Fast Timing Applications
for Nuclear Physics and Medical Imaging
Acireale 3-5 September 2019
Accademia di Scienze Lettere e Belle Arti degli Zelanti e dei Dafnici
Via Marchese di Sangiuliano, 17 - 95024 Acireale (Catania)

Performance of the ToF detectors in the FOOT experiment

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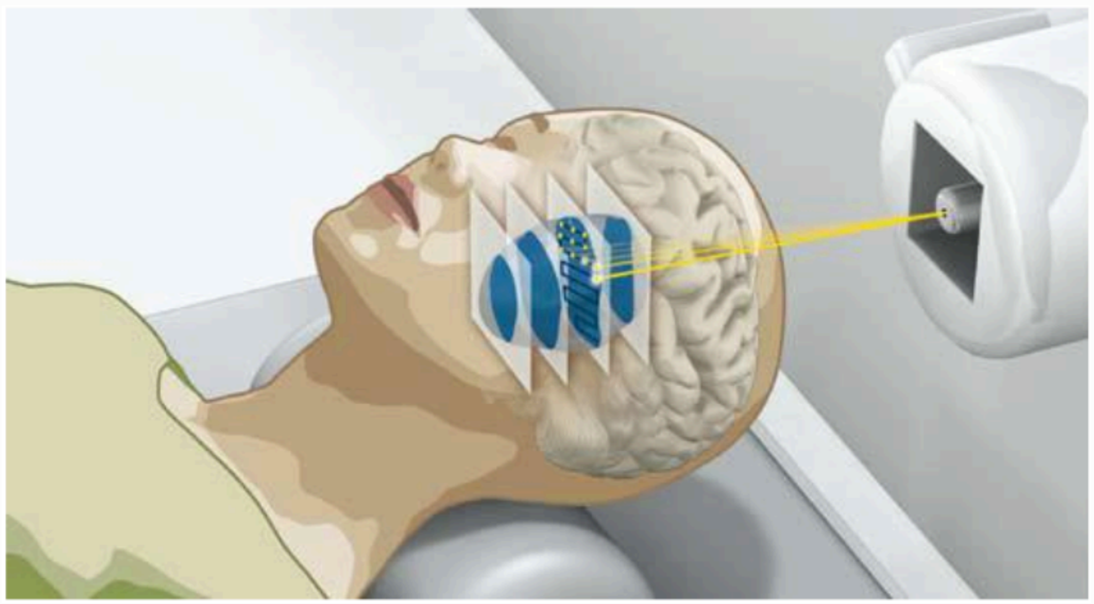
Istituto Nazionale di Fisica Nucleare

FOOT (FragmentatiOn Of Target)

- The FOOT is a fixed target experiment, whose goal is to measure fragmentation **cross-sections** of interest for **hadrontherapy** and **radioprotection in space**, with a **precision of ~5%**.

Hadrontherapy



- **Goal**: more accurate knowledge of fragmentation processes to improve the treatment quality.
- **Projectile fragmentation**: ^{12}C, ^{16}O beams @ 200-400 MeV/u , direct kinematic
- **Target fragmentation** in proton-therapy: same beams, inverse kinematic

Radioprotection in space

- **Goal**: more accurate knowledge of fragmentation processes to optimise the spacecraft shielding in the long term missions.
- ^{12}C, ^{16}O, ^{4}He, beams @ 700 MeV/u , direct kinematic

FOOT (FragmentatiOn Of Target)

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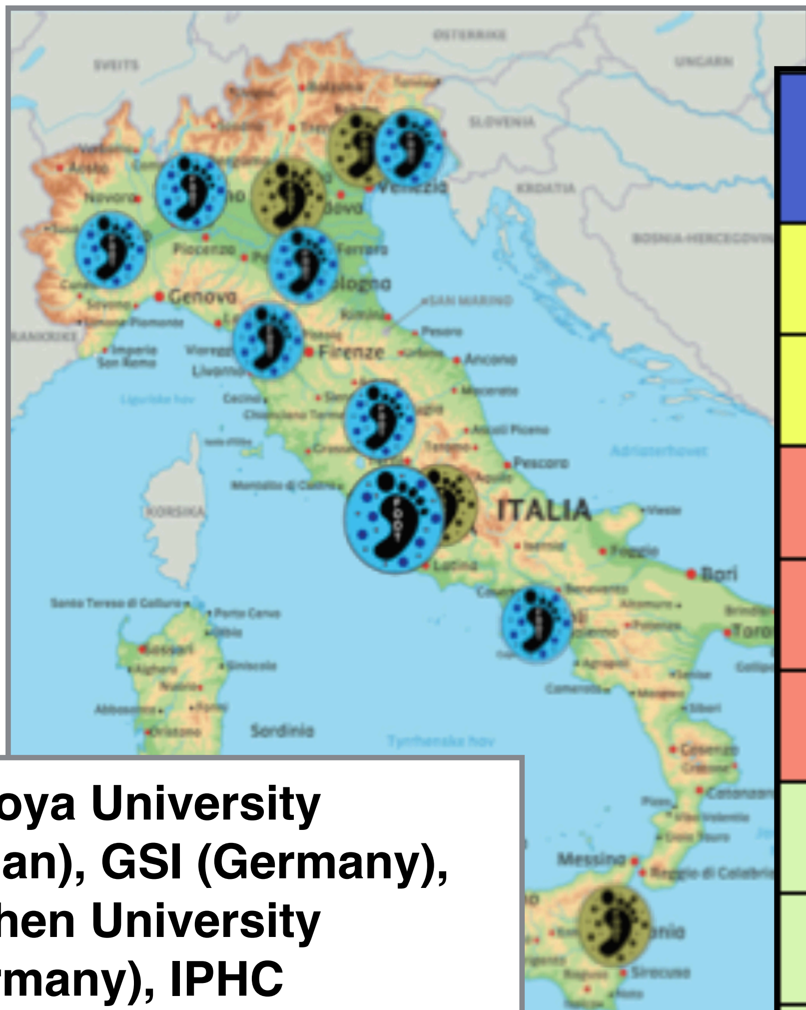
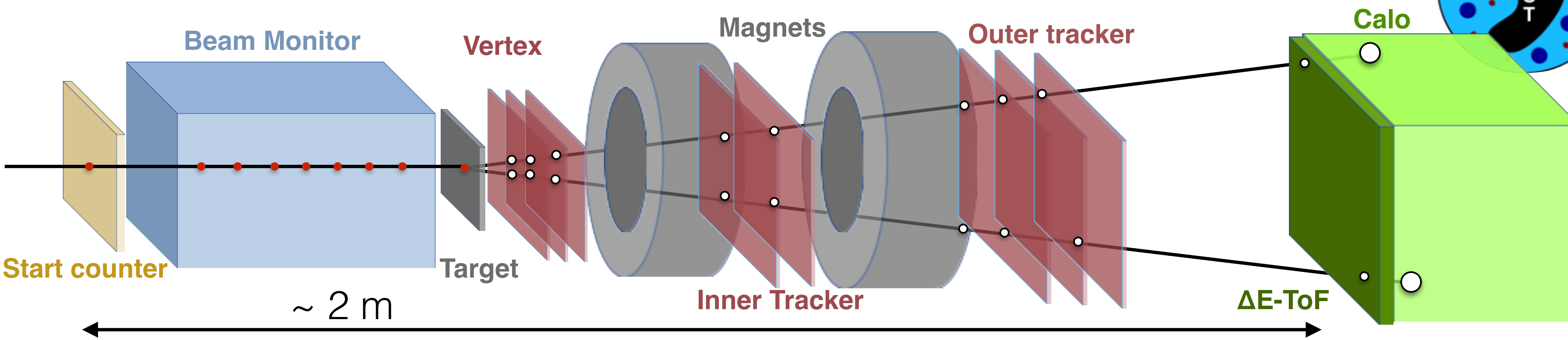


Nagoya University (Japan), GSI (Germany), Aachen University (Germany), IPHC Strasbourg (France), CNAO (Italy), 10 INFN sections/labs

Phys	Beam	Target	Energy (MeV/u)
Target Frag. PT	^{12}C	C, C_2H_4	100-200
Target Frag. PT	^{16}O	C, C_2H_4	100-200
Beam Frag. PT	^{12}C	C, C_2H_4, PMMA	200-350
Beam Frag. PT	^{16}O	C, C_2H_4, PMMA	200-400
Beam Frag. PT	^{4}He	C, C_2H_4, PMMA	150-250
Rad. Prot.space	^{4}He	C, C_2H_4, PMMA	500-1000
Rad. Prot.space	^{12}C	C, C_2H_4, PMMA	500-1000
Rad. Prot.space	^{16}O	C, C_2H_4, PMMA	500-1000

The FOOT setup

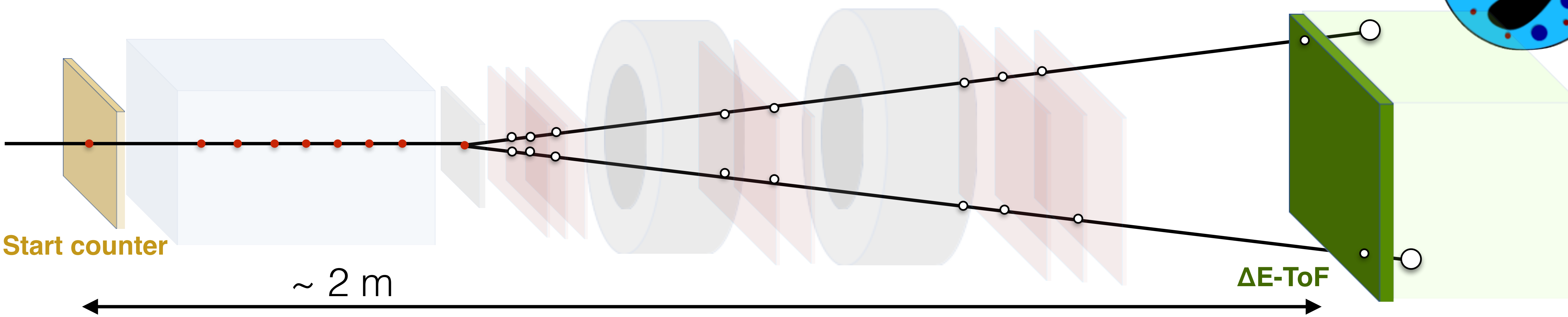


Sub-detector	Main features
Start Counter	250 μm plastic scintillator, SiPM read-out
Beam monitor	Drift Chamber Ar-CO_2
Target	C, C_2H_4 (2-5 mm)
Vertex	4 layers of Silicon Pixel detector, MIMOSA28 20x20 μm^2
Magnet	Halbach geomertry, 0.8-0.9 T
Inner Tracker	2 layers of Silicon Pixel detector, 20x20 μm^2
Outer tracker	3 layers of Micro Strip detector, 125 μm^2
ΔE - ToF	plastic scintillator 3 mm thick
Calorimeter	matrix of ~ 300 BGO crystals

- **Goal**: measurement of **Ekin, Z, A** of fragments
- Optimised for **Z>=3 fragments,** angular acceptance of the apparatus ± 10°
- **Table-top experiment**, easily movable to fit with the limited space of treatment and experimental rooms

- **Needed detector performance**:
$\sigma(p)/p \sim 5\%$, $\sigma(ToF) < 100ps$, $\sigma(E_{kin})/E_{kin} \sim 2\%$

The FOOT setup



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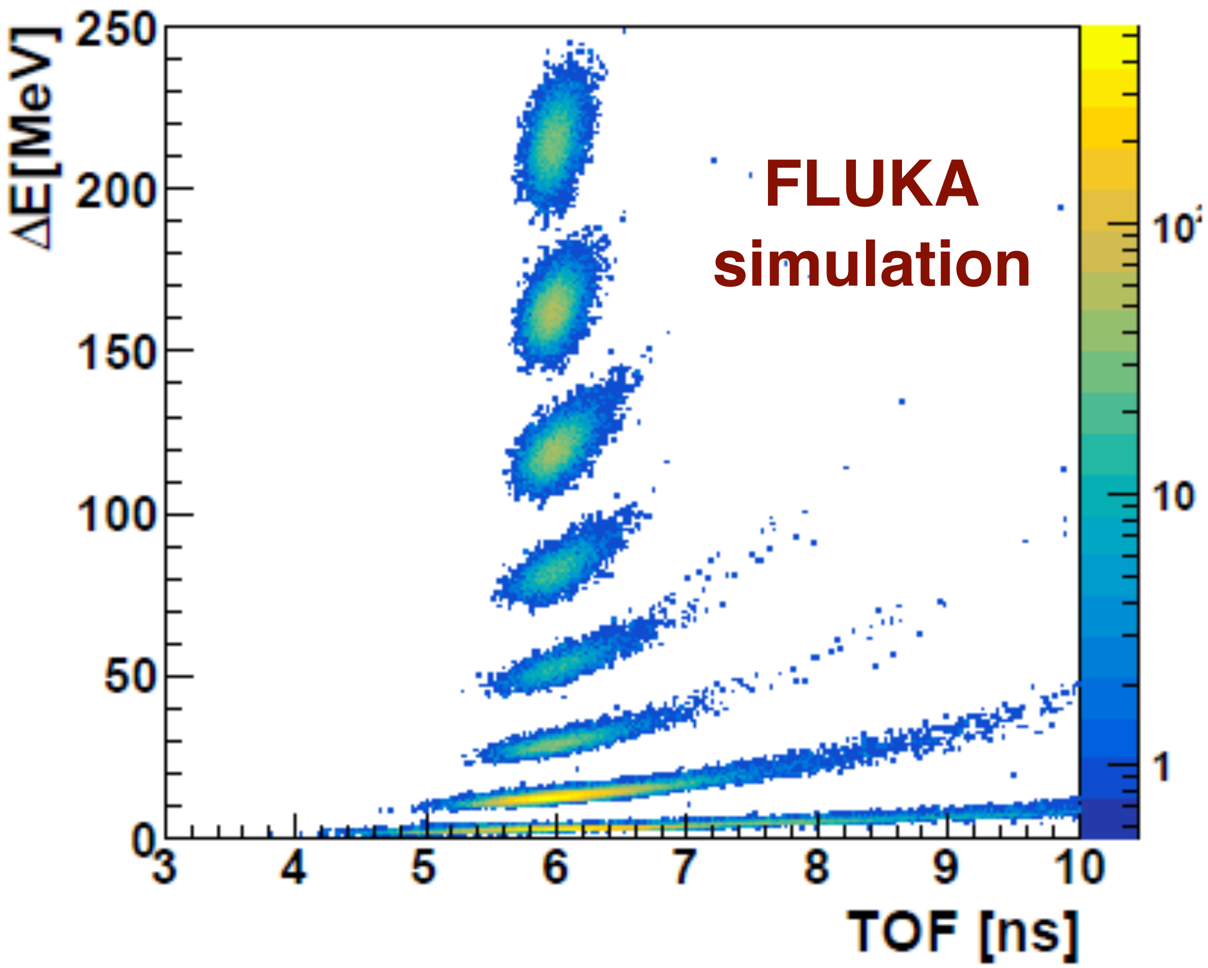
ToF for fragment Z identification

ΔE in SCN

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

ToF

Energy deposited ΔE vs ToF



^{16}O (200 MeV/u) —> C_2H_4

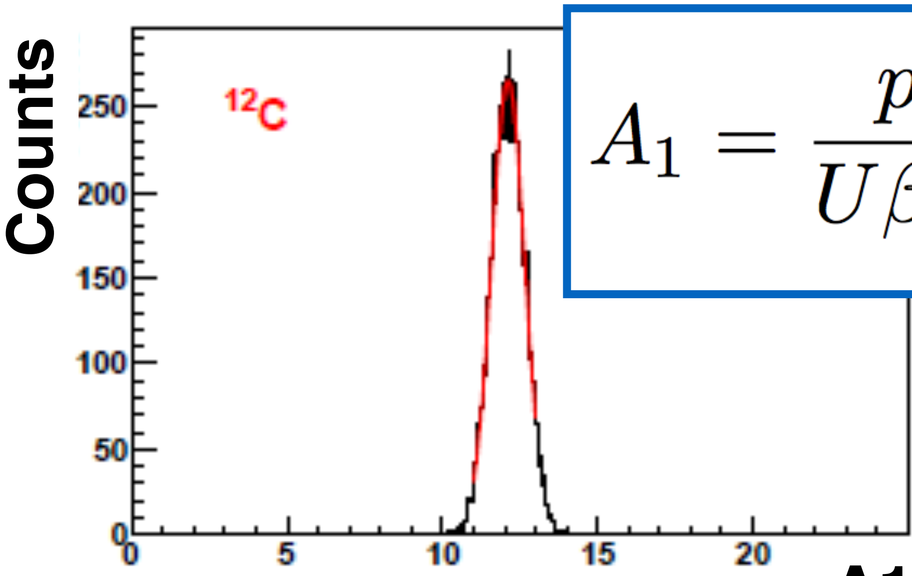
Reconstructed Z

Fragment	Z	$\sigma(Z)$ [%]
H	1.01±0.06	6.26
He	2.02±0.06	3.06
Li	3.03±0.07	2.46
Be	4.05±0.09	2.20
B	5.07±0.10	2.06
C	6.09±0.12	1.97
N	7.12±0.14	1.91
O	8.17±0.15	1.86

The Z resolution ranges between **2% (^{16}O)** and **6% (H)**

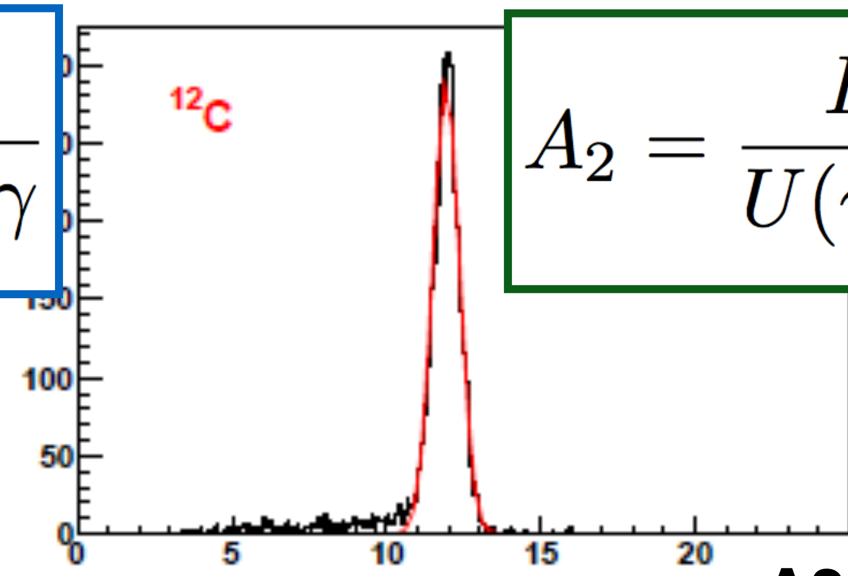
ToF for fragment A identification

Redundant Detector: different ways to determine A



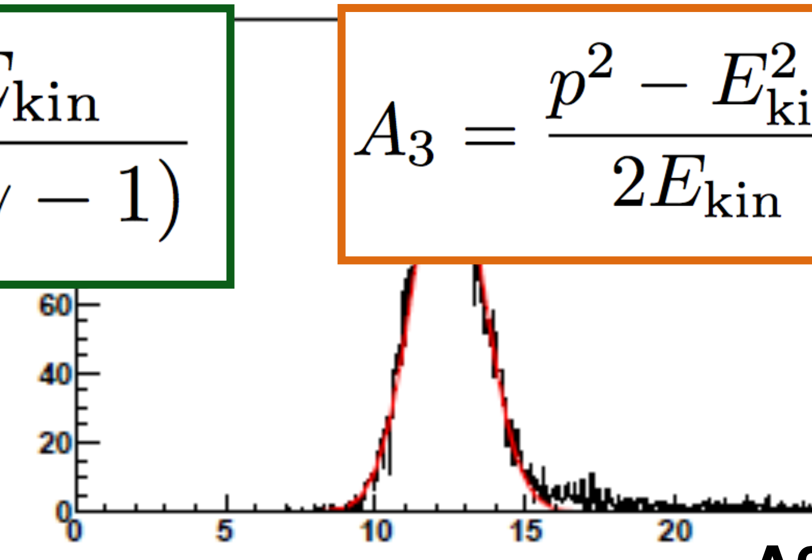
$$A_1 = \frac{p}{U\beta\gamma}$$

ΔE-ToF & Tracker



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

ΔE-ToF & Calo



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

Tracker & Calo

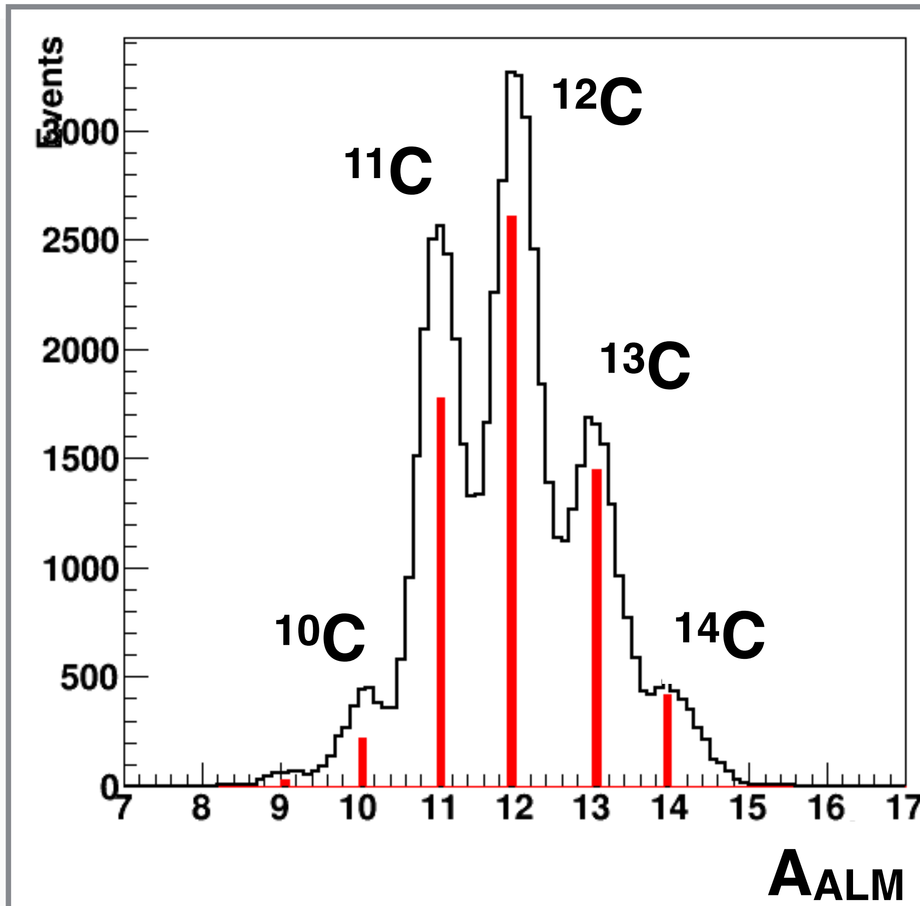
- Fit with the **Augmented Lagrangian Method (ALM)**
- Expected resolution on the atomic mass A ranging between **3% and 6%**, with the required detector resolution

FLUKA simulation

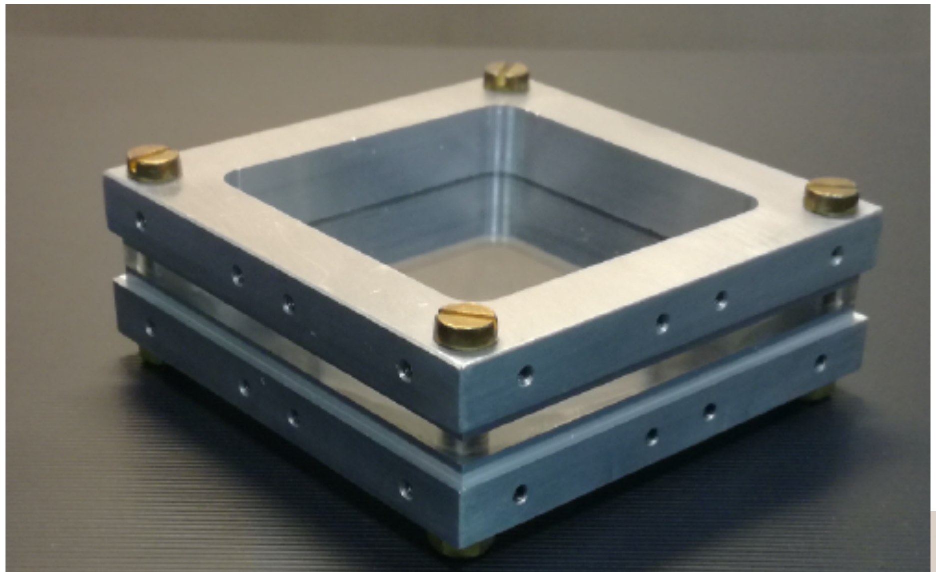
^{16}O (200 MeV/u) —> C_2H_4

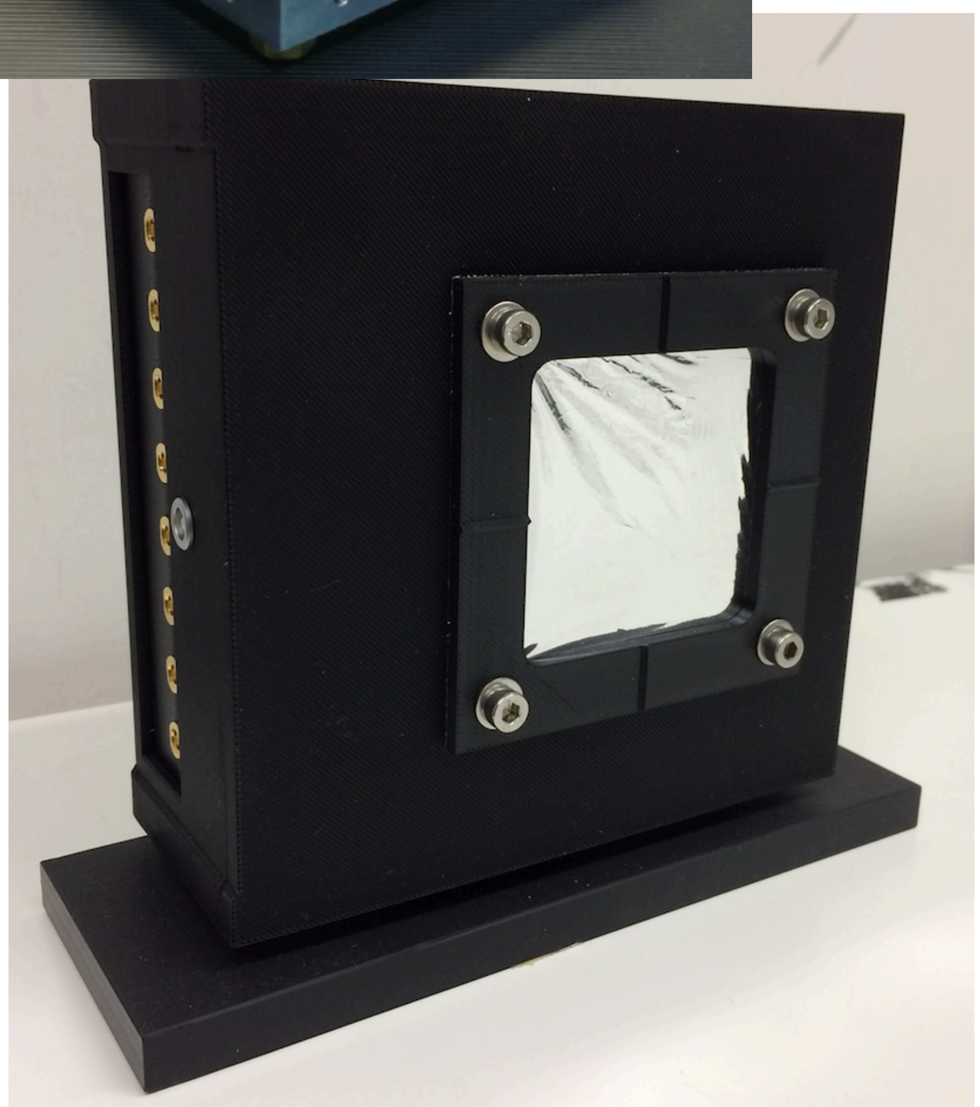
Resolutions:

- σ(p)/p = 4%
- σ(Ekin)/Ekin = 1.5%
- σ(ToF) = 100ps
- σ(ΔE)/ΔE = 3-10%



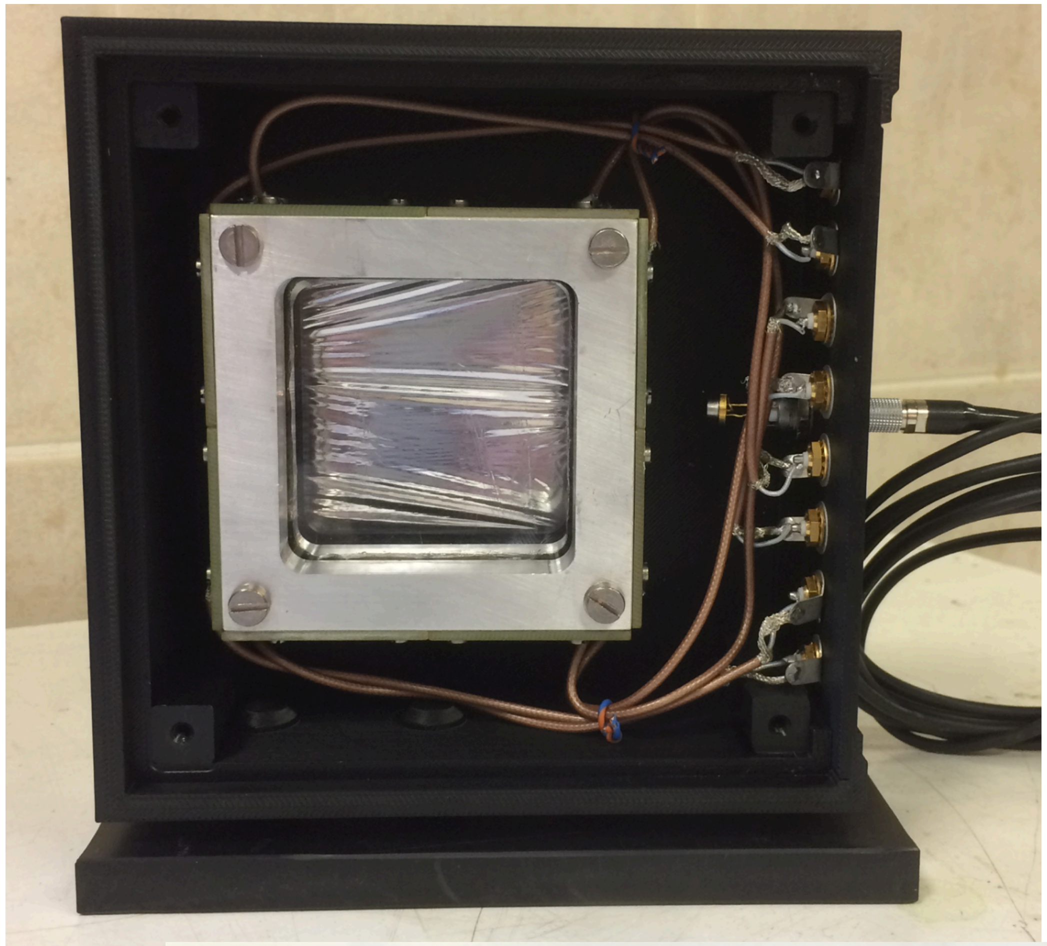
Start Counter detector



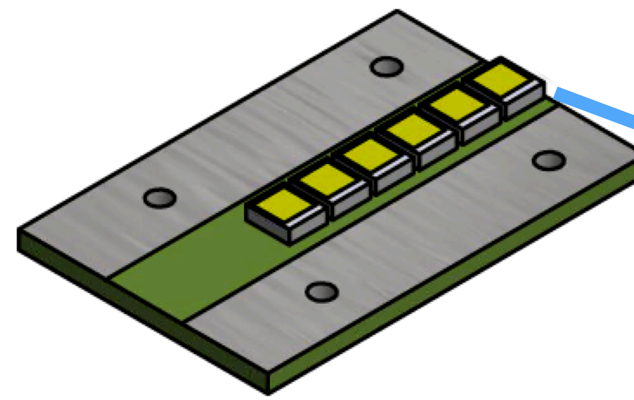


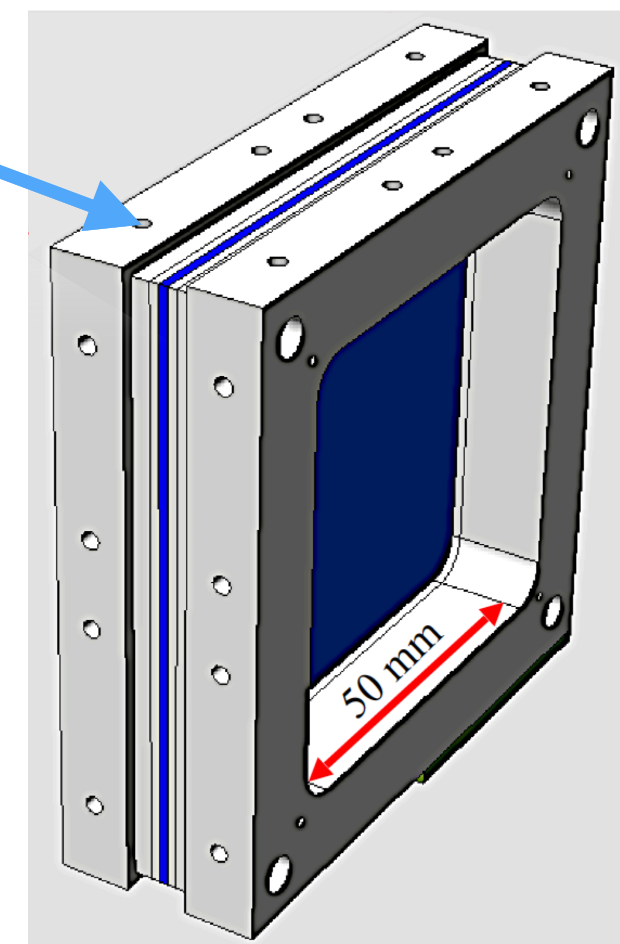
- **Goals:**
  - Incoming ions counter
  - Trigger
  - ToF start
- **Requirements**:
  - Minimise the fragmentation probability inside the detector active medium
  - ToF resolution below 100 ps
- **Active mean:**
  - **Plastic scintillator EJ-228**, 5 x 5 cm^2, **250μm thick,** incapsulated in an aluminum frame
  - Enclosed in a tight-light box with 2 thin aluminum (0.4 μm)+mylar windows (4μm)

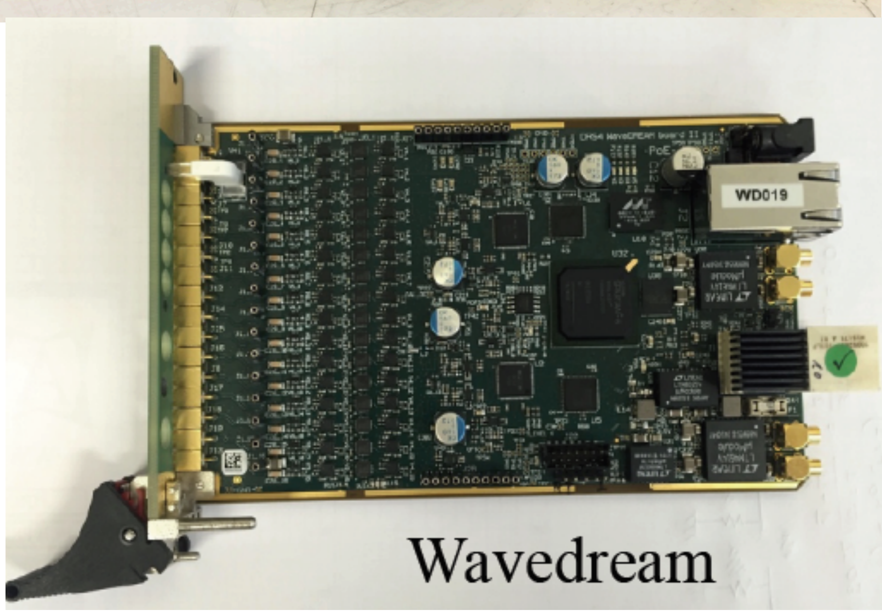
Start Counter read-out



- Read-out performed by **48 SiPM ASD-NUV3S-P**, (8 boards of 6 SiPM connected in series)
- The SiPMs are side-coupled to the scintillator, instrumenting 3.6/5 cm per side

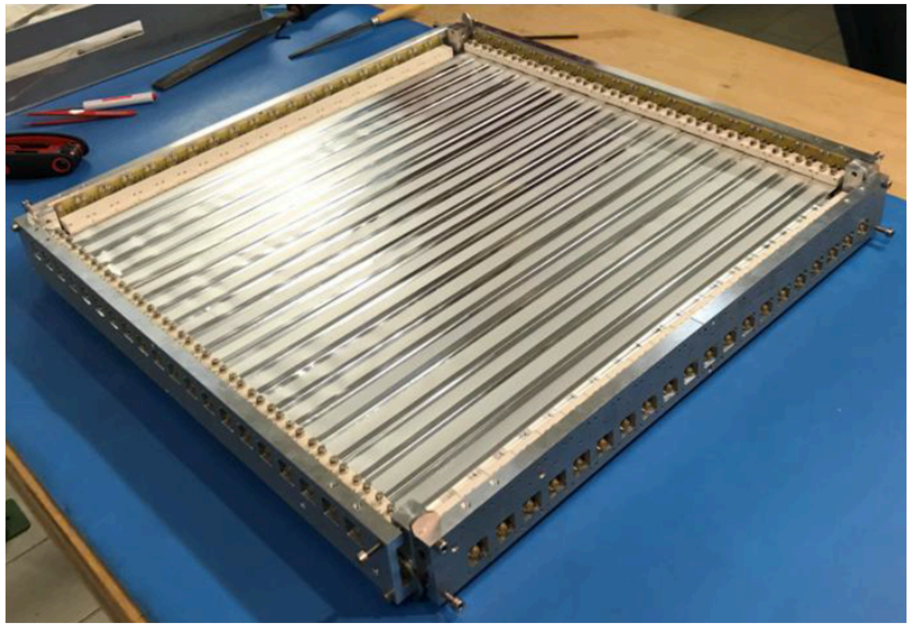


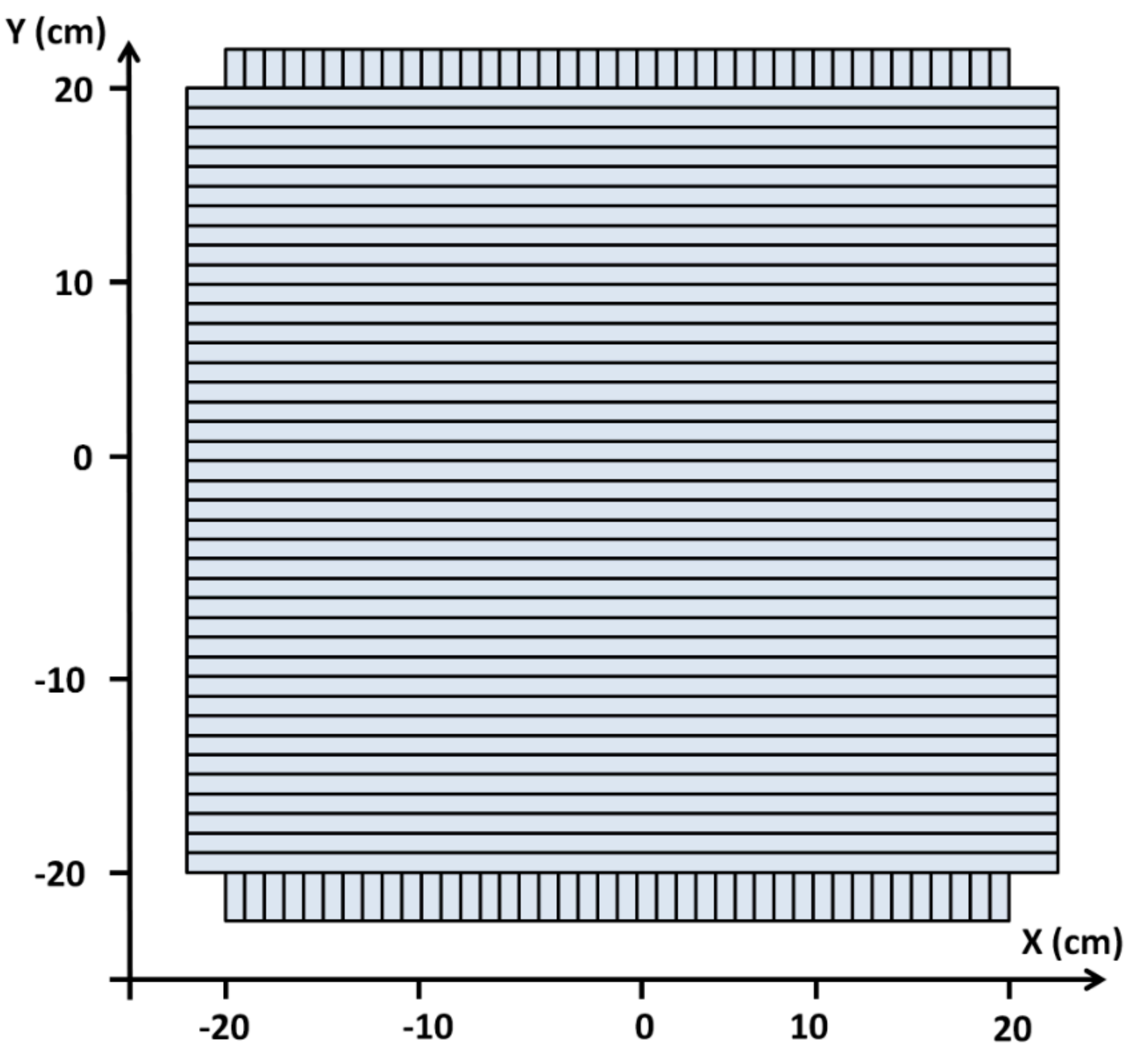




- The power supply and the ead-out of the SiPMs is provided by the WaveDream boards

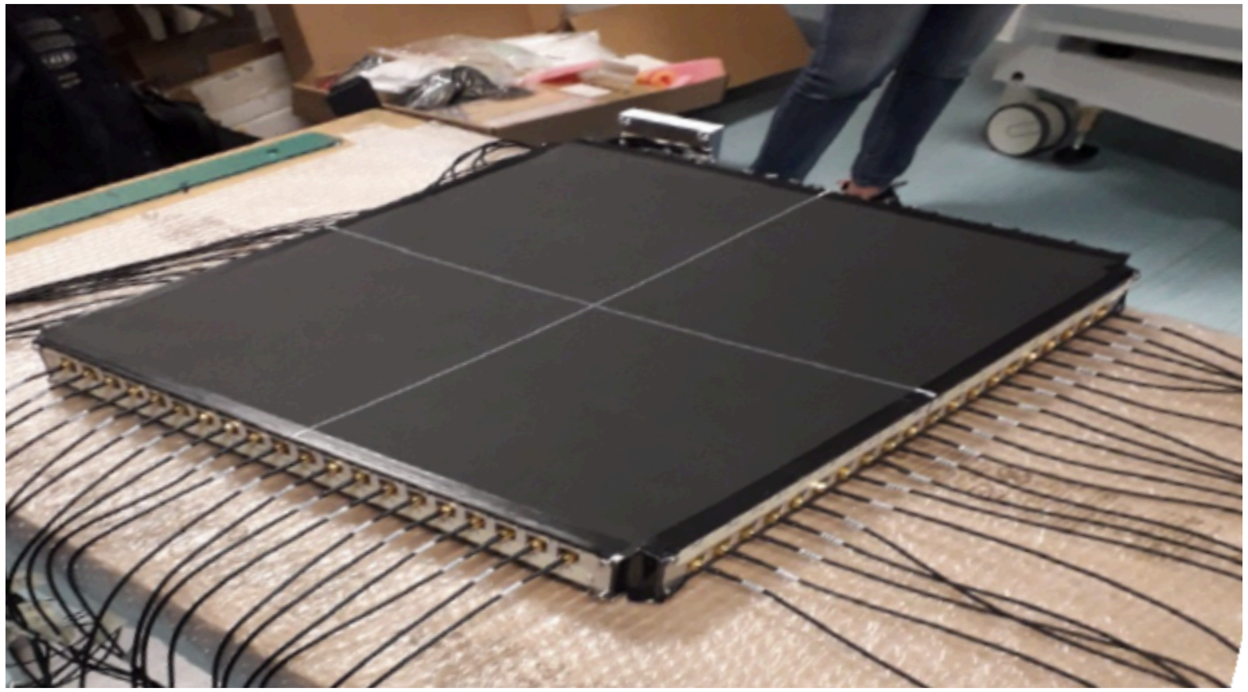
ΔE- ToF detector



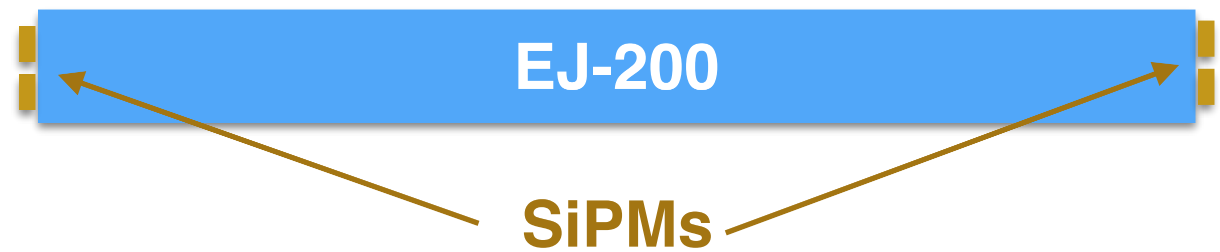


- **Goals:**
  - ΔE measurements for fragment Z identification
  - Trigger
  - ToF end
- **Requirements**:
  - Energy resolution at level of 5%
  - Time of Flight resolution below 100 ps
- **Active mean:**
  - 20x20 bars of **plastic scintillator EJ-200**, 2x44x0.3 cm^3**,** hold by an aluminum frame
  - Each bar is wrapped with and ESR specular reflector

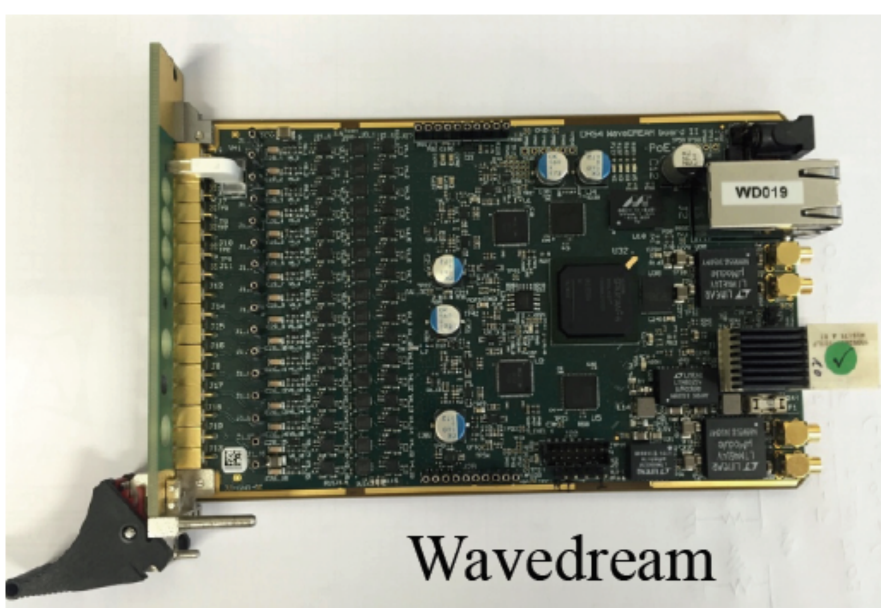
ΔE- ToF read-out

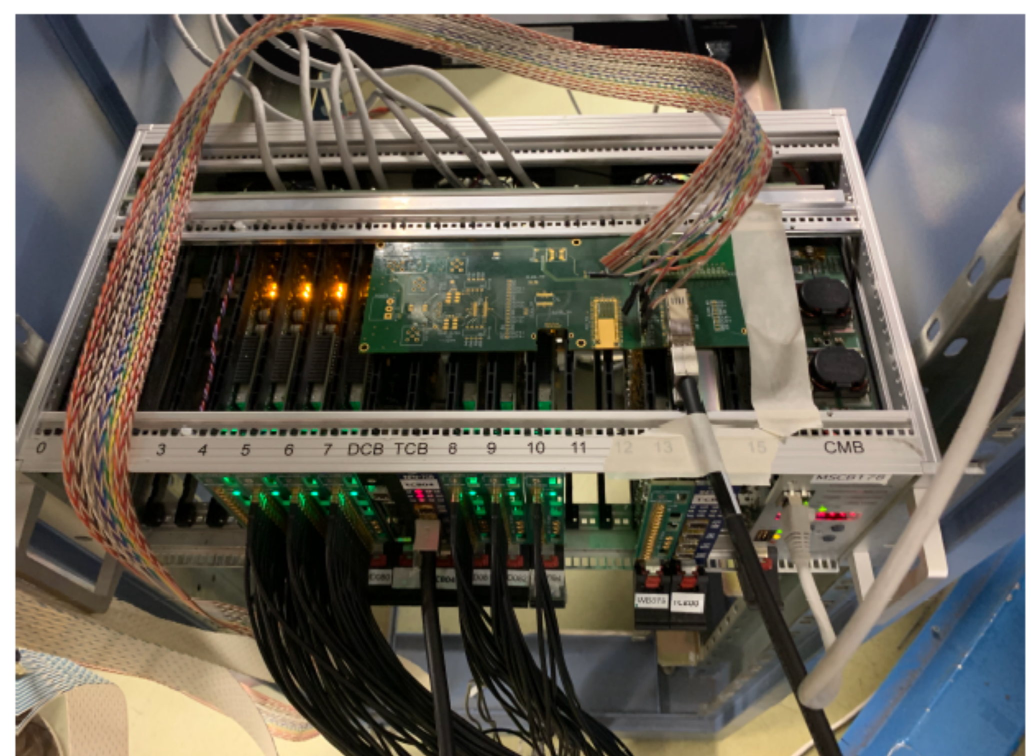


- Each bar side is coupled to 2 SiPM (**MPPC by Hamamatsu**) with 3x3 mm^2 active area, biased and read-out by a single channel.

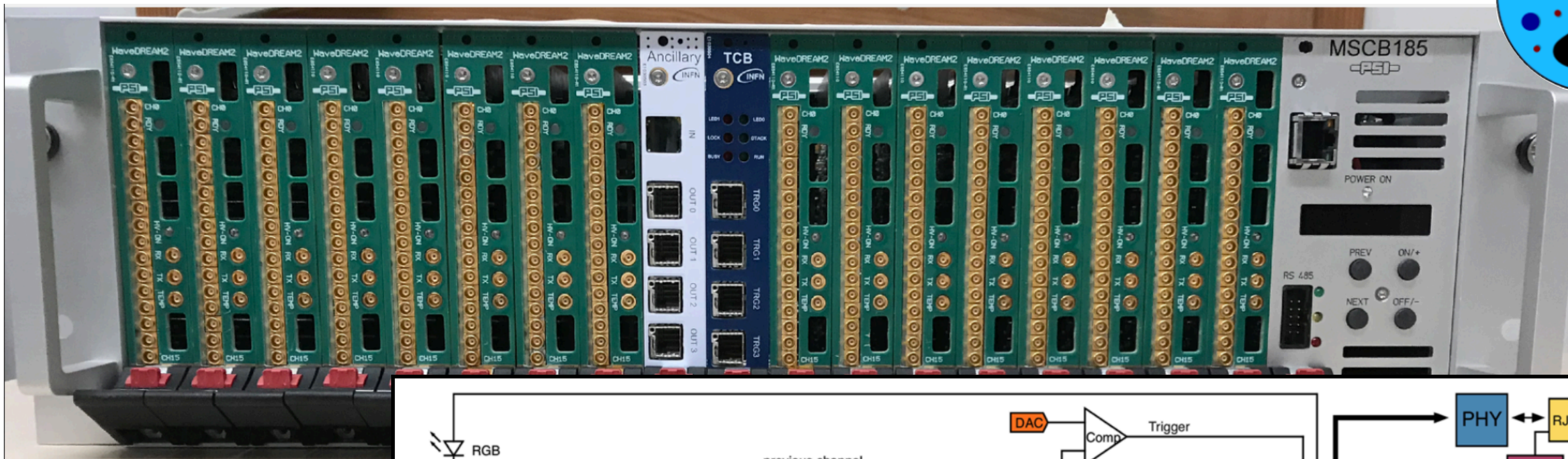


- The **80 channels** are powered and read-out with the same system base on the Wavedream board

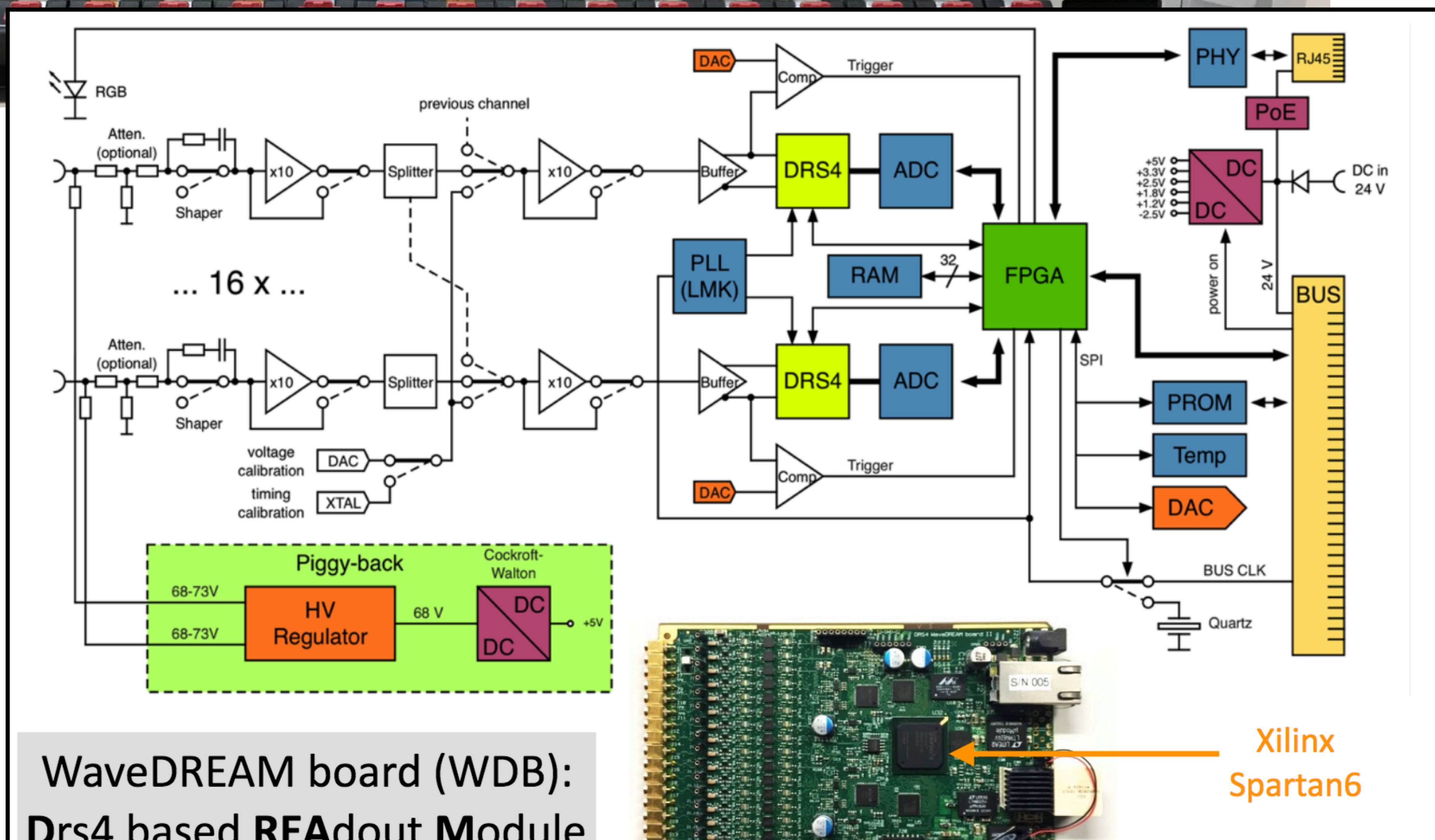




WaveDAQ system



- **WaveDREAM**
  - Power supply
  - GSPS digitisation (up to 5 GS/s)
- **TCB (Trigger Control Board)**
- **DCB (Data Control Board)**

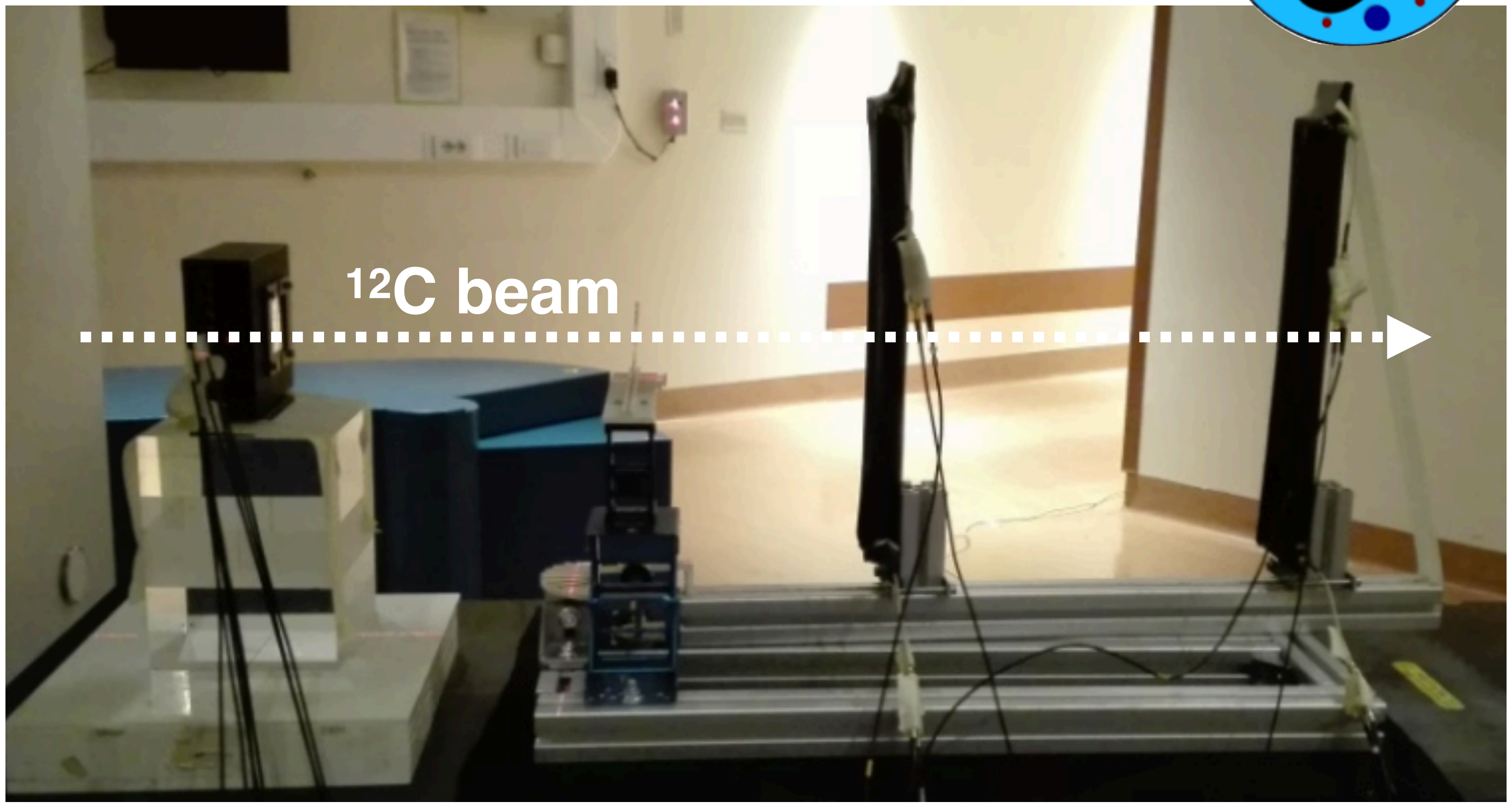


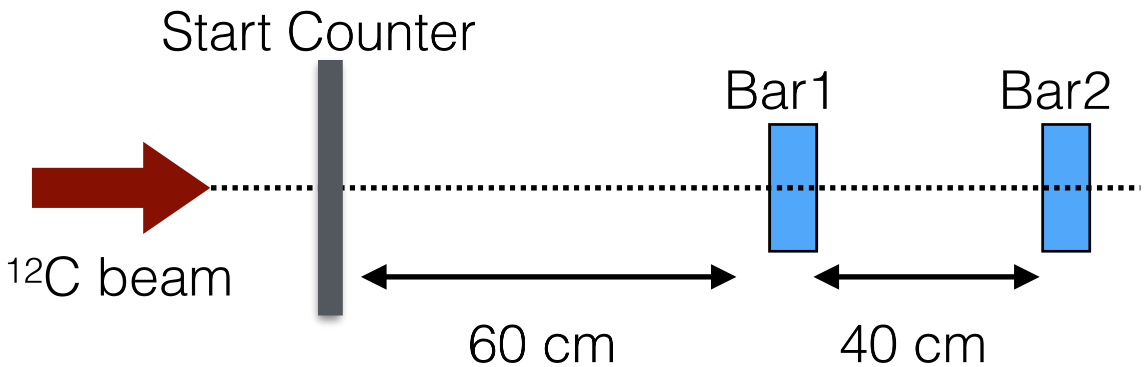
WaveDREAM board (WDB):
Drs4 based **REA**dout **M**odule

A.M. Baldini, et al., The design of the MEG II experiment, Eur. Phys. J. C 78 (2018) 230, http://dx.doi.org/10.1140/epjc/s10052-018-5845-6.

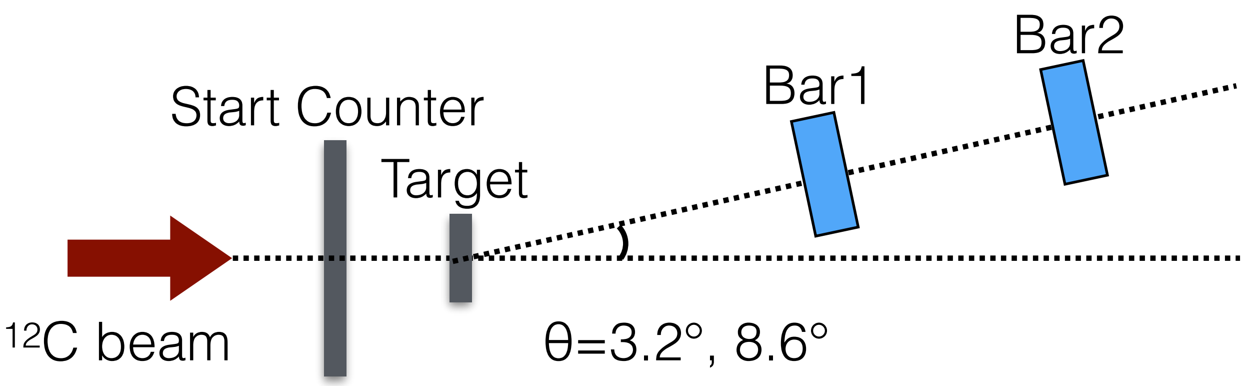
Test @ CNAO with ^{12}C ion beams

- ^{12}C energies ranging between 115 MeV/u and 400 MeV/u
- Setup (a) for energy calibration and ToF resolution evaluation
- Setup (b) for Z identification studies. Target material: PVT



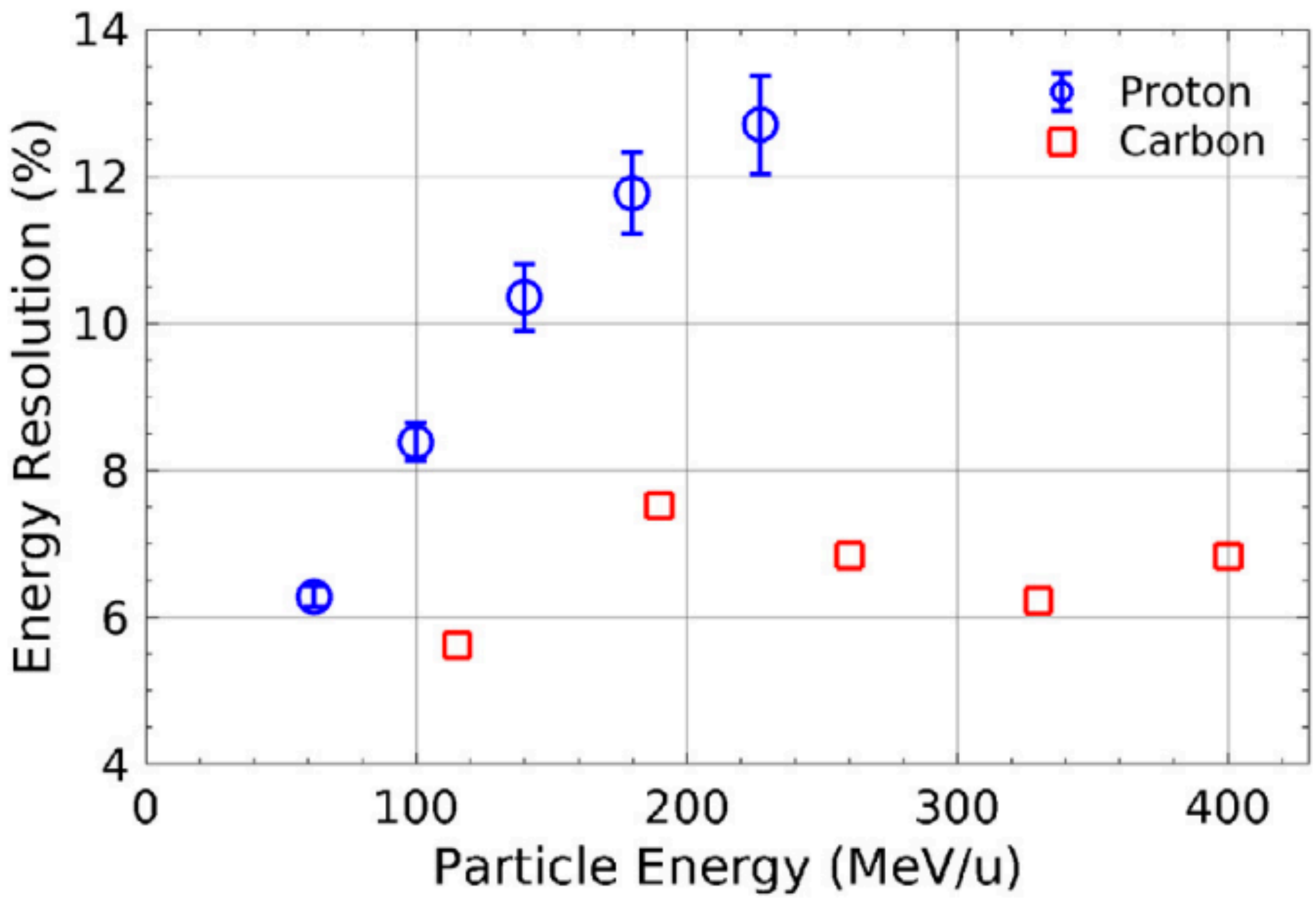


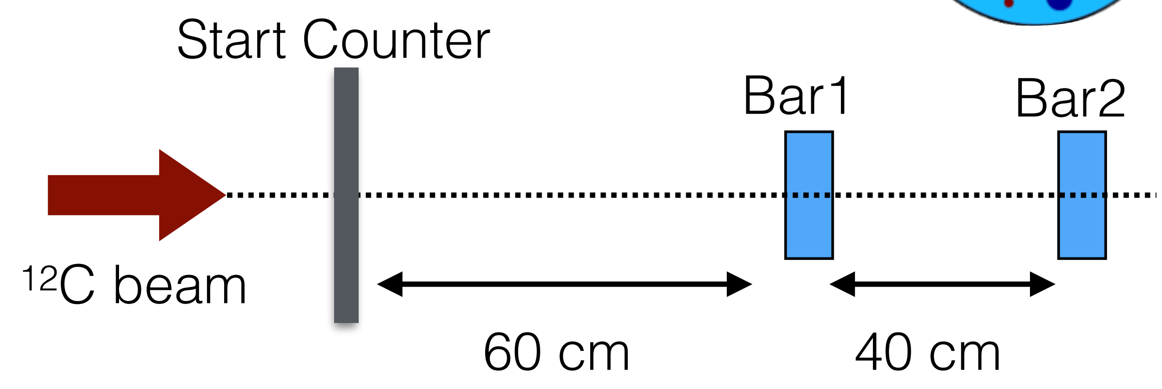
(a)



(b)

ΔE- ToF charge resolution



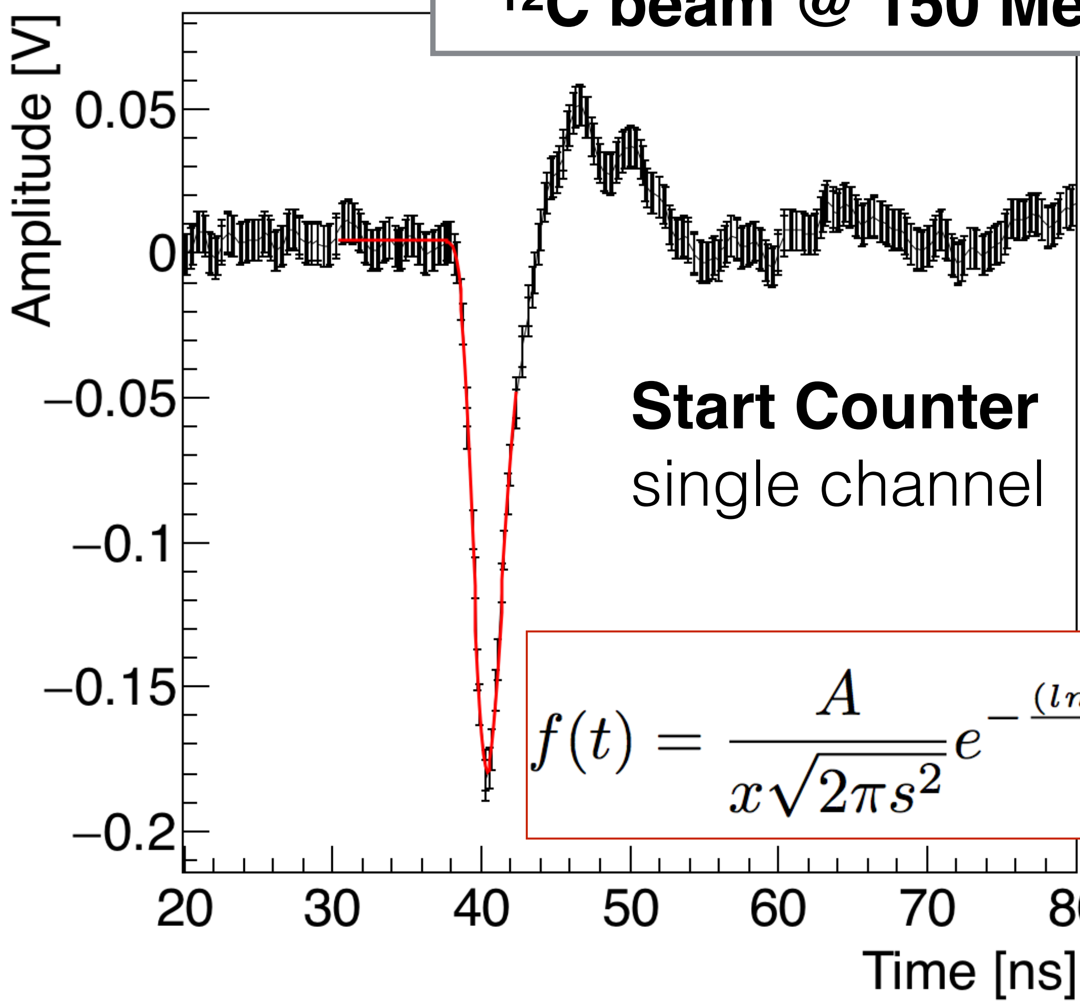


- Energy resolution **6-7%** with **Carbon ions,** up to **14%** with **proton** beams (test beam @ the Trento proton-therapy center)
- The resolution is crucial for the accuracy on the fragment Z reconstruction!

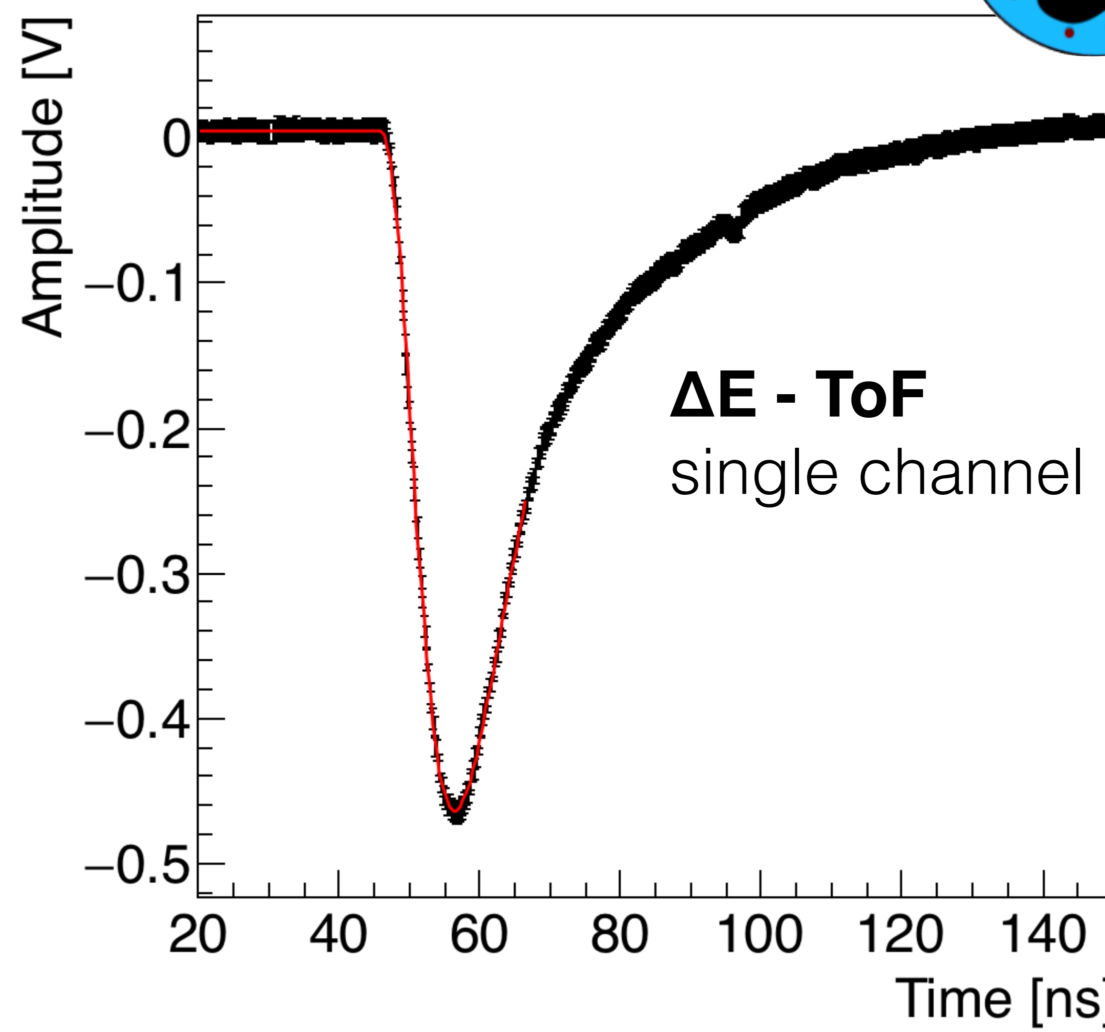
Development and characterisation o f a ΔE - ToF detector prototype for the FOOT experiment - Nuclear Inst. and Methods in Physics Research, A 916 (2019) 116–124

Time of Flight evaluation

^{12}C beam @ 150 MeV/u

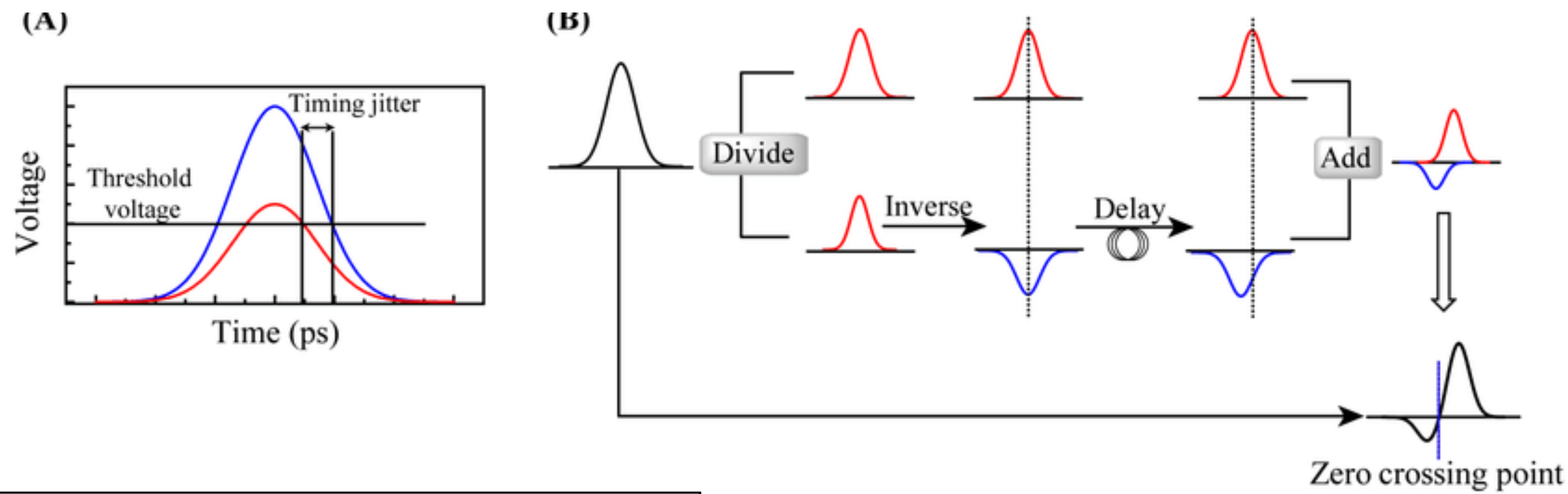


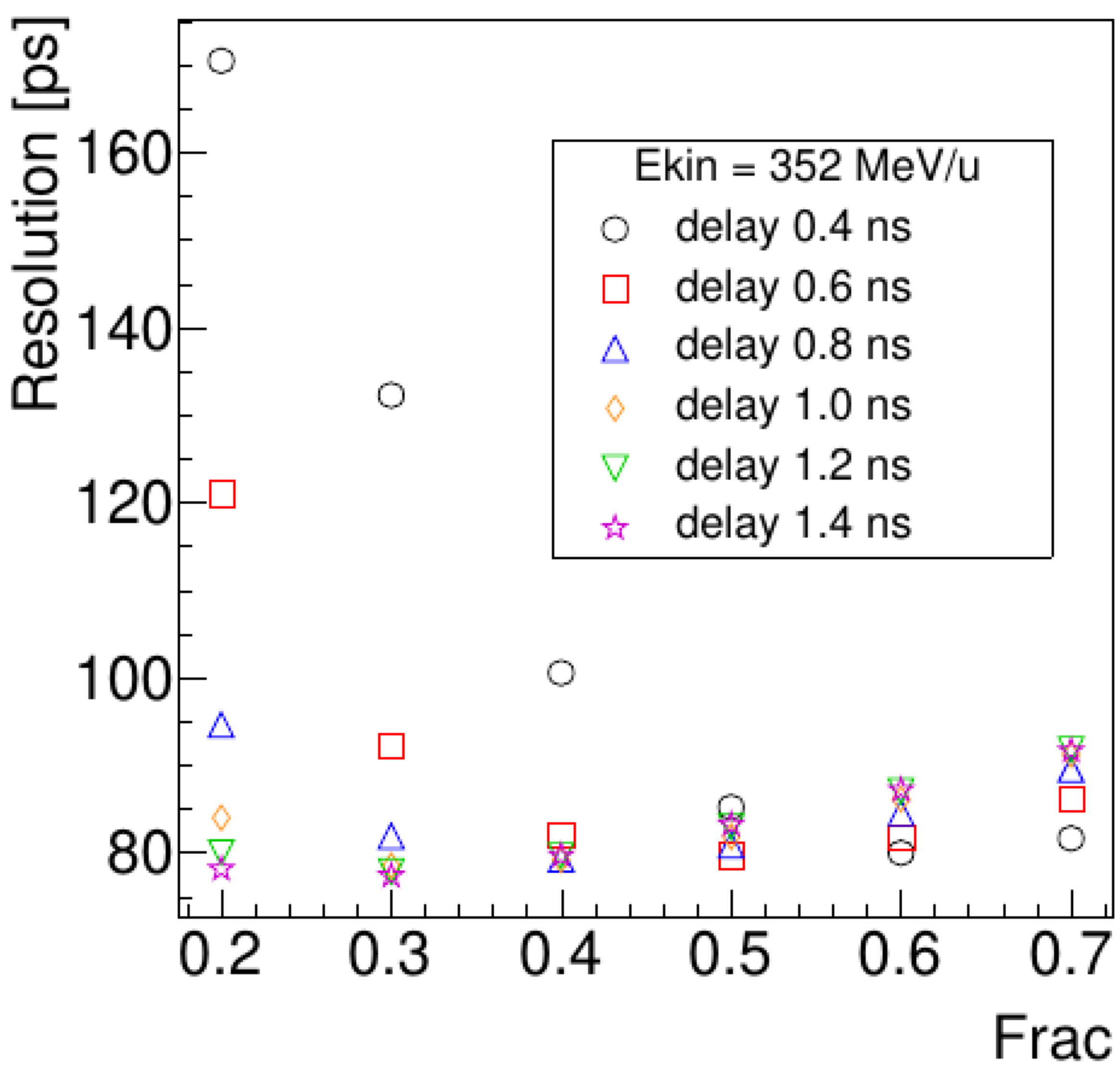
$$f(t) = \frac{A}{x\sqrt{2\pi s^2}} e^{-\frac{(ln\ x-m)^2}{2s^2}}$$



- Waveforms are fitted with a LogNormal distribution
- **CFD** algorithm to extract the arrival time of the single channels in the acquisition window (~200 ns)
- <u>Start Counter time</u> (**t_ST**)-> **weighted average** between channels according to their resolution
- <u>ΔE - ToF time of single bar (**t_TW**)</u>-> **arithmetic average** of the up-down channels

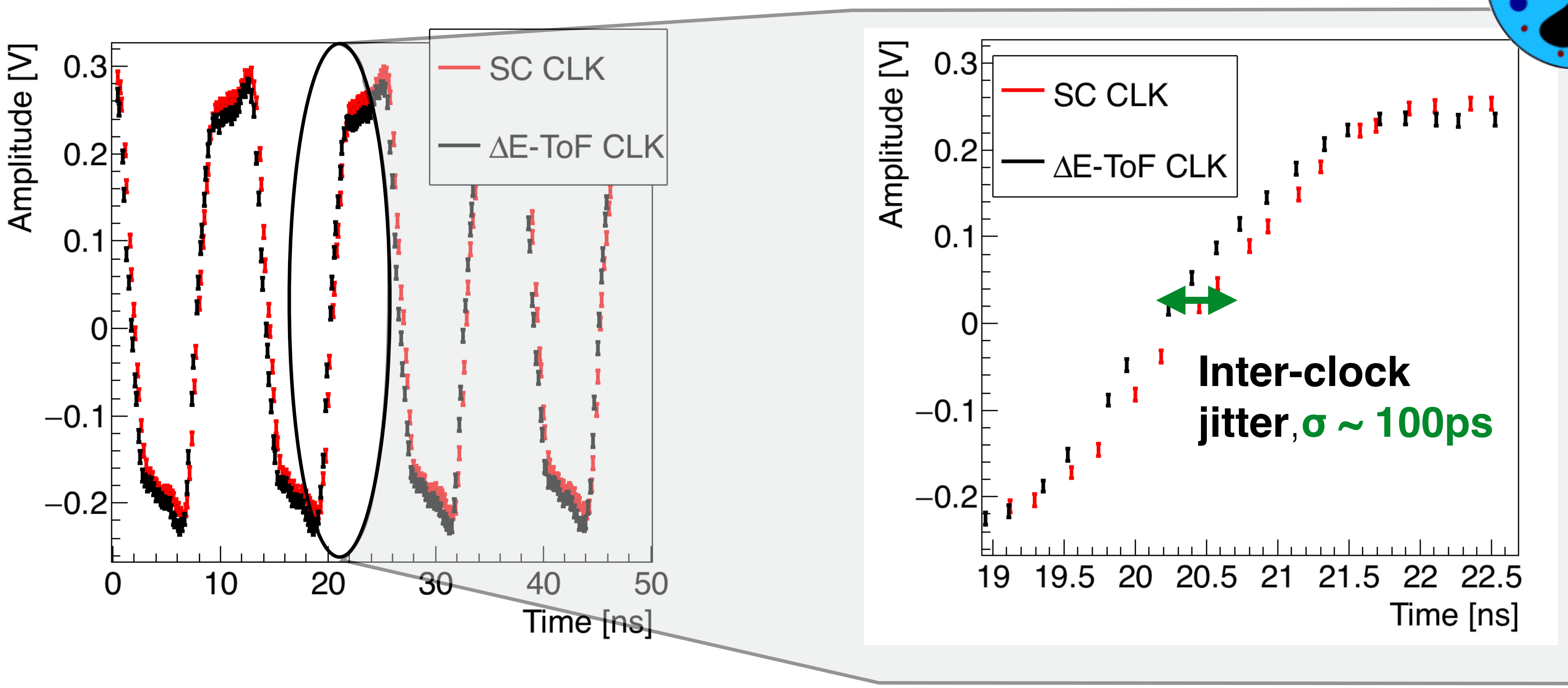
CFD optimisation





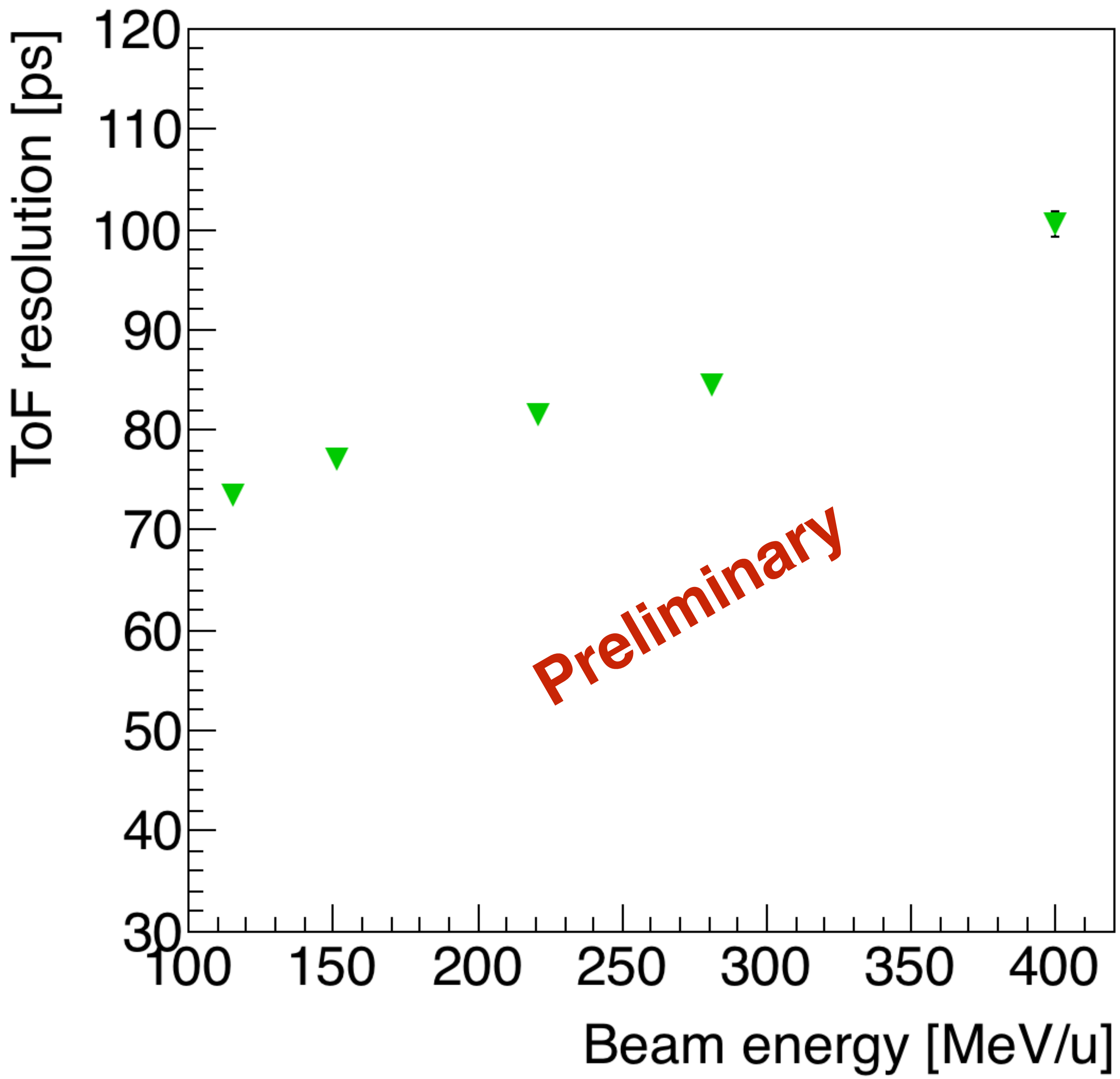
- **ΔE - ToF**: using a CFD algorithm to extract the arrival time we minimise the time walk due to the different signal amplitudes depending on the fragment position along the bar
- **Start Counter**: time walk due to the high released energy fluctuations

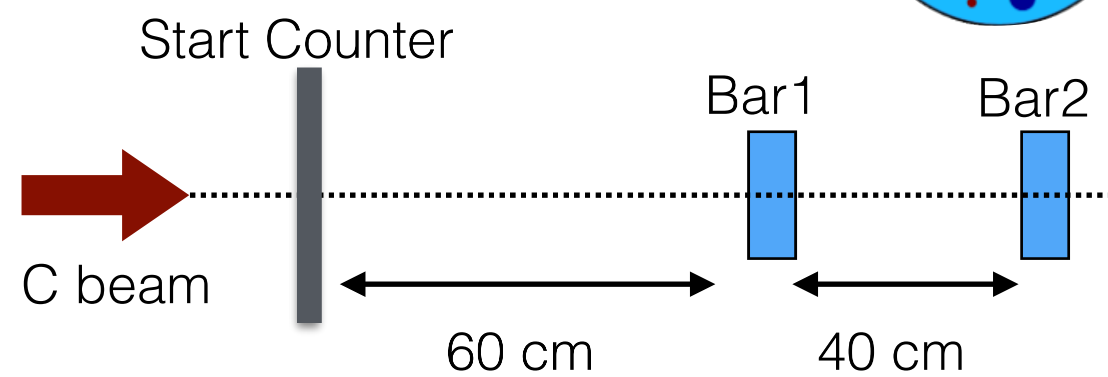
Sampling clock jitter subtraction



- The **time jitter between the sampling clock** (due to the internal WaveDream routing) has to be taken into account
- Linear fit on the all the clock rising edges are performed to extrapolate period and phase. The **clk phase is subtracted when computing the ToF**

ToF Resolution

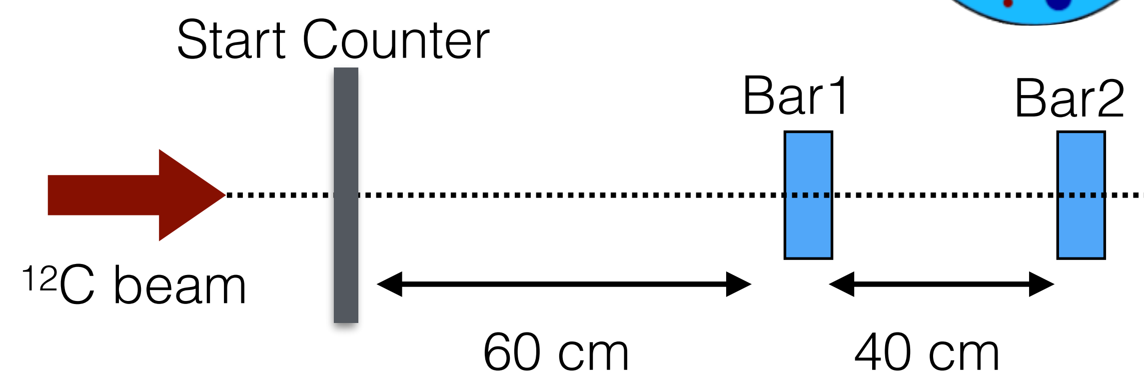




- The results match with the FOOT requirements!
- ΔE- ToF contribution 35-50 ps
- Start Counter contribution 60 -100 ps

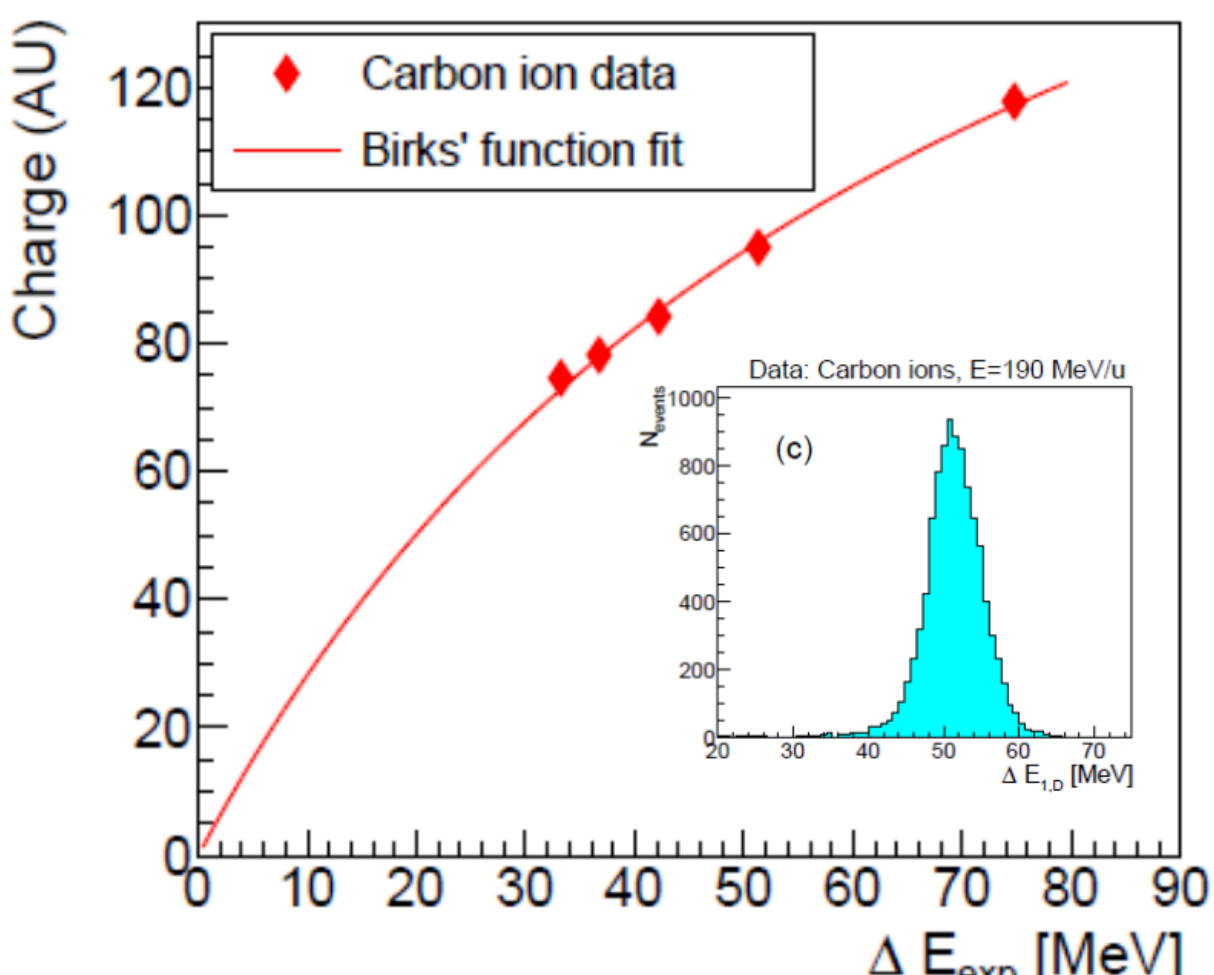
ΔE- ToF energy calibration

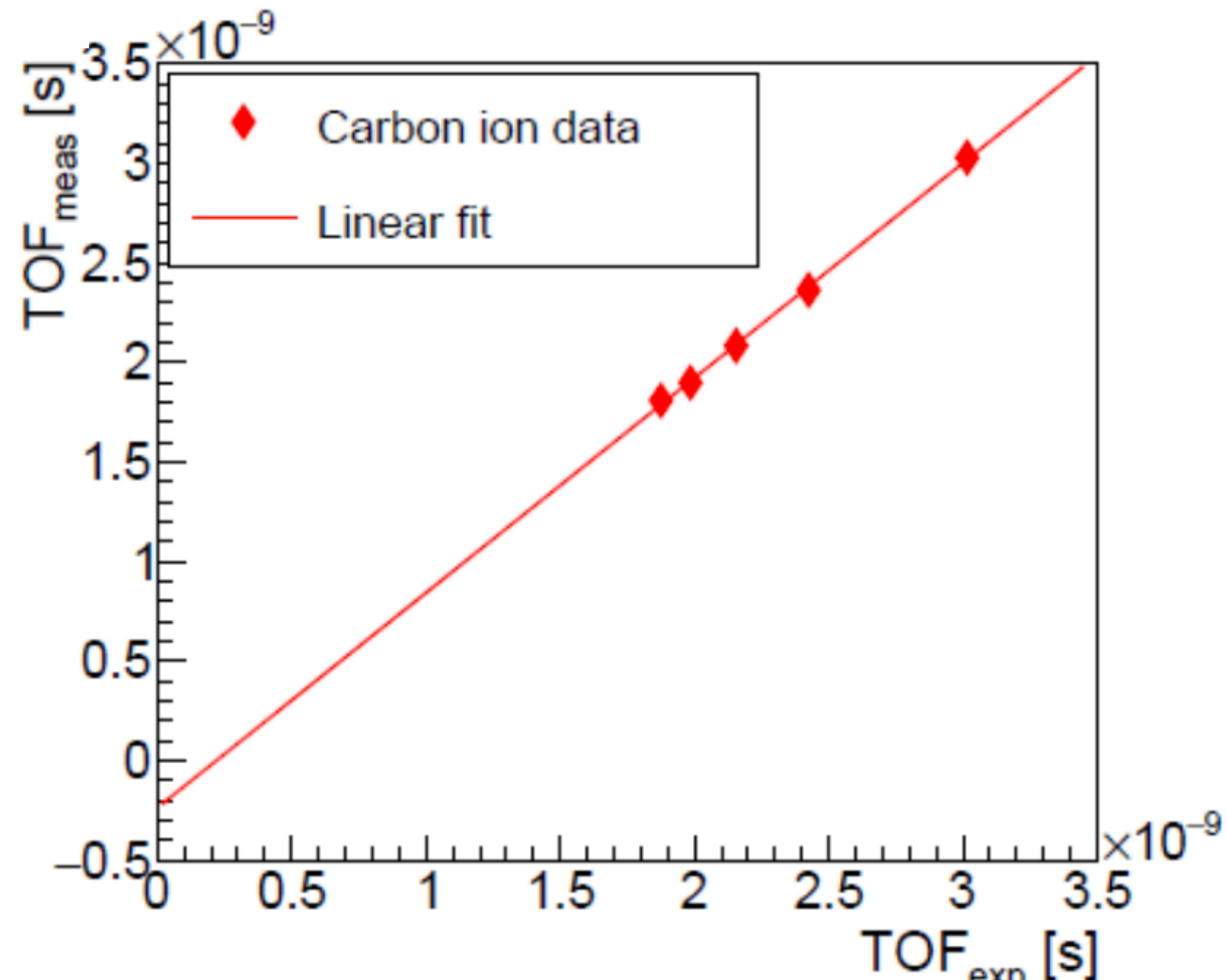
- Used 5 different beam energies (115 MeV/u, 190 MeV/u, 260 MeV/u, 300 MeV/u, 400 MeV/u) , with the beam at center of the two bars



- Saturation effect fitted as :

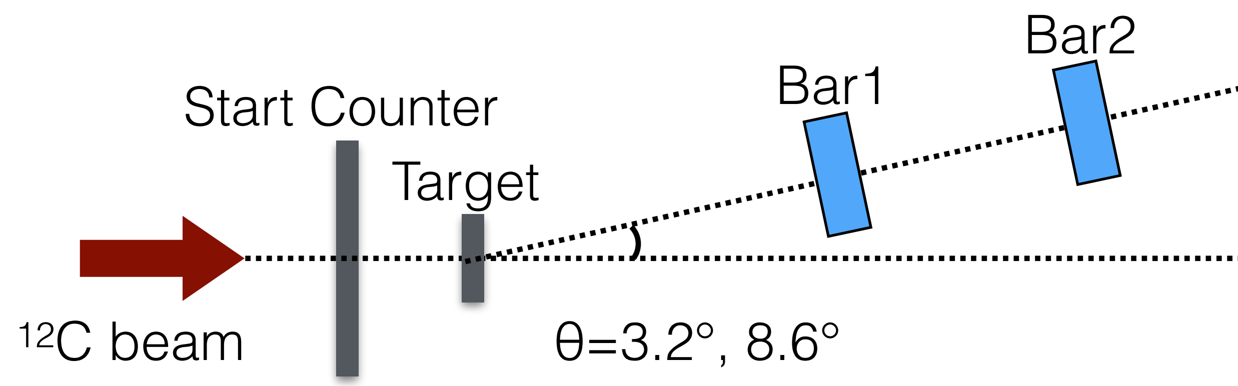
$$Q_{i,D}^{mode} = p_{a,i} \cdot \frac{\Delta E_{i,exp}^{mode}}{1 + p_{b,i}\Delta E_{i,exp}^{mode}}$$

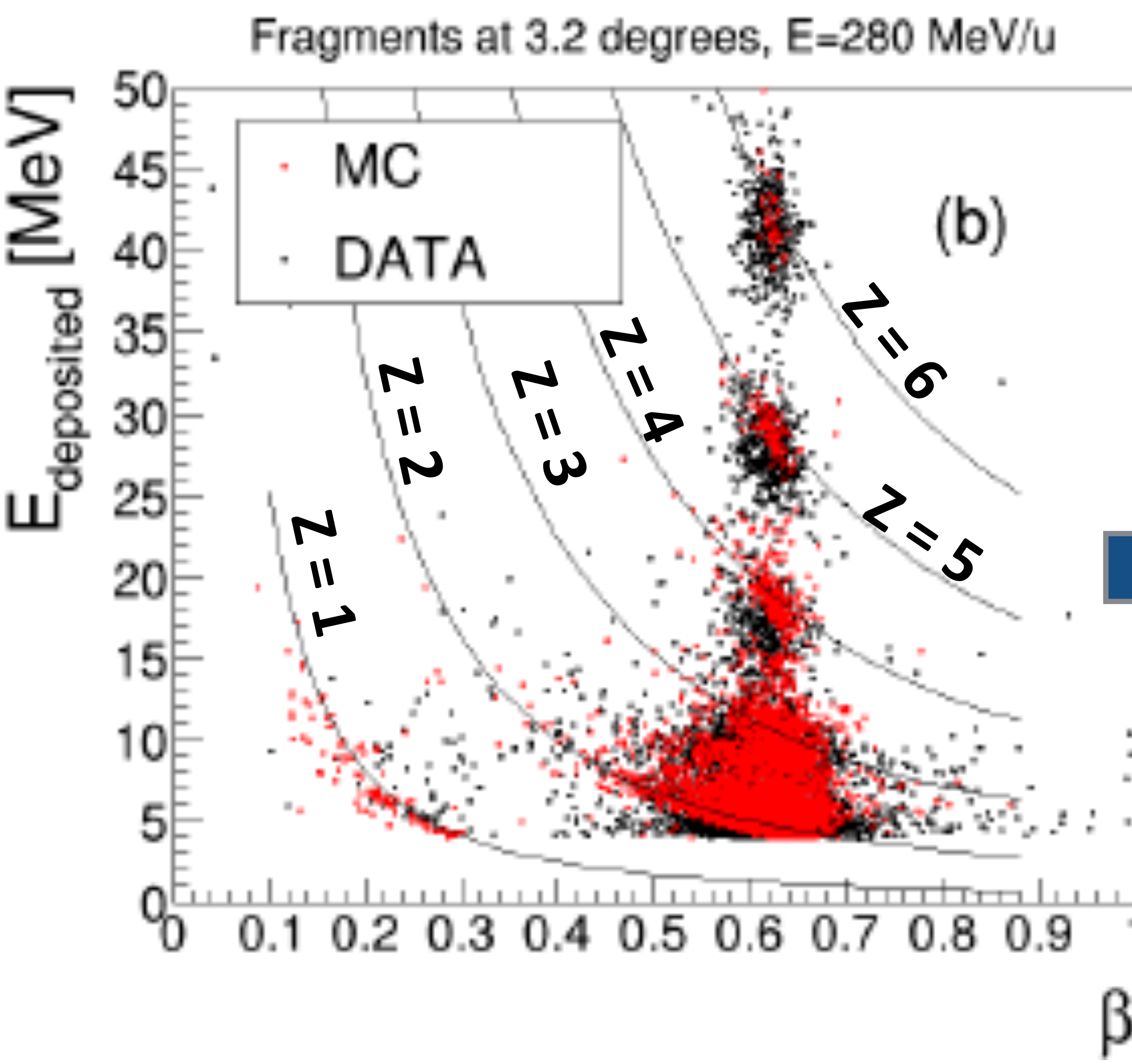


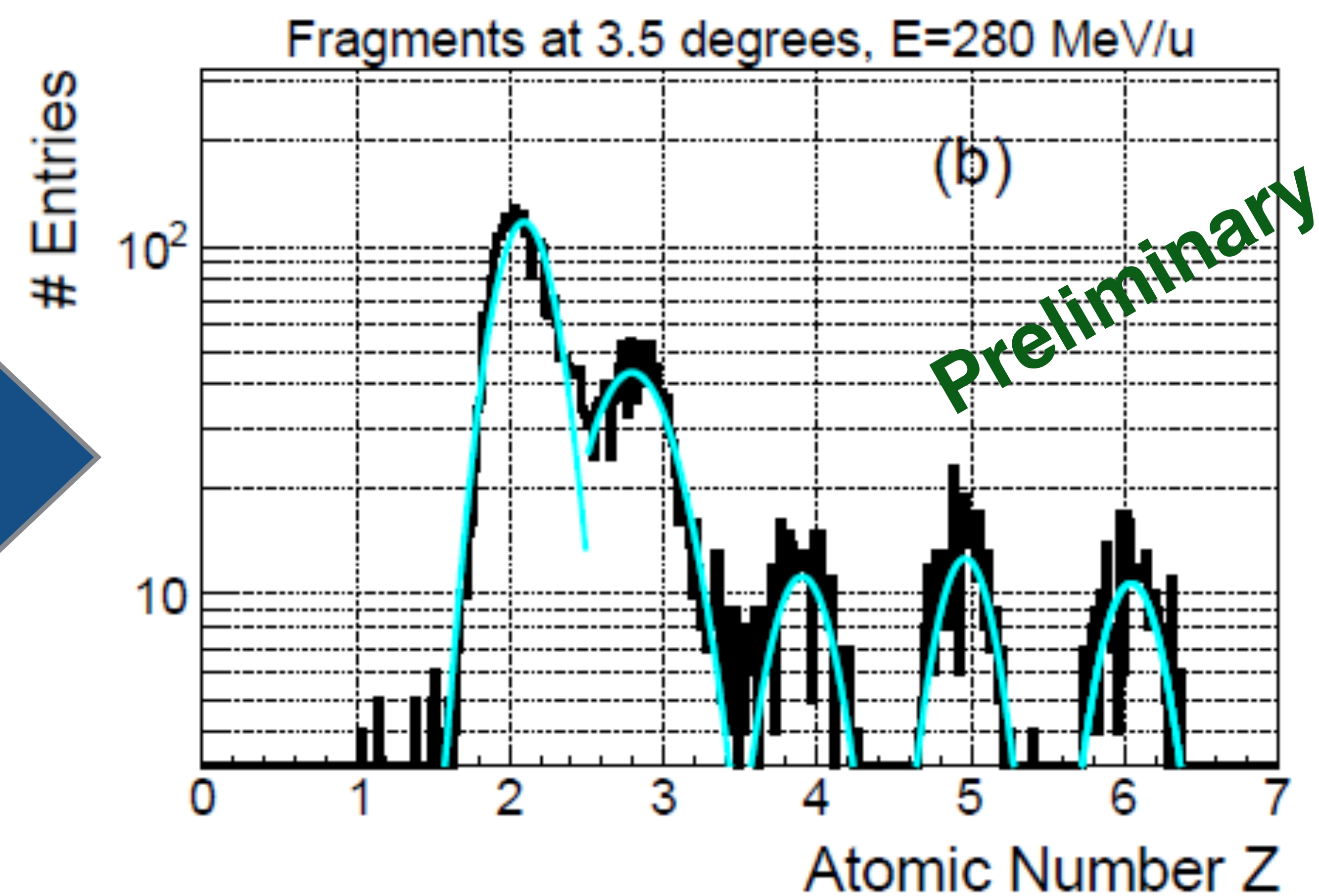


ΔE- ToF fragment identification

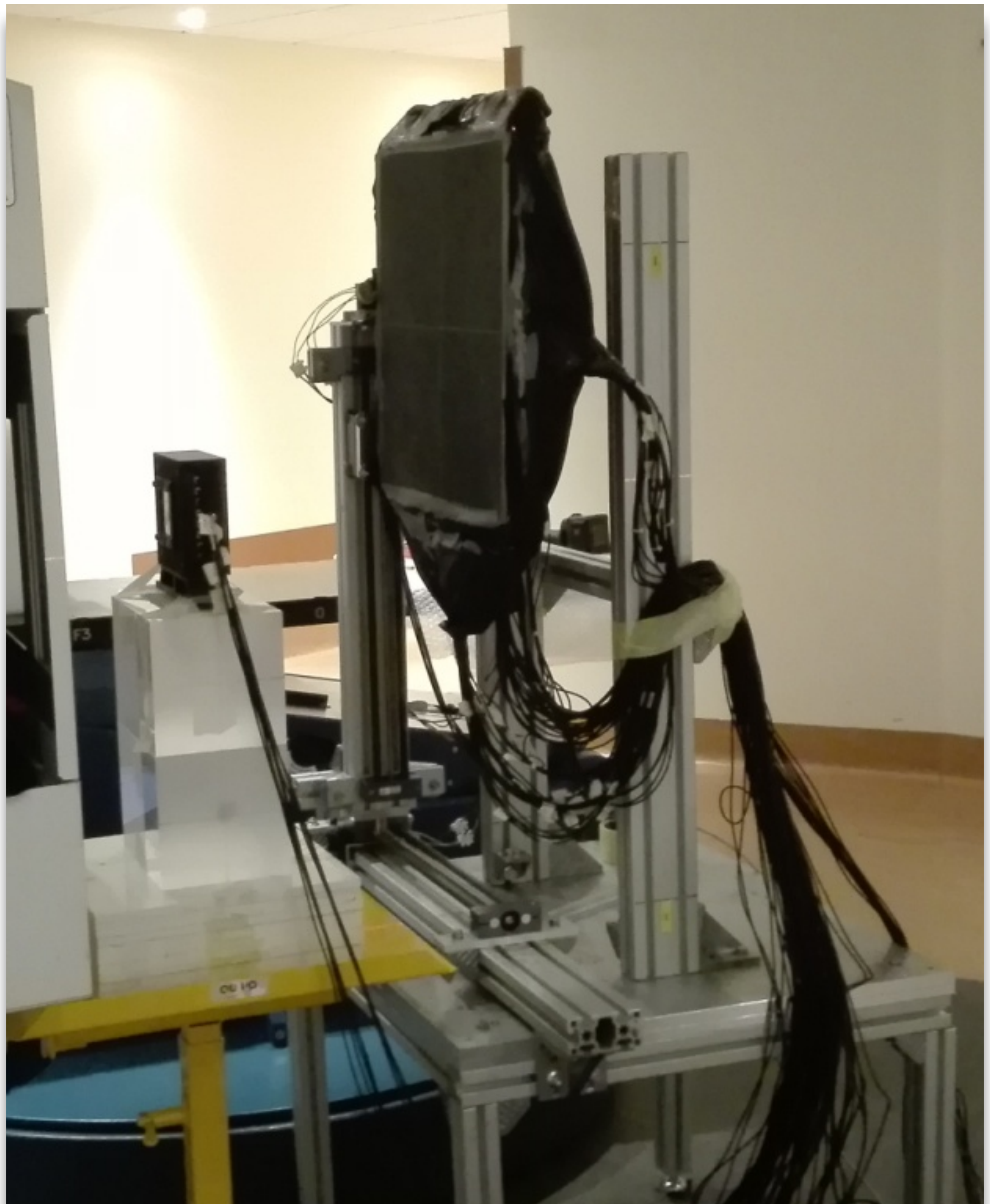
- MC simulation is useful to know which species are produced
- All the 6 Z predicted by the simulation can be distinguished! The Z resolution in the range 8-20% (to be optimised)

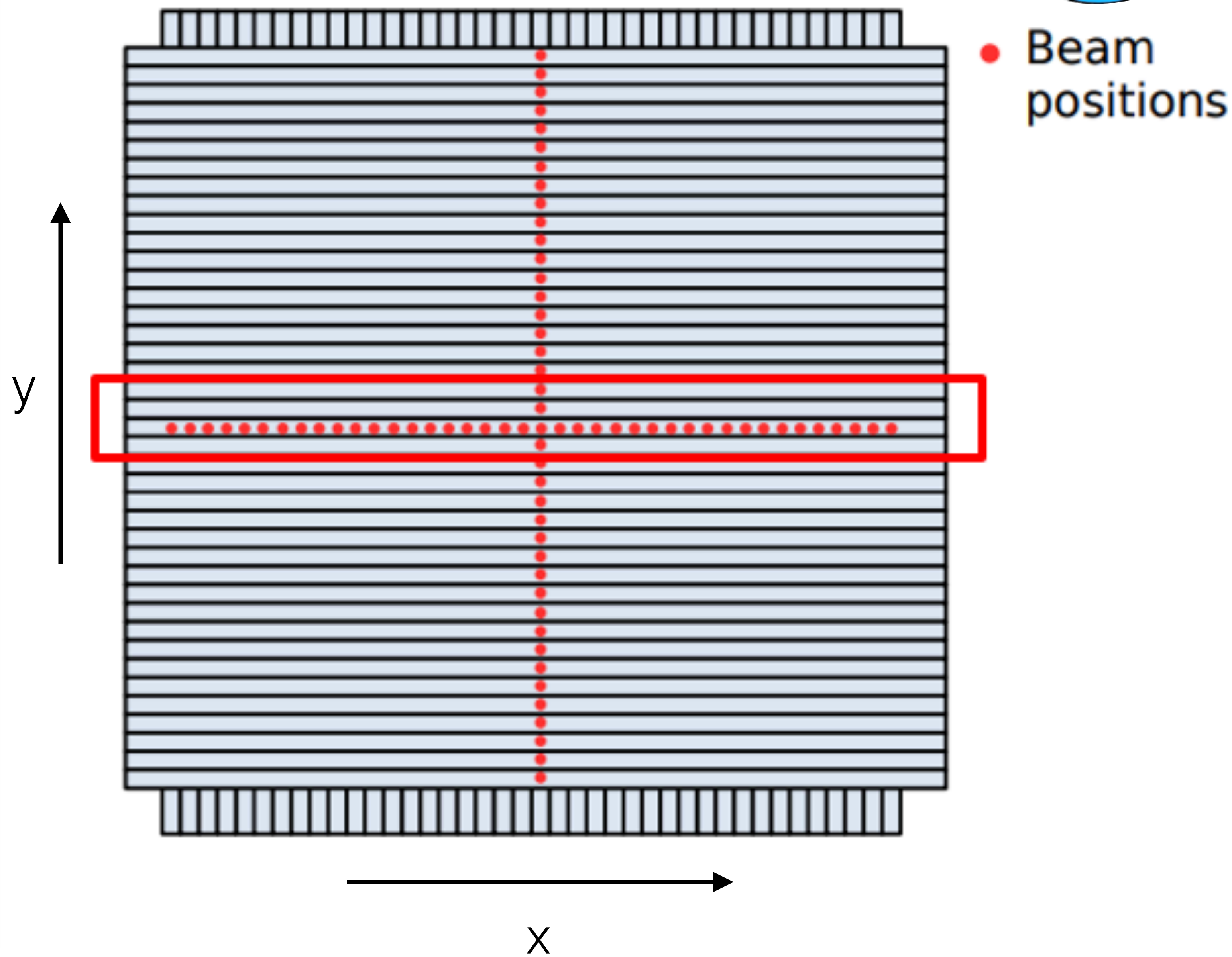






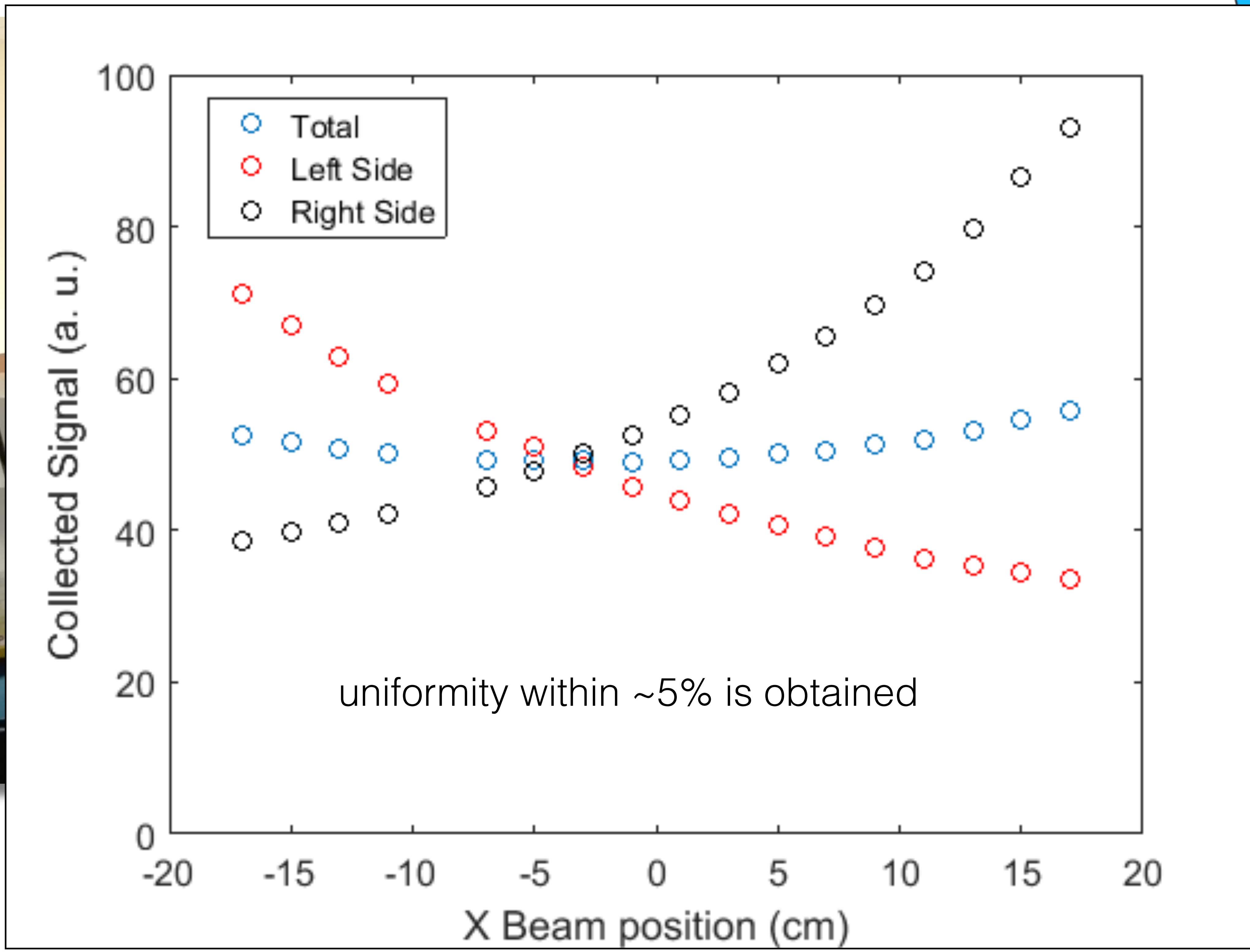
ΔE-ToF detector scan





- Time and energy resolution compatible with that measured in the previous test beam

ΔE-ToF detector scan



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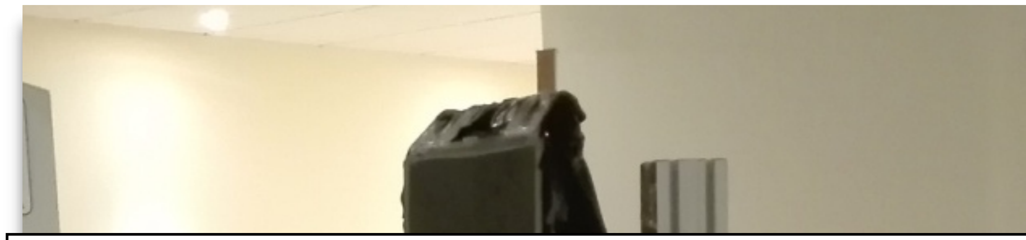
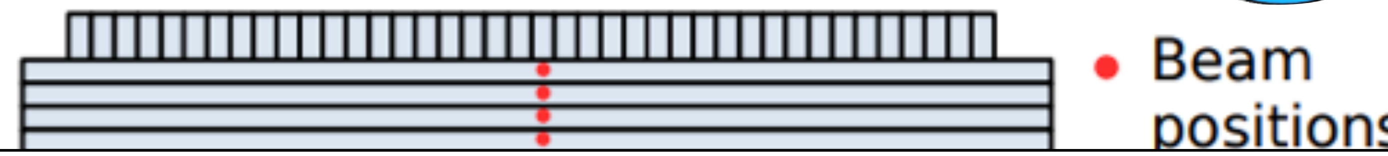
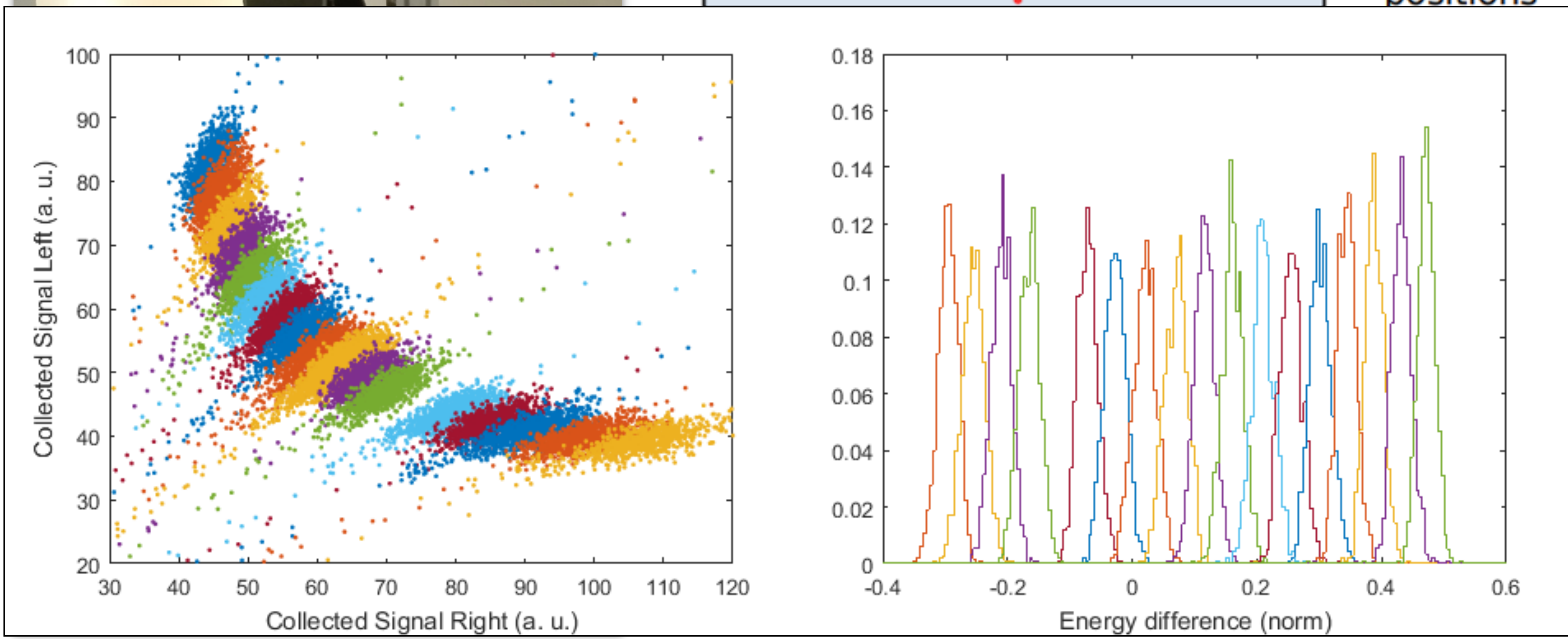
ΔE-ToF detector scan

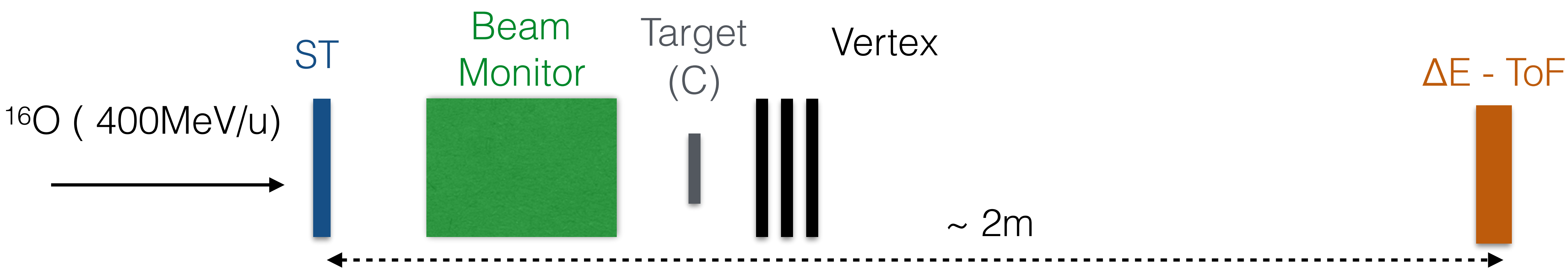


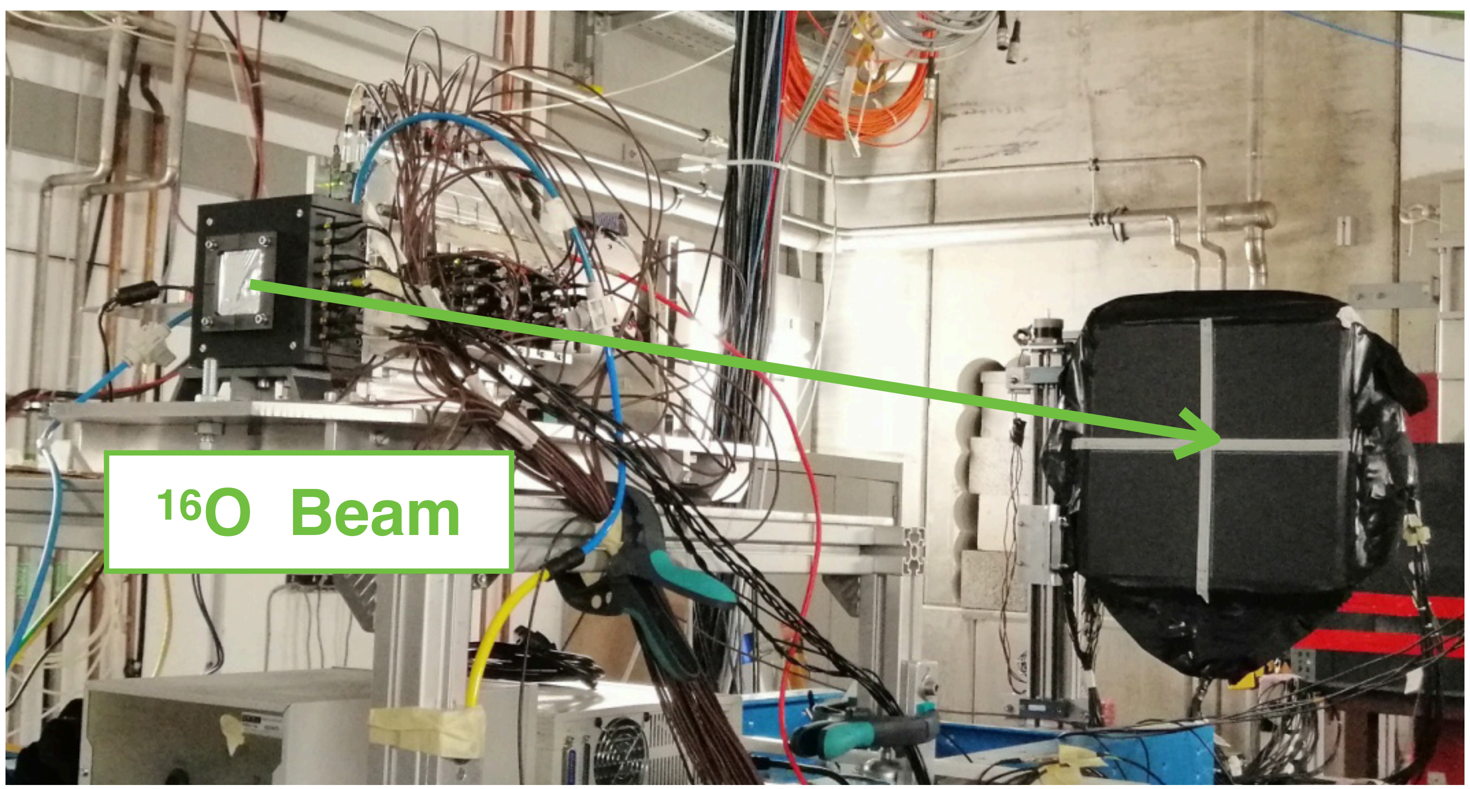




Signal collected at the two sides of the bar as a function of the beam position (irradiation has been performed at 2 cm step, at the center of each bar).

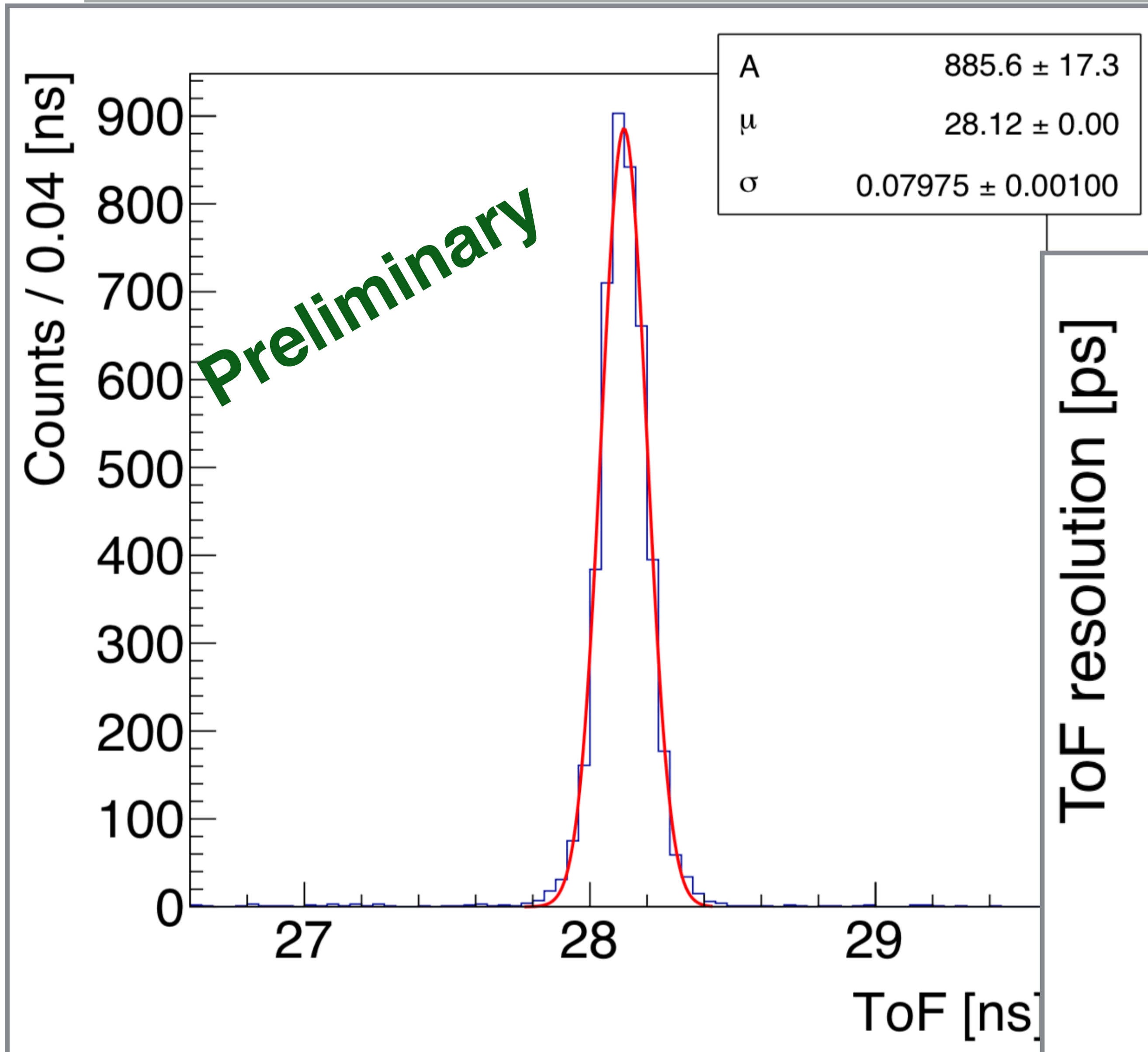
Test beam @ GSI with ^{16}O beam

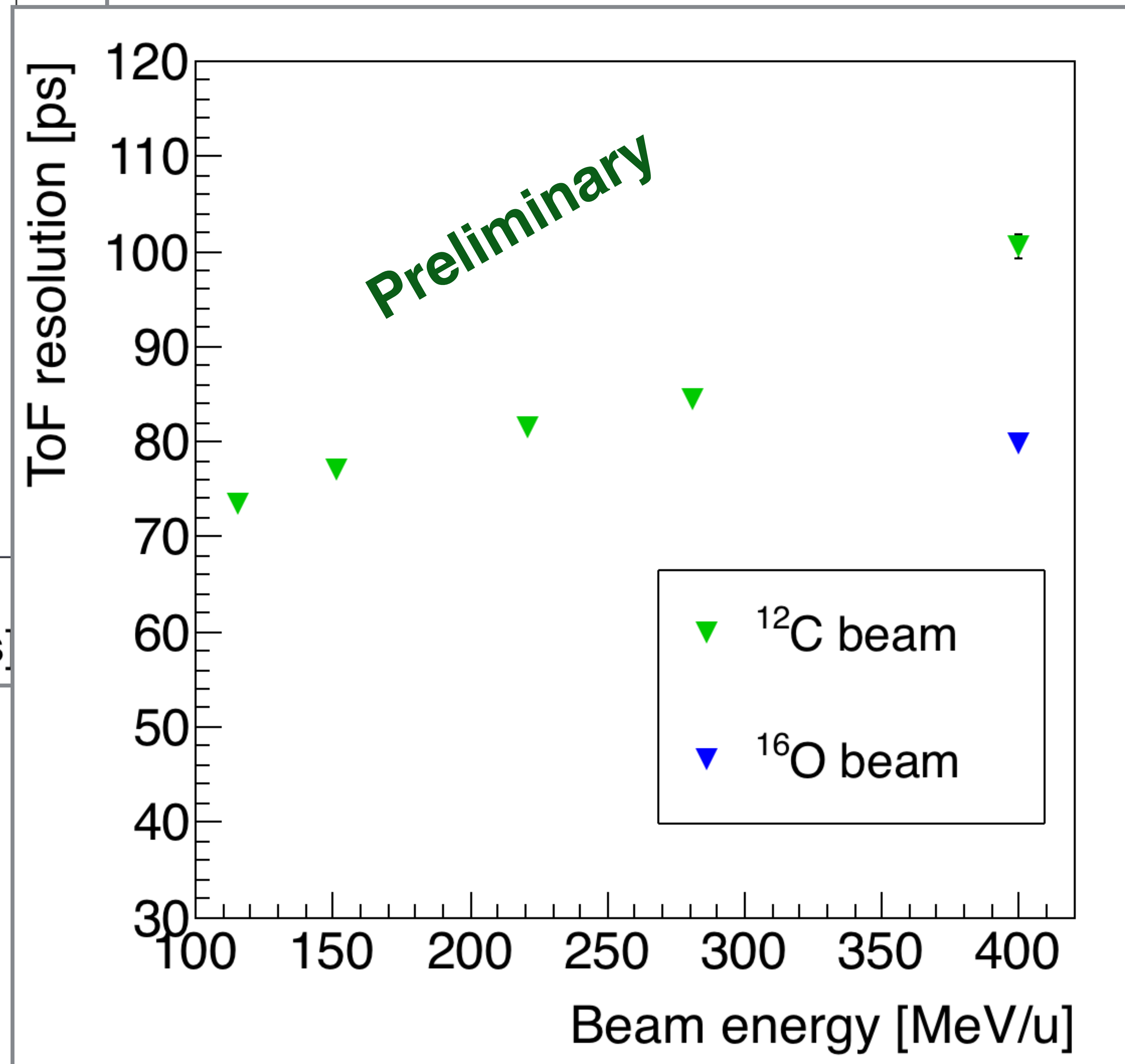




- First campaign involving different sub-detectors: test for trigger and DAQ
- Apparatus still not completed: no magnetic field, inner-outer tracking system and calorimeter missing
- **Charge-changing cross section measurements** could be performed

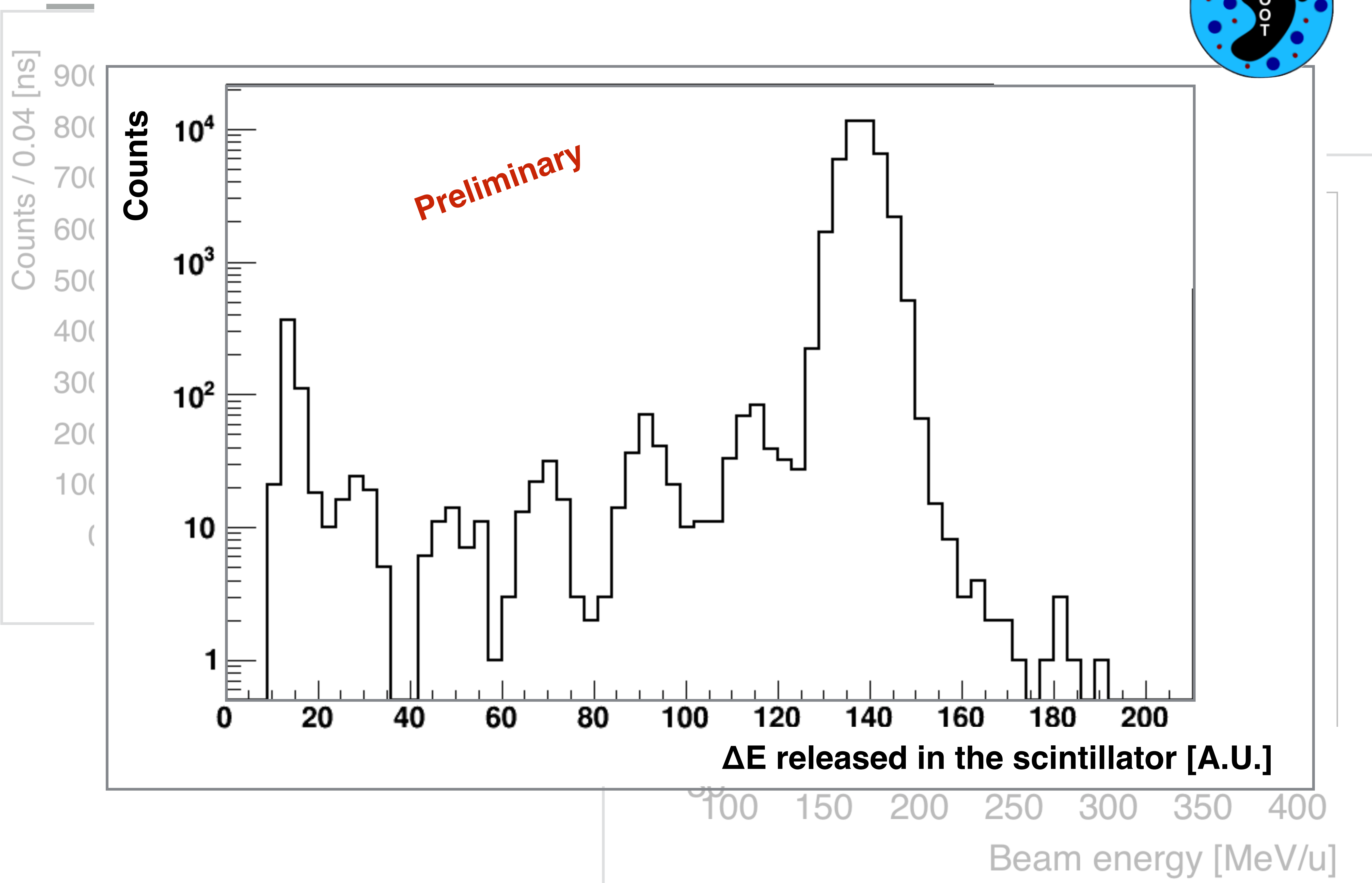
Test beam @ GSI with ^{16}O beams





- The measures ToF resolution (~80 ps) matches with the expectations!

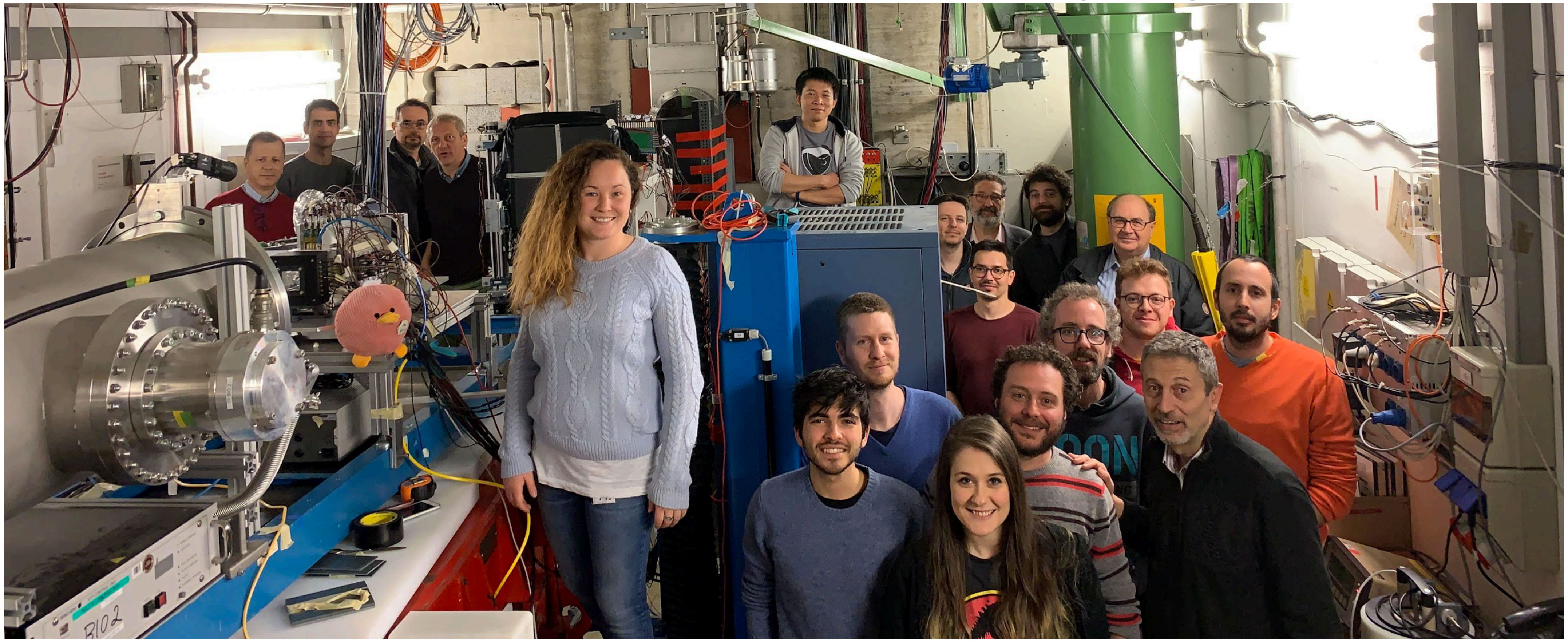
Test beam @ GSI with ^{16}O beams



Conclusions and future perspectives

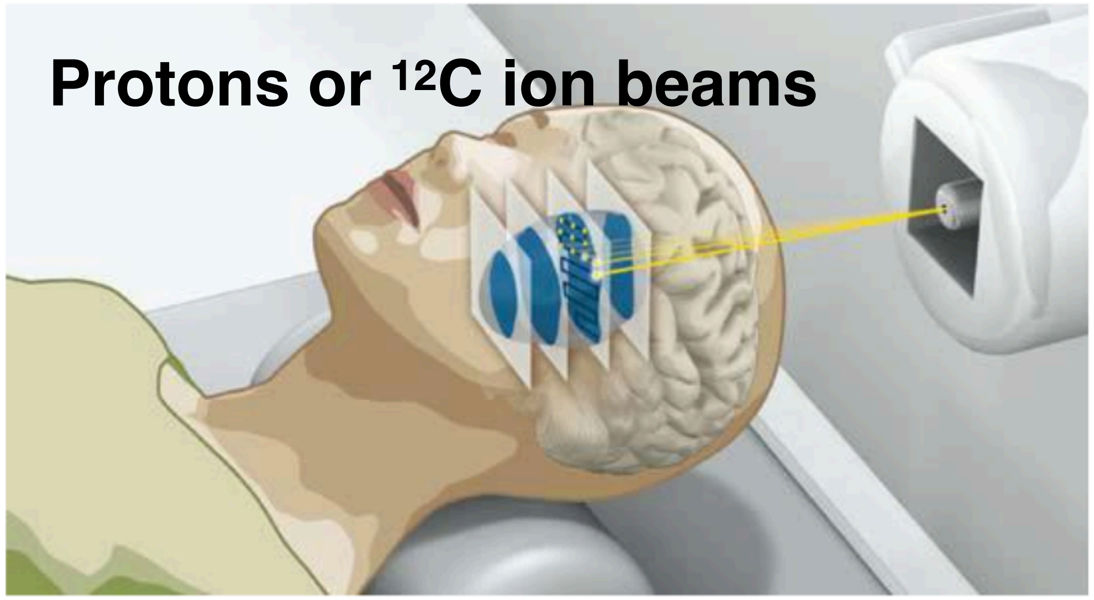
- The FOOT experiment has started in 2017, and few months ago the first data-taking @GSI facility with a partial setup has been performed. **The detectors performance matches with expectations!**
- The Microstrip detector, the calorimeter and the magnet development is ongoing. The full FOOT setup will be available in 2021.
- **Next data-taking campaign** are coming: @GSI (spring)2020, @CNAO(2020, to be scheduled)

The FOOT collaboration (a very very small part)

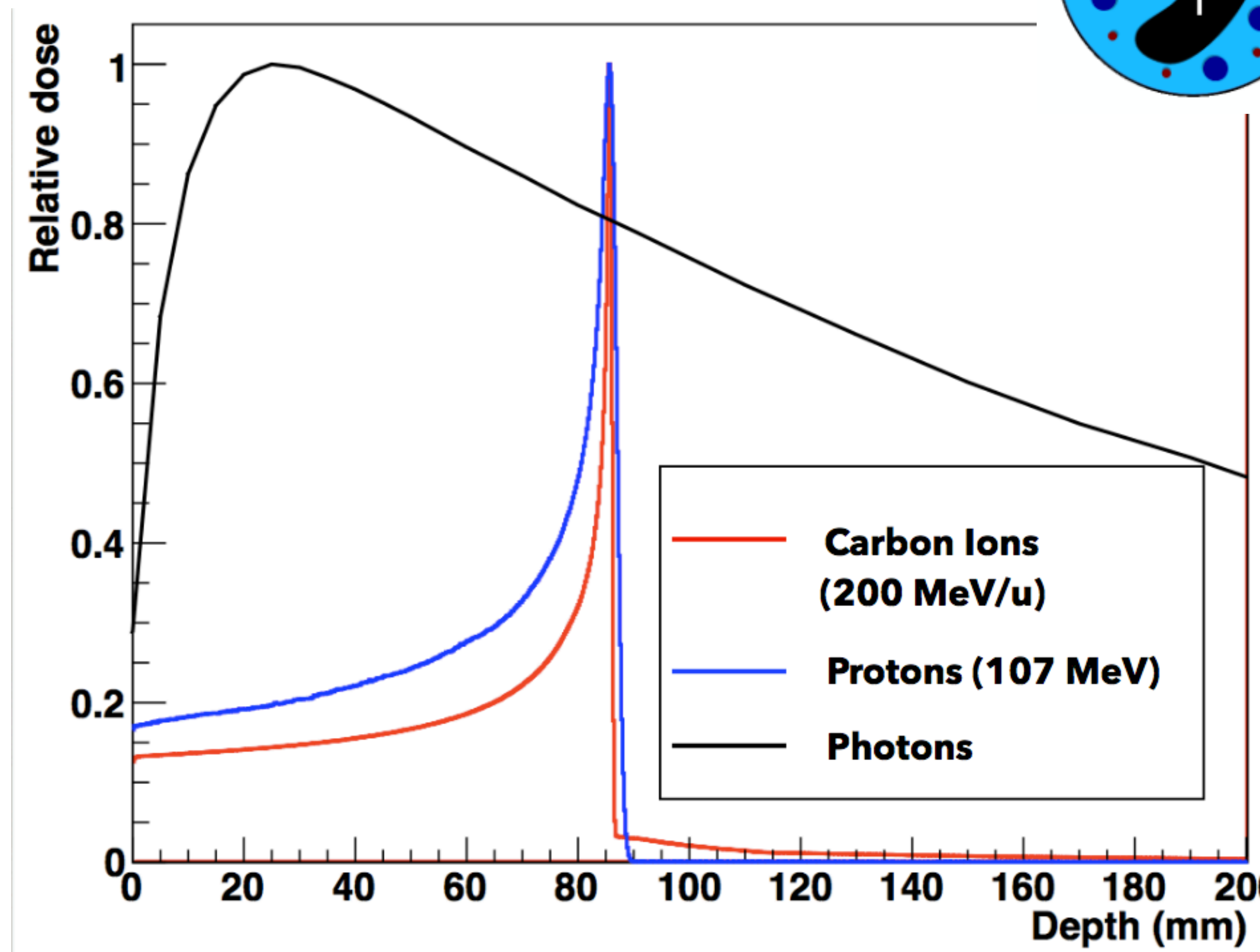


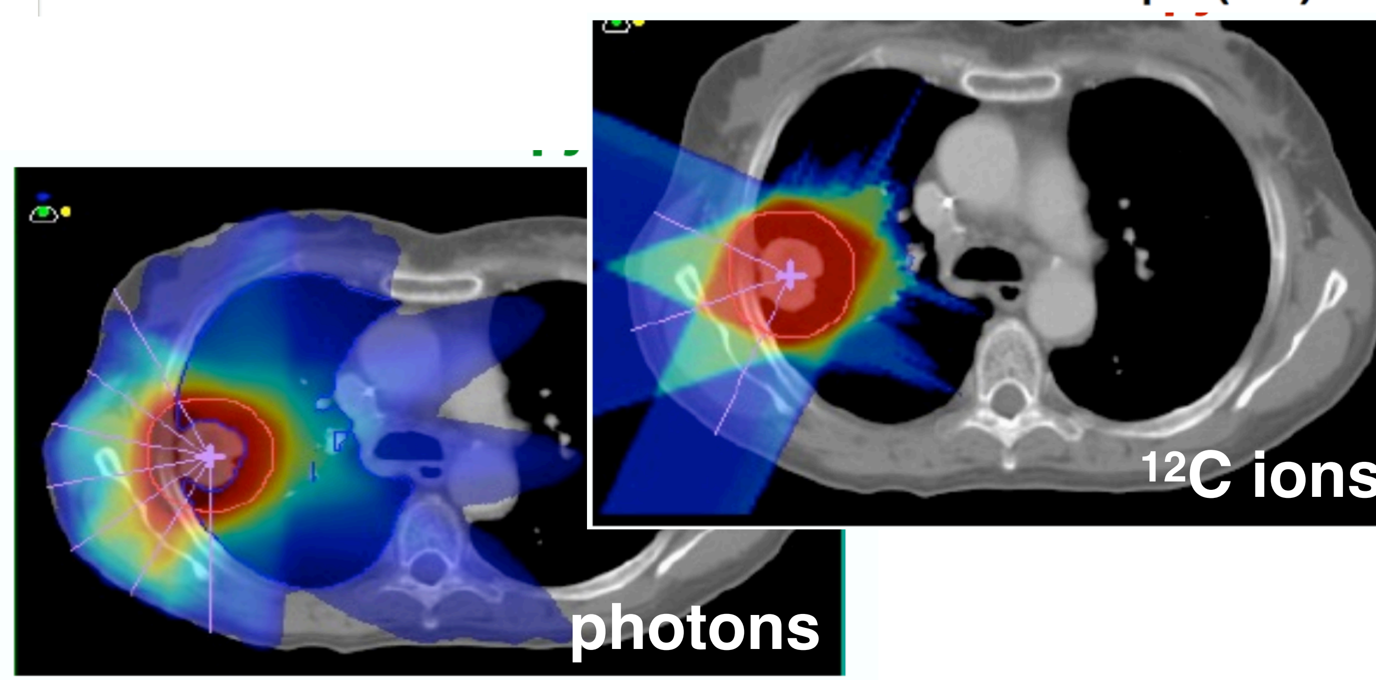
Back-up

The hadrontherapy rationale



- Beam penetration is a function of the beam energy (**60-250 MeV** for **protons**, **100-400 MeV/u for ^{12}C**).
- The dose is mainly released in the **Bragg peak**, at the end of the beam travel in the patient, allowing to better **spare the healthy tissues** wrt the conventional radiotherapy
- The **biological damage** is related to the released energy, ionization density and type of projectile used

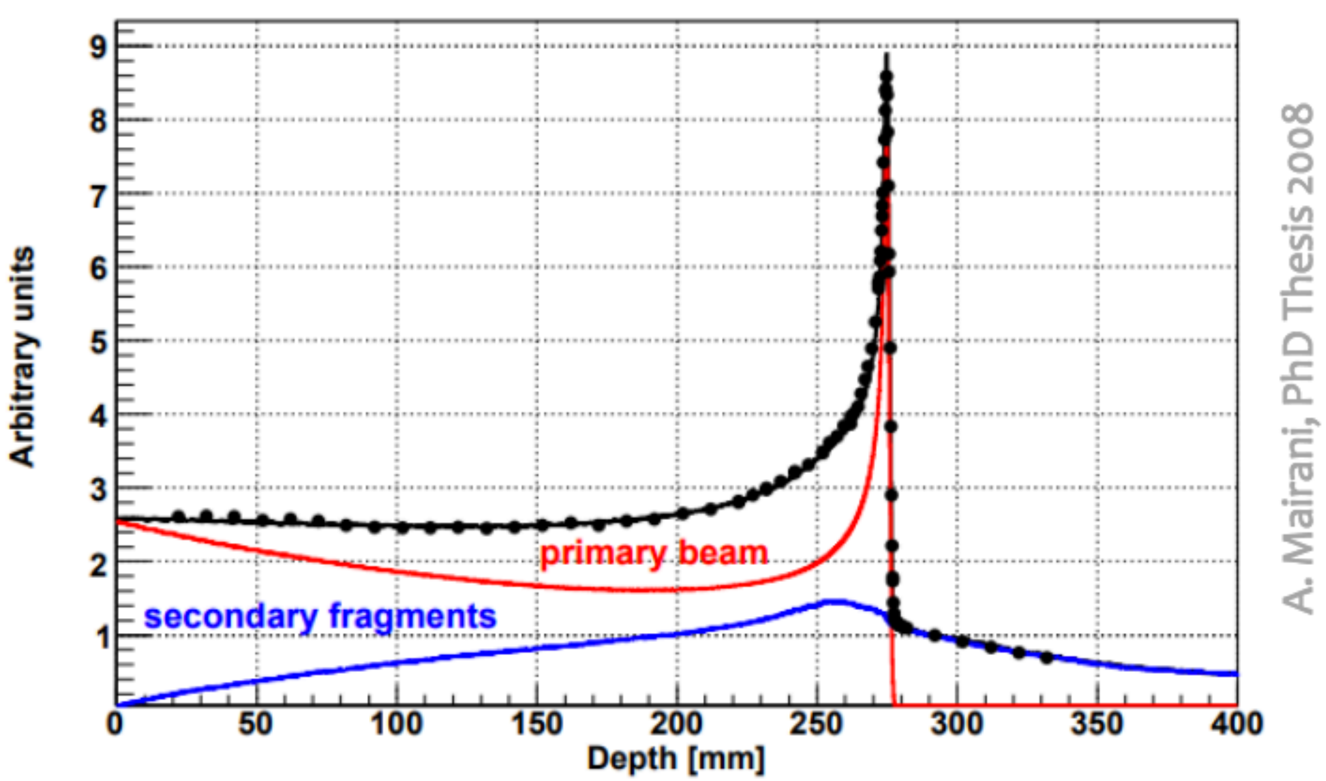




Role of fragmentation in hadrontherapy

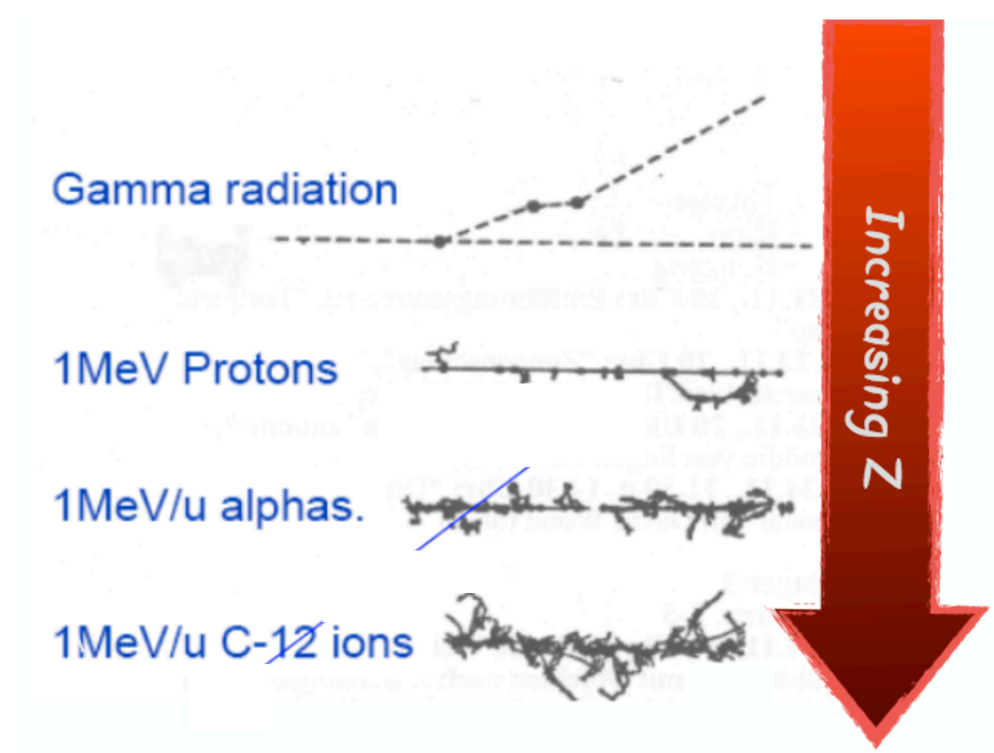
Projectile fragmentation (for Z>1 ion beams)

- ~ same velocity but different mass wrt the primary particles—> **longer range** causing a long **undesired tail beyond the Bragg peak**
- Mixed particle field of different cell killing effectiveness, considered in ^{12}C treatment but scarse validation data. Effect to be studied with alternative beams ^{4}He, ^{16}O

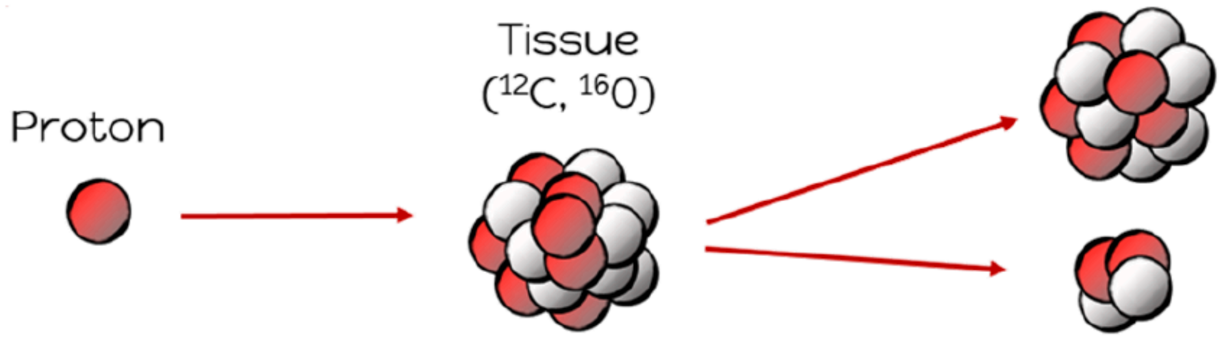


Target fragmentation

- **Low energy** fragments (range ~ 10 μm)
- Most abundant fragment expected: He, C, Be, O, N
- **No experimental data** for Z>3 ions and MC models not reliable.
- **Biological impact**: the radio biological effectiveness (RBE) is proportional to the dE/dx (—> **increases with the charge Z²**)



Target fragmentation in proton-therapy

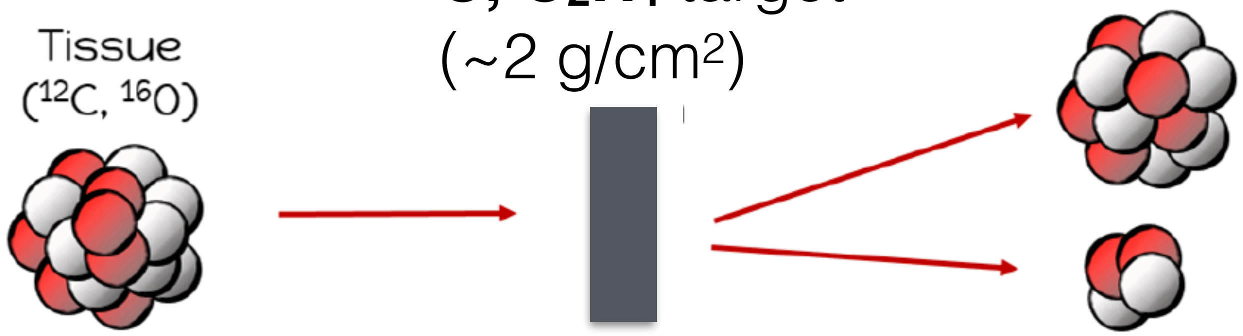


Target fragments:
low energy
and short range

Fragment	E (MeV)	Range (μm)
^{15}O	1.0	2.3
^{15}N	1.0	2.5
^{14}N	2.0	3.6
^{13}C	3.0	5.4
^{12}C	3.8	6.2
^{11}C	4.6	7.0
^{10}B	5.4	9.9
^{8}Be	6.4	15.7
^{6}Li	6.8	26.7
^{4}He	6.0	48.5
^{3}He	4.7	38.8
^{2}H	2.5	68.9

Fragments remain in the target! → **Inverse kinematic approach**

C, C_2H_4 target
(~2 g/cm^2)



Beam fragments:
higher energy
and longer range

fragmentation probability ~ 10^{-3}

$$\Lambda\left(P_{\text{beam}}\right)$$

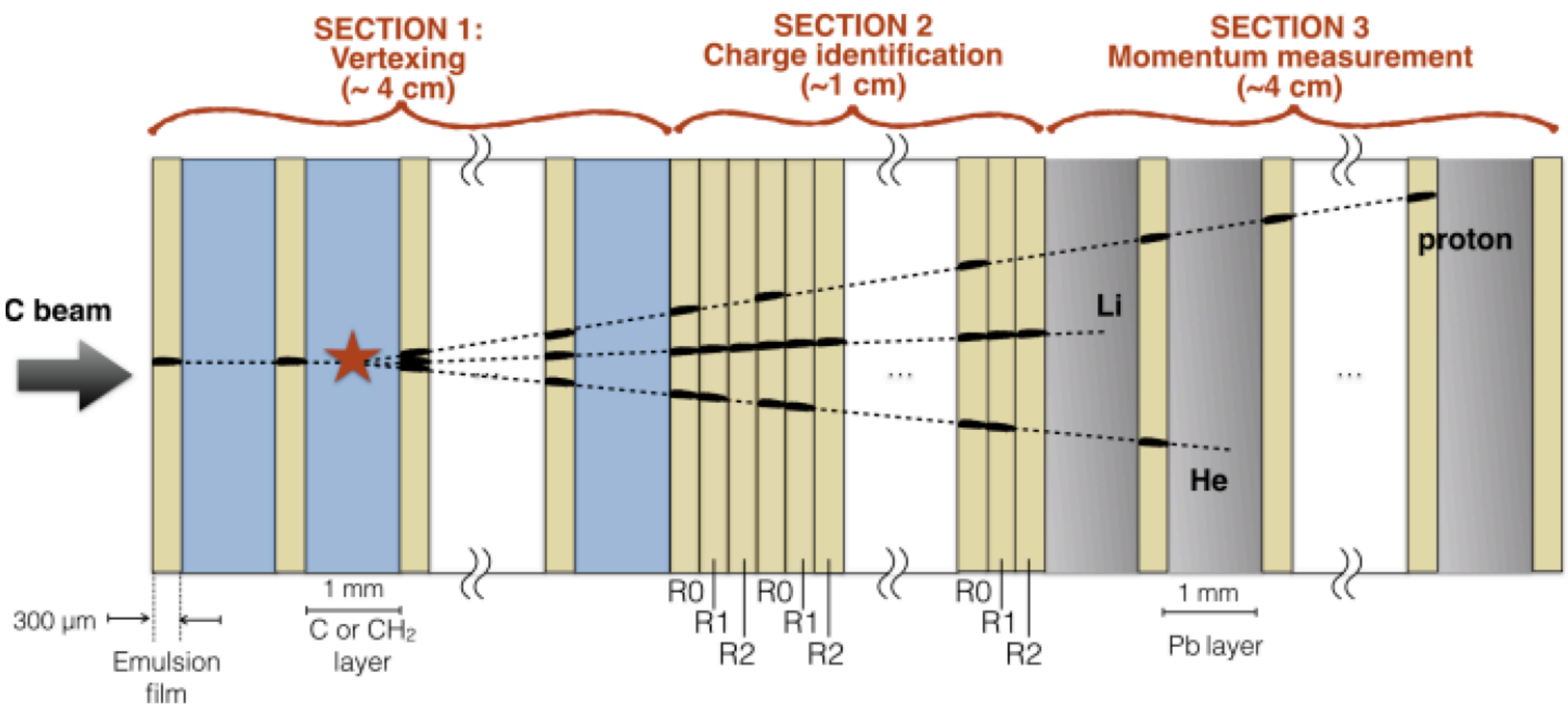
Lab. Frame ⟷ Patient Frame

By applying a **Lorentz transformation** we switch from the laboratory frame to the "patient frame"

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

The **cross section** on ^{1}H is computed by **subtraction**

The FOOT emulsion setup



- **Section1**: target plates (C/C_2H_4) interspersed with emulsion films —> vertex detector
- **Section2**: emulsion films only —> charge identification for low Z fragments
- **Section3**: lead planes interspersed by emulsion films: momentum measurement and isotopic ID

- **Low Z fragments** are emitted @ large angles (up to 75° wrt the beam direction)
- Kinematic quantities and fragment identification provided by tracks of fragment reconstructed in the emulsions (automatic scanning performed by a microscope)

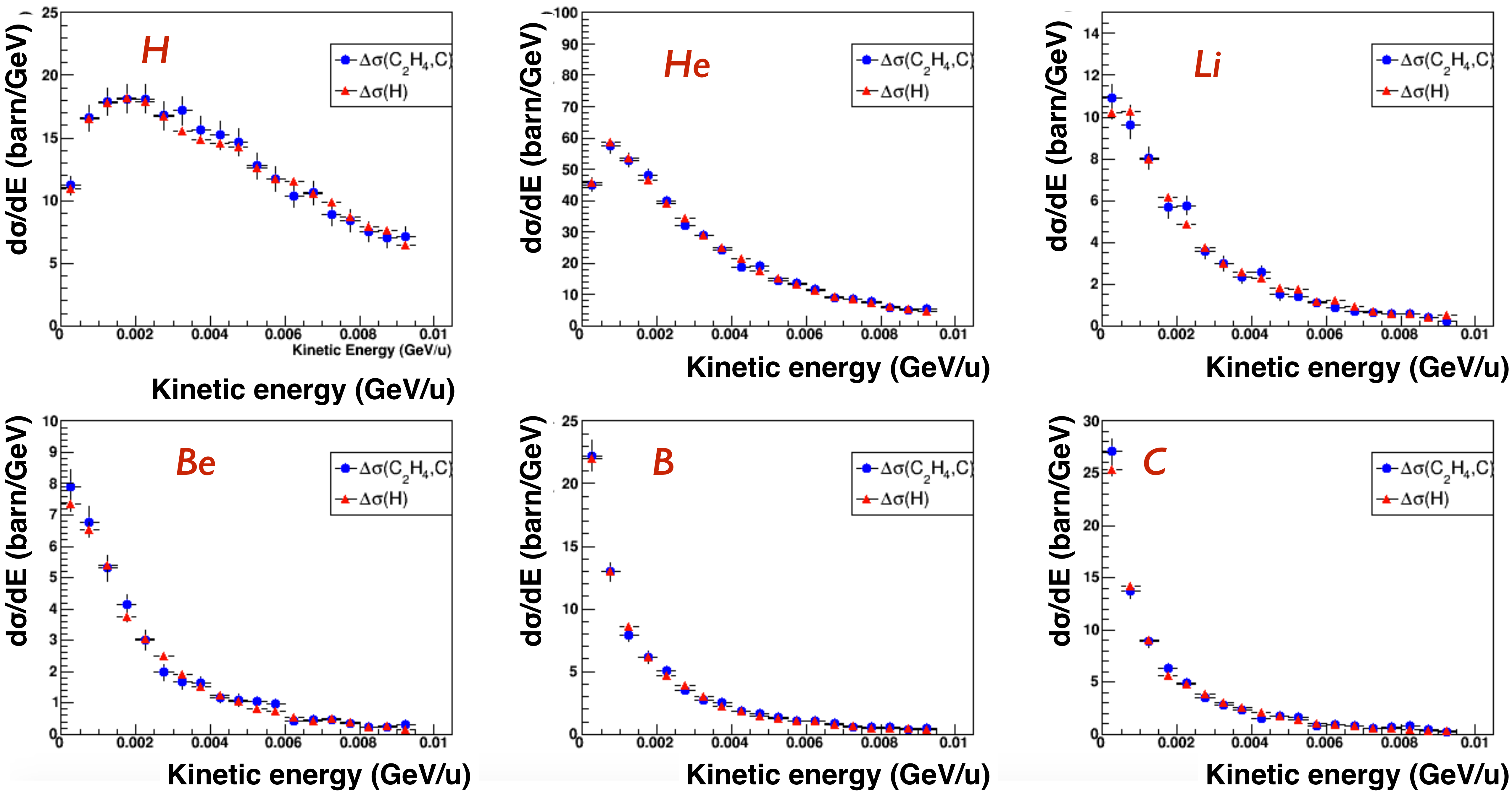
FLUKA simulation

^{16}O (200 MeV/u) —> C_2H_4

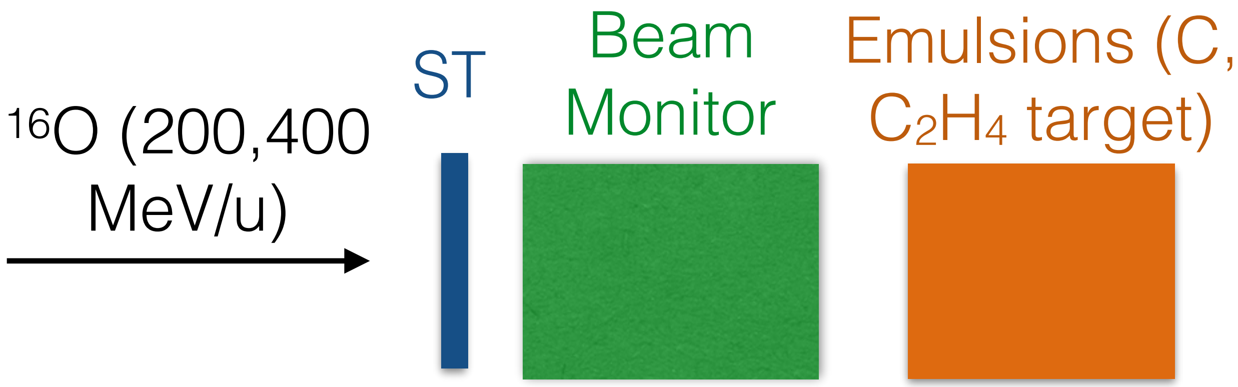
Cross-section measurement

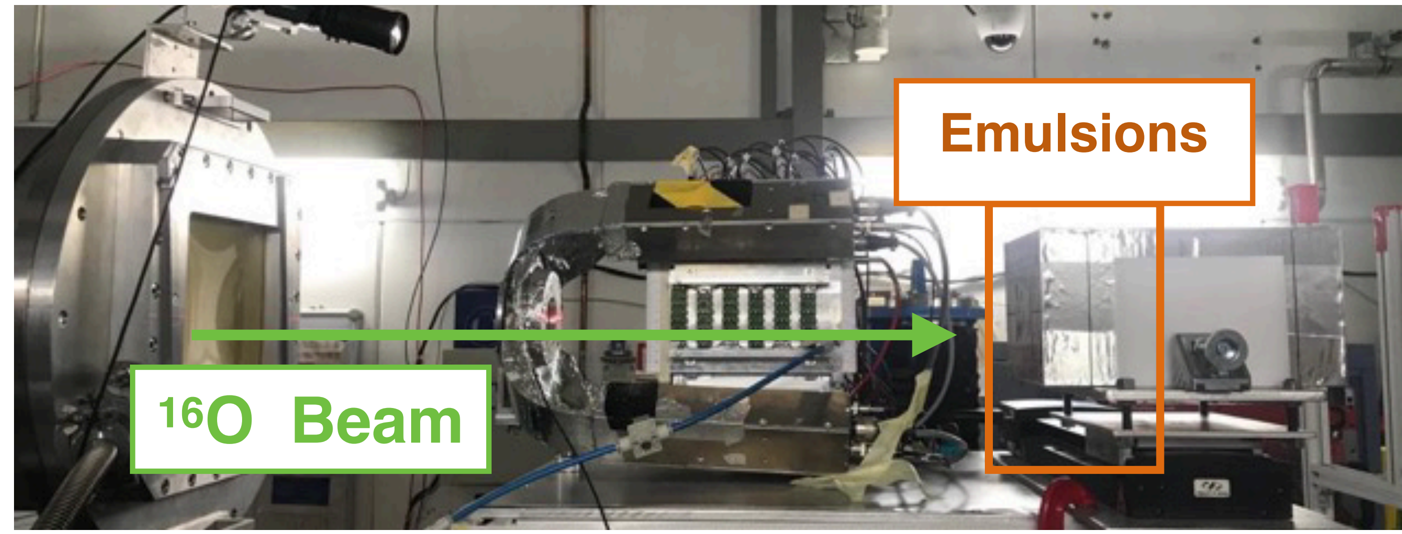
$$\frac{d\sigma_f}{dE_{\mathrm{kin}}} = \frac{Y_f - \mathrm{BKG}_f}{N_{\mathrm{ion}} \cdot N_{\mathrm{t}} \cdot \Omega_{E_{\mathrm{kin}}} \cdot \varepsilon_f}$$

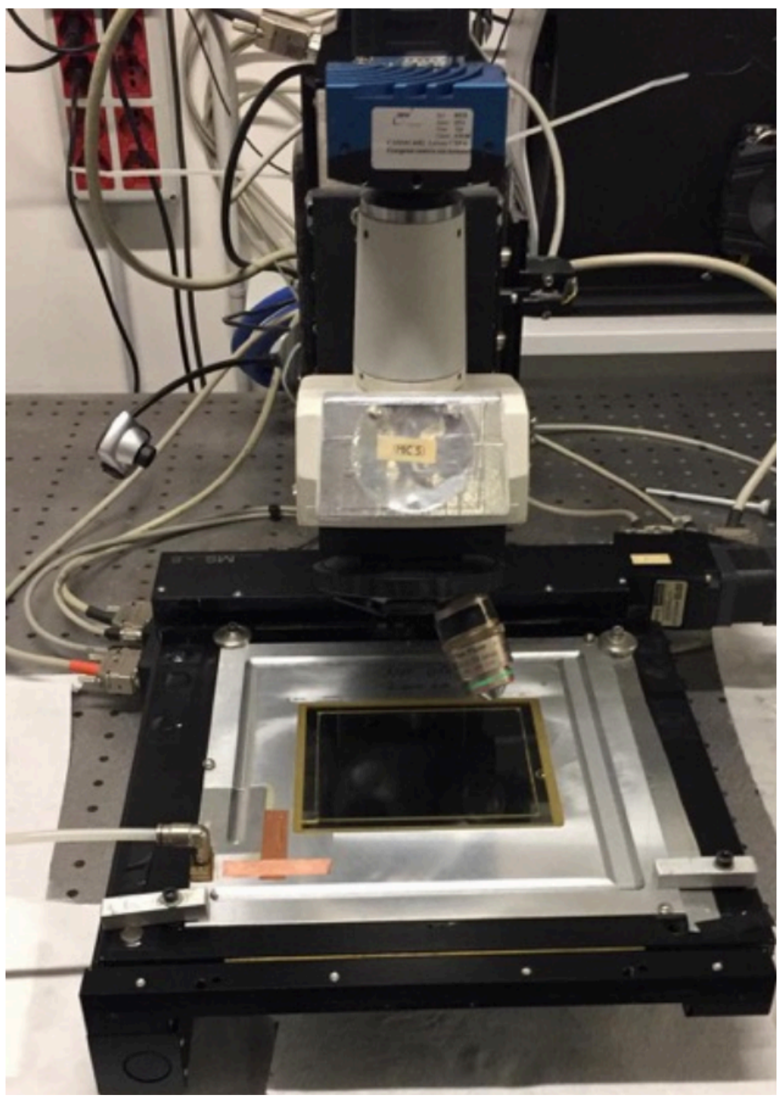
- To check the validity of the target cross sections combination method we evaluated both the **cross section on hydrogen target** and the cross section obtained from the **difference method.**



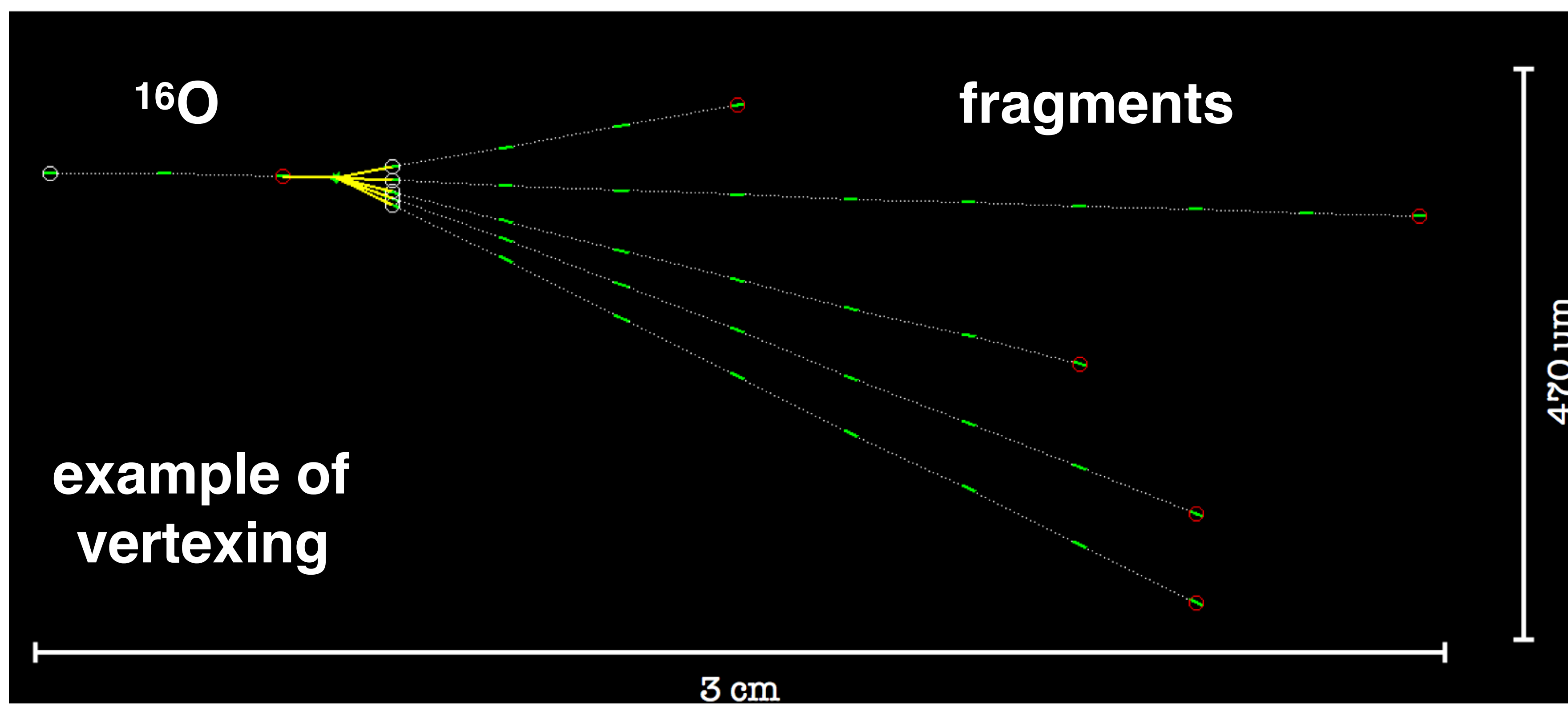
Data taking @ GSI: emulsions





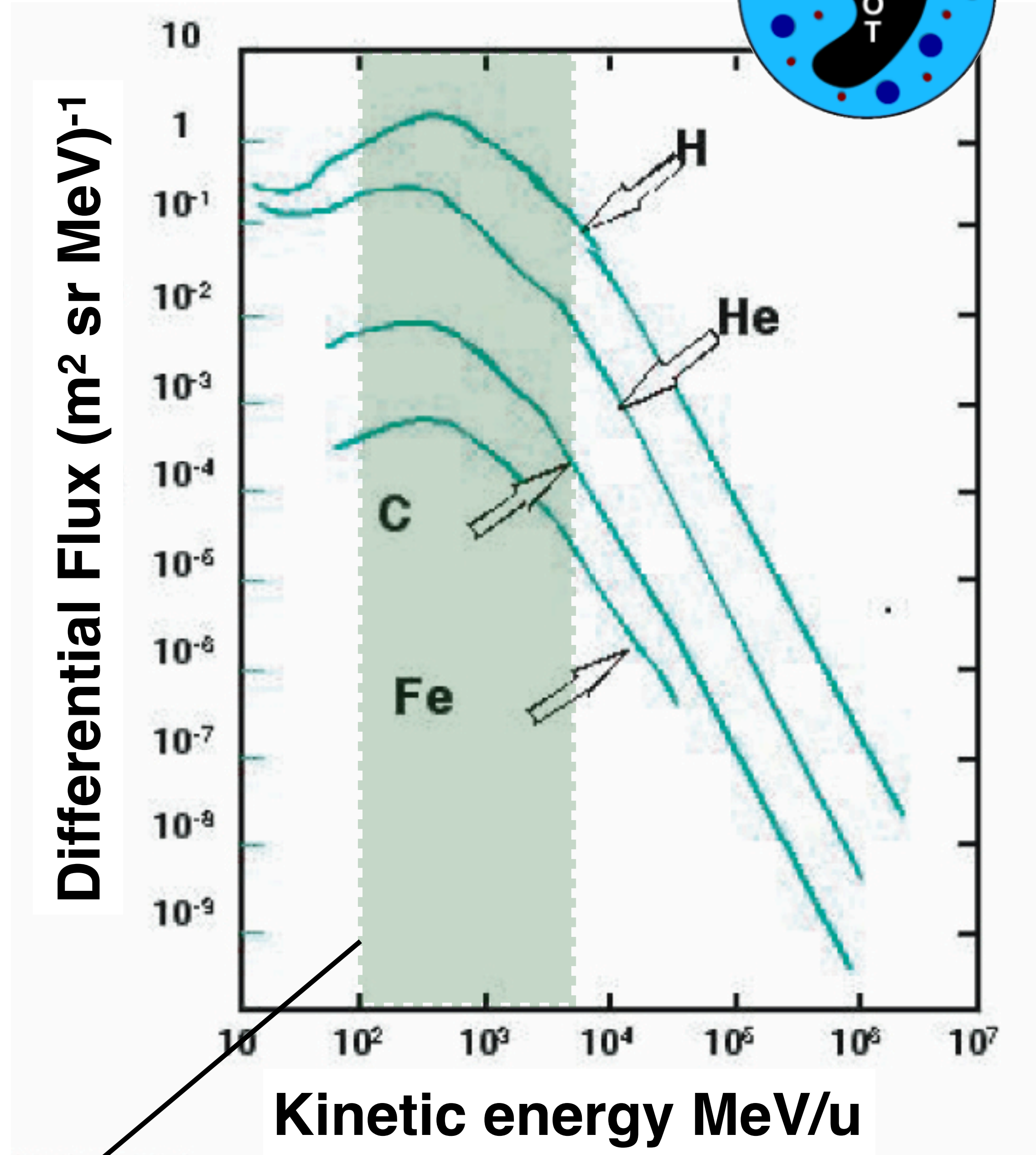


- The emulsion scanning is ongoing @ Naples with a dedicated microscope providing an **automatic scanning procedure**.



Role of fragmentation in radioprotection in space

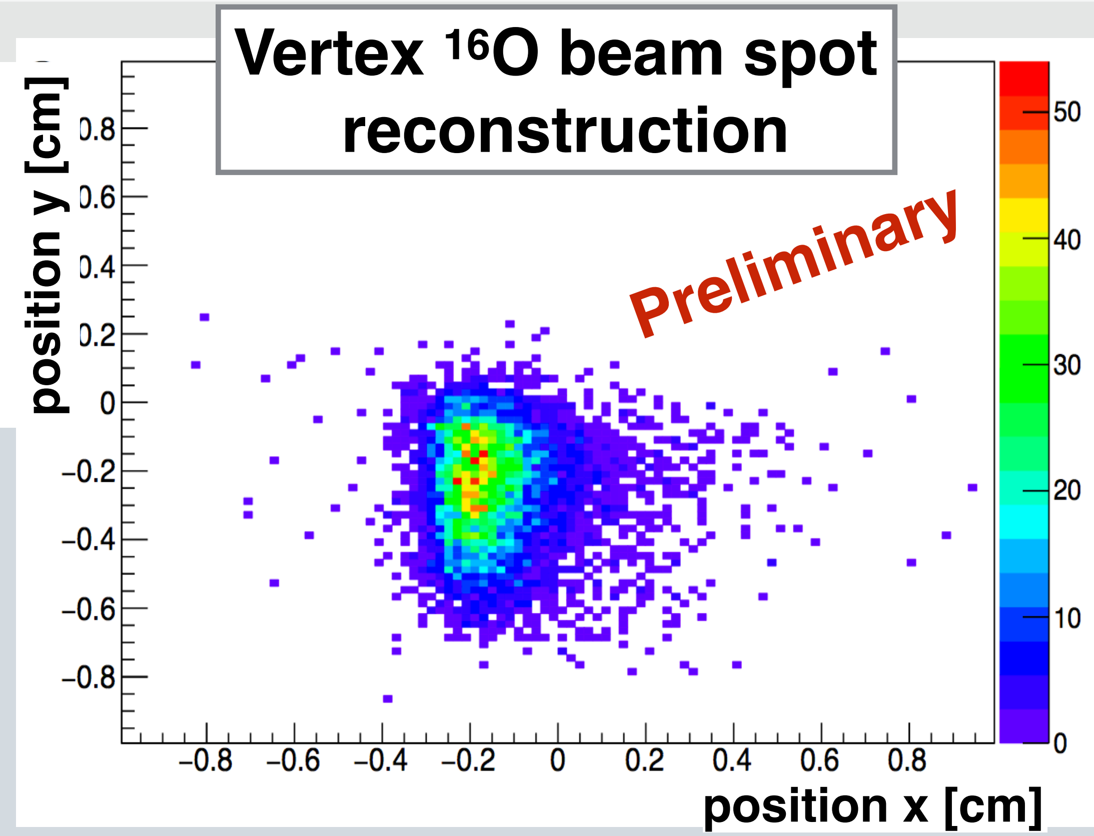
- Long term missions in space expose the astronauts to a huge dose release
- The fragments produced in the shielding material of the **He, C, O** components of **Galactic Cosmic Rays** significantly contribute to the total dose—> the choice of the **spacecraft shielding material** is crucial for the long term missions far from Earth
- <u>An accurate knowledge of the He, C, O fragmentation **x-sections** is needed to design efficient shields</u>

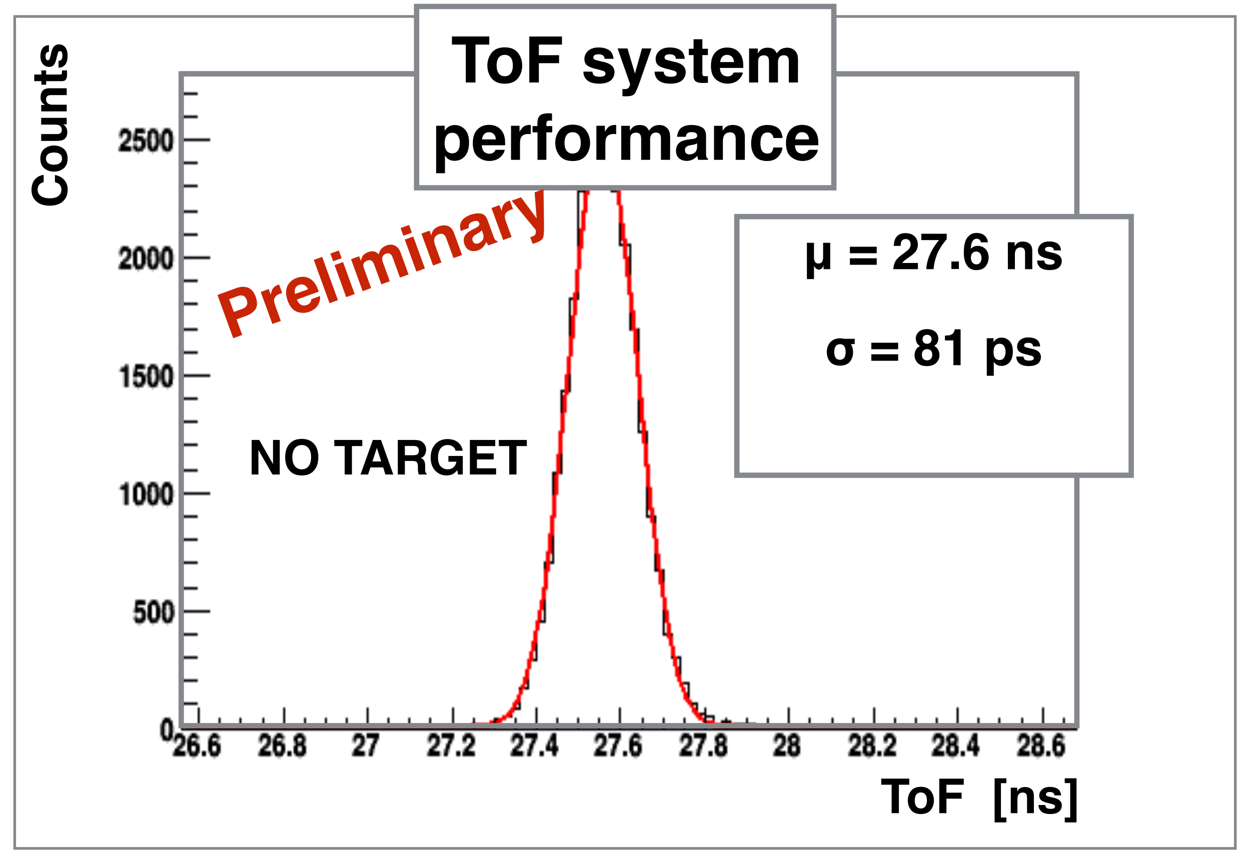


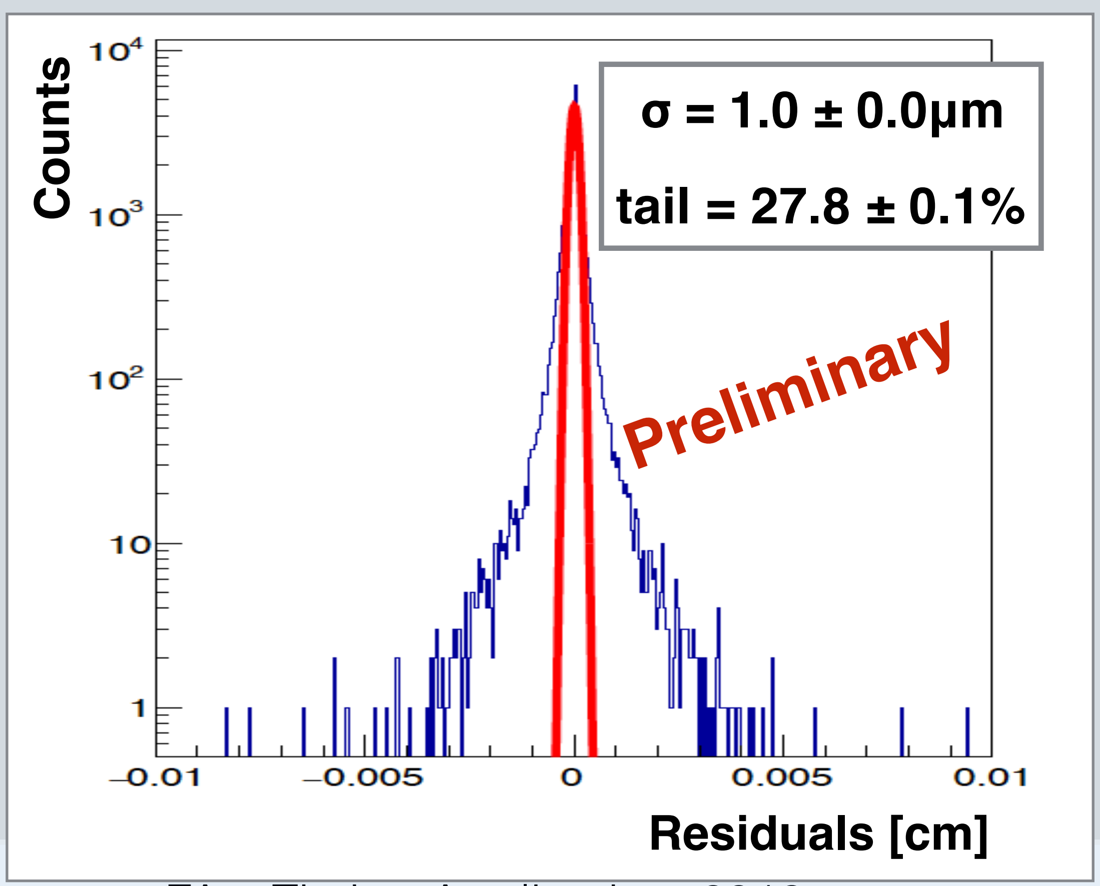
Mars mission:
dose ~300 times larger than that absorbed on Earth, **3% risk of Cancer death**

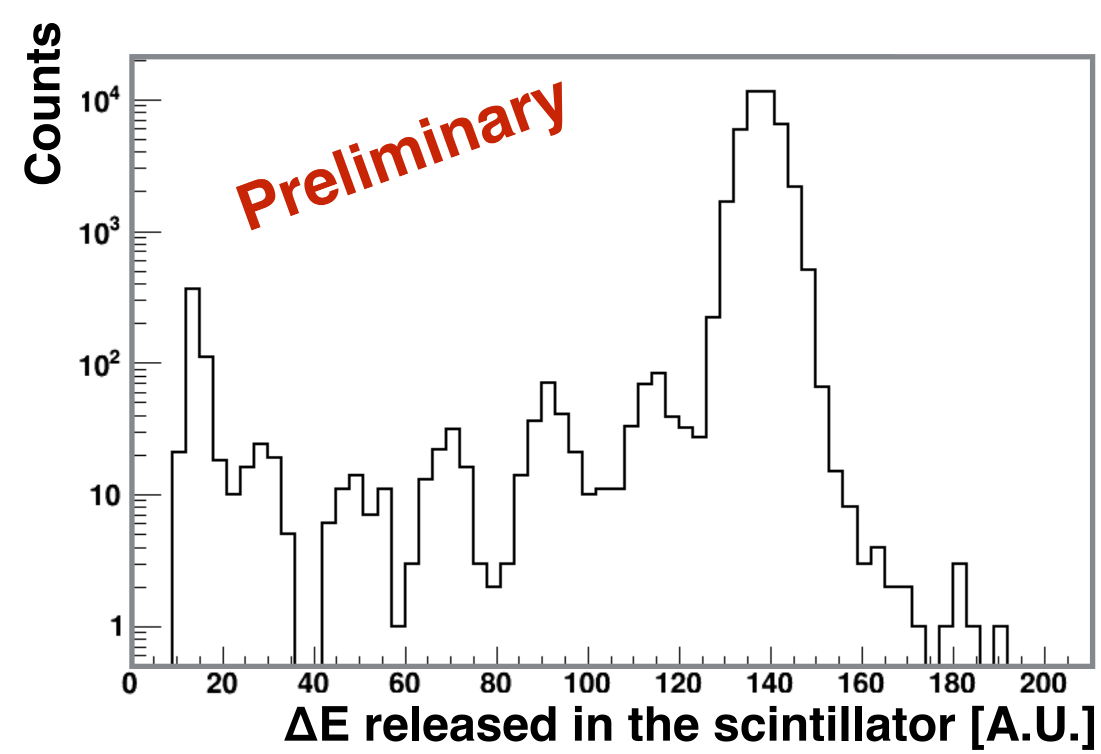
~87% of **protons**, ~12 % **He** ions, ~1% heavier ions (mainly **O,C,N**), peaked in the **700 MeV/u - 1 GeV/u energy** range

GSI first results



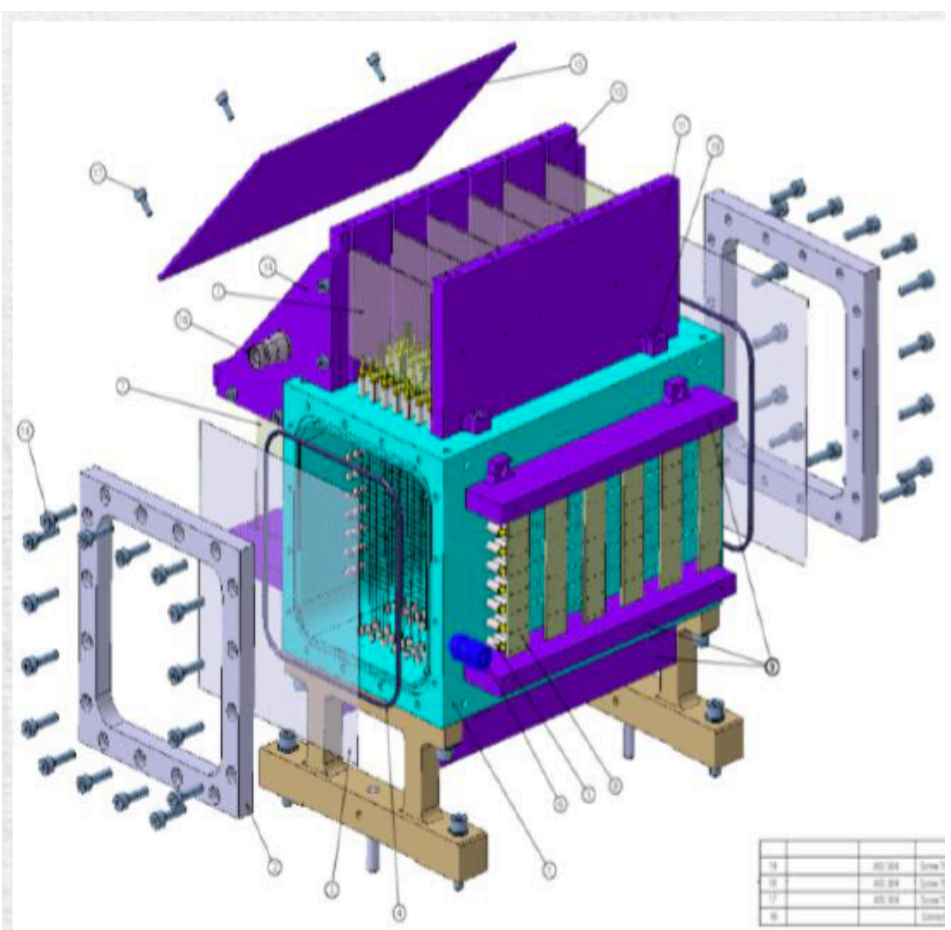


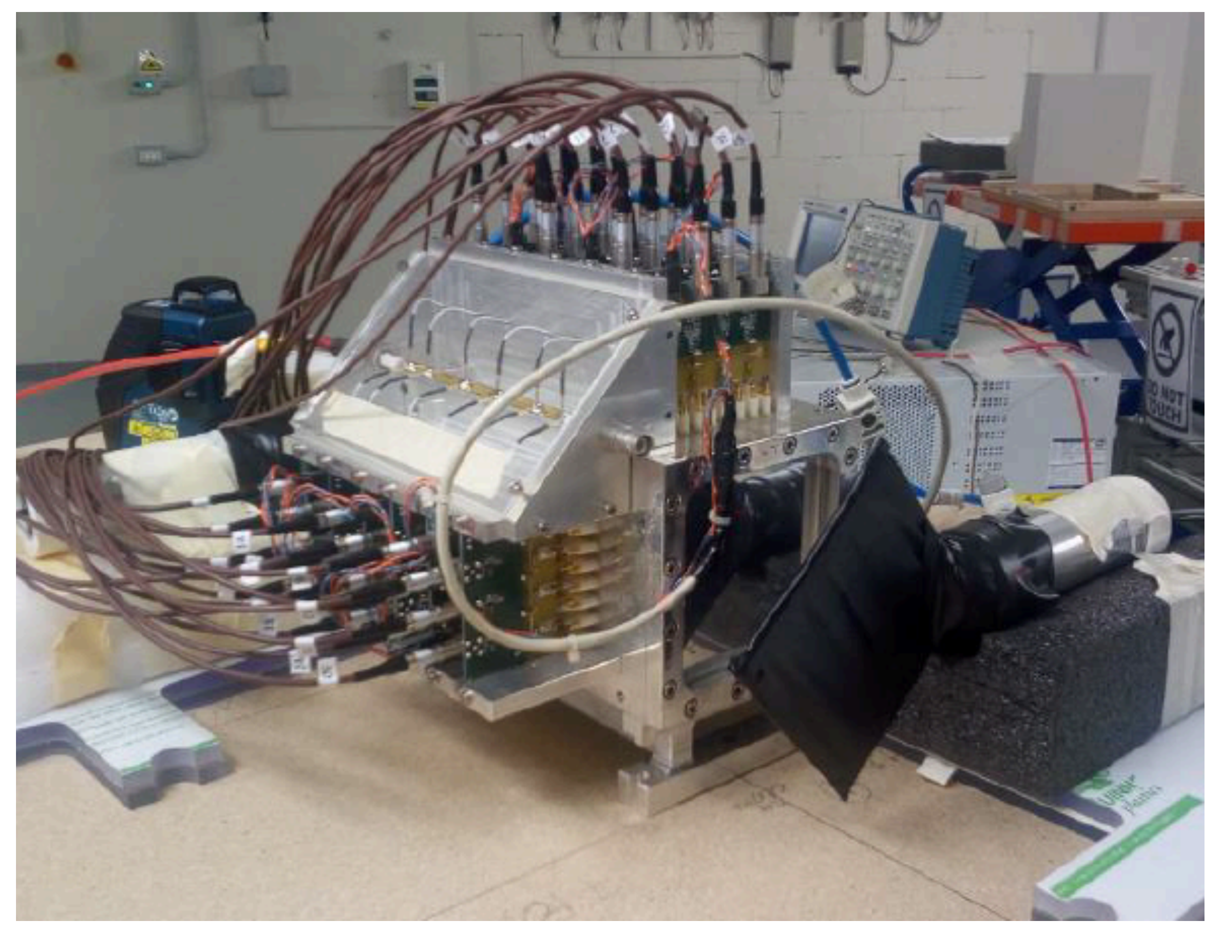




Beam monitor

- Ar-CO2 Drift chamber
- 6+6 orthogonal layers of wires, 3 cells per layer (hit resolution ~ 150 μm on ^{12}C beam)
- Provides the beam direction (~mrad resolution) and position
- It could be used to reject the fragmentation events ins the start counter

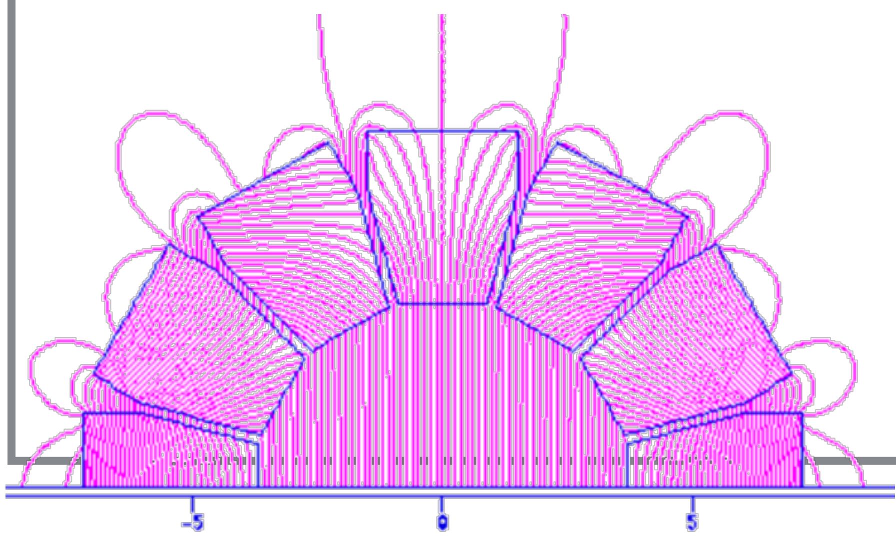




Tracking region

Magnet

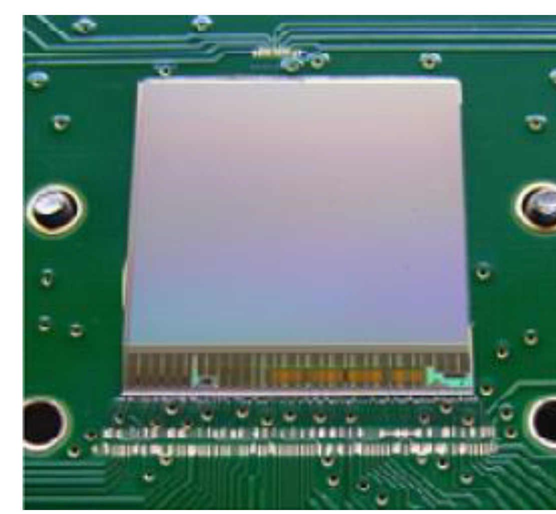
- Halbach cylindrical geometry
- Uniform dipolar magnetic field
- B proportional to $\ln(R_{out}/R_{in})$
- **B ~ 0.8 -0.9 T**



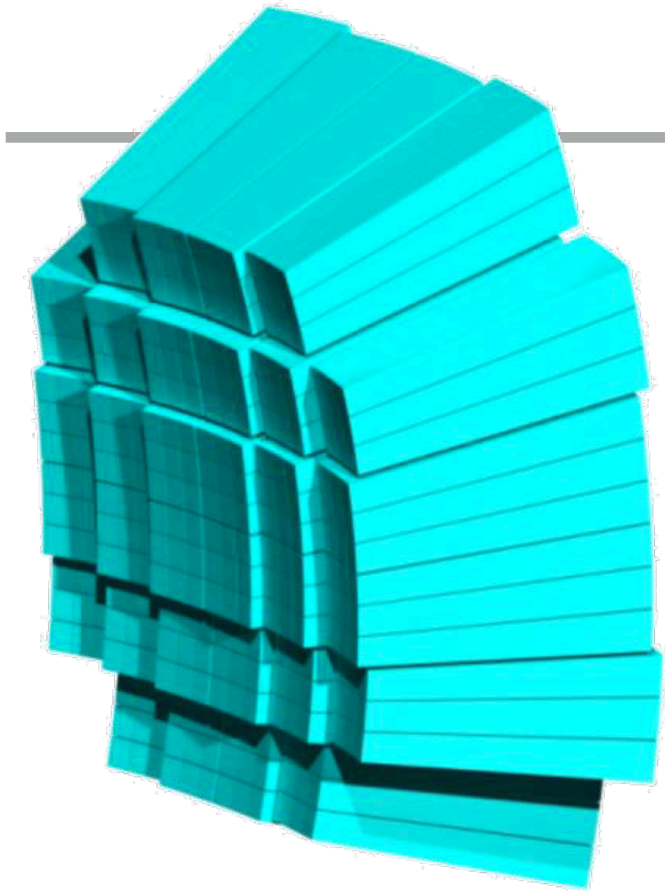
MSD

- Silicon Micro Strip detector
- 3 layers 9 x 9 cm
- 125 μm pitch
- < 30 μm resolution

- MIMOSA28 Chips
- 50 μm thick, 20.9 μm pitch
- **Vertex detector**: 4 layers 2 x 2 cm^2
- **Inner tracker**: 2 layers, 8 x 8 cm
- First two stages of the tracking system



Calorimeter



- ~300 BGO crystals
- SiPM readout + Waveform digitiser DAQ
- 1-4 % energy resolution (test beam @CNAO, GSI)