FOOT: a project for fragmentation studies in hadrontherapy and space radioprotection

FOOT: **F**ragmentati**O**n **O**f **T**arget

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for the FOOT Collaboration

SIF

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Nuclear fragmentation

Nuclear fragmentation plays a role in several aspect of radiotherapy

- with proton
- with high Z ion beam (i.e. Particle Therapy)

Nuclear fragmentation is crucial in radio protection in long term space mission

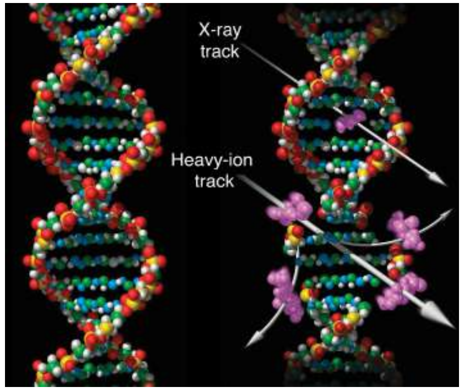
What is still missing to know about light ions fragmentation?

It is essential to know, for any beam of interest and on thin target:

- Production yields of all $Z \leq Z_{beam}$ fragments
- $d^2\sigma / (d\Omega\ dE)$ wrt angle and energy, with large angular acceptance
- For any beam energy of interest (100-400 MeV/n)
- Thin target measurement

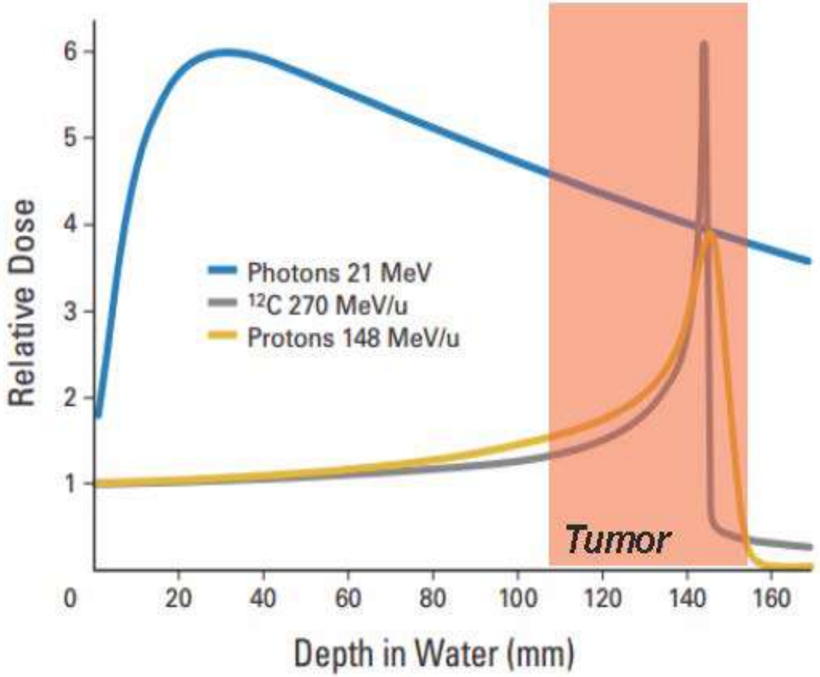
- Not possible an exhaustive set of measurements for all beams and on all materials;
- to train a nuclear interaction model by the measurements should be a good goal !!

Charged Particle Therapy

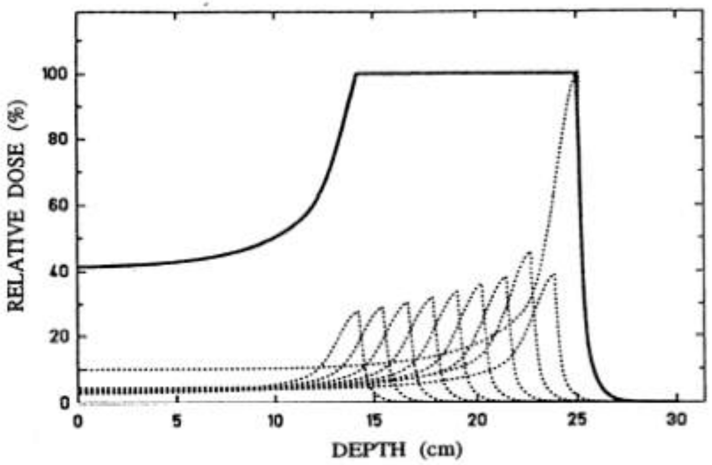


- Radiotherapy is based on the use of ionizing radiation to kill the cancer cells, by damaging the DNA chain.

- Charged Particle vs photons



Schulz-Ertner et al. *J. Clin. Oncol.* (2007)



- ✓ Peak of dose released at the end of the track, **allows sparing the healthy tissues**
- ✓ Beam penetration in tissue is function of the beam energy
- ✓ Accurate conformal dose to tumor with Spread Out Bragg Peak
- ✓ Greater biological effectiveness, increasing with the beam charge, well performing with radioresistant tumors

Nuclear fragmentation: target and beam

Proton Beam

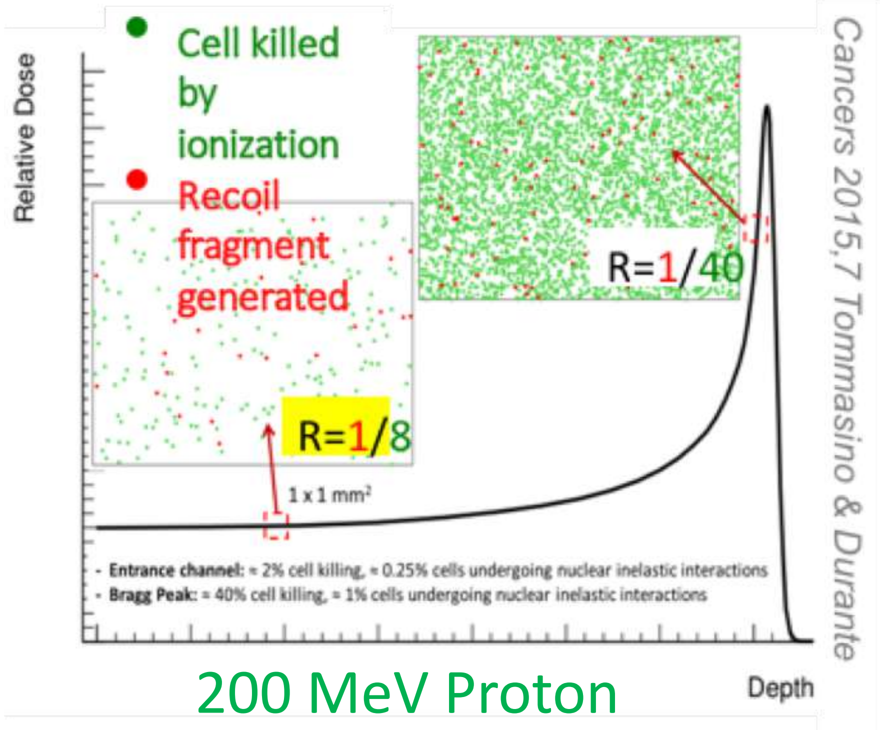
Target fragmentation

- Small range fragments (~tens of μm)
- Missing experimental data for heavy fragments (**He, C, Be, O, N)** having the greatest contribution to the dose
- Increase of biological damage (~ 10%) in the entrance channel (Grun 2013)

Charged particle

Beam and target fragmentation

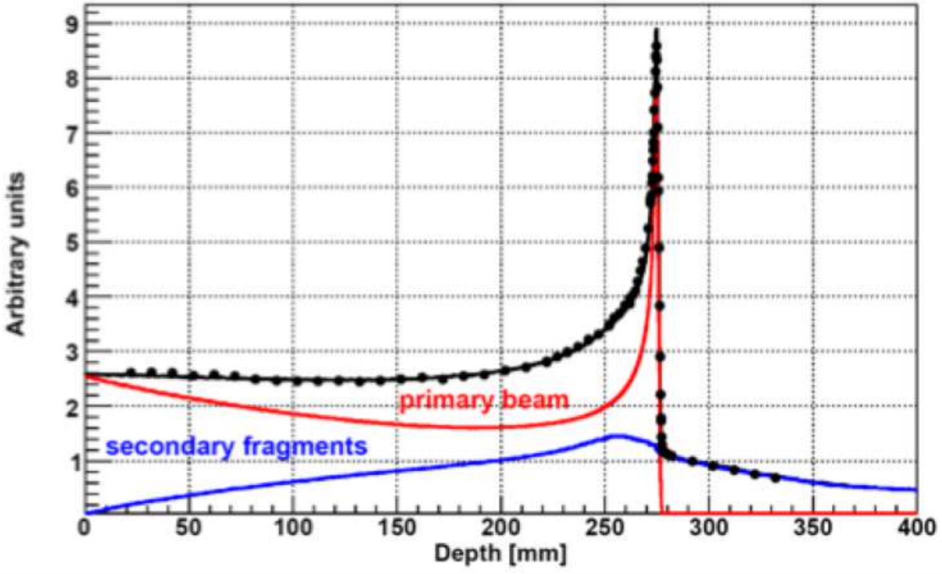
- Fragments have the same velocity of the beam, but the lower mass allows longer range producing tail beyond the Bragg peak
- Scarce validation data for ^{12}C clinical beam
- New beams (^{4}He and ^{16}O) to be study



200 MeV Proton

Measurements of nuclear fragmentation cross sections

useful to develop a new generation of biologically oriented Treatment Planning Systems for proton and particle therapy



Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

FOOT – FragmentatiOn Of Target experiment (INFN - 2017)

Goals:

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

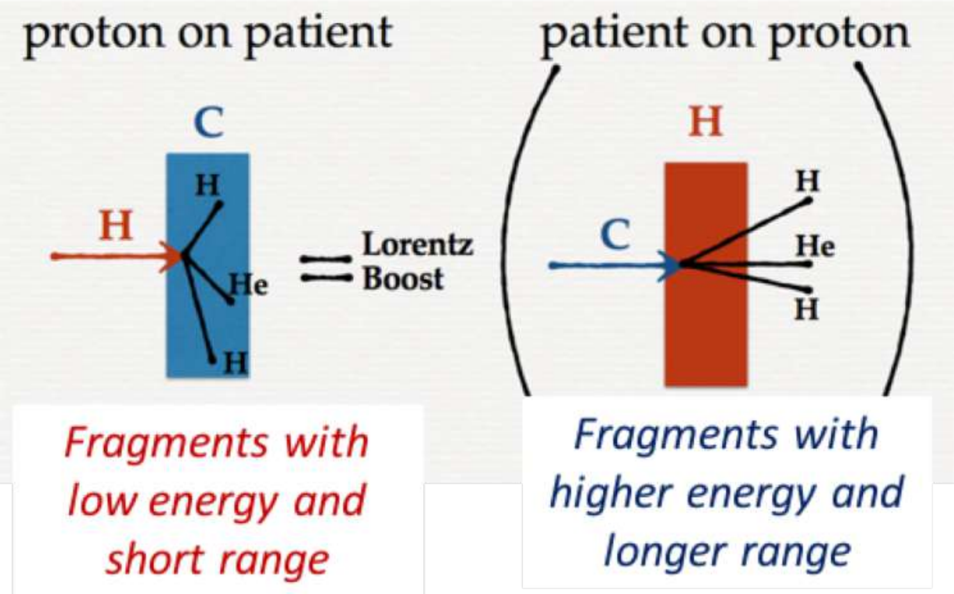
- Data taking for beams at therapeutic energies and at high energy (space radioprotection):
  - 200 MeV for protons
  - 250 MeV/n (700 MeV/n) for He ions
  - 350 MeV/n (700 MeV/n) for C ions
  - 400 meV/n (700 MeV/n) for O ions
- target simulating the human tissue (C, C_2H_4, 0)

Experimental strategy:

✓ Inverse kinematic approach with double target

✓ Experimental apparatus: electronic detector and emulsion spectrometer

FOOT: Inverse kinematic approach
(target fragmentation in proton therapy)



p on O_2 200 MeV/n

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

- Protons @ E_{kin}= 200 MeV (β~0.6) on a "patient" (98% C, O, and H nucleus)

↓

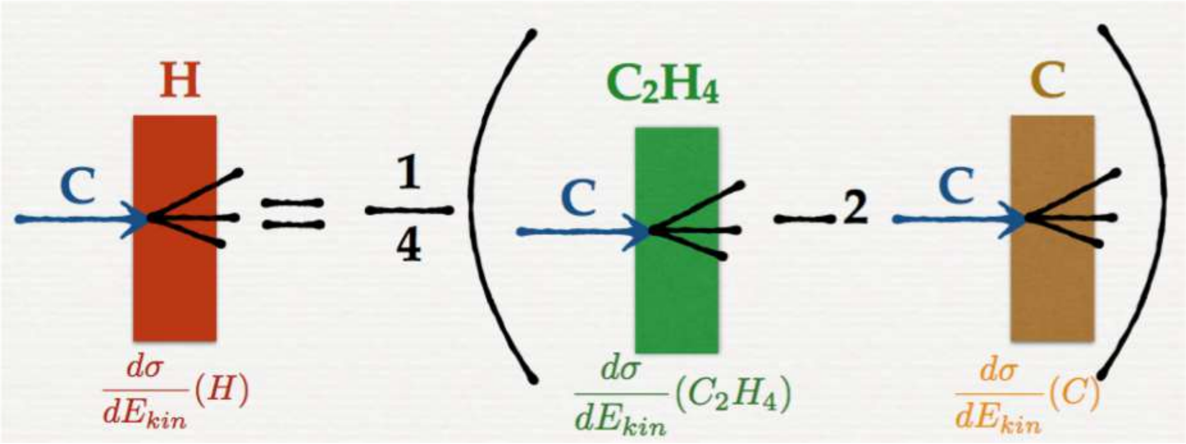
- can be replaced by ^{16}O, ^{12}C ion beams (E_{kin} ~ 200 MeV/n β~0.6) impinging on a target made of protons (C → H)
- by applying the Lorentz transformation (well known β) it is possible to switch from the ***lab. frame*** to the ***patient frame***

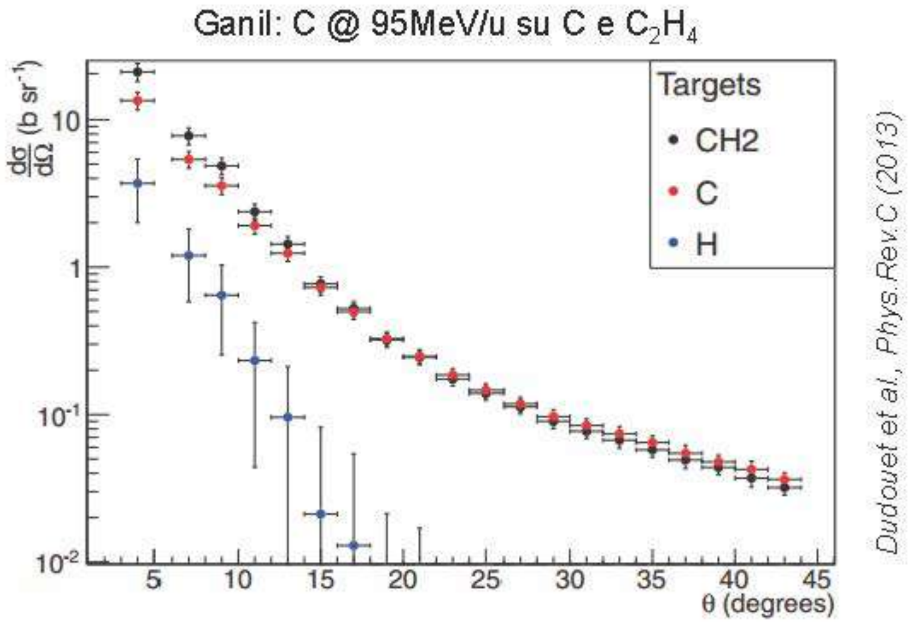
Requirements: the fragment direction must be well measured in the lab. frame to obtain the correct energy in the patient frame

FOOT: Double target

- H target? Use twin targets made of C and polyethylene $(C_2H_4)_n$ and obtain the fragmentation results on H target from the difference
- C → H cross-section can be estimated by subtracting C → C_2H_4 and C → C cross-sections

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





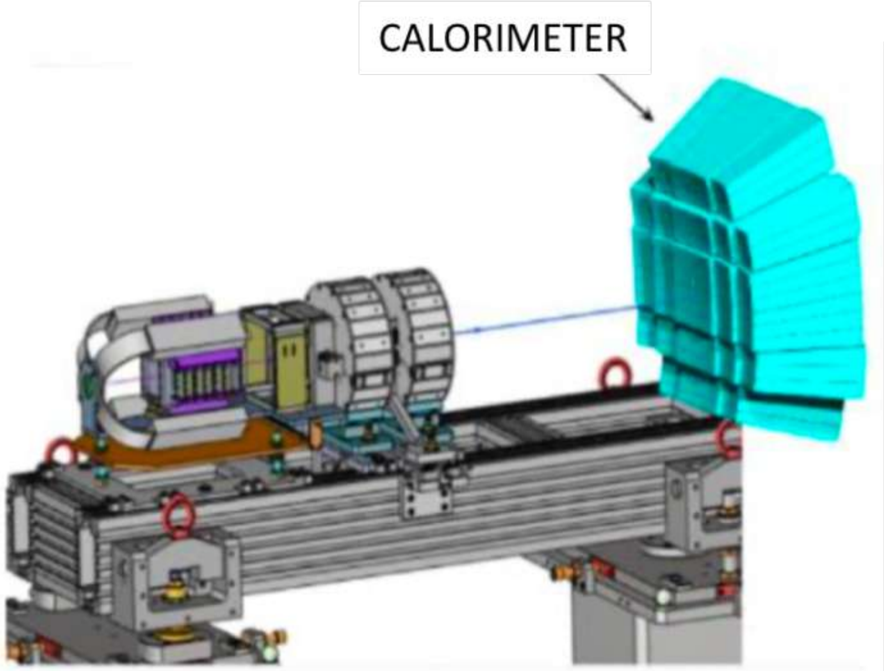
- GANIL experimental data

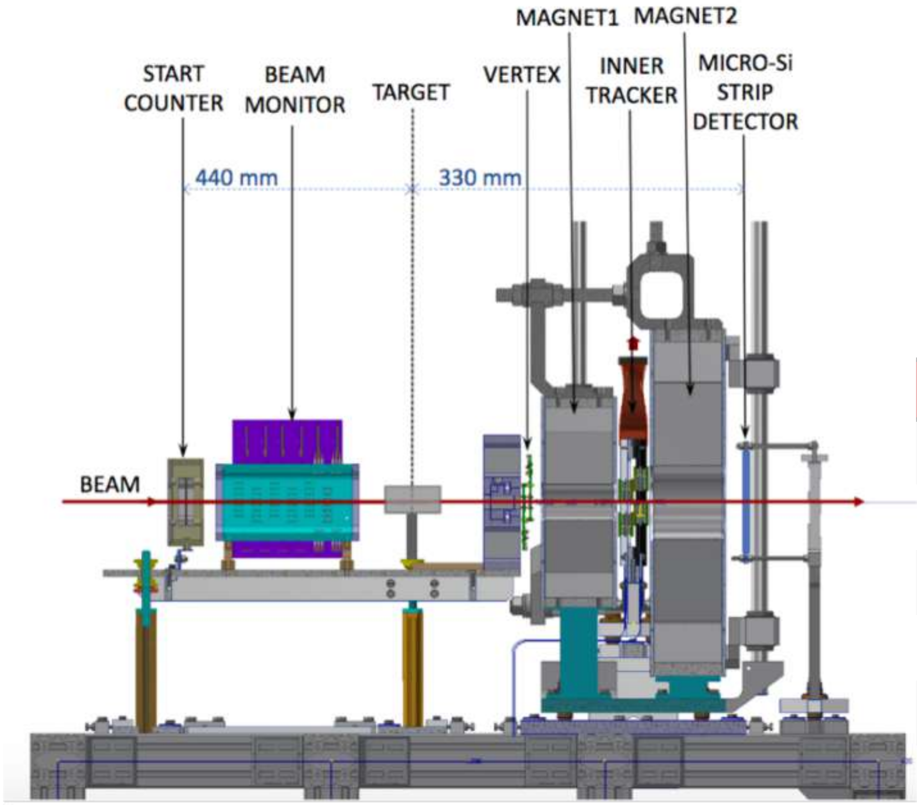
FOOT Detector

- a “table top” detector (< 2 m long)
- electronic detector optimized for fragments with Z ≥ 3 and angular acceptance ± 10°
- emulsion spectrometer detecting light charged fragments at large angle (up to 70°)
- required perfomances:

$$\frac{\Delta p}{p} \approx 5\,\% \qquad \Delta TOF \approx 100ps \qquad \frac{\Delta(dE)}{dE} \approx 2\,\% \qquad \frac{\Delta Ekin}{Ekin} \approx 2\,\%$$

FOOT Detector

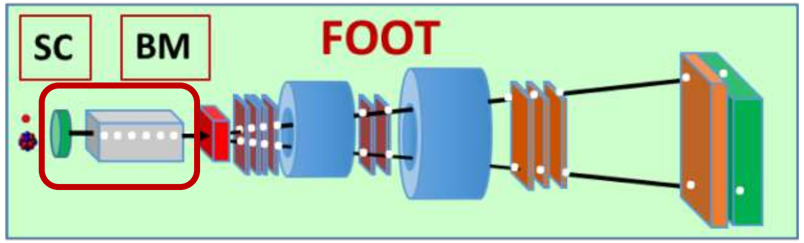


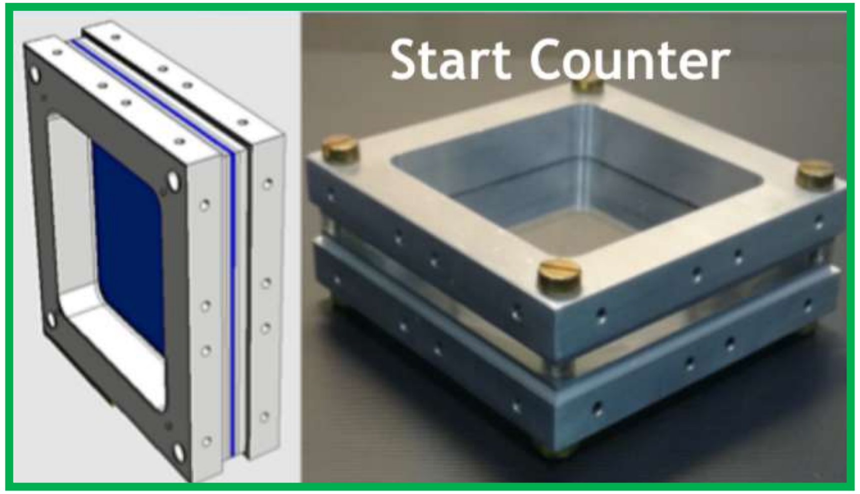


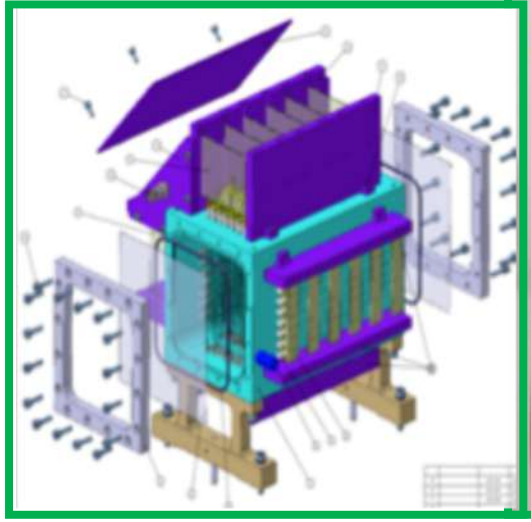
Electronic detector

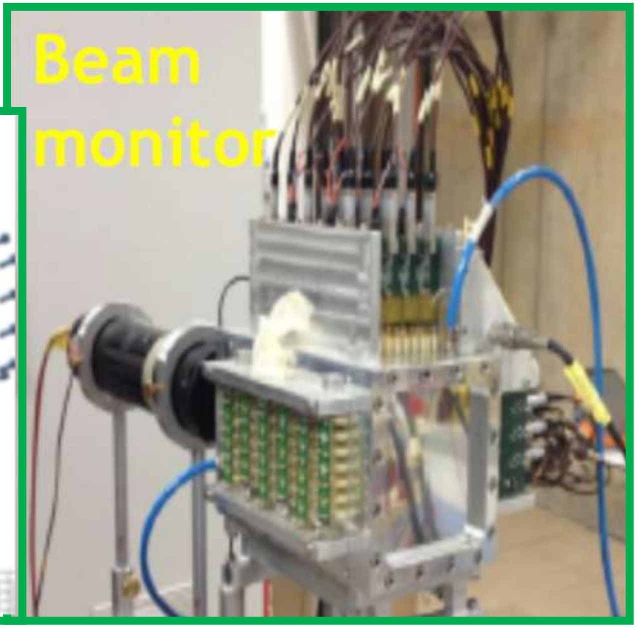
Sub-detector	Main features	
Start counter	Plastic scintillator 250 μm	Stat TOF, counts primaries
Beam monitor	Drift chamber (12 layers of wires)	Beam position
Target	C / C_2H_4	
Vertex	4 layers silicon pixel (20x20 μm)	Vertex position
Permanent Magnet	Halbach geometry 0.8 T	
Inner Tracker	2 layers silicon pixel (20x20 μm)	Magnetic spectrometer: Δp/p
Outer Tracker	3 layers of Silicon strip (125 μm pitch)	
Scintillator	2 layers of 20 barrels (2x40x0.3 cm)	Stop TOF, dE/dx
Calorimeter	360 BGO crystals (2x2x14 cm)	Kinetic energy

FOOT Detector: interaction region









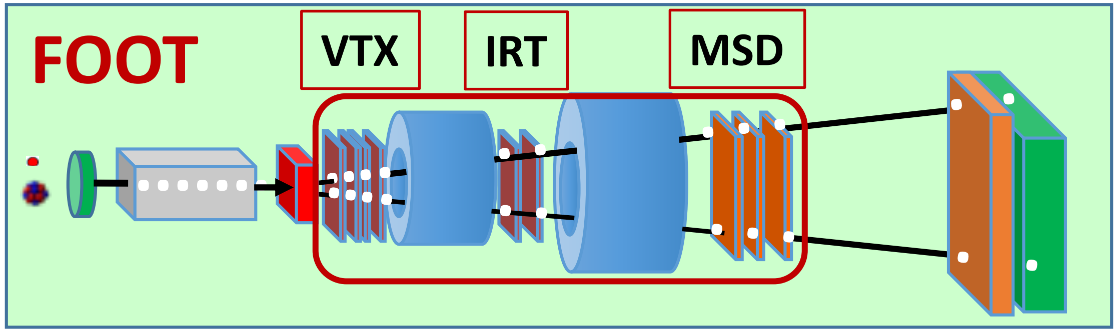
Trigger and TOF start

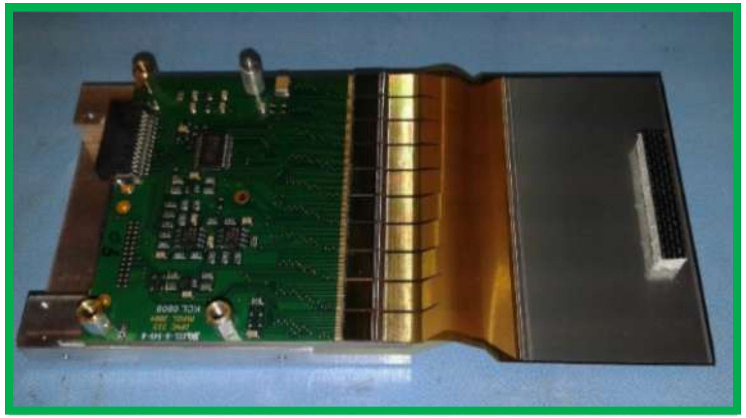
- 250 µm plastic scintillator read out by 48 SiPM (12/side)
- Readout at 5 Gsample/s
- Time resolution: 65 ps for ^{12}C @ 200 MeV/n (CNAO beam)

Beam position and direction

- Drift chamber with 6+6 XY planes
- Gas: Ar/Co2 (80/20%)
- Hit resolution on ^{12}C beam @ 400 MeV/n : <150 µm (GSI beam)

FOOT Detector: tracking region



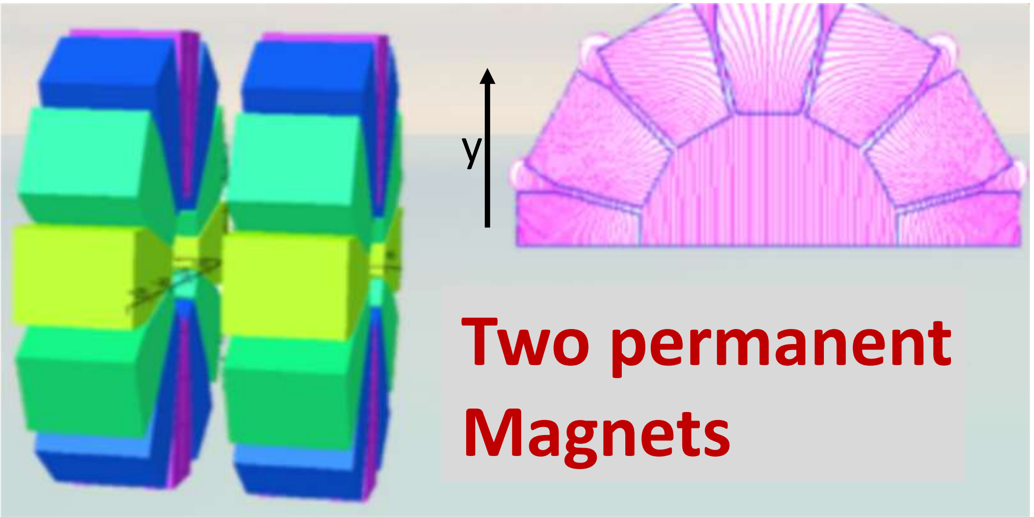


Micro Strip Detector

- **MSD**: 3 layers of Si strip detectors (120 μm × 9 cm)

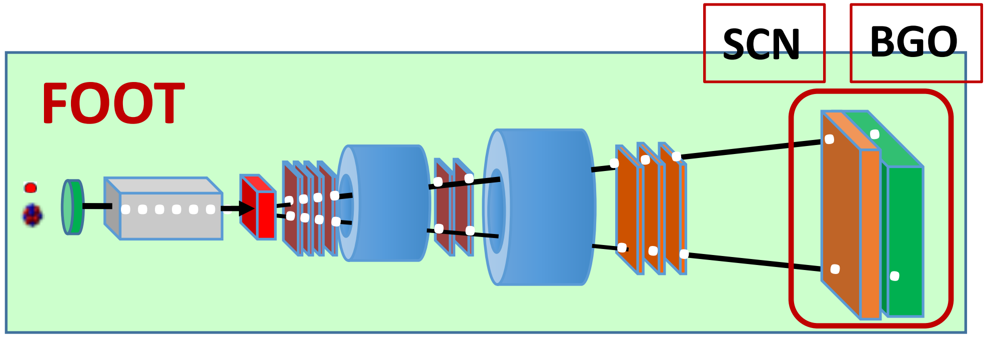
Vertex e Inner Tracker

- **Vertex**: 4 layers of Si pixel detectors (20 × 20 μm)
- **Inner tracker**: 2 layers of Si pixel detectors (20 × 20 μm)

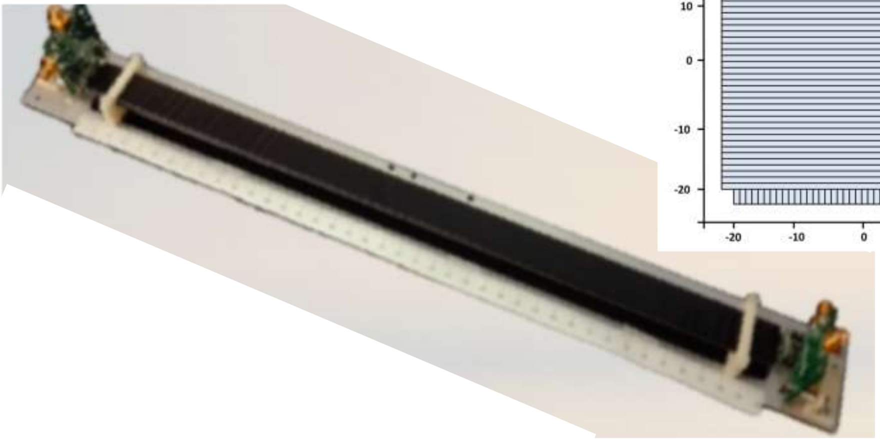


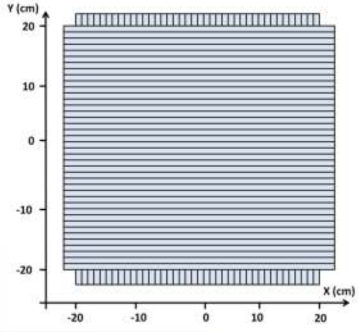
- **Permanet magnet:** Halbach geometry
- **B field:** in the y direction, max 1.1 T

FOOT Detector: downstream region



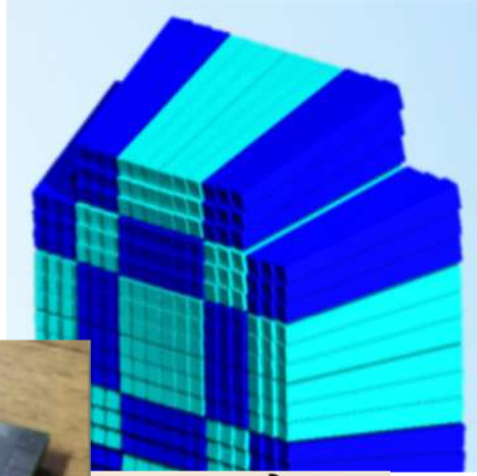
Plastic Scintillator ΔE/E and TOF stop measurements



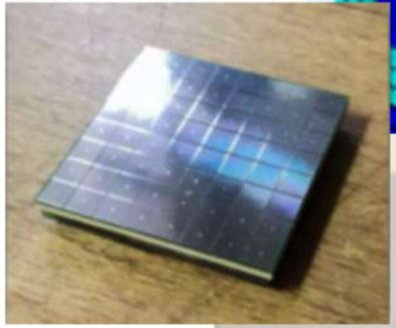


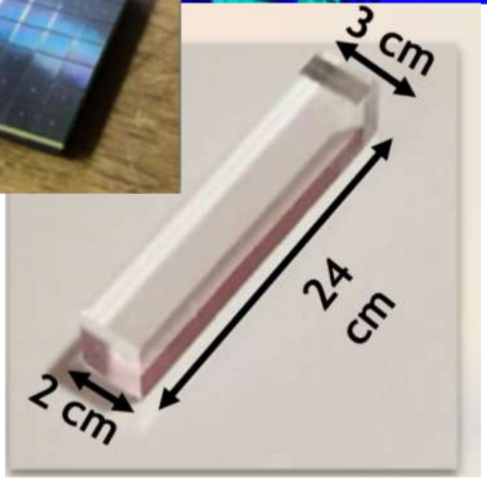
- 40 x 2 x 0,3 cm^3 plastic scintillator bars
- 2 XY layers of 20 bars
- Readout: 4 x $3mm^2$ SiPM/bar
- 35 ps resolution @ ^{12}C at 200 MeV/n (CNAO)

BGO Calorimeter



- Readout: SiPM 8x8 mm^2 cell 20 μm
- Voltage breakdown 53 V





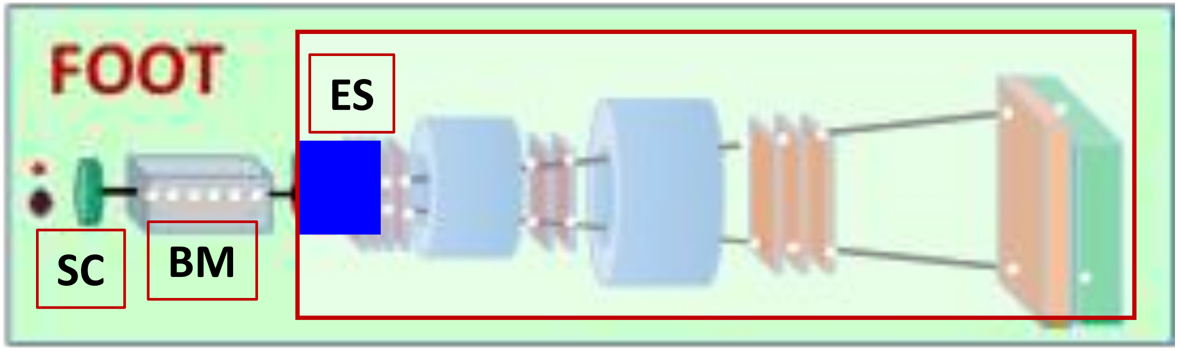
- 400 BGO crystals
- Z_{eff} = 74
- ρ_{BGO} = *7.13 g/cm³*
- *Total weight 330 Kg*

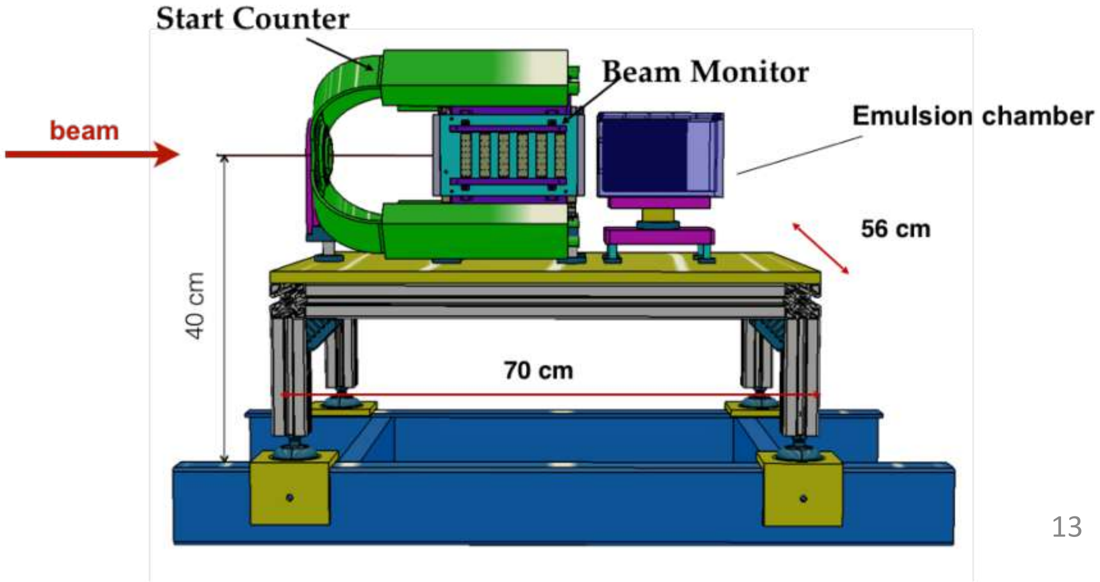
FOOT Detector: Emulsion spectrometer

- It measures fragments as protons, deuterons, He and Li ($Z \leq 3$) emitted within a wider angular aperture (up to 70°) with respect to heavier nuclei

- Detector based on the concept of Emulsion Cloud Chamber – **ECC – a sequence of emulsion films and passive layers**

- The measurement setup integrates the ECC with the start counter and the beam monitor of the electronic detector



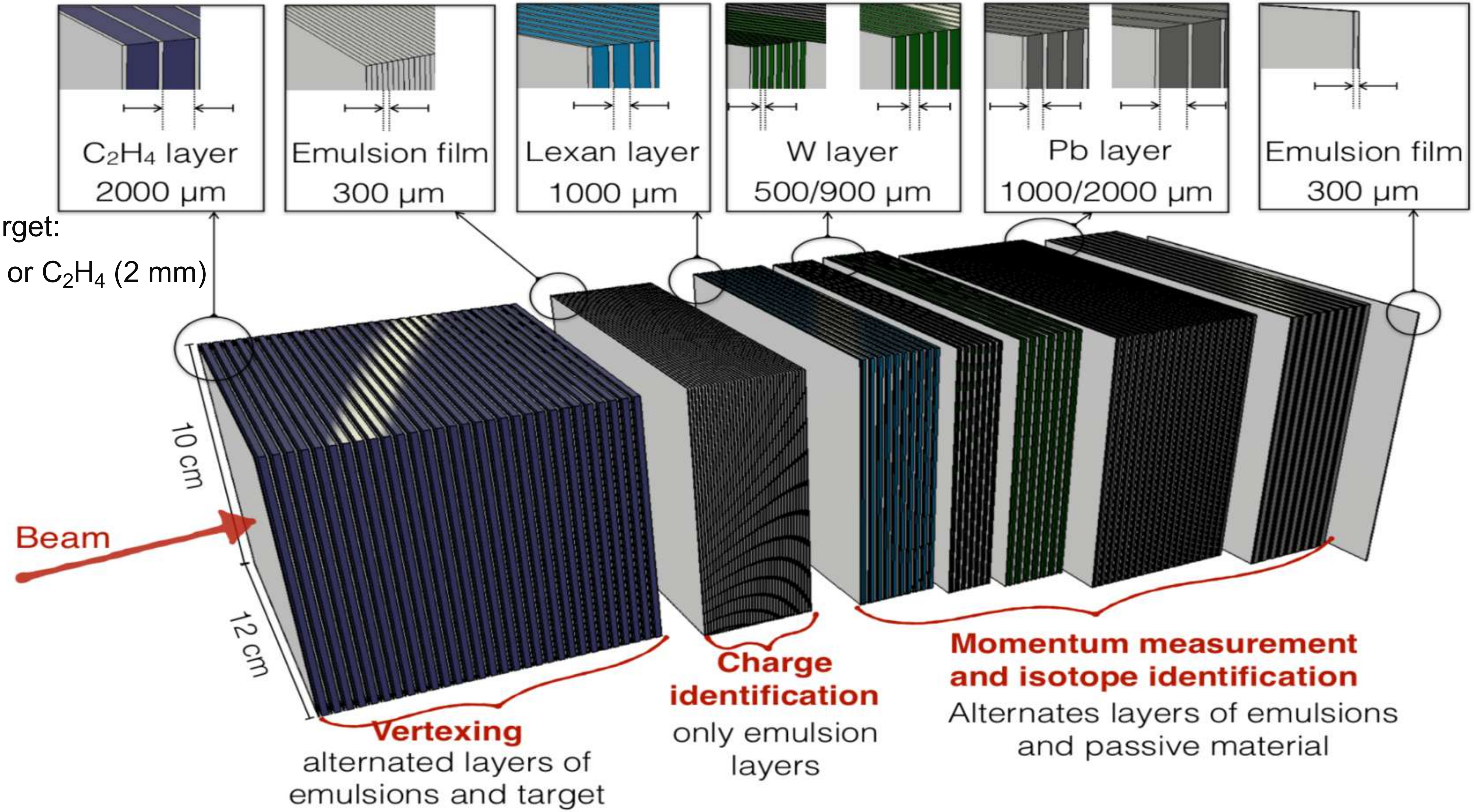


FOOT: Emulsion Spectrometer Layout

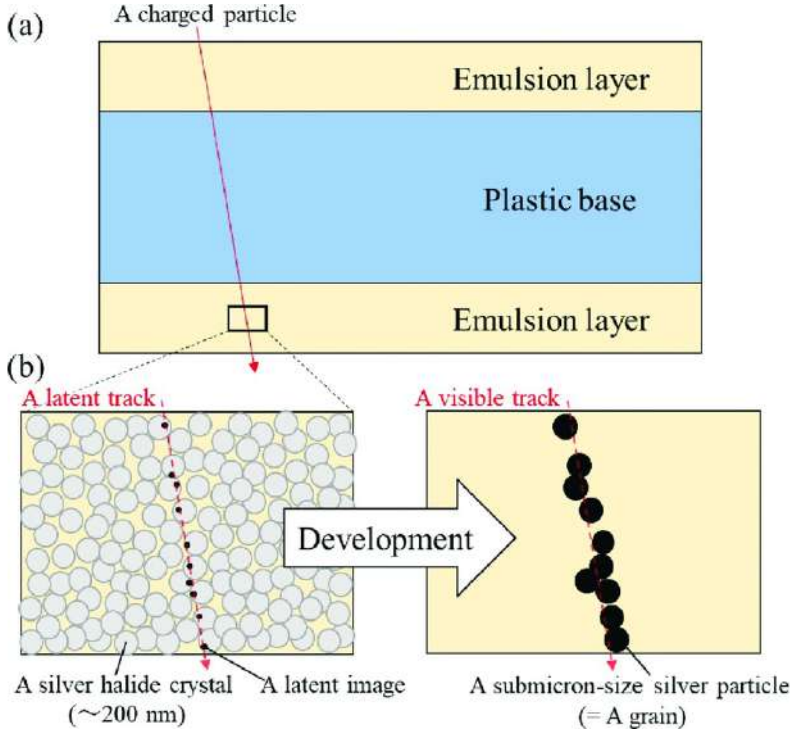
- Based on the concept of the Emulsion Cloud Chamber (ECC)

Double target:

C (1 mm) or C_2H_4 (2 mm)



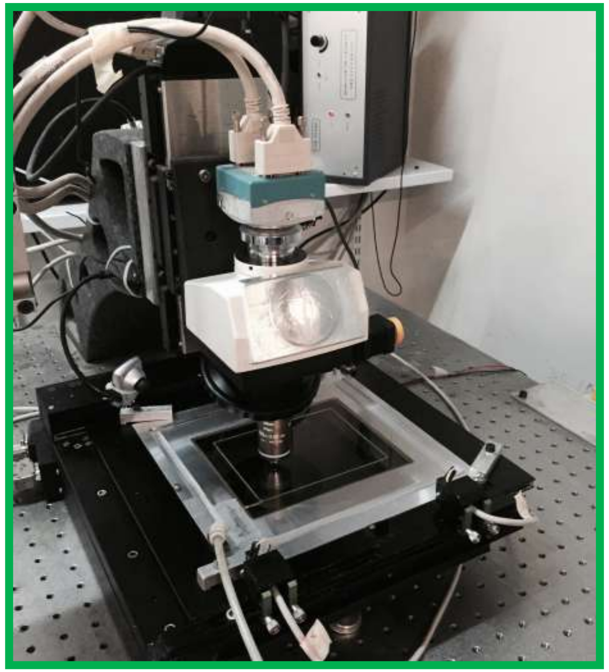
NUCLEAR EMULSIONS: HOW THEY WORK?



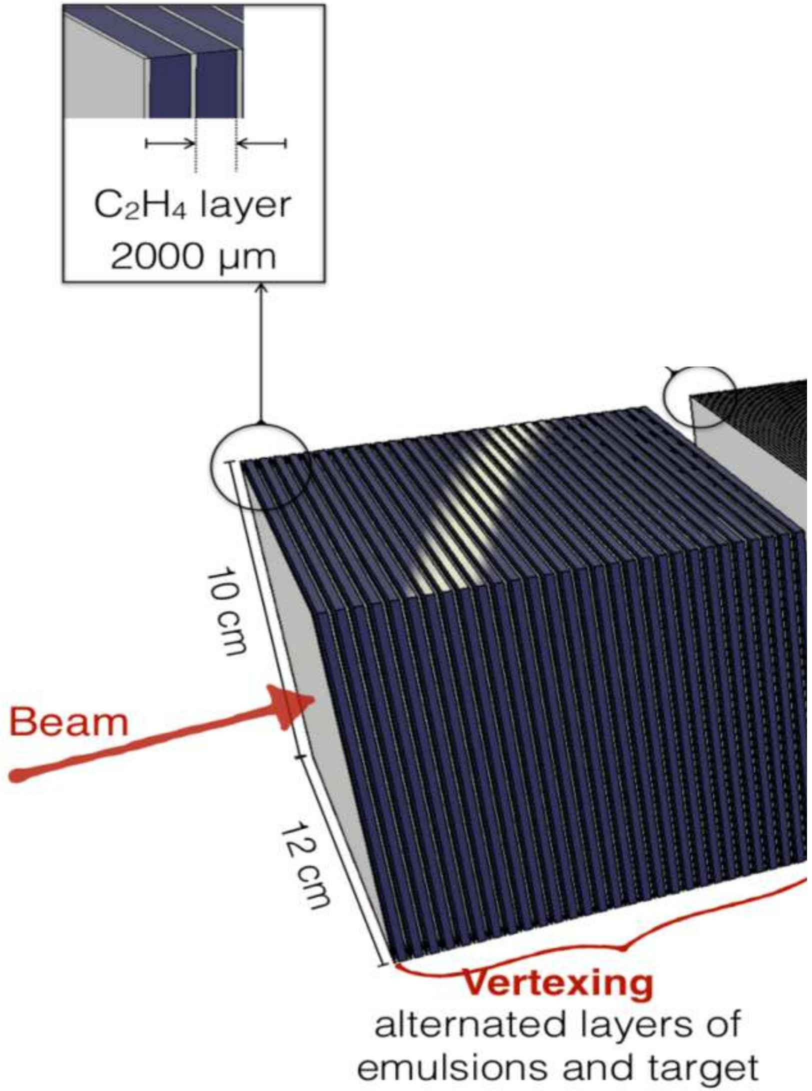
- Film dimensions:
  - Surface: 125 mm x 100 mm
  - Total thickness: 350 µm
    - Emulsion Layers: 2x70µm
    - Plastic Base: polystyrene: 210 µm
- sensitivity: 30 - 50 grains/100 µm
- spatial resolution: ~ µm
- angular resolution: mrad

- The nuclear emulsion films consist of two thick sensitive emulsion layers, made of a gel with interspersed AgBr crystals, deposited on both sides of a plastic base.
- When a charge particle crosses the nuclear emulsion layer, a sequence of AgBr crystals is sensitized along its trajectory, producing a latent image.
- A chemical development process turns the latent image into a sequence of dark silver grains along the particle trajectory.

- An automated microscope acquires the images impressed on nuclear emulsion films.
- A dedicated software recognizes aligned clusters of dark pixels produced by the penetrating particle

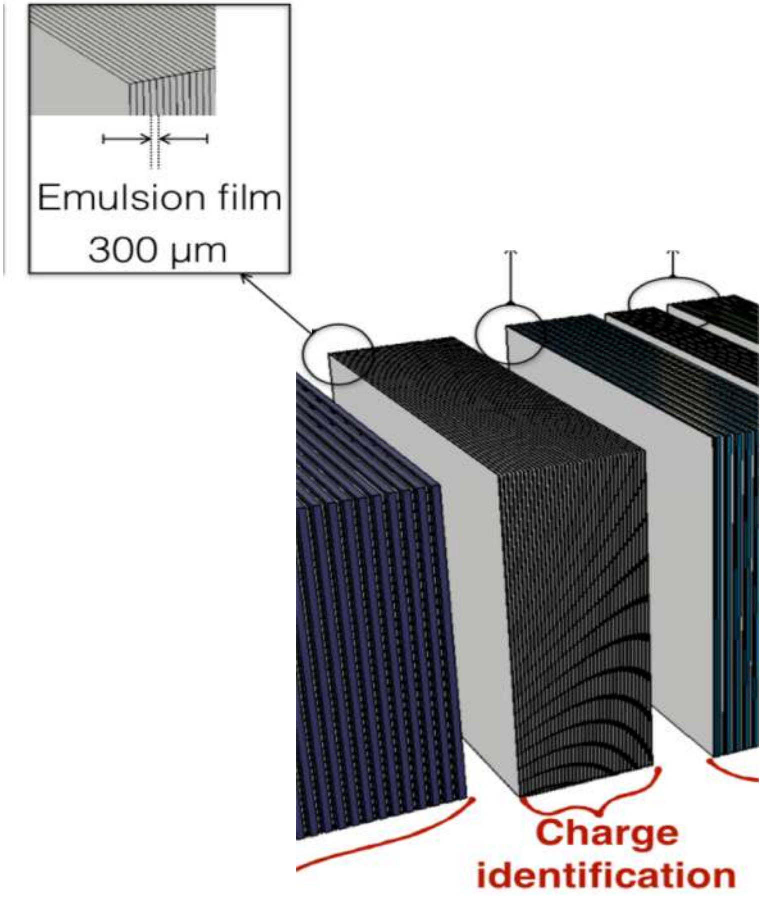


FOOT: Emulsion Spectrometer – Vertexing



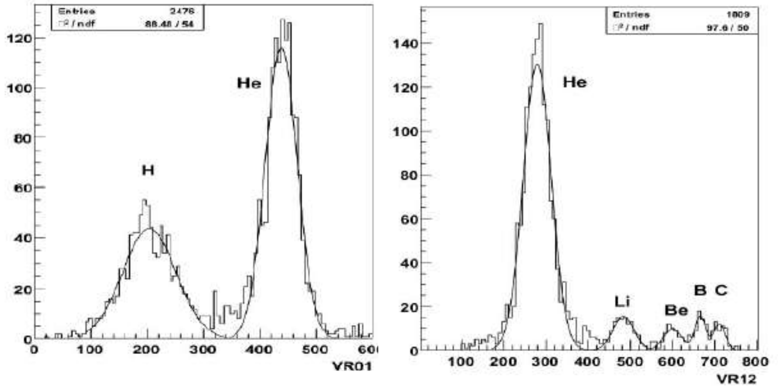
- ✓ Alternate target layers of C (1 mm) or C_2H_4 (2 mm) and emulsion films
- ✓ Vertex detector and particle tracking
- ✓ Chamber thickness defined by the interaction length → obtain a sufficiently high number of interactions
- ✓ About 30 % of Oxygen ions @200 MeV/n interacting in 6 cm C_2H_4 (~ 30 cells)
- ✓ About 30% of Carbon ions @ 700 MeV/n interacting in 8 cm C_2H_4 (~ 40 cells)
- ✓ **Detector structure optimized by FLUKA simulations**

FOOT: Emulsion Spectrometer – Charge identification



- ✓ Charge identification for low Z fragments (H, He, Li)
- ✓ To expand the dynamic range of the ionization response (hence the sensitivity) of nuclear emulsions a thermal treatment is applied
- ✓ Emulsions have a different thermal treatment according to its position in the elementary cell

- **R0:** Not thermally treated
  - ✓ **Sensitive to all particles**
- **R1**: 24 h at T1=**28°C** and RH = 95%
  - ✓ **Sensitive to Z ≥ 1**
- **R2**: 24 h at T2=**34°C** and RH = 95%
  - ✓ **Sensitive to Z ≥ 2**
- **R2**: 24 h at T2=**36°C** and RH = 95%
  - ✓ **Sensitive to Z ≥ 3**

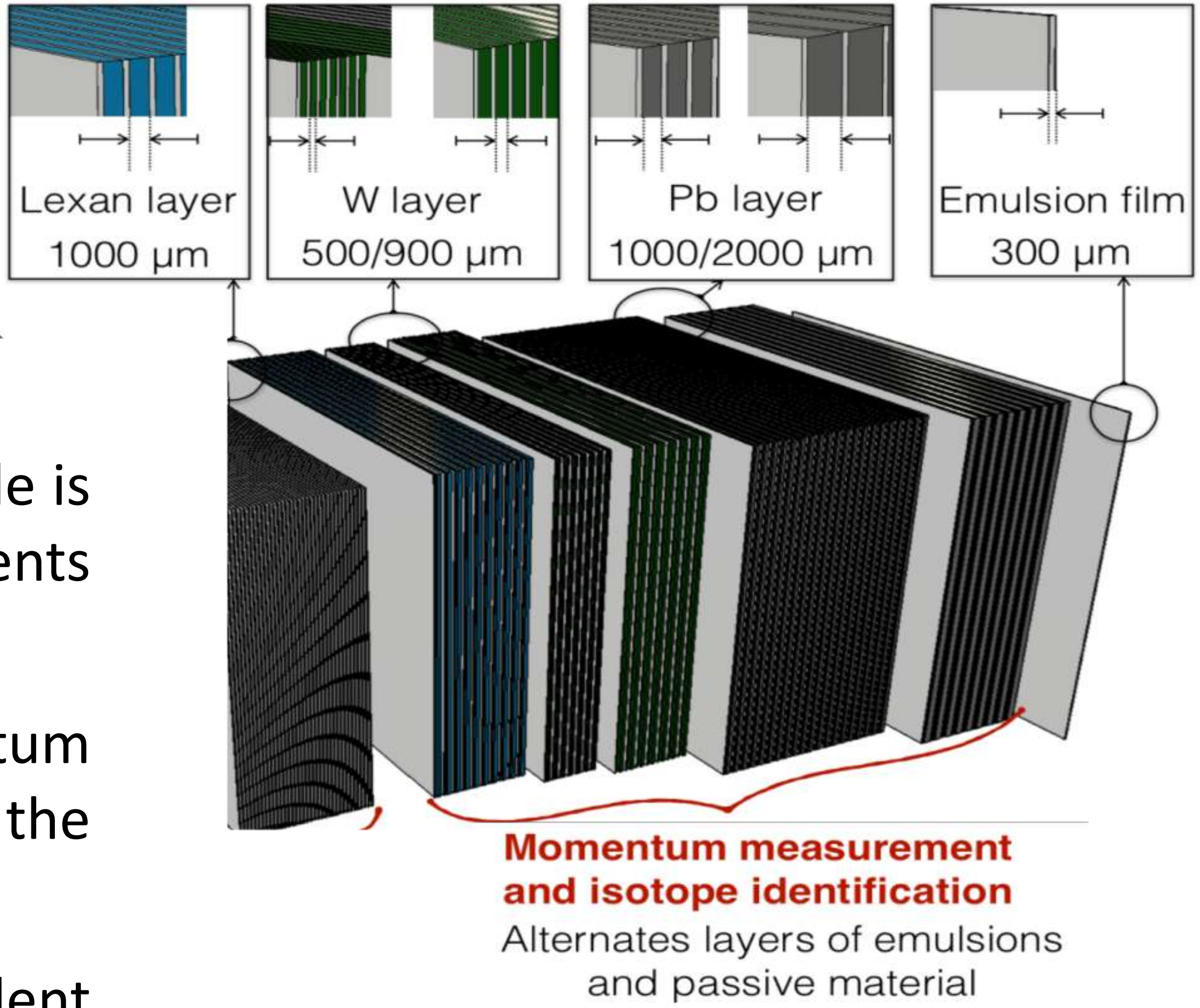


G. De Lellis et al. JINST 2, 2007, P06004

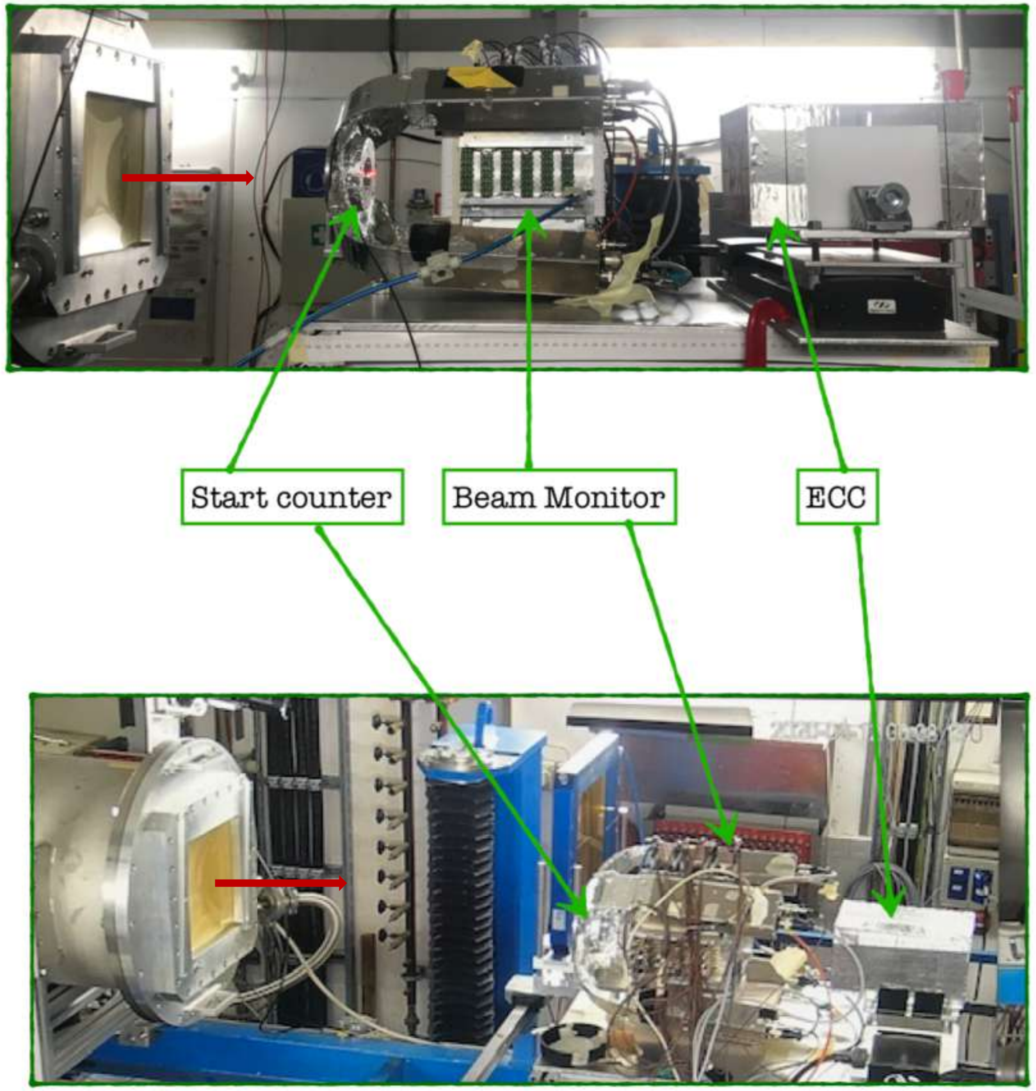
See: Giuliana Galati «Fragmentation measurements with the emulsion spectrometer of the FOOT experiment»

FOOT: Emulsion Spectrometer – momentum measuremets

- ✓ Emulsion films interleaved with passive layers with encreasing density (plastic and lead) (**30-50** passive layers)
- ✓ Dedicated to the momentum measurements by using the range method and the Multiple Coulomb Scattering (MCS)
- ✓ Range Method: the kinetic energy of the particle is estimated on the basis of the range measurements (NIST data)
- ✓ The MCS estimates the particles momuntum through the measurements of the position and the slope of the particles trajectory
- ✓ Isotopic identification: by means two indipendent methods for the momuntum measurements



FOOT: Emulsion spectrometer data taking

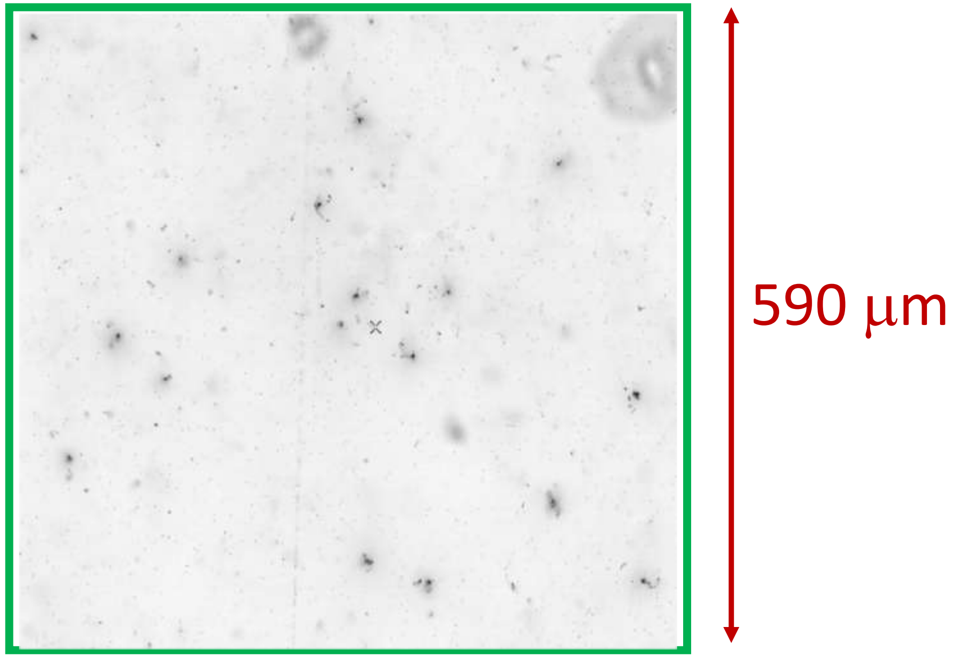


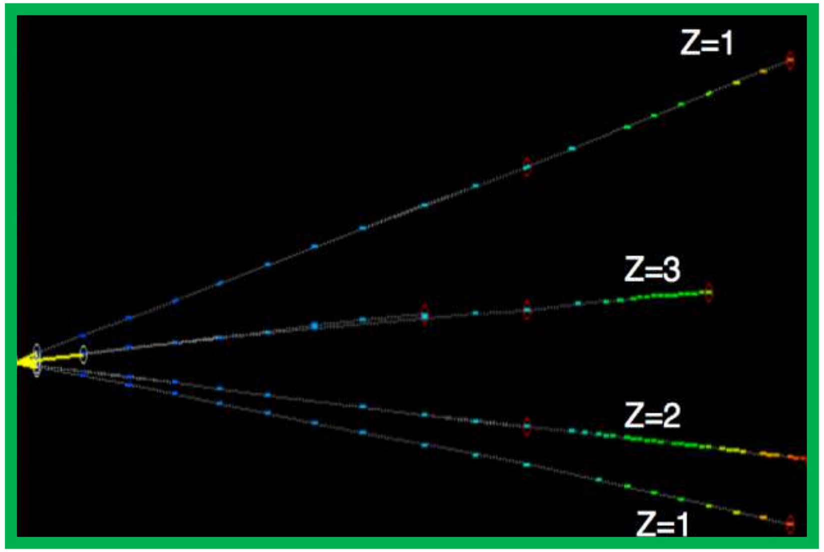
- GSI (March 2019)
- ^{16}O (200, 400 MeV/n)
- 4 ECC exposed (C and C_2H_4 target)
- Analysis partially completed

- GSI (February 2020)
- ^{12}C (700 MeV/n)
- 2 ECC exposed (C and C_2H_4 target)

FOOT: Emulsion Spectrometer – Analysis

^{16}O (200 MeV / n) passing through the nuclear emulsions





^{16}O (200 MeV / n) on C_2H_4 target: Vertex reconstruction

See: Giuliana Galati «Fragmentation measurements with the emulsion spectrometer of the FOOT experiment»

Conclusions

- Target fragmentation and beam are ”hot” topics in Charged Particle Therapy and Space Radioprotection

- The FOOT detector will measure both target fragmentation in proton therapy and projectile fragmentation in charged particle therapy (He, C and O); energy of space radioprotection interest will be also investigated

- The FOOT experiment has done the data taking with the emulsion spectrometer in April 2019 e February 2020 at GSI (^{16}O @ 200 and 400 MeV/n, ^{12}C @ 700 MeV/n); first results on charge identification with the emulsion spectrometer will be published soon

- FOOT electronic detector first overall test in December 2020 at CNAO

FOOT collaboration

http://web.infn.it/f00t/index.php

- **10 INFN sections/labs & most of the funding**
- Nagoya University (Japan), GSI (Germany) Aachen University (Germany), IPHC Strasbourg (France), CNAO (Italy)
- **More than 80 researchers, 60% permanent, 40 FTE**