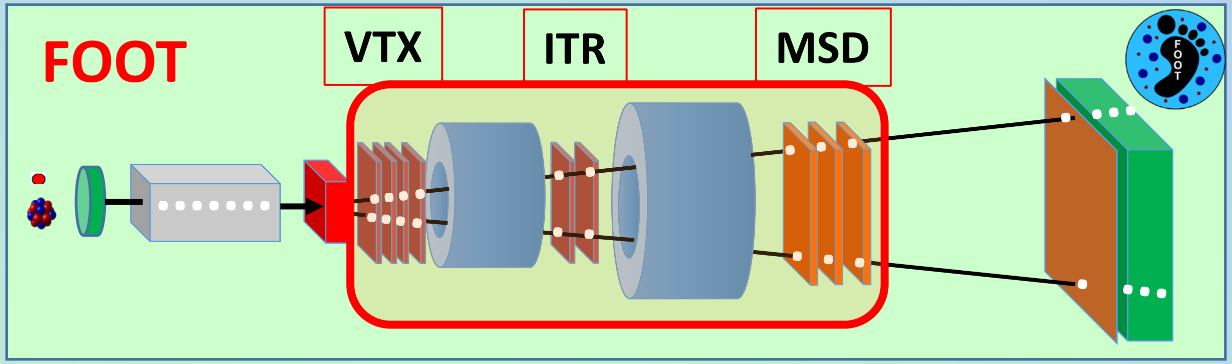
Beam monitor

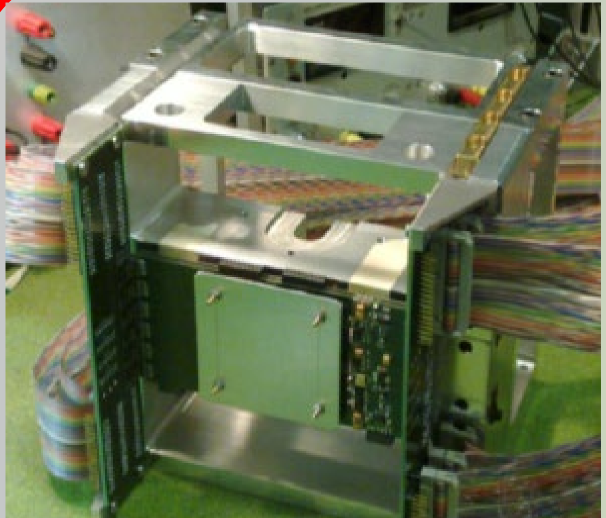
Direzione beam dopo aver passato lo start counter

$$\begin{pmatrix} ct' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \gamma & 0 & 0 & -\beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\beta\gamma & 0 & 0 & \gamma \end{pmatrix} \cdot \begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \gamma ct - \beta\gamma z \\ x \\ y \\ -\beta\gamma ct + \gamma z \end{pmatrix}$$

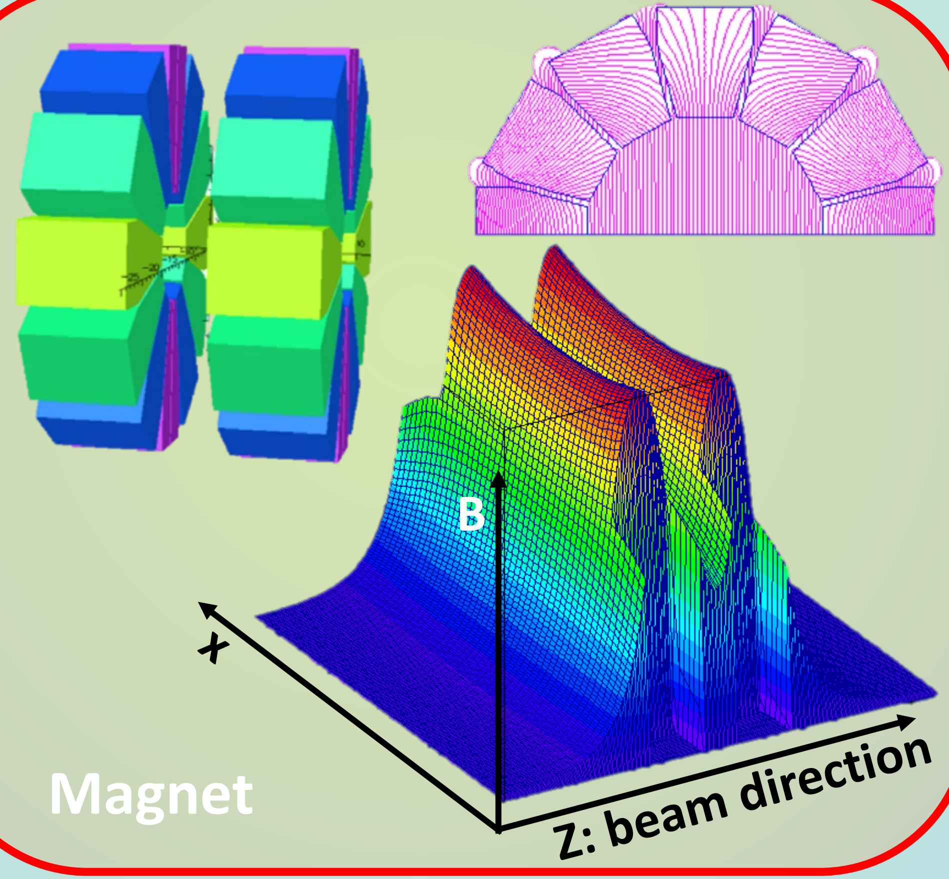


Tracking region




Vertex & Inner Tracker

VTX: 4 layers of Si pixel (20 x 20 μm)
ITR: 2 layers of Si pixel (20 x 20 μm)



Magnet

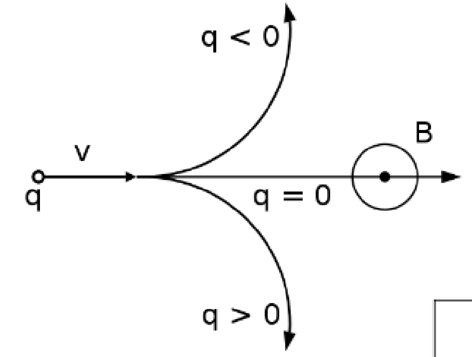
2 permanent magnets
Hallbach geometry
B field in y direction (max 0.8 T)


Micro Strip Detector (MSD)

MSD:
3 layers of Si strips (120 μm x 9 cm)

Momentum reconstruction

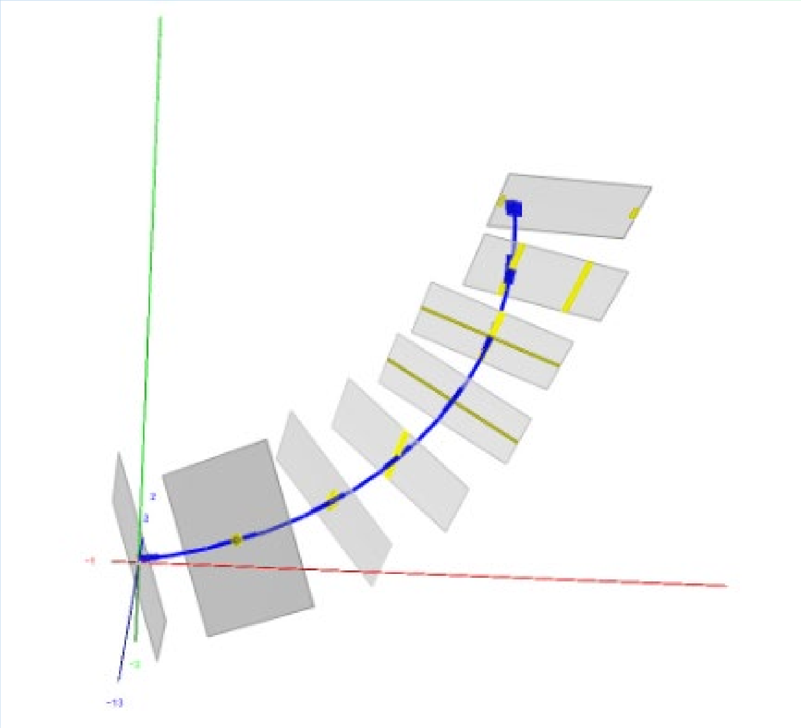
tracker



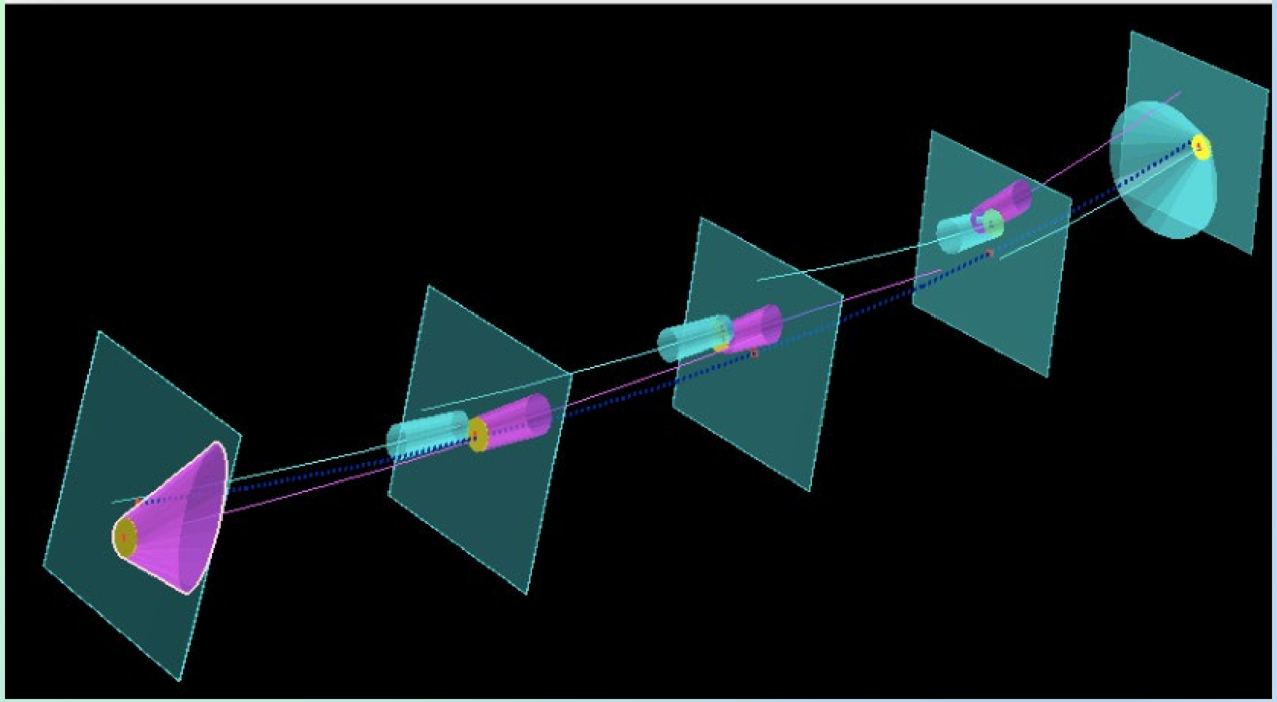
$$\vec{F} = q\vec{v} \times \vec{B}$$

$$\frac{mv^2}{r} = qvB$$

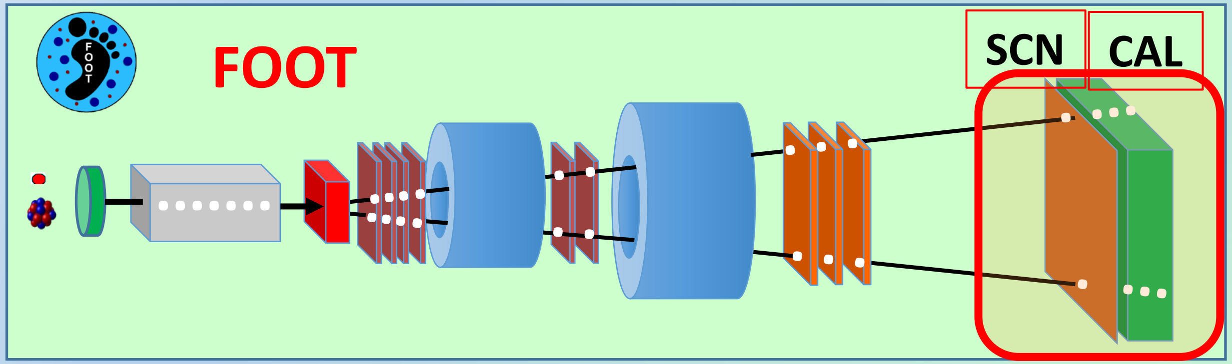
$$\boxed{p\left[\frac{GeV}{c}\right] = 0.3\ \mathrm{B[T]}\ \mathrm{R[m]}}$$

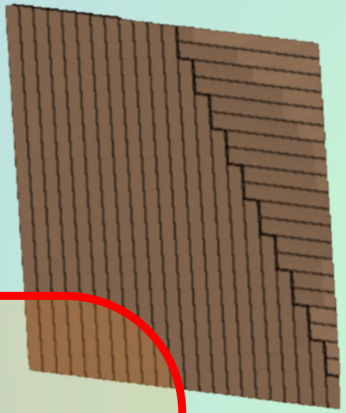


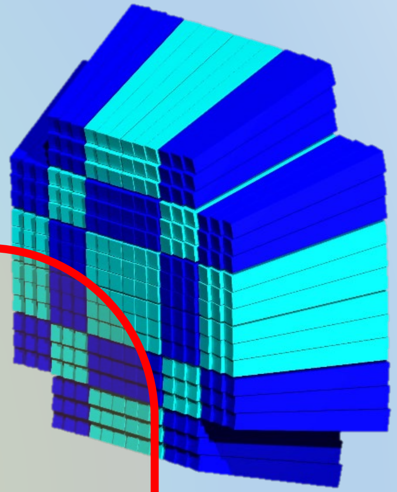
Trajectory reconstruction



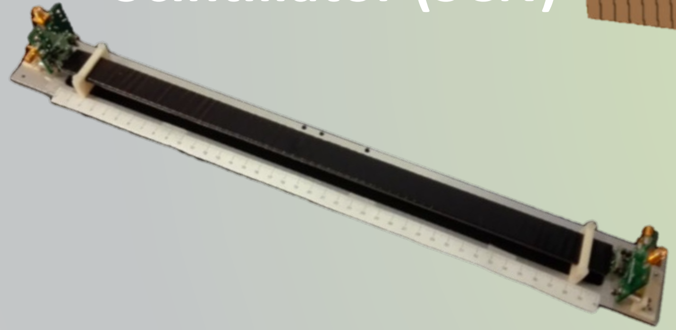
downstream region







Scintillator (SCN)



40 x 2 cm plastic scintillator bars
3 mm thickness
2 layers of 20 bars
Silicon PhotoMultiplier (SiPM)

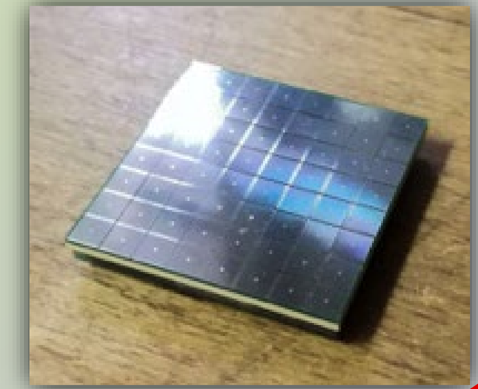
ΔE-Tof

Calorimeter (CAL)

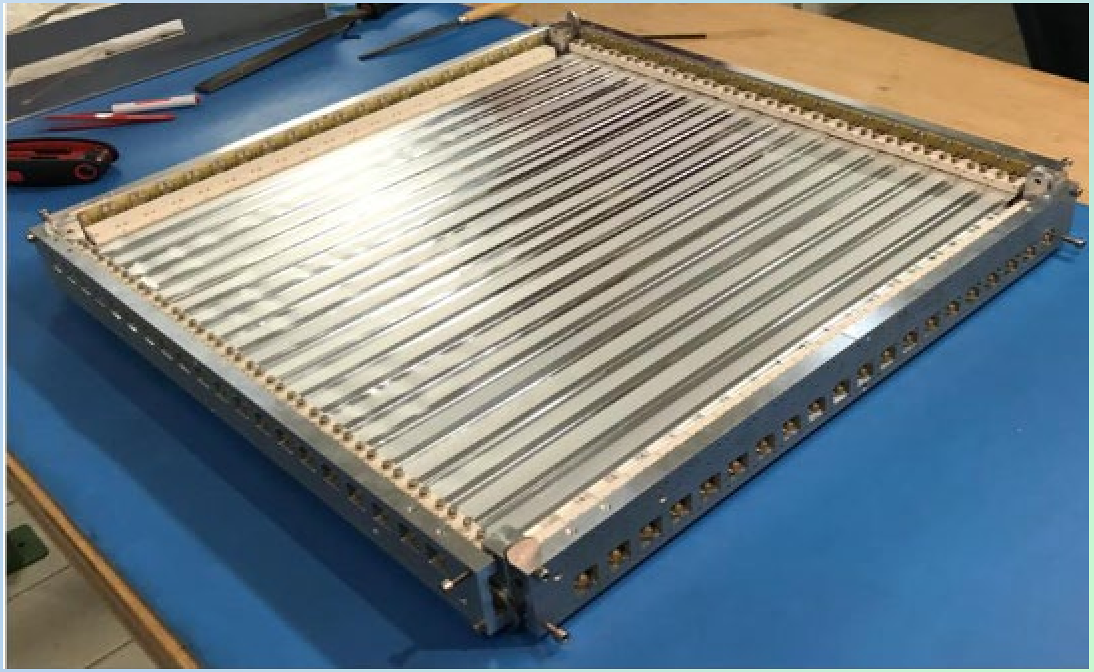
BGO – ($Bi_4Ge_3O_{12}$)
Inorganic scintillator

Z_{Bi} = 83
P_{BGO} = *7.13 g/cm³*
Weight = 1.027 kg
Total weight 330 Kg

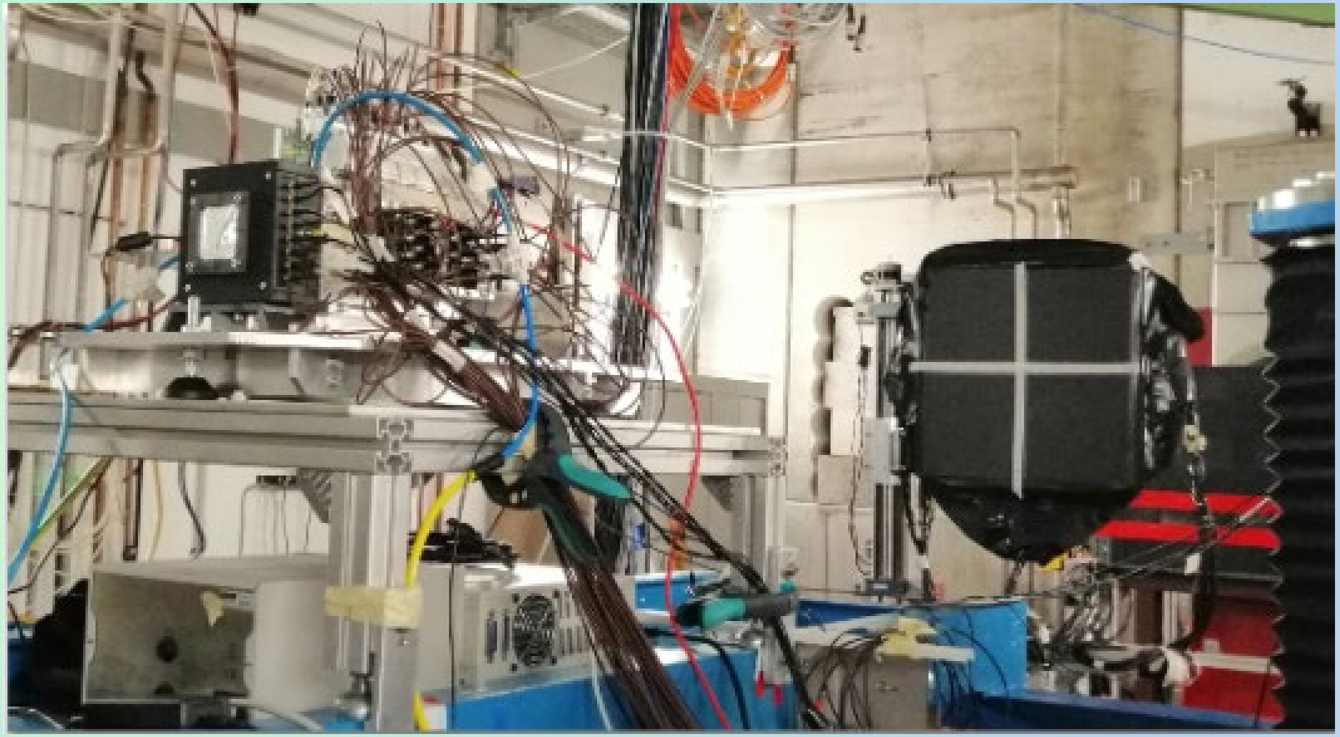
SiPM
Pitch 50 µm
Voltage breakdown 53 V

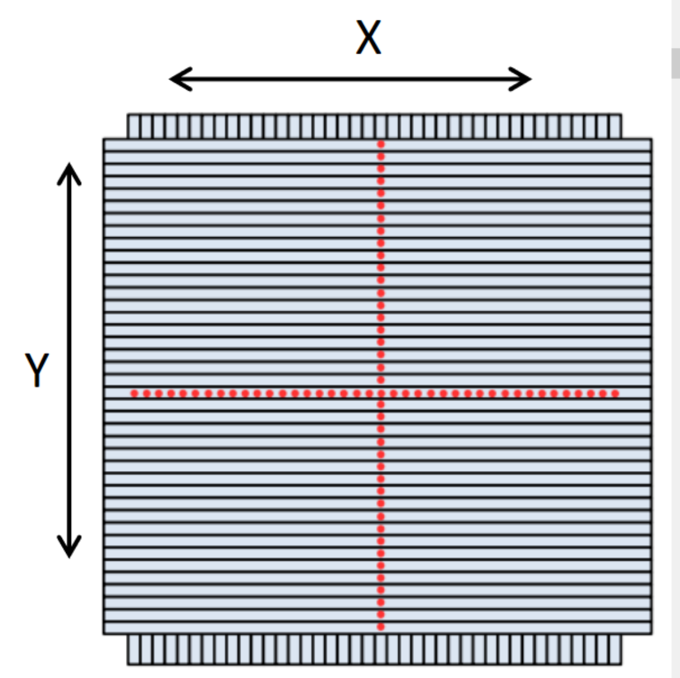


Tof Wall



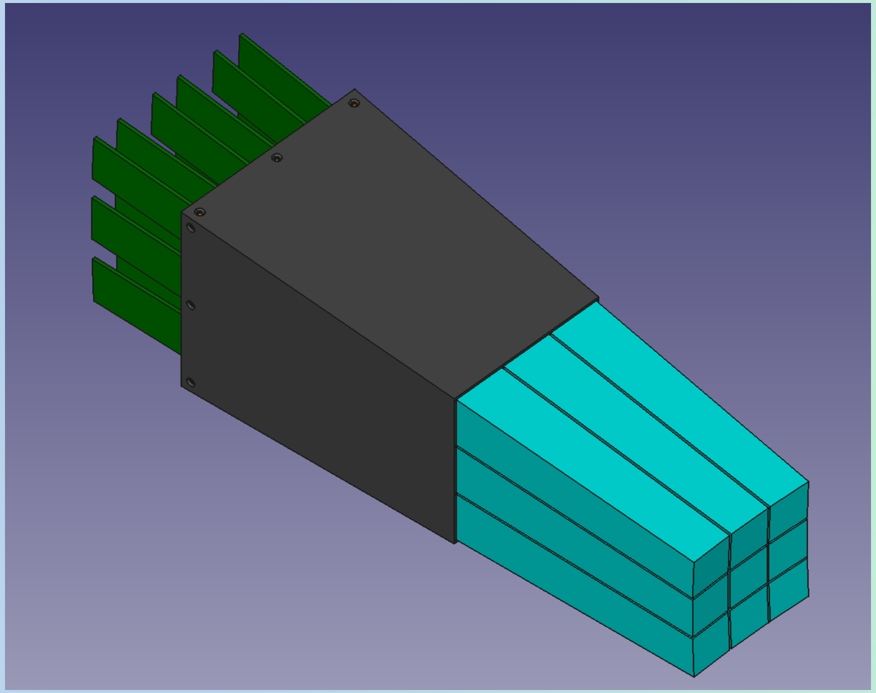
Measure de/dx and tof

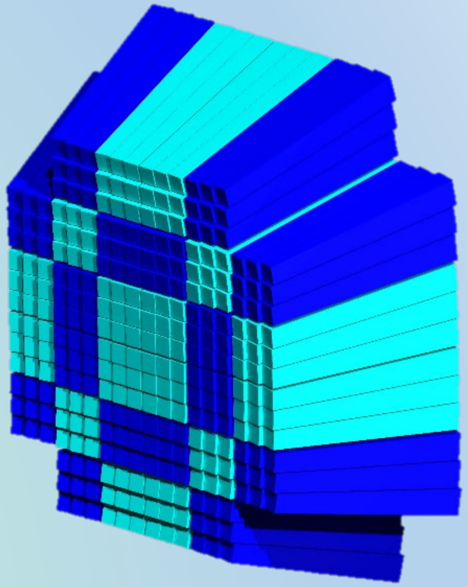


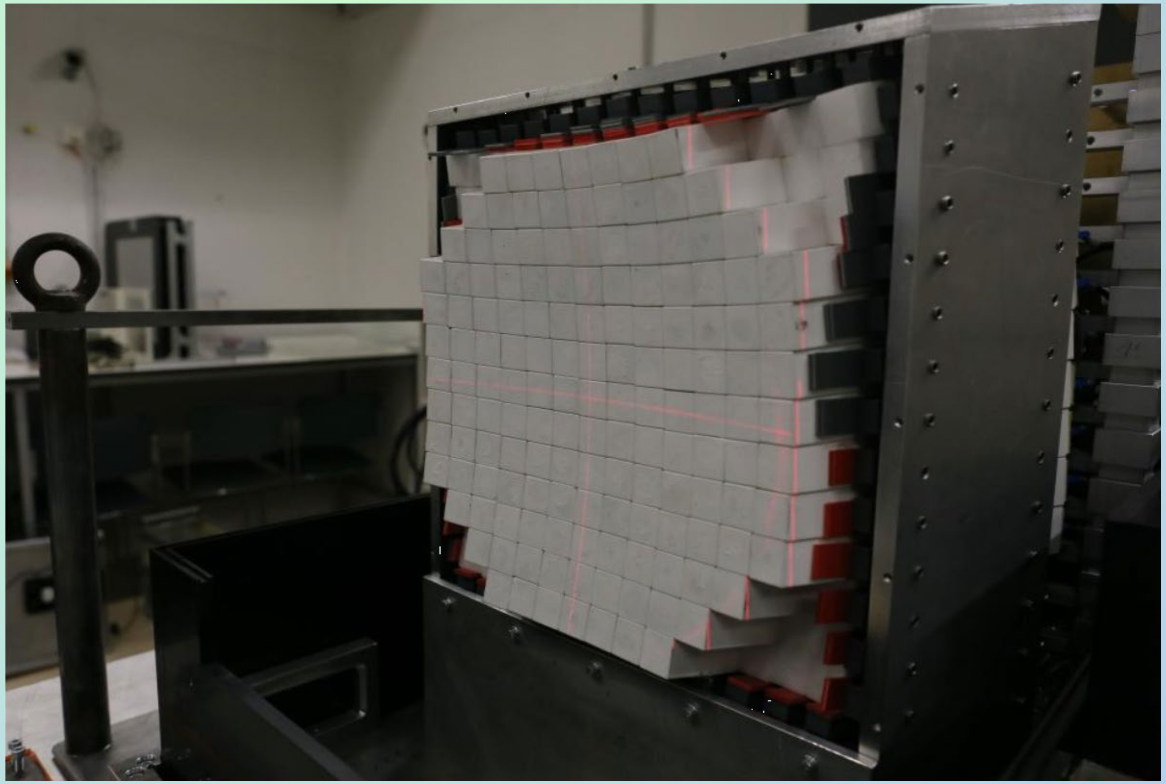


Calorimeter

Measure kinetic energy





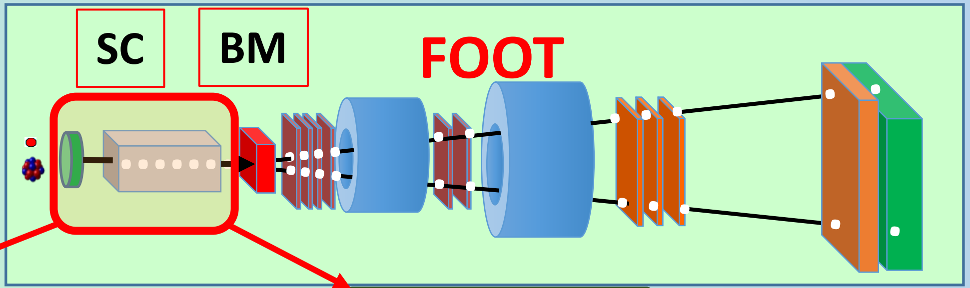


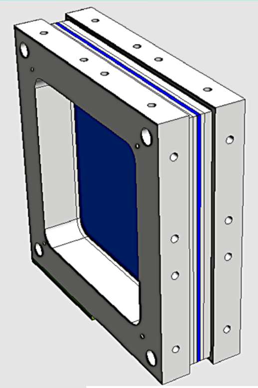
Performance

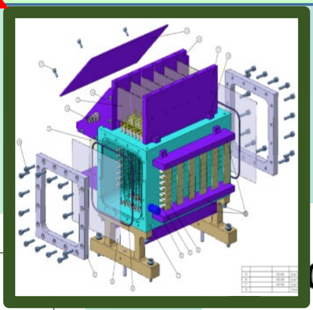
Beam definition: SC + BM

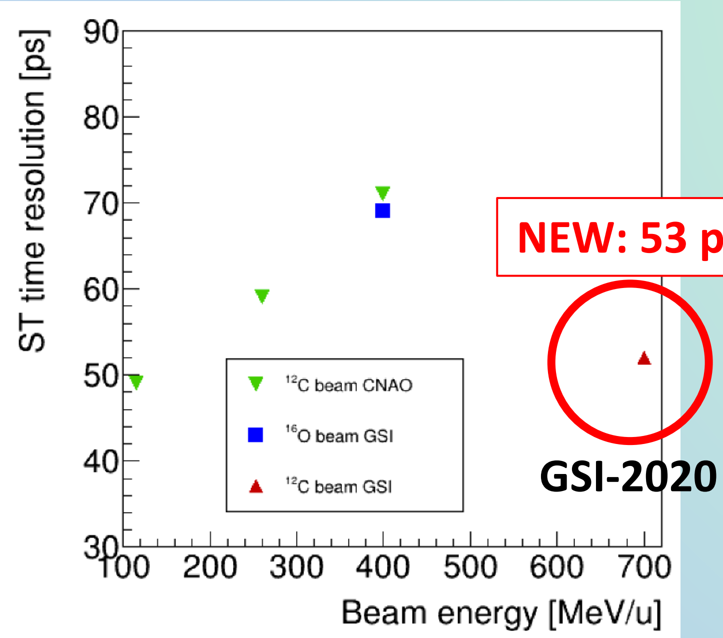
$$\frac{d\sigma_f}{dE_{kin}} = \frac{(Y_f - Bkg_f)^U}{N_{Prim} \cdot N_t \cdot \Omega_{Ekin}\, \epsilon_f}$$

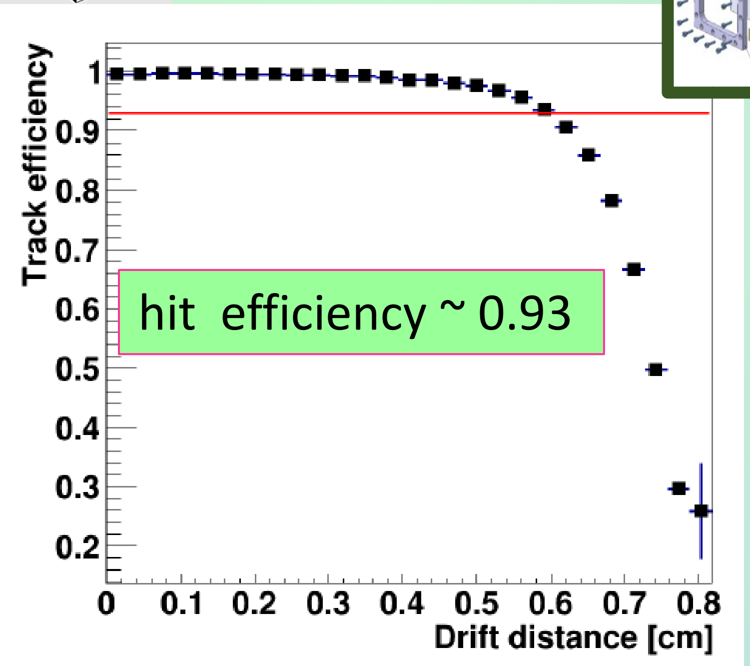
- Count n° of particles
- Initial Trigger
- Time start
- Discard SC fragmentation
- Extrapolate vertex direction
- Evaluate beam direction

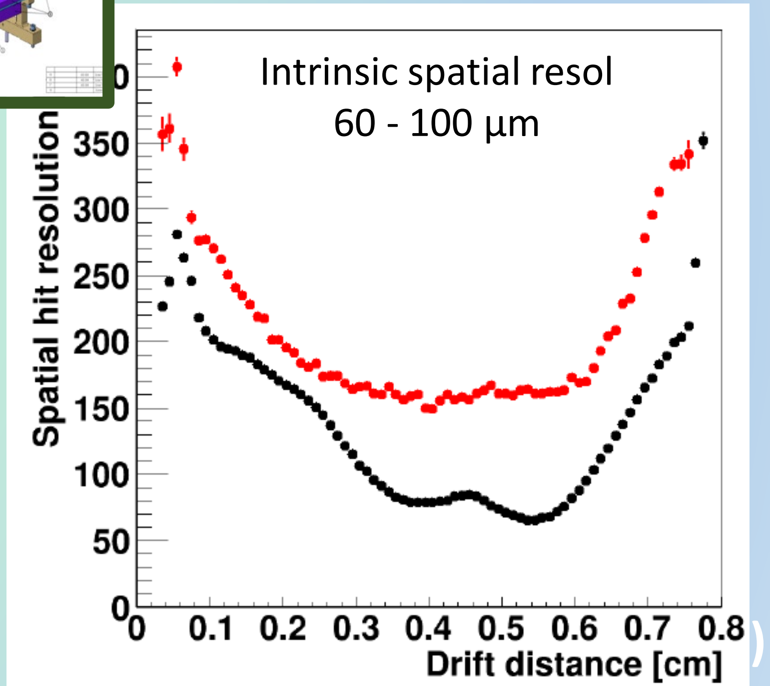












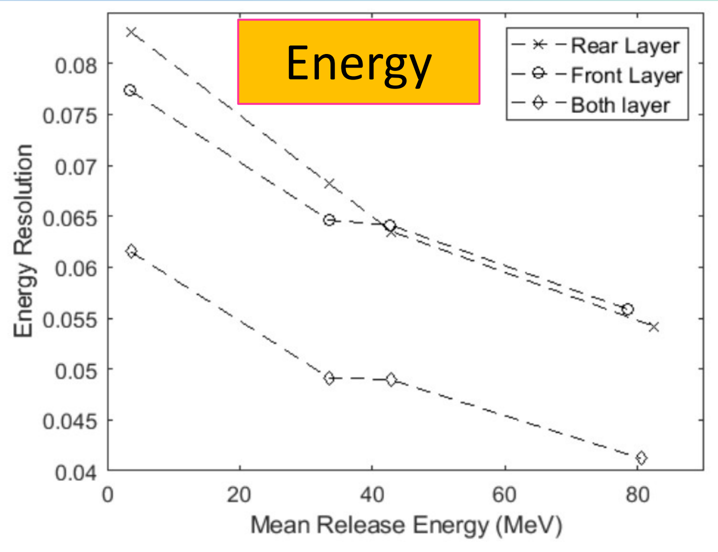
Angular resolution:
- 1.6 mrad p@228 MeV/u
- 2.1 mrad p @ 80 MeV/u

Spatial resolution:
- 150 ± 10 µm p@228 MeV/u
- 300 ± 10 µm p@ 80 MeV/u

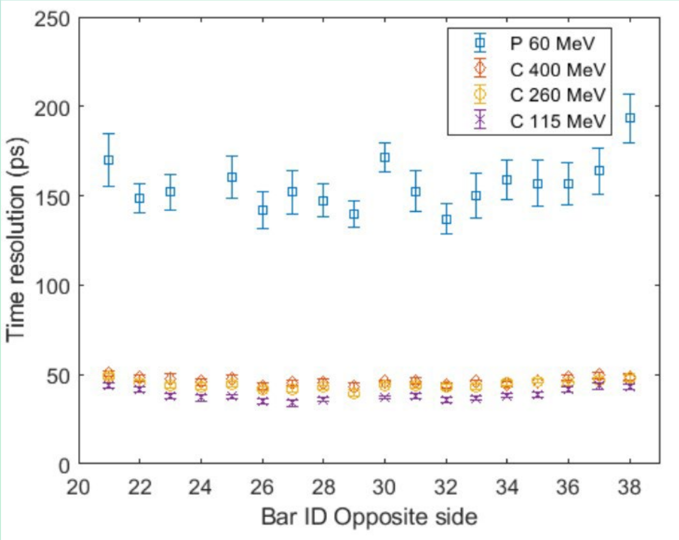
Tof Wall

Detector is complete

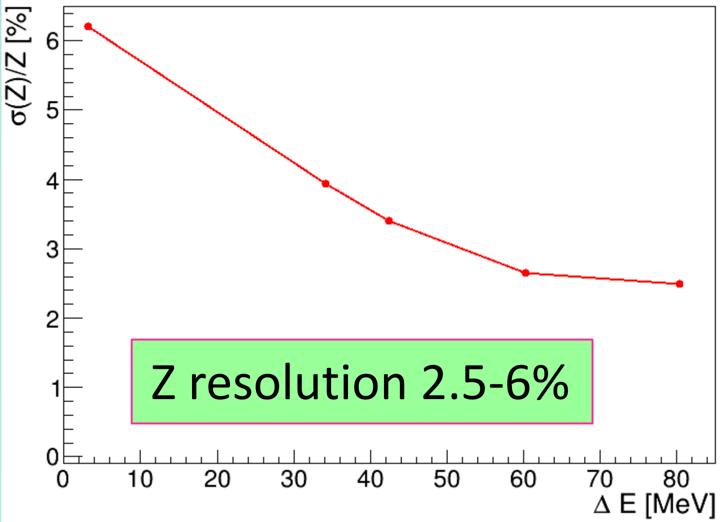
Data taking at CNAO-GSI (march-april 2019) and CNAO (dec 2019)

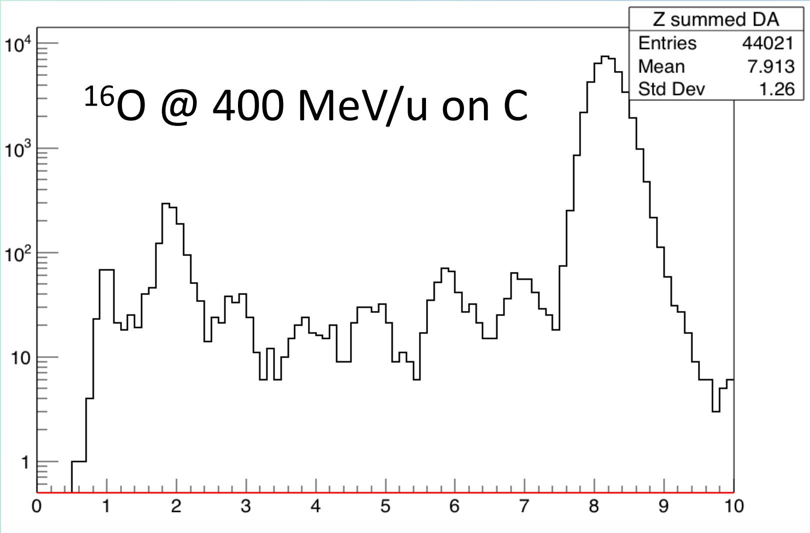


Tof



CNAO + GSI



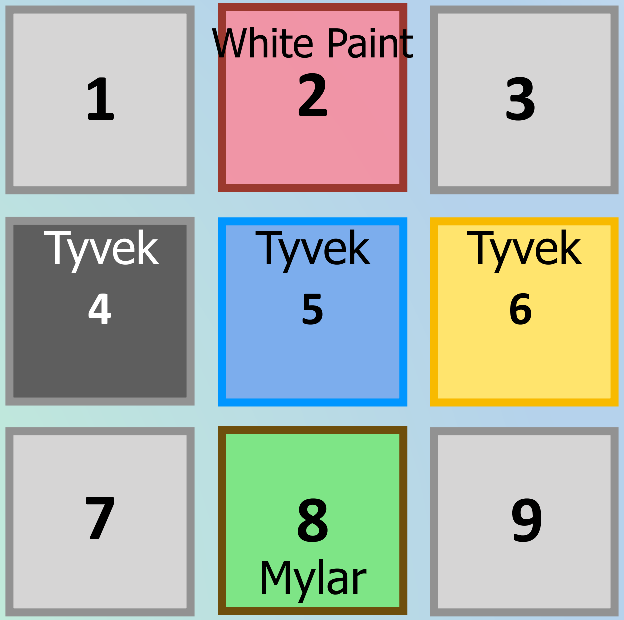


Resolution:

- Energy: 4-6 %
- Time SCN: 40-50 ps for ^{12}C and 150-190 ps for p
- Tof (SC+TofW): 50-75 ps for ^{12}C – ^{16}O
  250 ps for p
- Position: 7 mm for 12C and 15 mm for p

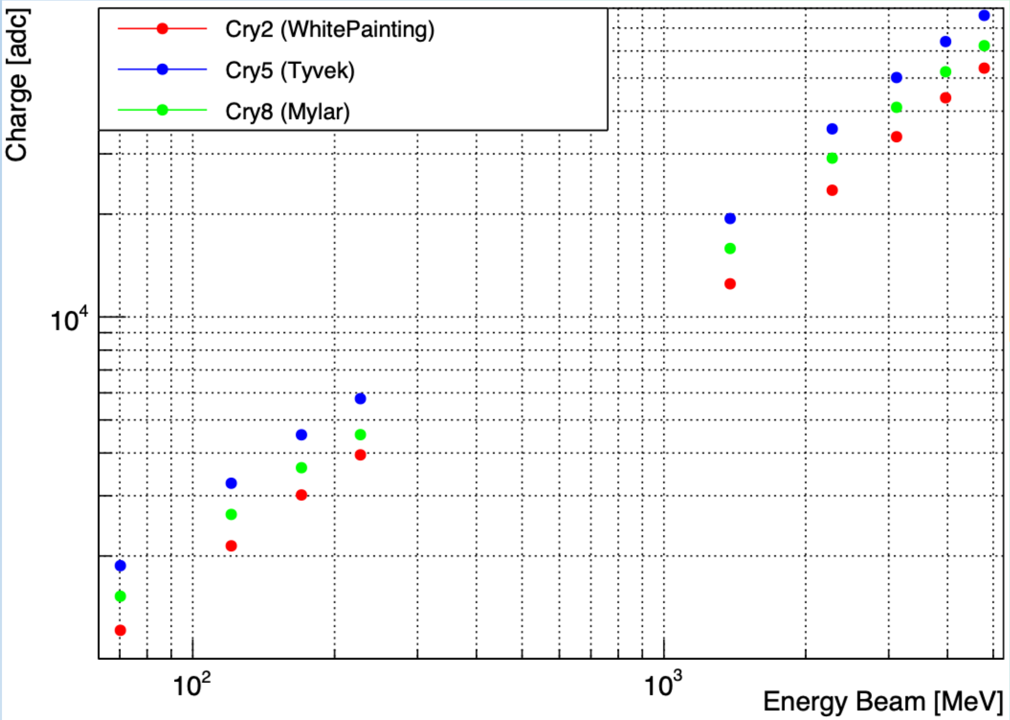
Paper circulates inside collaboration

Calorimeter, 1



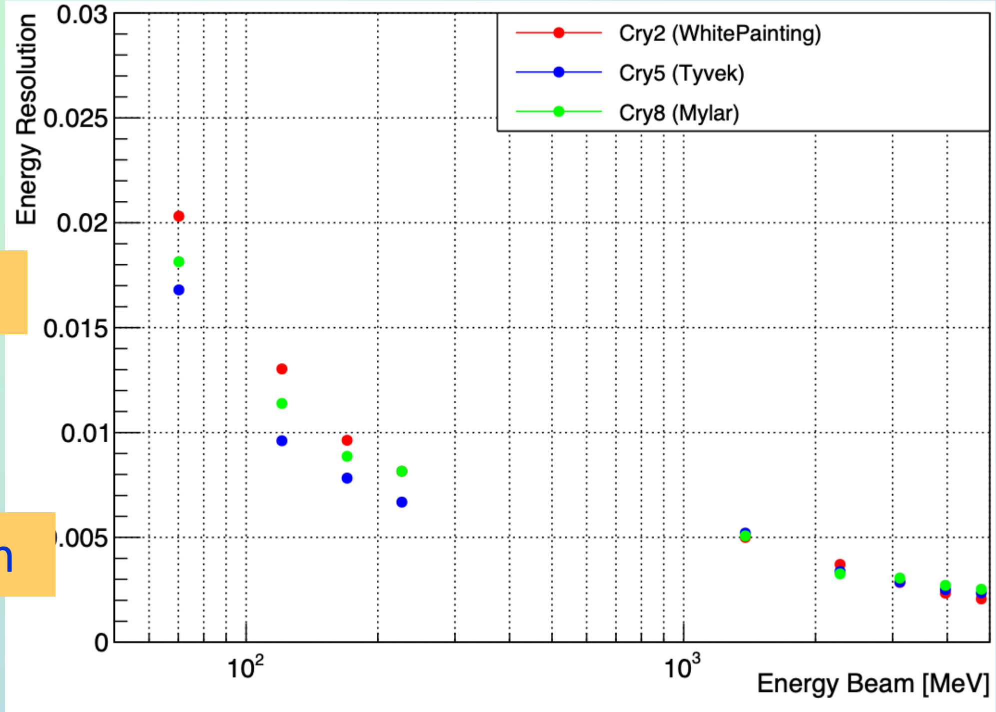
TEST BEAM OVERVIEW:

- 9 crystals
- 15 µm SiPM arrays
- 3 reflective wrappings: White Painting, Mylar and Tyvek
- Proton Energy: 70, 120, 170, 227 MeV
- Carbon Energy: 115, 190, 260, 330, 399 MeV/A
- Temperature part:
  - For each energy 4 different temperature



Tyvek reflects more light

Better Energy Resolution



Performances: charge Z reconstruction

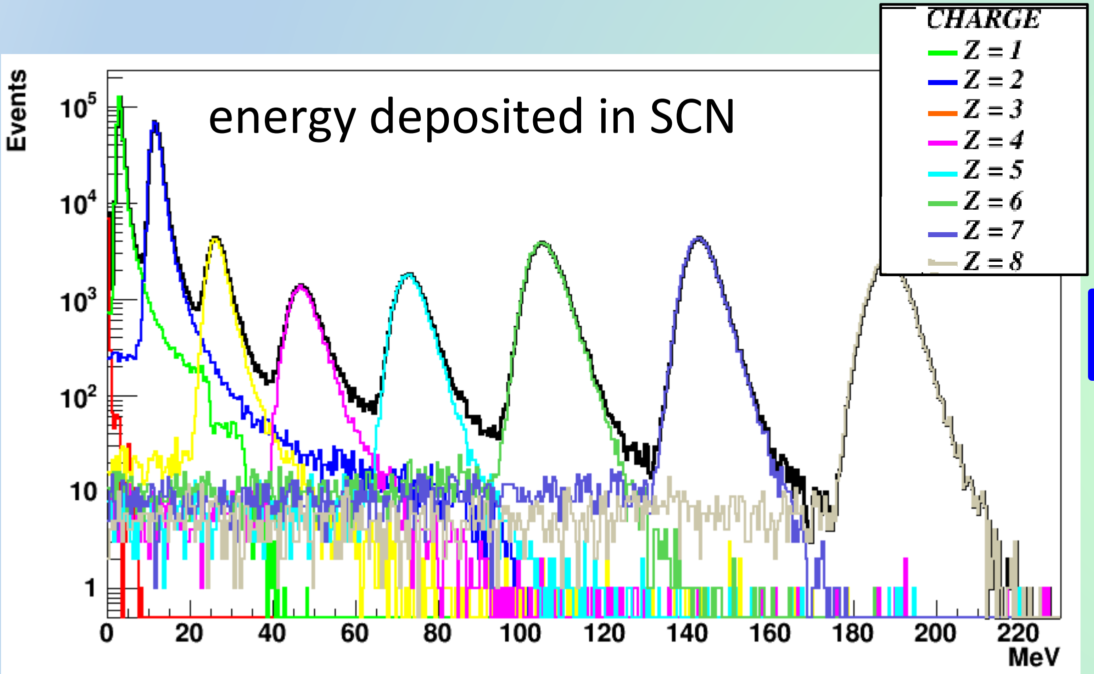
^{16}O (200 MeV/u)→ C_2H_4

Fragment univocally defined by Z and A

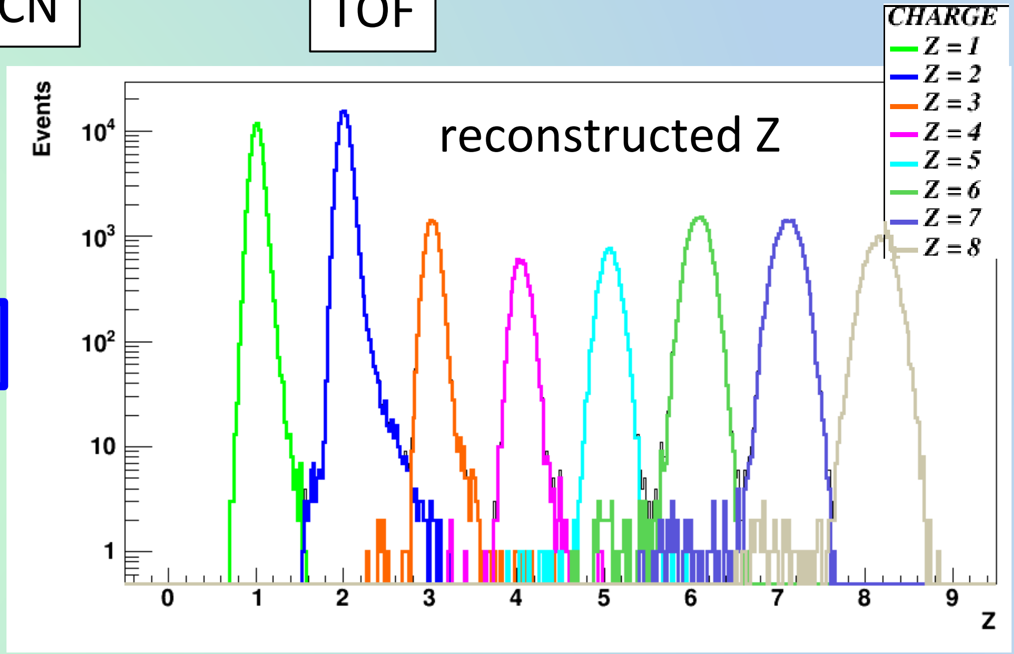
$$-\frac{dE}{dx} = \frac{\rho \cdot Z}{A} \frac{4\pi N_A m_e c^2}{M_U} \left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2 \frac{z^2}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

SCN

TOF



Fluka simulation



^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B	^{12}C	^{14}N	^{16}O
1	2	3	4	5	6	7	8
1.01±0.09	2.01±0.06	3.03±0.08	4.05±0.09	5.06±0.10	6.09±0.12	7.11±0.14	8.15±0.15

Z Resolution : **9%** **3%** **2.0%**

wrong charge assignment < 1%

FOOT Performances: Number of mass reconstruction

- Reconstruction

$$A_1 = \frac{m}{U} = \frac{p}{U\,\beta\,\gamma}$$

TRACKER, TOF

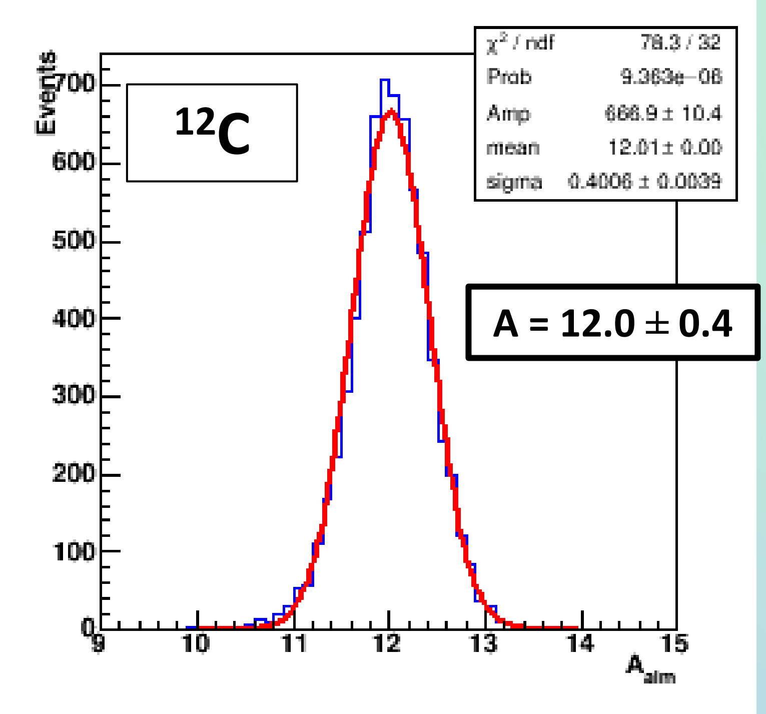
$$A_2 = \frac{m}{U} = \frac{E_{kin}}{U(\gamma - 1)}$$

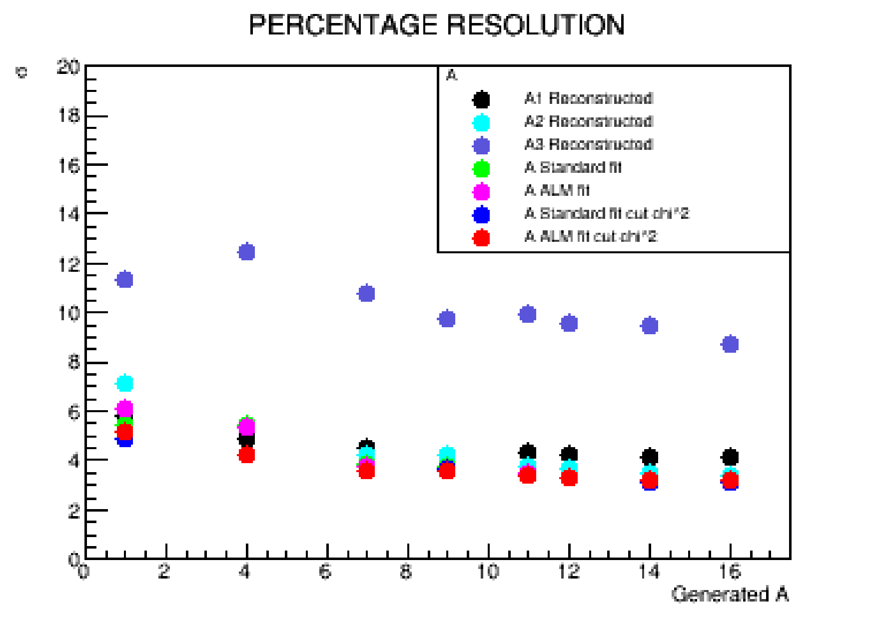
CALO, TOF

$$A_3 = \frac{m}{U} = \frac{p^2 - {E_{kin}}^2}{2E_{kin}}$$

TRACKER, CALO

- Fit Methods: **STANDARD χ^2** and **ALM**





^{16}O (200 MeV/u)→ C_2H_4

Data simulated by Fluka

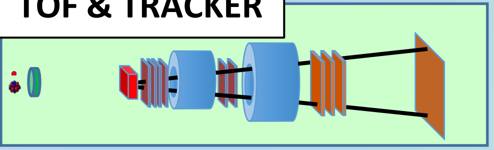
Resolution for heavy fragments ~ 3-4%

Performances: Number of mass A (ex of ^{12}C)

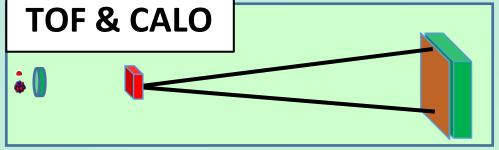
Fluka simul ^{16}O (200 MeV/u)→ C_2H_4

REDUNDANT Detector → different ways to determine A

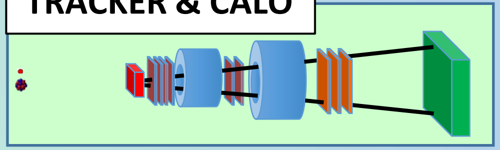
TOF & TRACKER



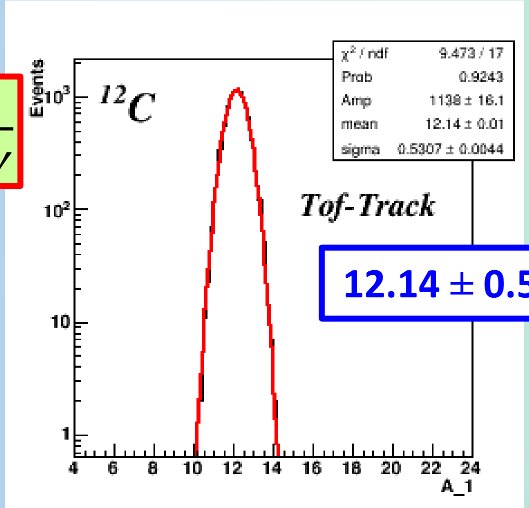
TOF & CALO



TRACKER & CALO

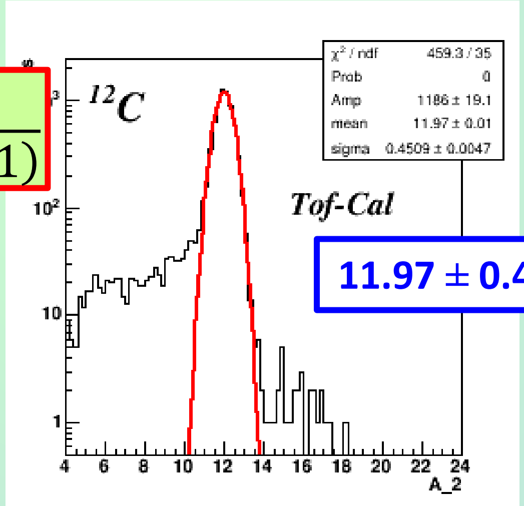


$$A_1 = \frac{p}{U\,\beta\,\gamma}$$



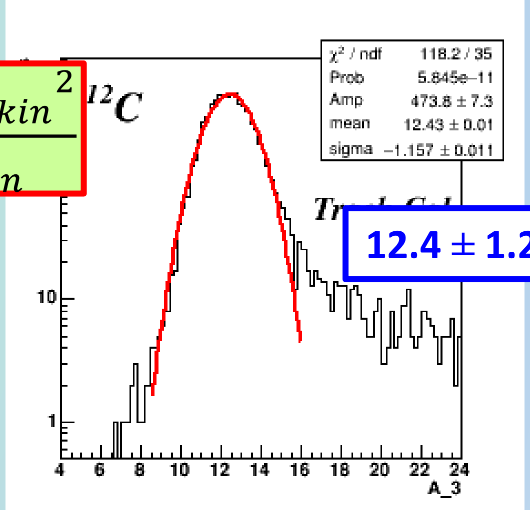
12.14 ± 0.53

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



11.97 ± 0.45

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



12.4 ± 1.2

A Reconstruction and fit

TOF (β) – TRACKER (p)

$$A_1 = \frac{m}{U} = \frac{p}{U\,\beta\,\gamma}$$

TOF (β)– CALO (E_{kin})

$$A_2 = \frac{m}{U} = \frac{E_{kin}}{U(\gamma - 1)}$$

TRACKER (p) – CALO (E_{kin})

$$A_3 = \frac{m}{U} = \frac{p^2 - {E_{kin}}^2}{2E_{kin}}$$

- **Standard χ^2 Fit**
  - Taking into account the correlation between A_1, A_2 and A_3

$$f = \left(\frac{(tof_{reco} - t)}{\sigma tof_{reco}}\right)^2 + \left(\frac{(p_{reco} - p)}{\sigma p_{reco}}\right)^2 + \left(\frac{(E_{kin,reco} - E_{kin})}{\sigma E_{kin,reco}}\right)^2 + (A_1 - A \quad A_2 - A \quad A_3 - A)\begin{pmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{pmatrix}\begin{pmatrix} A_1 - A \\ A_2 - A \\ A_3 - A \end{pmatrix}$$

$$C = (A \cdot A^T)^{-1} \qquad A = \begin{pmatrix} \frac{\partial A_1}{\partial t}dt & \frac{\partial A_1}{\partial p}dp & 0 \\ \frac{\partial A_2}{\partial t}dt & 0 & \frac{\partial A_2}{\partial E_{kin}}dE_{kin} \\ 0 & \frac{\partial A_3}{\partial p}dp & \frac{\partial A_3}{\partial E_{kin}}dE_{kin} \end{pmatrix}$$

- **Augmented LagrangianFit (ALM)**

$$\tilde{\mathcal{L}}(\vec{x}\,;\lambda,\,\mu) \equiv f(\vec{x}) - \sum_a \lambda_a c_a(\vec{x}) + \frac{1}{2\mu}\sum_a c_a^2(\vec{x}).$$

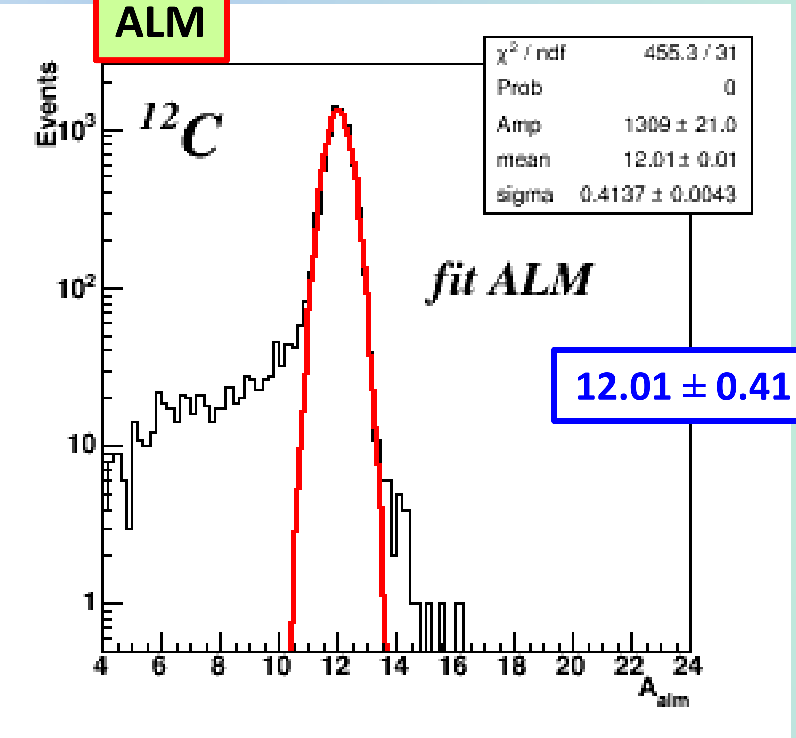
Performances: Number of mass A (ex of ^{12}C)

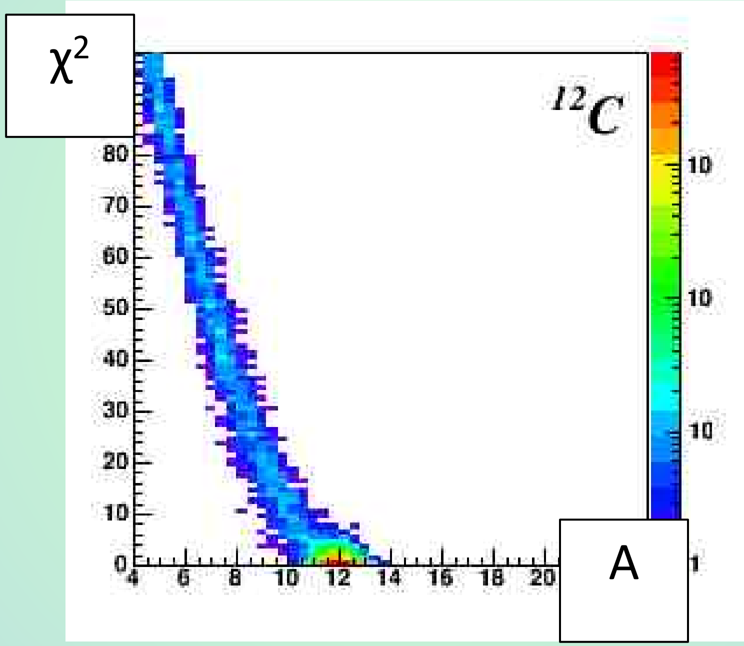
Fluka simul ^{16}O (200 MeV/u)→ C_2H_4

FIT Methods:

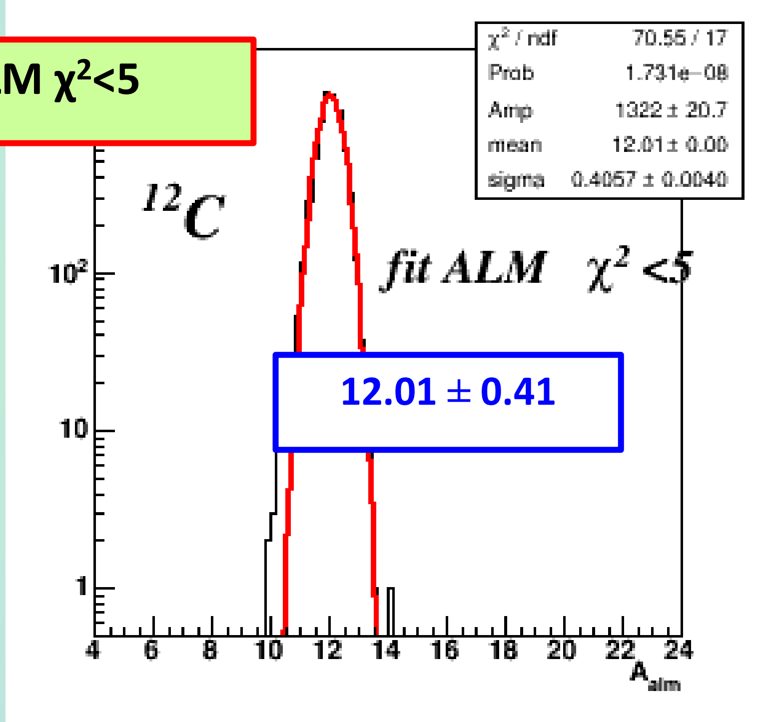
- **Standard χ^2**
- **Augmented Lagrangian (ALM)**

ALM





ALM χ^2<5

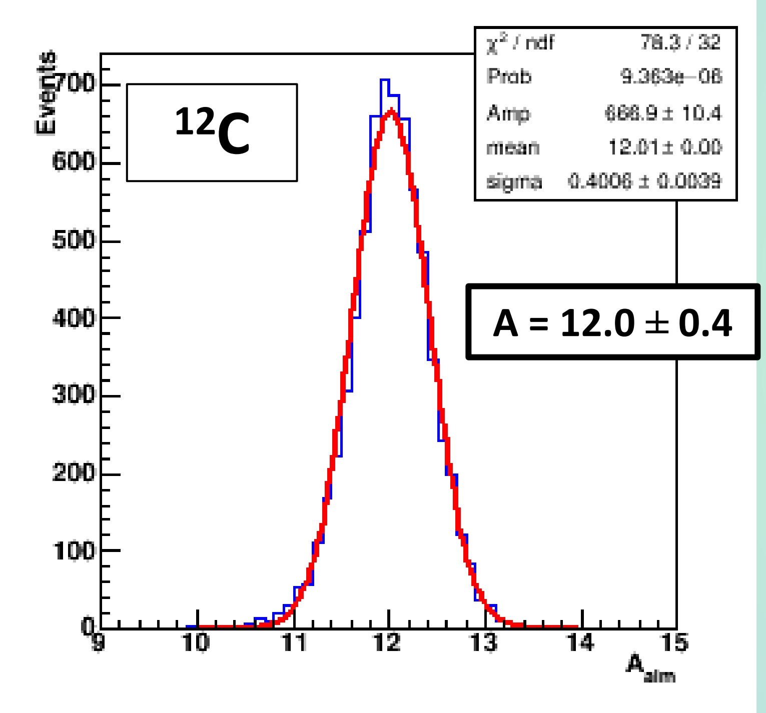


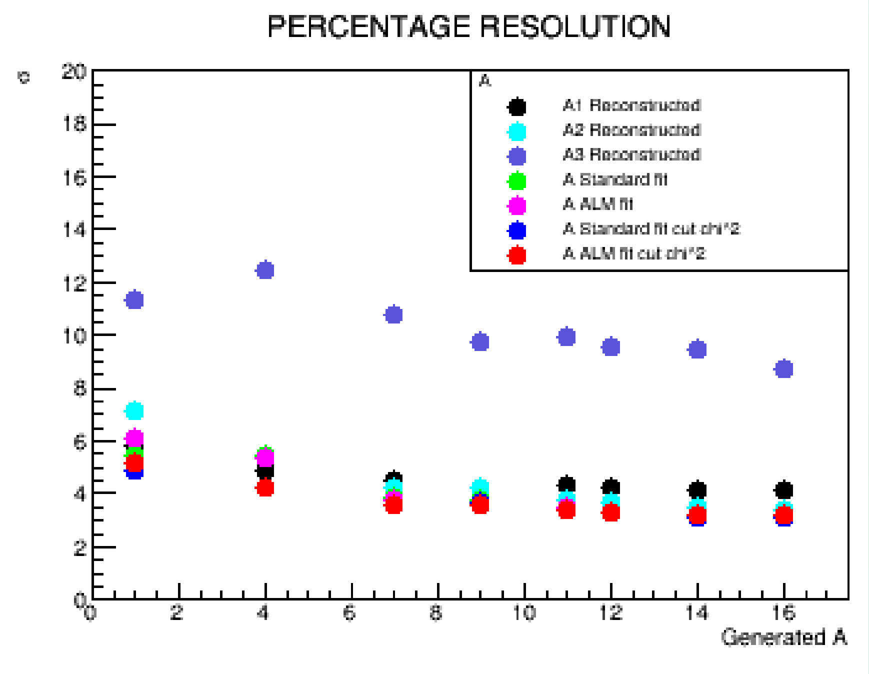
Fit cut the wrong reconstructed fragments

FOOT Performances: Number of mass reconstruction

^{16}O (200 MeV/u)→ C_2H_4

Simulation by Fluka

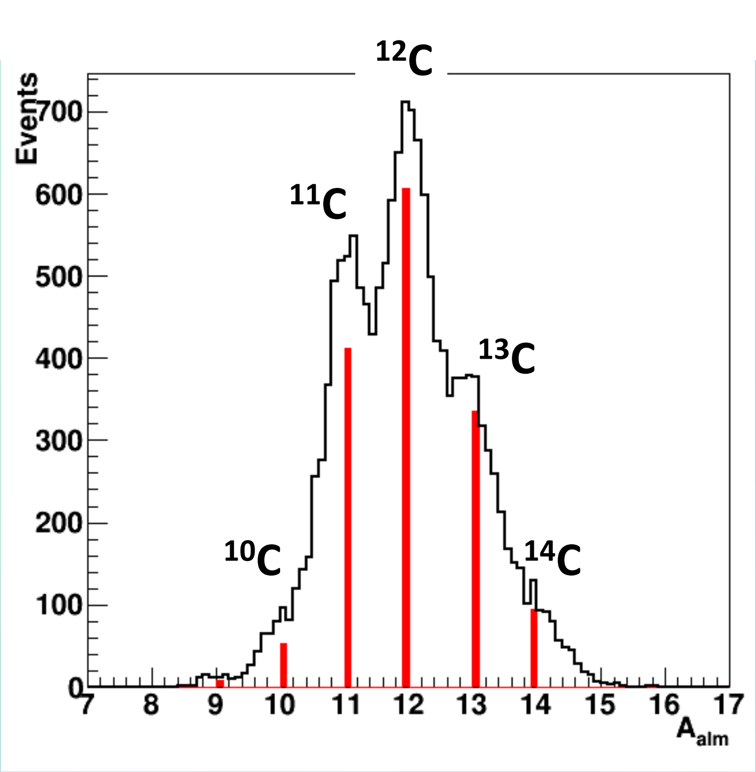




Resolution for heavy fragments ~ 3-4%

Conservative Resolutions

- **$\Delta p/p$ → 4%**
- **$\Delta E_{kin}/E_{kin}$ → 1.5%**
- **Δtof → 70 – 140 ps**
- **$\Delta(dE)/dE$ → 3 -10%**



Possibility to disentangle isotopes

FOOT Performances: Isotopes separation (example of C)

Data simulated by Fluka

Conservative Resolutions

- **$\Delta p/p$ → 4%**
- **$\Delta E_{kin}/E_{kin}$ → 1.5%**
- **Δtof → 70 -140 ps**
- **$\Delta(dE)/dE$ → 3-10 %**

^{16}O (200 MeV/u) → C_2H_4

Resolutions from Test Beam

- **$\Delta p/p$ → 4%**
- **$\Delta E_{kin}/E_{kin}$ → 1.0%**
- **Δtof → 50 – 100 ps**
- **$\Delta(dE)/dE$ → 3-10%**