IWM-EC 2018
22^{nd} - 25^{th} May 2018
Catania, Italy
International Workshop on Multi facets of Eos and Clustering

Istituto Nazionale di Fisica Nucleare

The FOOT (Fragmentation Of Target) experiment

International Workshop on Multi facets of Eos and Clustering

22 May 2018

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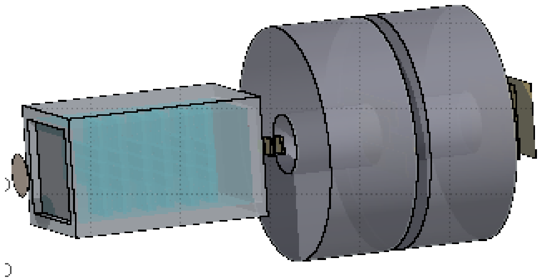
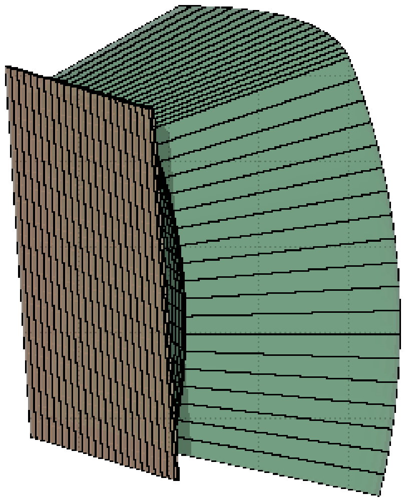
on behalf of the FOOT collaboration

Outline

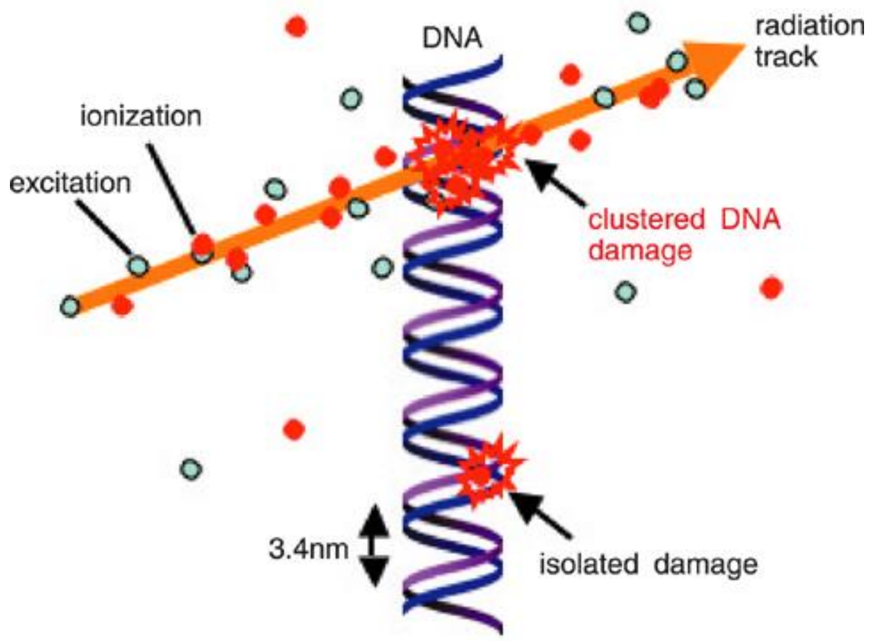
- ➢ Radiotherapy and particle therapy
- ➢ Nuclear fragmentation in hadrontherapy
- ➢ The FOOT experiment goals
- ➢ Experimental strategies
- ➢ Experimental setups
  - ❑ Emulsion setup
  - ❑ Electronic setup
- ➢ Fragment identification
- ➢ Test beams
- ➢ Conclusions





Cancer treatment & Radiotherapy

Radiotherapy employs different kinds of radiation to destroy cancer cells, by damaging their DNA and thus invalidating their duplicating capability.



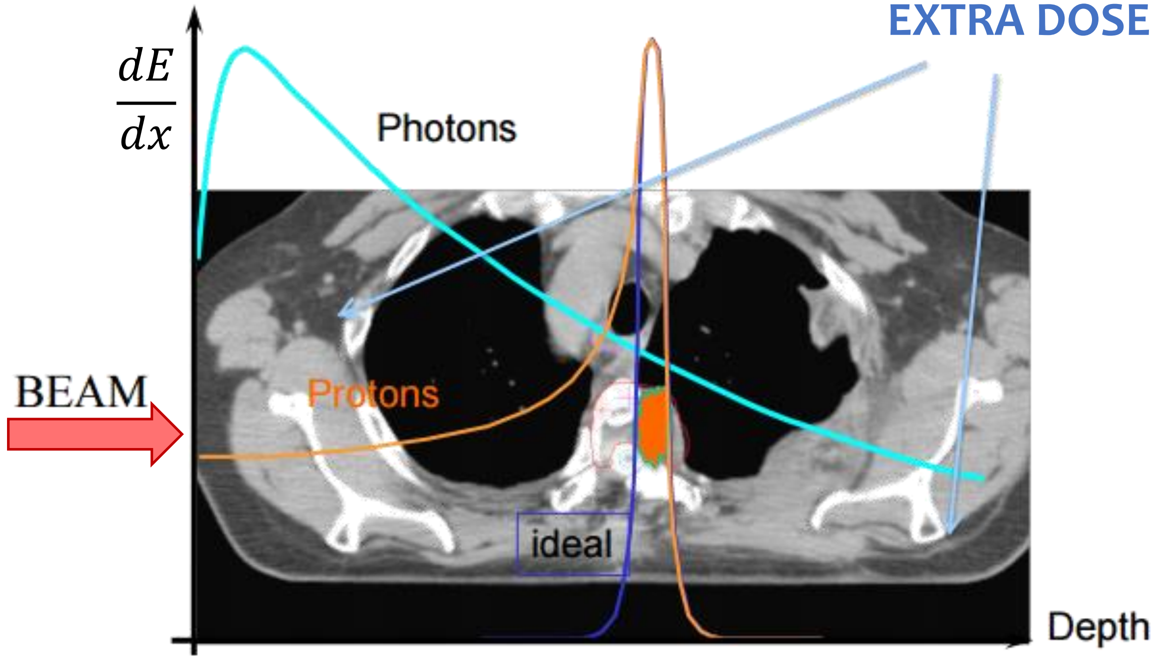
Conventional radiotherapy

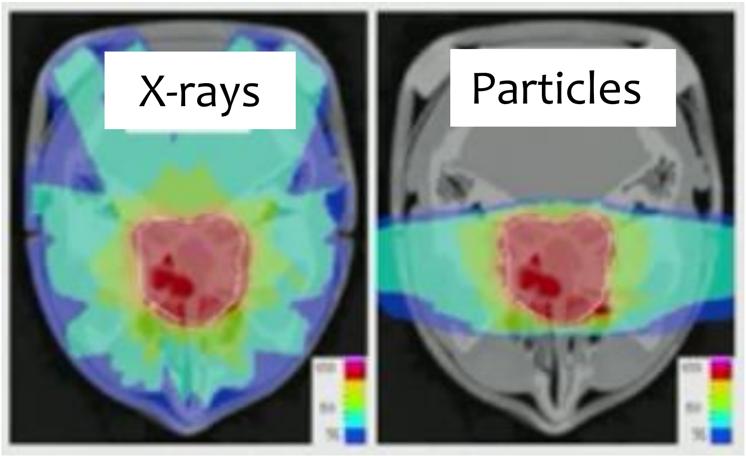
- Mainly **photons** (linear accelerator ~10 MV) and sometimes electrons
- Several beams from different directions are superimposed
- Not so expensive, well known and reliable

Particle therapy or hadrontherapy

- Relatively new and expensive technique
- Mainly **protons** and **carbon ions** (but also helium and oxygen)

WHY PARTICLE THERAPY?





Better **tumor local control** because of:

Spatial selectivity
- higher conformity of dose to the target volume (**Bragg Peak**)
- smaller lateral scattering

→ better sparing of normal tissues

Biological effectiveness
- greater biological effectiveness (increases with the charge)

→ radioresistant tumors

But:

More complex and expensive instrumentation is needed

Sensitive to target motion

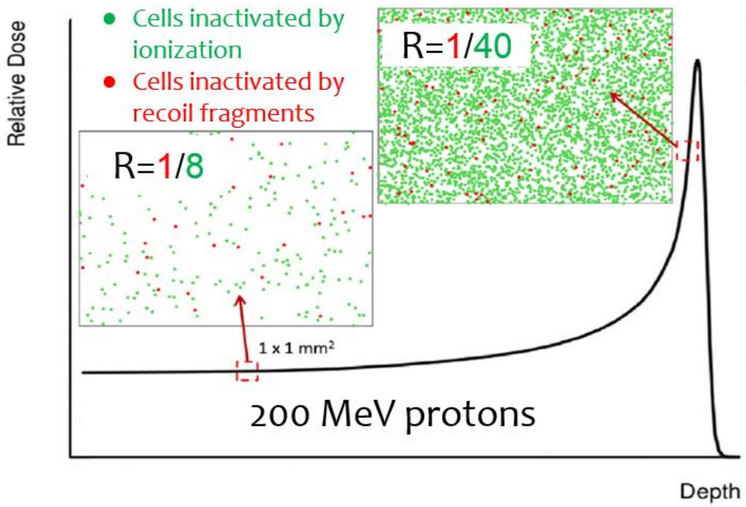
The role of nuclear fragmentation

Proton Therapy

- Target fragmentation
- Low energy fragments: **small range** (~tens of μm)
- Most abundant fragments expected: **He, C, Be, O, N**
- No experimental data for heavy (Z≥3) fragments
- High Z fragments: **high cell killing effectiveness** (∝ dE/dx → increases with the charge)
- Increase of **biological damage** (~10%) in the entrance channel (Grun 2013)
- Higher production cross section in the **entrance channel** (increases with beam energy)

Ion Therapy

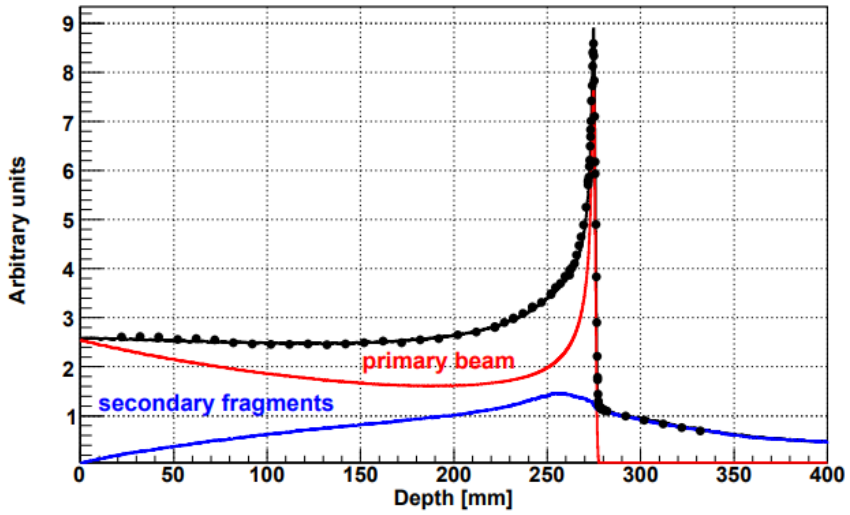
- Both projectile and target nuclei fragmentation
- Same velocity but lower mass wrt primary particles: **long range**
- Unwanted **tail** beyond the Bragg peak
- **Mixed particle field** of different cell killing effectiveness: considered in ^{12}C treatment, but still scarce validation data. Effect to be studied with new beams: ^{4}He, ^{16}O



Tommasino and Durante, *Cancers* (2015)

MC nuclear models not enough reliable.

Improve the knowledge of the **p→patient** (**p → H,C,O**) interaction at therapeutic energies (100-200 MeV) is **needed to implement sound radiobiological models.**



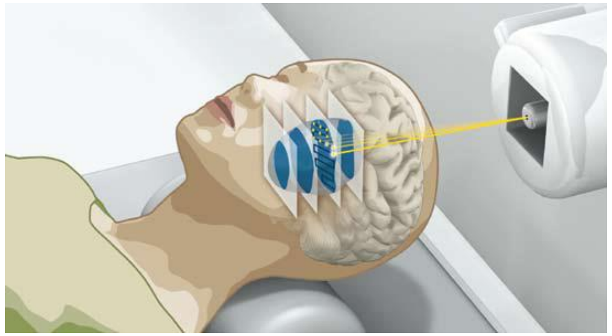
A. Mairani, PhD Thesis 2008

FOOT GOALS

- Fragments production cross sections (at level of 5%)
- Fragments energy spectra dσ/dE (energy resolution ~1 MeV/u)
- Charge ID (at the level of 2-3%)
- Isotopic ID (at the level of 5%)

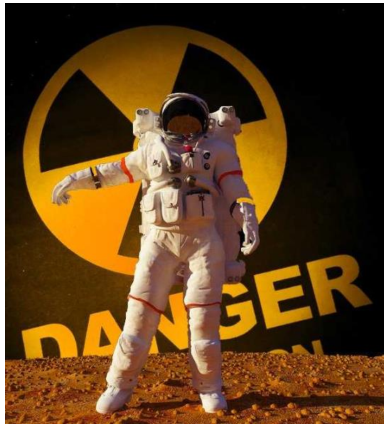
Particle therapy

- Cross section for therapeutic beams at therapeutic energies:
  - 200 MeV for protons
  - 250 MeV/u for He ions
  - 350 MeV/u for C ions
  - 400 meV/u for O ions
- Tissue-like target (H, C, O)

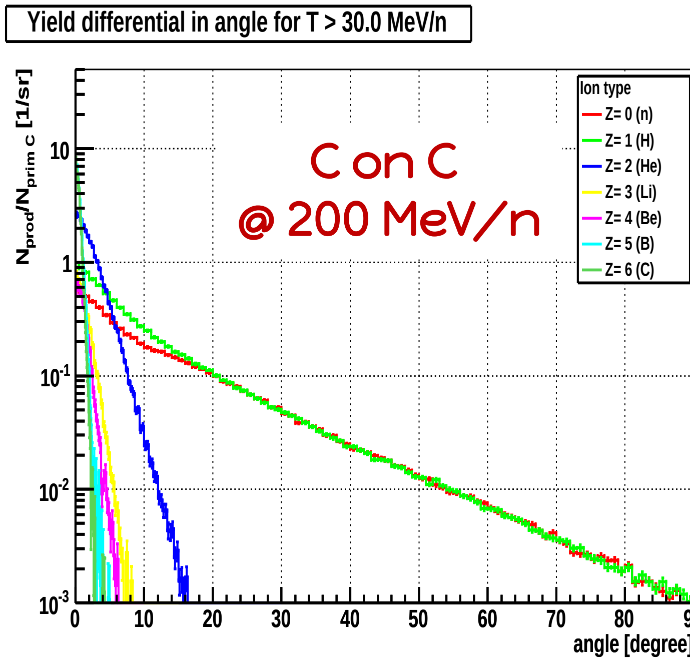


Space radioprotection

- Cross section for high energy:
  - 700 MeV/u for He ions
  - 700 MeV/u for C ions
  - 700 meV/u for O ions
- H, C, O targets



FOOT: STUDY OF TARGET FRAGMENTATION



Estimation of the angular distribution of target fragments, obtained with the FLUKA MC code.

Heavy (Z>2) fragments produced at small angle (<10°).
Light fragments produced in a broader angle.

Two experimental setups

200 MeV/u p on Oxygen

No experimental data

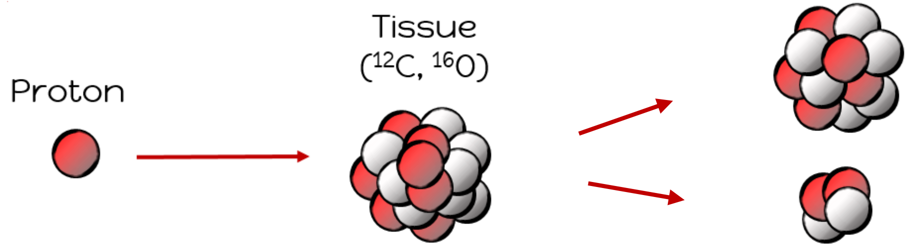
Fragment	E (MeV)	LET (keV/μm)	Range (μm)
^{15}O	1.0	983	2.3
^{15}N	1.0	925	2.5
^{14}N	2.0	1137	3.6
^{13}C	3.0	951	5.4
^{12}C	3.8	912	6.2
^{11}C	4.6	878	7.0
^{10}B	5.4	643	9.9
^{8}Be	6.4	400	15.7
^{6}Li	6.8	215	26.7
^{4}He	6.0	77	48.5
^{3}He	4.7	89	38.8
^{2}H	2.5	14	68.9

Tommasino and Durante, *Cancers* (2015)

Estimation of the energy and range of target fragments obtained with an analytical model

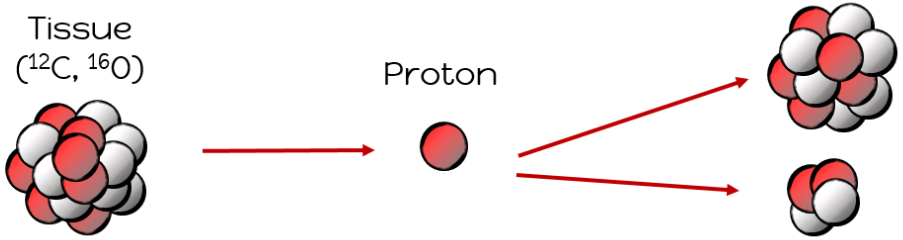
Target fragmentation: experimental strategies

DIRECT KINEMATICS ?

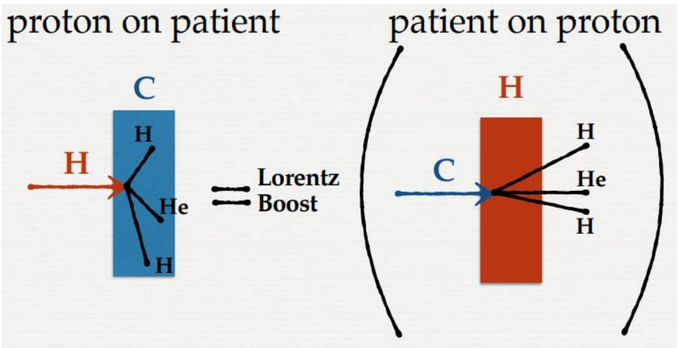


Target fragments: low energy and short range

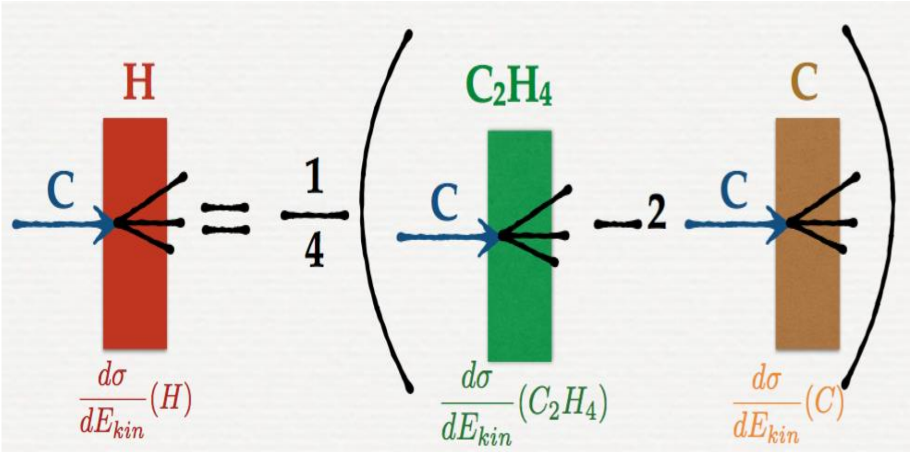
INVERSE KINEMATICS



Beam fragments: higher energy and longer range



By applying the **Lorentz transformation** it is possible to switch from the laboratory frame to the «patient frame»



TARGET CHOICE

Hydrogen gas target:

- Low interaction probability
- Not allowed in therapy facilities

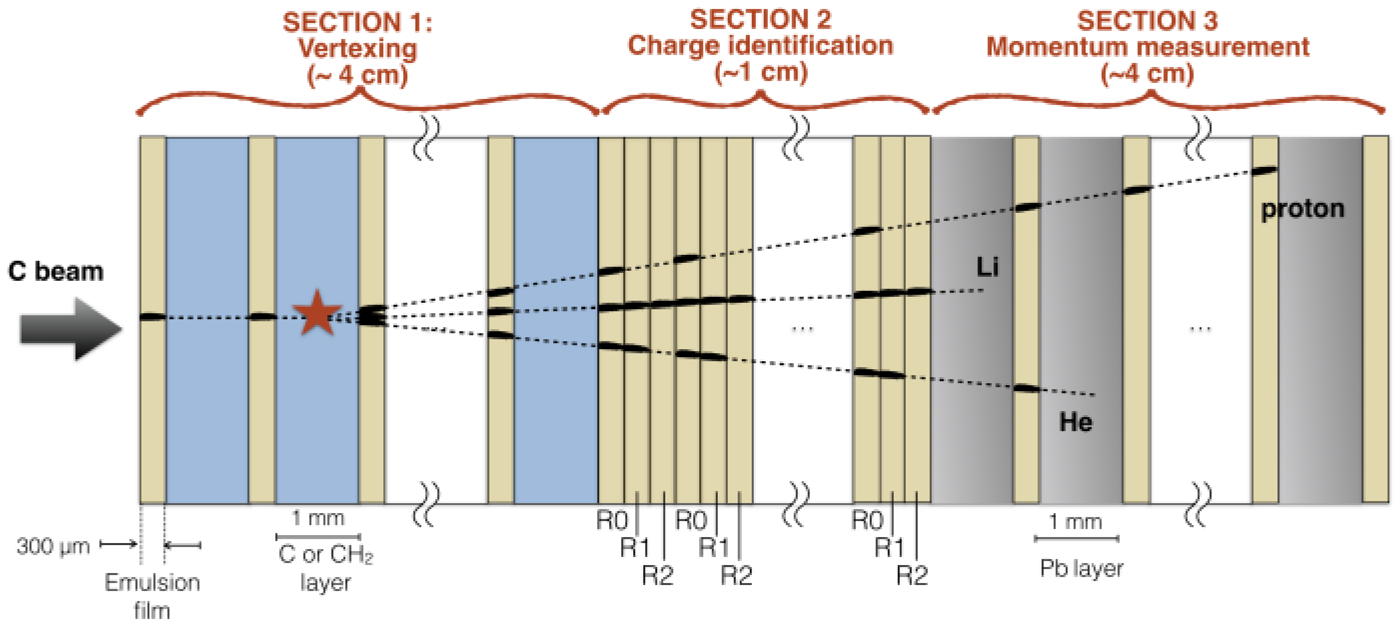
Hydrogenated target $(C_2H_4)_n$

+

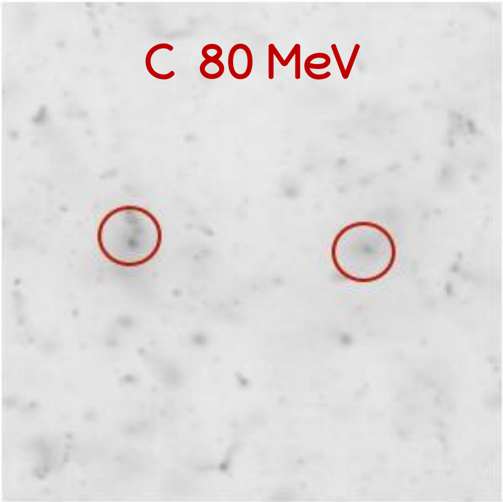
Graphite target (C)

Fragmentation cross sections on H can be measured by **subtracting the cross sections of** $(C_2H_4)_n$ and C

The FOOT experiment: emulsion setup



- Low Z (**Z<3**) fragments emitted at **large angles** (up to 75° wrt the beam direction)
- The developed emulsions are scanned by an automated microscope
- Images are analyzed by a dedicated software to recognize clusters of aligned dark pixels (i.e. tracks produced by ionizing particles)

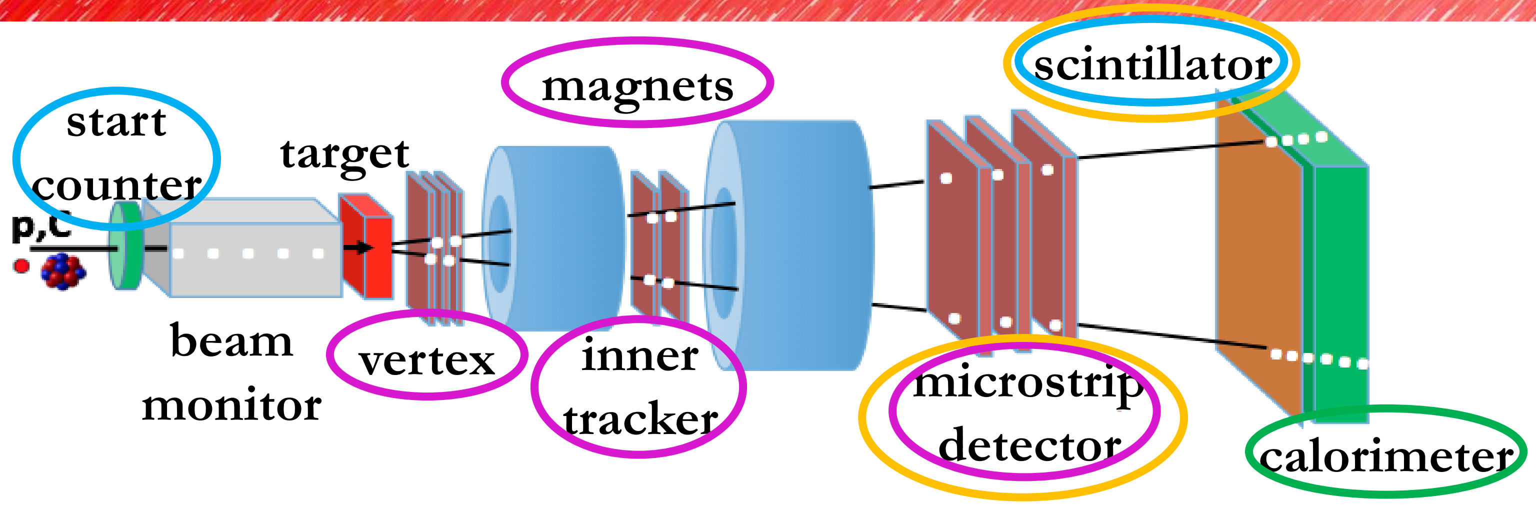


Section 1:
Target plates (C/C_2H_4) interleaved with emulsion films
- Vertex detector

Section 2:
Emulsion films only
- Charge identification for low Z fragments (H, He, Li)

Section 3:
Lead planes interleaved with emulsion films
- Momentum measurement and isotopic ID

The FOOT experiment: electronic setup



Minumum required performances

- 10° polar angle (optimized for Z>2 fragments)
- $\sigma(TOF)$~100 ps
- $\sigma(p)/p$ ~5%
- $\sigma(E_k)/E_k$ ~2%
- $\sigma(\Delta E)/\Delta E$ ~2%

Pre-target region

Start counter

- Plastic scintillator 250 µm
- ➢ Counts primaries
- ➢ Starts ToF measurement

Beam monitor:

- $Ar\text{-}CO_2$ drift chamber
- 3 cells x 12 XY planes
- ➢ Detects pre-target fragmentation
- ➢ Measures primaries position and direction

Magnetic spectrometer

Vertex

- 4 layers of silicon pixel detectors 50µm
- ➢ Reconstructs vertex position

Inner tracker

- 2 layers of silicon pixel detectors 50 µm
- ➢ Tracking in magnetic field

Microstrip detector

- 3 layers of silicon microstrips 150 µm
- ➢ Tracking in magnetic field

Magnets

- 2 magnets in Hallback configuration
- Max field 0,8 T

Calorimeter region

Scintillator

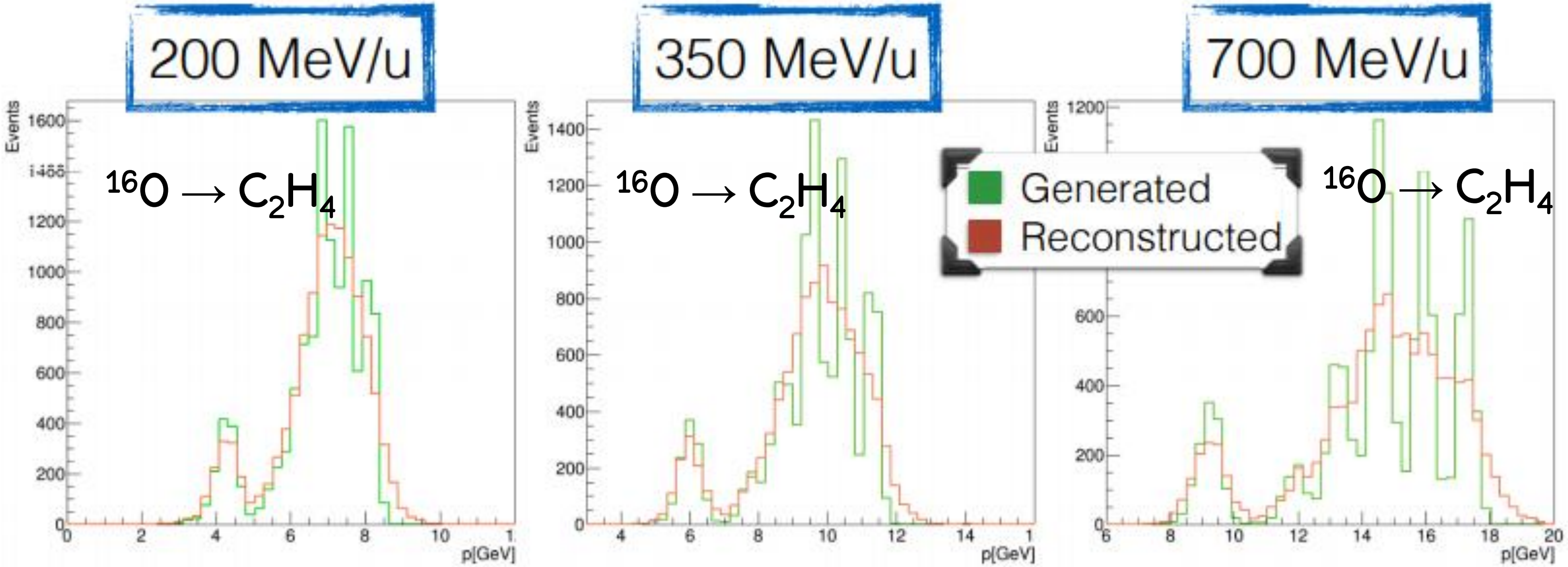
- ➢ 2 layers of 3 mm thick plastic scintillator bars orthogonally oriented
- ➢ Measures ToF
- ➢ Measures energy release

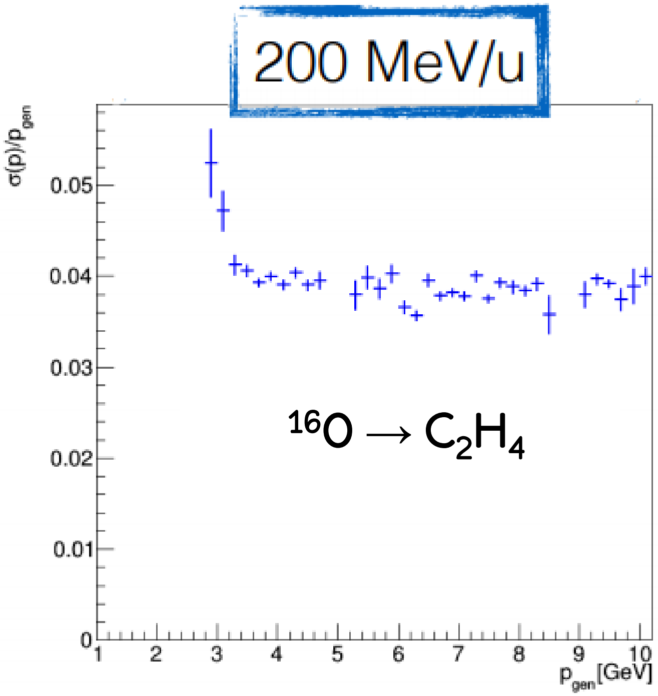
Calorimeter

- ➢ 360 BGO crystals 24 cm long
- ➢ Measures kinetic energy

Momentum reconstruction

- Track information from the magnetic spectrometer
- Recursive algorithm that predicts the trajectory from detector layer to layer, also considering multiple scattering and magnetic field → kalman filter → Genfit
- **High filter reconstruction efficiency**
- At present no pattern recognition → kalman filter is fed with pre-selected hits corresponding to the same track

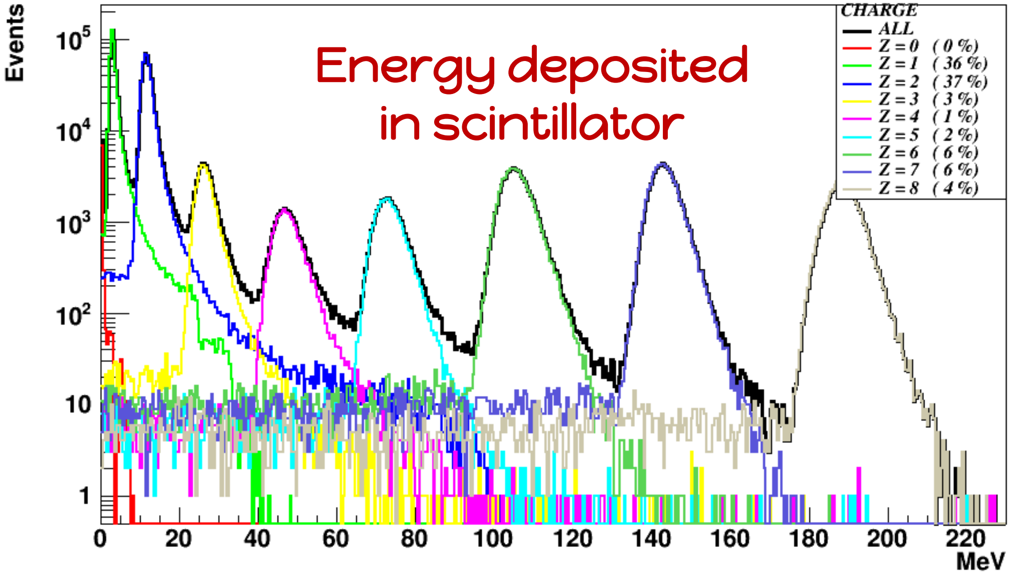


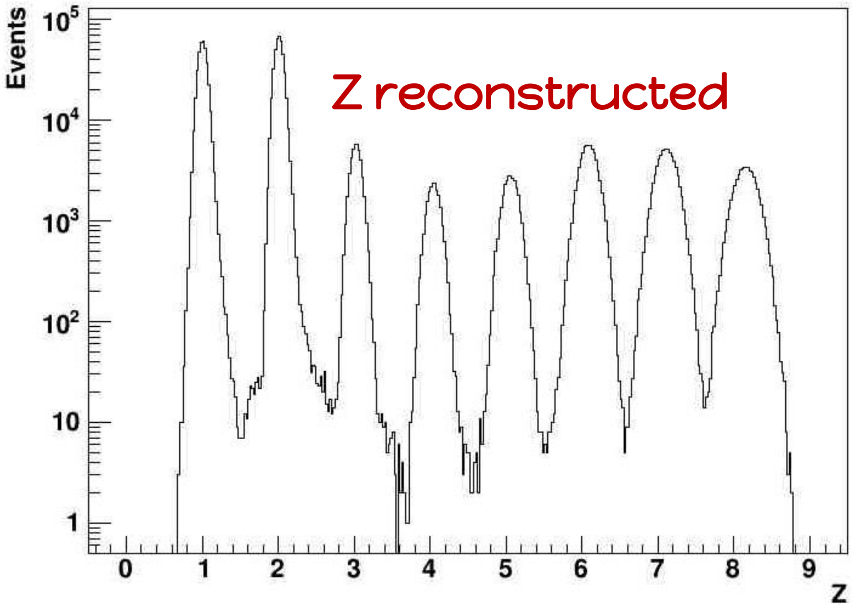


Charge ID

The fragment charge can be retrieved from the energy deposited in the scintillator.
From the **Bethe-Bloch** equation:

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





^{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 ± 0.05	2.02 ± 0.06	3.03 ± 0.08	4.05 ± 0.10	5.07 ± 0.11	6.09 ± 0.14	7.11 ± 0.16	8.15 ± 0.18

Z resolution range:
2% (^{16}O) - **5%** (^{1}H)

Mass ID

Mass can be calculated by combining the reconstructed quantities:

- Momentum (magnetic spectrometer)
- ToF (scintillator)
- Kinetic energy (calorimeter)

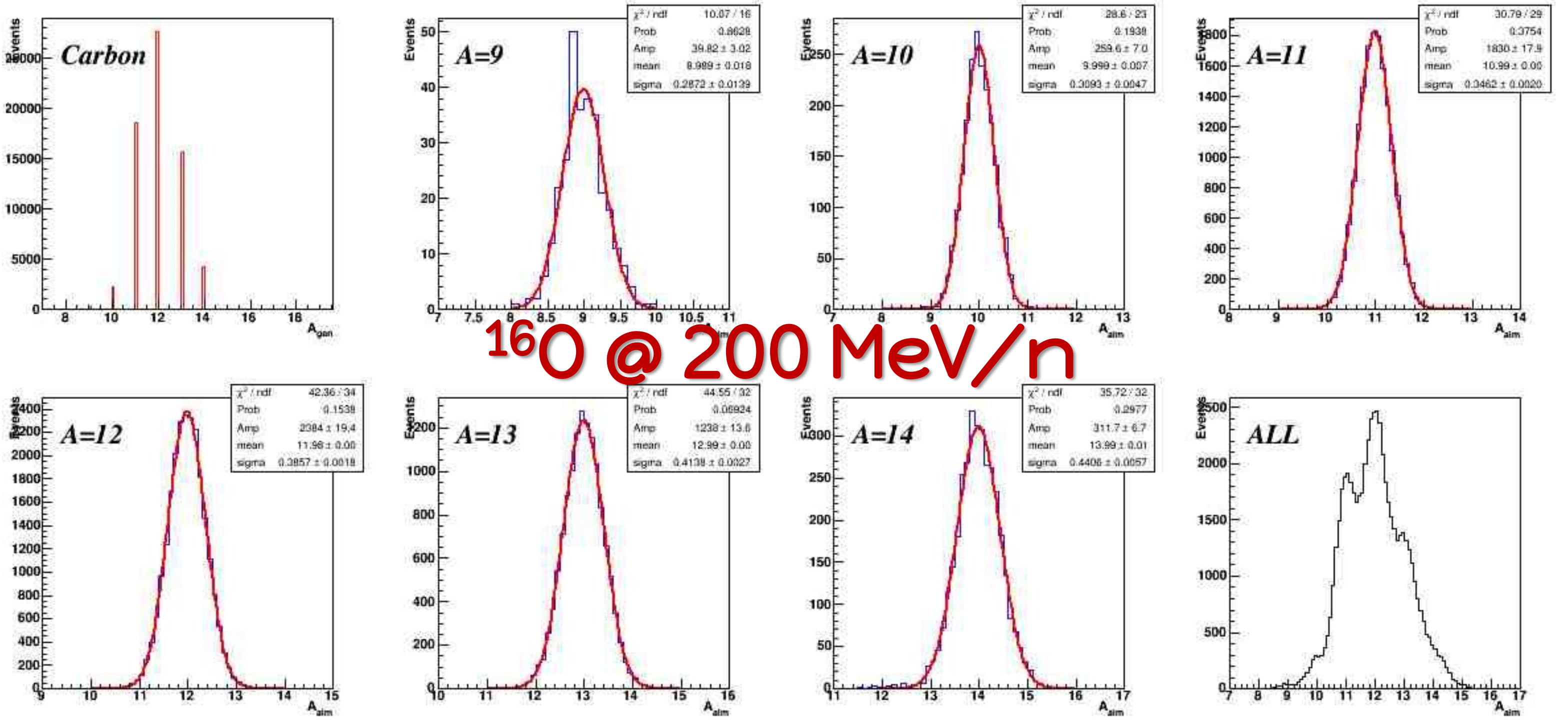
$$A_1 = \frac{p}{Uc\beta\gamma} \qquad A_2 = \frac{E_k}{Uc^2(\gamma - 1)} \qquad A_3 = \frac{p^2c^2 - {E_k}^2}{2Uc^2E_k}$$

Fit methods used:

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

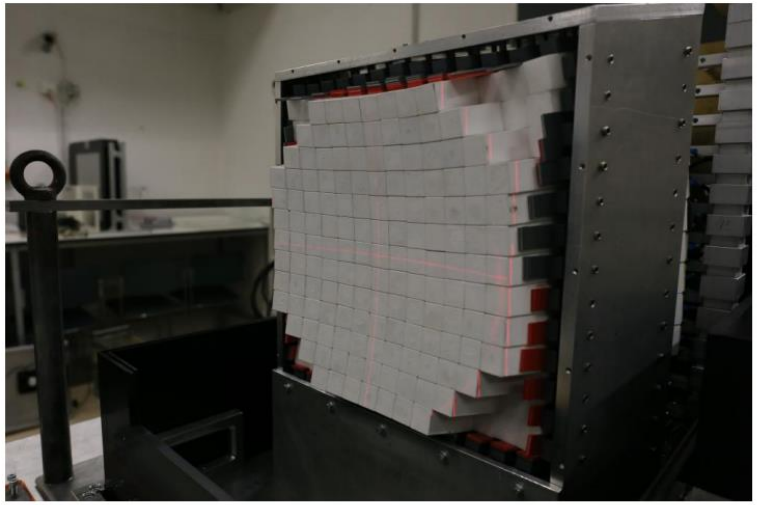
Resolutions for all the reconstructed quantities have been considered:

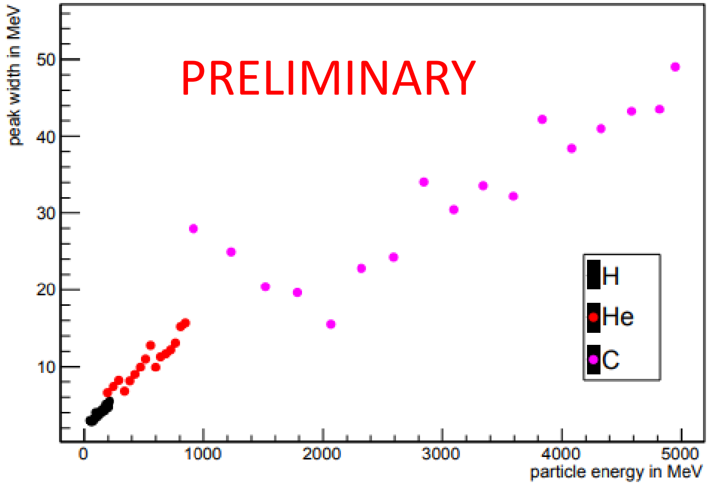
- Momentum: 4.5%
- Kinetic Energy: 1.5%
- ToF: 70 - 100 ps depending on Z



^{16}O @ 200 MeV/n

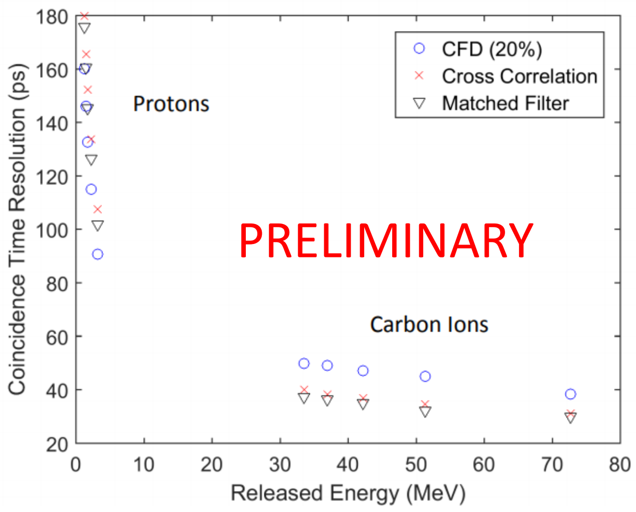
Test beams

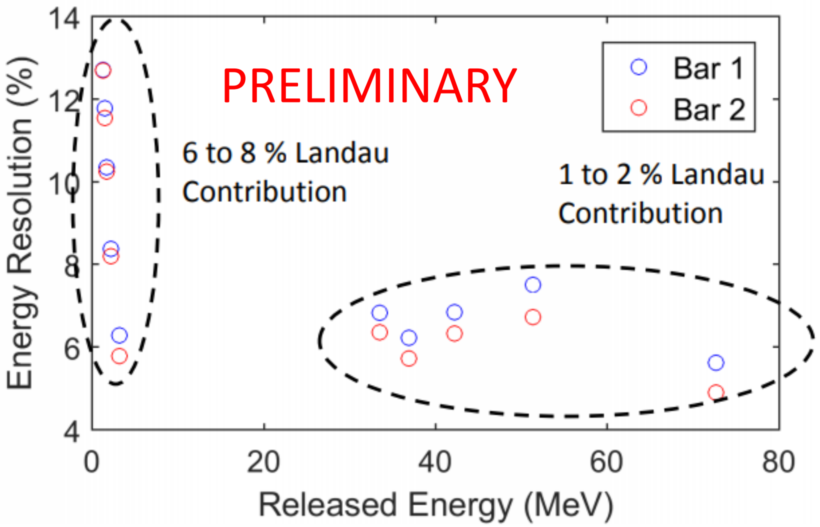




CALORIMETER

- 145 BGO crystals tested in Heidelberg
- Beams used:
  - p: 50 MeV - 220 MeV
  - He: 50 MeV/u - 220 MeV/u
  - C: 100 MeV/u - 430 MeV/u
- Contribution from beam energy spread, detectors and electronics included
- **Energy resolution: 1%-3%**





SCINTILLATOR

- **Time resolution:**
  - protons 100 - 180 ps
  - C ions <50 ps
- **Energy resolution:**
  - Landau fluctuations included
  - protons 5 - 12%
  - C ions 7%

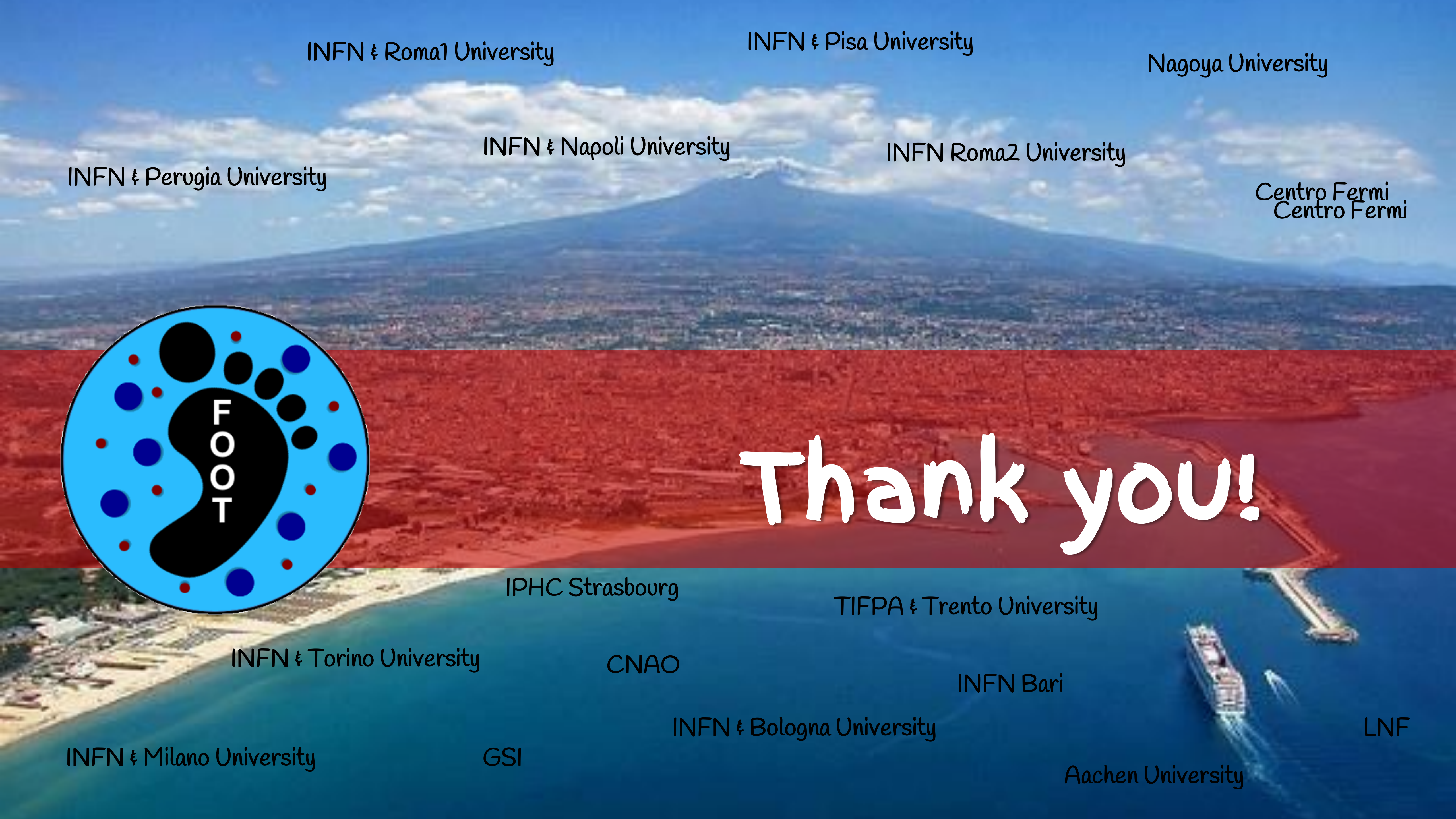
Conclusions & future perspectives

The FOOT experiment goal is to experimentally determine the production cross sections of fragments for beams, energy and targets relevant in hadrontherapy and radioprotection in space.

The final electronic experimental setup is still under development. MC simulation (FLUKA) have been and are still used to improve the detector layout and study the performances.

Several experimental tests have been performed in different facilities (LNS, Trento protontherapy center, CNAO), others are planned.

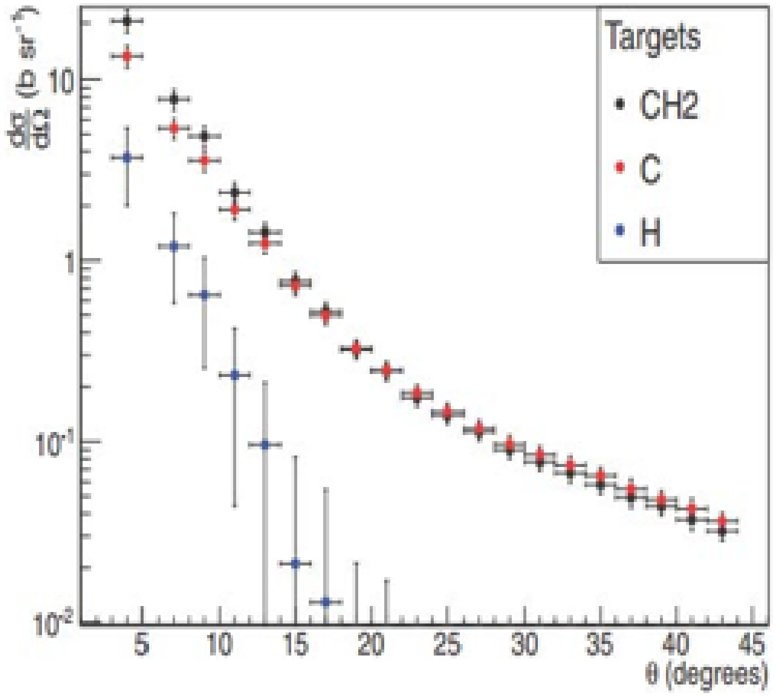
Data taking with the emulsion setup is planned in late 2018 at GSI, while the acquisition with the electronic setup is foreseen in 2020 (GSI/CNAO/ Heidelberg Ion Therapy Center).


INFN & Roma1 University
INFN & Pisa University
Nagoya University
INFN & Napoli University
INFN Roma2 University
INFN & Perugia University
Centro Fermi
Centro Fermi
FOOT
Thank you!
IPHC Strasbourg
TIFPA & Trento University
INFN & Torino University
CNAO
INFN Bari
INFN & Bologna University
LNF
INFN & Milano University
GSI
Aachen University

Spares

Double target strategy

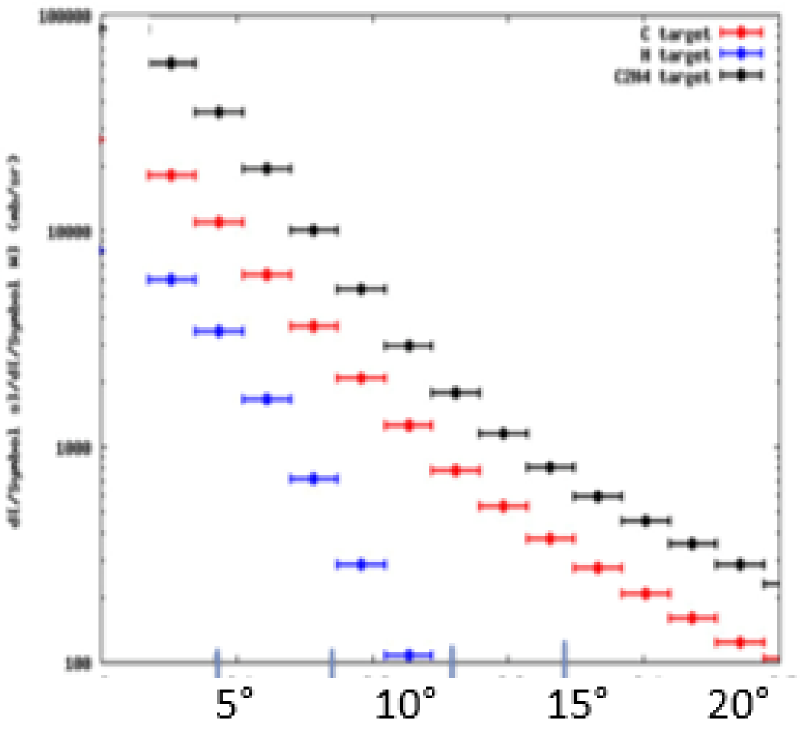
C @ 95 MeV/n on C and C_2H_4



Dudouet et al., Phys.Rev.C (2013)

➢ GANIL experimental data

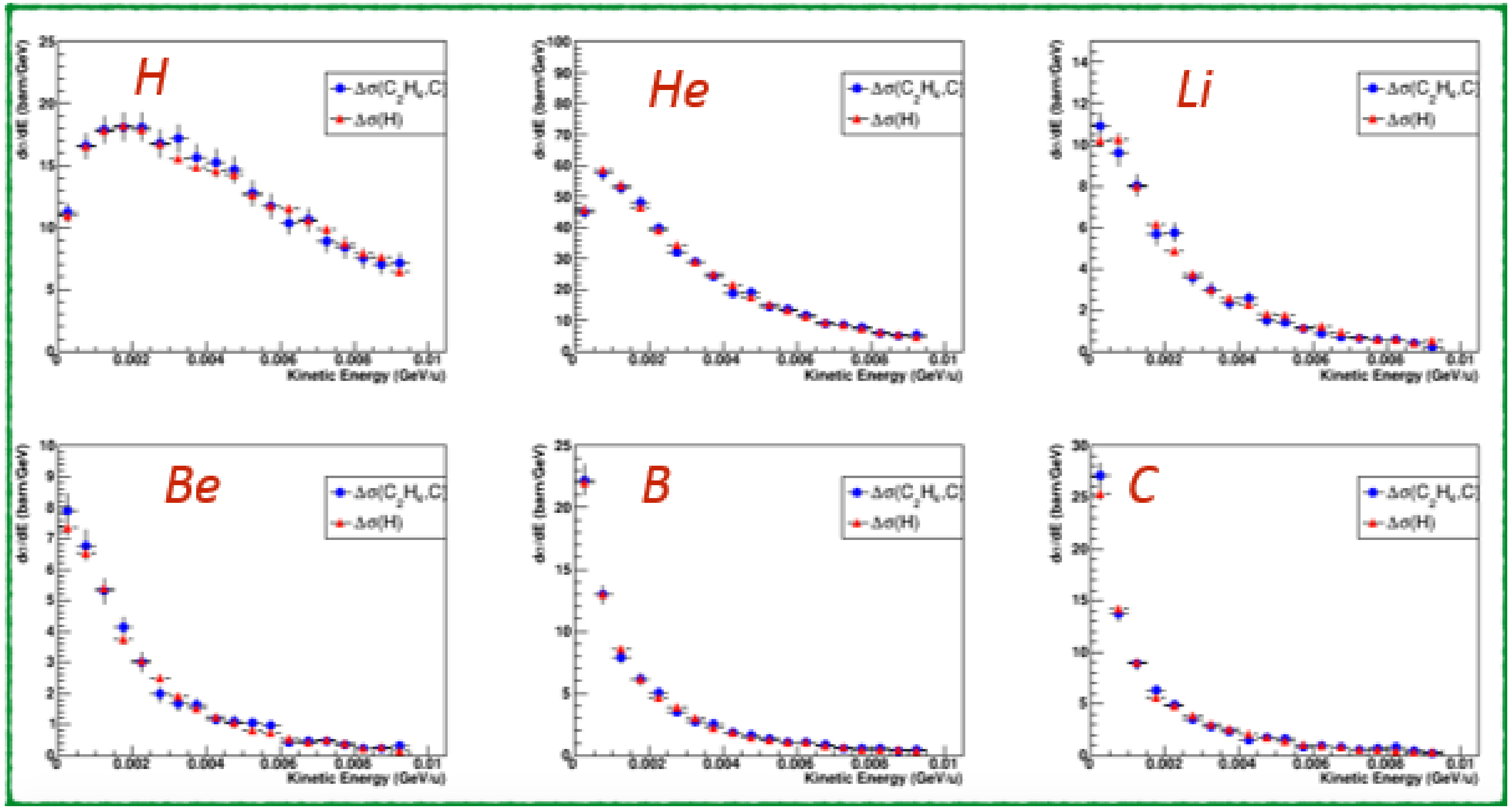
C @ 200 MeV/n on C and C_2H_4



➢ Fluka simulation in the FOOT experiment

H->C differential cross sections

MC (FLUKA) comparison between cross section on H target or by difference of C-> C and C-> C_2H_4



FOOT PHYSICS PROGRAM

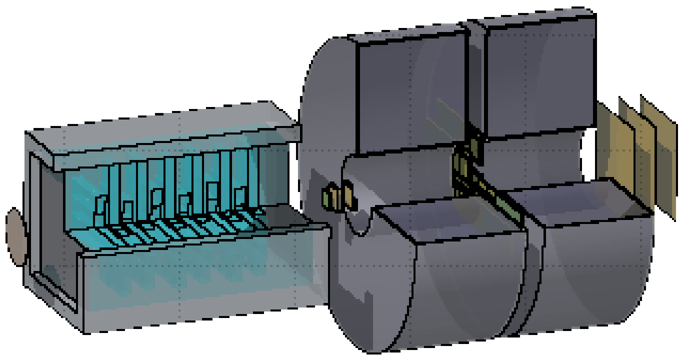
Method of cross section difference is crucial to obtain X section on pure elements:

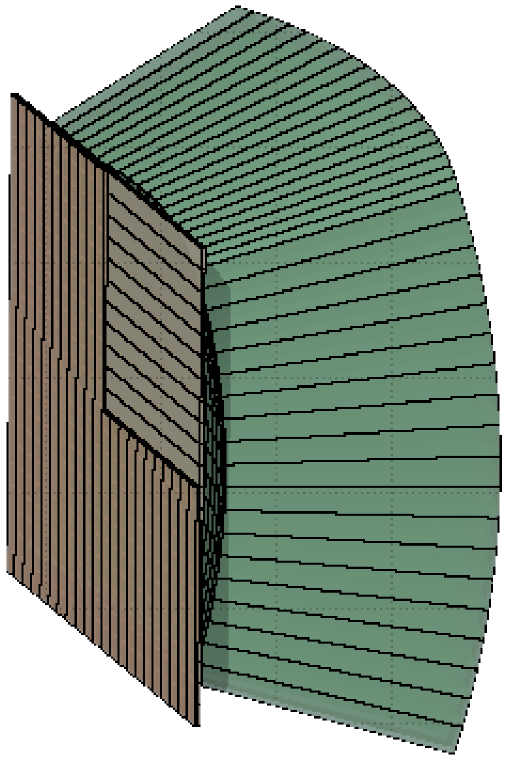
- Using C, C_2H_4 ➔ cross sections on C and H
- Using C, C_2H_4, PMMA ➔ cross sections on C, O and H

PMMA is a combination of C,O,H.

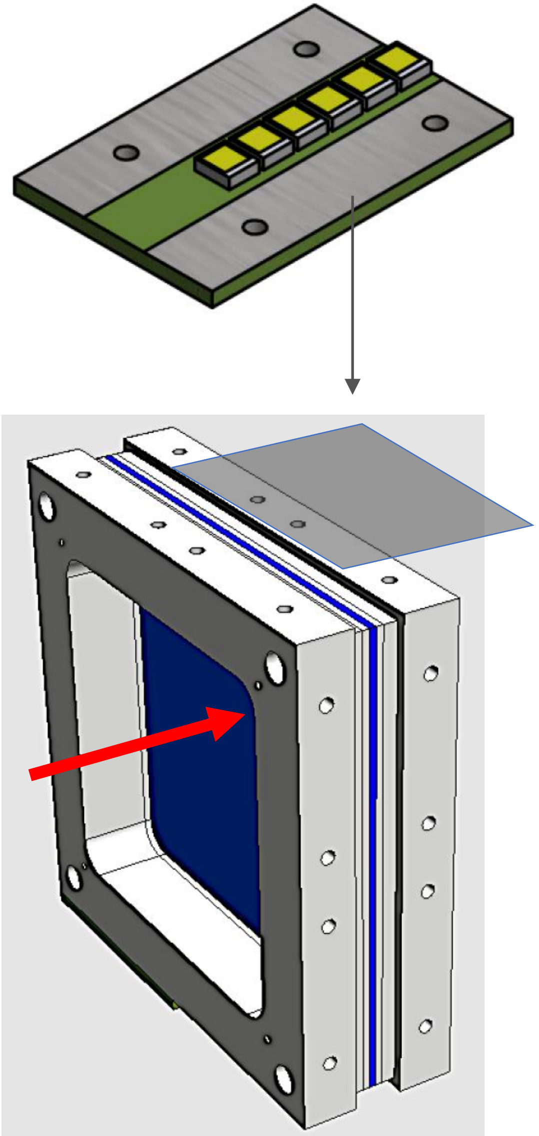
Phys	Beam	Target	Energy (MeV/u)	Inv/direct
Target Frag. PT	^{12}C	C, C_2H_4	200	inv
Target Frag. PT	^{16}O	C, C_2H_4	200	inv
Beam Frag. PT	^{12}C	C, C_2H_4, PMMA	350	dir
Beam Frag. PT	^{16}O	C, C_2H_4, PMMA	400	dir
Beam Frag. PT	^{4}He	C, C_2H_4, PMMA	250	dir
Rad. Prot.space	^{4}He	C, C_2H_4, PMMA	700	dir
Rad. Prot.space	^{12}C	C, C_2H_4, PMMA	700	dir
Rad. Prot.space	^{16}O	C, C_2H_4, PMMA	700	dir

Electronic detector

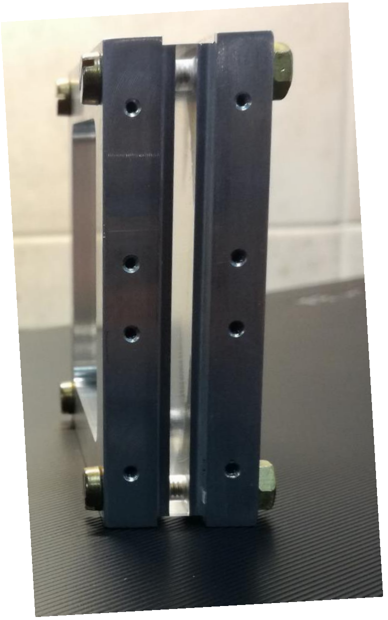


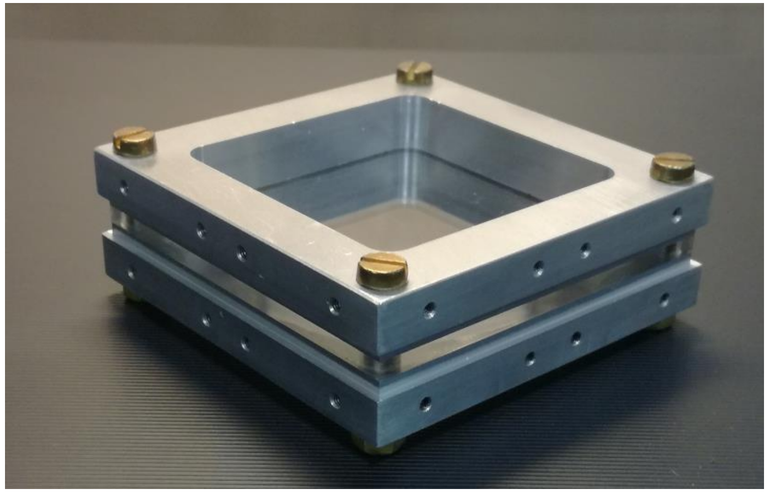


Start counter



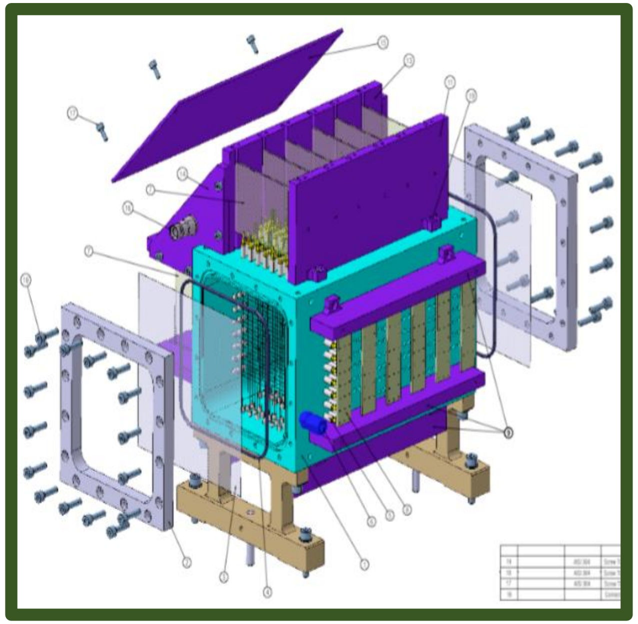
- 250 μm plastic scintillator read out by 48 SiPM (12/side) to improve light collection
- Needed for measurements @ 700 MeV/u
- Test beam at CNAO carbon in autumn

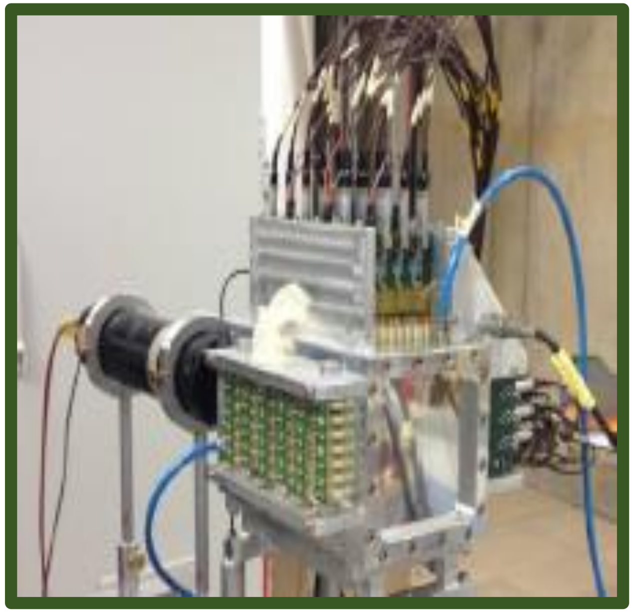




Beam monitor

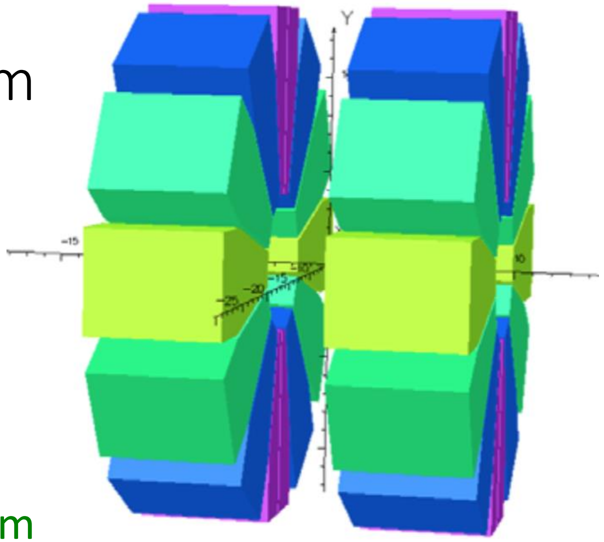
- Drift chamber: 6+6 orthogonal layers of wires, with three drift cells (1.8x1.5 cm^2) per layer
- measure the impinging beam angle on the target with mrad angular resolution
- Detect beam fragmentation on Margherita
- Hit resolution: 150μm on ^{12}C beam

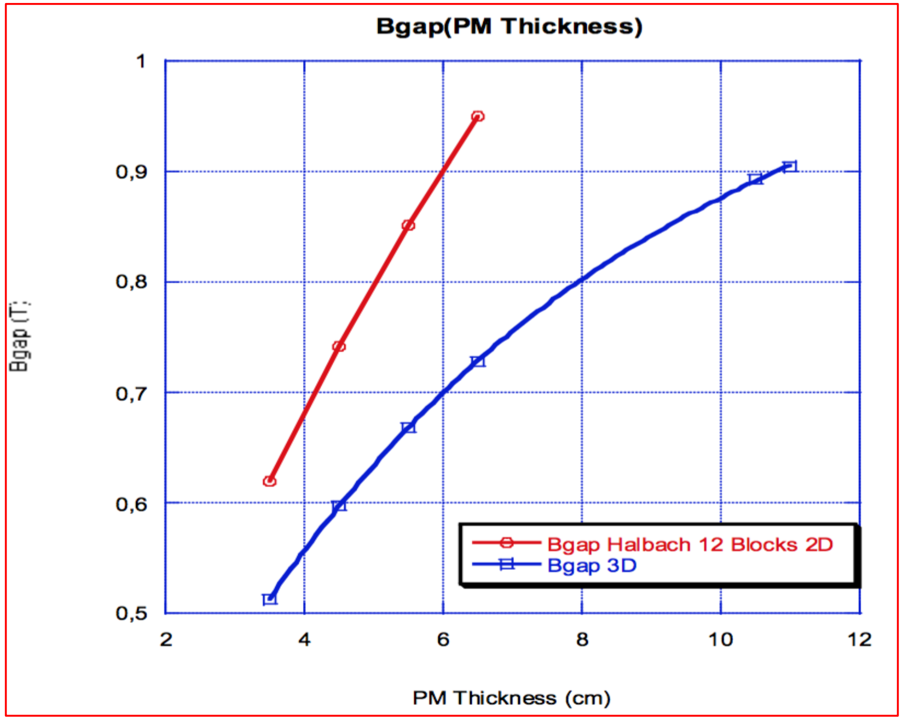


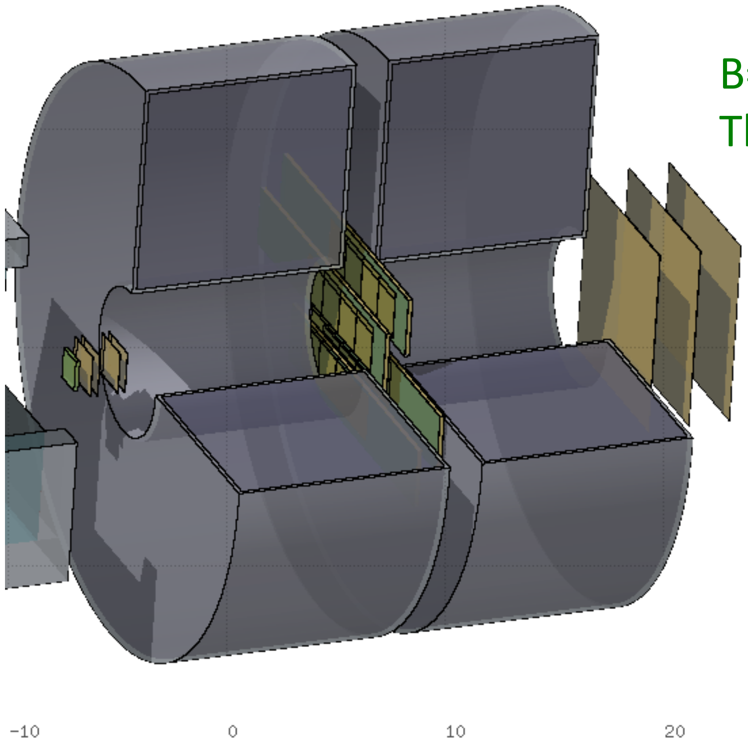


MAGNETS

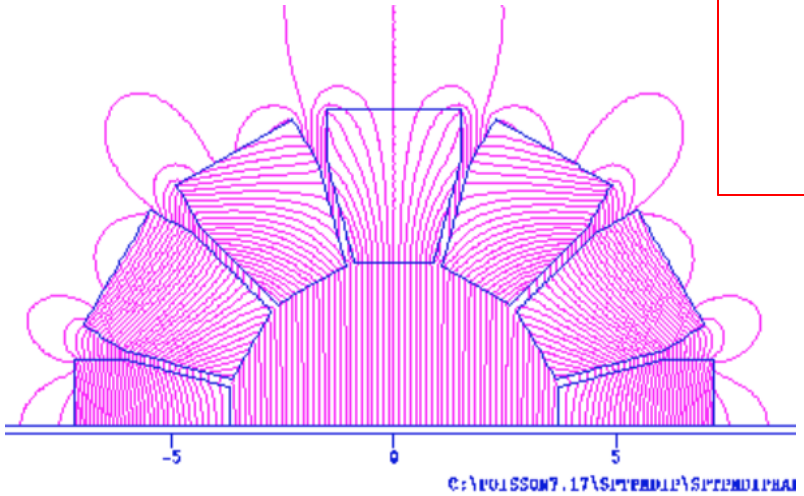
Halbach geometry provides uniform transverse magnetic field in a cylindrical geometry: B field proportional to $\ln(R_{out}/R_{in})$



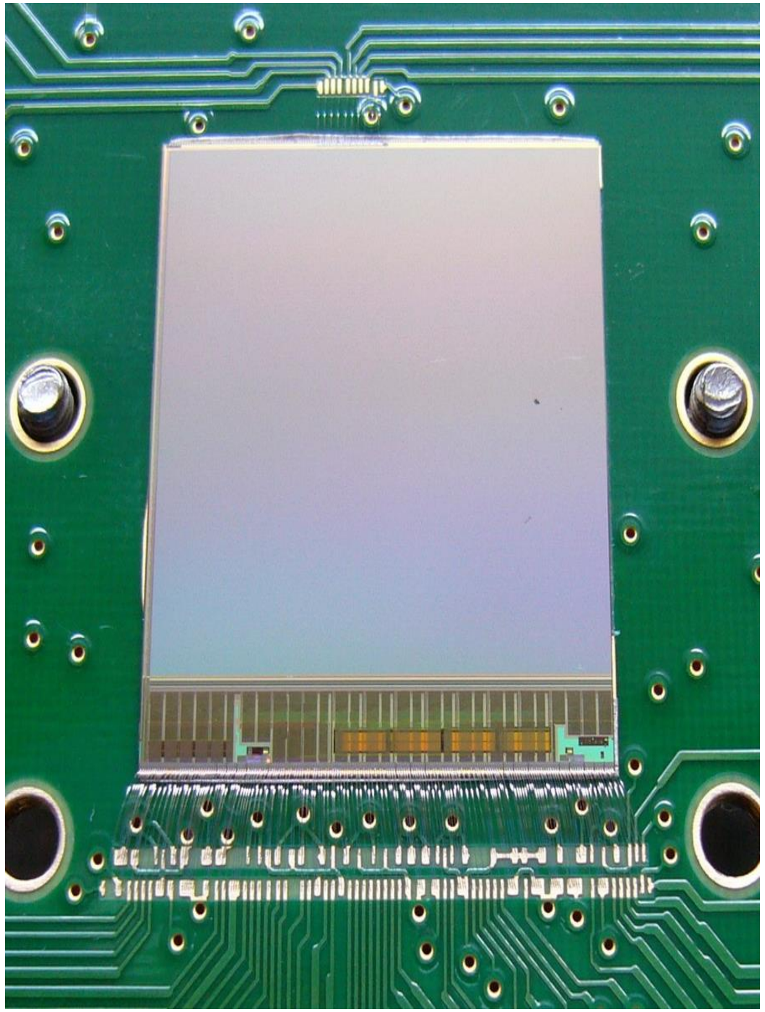




B=0.8T
Thick=8cm



Vertex: Mimosa28 chip

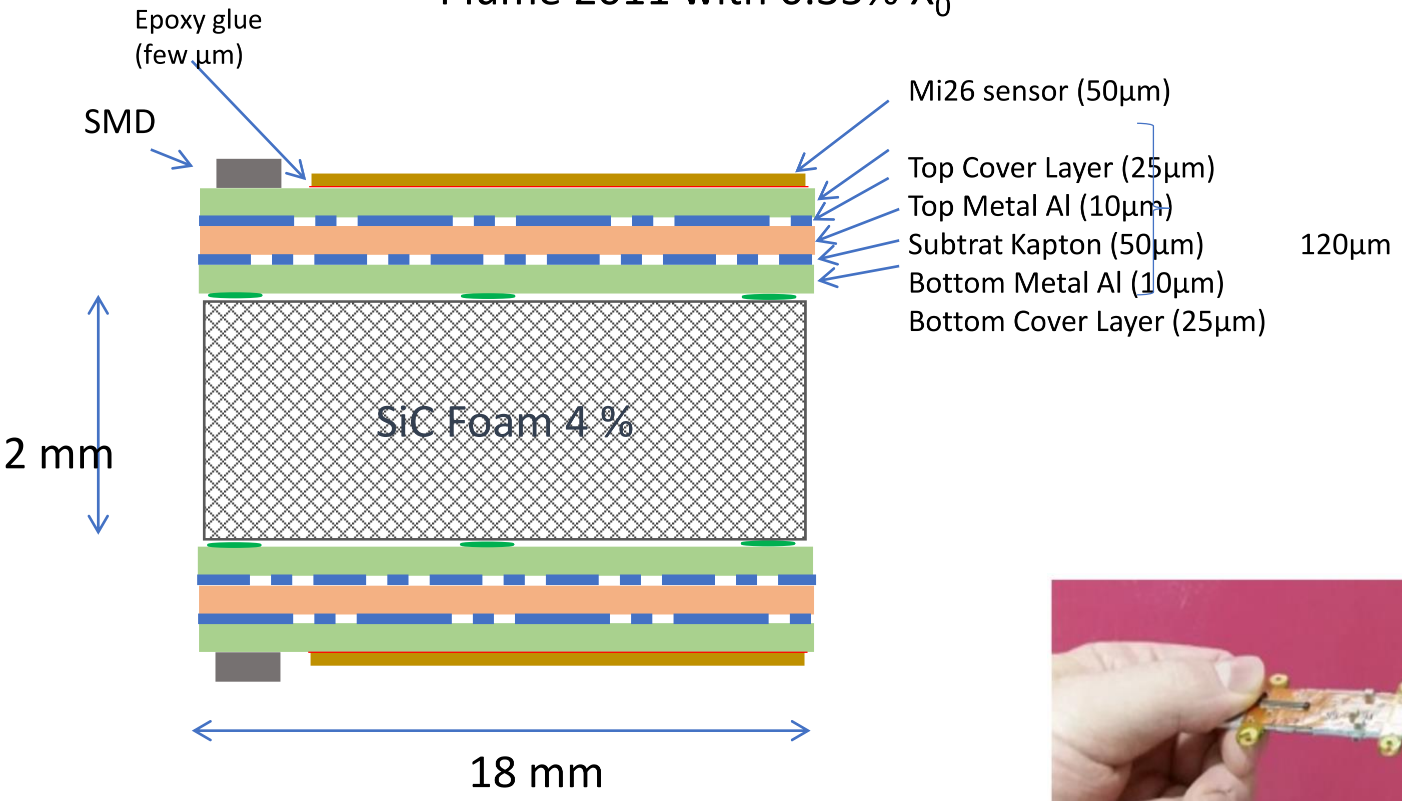


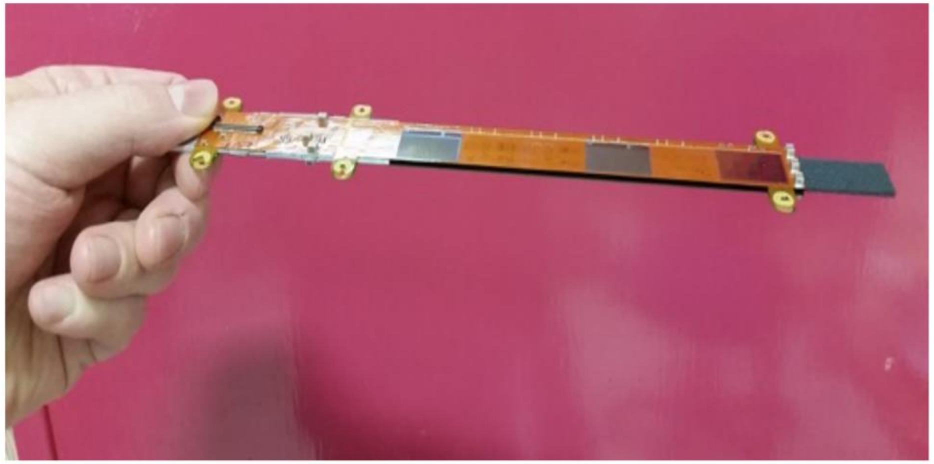
- MAPS (AMS 0.35 µm, 15 µm epi-layer)
- 50 µm thickness
- 928 (rows) x 960 (columns) pixels
- 20.7 µm pitch
- Size 20.22 mm x 22.71 mm
- chip readout time 185.6 µs
- Digital Zero Suppressed Output

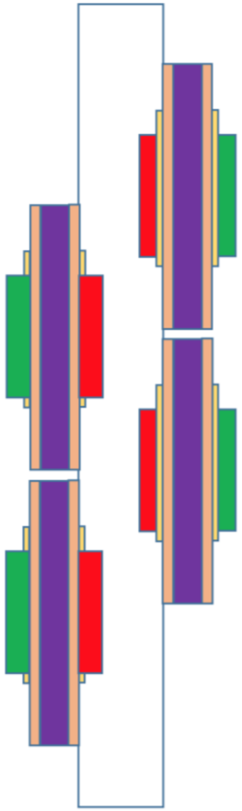
By IPHC In2p3 Strasbourg

Inner tracker

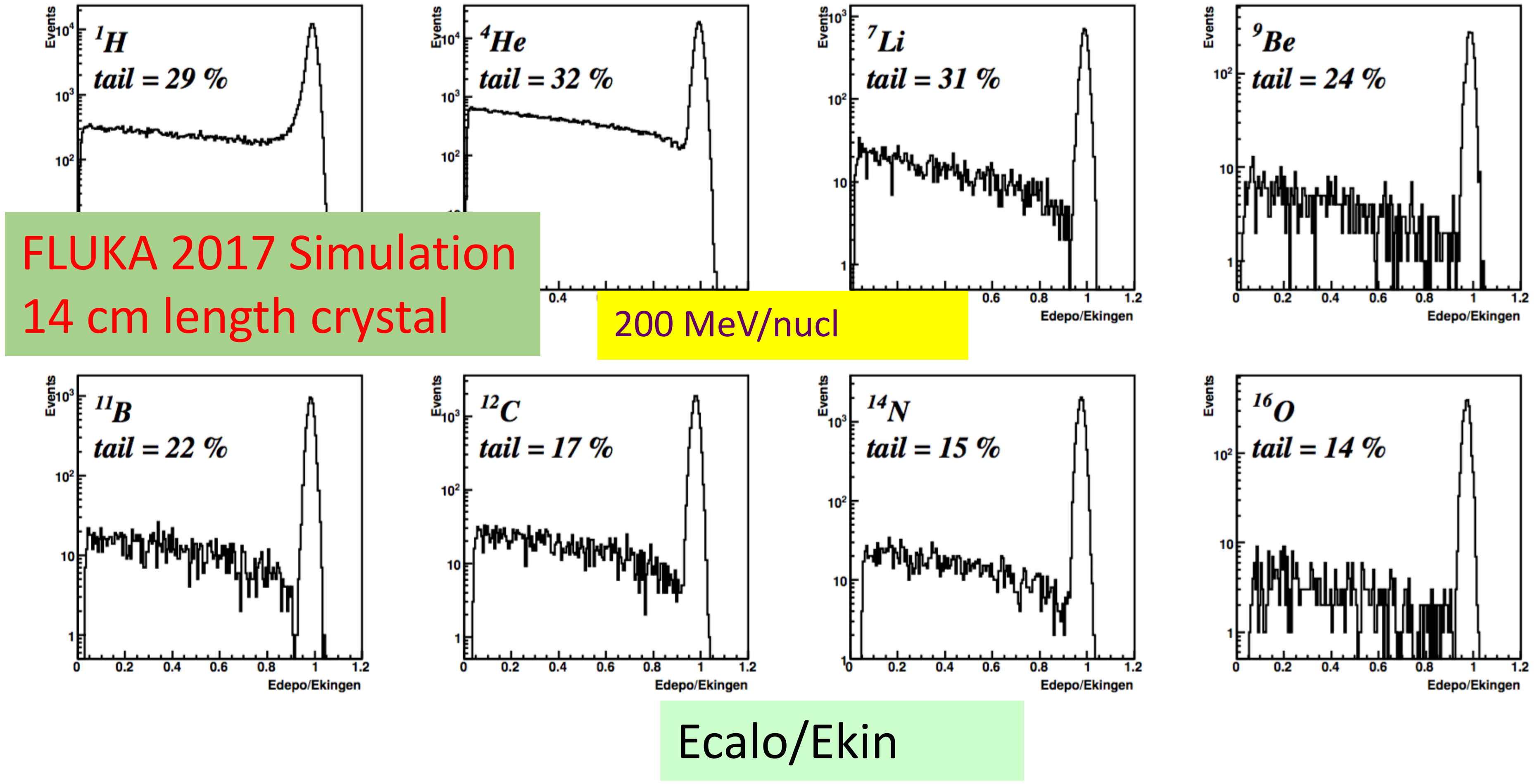
Plume 2011 with 0.35% X_0







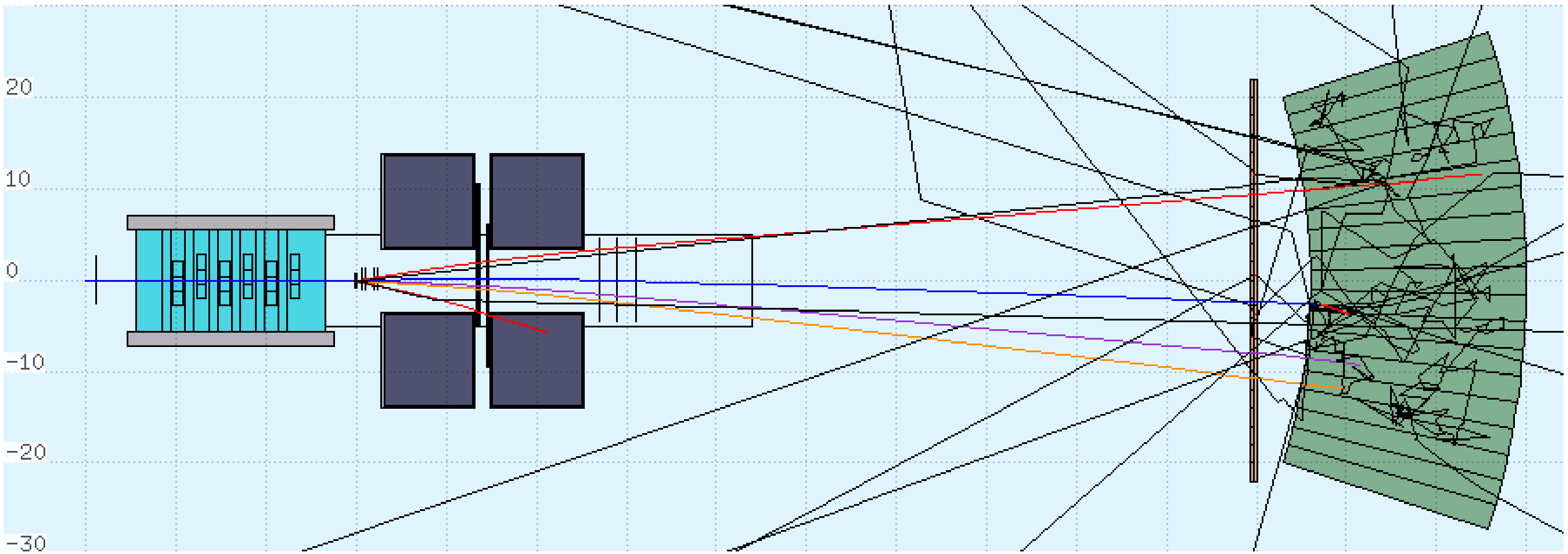
Neutron leakage in calorimeter

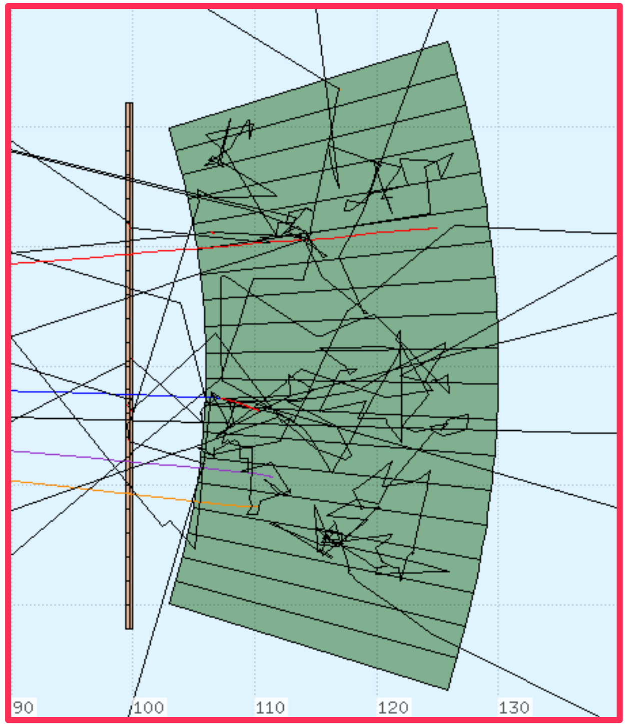


The neutron leakage in BGO seems to be more and more important for energy higher than 200 MeV/nucl and for light fragments (!)

Even if the TOF and momentum can tag such events, these must be minimized to keep the systematic under control.

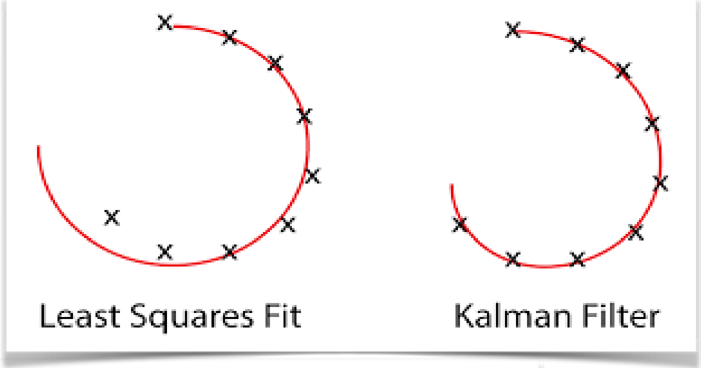
Event display

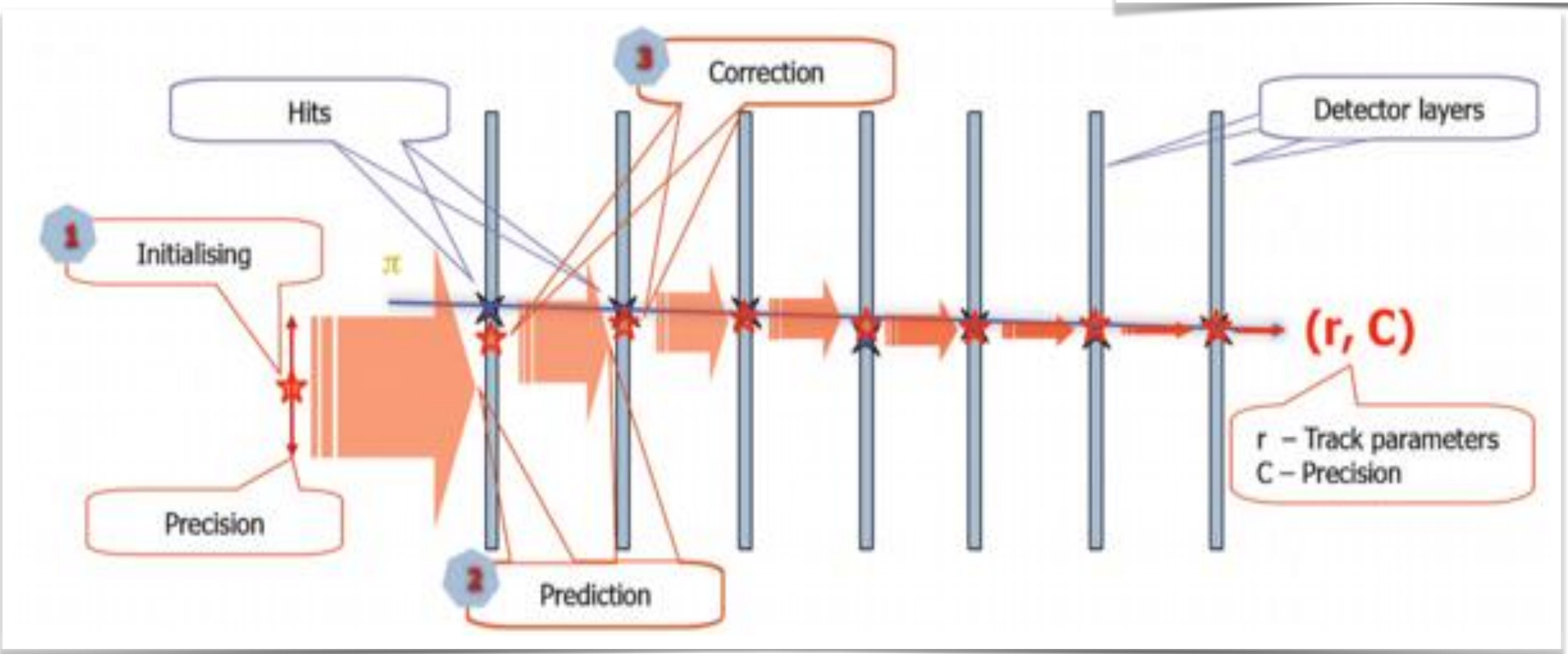




Kalman filter

- Recursive algorithm that accurately takes into account multiple scattering;
- Each layer **prediction** is corrected using the **observed hit -> track uncertainty** decreases layer by layer.
- Precise description of geometry and material needed





Isotopic ID

Standard χ^2

$$f = \left(\frac{TOF - T}{\sigma_{TOF}}\right)^2 + \left(\frac{p-P}{\sigma_p}\right)^2 + \left(\frac{E_k - K}{\sigma_{E_k}}\right)^2 +$$

$$\begin{pmatrix} A_1 - A, & A_2 - A, & A_3 - A \end{pmatrix} \begin{pmatrix} B_{00} & B_{01} & B_{02} \\ B_{10} & B_{11} & B_{12} \\ B_{20} & B_{21} & B_{22} \end{pmatrix} \begin{pmatrix} A_1 - A \\ A_2 - A \\ A_3 - A \end{pmatrix}$$

$$B = \left(C \cdot C^T\right)^{-1}$$

$$C = \begin{pmatrix} \frac{\partial A_1}{\partial T} dT & \frac{\partial A_1}{\partial P} dP & 0 \\ \frac{\partial A_2}{\partial T} dT & 0 & \frac{\partial A_2}{\partial K} dK \\ 0 & \frac{\partial A_3}{\partial P} dP & \frac{\partial A_3}{\partial K} dK \end{pmatrix}$$

ALM

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

$$f(\vec{x}) = \left(\frac{TOF - T}{\sigma_{TOF}}\right)^2 + \left(\frac{p-P}{\sigma_p}\right)^2 + \left(\frac{E_k - K}{\sigma_{E_k}}\right)^2$$

$$\sum_a \lambda_a c_a(\vec{x}) + \frac{1}{2\mu} \sum_a c_a^2(\vec{x}) = \lambda_1 (A_1 - A) + \lambda_2 (A_2 - A) + \lambda_3 (A_3 - A) + \frac{1}{2\mu}\left((A_1 - A)^2 + (A_2 - A)^2 + (A_3 - A)^2\right)$$