FOOT: Fragmentation Of Target Experiment

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on behalf of the FOOT Collaboration

RAD9 conference

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FOOT goal

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 Treatment Planning System (TPS)

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)

101 members (60% staff):

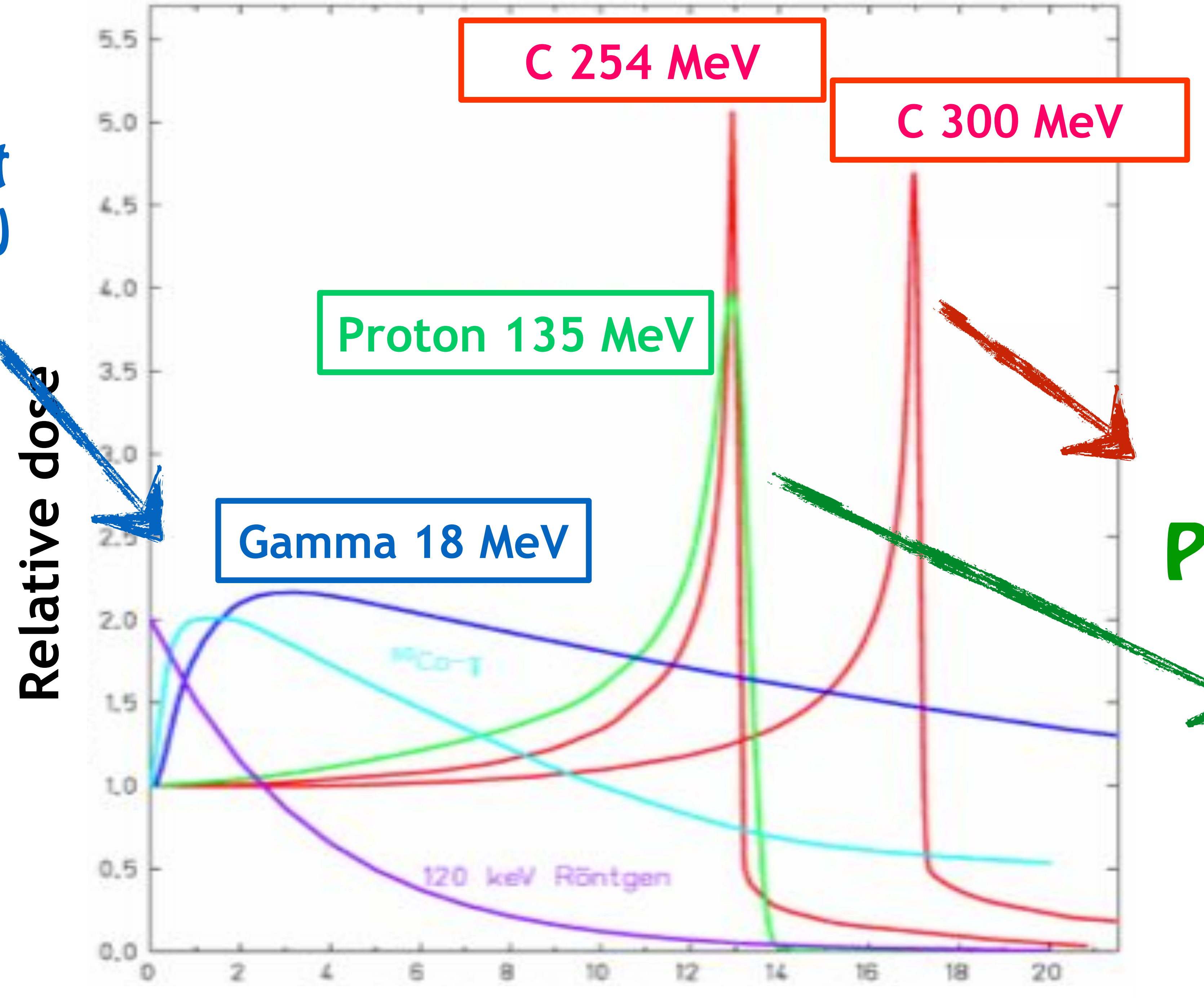
* 10 INFN Sections
* 5 laboratories: Frascati, CNAO, Trento, GSI,IPHC (Strasbourg)
* 12 Italian Universities
* 2 foreign Universities: Aachen, Nagoya
* Centro Fermi

Physics program:

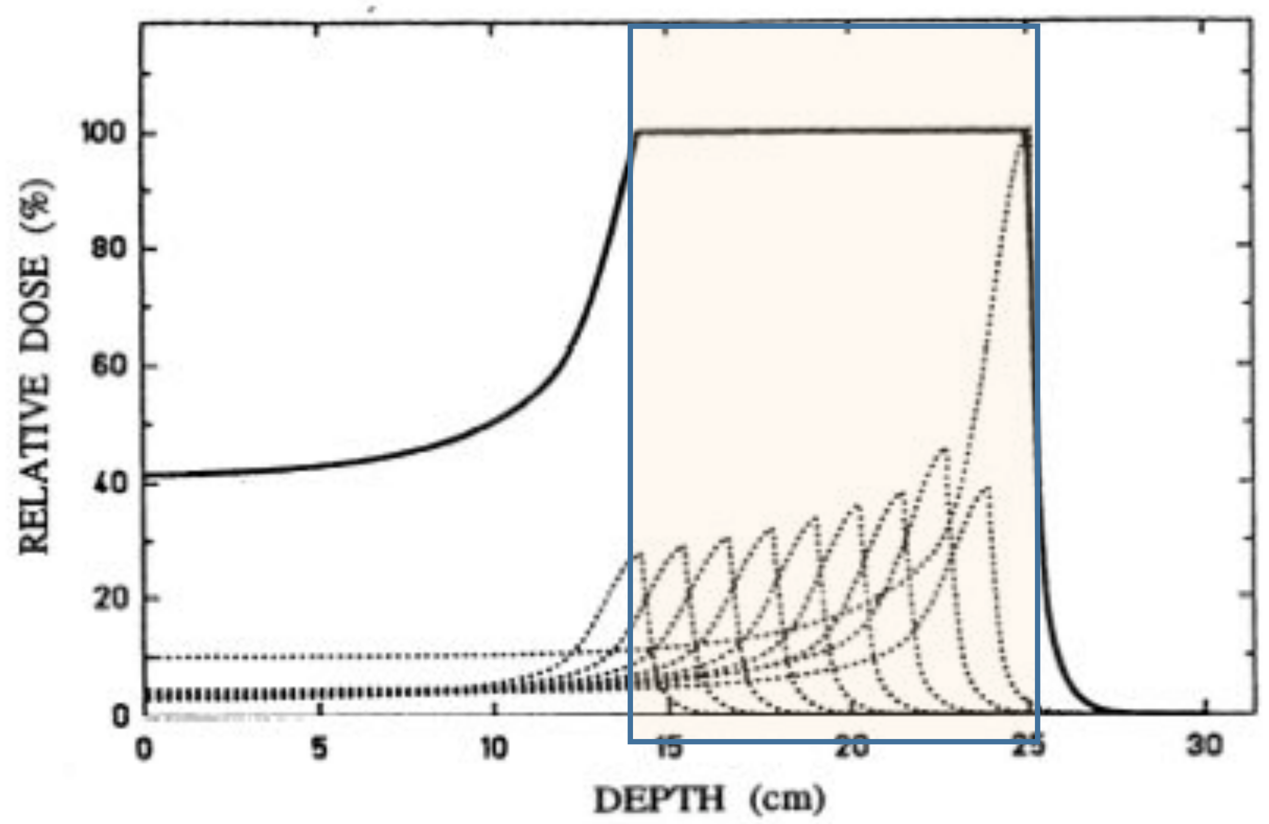
* Hadrontherapy:
* Nuclear fragmentation @ 200 MeV/u
* Radioprotection in Space:
* Nuclear fragmentation @ 700 MeV/u

Hadrontherapy VS Radiotherapy

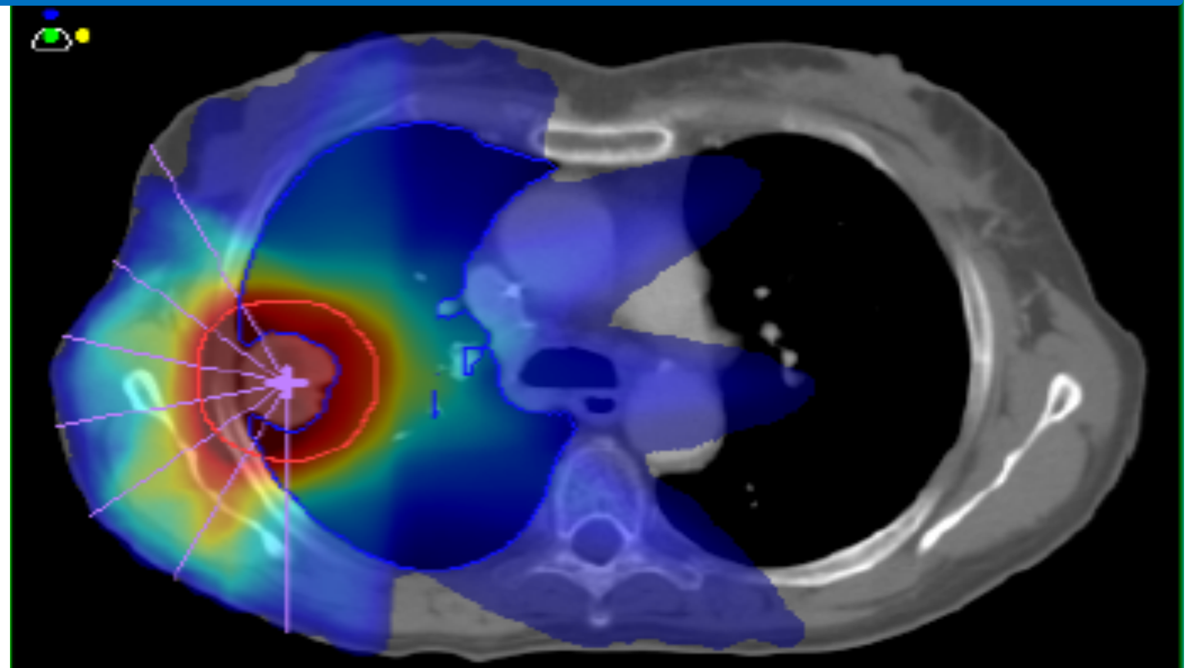
Gamma
Superficial Energy deposit
Ionization (Compton, pair)



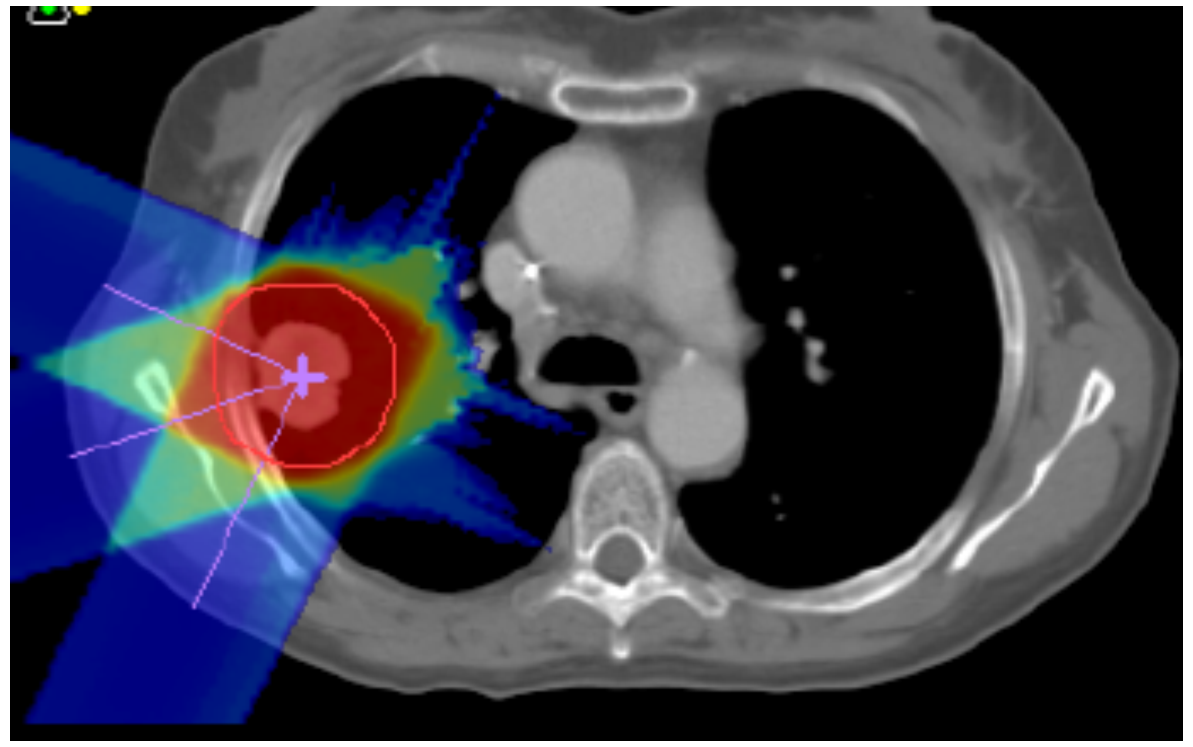
Proton/charged ion
Brag Peek
Long Range
Fragmentation



Radiotherapy, IMRT 7 fields



Hadrontherapy, proton



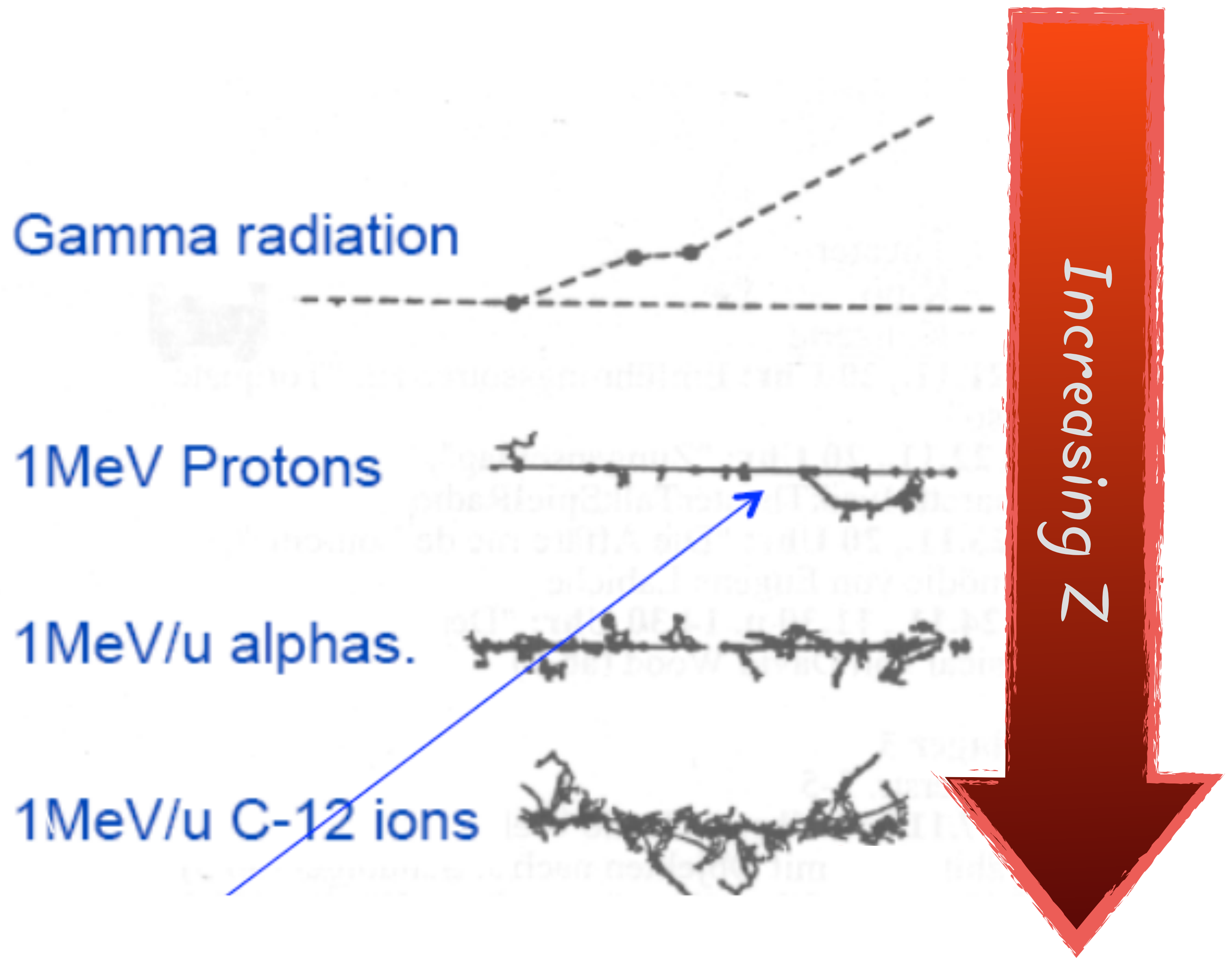
Pros and cons

- 🙂 Dose release maximum at the end
- 🙂 Penetration depends on energy
- 🙂 More efficient than γ
- 🙂 Less damage outside tumour
- ☹ MORE expensive than γ

Damage on DNA

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

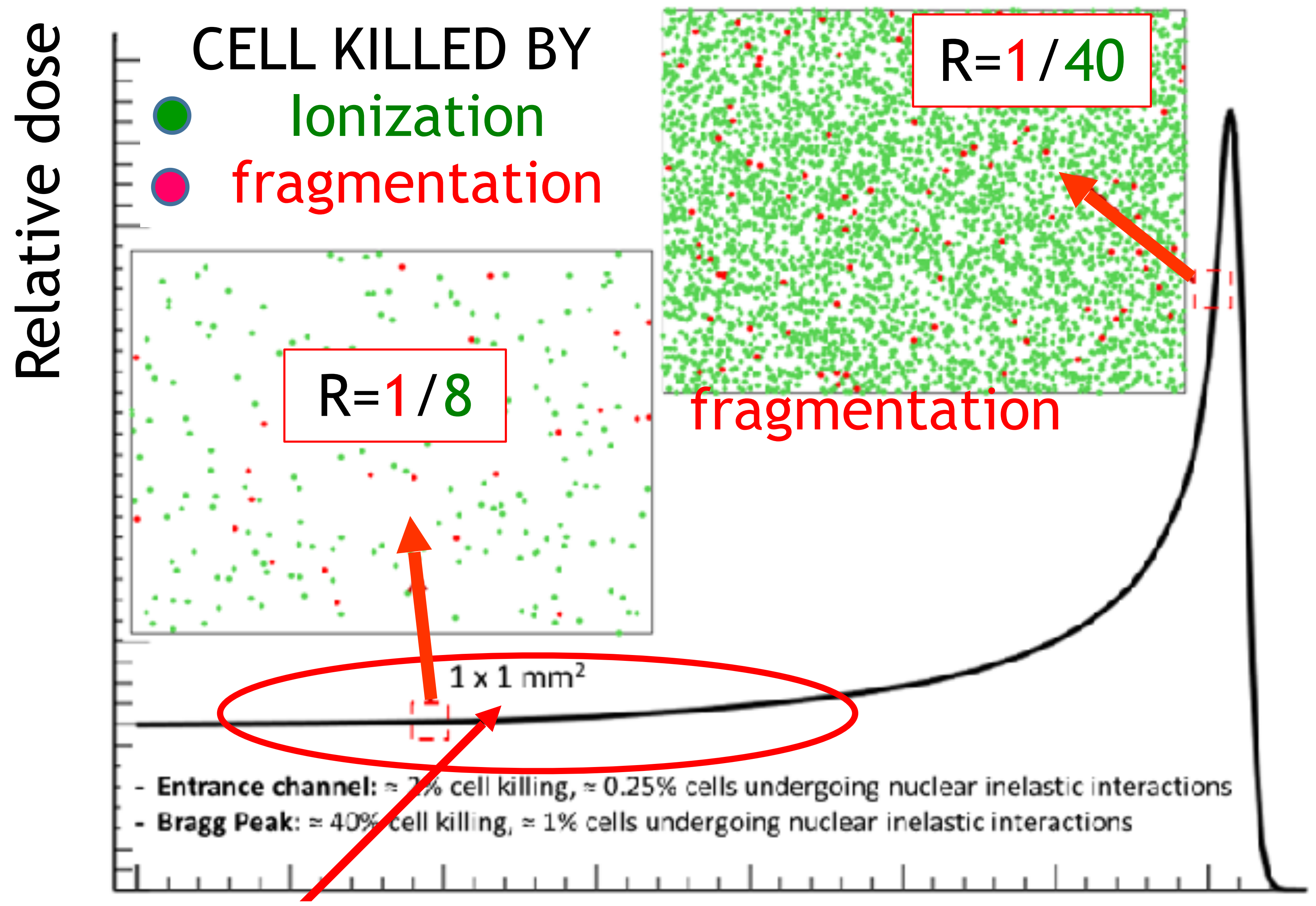
Ionising tracks @ nanoscale



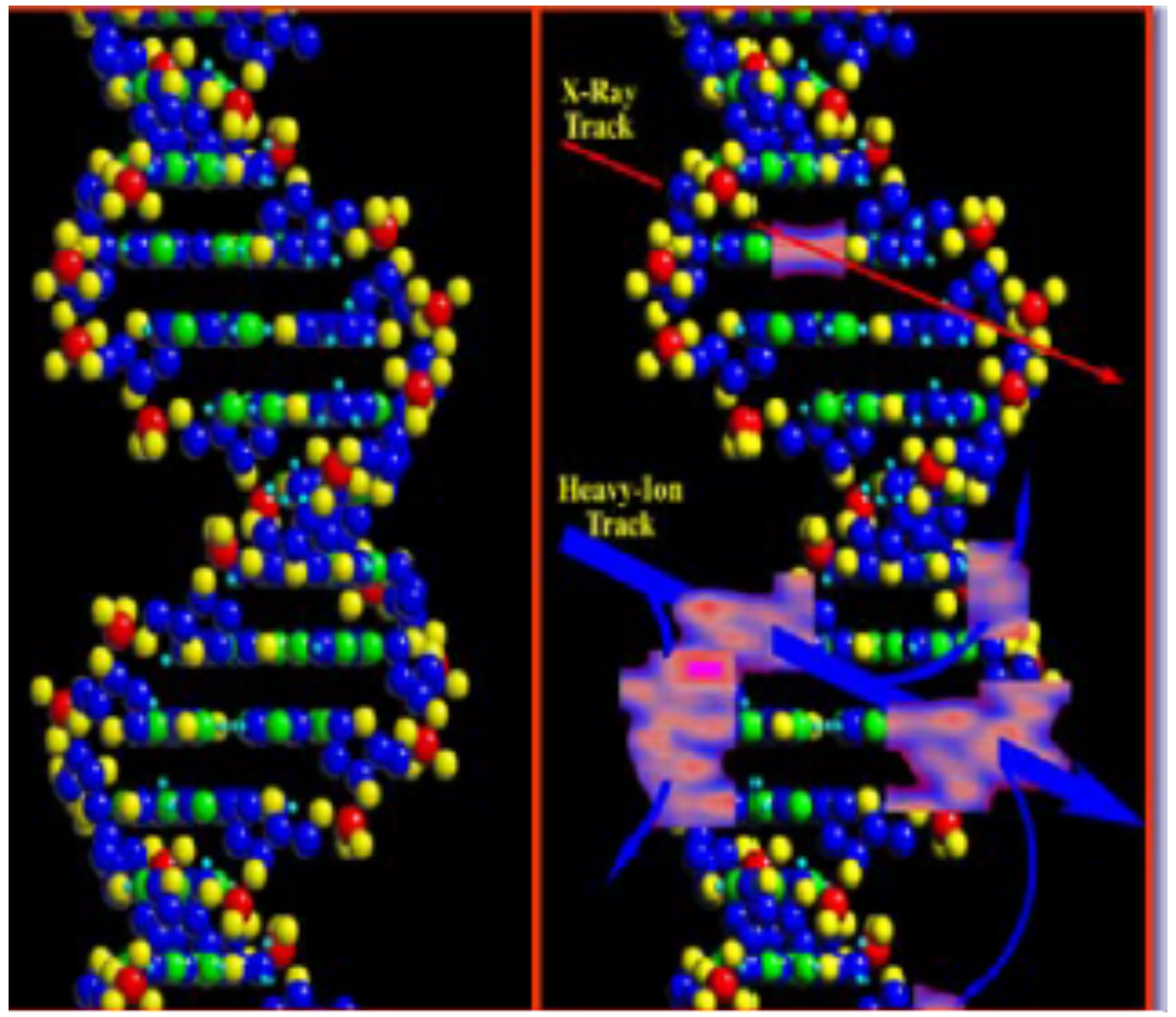
Higher Z → Higher damage

... but necessary to know the Nuclear fragmentation cross sections

200 MeV proton → water



Courtesy of NASA



Double strand break

irreparable damage

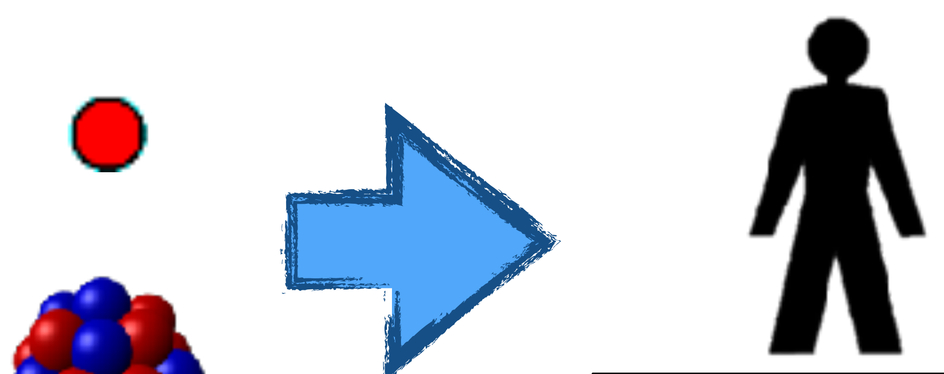
Target-Projectile fragmentation

Projectile

Target at rest

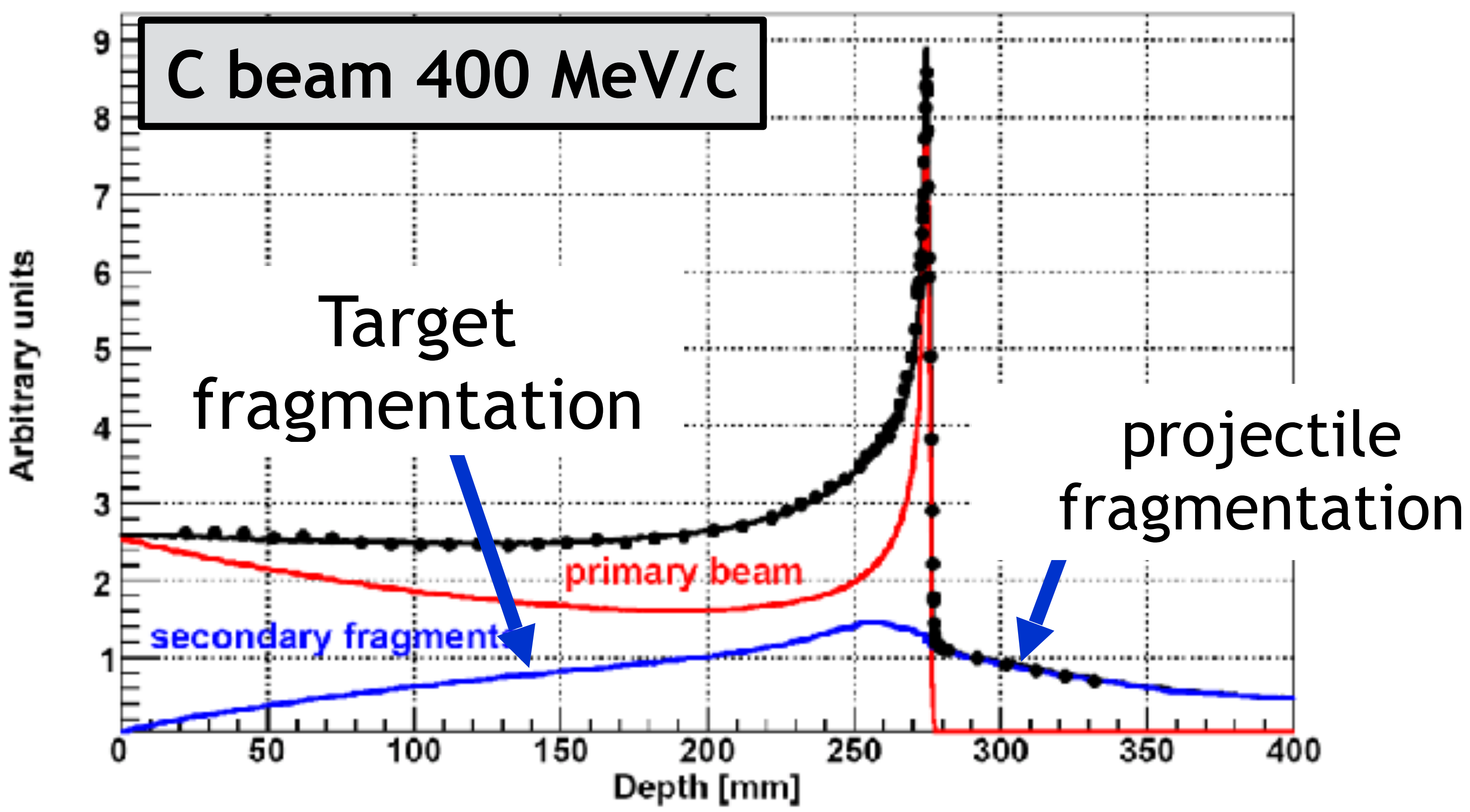
p

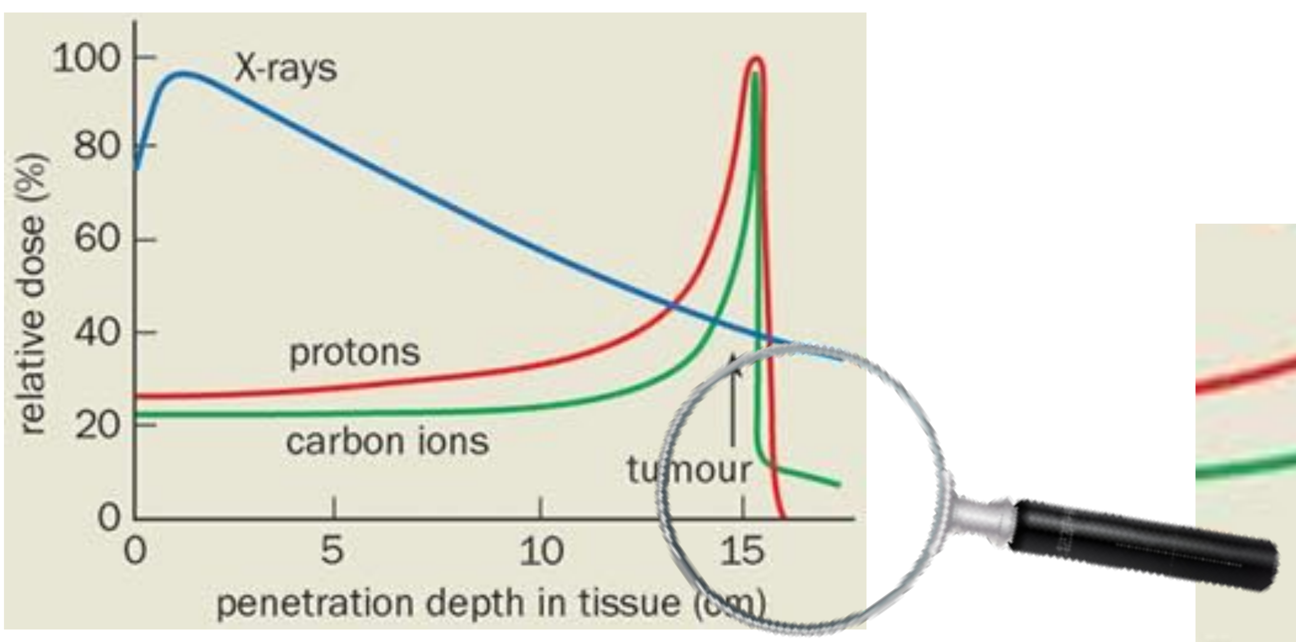
C

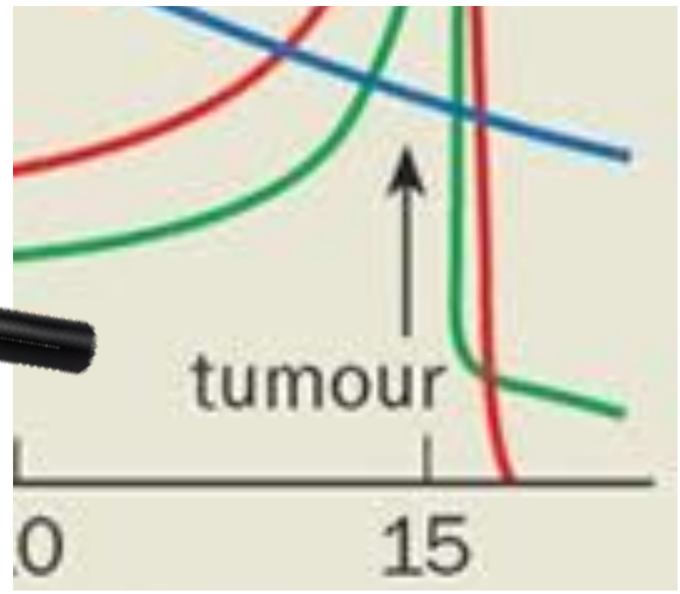


H, C, O
(95%)

- p + H → No fragmentation
- p + C,O → Target fragmentation —> Low Energy and Range
- C + H → Projectile Fragmentation —> high energy and long range
- C + C,O → Both fragmentation



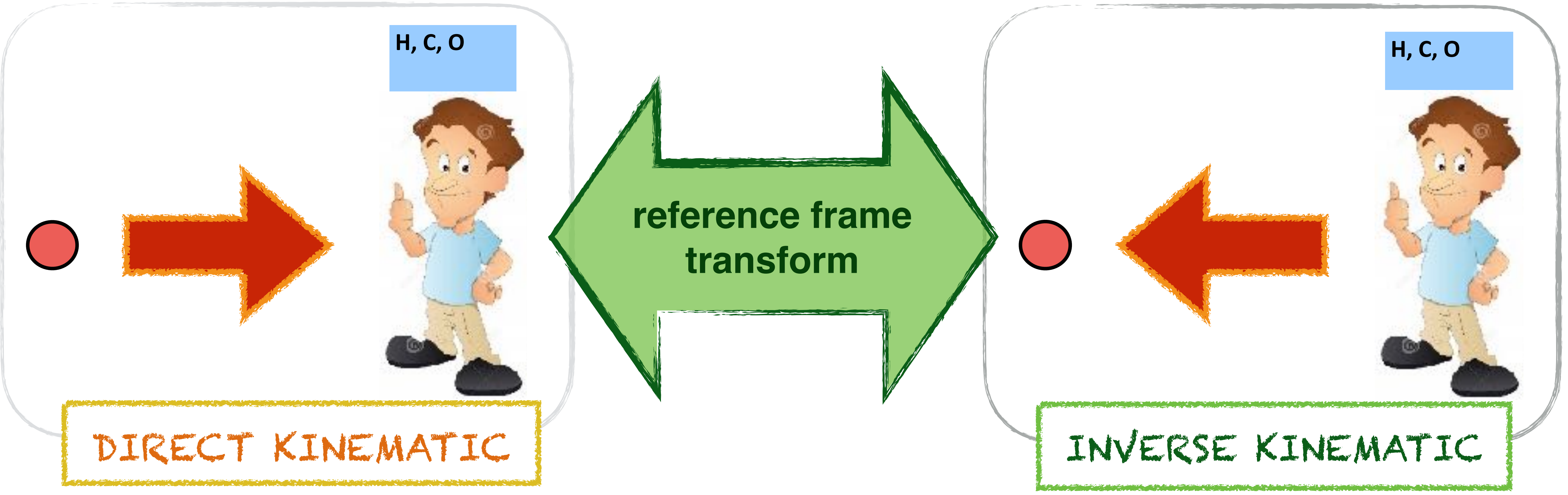




Tail present only when using Carbon

Target fragmentation measurement

Problem: Need to measure target fragments **BUT** fragments remain in target

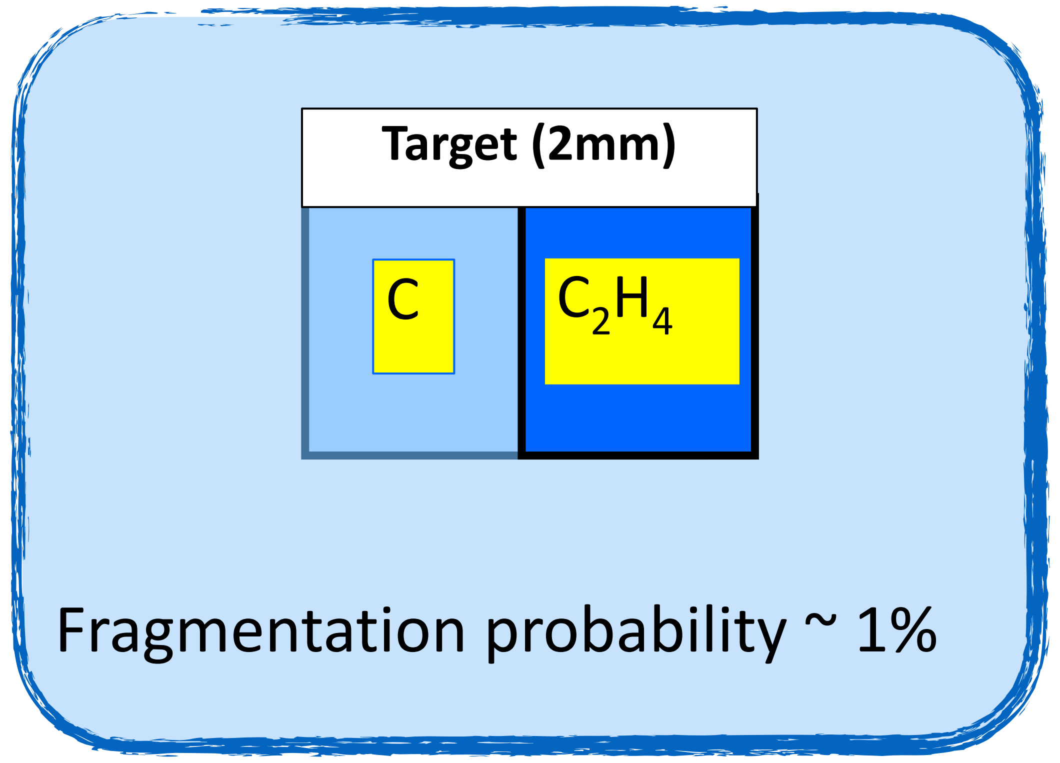


Shoot C,O (,H) on proton beam

Reference frame back-transformation = **Lorentz boost** to the final products (subtract the projectile momentum).

Problem (again): Hydrogen target

Solution

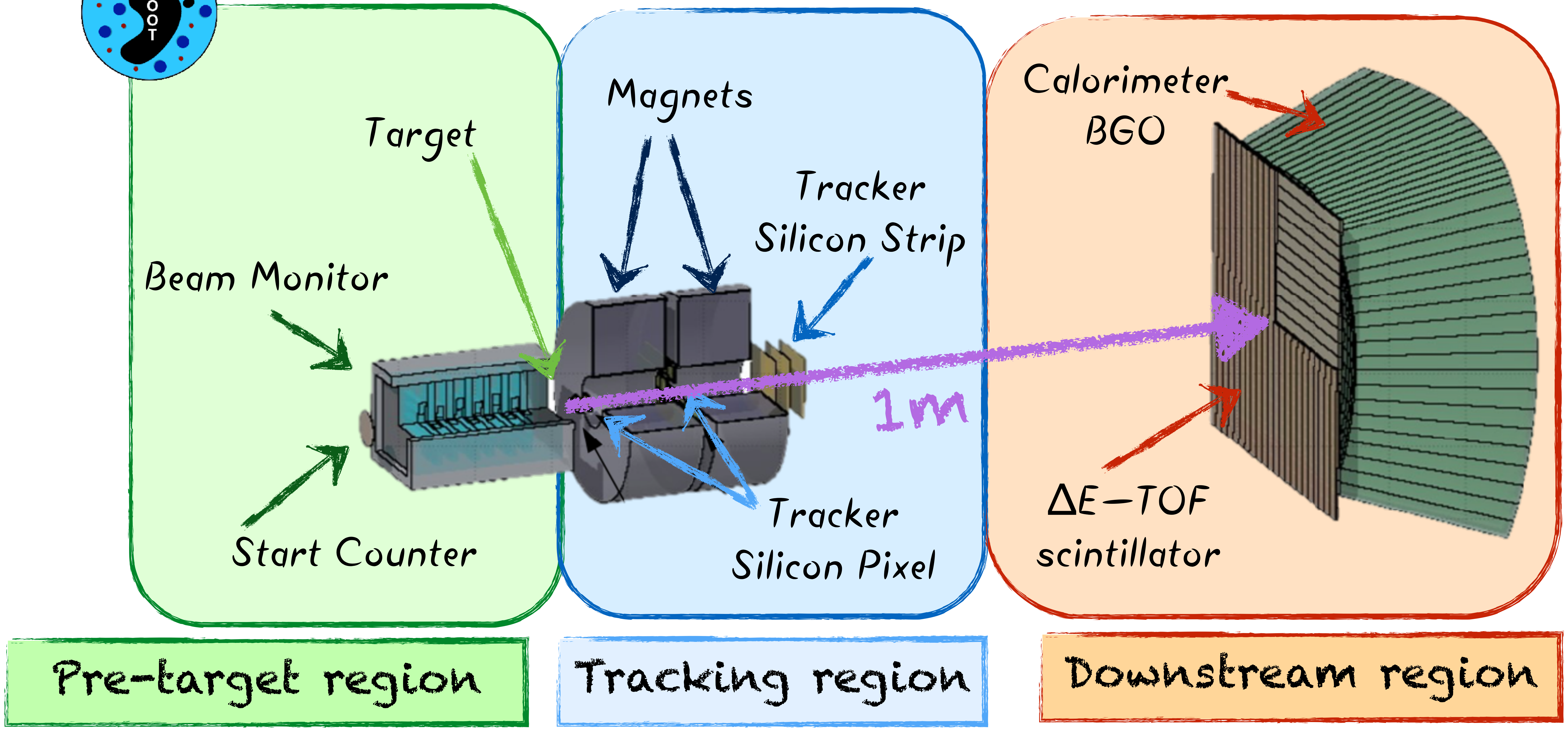


- Polyethylene target C_2H_4 + carbon target (graphite)
- Subtract the cross section on carbon to the one on polyethylene

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

FOOT Detector (in construction)

Electronic Setup



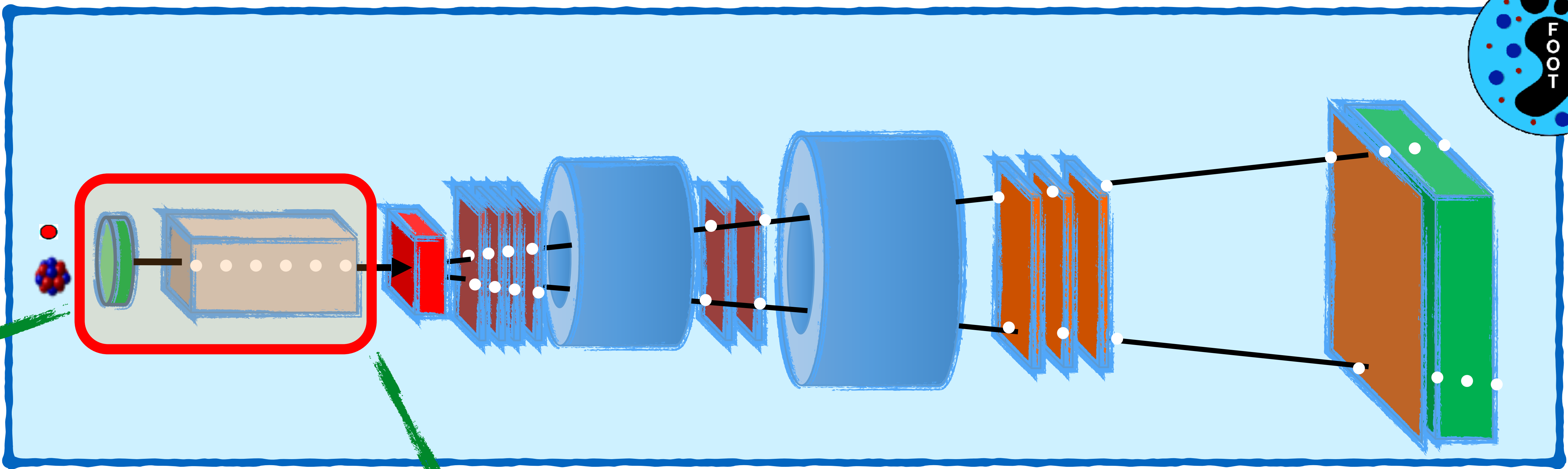
Heavy fragments

n, p, D, T, He

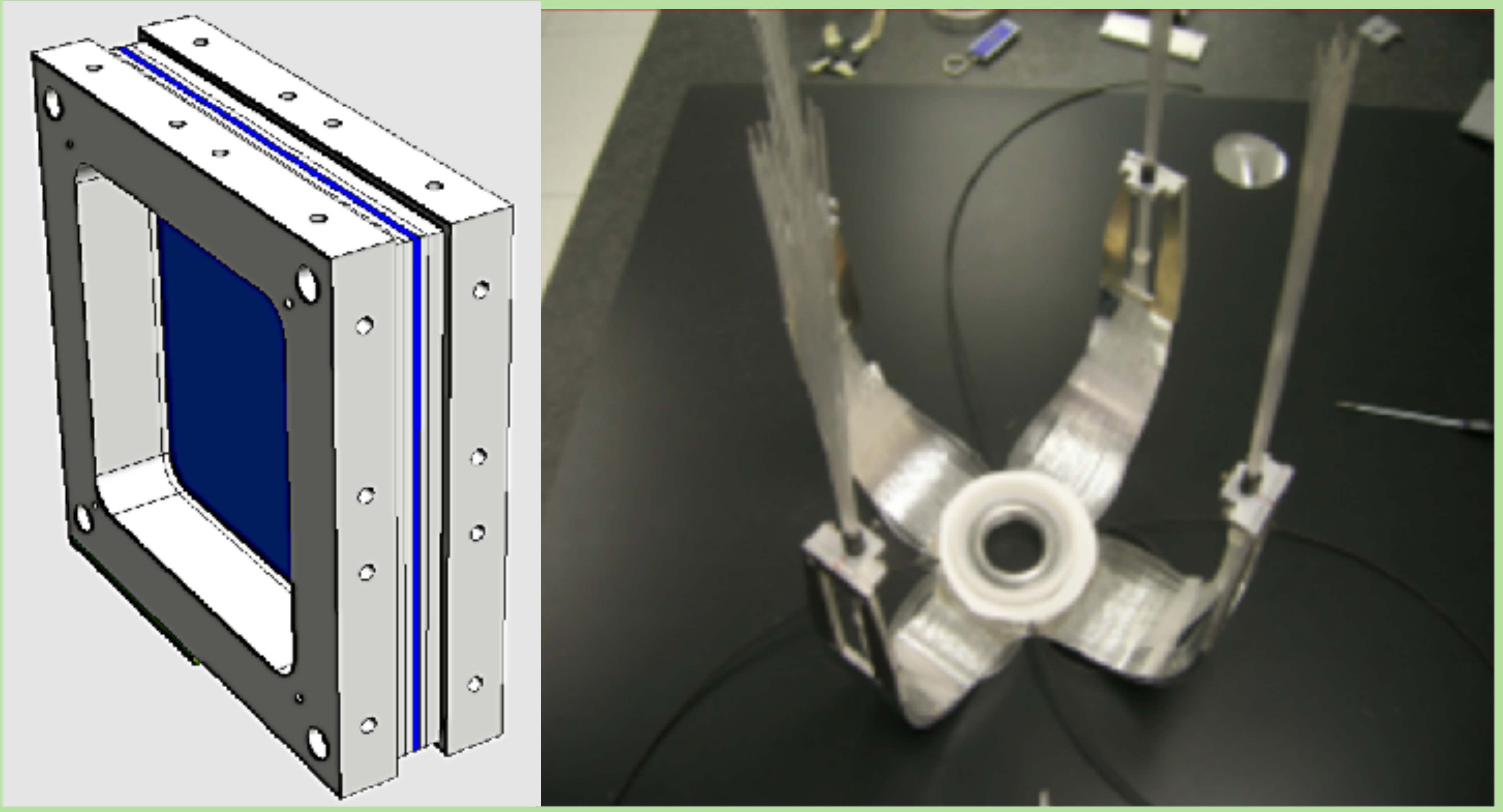
Angular open

± 10°

Pre-target region



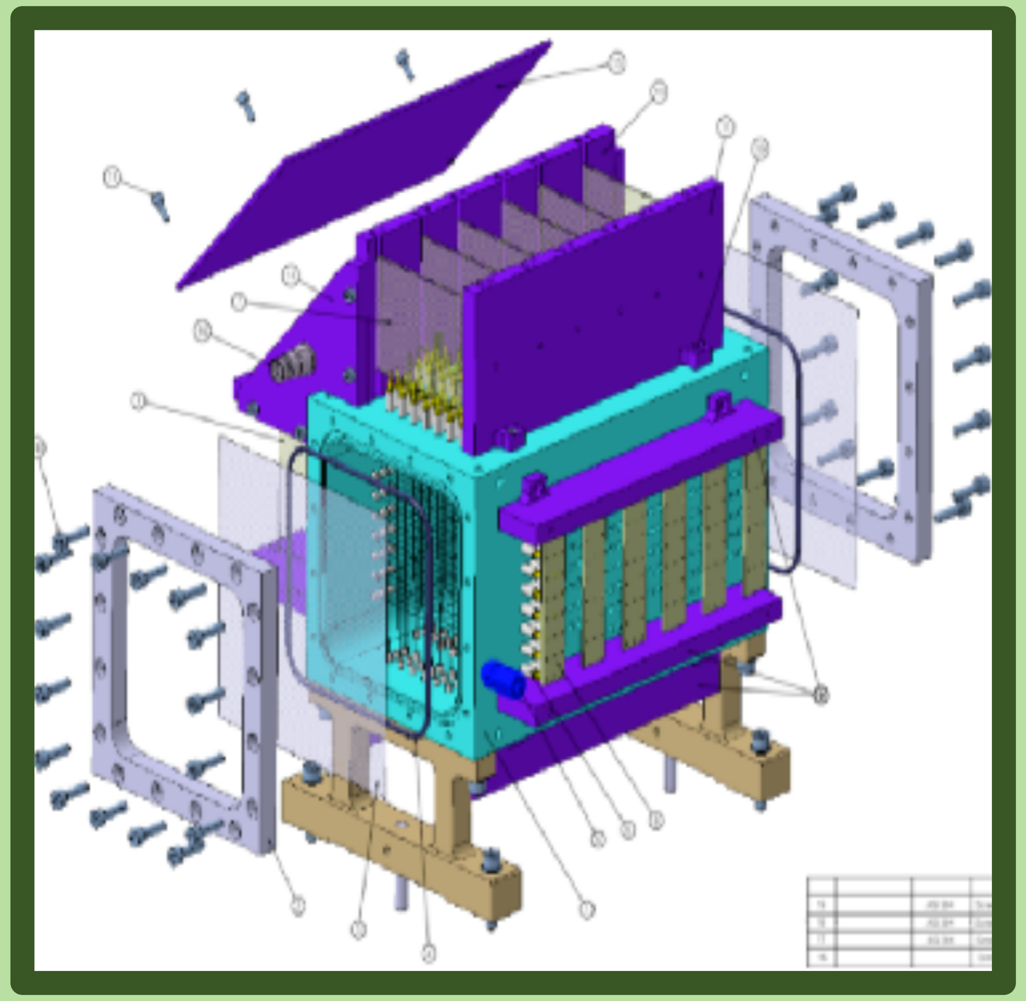
Start Counter (SC)

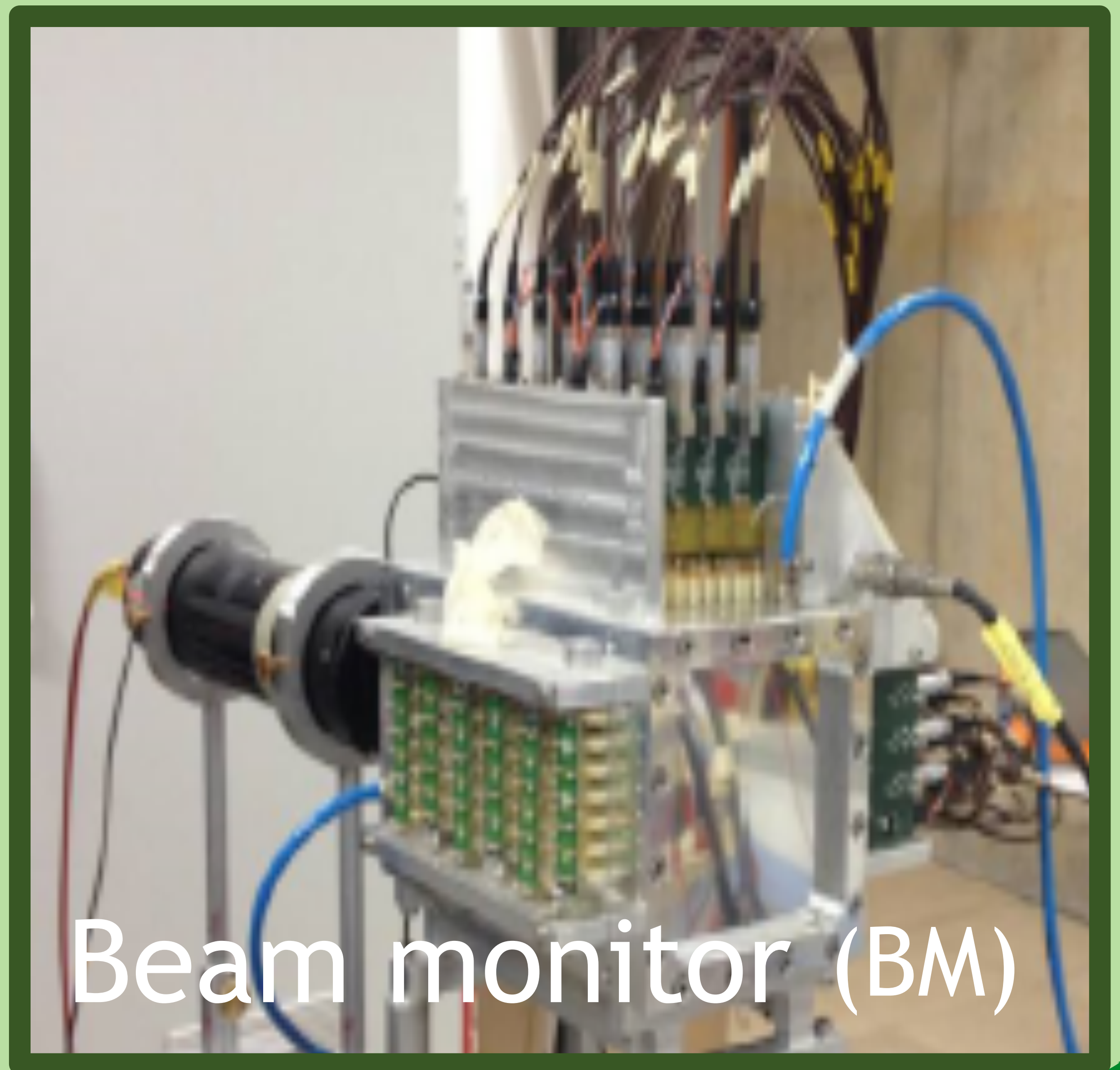


Trigger and ToF start

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

Beam Monitor (BM)

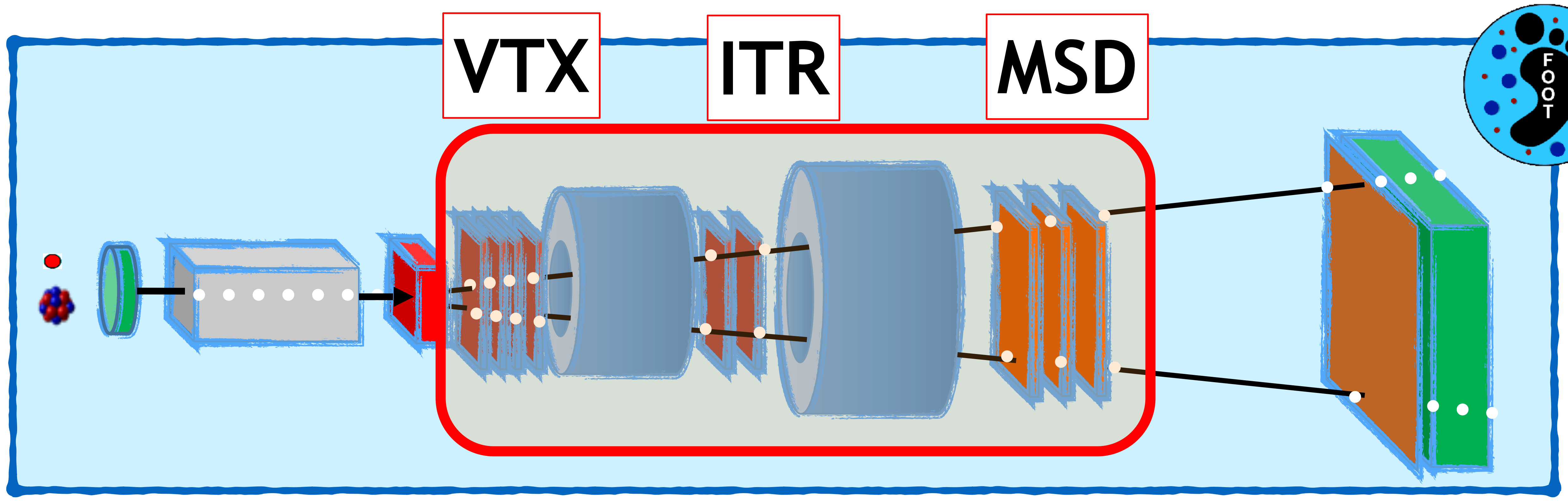


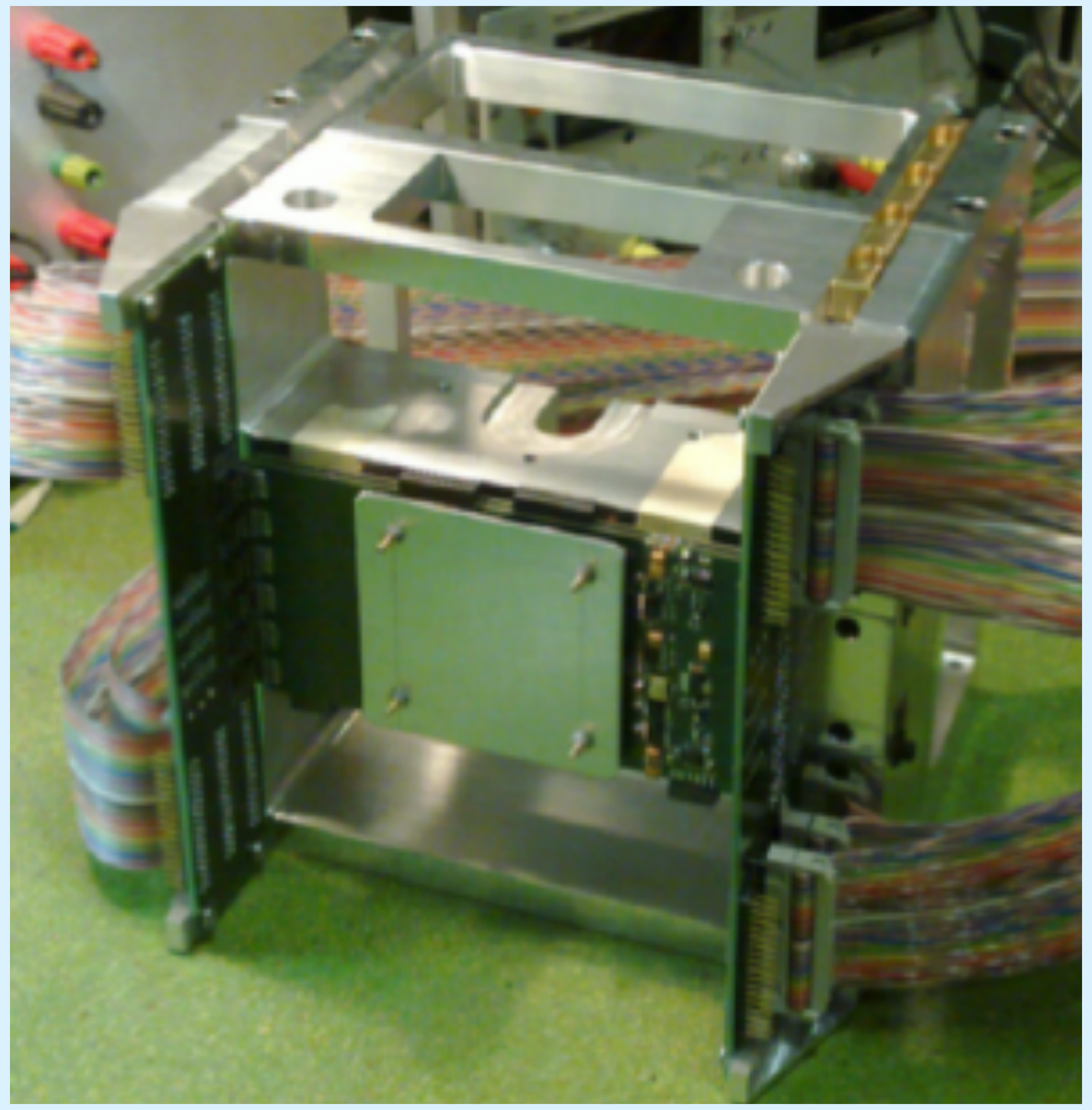


Beam momentum/direction & fragmentation

Drift chamber
Gas: Ar/Co_2 (80/20%)

Tracking region

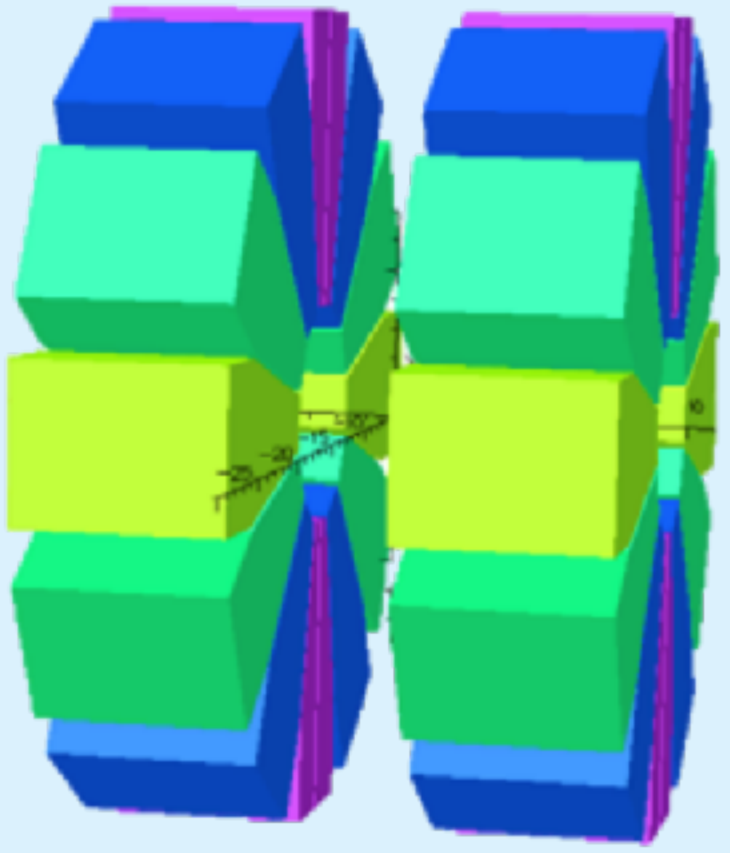


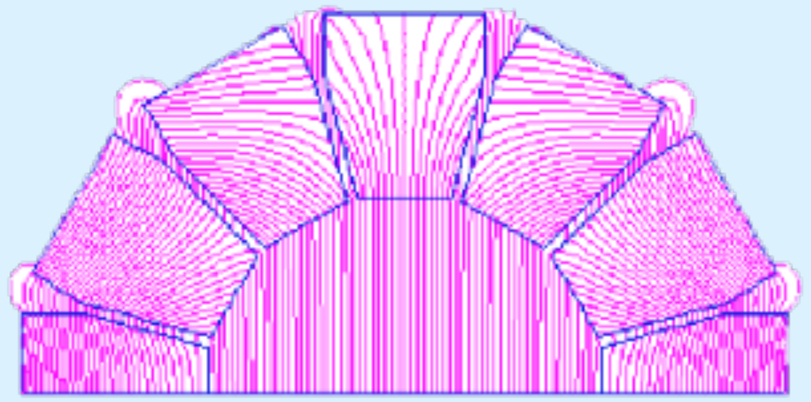


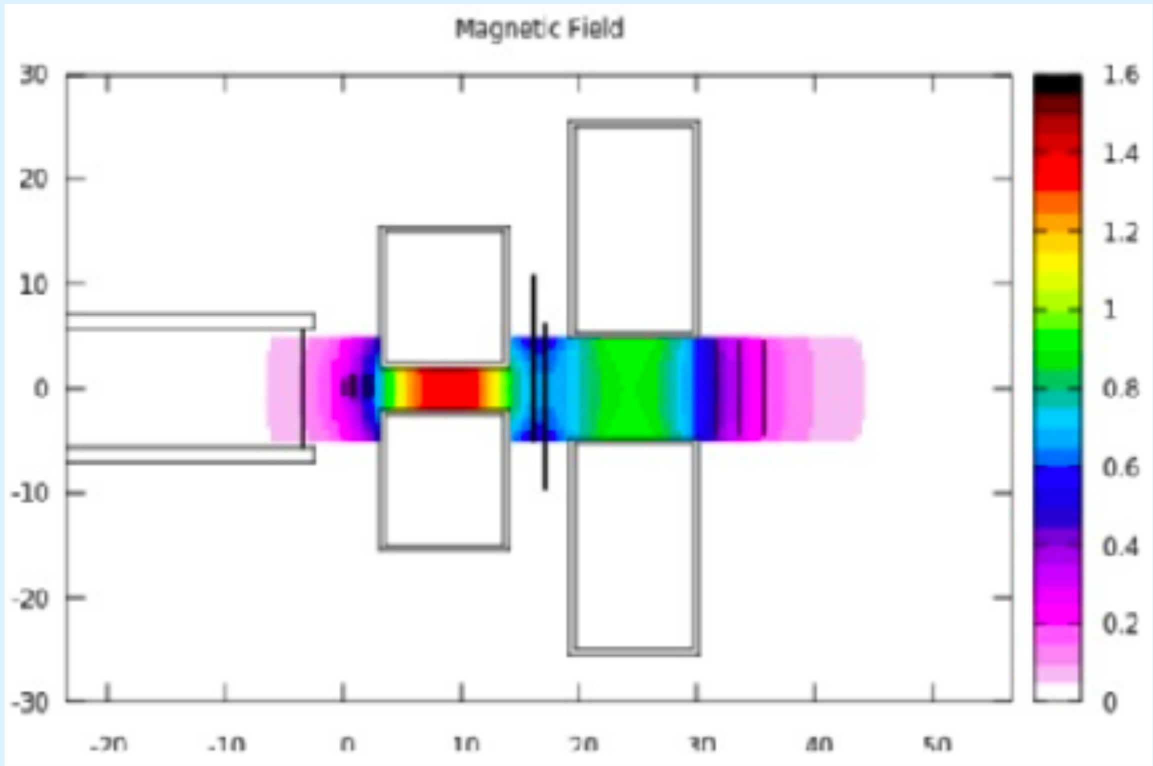
VTX: 4 layers of Si pixel (20 x 20 μm)
ITR: 2 layers of Si pixel (20 x 20 μm)

Vertex & Inner Tracker

Magnet

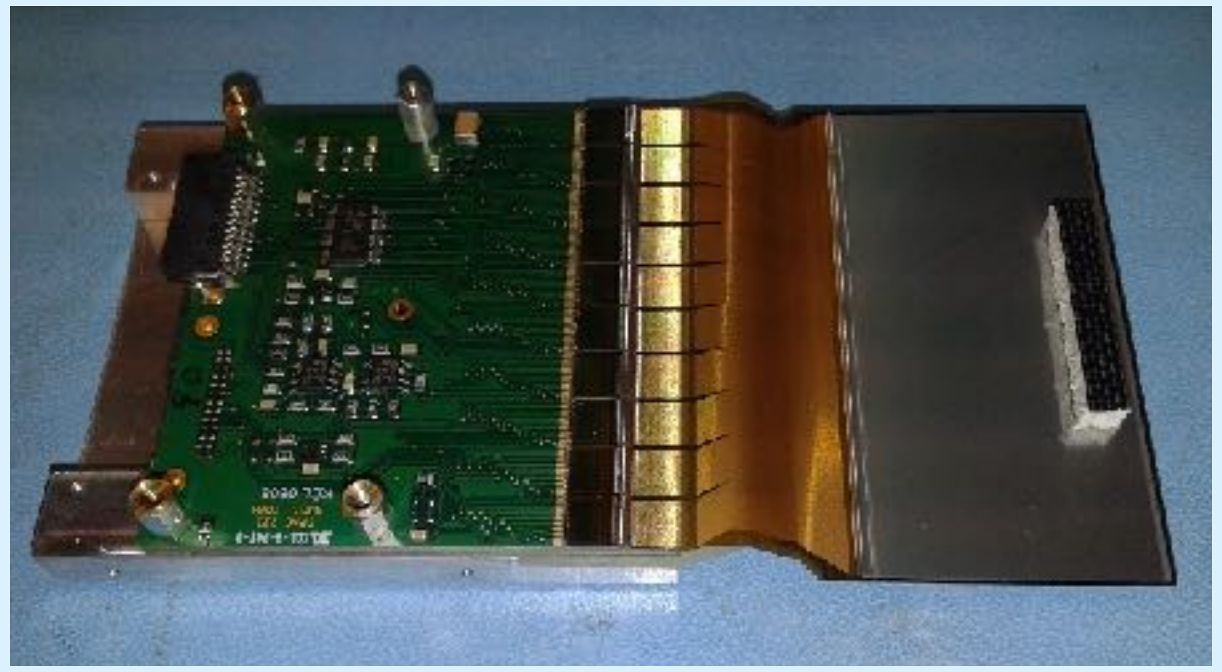






2 permanent Hallbach magnets

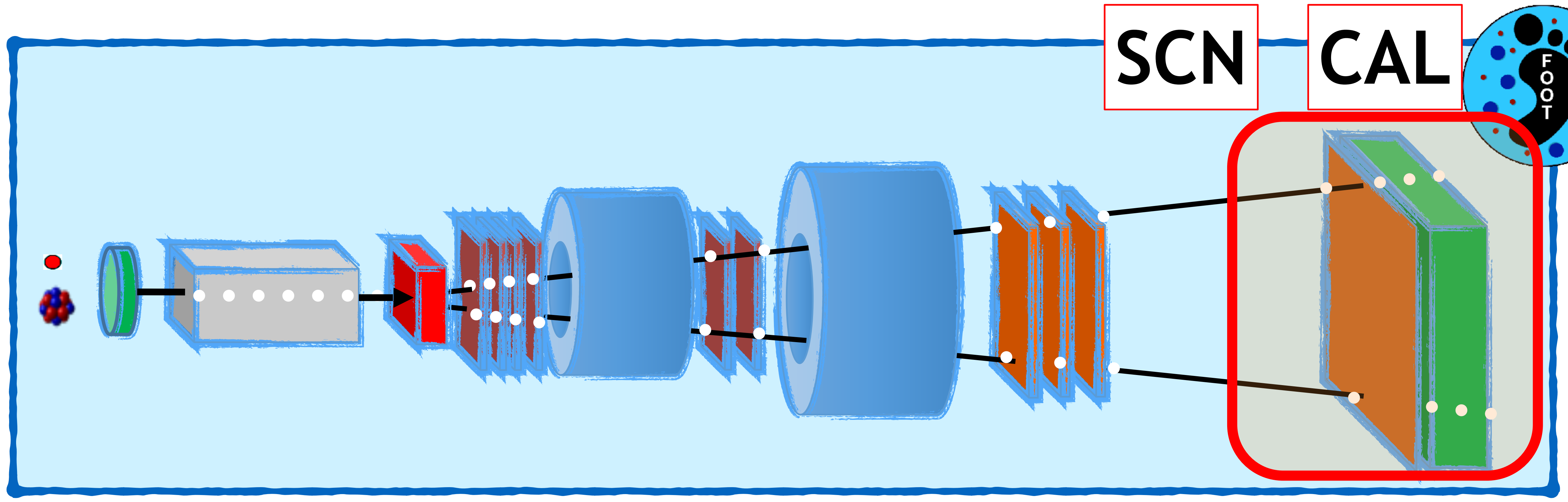
B field in y axis (max 0,9 and 1.1 T respectively)



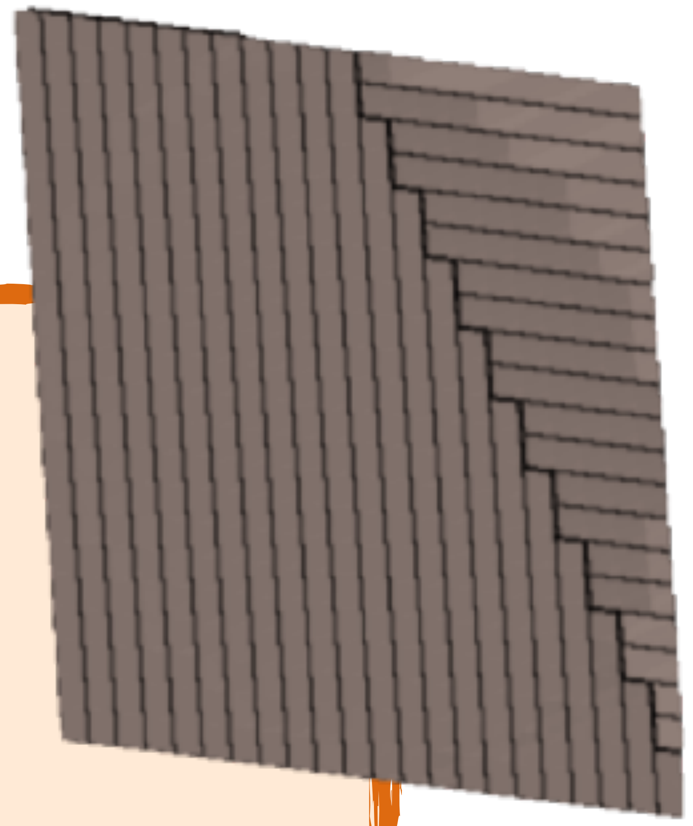
3 layers of Si strips
(120 μm x 9 cm)

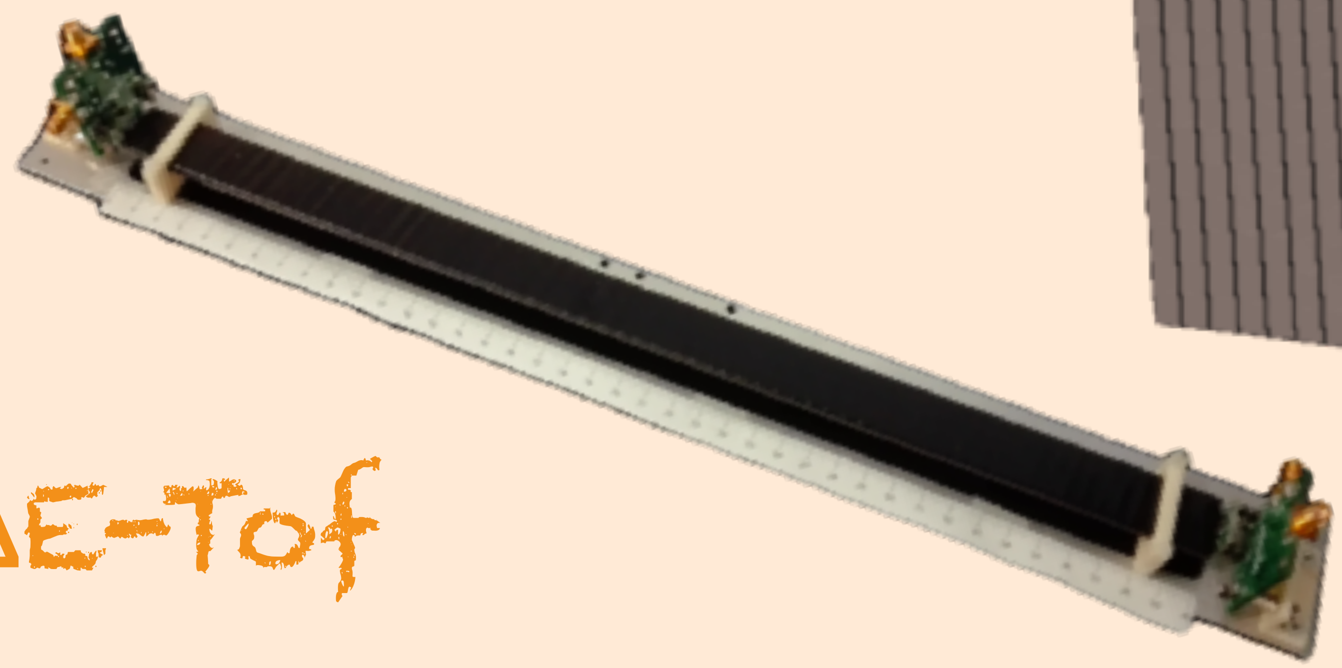
Micro Strip Detector (MSD)

Downstream region



Scintillator (SCN)

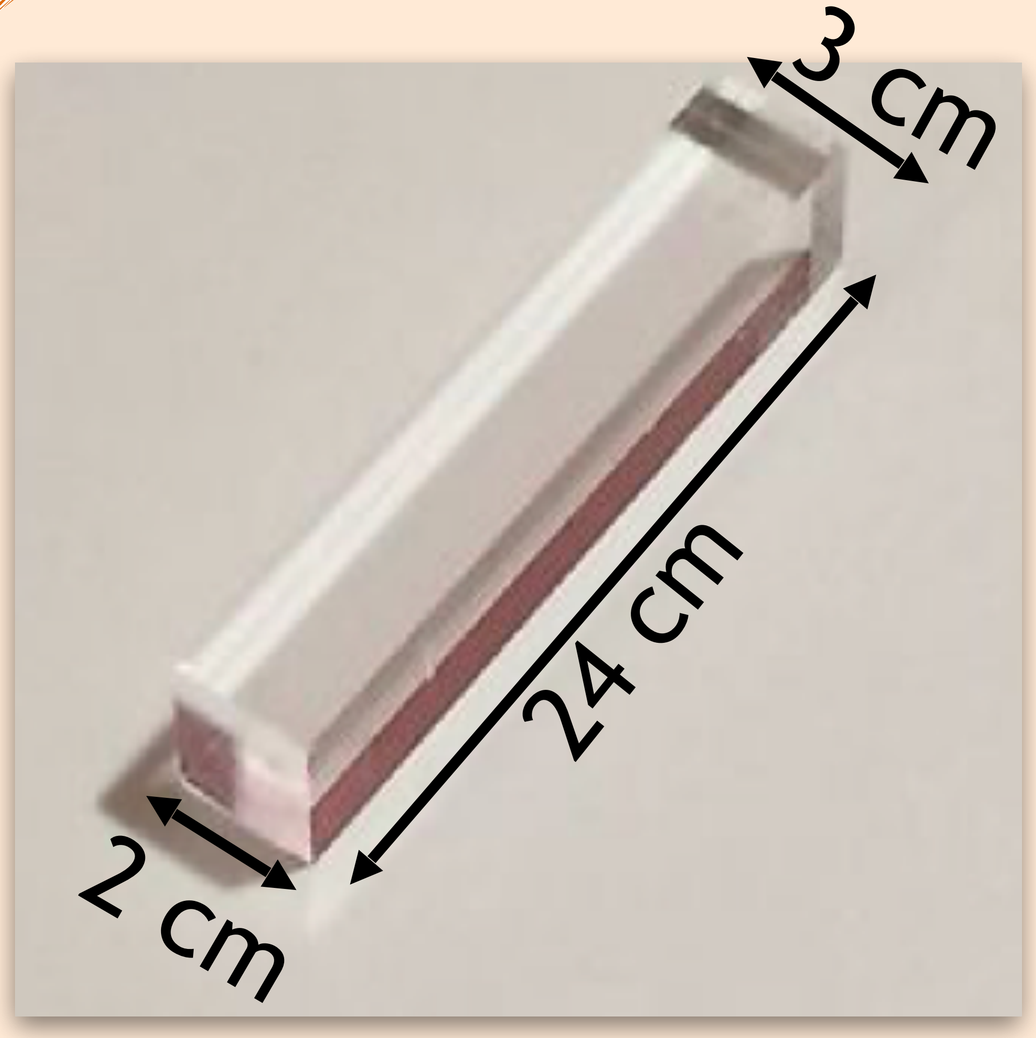




ΔE-Tof

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

Calorimeter (CAL)



BGO - ($Bi_4Ge_3O_{12}$)

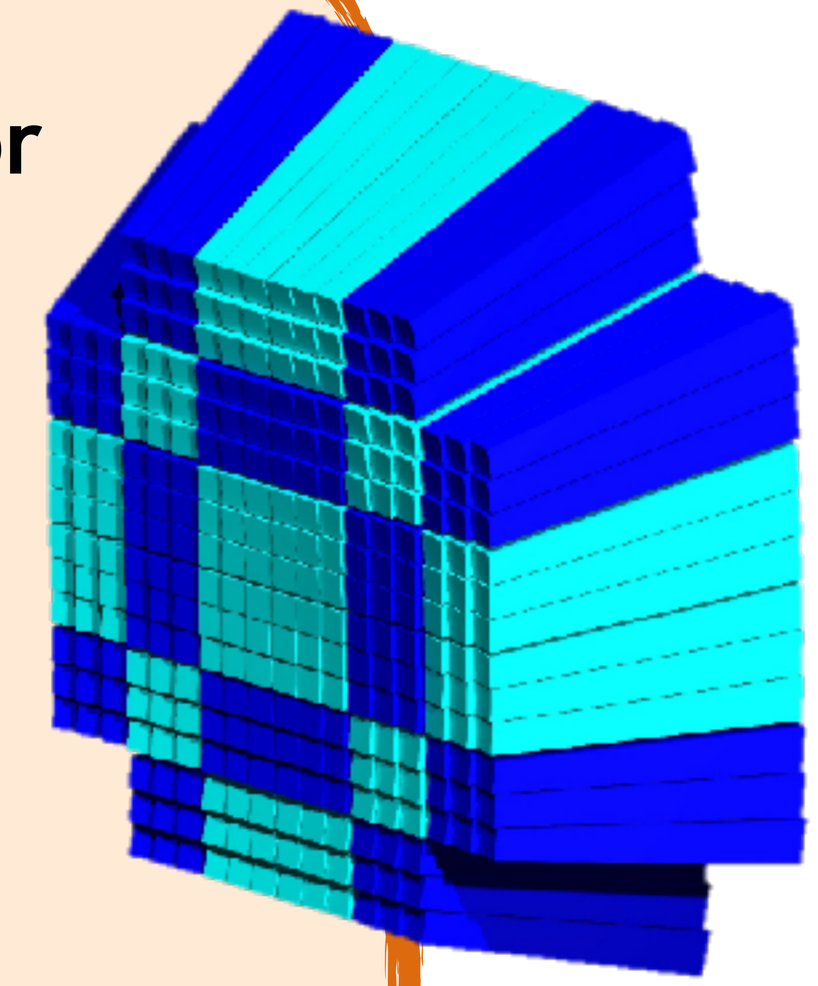
Inorganic scintillator

$Z_{Bi} = 83$

$P_{BGO} = 7.13\ g/cm^3$

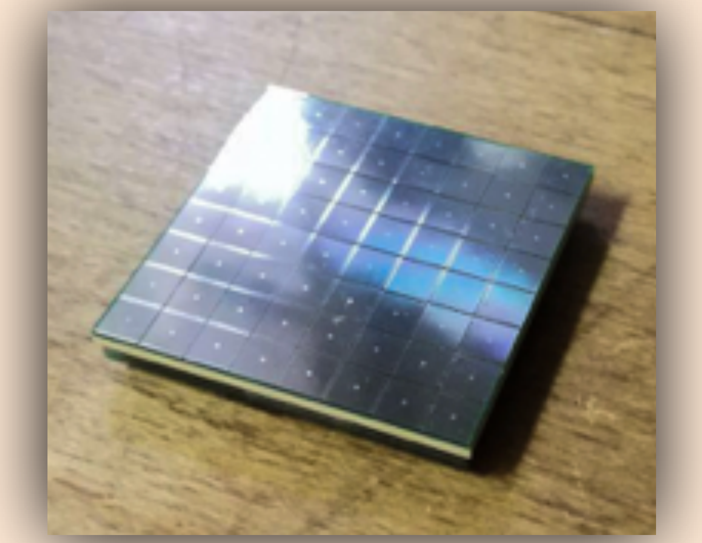
Weight = 1.027 kg

Total weight 330 Kg



SiPM. Pitch 50 μm

Voltage breakdown 53 V



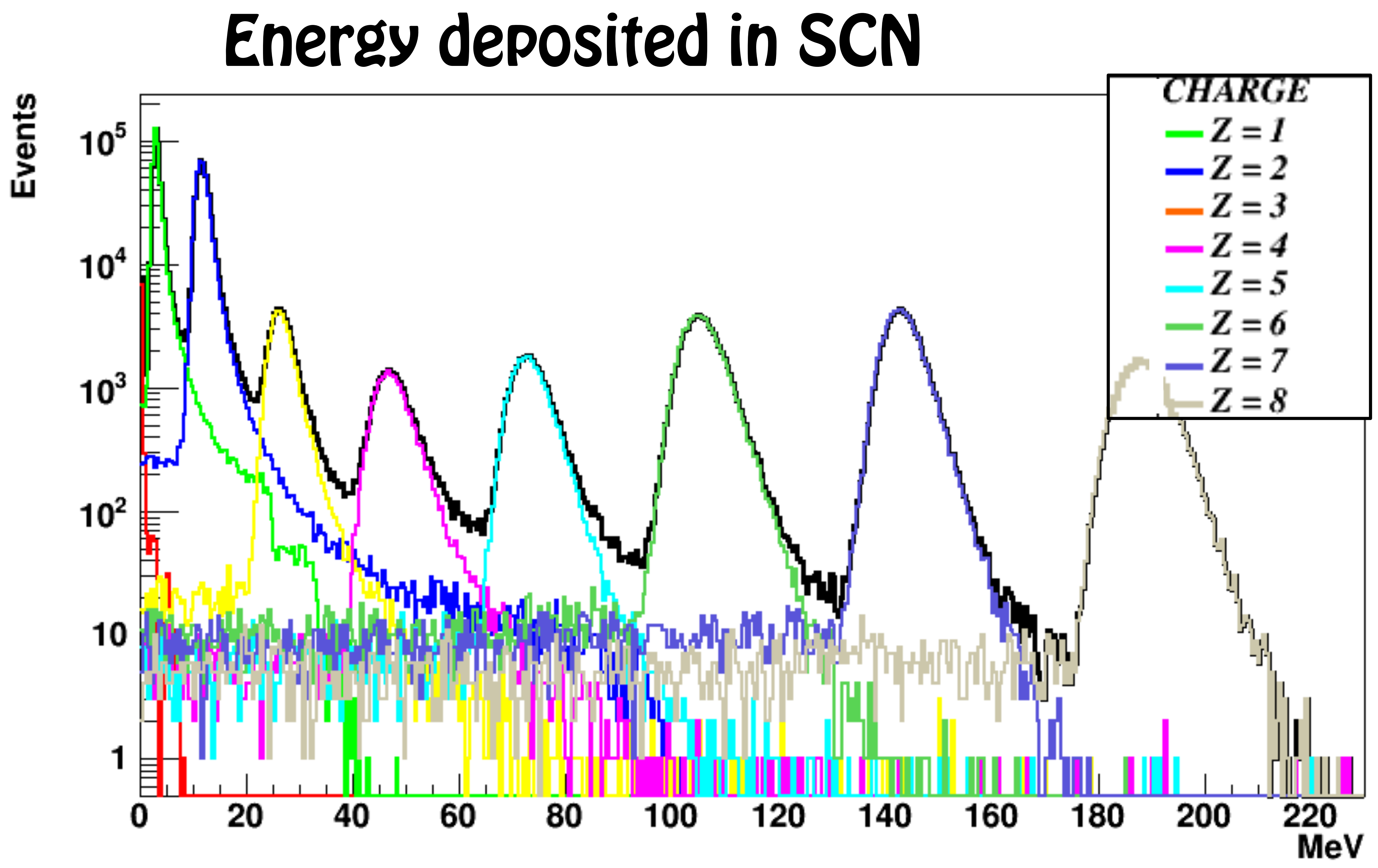
MC studies

Charge Z reconstruction

- FOOT's power to separate fragments by charge is tested on FLUKA MC simulation of ^{16}O beam at 200 MeV/u energy on a C_2H_4 target.

- This is a distribution of the simulated energy loss dE/dx in the scintillator with contributions separated by fragment's charge.

- The black one is the total contribution.



Charge Z reconstruction

* Scintillator energy deposit dE/dx is dependent from fragment's charge Z following the well known Bethe—Block formula below

SCN

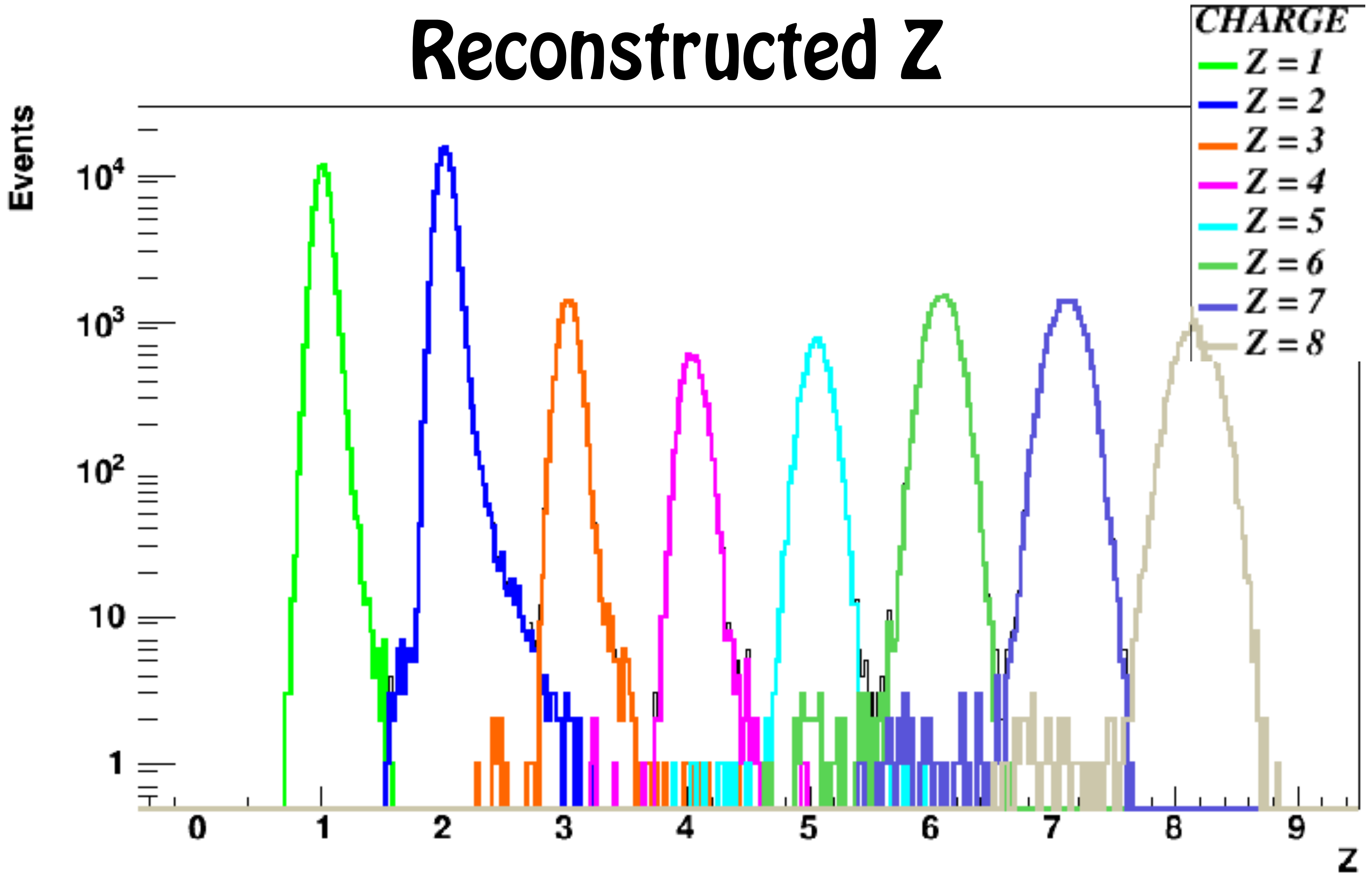
$$-\frac{dE}{dx} = \frac{\rho \cdot Z}{A} \frac{4\pi N_A m_e c^2}{M_U} \left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2 \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

TOF

* Z can be obtained by fitting the dE/dx with several Bethe—Block fits (with different Z hypothesis) knowing the β parameter from TOF measurement.

Charge Z reconstruction

* Event distribution as a function of Z obtained from an ideal fit as described in the side before.
* Estimated the charge reconstructed resolution for each fragment in the blue table
* Estimated the charge misidentification probability (< 1%)
* Preliminary performance estimated on MC with several assumption on detector performance



Z resolution = 2.0% (9% p, 6% He)

^{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

Charge misidentification < 1%

Number of mass A

* Number of mass A can be evaluated in 3 different ways using well known relativistic mass formulas:

  - by using β parameter (from TOF) and momentum measurement (from tracker)

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

    TOF & TRACKER

  - by using γ parameter (from TOF) and total kinetic energy (from calorimeter)

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

    TOF & CALO

  - by using momentum measurement (from tracker) and total kinetic energy (from calorimeter)

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

    TRACKER & CALO

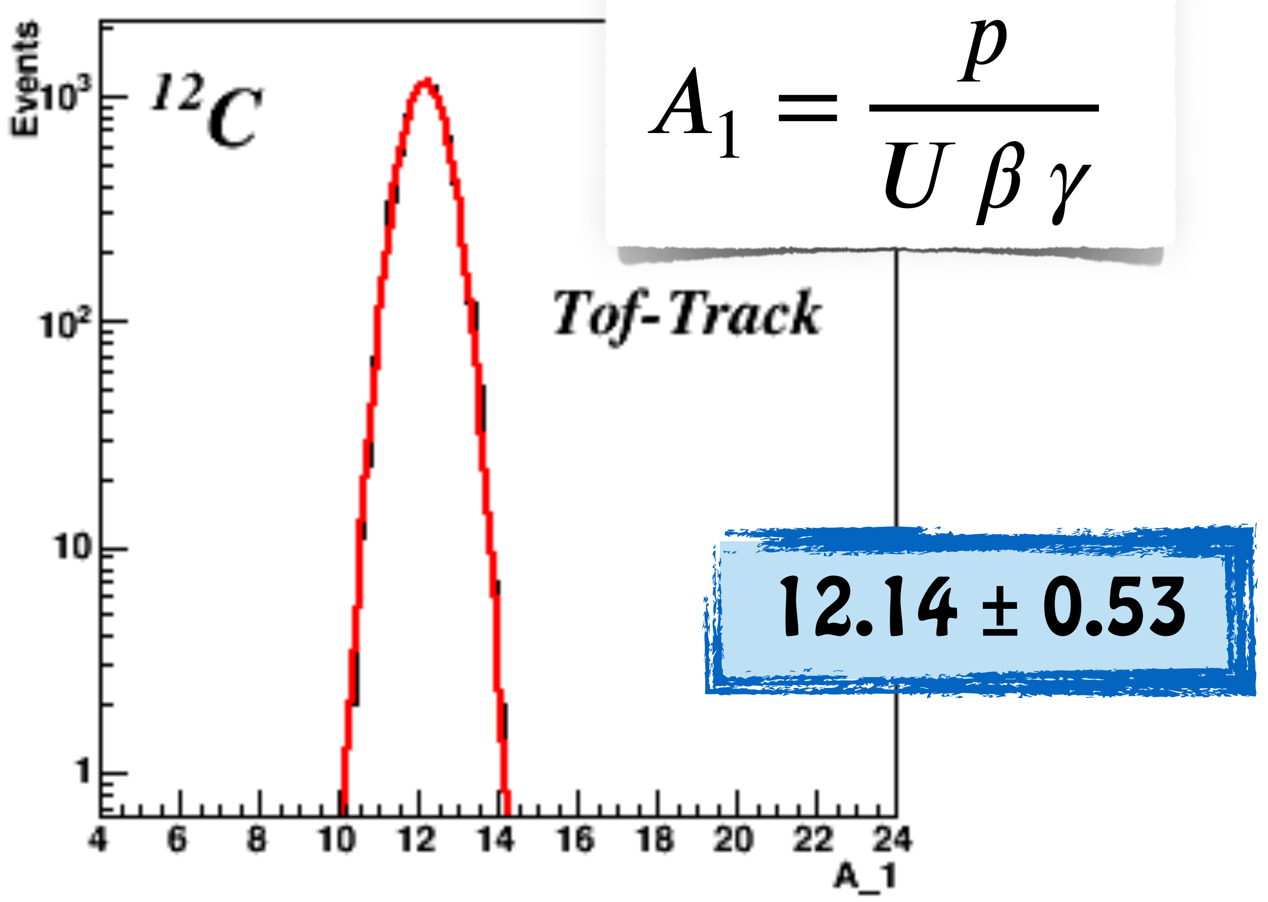
  -

Number of mass A

- All the 3 methods are possible in FOOT, useful for redundancy
- The 3 separate methods are applied on MC simulated event, shown here the case selecting Carbon fragments
- Gaussian fit is performed on the selected events, extracting mean mass value and sigma (quoted in the blue box)

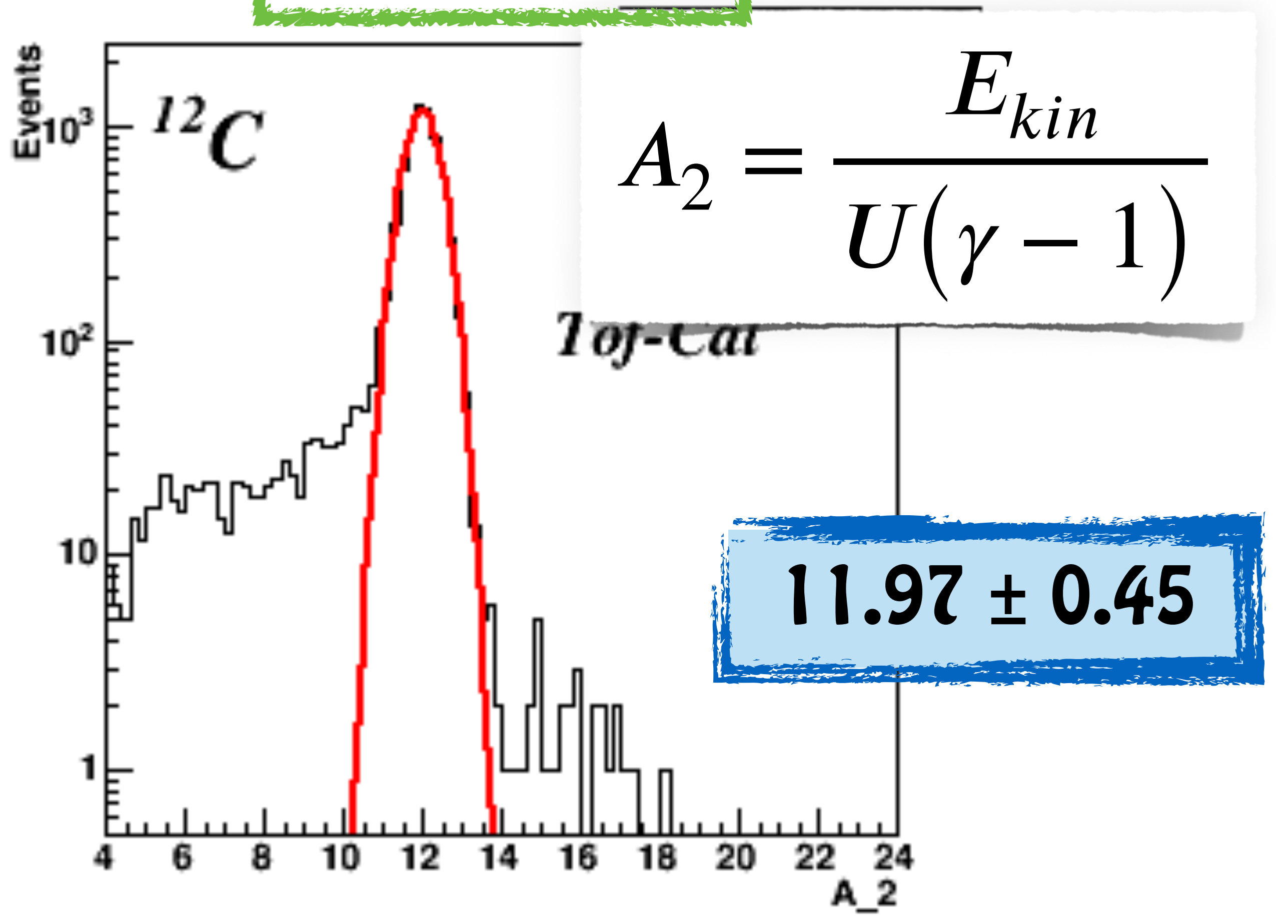
TOF & TRACKER

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



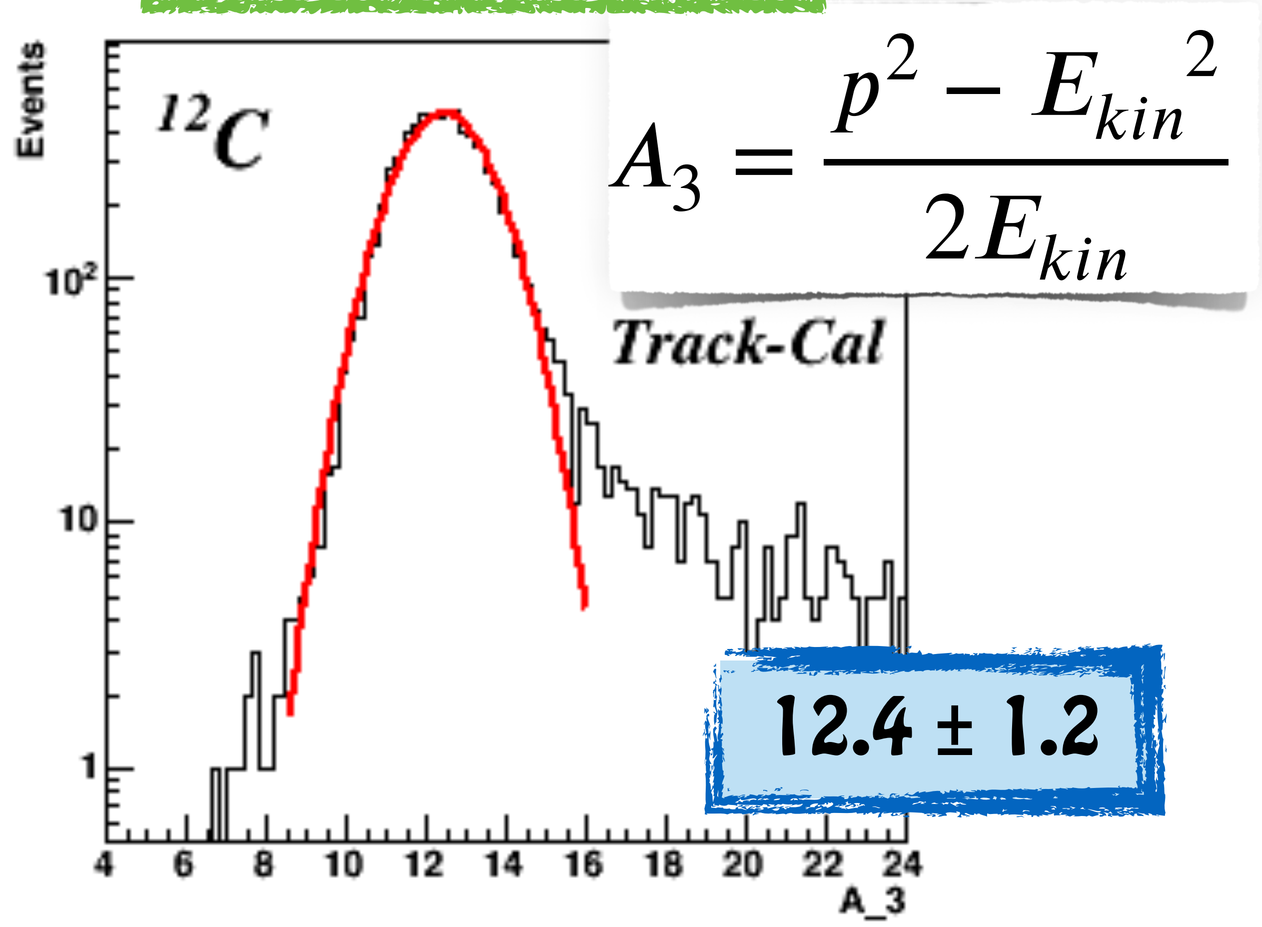
TOF & CALO

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



TRACKER & CALO

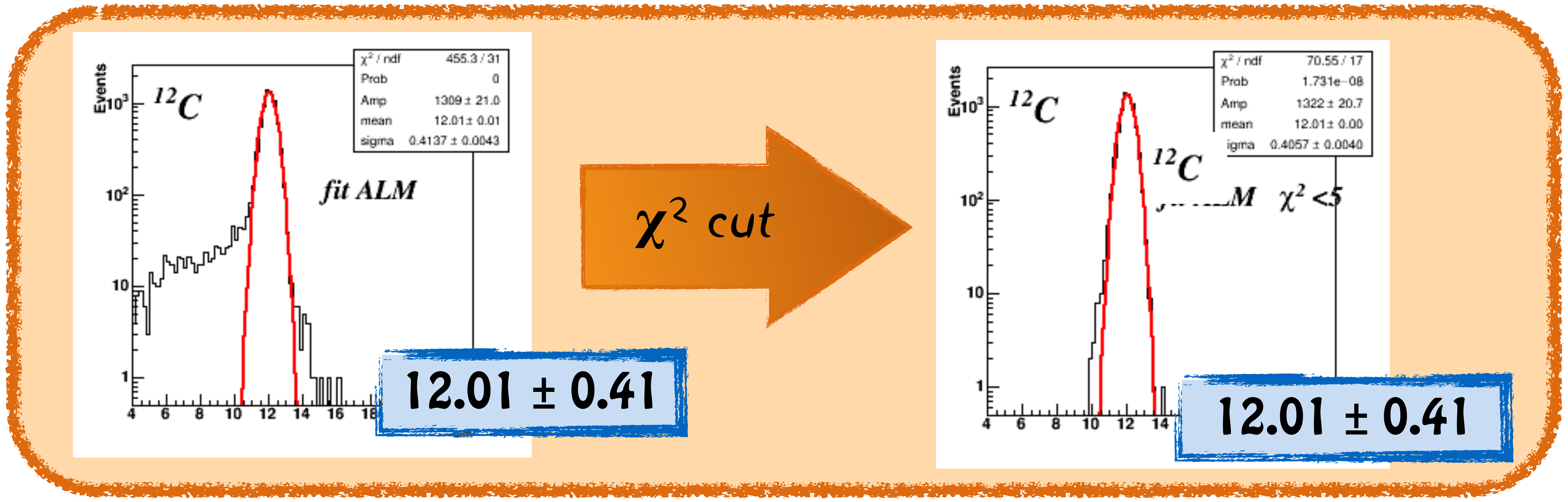
$$A_3 = \frac{p^2 - E_{kin}{}^2}{2E_{kin}}$$



Number of mass A

- Improving the result is possible by combining the 3 methods described before with an Augmented Lagrangian Method (ALM).
- Presented below the obtained combined result, to be compared with the ones from previous page
- The event tail observed can be remove with a simple χ^2 cut, as shown below

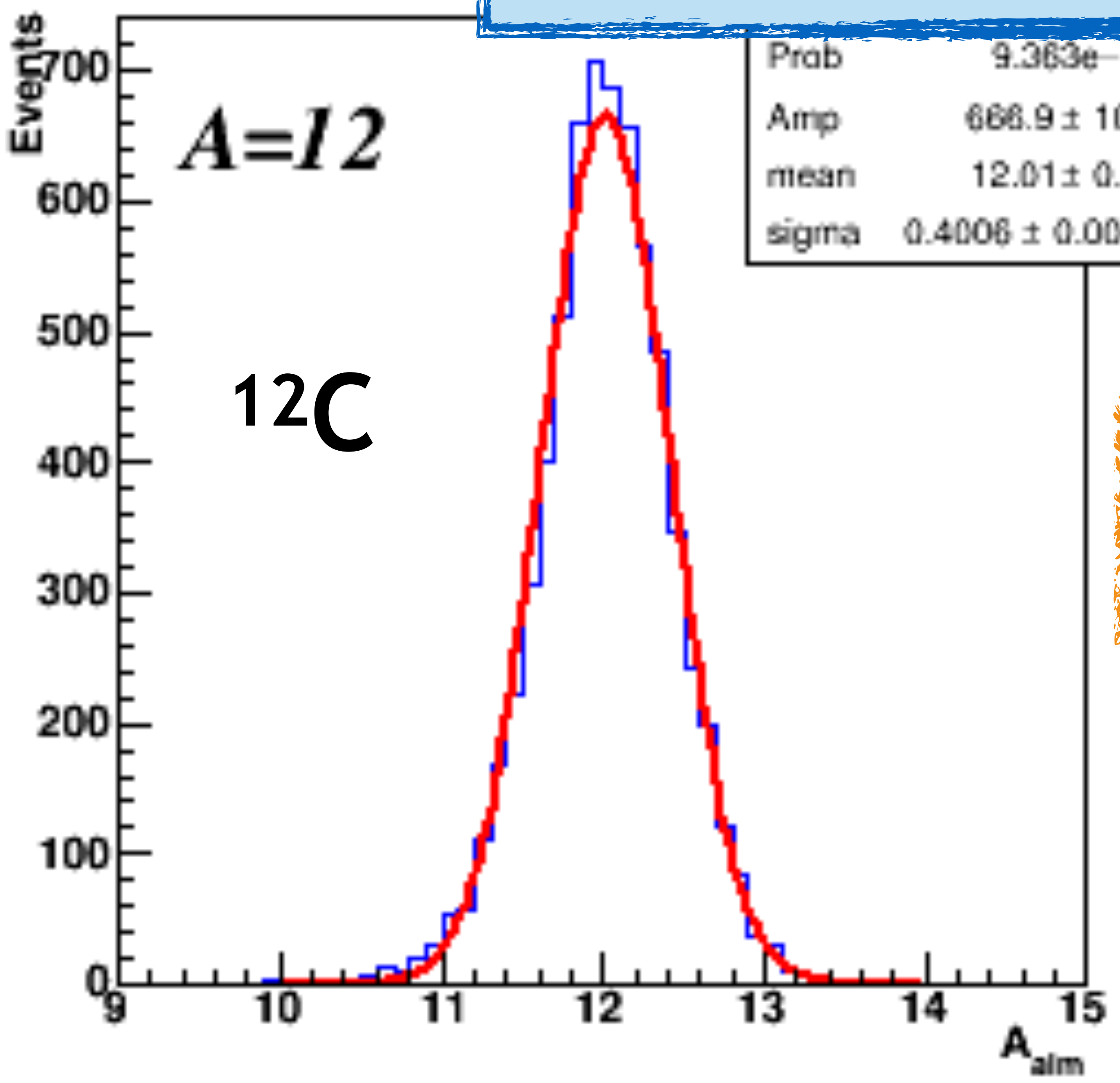
Final result with Augmented Lagrangian Fit (ALM)

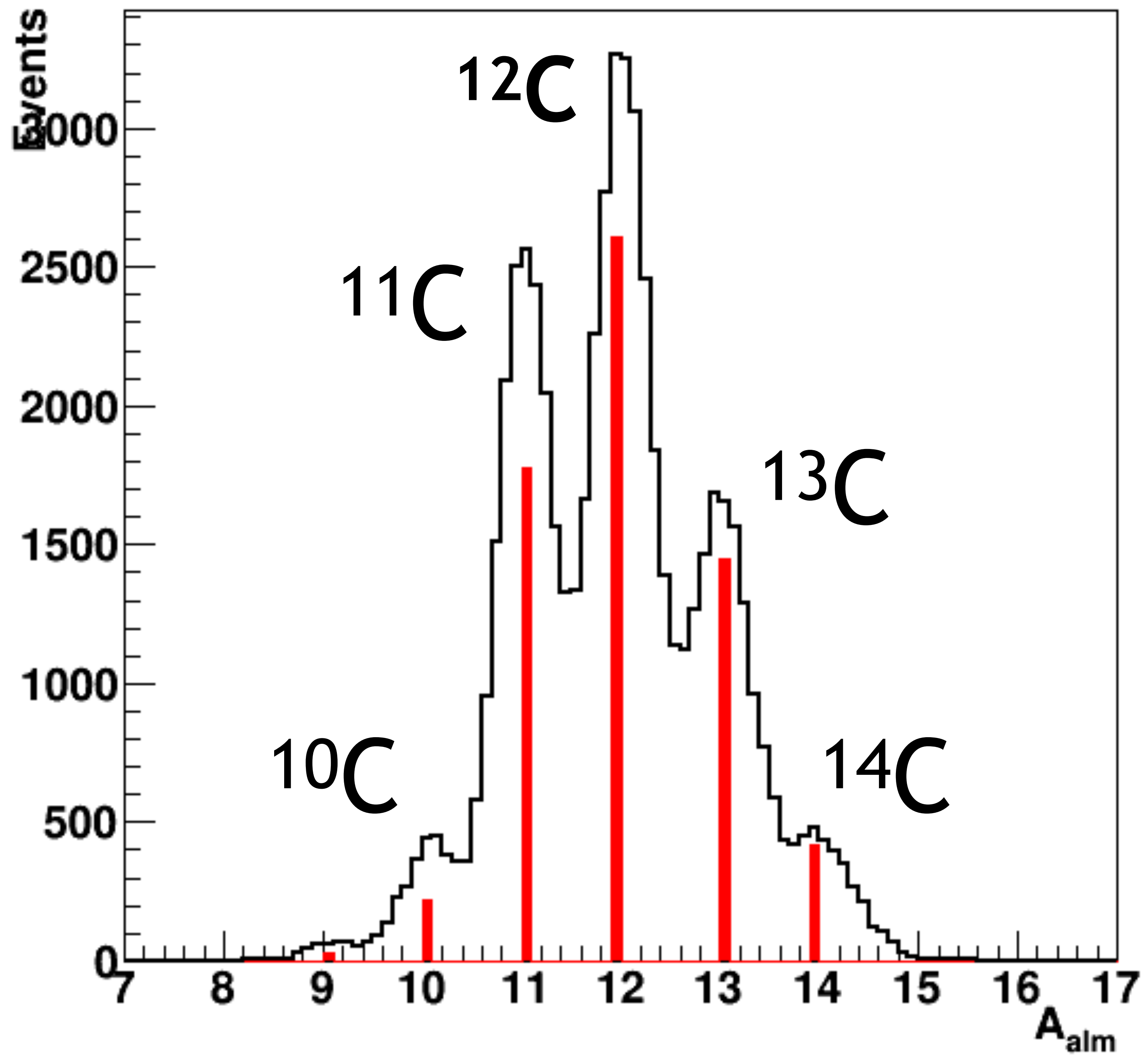


Mass reconstruction

- Using the ALM on each Carbon isotope and performing a Gaussian fit it is possible to count the number of each fragment produced.
- From this, it is straight-forward to obtained the fragmentation cross-section.
- This can be performed for each fragment ion produced.

A = 12.0 ± 0.4





Possibility to disentangle isotopes!!!
(C most difficult)

Data-taking results

Data-taking

* First FOOT data—takings in 2019 with a partial detector setup (missing Calorimeter, Inner Tracker, Magnets and Microstrip detector)
* Data acquired at CNAO and GSI laboratories using proton, Carbon and Oxygen beams at different energies.
* Performed:
  * Scintillator performance study
  * Fragment charge reconstruction
* Results published @ https://doi.org/10.1016/j.nima.2021.165206

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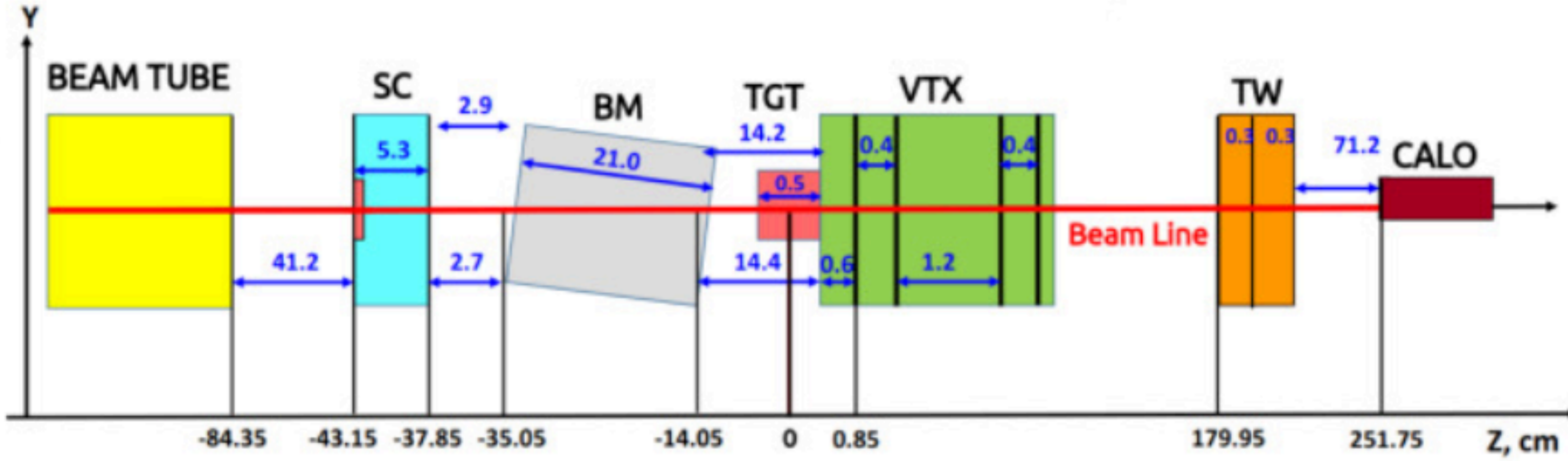
ELSEVIER

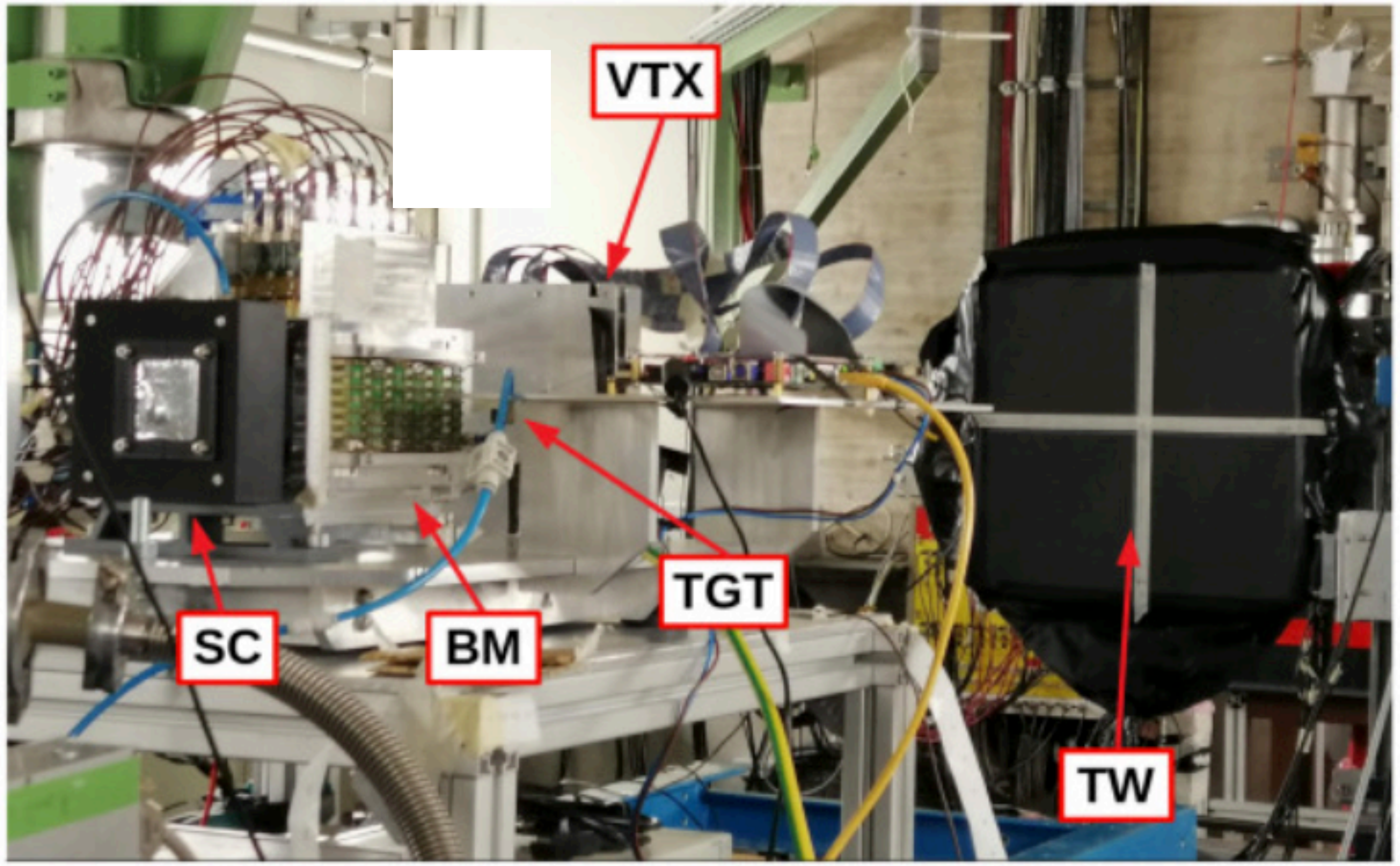
Charge identification of nuclear fragments with the FOOT Time-Of-Flight system

A.C. Kraan[1], R. Zarrella[20,4,a,*], A. Alexandrov[10,19,33,34], B. Alpat[11], G. Ambrosi[11], S. Argirò[28,17], R. Arteche Diaz[30], N. Bartosik[17], G. Battistoni[8], N. Belcari[2,1], E. Bellinzona[15], S. Biondi[4,20], G. Bruni[4], P. Carra[2,1], P. Cerello[17], E. Ciarrocchi[2,1], A. Clozza[7], S. Colombi[15,16], G. De Lellis[19,10], A. Del Guerra[2,1], M. De Simoni[12,26], A. Di Crescenzo[19,10], B. Di Ruzza[15], M. Donetti[5], Y. Dong[8,23], M. Durante[6,32], R. Faccini[26,12], V. Ferrero[17], E. Fiandrini[11,24], C. Finck[14], E. Fiorina[17], M. Fischetti[12,22], M. Francesconi[2,1], M. Franchini[4,20], G. Franciosini[12,26], G. Galati[10], L. Galli[1], V. Gentile[10,31], G. Giraudo[17], R. Hetzel[3], E. Iarocci[7], M. Ionica[11],

Data-taking setup



(a)

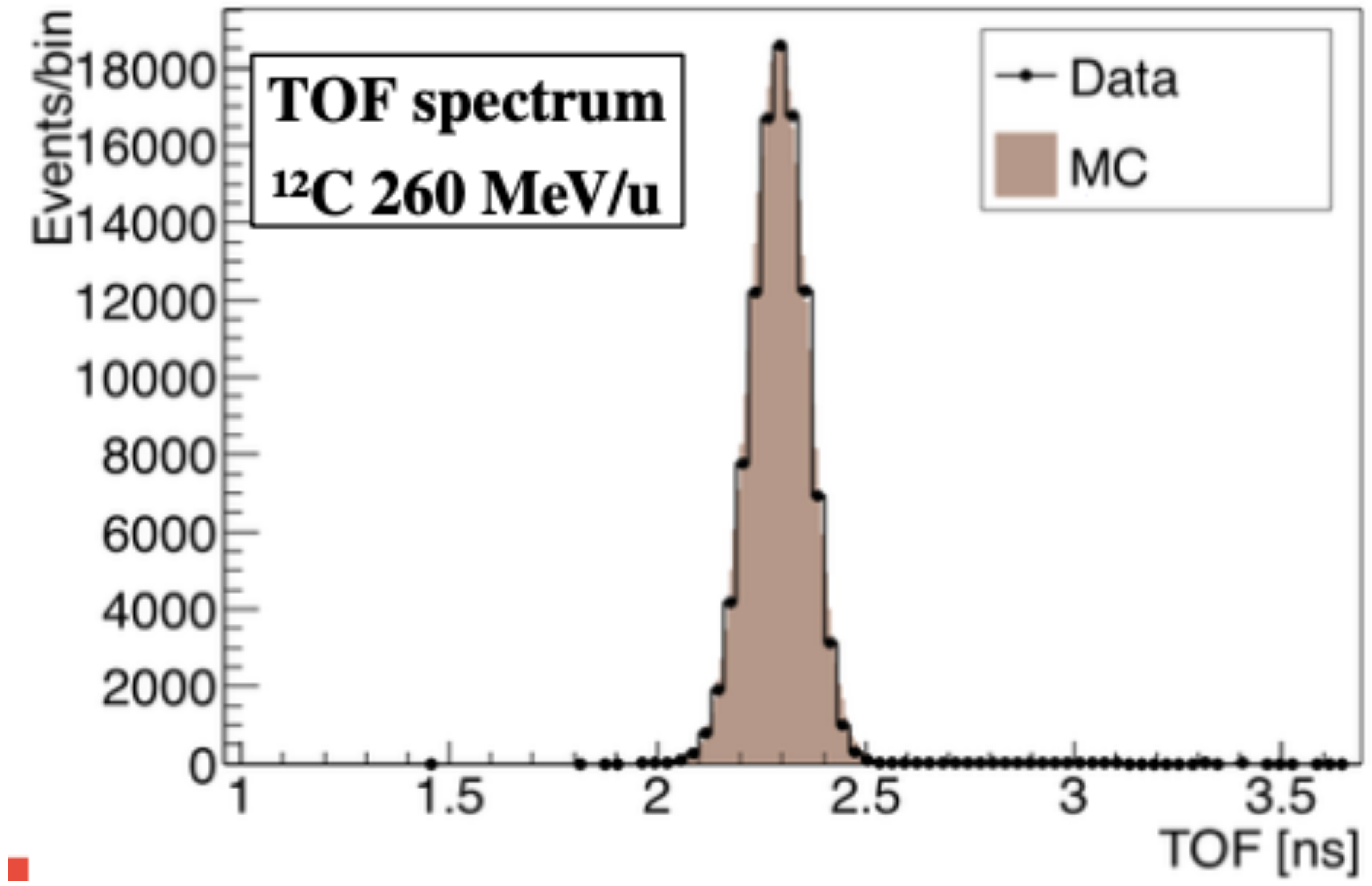


(b)

* Partial FOOT setup used for data tacking
* No magnetic filed present

Data-taking results

* TOF resolution measured between Start–Counter and Scintillator
* TOF data spectra for calibrated data (black) and tuned MC simulations (brown).



Compatible with MC simulation

Extracted TOF resolution

Particle	E_{beam} [MeV/u]	σ (TOF) [ps]
p	60	264.9 ± 0.8
^{12}C	115	54.4 ± 0.1
^{12}C	260	66.4 ± 0.2
^{12}C	400	73.6 ± 0.2
^{16}O	400	75.6 ± 0.6

Found out a resolution **well suited** for FOOT physic program

Data-taking results

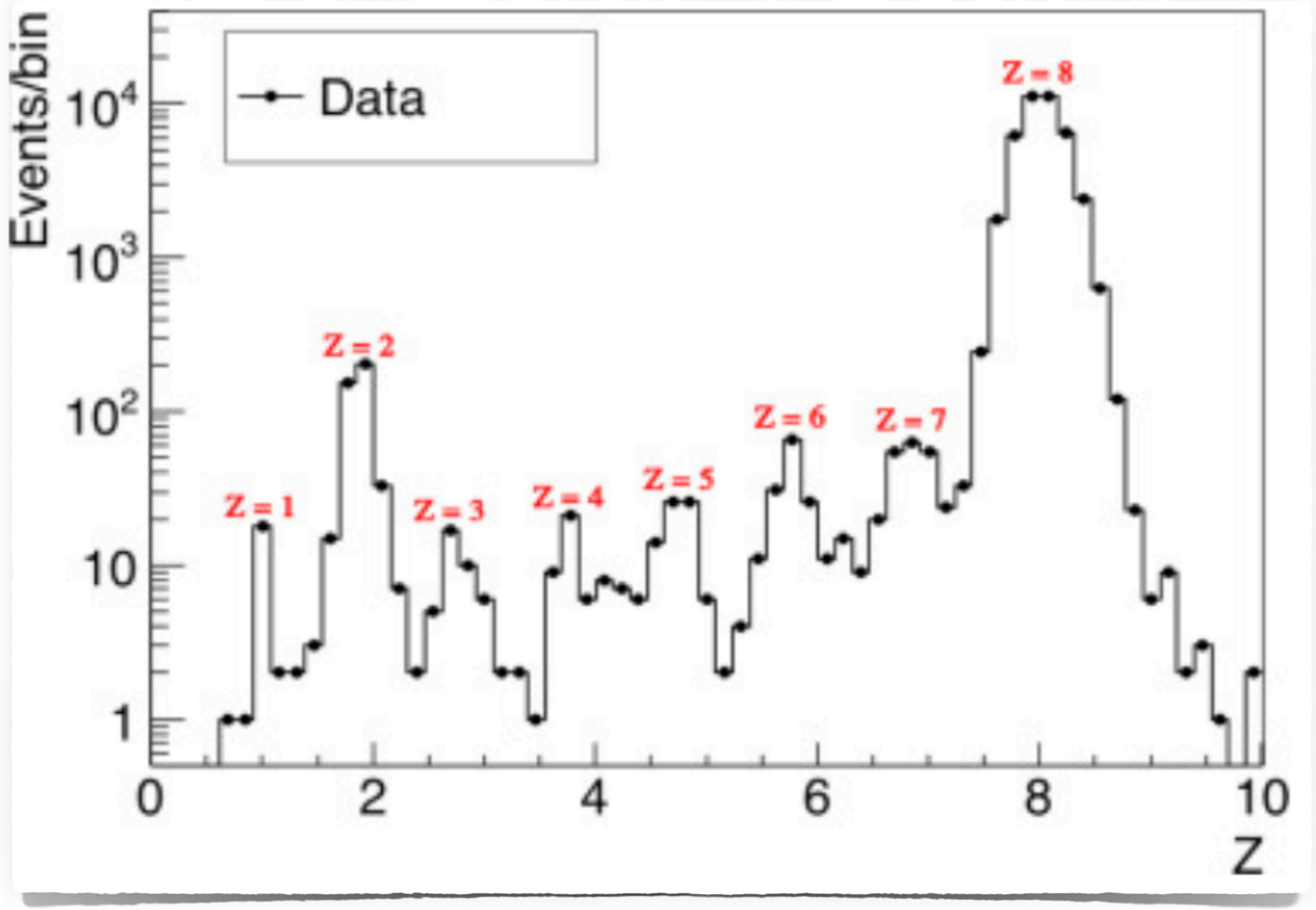
* Reconstruction of the charge of the beam particles with a Gaussian fit, measuring charge resolution.
* Table below reports the mean (charge measure) and sigma (resolution) parameter of the charge fit
* Charge resolution compatible with the overall requirements of the experiment

Particle	E_{beam} [MeV/u]	$\mu(Z)$	$\sigma(Z)$	$\sigma(Z) / \mu(Z)$ [%]
p	60	0.96	0.06	6.10 ± 0.02
^{12}C	115	6.17	0.15	2.51 ± 0.01
^{12}C	260	6.01	0.21	3.52 ± 0.01
^{12}C	400	6.07	0.24	3.85 ± 0.01
^{16}O	400	8.07	0.22	2.67 ± 0.02

Data-taking results

* Reconstructed the charge of the ion fragments produced in case of Oxygen beam colliding on graphite target (2mm)

* Good ion discrimination!



Conclusion and Future

- 🚧 FOOT detector under construction 🚧
- Wide physic program on Hadrontherapy (experiment goals)
  - Both projectile and target fragmentation , fragment identification in both Z and A!
  - Differential fragmentation Xsec (in angle and energy) with < 5% precision!
- First data—taking results (with partial detector setup) are presented
  - TimeOfFlight (TOF) resolution performed: ~250ps for protons and < 75ps for heavier ions
  - Charge resolution measurement presented diving a good charge discrimination power for ion fragments, as shown
- Full data taking foreseen in 2022, with Carbon, Oxygen and Helium beams.

Thanks