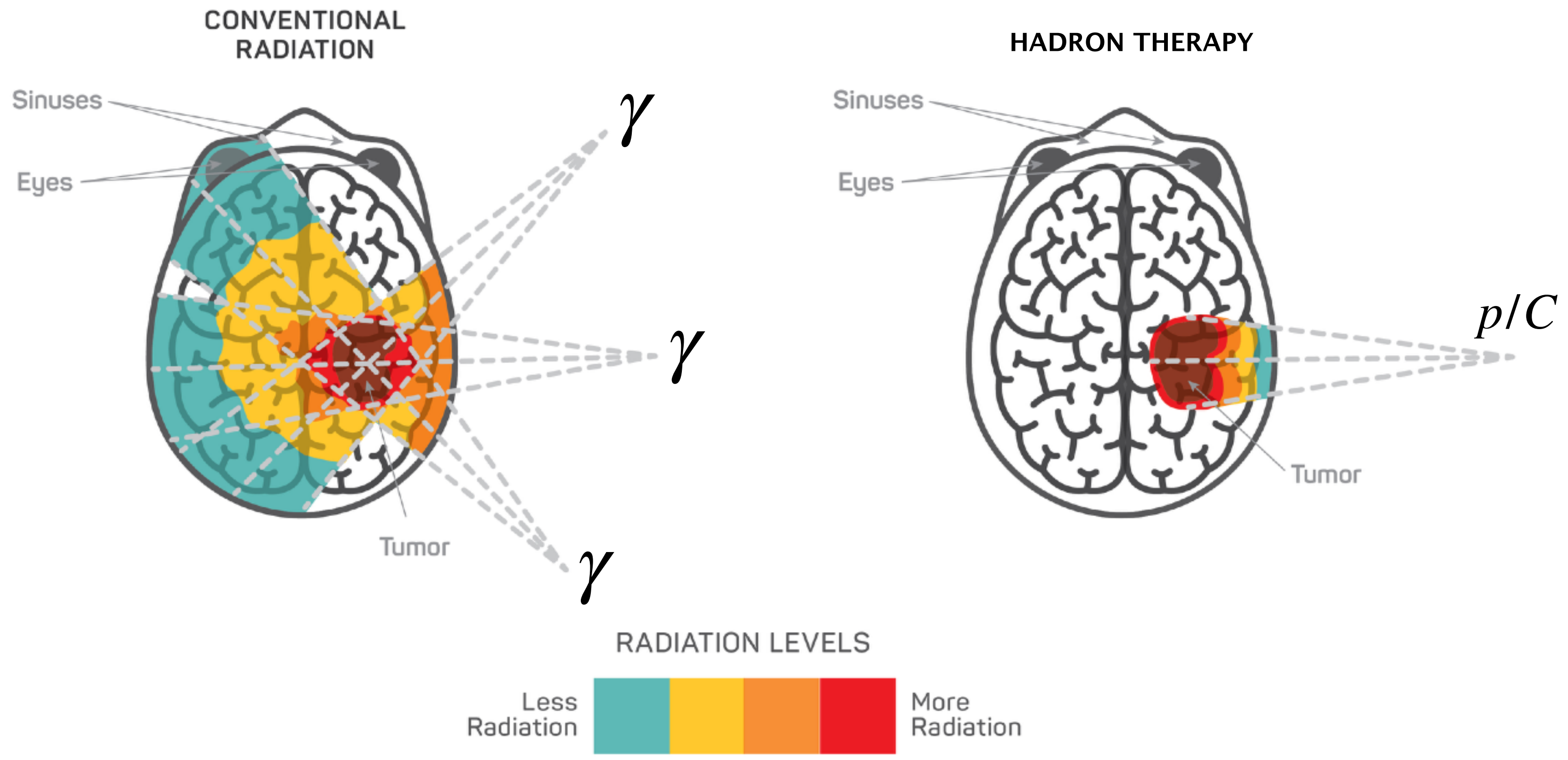
21.11.2019 Paris, France

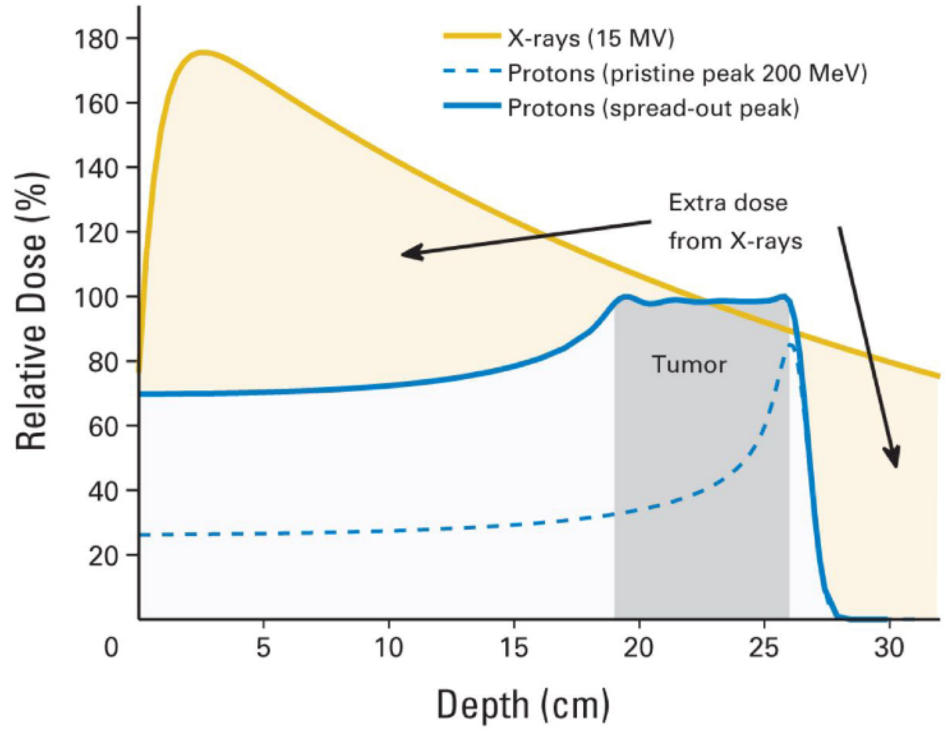
Design and performance of the Calorimeter for the FOOT experiment

Lorenzo Scavarda
(INFN Torino, Italy)

Calculation of the cross section of secondary fragments in:

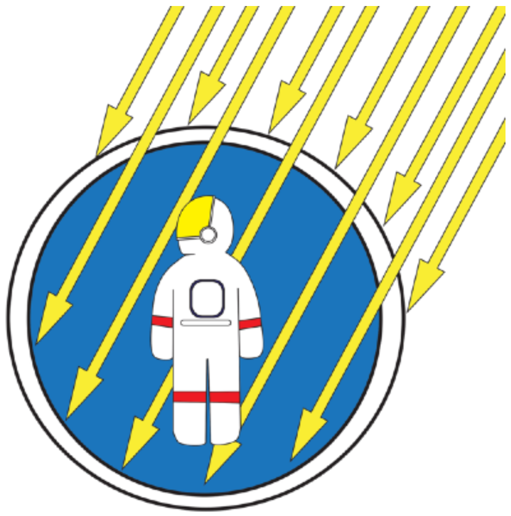
1 Hadron therapy treatments:





2 Space Missions:

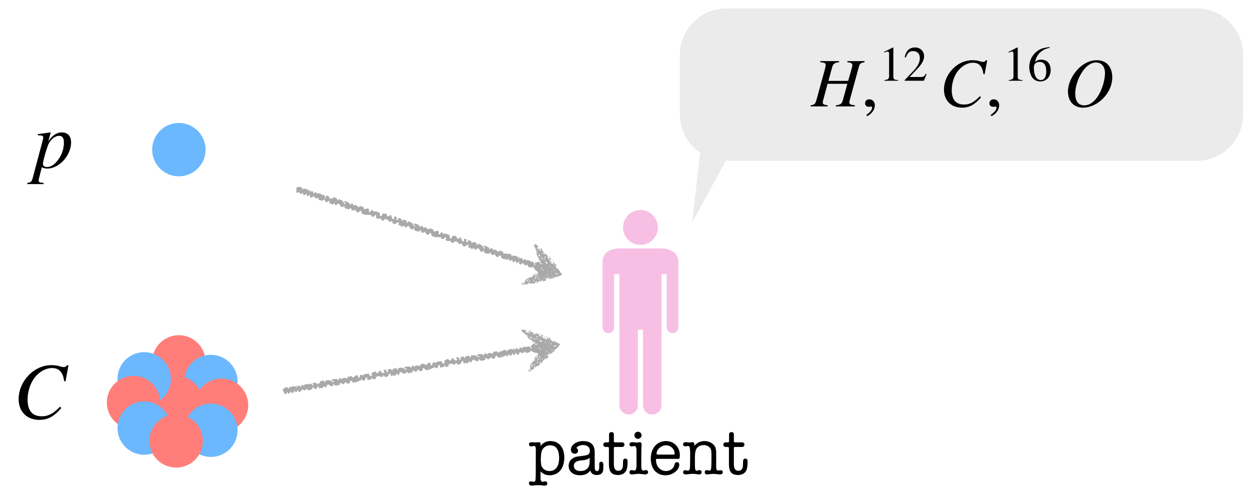
Particles in space (p) when interacting with walls/shielding of spacecraft produce secondary fragments



Target-Projectile fragmentation

Fill the gap in experimental data:

- 50-250 MeV for protons
- 50-400 MeV/u for carbon ions
- up to 700 MeV/u for radio protection in the space missions



- p + H ⟶ no fragments
- C + H ⟶ **projectile** fragments
- p + C/O ⟶ **target** fragments
- C + C/O ⟶ **projectile** + **target** fragments
  - ⟶ fragments **can be** detected: long range
  - ⟶ fragments **can't be** detected: short ranges (μm) and low energies (eV)

Strategy

Problem: Target fragmentations

Direct Kinematic

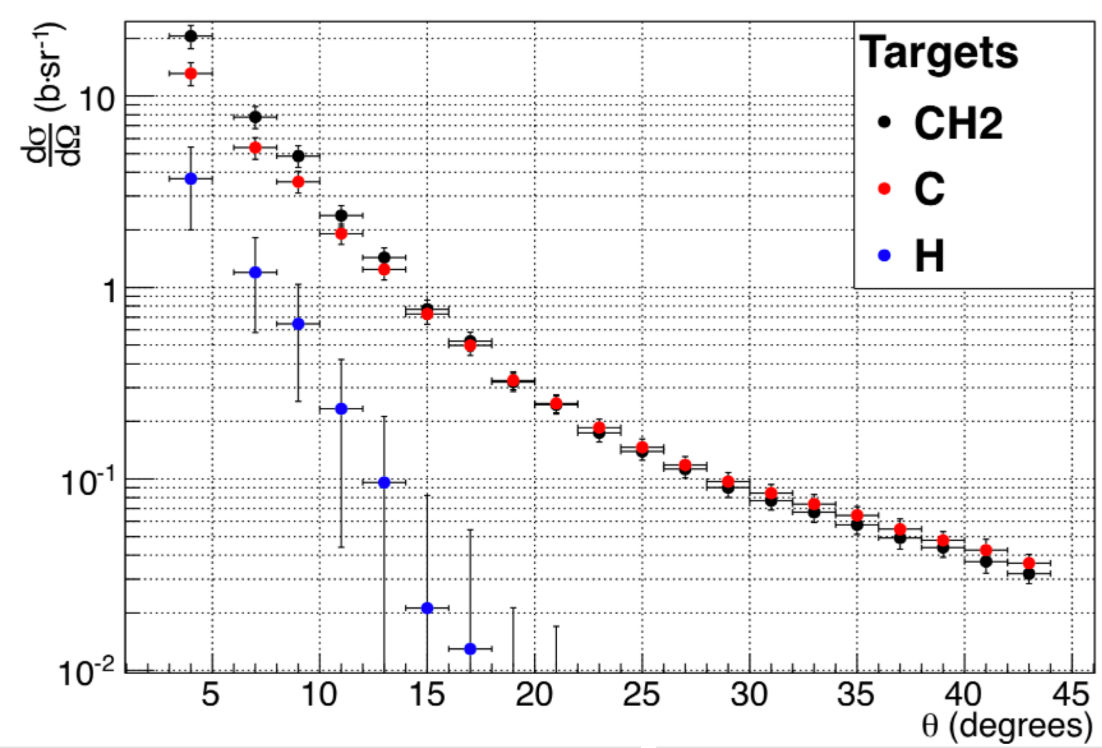
Inverse Kinematic

Solution: Inverse Kinematic. Shoot C/O on H target fragments have longer range due to Lorentz boost

Problem: Hydrogen Target. Density of gas is too low (low interaction probability)

Solution: polyethylene target + Carbon target

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



Requirements:

$$\frac{\delta E_k}{E_k} < 2\,\%$$

$$\frac{\delta p}{p} < 5\,\%$$

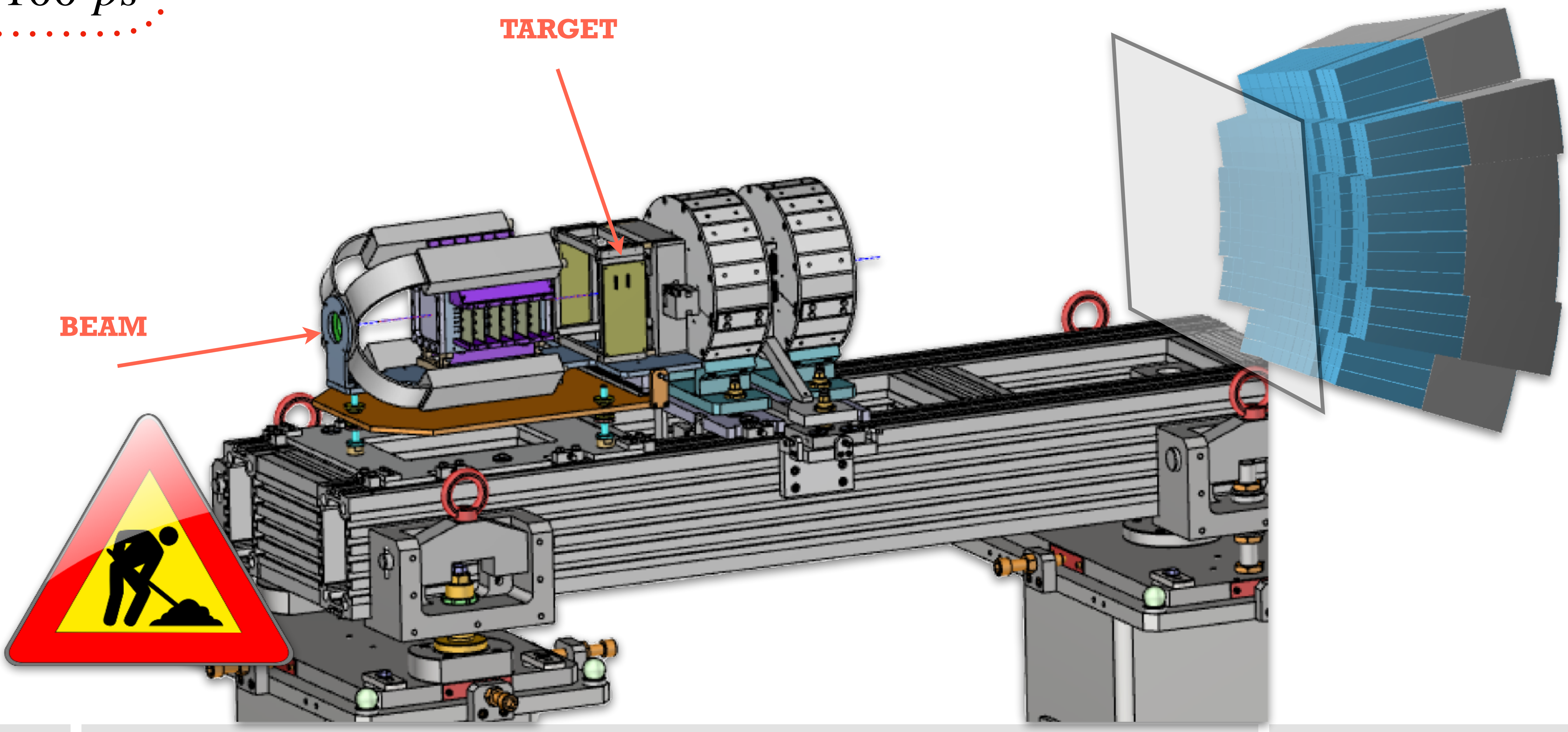
$$TOF < 100\ ps$$

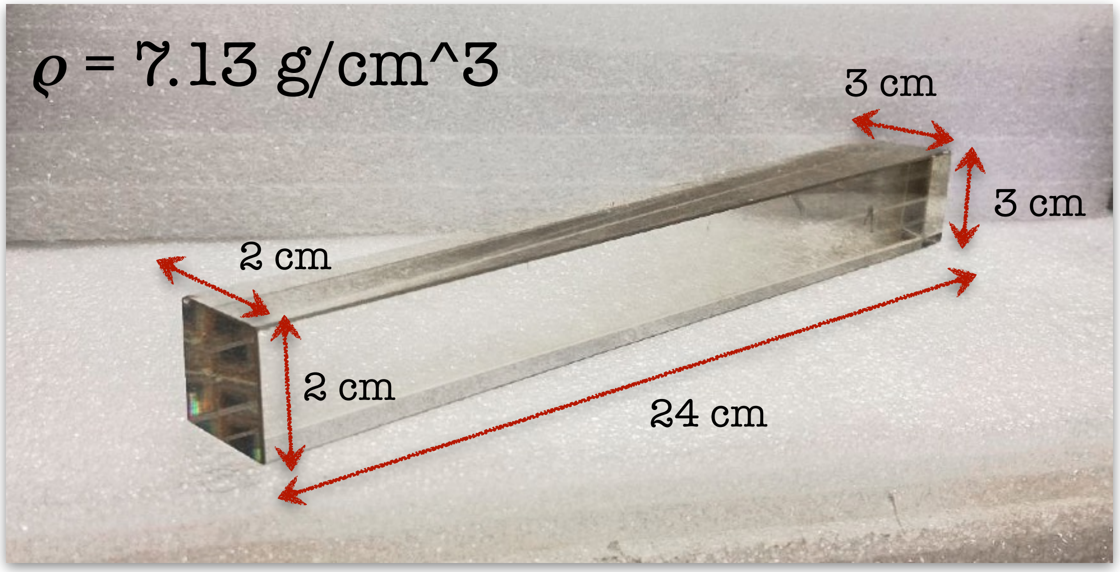
Fragment mass

$$5\,\% < \frac{\delta A}{A} < 10\,\%$$

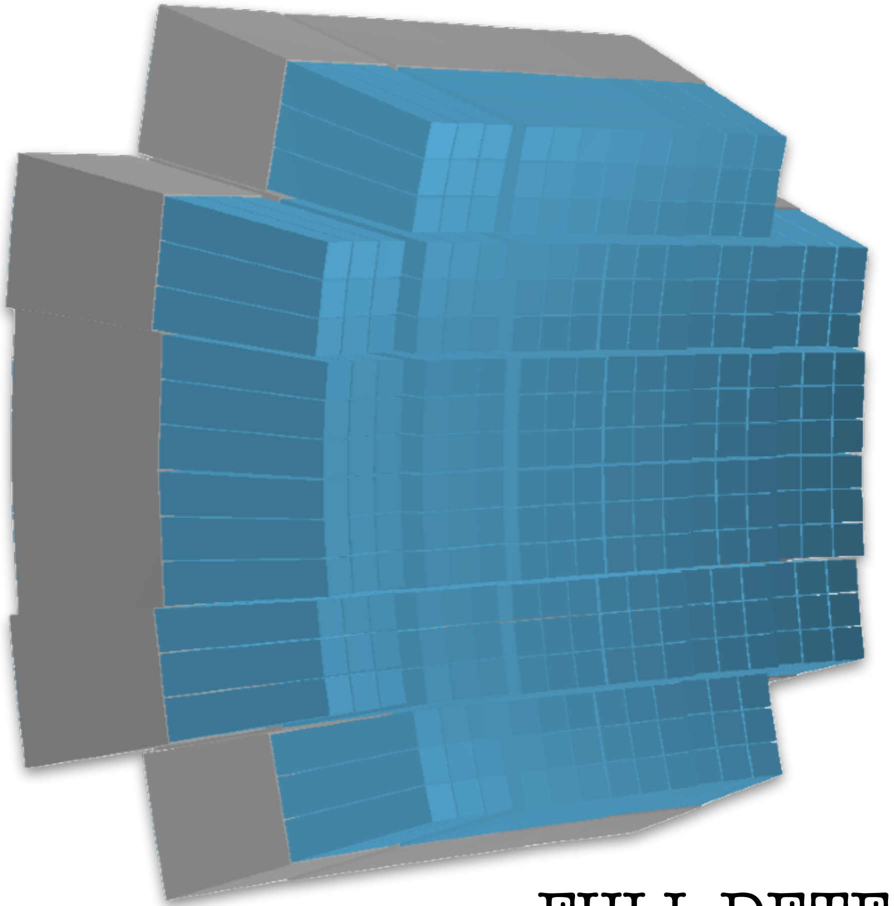
Cross sections

$$\frac{\delta(d\sigma/dE_k)}{d\sigma/dE_k} < 5\,\%$$

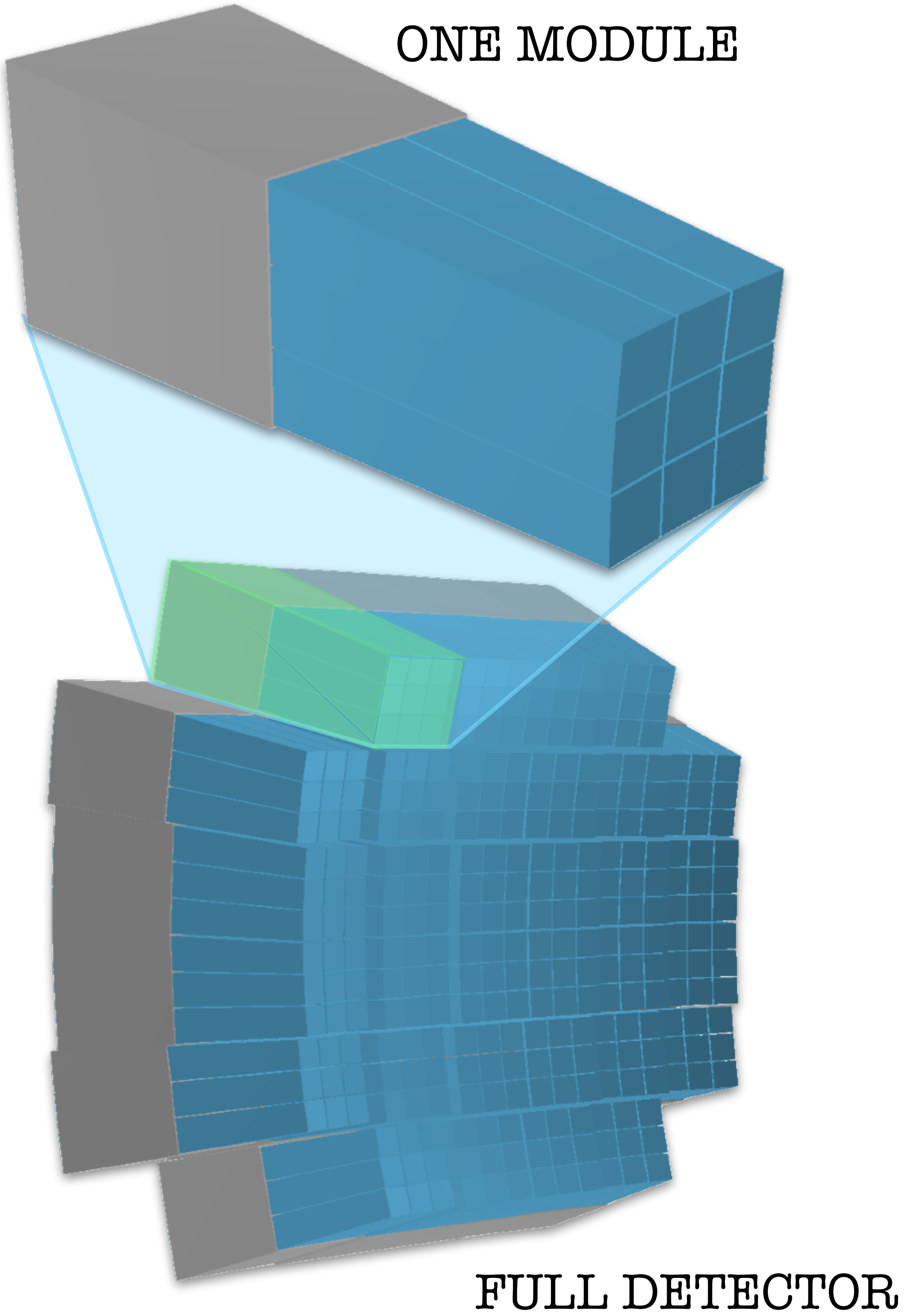


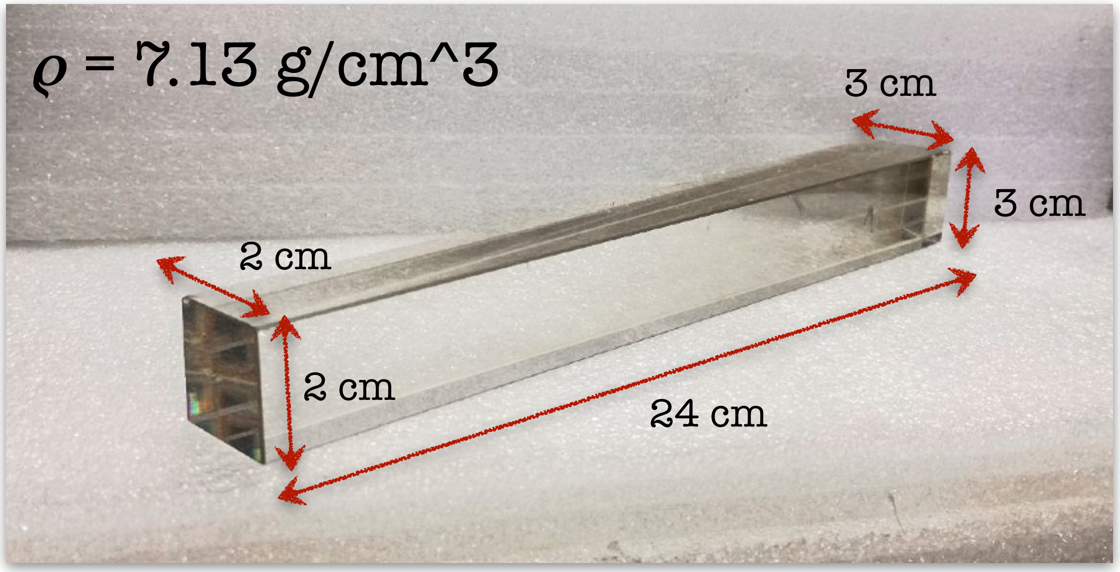


ONE CRYSTAL



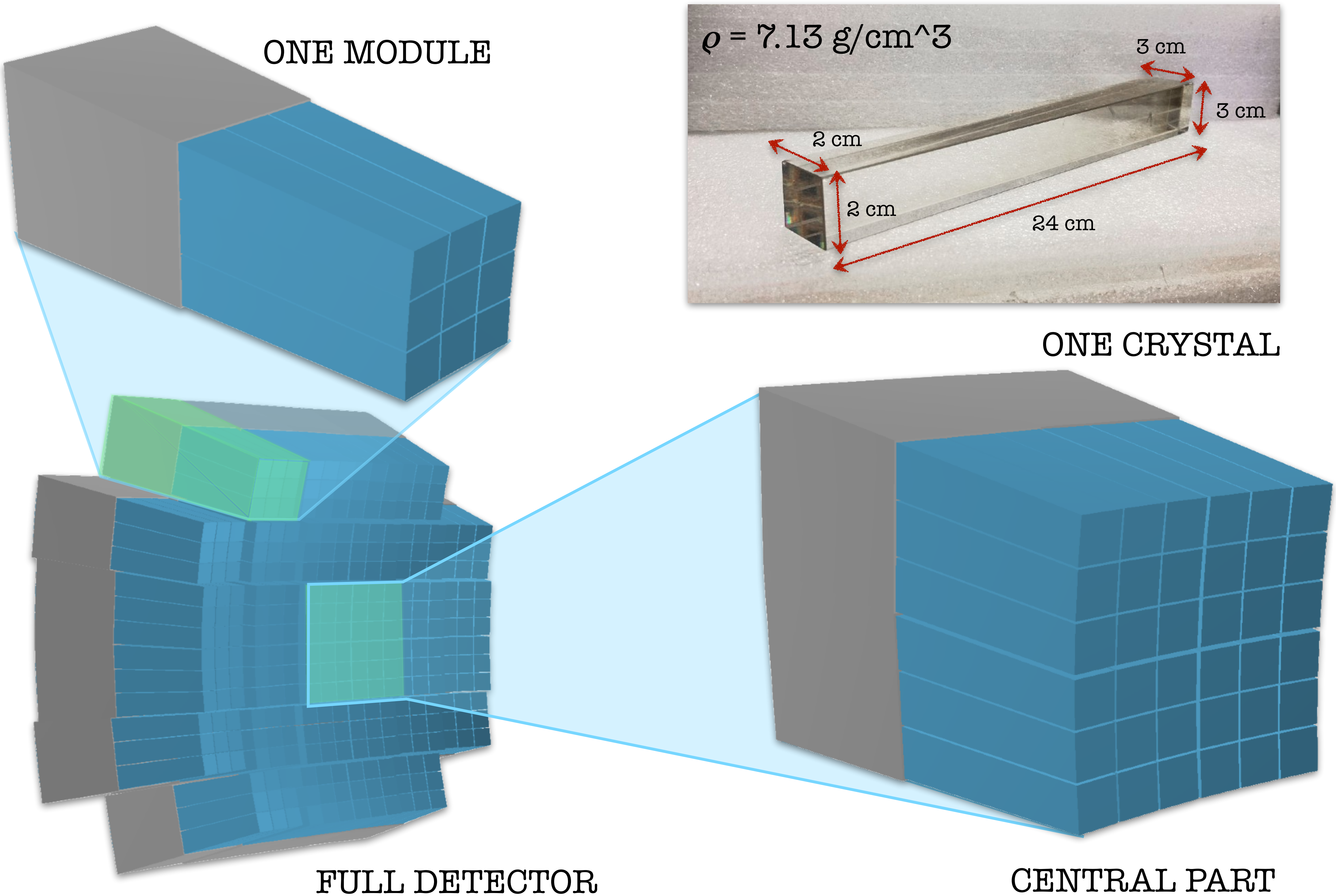
FULL DETECTOR





ONE CRYSTAL

Calorimeter Arrangment

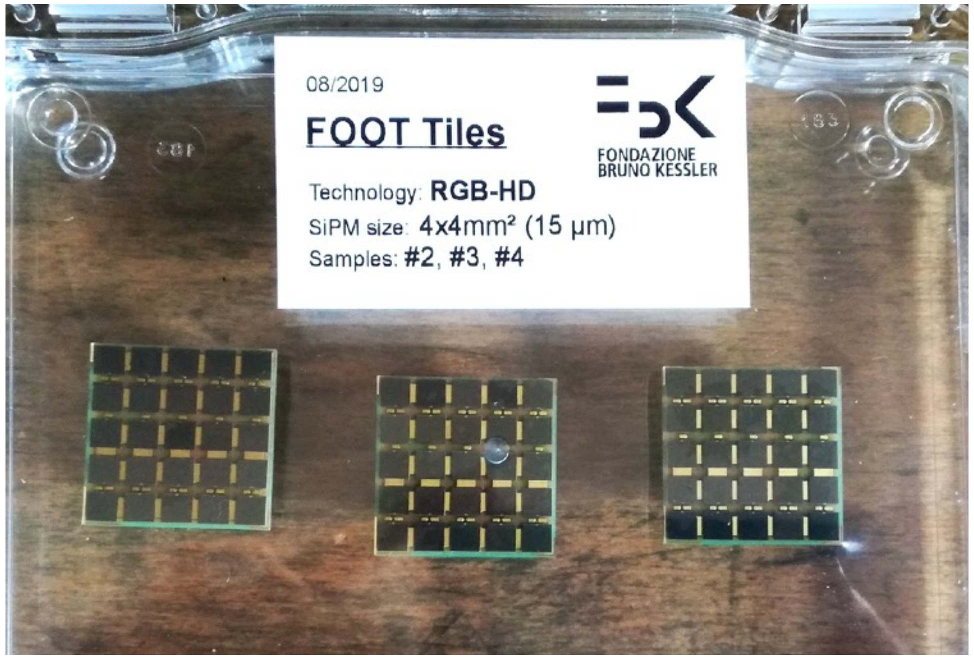


Test beam setup

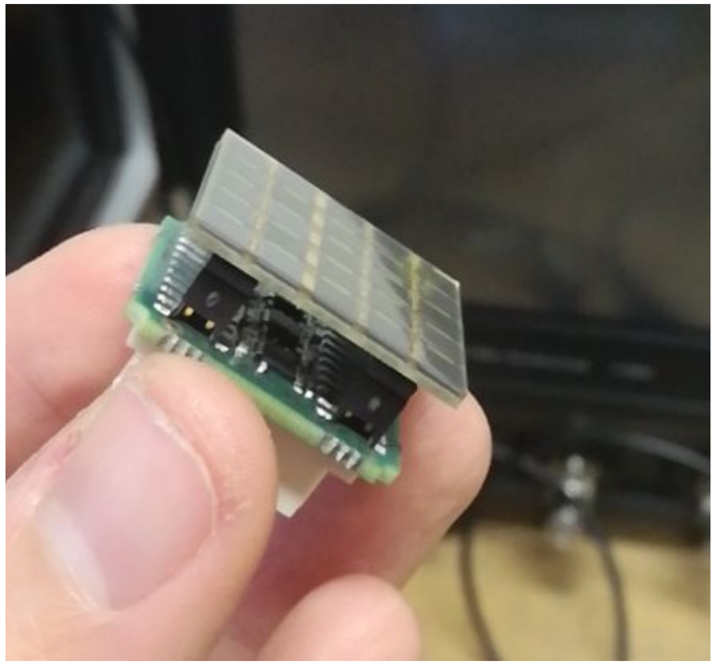
October 2019

fondazione CNAO
Centro Nazionale di Adroterapia Oncologica

15 µm SiPM arrays,
25 SiPMs in each tile



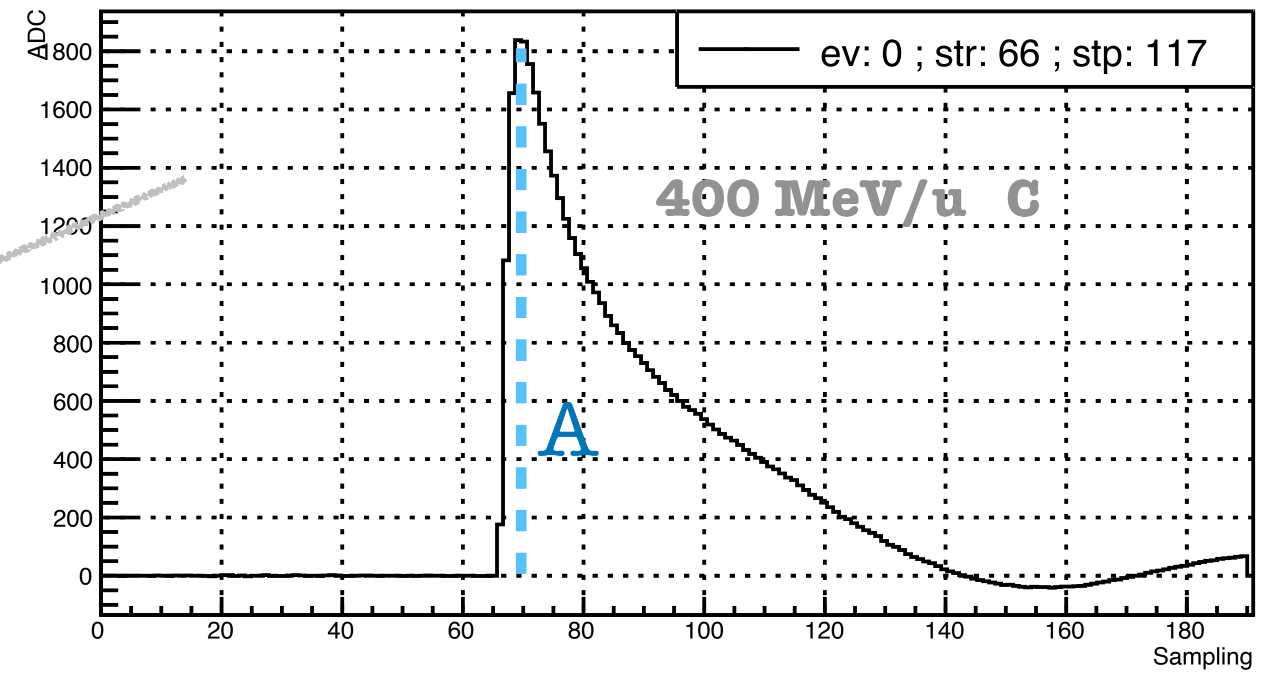
SiPM readout board

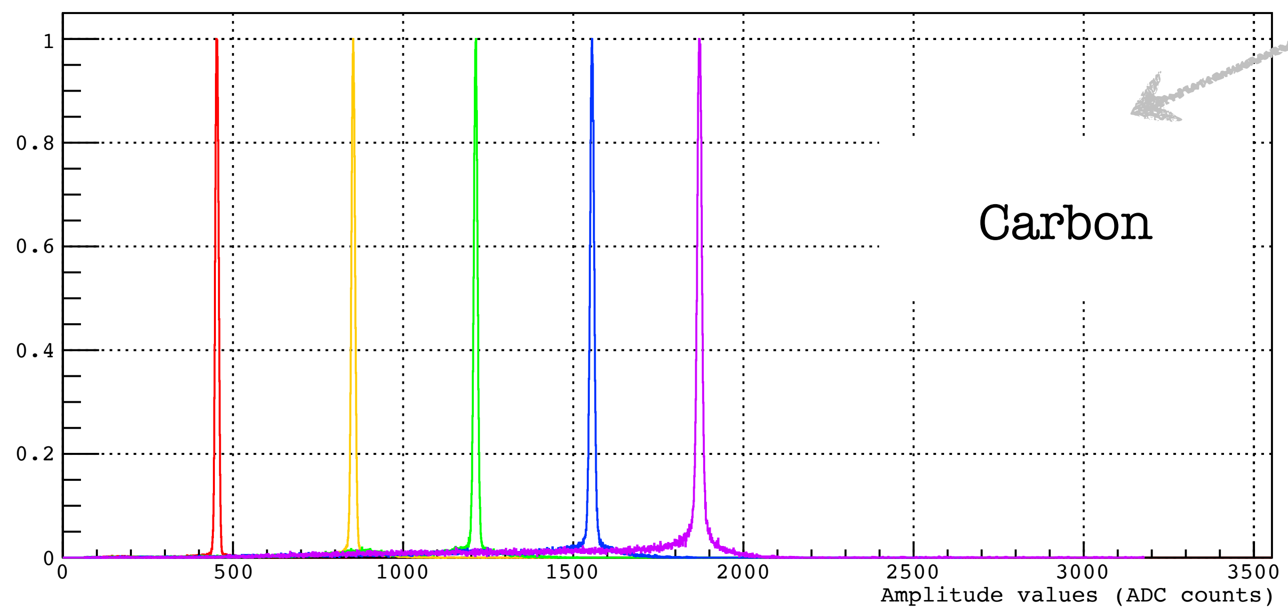


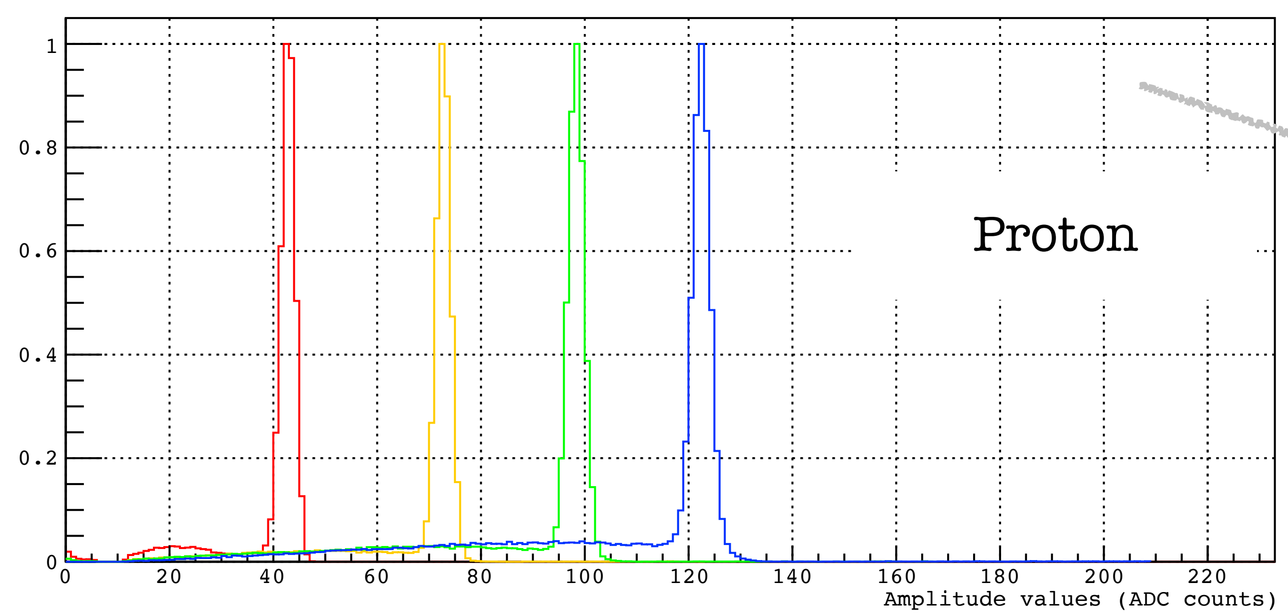
V1740, 2V, 65 Mhz

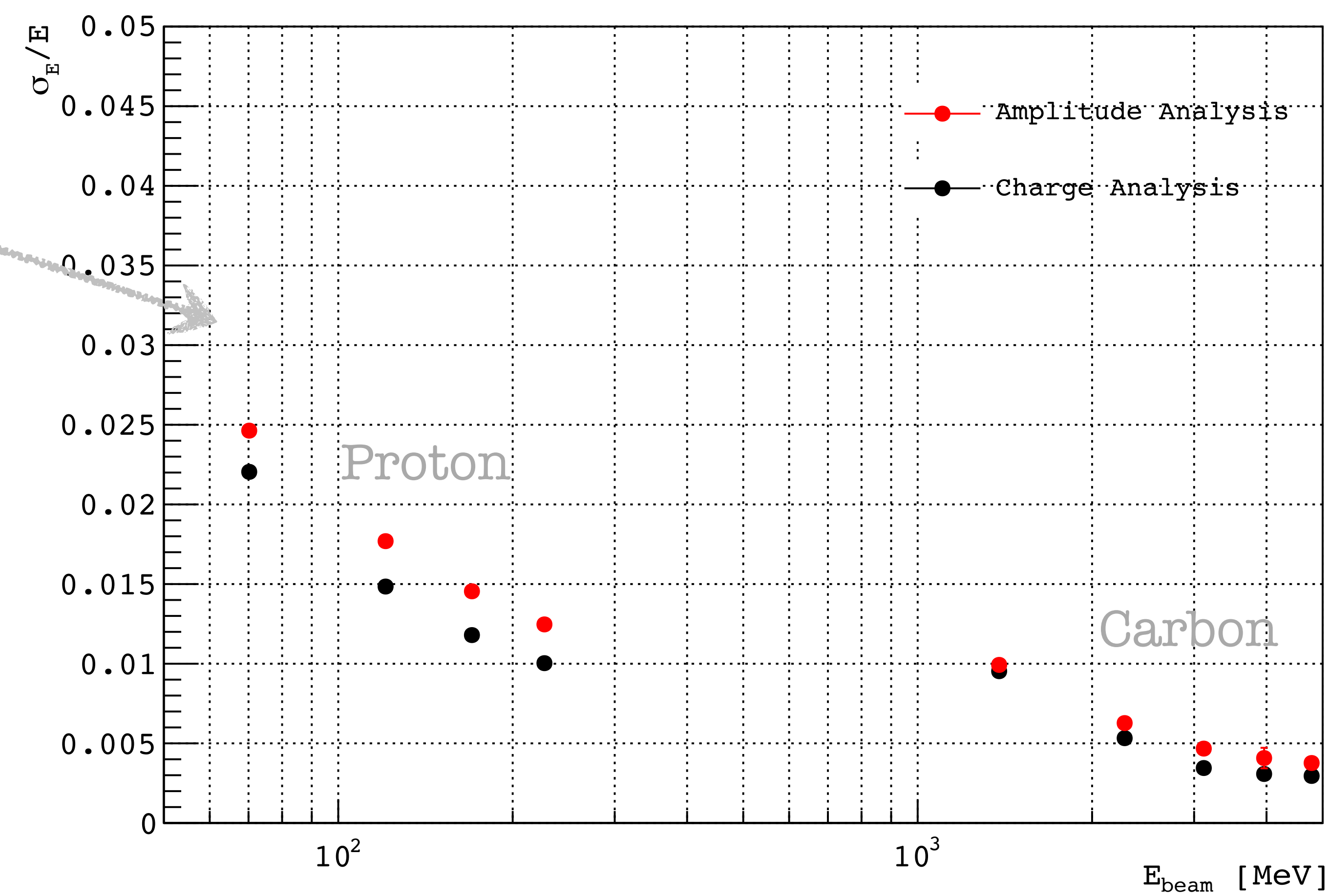
Test beam results

October 2019



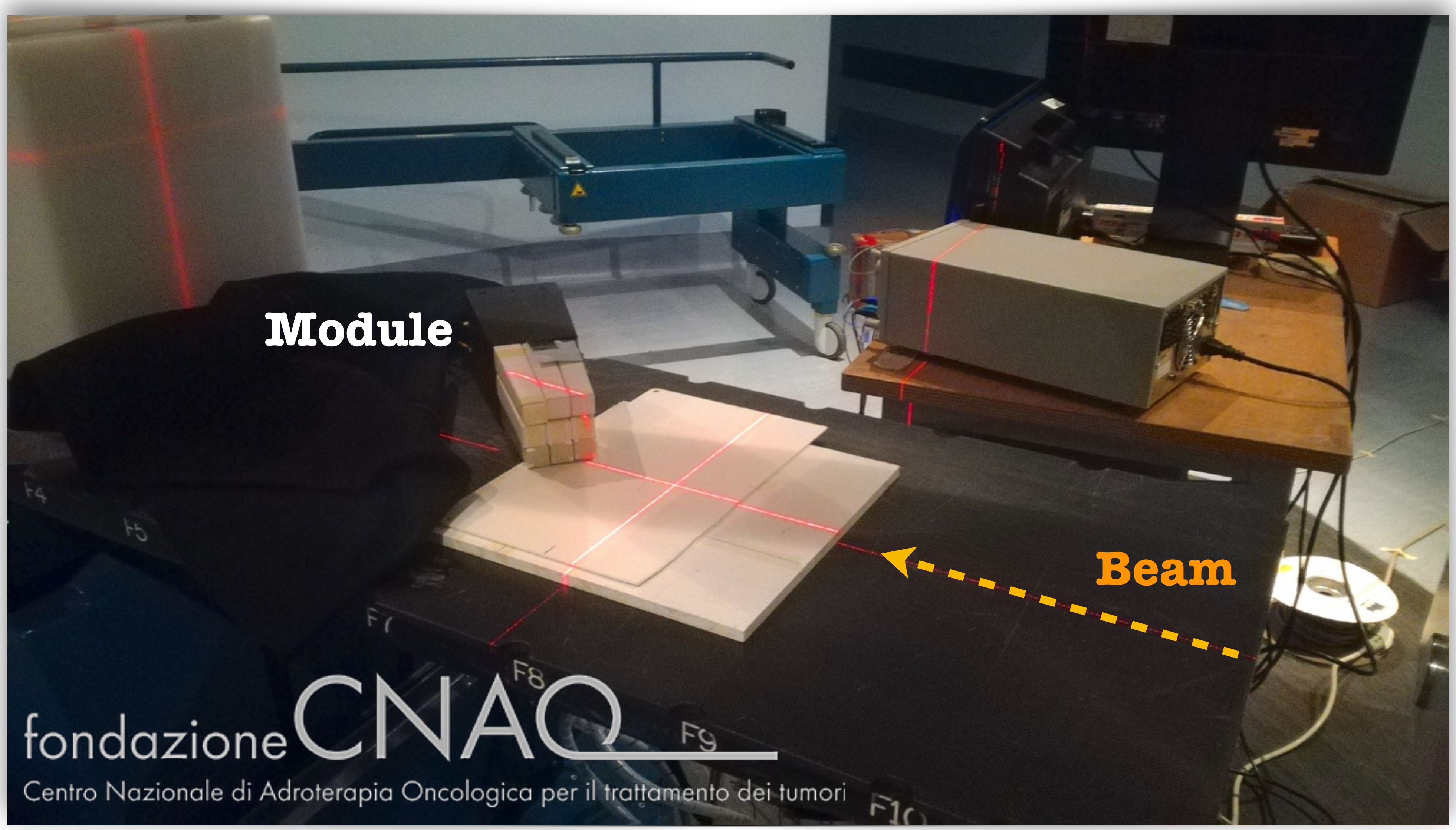






p beam: 70, 120, 170, 220 MeV
C beam: 115, 190, 260, 330, 400 MeV/u

November 2019



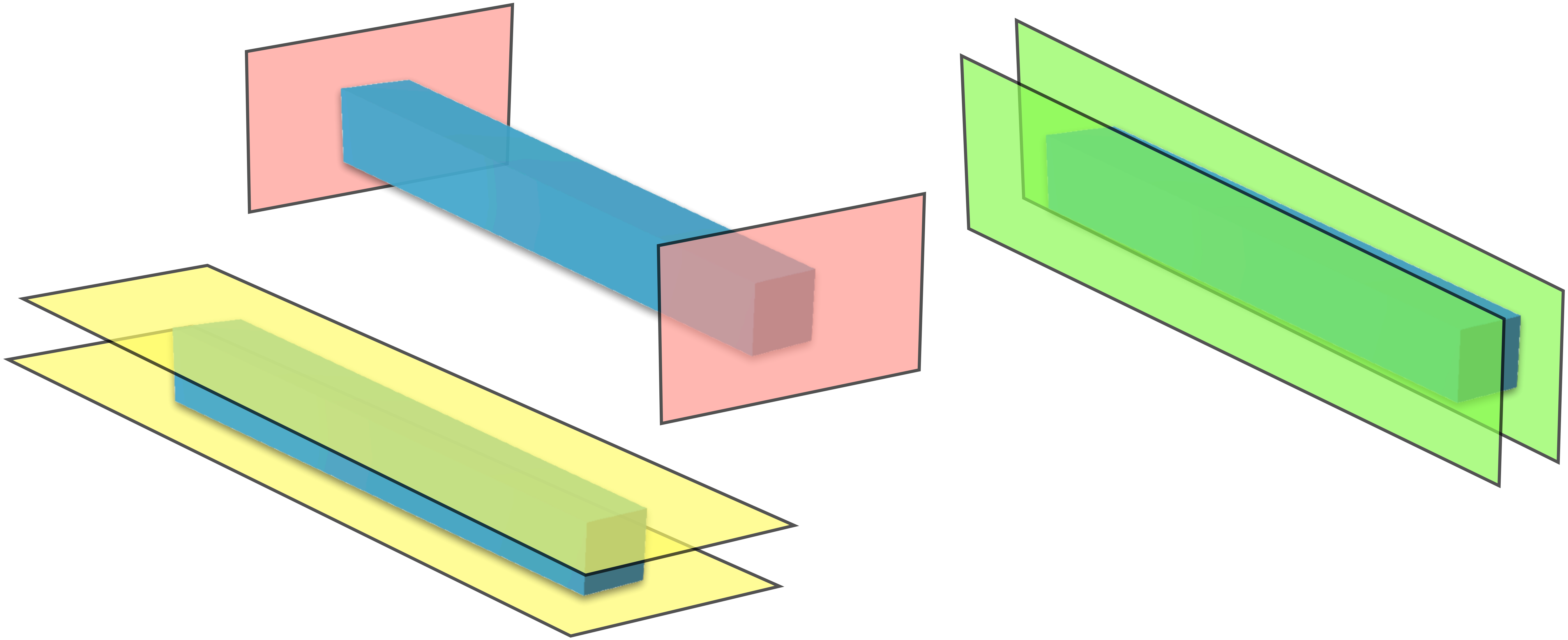
Test beam on the first module of the calorimeter:

- proton and carbon scans in the 9 crystal with module parallel to the beam line
- proton and carbon scans with the module rotated of 25°, 30° and 45°
- analysis is ongoing

Calorimeter geometry in FLUKA

The challenge: the crystals of calorimeter have truncated pyramid shape: there isn't among the standard bodies in FLUKA

Solution: intersection of 6 different planes (PLA body)



Difficulty encountered: definition of air region

Difficulty encountered with FLUKA

One crystal:

AIR 5 air — ... — (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)

n crystal:

AIR 5 air — ... — (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)
— ...
— ...
— (PLA0n1+PLA0n2+PLA0n3+PLA0n4+PLA0n5+PLA0n6)

too many parenthesis! X

Difficulty encountered with FLUKA

One crystal:

AIR 5 air — ... — (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)

n crystal:

AIR 5 air — ... — (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)
— ...
— ...
— (PLA0n1+PLA0n2+PLA0n3+PLA0n4+PLA0n5+PLA0n6)

too many parenthesis! X

Solution0: write the air definition w/o parenthesis

Difficulty encountered with FLUKA

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AIR 5 air – ... – (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)

n crystal:

AIR 5 air – ... – (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)
– ...
– ...
– (PLA0n1+PLA0n2+PLA0n3+PLA0n4+PLA0n5+PLA0n6)

too many parenthesis! **x**

Solution0: write the air definition w/o pa **x** nthesis ⟶ too difficult for 288 crystals

Difficulty encountered with FLUKA

One crystal:

AIR 5 air – ... – (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)

n crystal:

AIR 5 air – ... – (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)
– ...
– ...
– (PLA0n1+PLA0n2+PLA0n3+PLA0n4+PLA0n5+PLA0n6)

too many parenthesis! X

Solution0: write the air definition w/o parenthesis X ⟶ too difficult for 288 crystals

Solution1: AIR 5 air – ... – (...airPLAmod1...)–(...airPLAmod2...)– ...

Difficulty encountered with FLUKA

One crystal:

AIR 5 air – ... – (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)

n crystal:

AIR 5 air – ... – (PLA001+PLA002+PLA003+PLA004+PLA005+PLA006)
– ...
– ...
– (PLA0n1+PLA0n2+PLA0n3+PLA0n4+PLA0n5+PLA0n6)

too many parenthesis! X

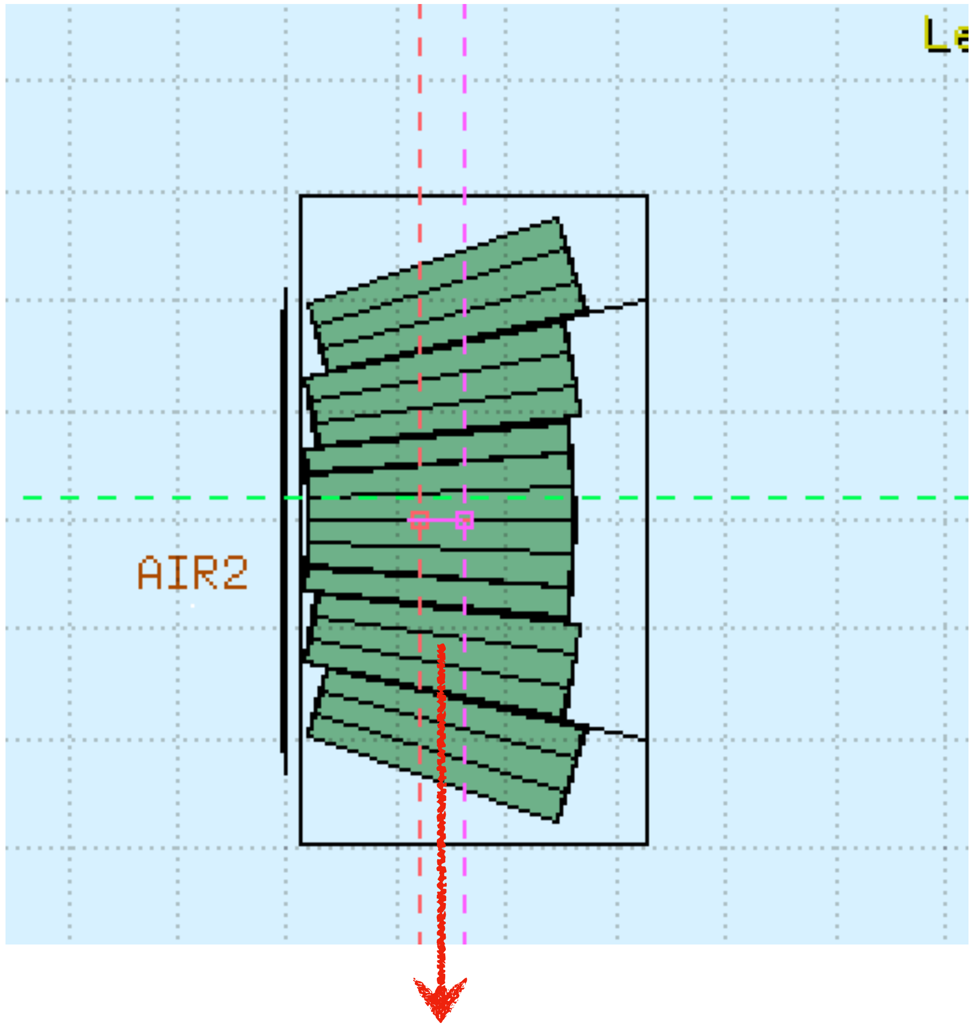
Solution0: write the air definition w/o p X nthesis ⟶ too difficult for 288 crystals

Solution1: AIR 5 air – ... – (...PL X mod1...)–(...PLAmod2...)– ...

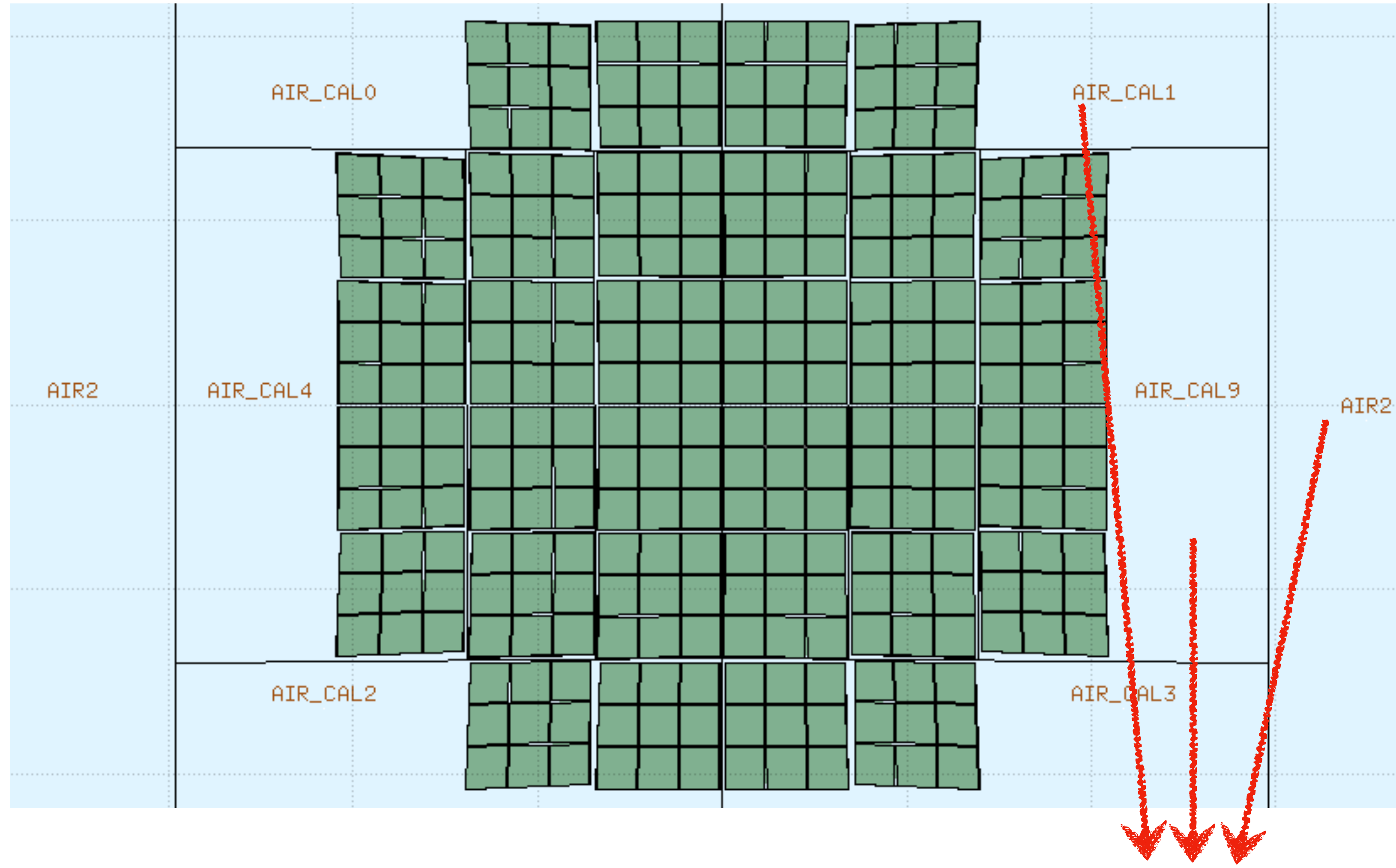
again too many parenthesis!

Solution2: divide the main air in different smaller pieces containing 4 air module boxes each

Full geometry

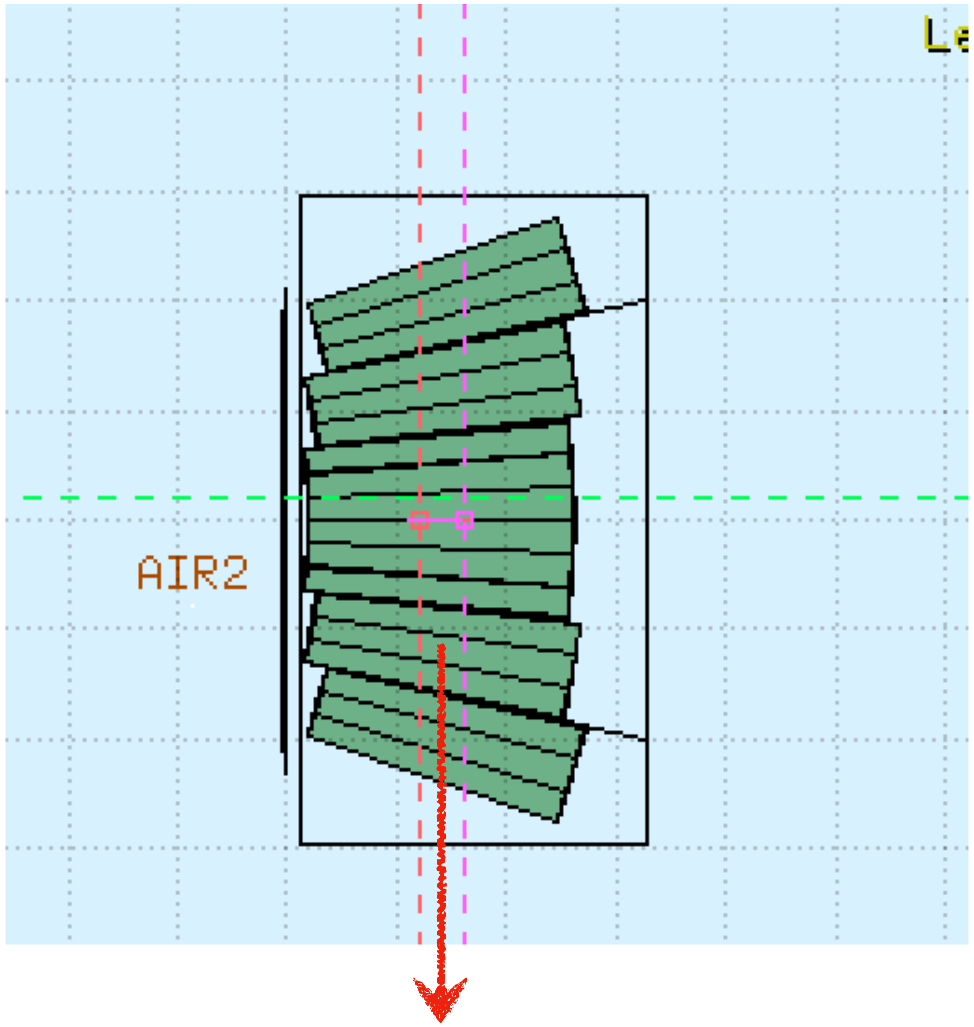


Module aren’t perfectly aligned

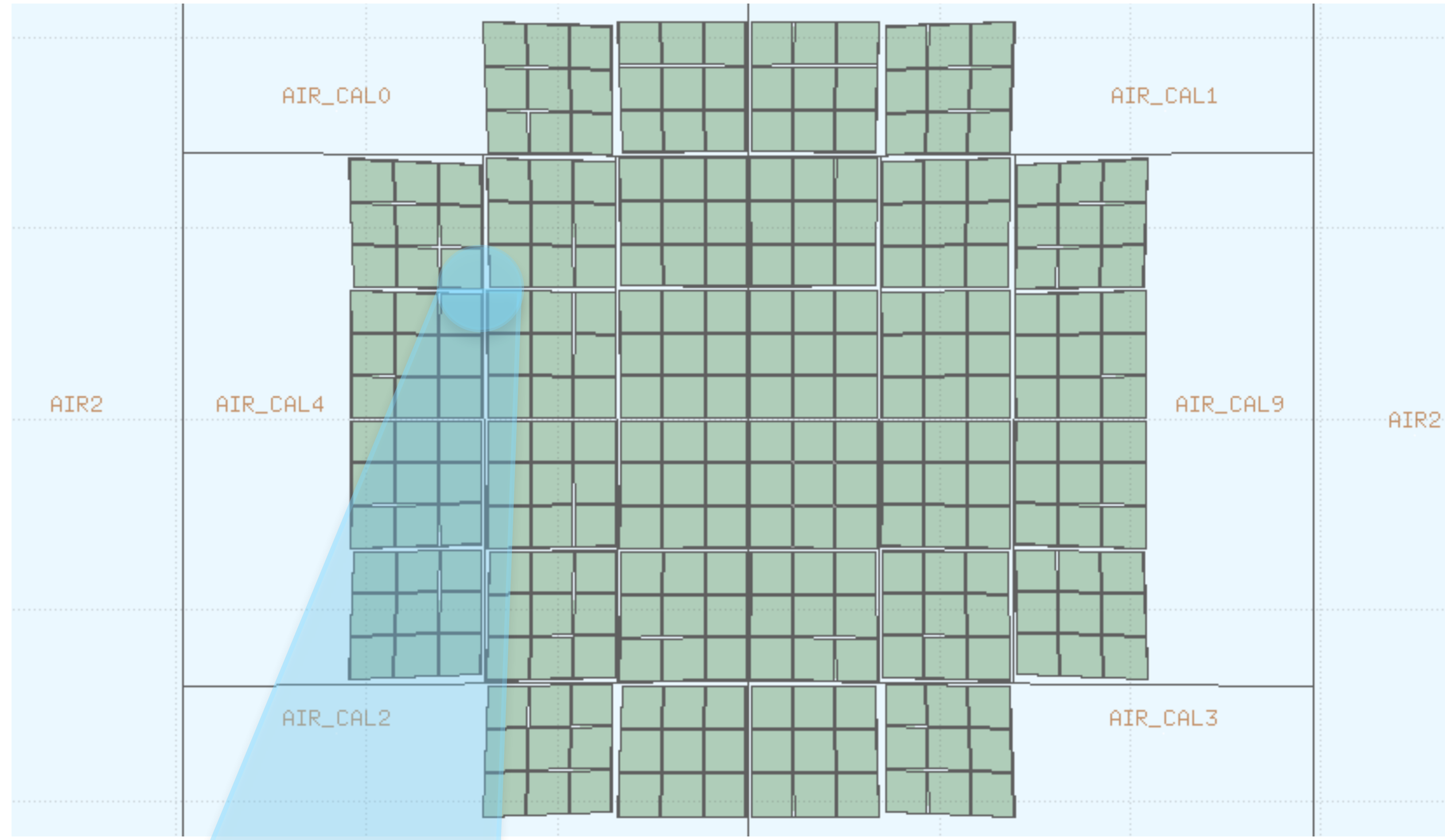


10 different air boxes
with 4 air module boxes

Full geometry



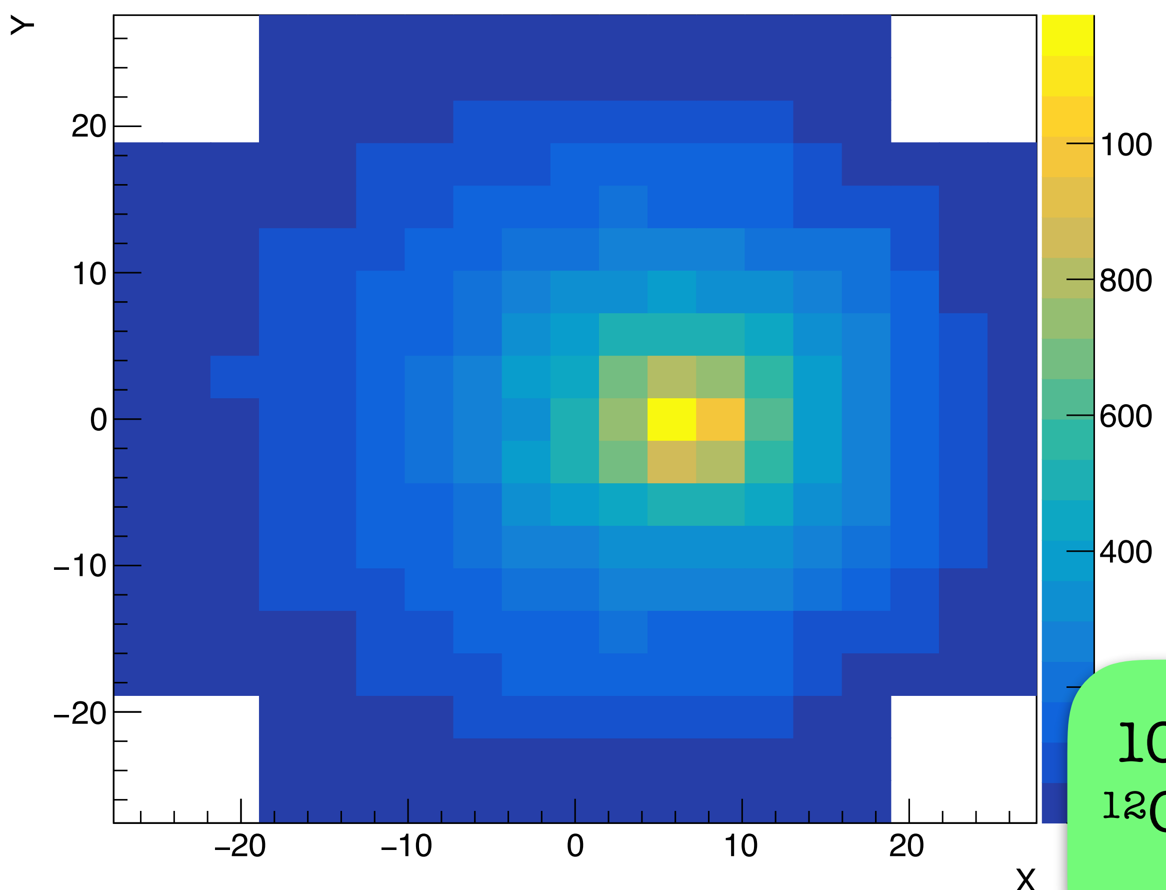
Module aren’t perfectly aligned

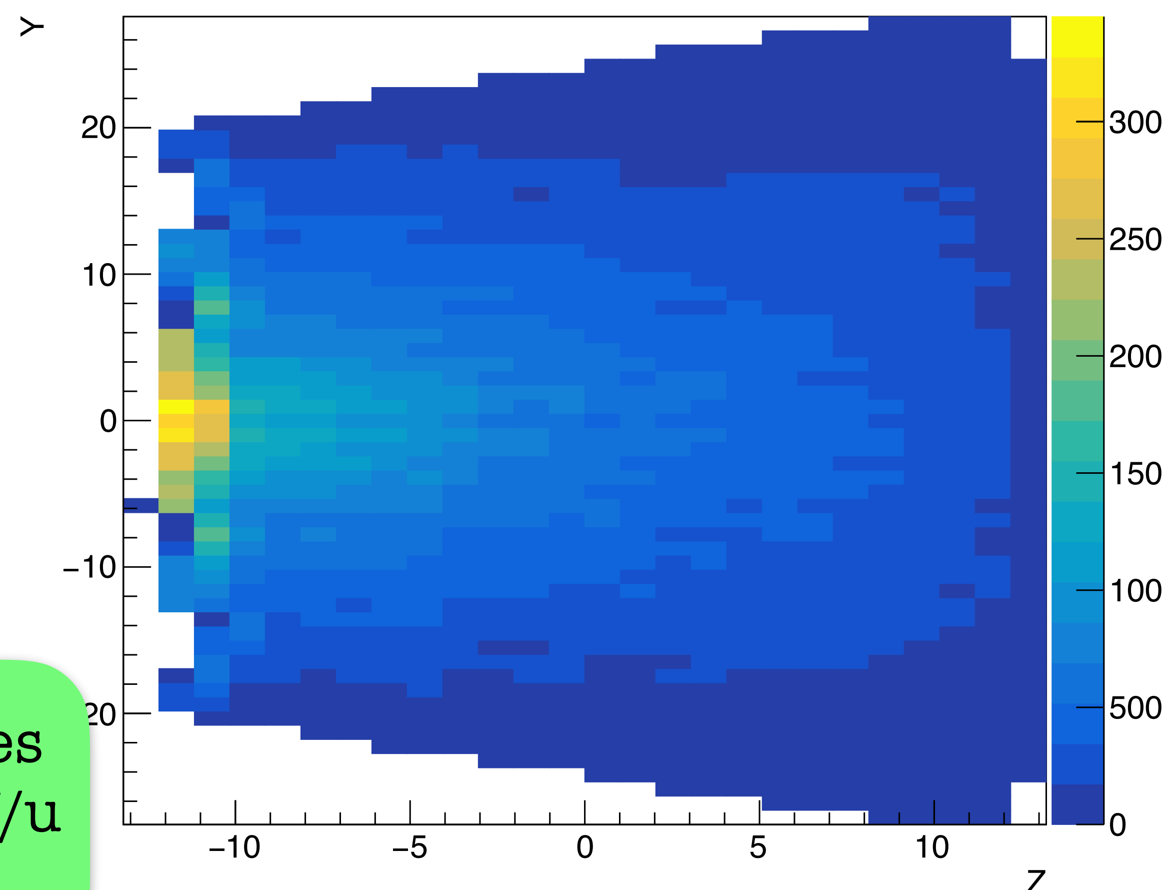


Hard coded! !

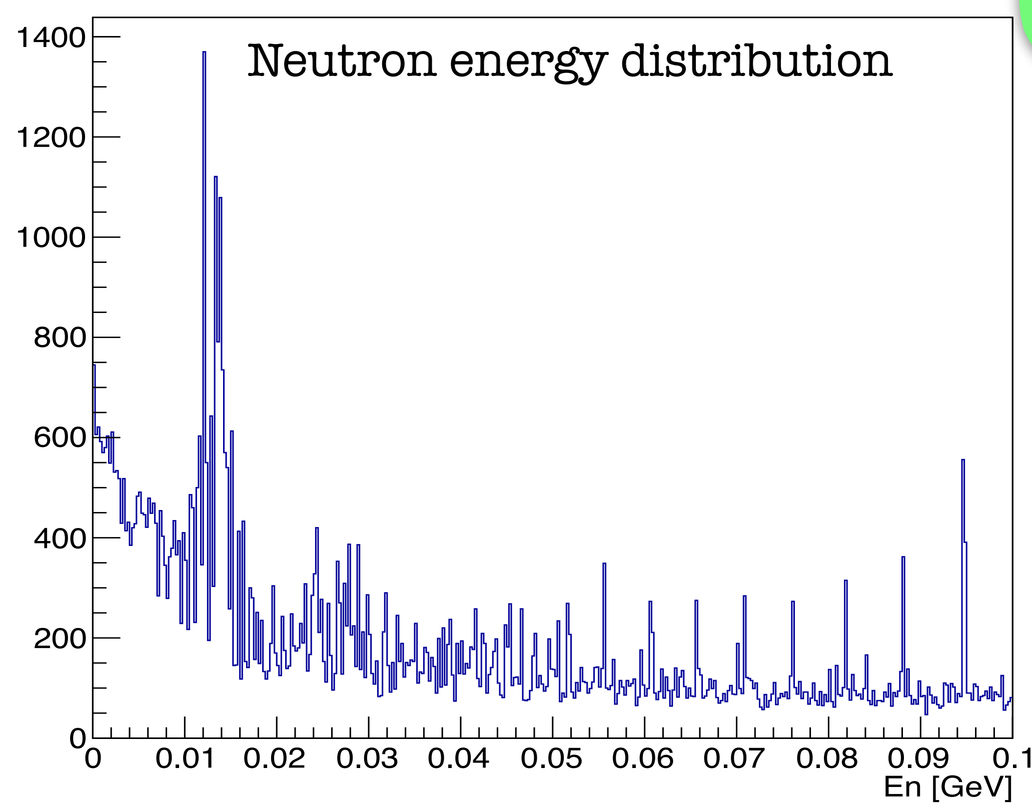
Warning: the geometry of calorimeter is pointing and some regions could be overlapped: little pieces of air between different modules were added by hand

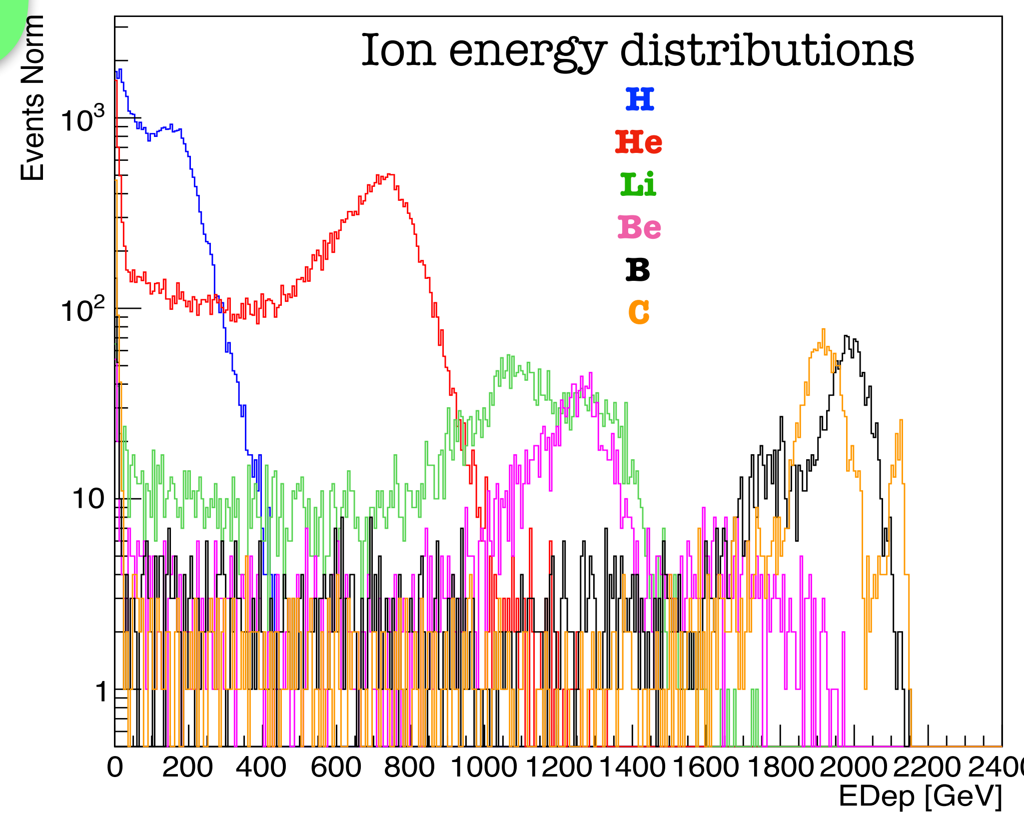
preliminary MonteCarlo results





10^7 primaries
^{12}C 200 MeV/u
C target





Conclusions

- FOOT experiment will measure differential cross section for secondary fragment production relevant for handrontherapy and radioprotection in space
- The combination of different detectors will provide a robust measurement of energy as well as fragment identification through A
- The first calorimeter module was constructed and tested at CNAO
- The performance achieved are encouraging (energy resolution < 2%)
- The full calorimeter geometry in FLUKA is ready and has been added in FOOT framework

Thank you for the attention!

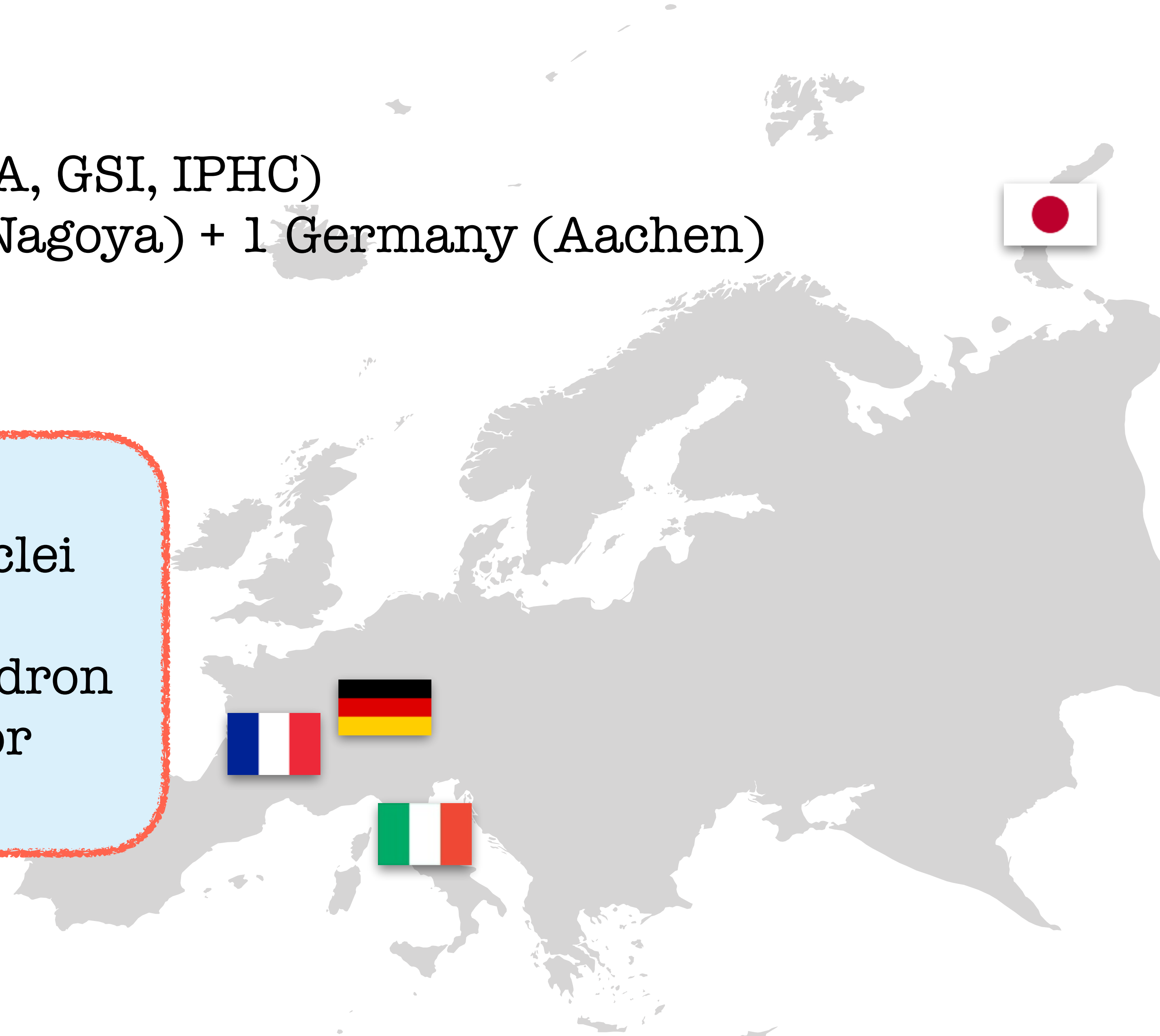
BACKUP

FOOT: Collaboration

FOOT (**F**ragmentati**O**n **O**f **T**arget) is an experiment under construction approved by INFN (**I**stituto **N**azionale di **F**isica **N**ucleare) in 2017

Comprises about 100 members:

- 10 INFN sections
- 5 laboratories (Frascati, CNAO, TIFPA, GSI, IPHC)
- 14 universities (12 Italy + 1 Japan (Nagoya) + 1 Germany (Aachen)

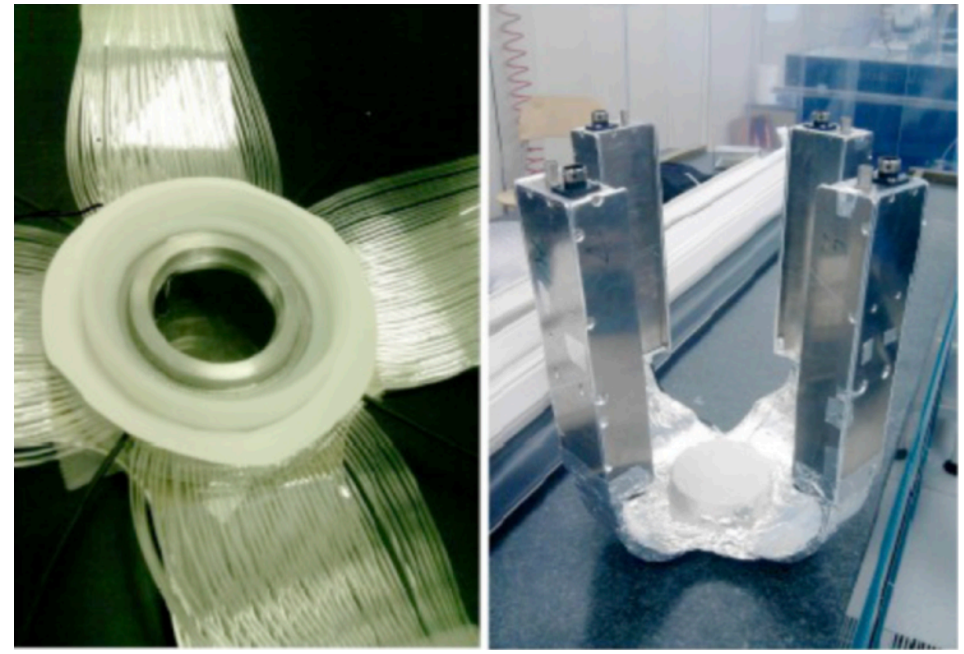


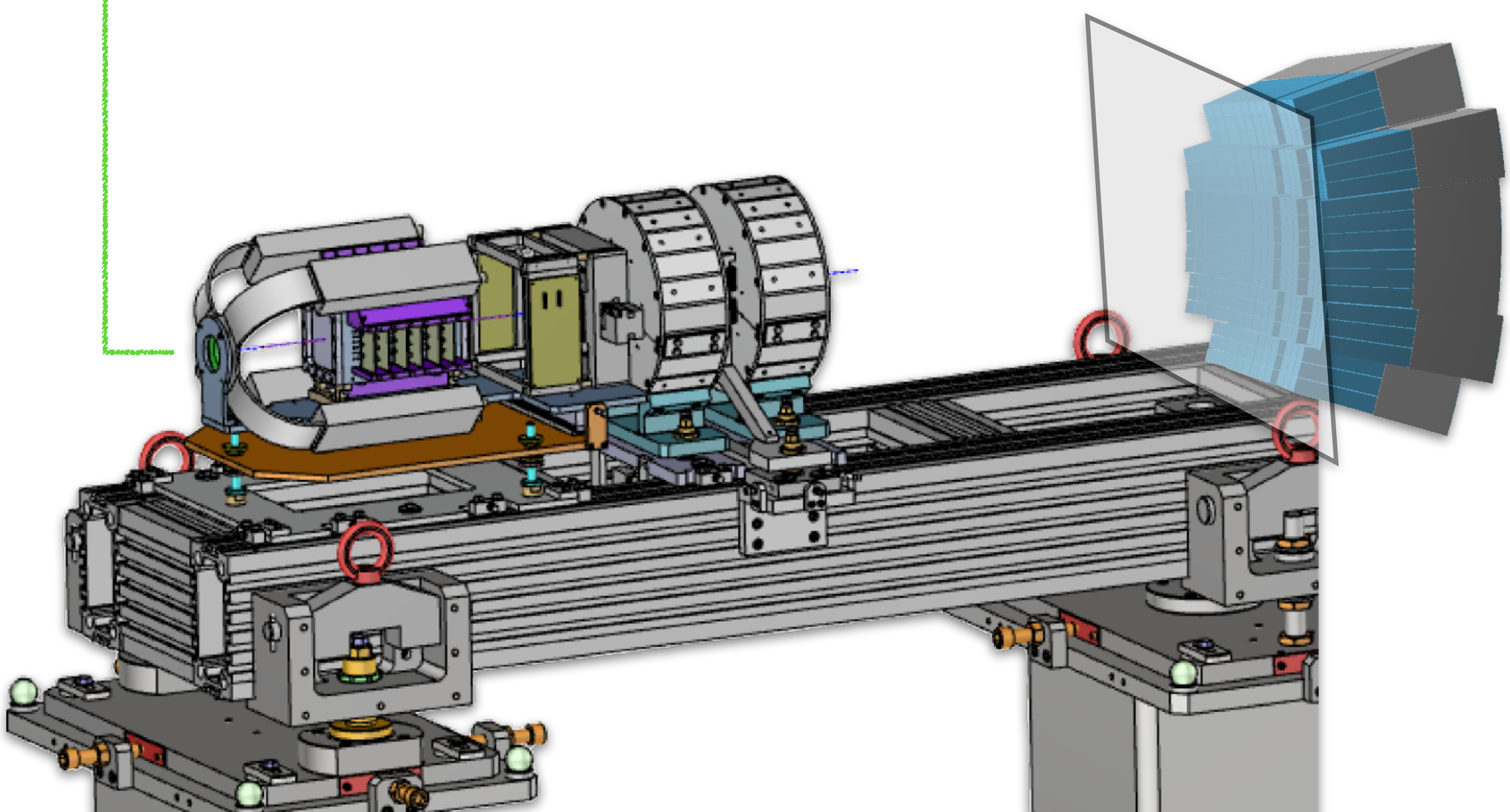
GOAL

Measurement of proton and light nuclei fragmentation cross sections in order to improve the TPS for the hadron therapy and the radio protection for space missions

- Trigger
- Start for TOF

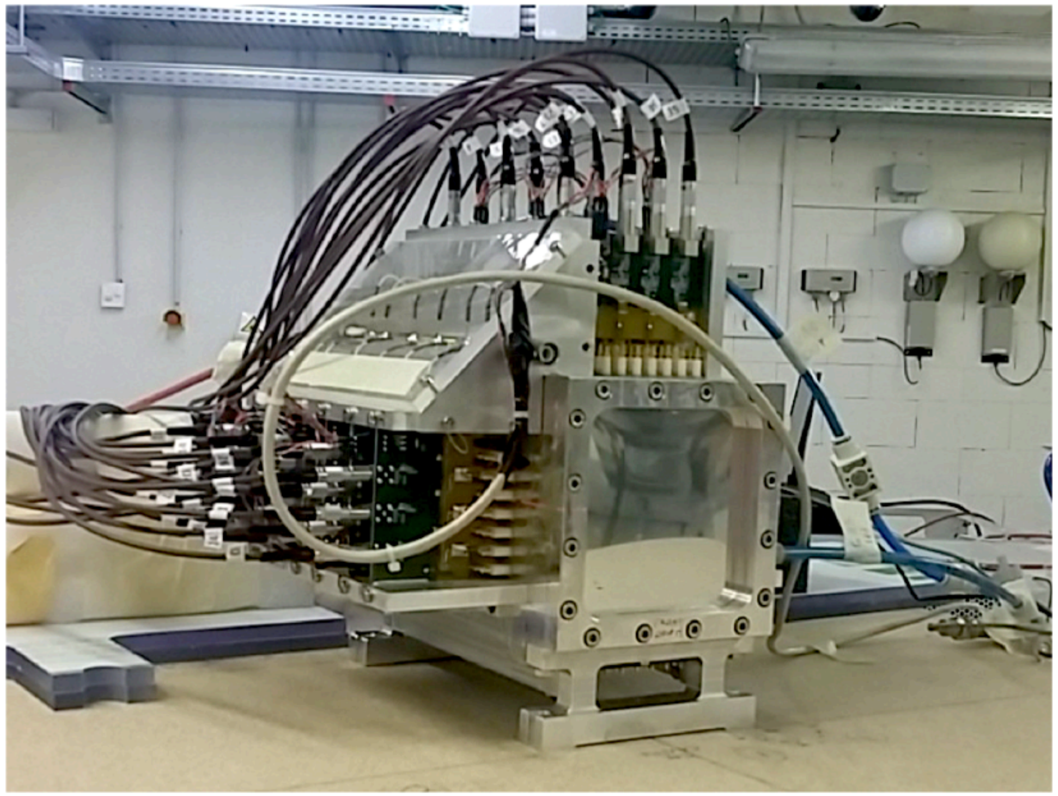
- Plastic Scintillator
- Radius = 50 mm
- Thick = 250 μm
- Readout: 4 PMTs w/ 400 optical fibers

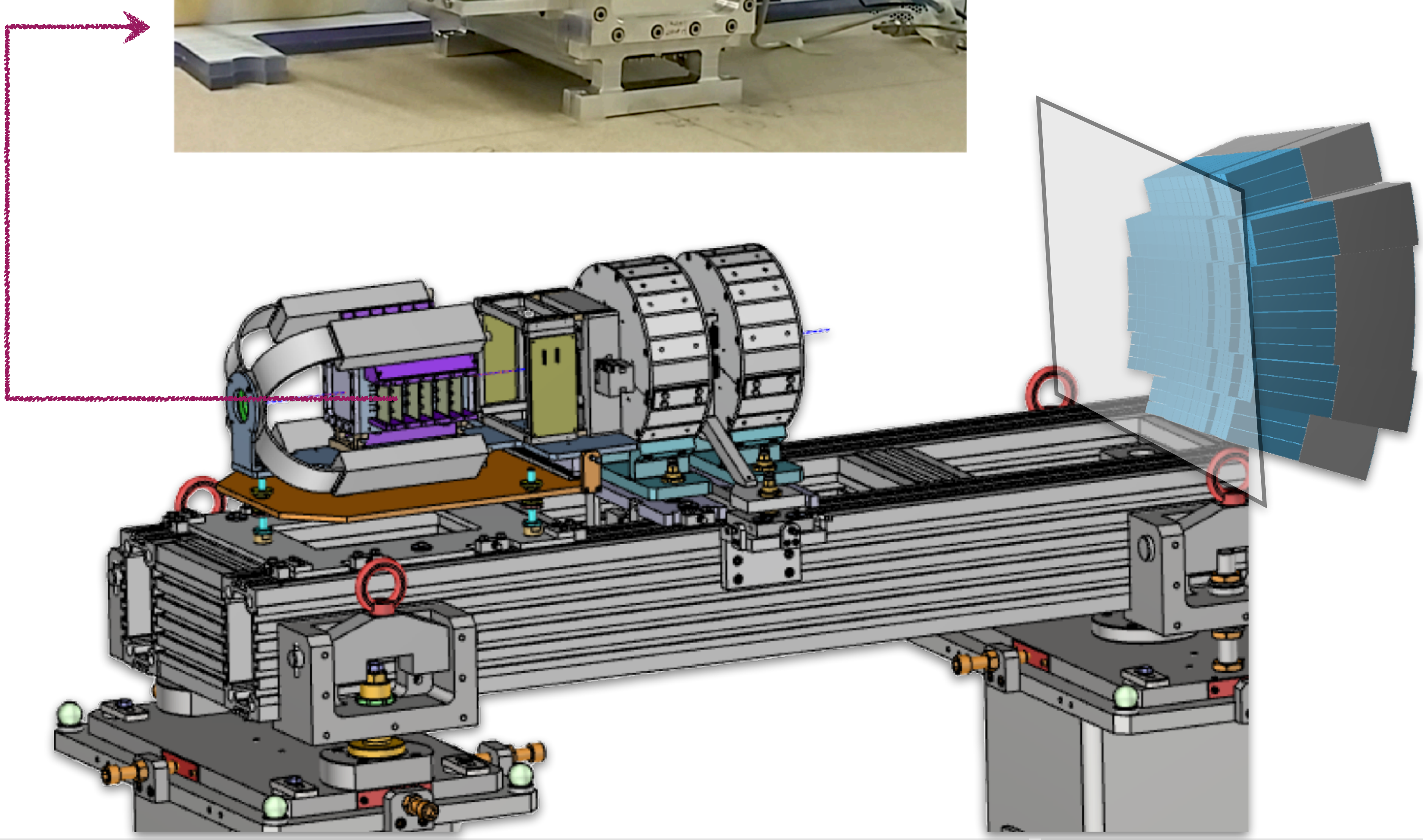




- Direction of the beam

- Gaseous drift chamber
- Ar (80%) + CO_2 (20%)

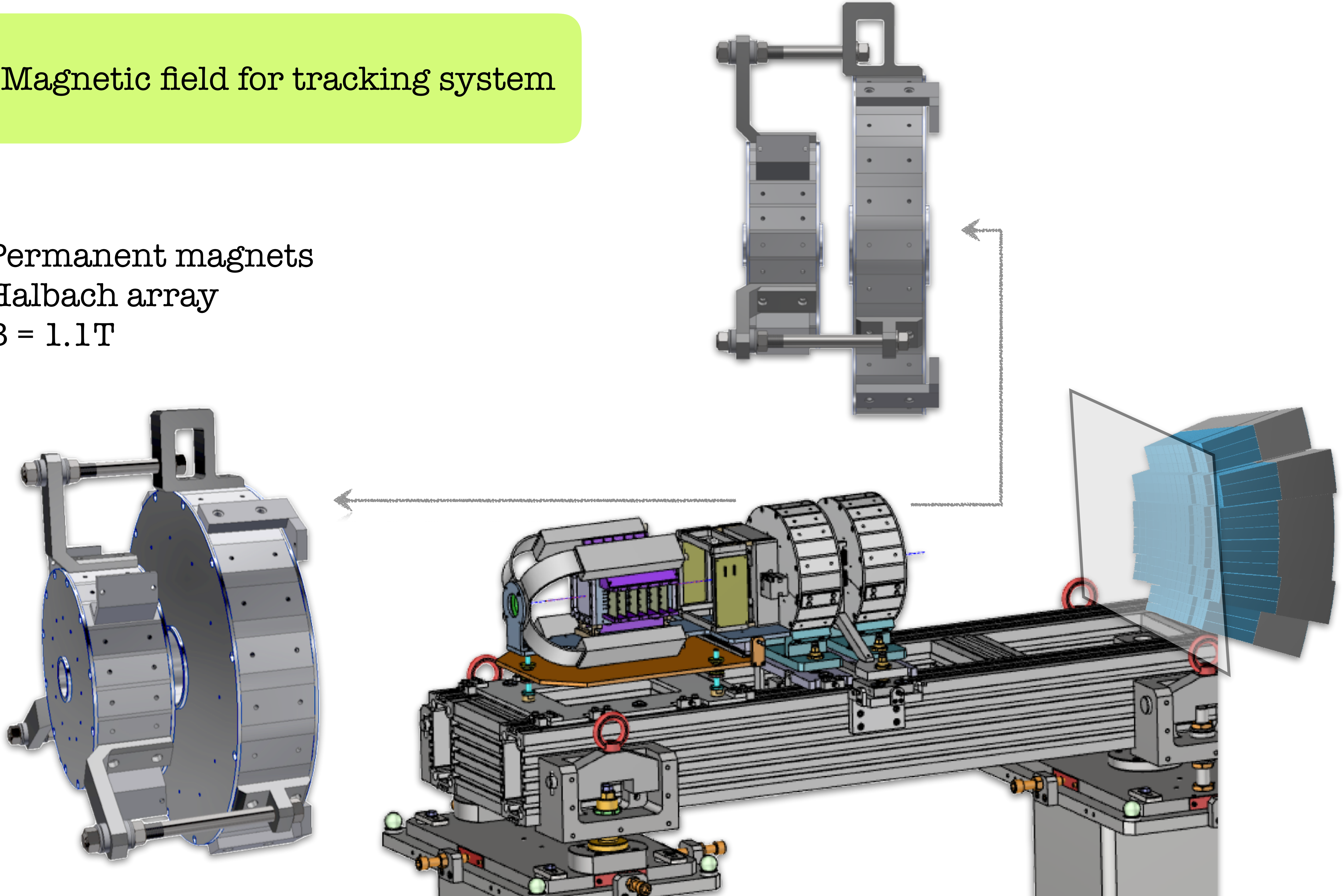




FOOT: Magnets

- Magnetic field for tracking system

- Permanent magnets
- Halbach array
- B = 1.1T

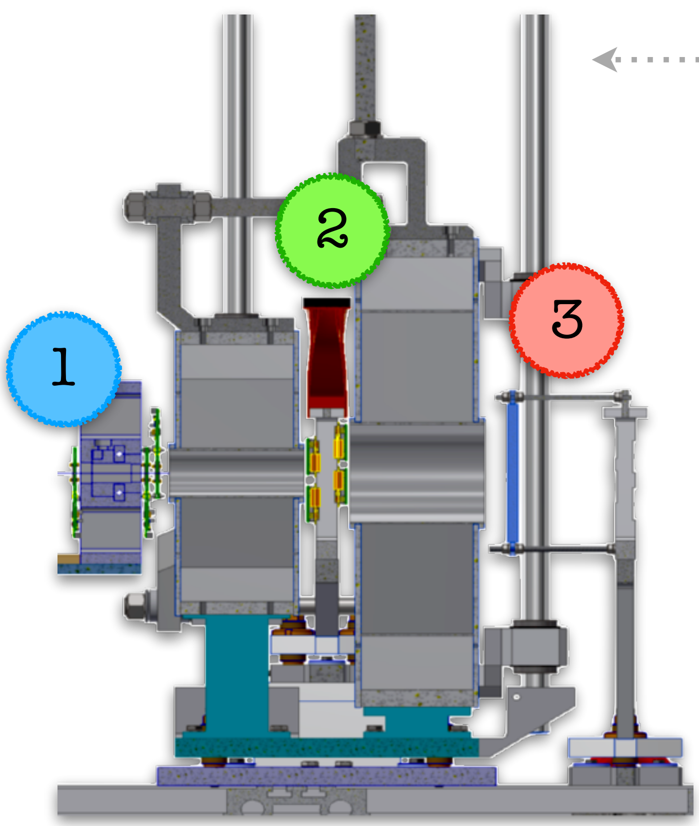


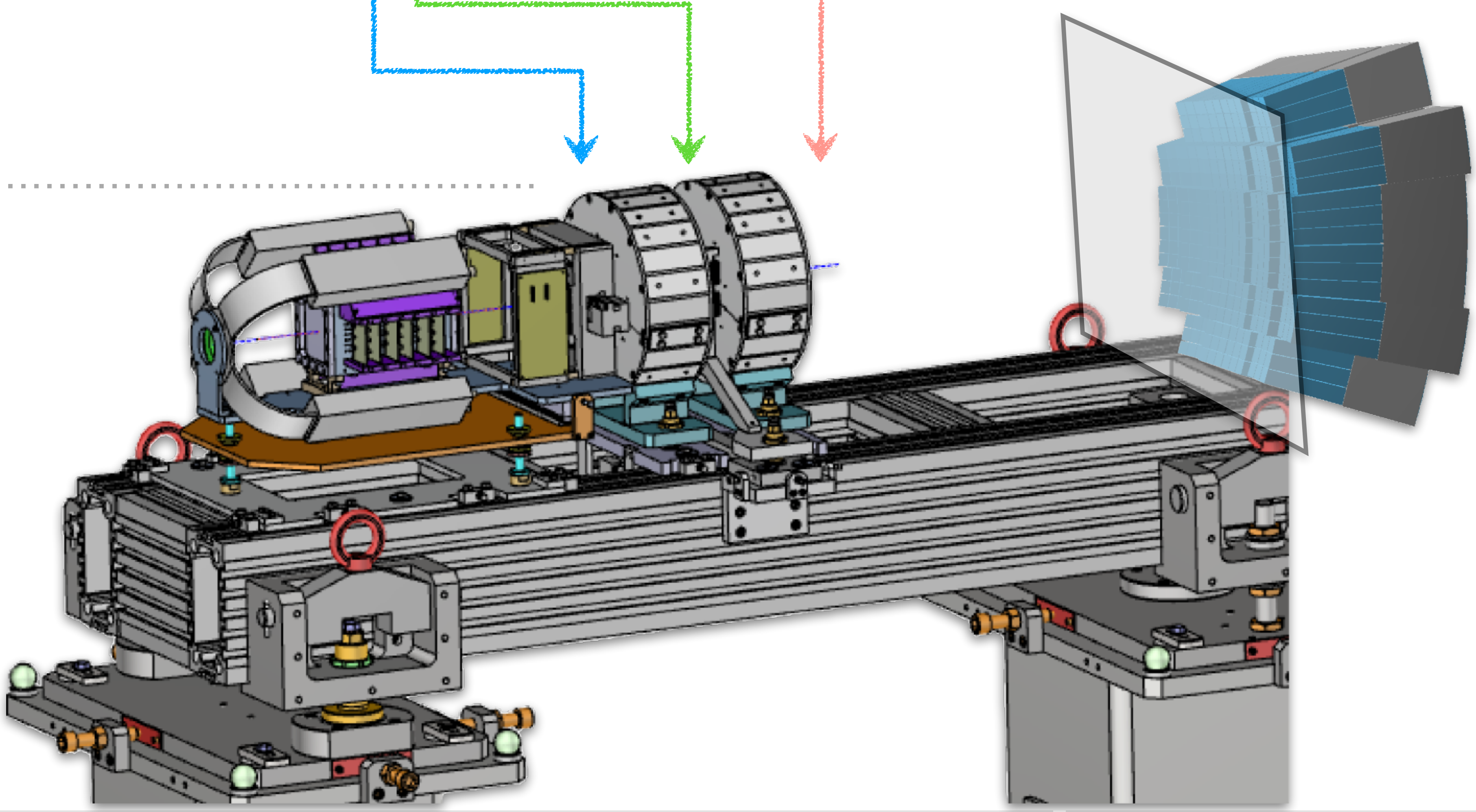
FOOT: Tracking System

1. Target: C_2H_4 + C

1. **4** layers of Si **pixel** sensor **before** magnets (20x20 µm pitch)
2. **2** layers of Si **pixel** sensor **between** magnets (20x20 µm pitch)
3. **3** layers of Si **strip** sensor **after** magnets (120 µm pitch)

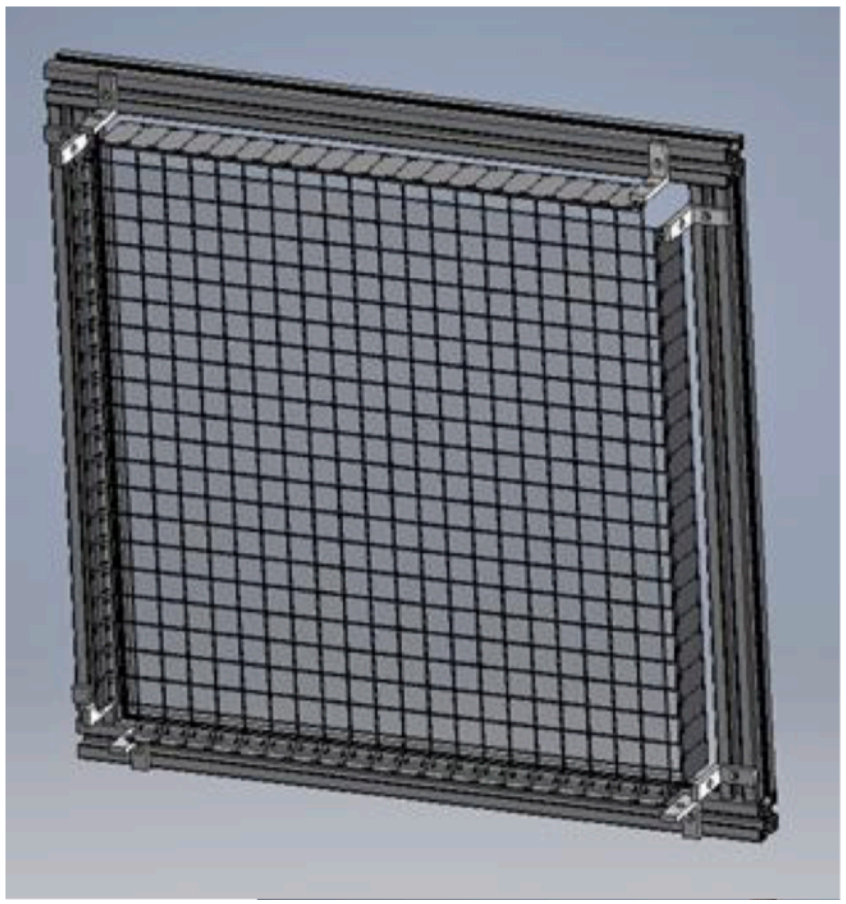
- Tracks
- Momentum

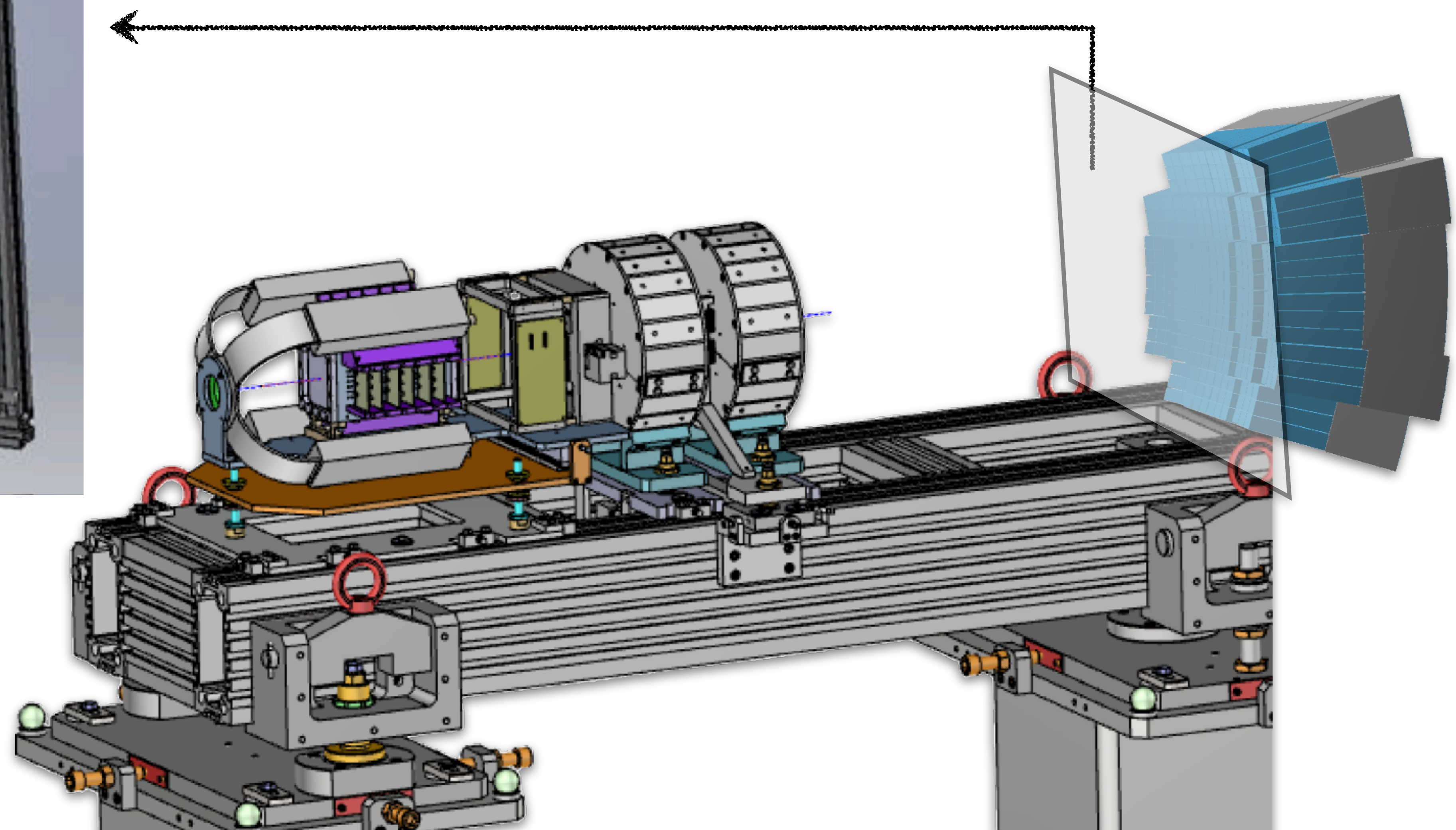




- 2 layers x20 bars of plastic scintillator
- readout w/ SiPMs

- dE/dx
- Stop for TOF
- Z





Test beam update:

$\Delta p/p \sim 4\,\%$

$\Delta E_k/E_k \sim 1.5\,\%$

$\Delta TOF \sim 70 - 140\ ps$

$\Delta(dE)/dE \sim 3 - 10\,\%$

ΔE+TOF: 40 ps

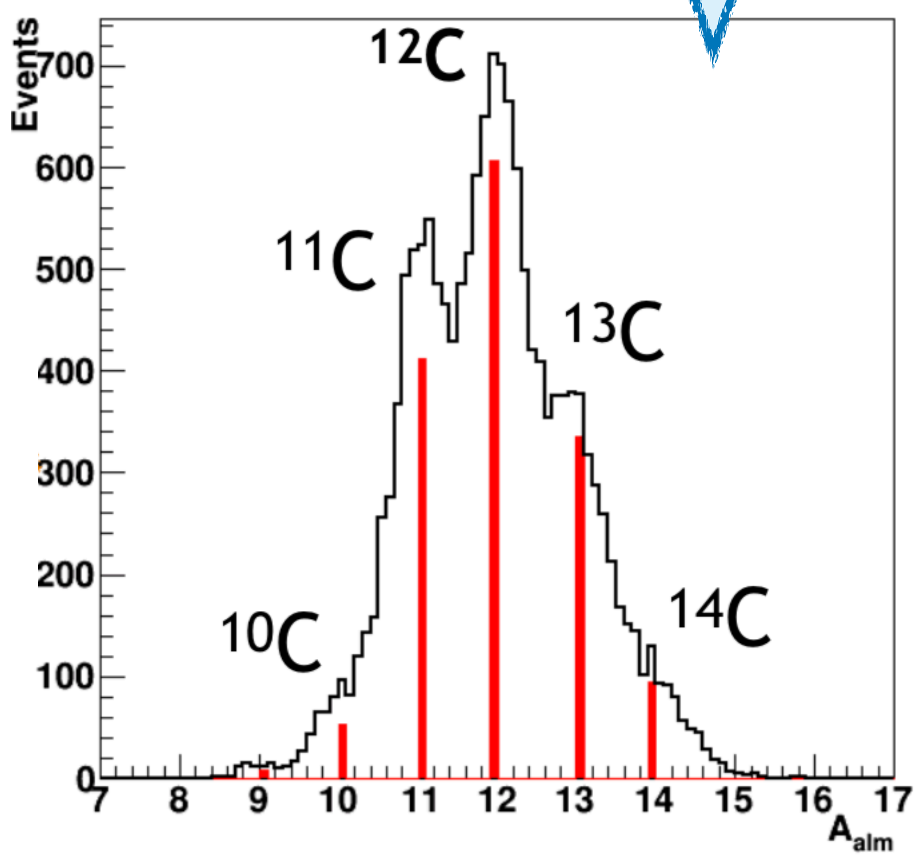
Calo: 1%

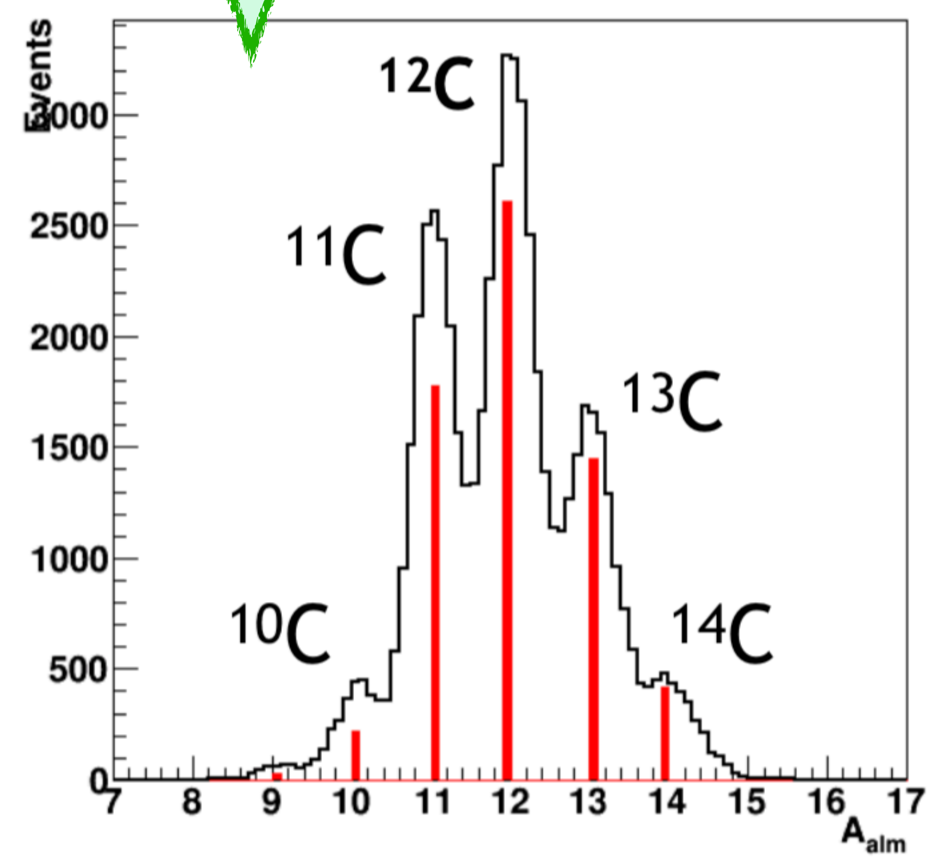
$\Delta p/p \sim 4\,\%$

$\Delta E_k/E_k \sim 1\,\%$

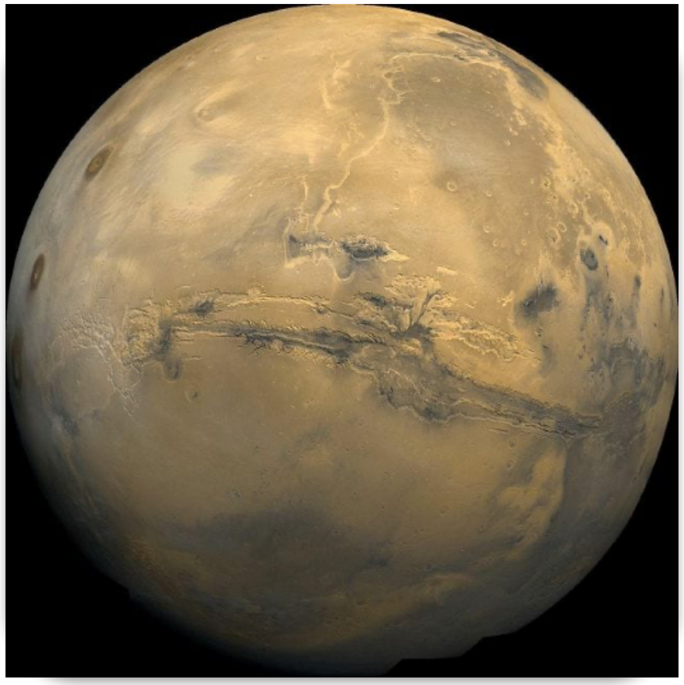
$\Delta TOF \sim 100\ ps$

$\Delta(dE)/dE \sim 3 - 10\,\%$





Possibility to distinguish isotopes!

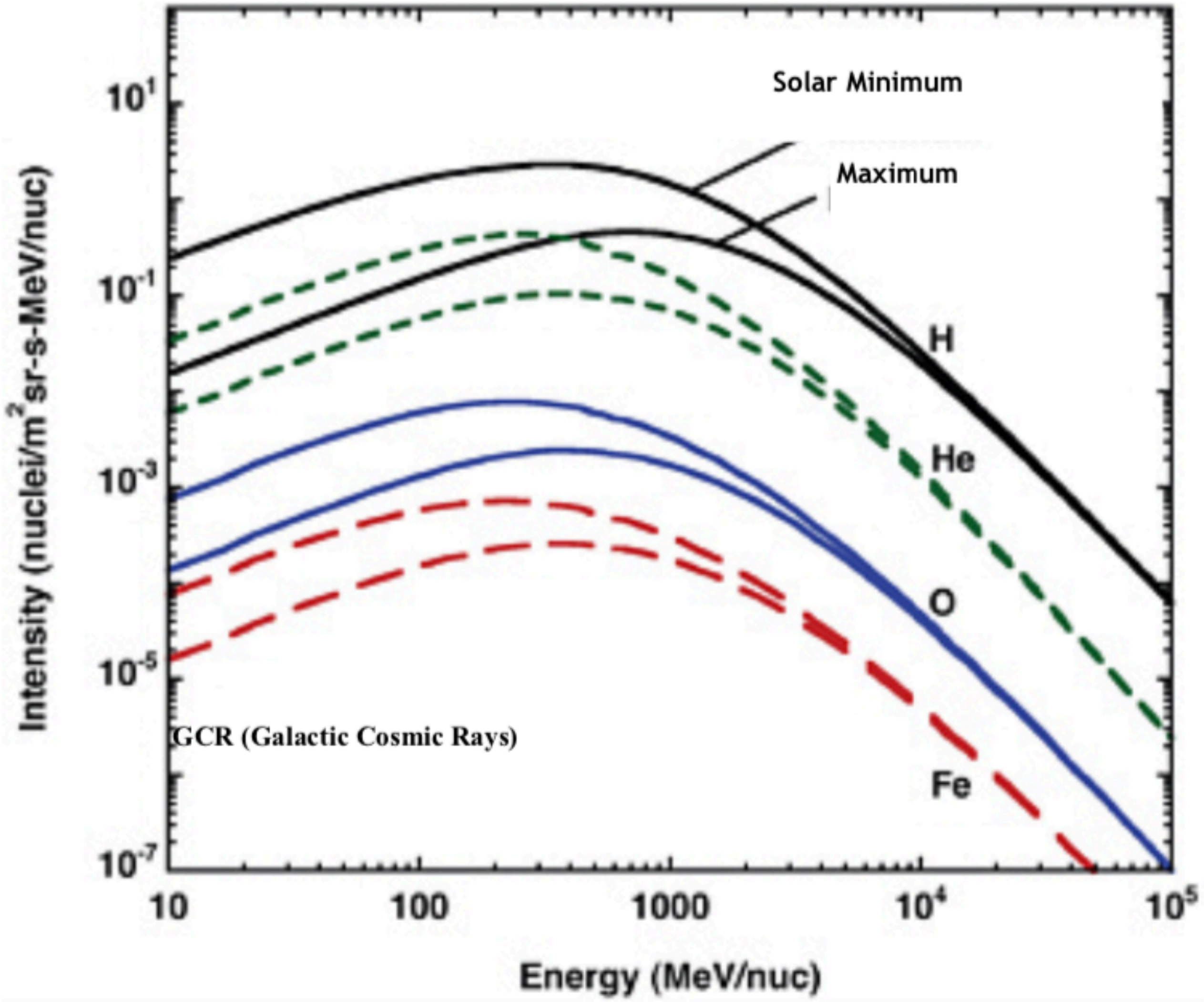


Mission to Mars!

No magnetosphere
Very thin atmosphere → No protection to GCR and SPE

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

On Earth: 2.64 mSv/year



Best determination of A

Two procedures for the best determination of A:

- a standard minimization:

$$f = \left(\frac{TOF - T}{\sigma_{TOF}}\right)^2 + \left(\frac{p - P}{\sigma_p}\right)^2 + \left(\frac{E_k - K}{\sigma_{E_k}}\right)^2 + \tag{9}$$
$$(A_1 - A, \quad A_2 - A, \quad A_3 - A) \begin{pmatrix} B_{00} & B_{01} & B_{02} \\ B_{10} & B_{11} & B_{12} \\ B_{20} & B_{21} & B_{22} \end{pmatrix} \begin{pmatrix} A_1 - A \\ A_2 - A \\ A_3 - A \end{pmatrix}$$

where TOF, p, E_k, A_1, A_2 and A_3 are the reconstructed quantities, σ_{TOF}, σ_p, σ_{E_k} are the uncertainties, T, P, K and A are the fit output parameters.

- an Augmented Lagrangian Method (ALM):

The ALM approach performs a constrained minimization in a large parameter space. All the details of the method can be find in [100]. Here only the basilar points are recalled, to allow a better comprehension of the text. The method minimizes a Lagrangian function L expressed by:

$$L(\vec{x}, \lambda, \mu) \equiv f(\vec{x}) - \sum_a \lambda_a c_a(\vec{x}) + \frac{1}{2\mu} \sum_a c_a^2(\vec{x}) \tag{11}$$

where f, in analogy with the standard χ^2 method, is defined as:

$$f(\vec{x}) = \left(\frac{TOF - T}{\sigma_{TOF}}\right)^2 + \left(\frac{p - P}{\sigma_p}\right)^2 + \left(\frac{E_k - K}{\sigma_{E_k}}\right)^2 \tag{12}$$

both the summation runs over the three constraints (A_1, A_2 and A_3) with the relation:

$$\sum_a \lambda_a c_a(\vec{x}) + \frac{1}{2\mu} \sum_a c_a^2(\vec{x}) = \lambda_1 (A_1 - A) + \lambda_2 (A_2 - A) + \lambda_3 (A_3 - A) + \tag{13}$$
$$\frac{1}{2\mu} \left((A_1 - A)^2 + (A_2 - A)^2 + (A_3 - A)^2\right)$$

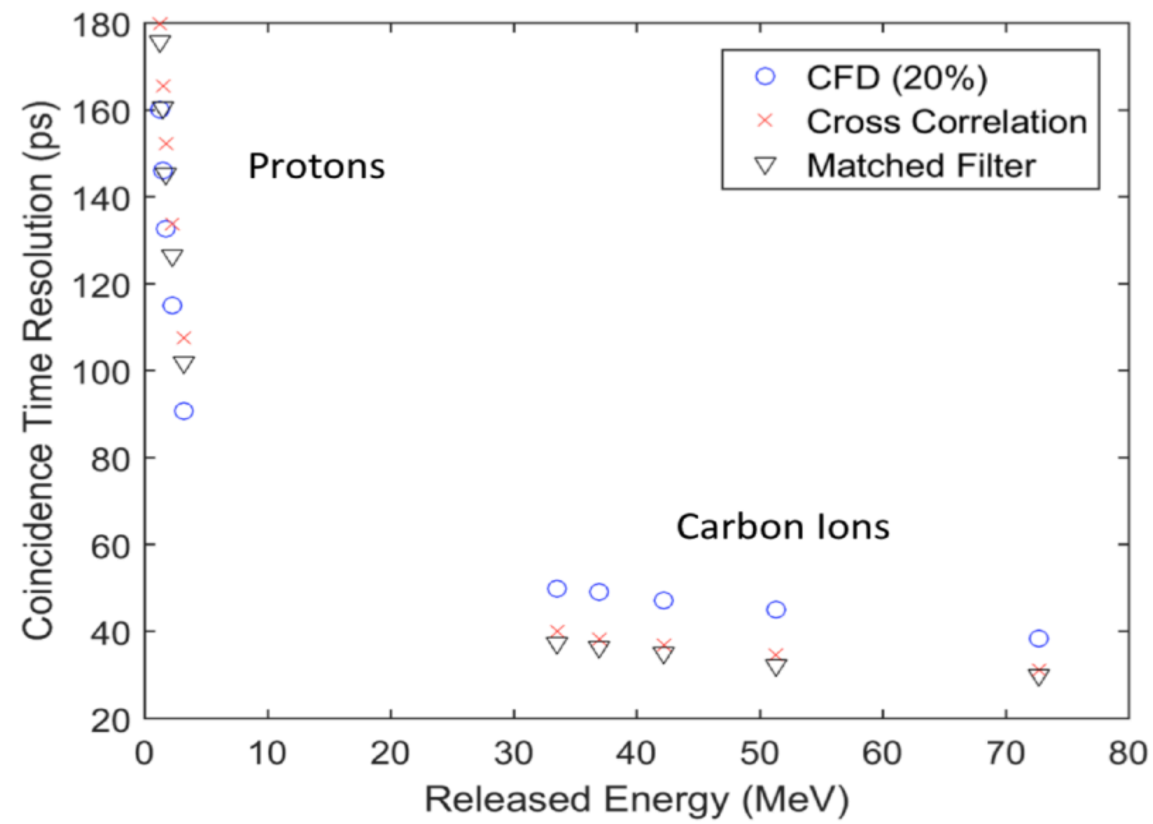
where λ are variable Lagrange multiplier parameters, while μ is the penalty term fixed to 0.1. The use of a penalty term forces the fit to give more strength to the constraints: the lower is μ the greater is the effect of the constraints.

from FOOT Conceptual Design Report

Charge Reconstruction

TOF and Start counter tested at CNAO:

- $\sigma_t \sim 90$ - 160 ps for protons
- $\sigma_t \sim 40$ - 50 ps for carbons



Bethe Bloch + ΔE-TOF:

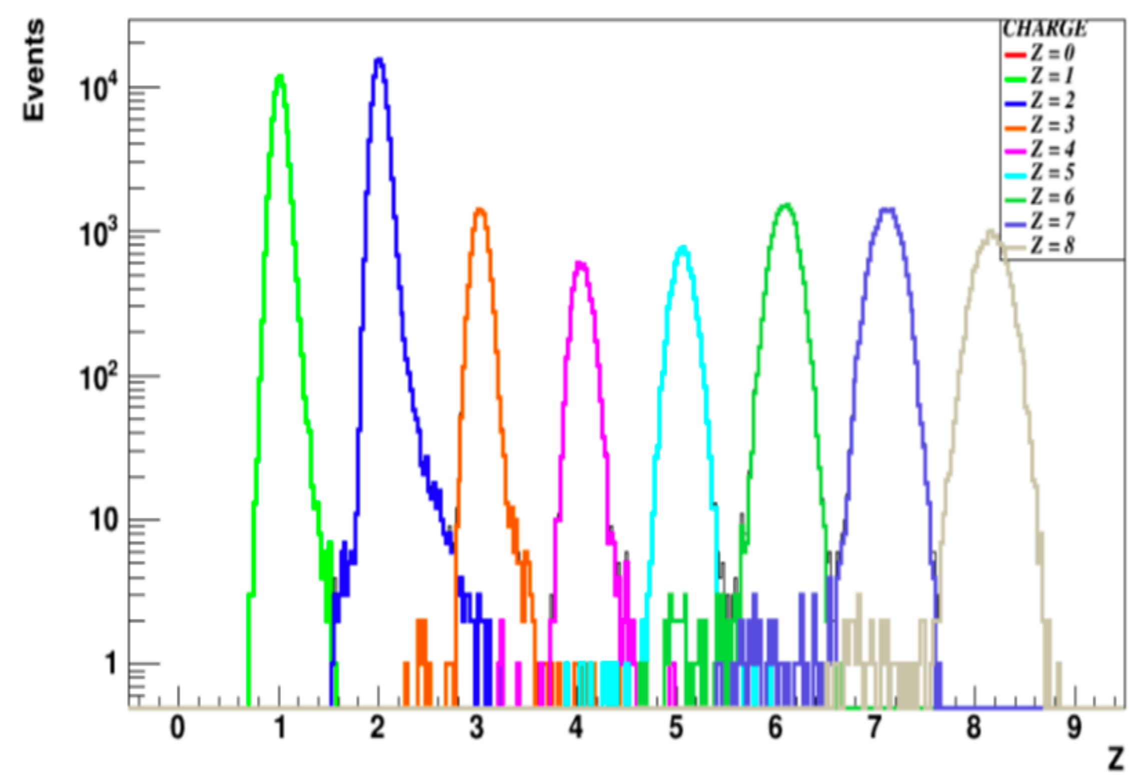
$$-\frac{dE}{dx} = Kz^2 * \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\cdot \ln\frac{2m_e c^2\beta^2\gamma^2 W_{max}}{I^2} - \beta^2\right]$$

ΔE+TOF

$$\beta = \frac{L}{TOF \cdot c}$$

From FLUKA simulations + σ_t measured at test beam:

- 2% < σ_Z < 6% for ^{16}O and ^{1}H respectively
- misidentification ≤ 1%

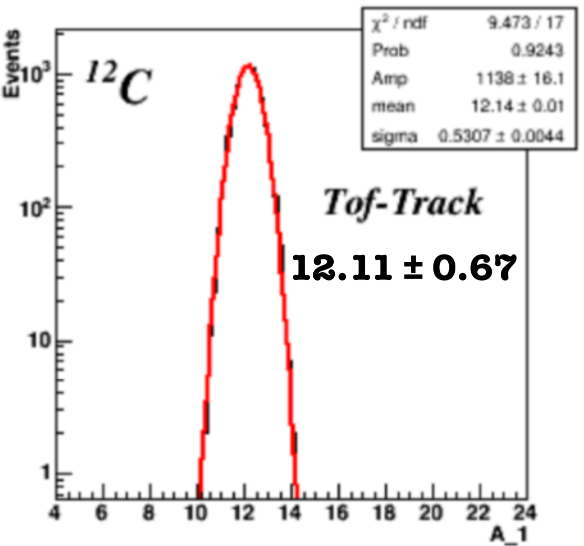


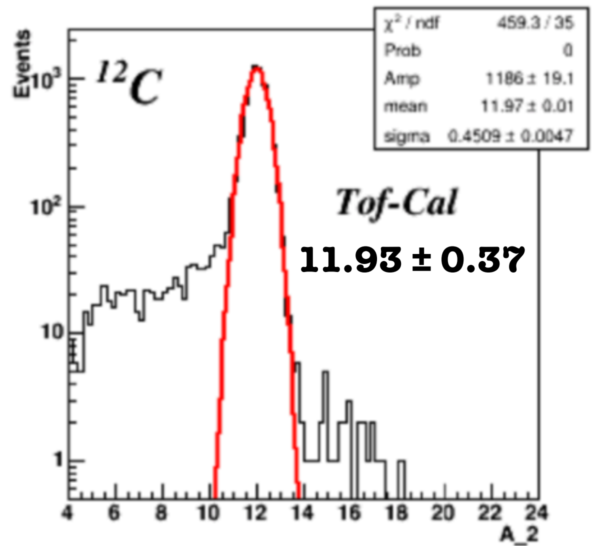
Mass Reconstruction

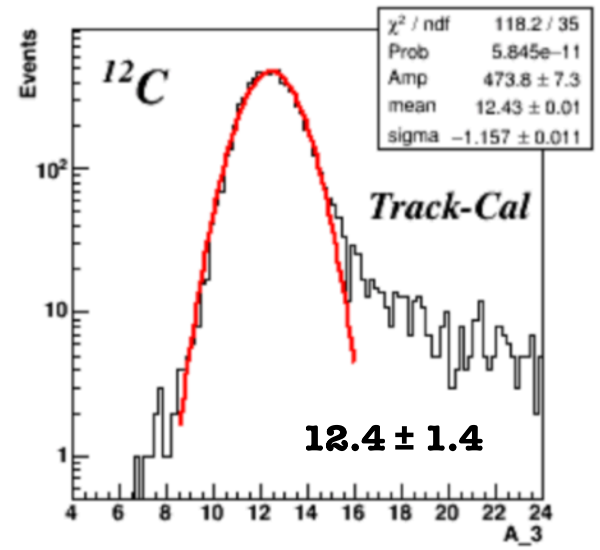
$$A_1 = \frac{1}{U \cdot c \cdot \gamma} \cdot \frac{p}{\beta}$$

$$A_2 = \frac{1}{U \cdot c^2} \cdot \frac{E_k}{\gamma - 1}$$

$$A_3 = \frac{1}{2 \cdot U \cdot c^2} \cdot \frac{p^2c^2 - E_k^2}{E_k}$$





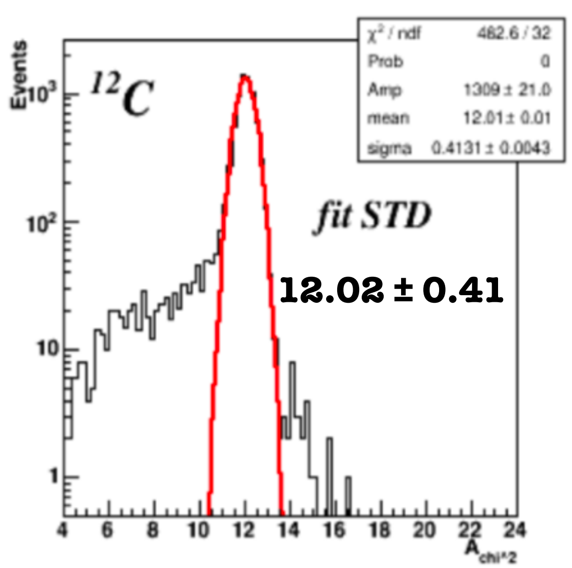


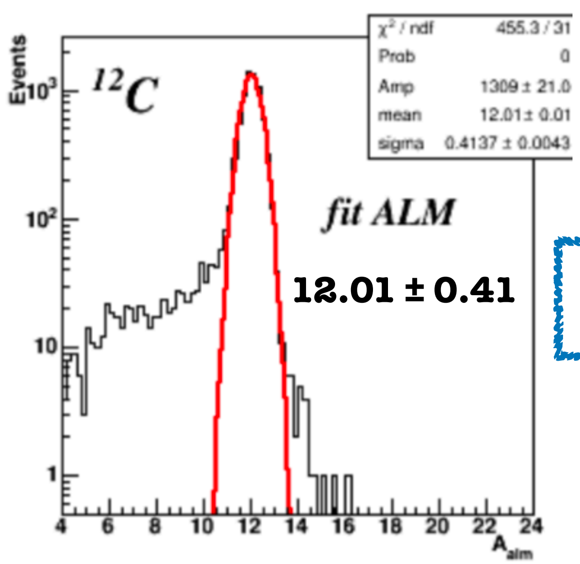
Resolutions for MC

- $\Delta p / p \sim 4\,\%$
- $\Delta E_k / E_k \sim 1.5\,\%$
- $\Delta TOF \sim 70 - 140\ ps$
- $\Delta (dE)/dE \sim 3 - 10\,\%$

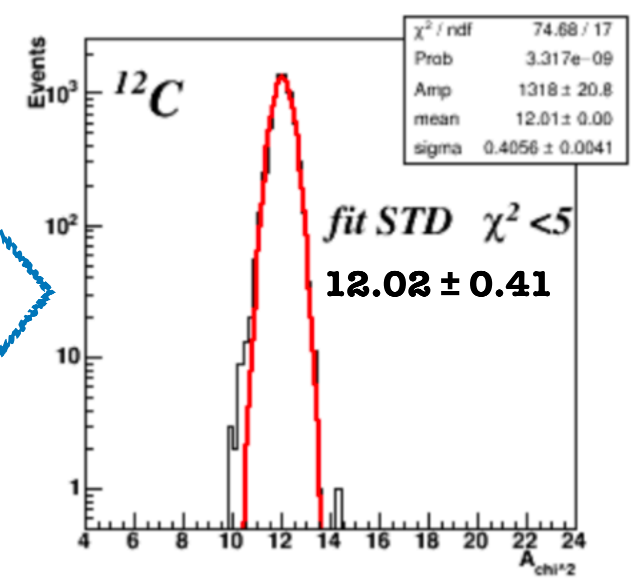
17% of fragments produce neutrons in the calorimeter that escape the detector

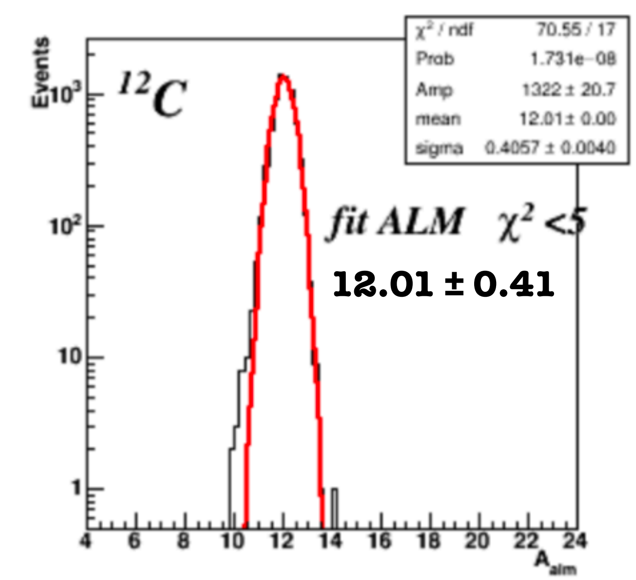
Combining the 3 methods:





χ^2 cut →





Redundancy of the FOOT detector allows to detect such events and remove them