Nuclear Emulsions in the FOOT experiment

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

An experiment for the measurement of nuclear fragmentation cross sections for Particle Therapy

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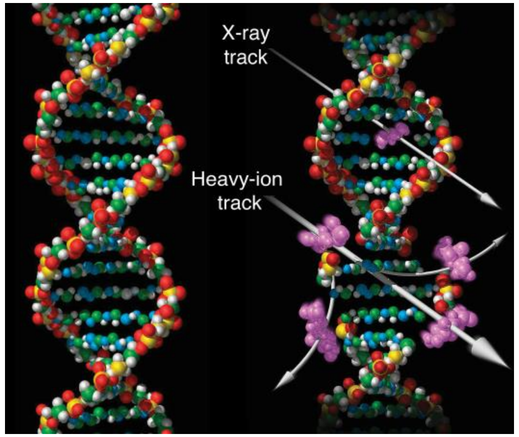
for the FOOT Collaboration

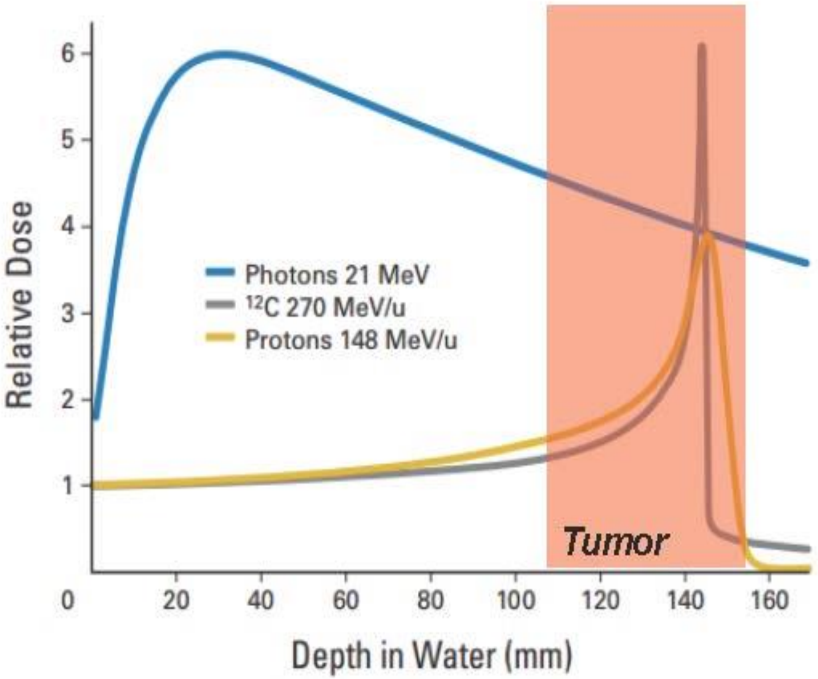
Second International Workshop on Nuclear Emulsions
for Neutrino Studies and WIMP Search
Anacapri 1rt June 2018

Charged Particle Therapy



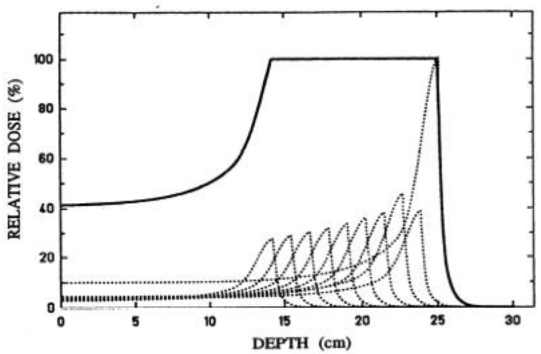
- Radiotherapy is based on the use of ionizing radiation to kill the cancer cells, by damaging the DNA chain.

- 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 normal tissue**
- ✓ 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

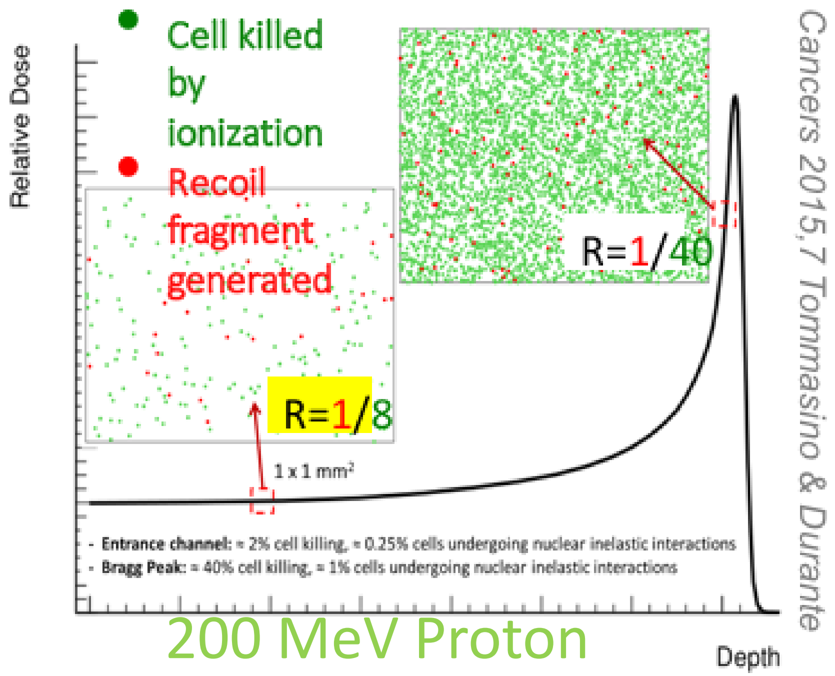
Target fragmentation

- 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)

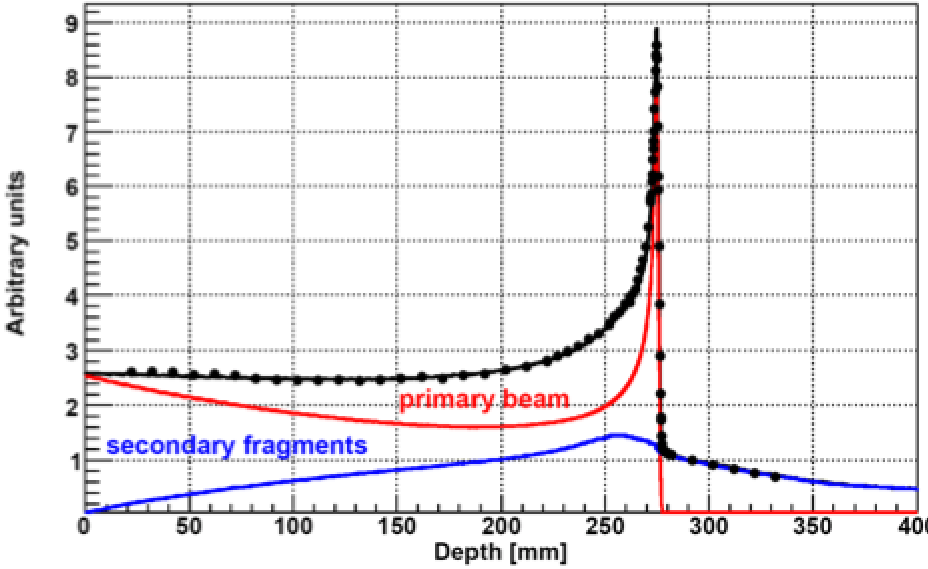
Charged particle

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



Measurements of nuclear fragmentation cross sections useful to develop a new generation of biologically oriented Treatment Planning Systems for proton and ion 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 founded by INFN in 2017

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%)

- 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

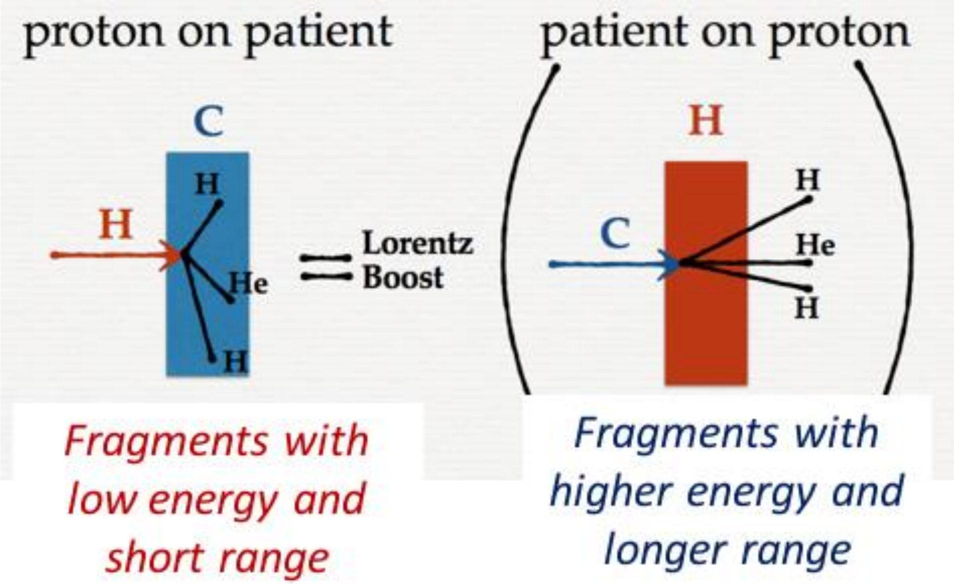
✓ Experimental apparatus: electronic detector and emulsion spectrometer

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)

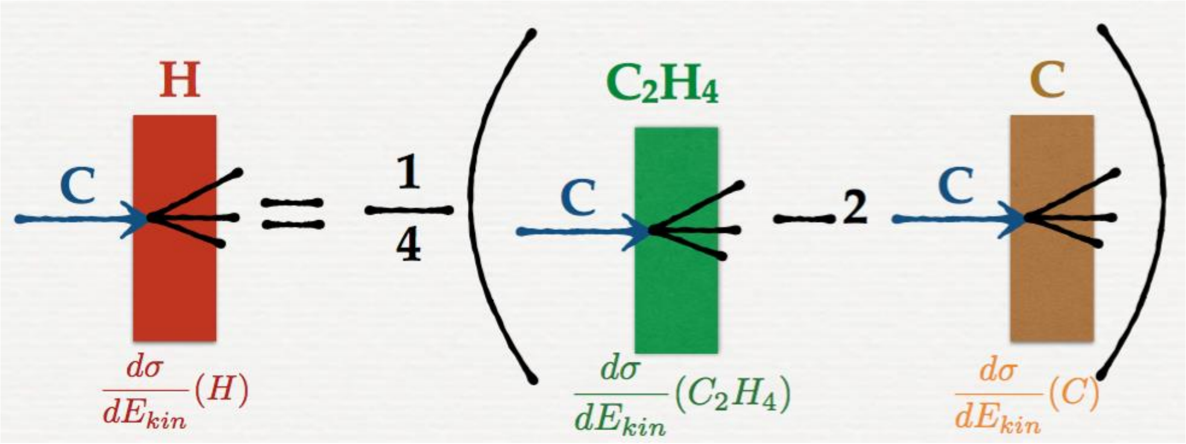
- by applying the Lorentz transformation (well known β) it is possible to switch from the ***lab. frame*** to the ***patient frame***

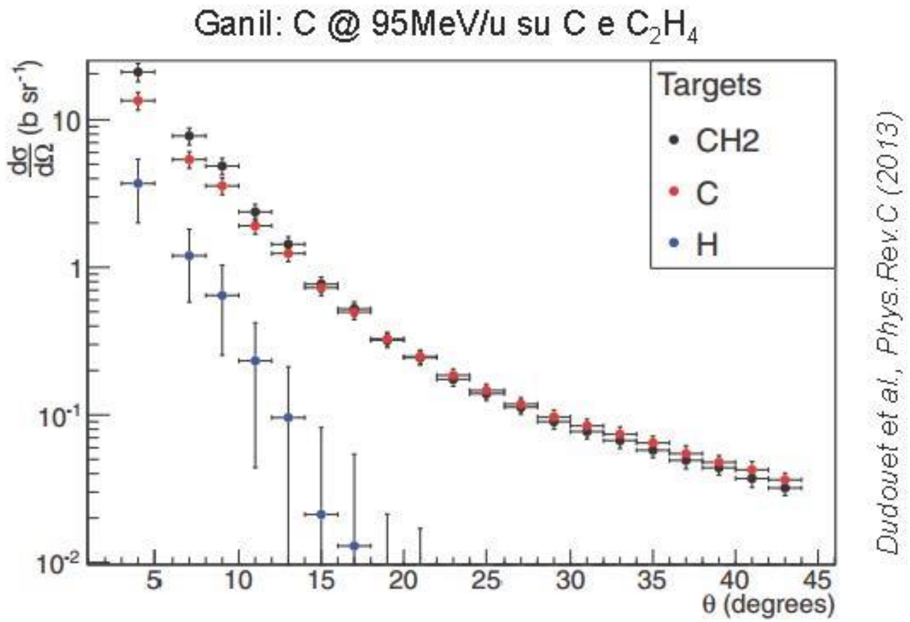
Requirements: the fragment direction must be well measured in the lab. frame to obtain the correct energy in the patient frame

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

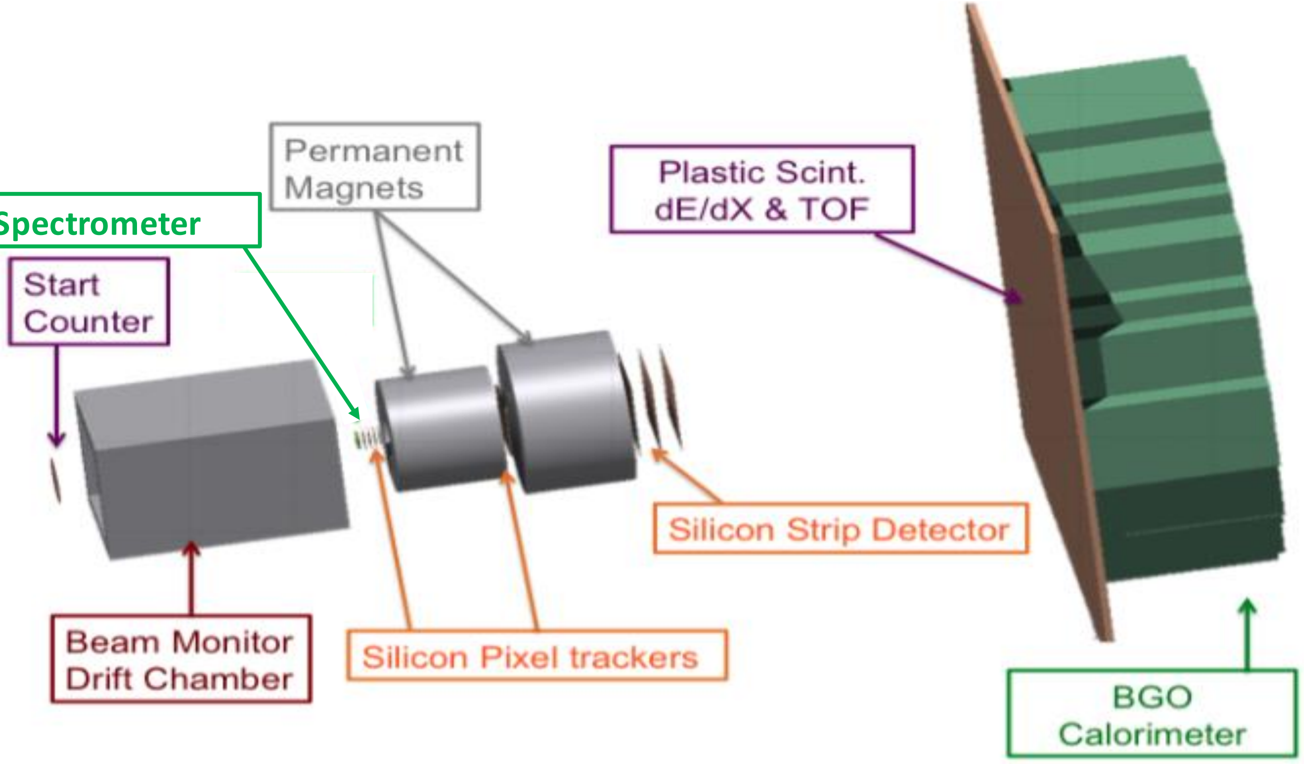
FOOT Detector

Design Solution to develop a "table top" detector (< 2 m long):

❖ electronic detector optimized for fragments with $Z \geq 3$ and angular acceptance ± 10°
❖ emulsion spectrometer detecting light charged fragments at large angle (up to 70°)

Required performances

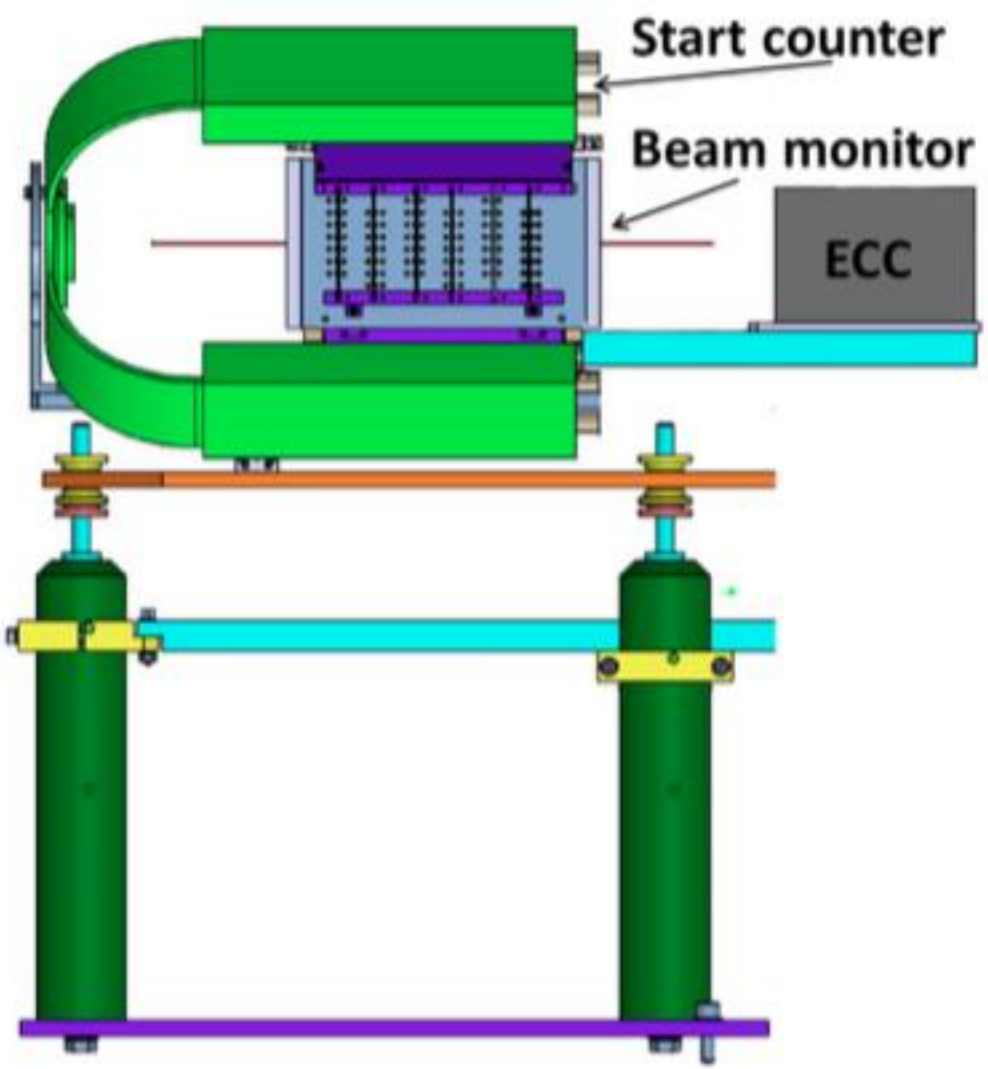
- $\Delta p/p \sim 5\ \%$
- Δ TOF ~ 100 ps
- $\Delta E_{kin} / E_{kin} \sim 2\ \%$
- $\Delta(dE)/dE \sim 2\ \%$



Electronic detector

Sub-detector	Main features	
Start counter	Plastic scintillator 250 µm	Start 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: Dp/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: Emulsion spectrometer

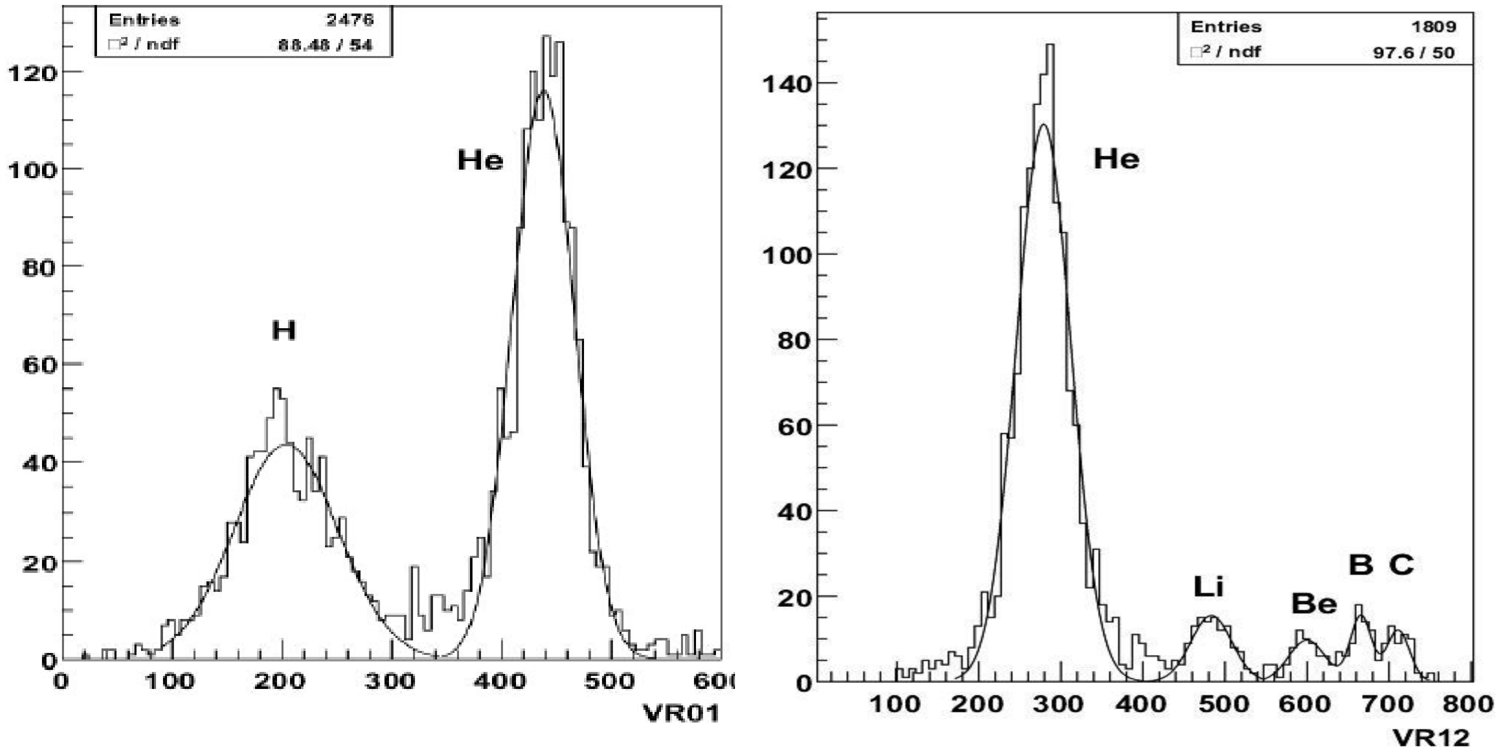


- It will measure fragments as protons, deuterons, He and Li emitted within a wider angular aperture (up to 70°) with respect to heavier nuclei
- Detector based on the concept of Emulsion Cloud Chamber – **ECC**
- The measurement setup will integrate the ECC with the start counter and the beam monitor of the electronic detector

FOOT Detector: Emulsion Spectrometer

Istituto Nazionale di Fisica Nucleare

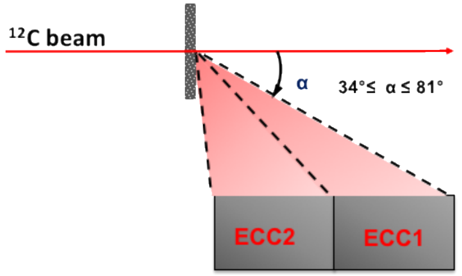
- The emulsion technique has been already exploited to study the fragmentation of Carbon ions in polycarbonate: identification of the secondary nuclei produced by fragmentation of 400 MeV/n ^{12}C can be achieved with high significance

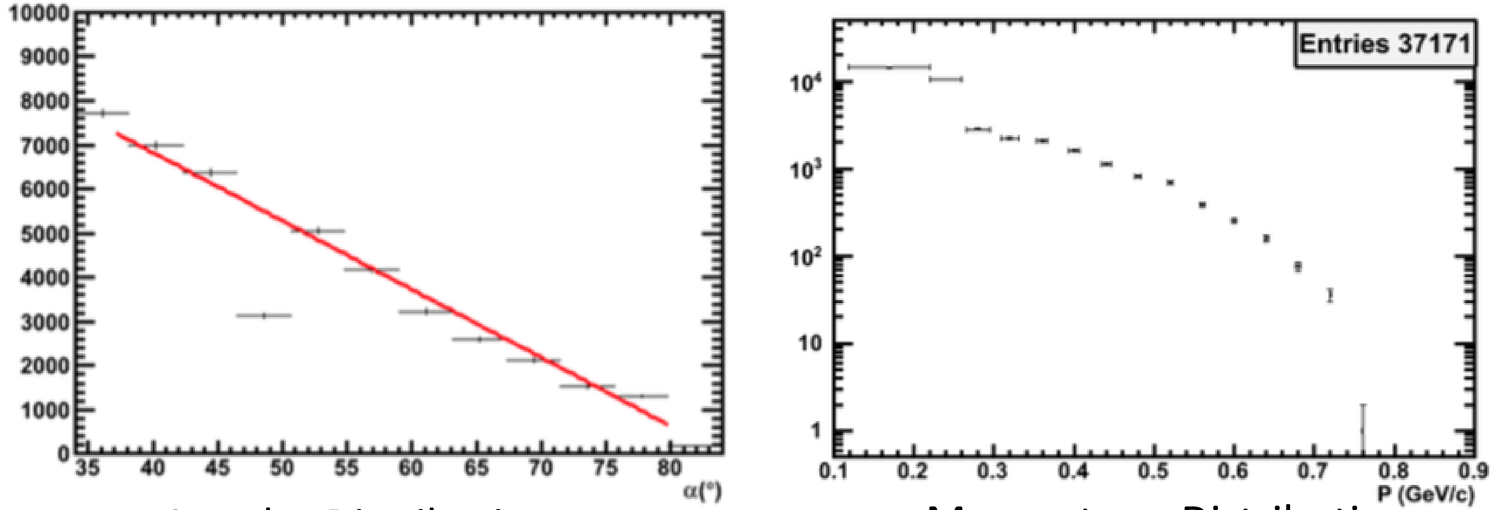


G. De Lellis et al. JINST 2, 2007, P06004

FOOT Detector: Emulsion Spectrometer

- Other study: large angle fragmentation and momentum measurements of a 400 MeV/n ^{12}C beam impinging on a composite target has been performed by using two ECC detectors to cover a range from 34° to 81° with respect to the beam axis



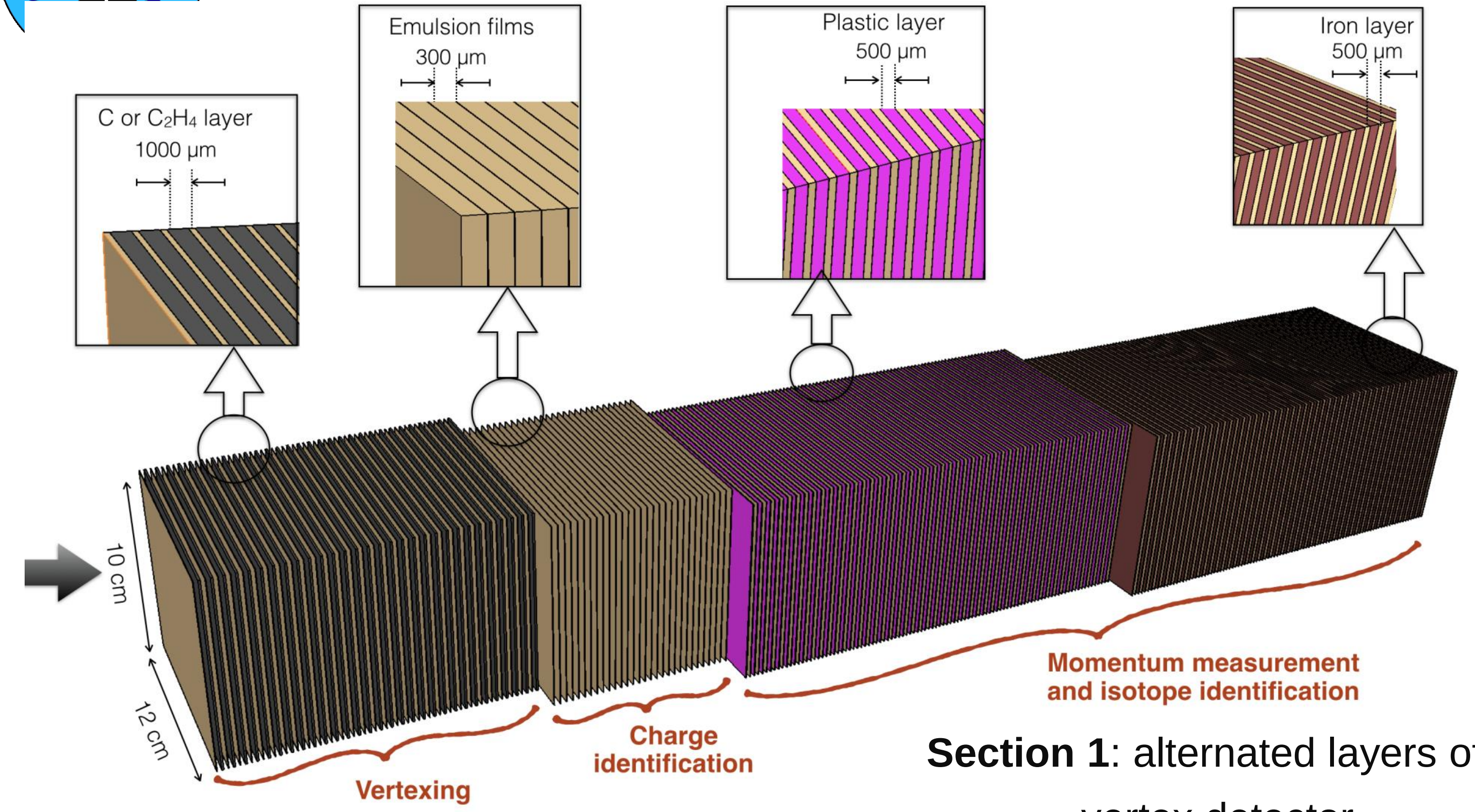


Angular Distribution

Momentum Distribution

A. Alexandrov et al., JINST 12 (2017) P08013

FOOT: Emulsion Spectrometer Layout



Section 1: alternated layers of emulsions and target (C/C_2H_4)

- vertex detector

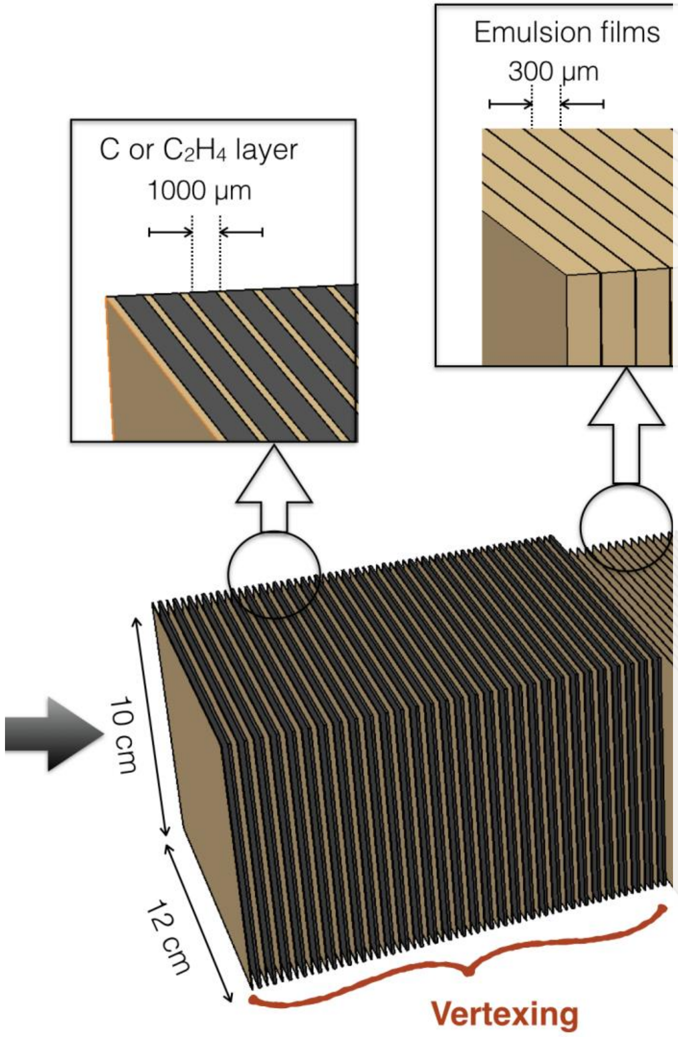
Section 2: made of emulsion films only

- charge identification for low Z fragments (H, He, Li)

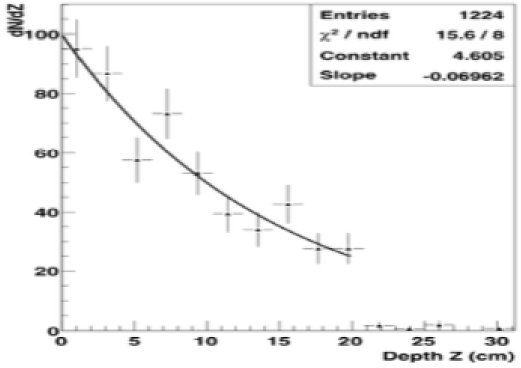
Section 3: alternated layers of emulsions and passive materials (plastic and lead)

- Momentum measurement by range method and Multiple Coulomb Scattering (MCS)
- Isotopic identification

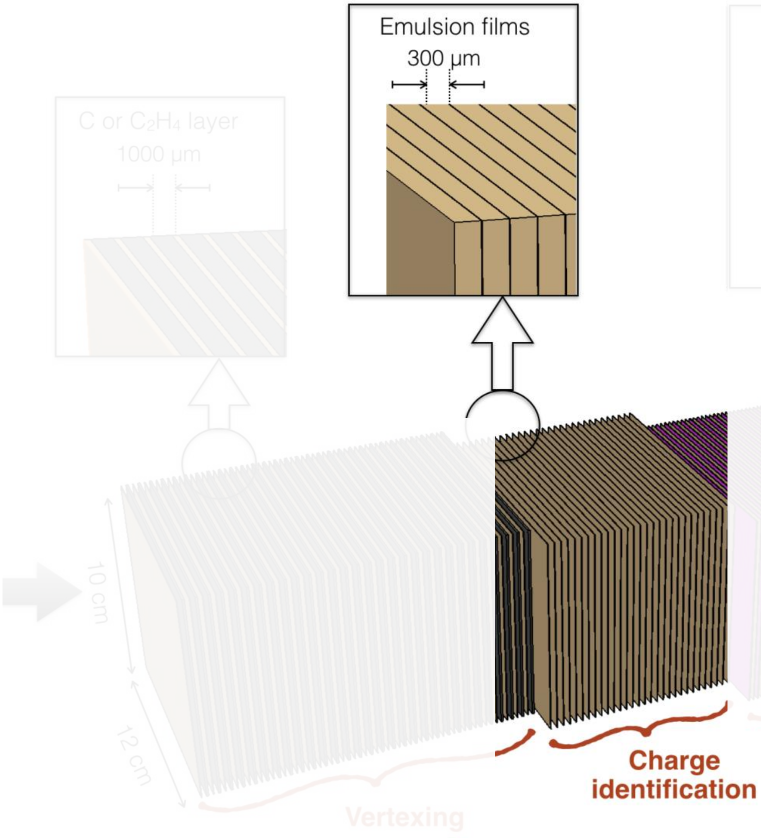
FOOT: Emulsion Spectrometer – section 1



- ✓ Alternate target layers of C or C_2H_4 (1 mm) and emulsion films
- ✓ Vertex detector and particle tracking
- ✓ Chamber thickness defined by the interaction length → obtain a sufficiently high number of interactions
- ✓ 20% of Carbon ions interacting in 3 cm Lexan (G. De Lellis, Nucl. Phys. A Vol. 853, 2011)
- ✓ Total length ~ 30 cells = 39mm (**30** films)



FOOT: Emulsion Spectrometer – section 2



Cell	3	9	13	20
$H-He$	3.3	4.5	6.5	
$He-Li$	2.6	3.9	4.3	5.0
$Li-Be$	1.7	2.7	3.1	3.5

✓ Charge identification for low Z fragments (H, He, Li)

✓ Emulsion will have a different thermal treatment according to its position in the elementary cell:

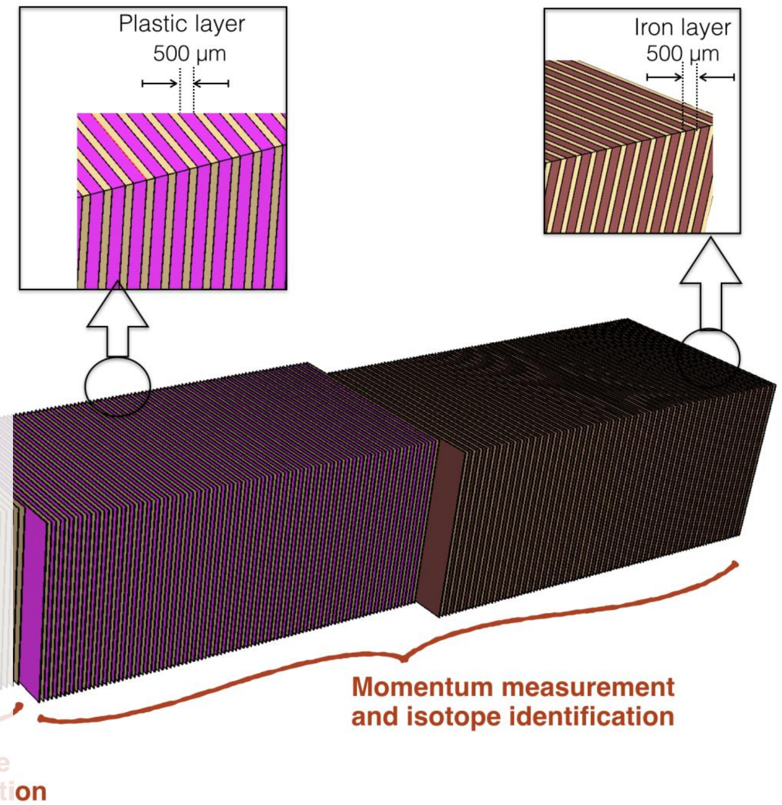
- **R0:**
  - Not refreshed
  - **Sensitive to m.i.p.**
- **R1:**
  - Appropriate refreshing for protons
  - **Sensitive to protons**
- **R2:**
  - Appropriate refreshing for He
  - **Sensitive to He**

To obtain a 3σ He-Li separation, 9 cells are necessary (**27 films**)

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

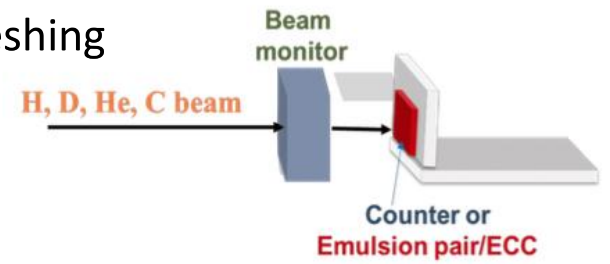
FOOT: Emulsion Spectrometer – section 3

- ✓ Emulsion films interleaved with passive layers (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

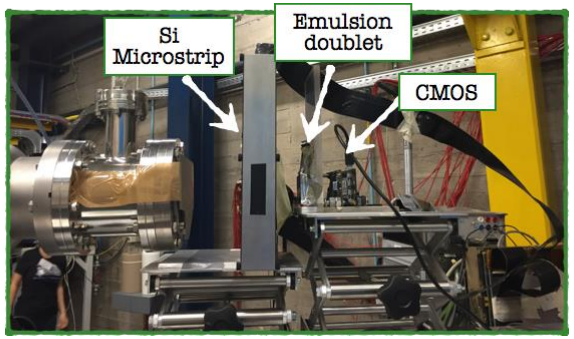


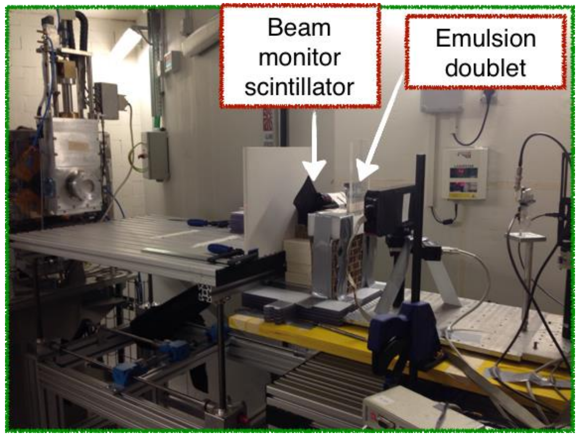
FOOT: Emulsion Spectrometer – test beam

- New nuclear emulsions, produced by Nagoya group, have been tested to assess the refreshing procedures and to define the correct working point for the particle identification (Z<3)

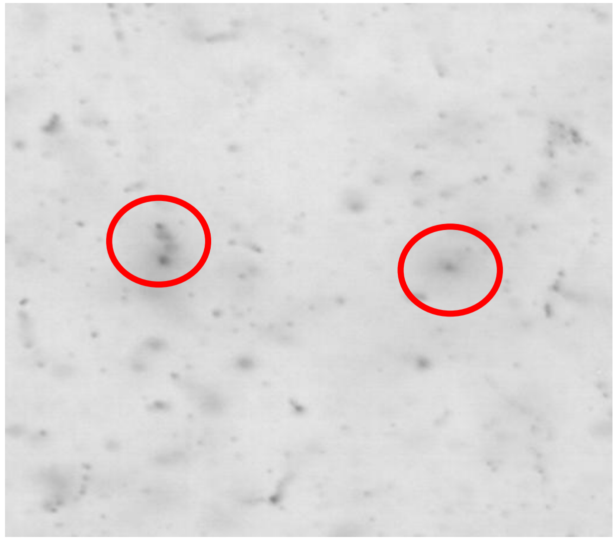


- LNS test beam with 80 MeV proton, deuterium, helium and carbon
  - ✓Exposure of nuclear emulsion to calibrate the response at different ionizing beam (charge identification)
  - ✓Exposure of two Emulsion Cloud Chambers for the isotopic identification
- Proton Radiotherapy Center in Trento test beam with 50, 200 and 80 MeV

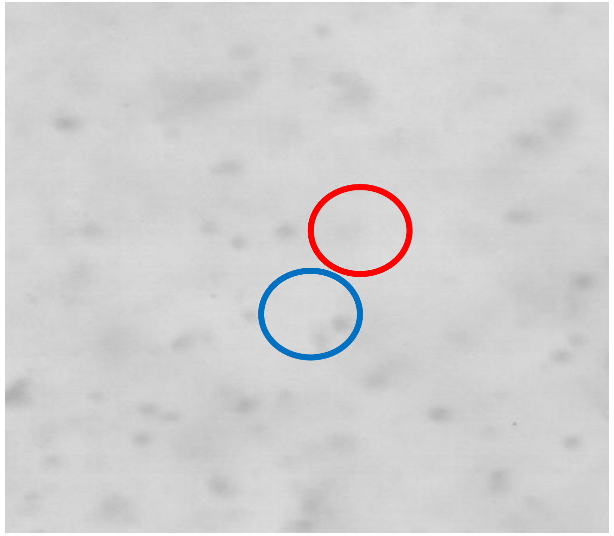




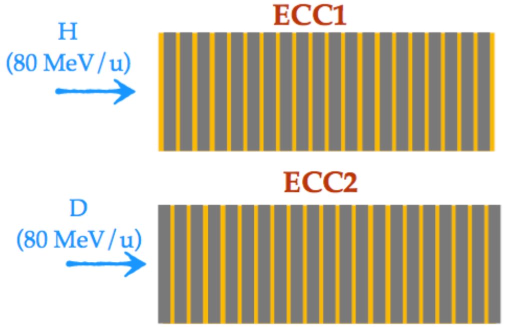
C (80 MeV)



H (80 MeV)

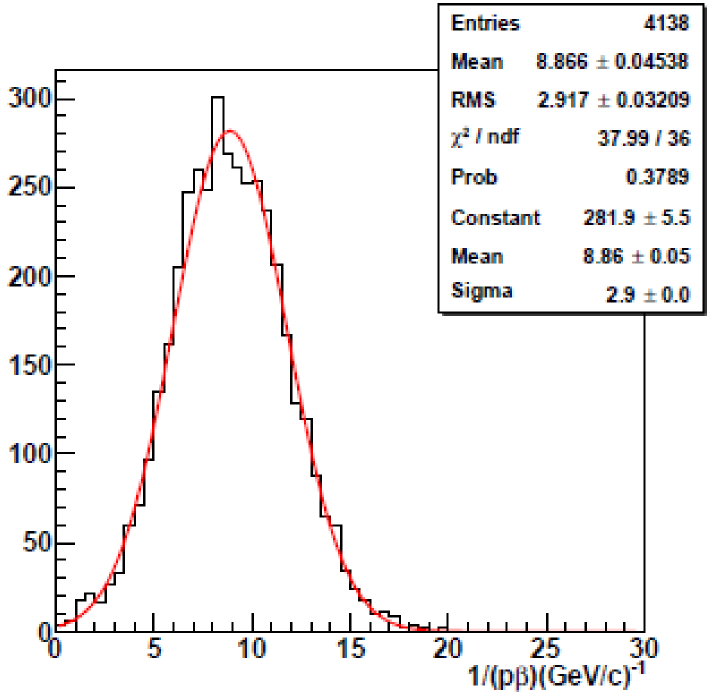


FOOT: Emulsion Spectrometer – test beam

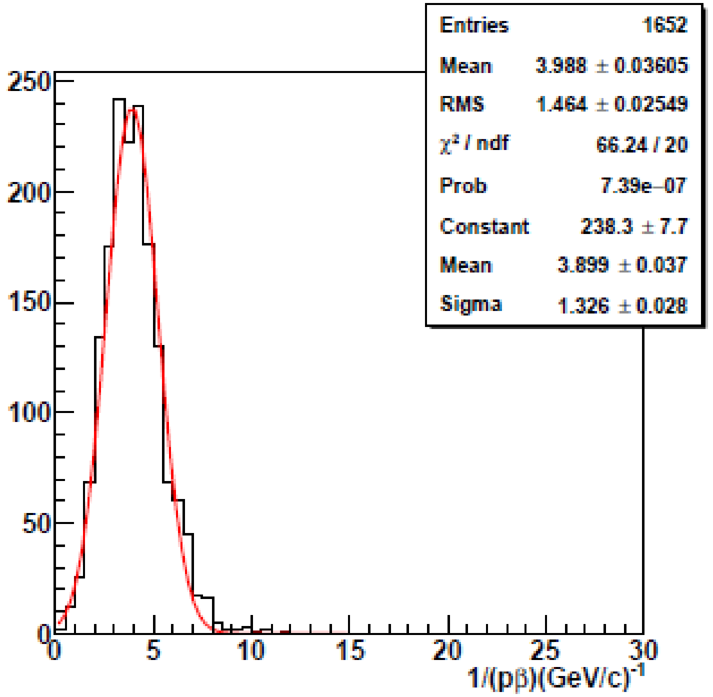


- Test with data an algorithm for isotopic identification
- Exposure of two ECC to H and D @ 80 MeV/n
- ECC: 21 nuclear emulsions spaced by 20 stainless steel layers (0.5 mm thick, X_0 = 1.76 cm)

- Expected 1/pβ: 0.0068 MeV^{-1}
- Measured 1/pβ: 0.008±0.003 MeV^{-1}



- Expected 1/pβ: 0.0034 MeV^{-1}
- Measured 1/pβ: 0.004±0.002 MeV^{-1}



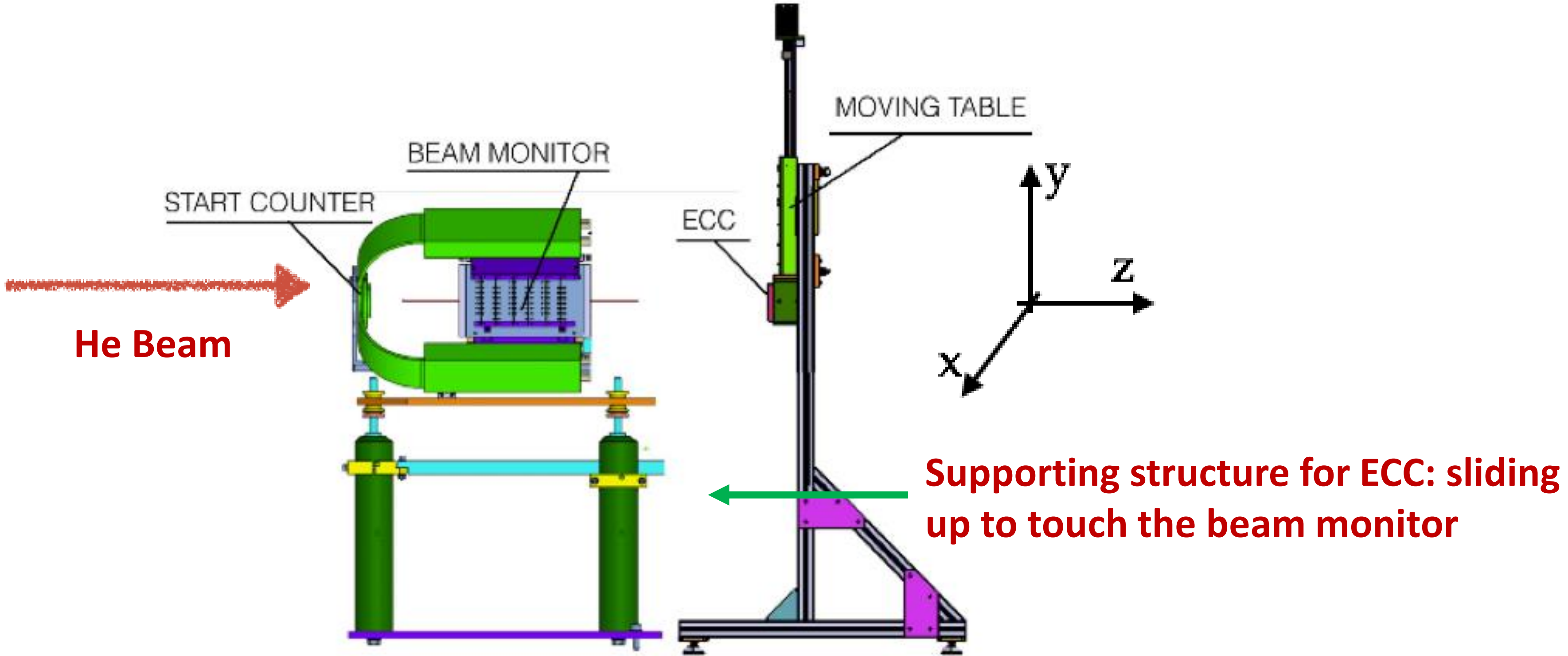
- Preliminary estimation of **pβ** from OPERA algorithm [1] assuming the fitted track not to lose energy during its path (10 layers)
- Combination of **p** measurement by range and MCS (dependent on the mass) provides **isotope identification**

[1] N. Agafonova et al. Momentum measurement by the Multiple Coulomb Scattering method in the OPERA lead emulsion target. New J. Phys., 14:013026, 2012

FOOT: Emulsion Spectrometer – first run

- Planned for November 2018 at GSI
- He @ 700 MeV/n on C target
- ECC structure: almost 110 nuclear emulsions are needed

- The emulsion setup will be XY stage remotely controlled to avoid pile-up (particle density < 10 particles/mm^2)
- The start counter and the beam monitor will provide a feedback (impact point and rate) to the stage movement



Conclusions

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

- 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 been approved and funded by INFN for 2018-2021

- FOOT emulsion spectrometer data taking in November 2018 (GSI)

- Whole detector data taking foreseen in early 2020 (CNAO/Heidelberg/GSI)

FOOT collaboration

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

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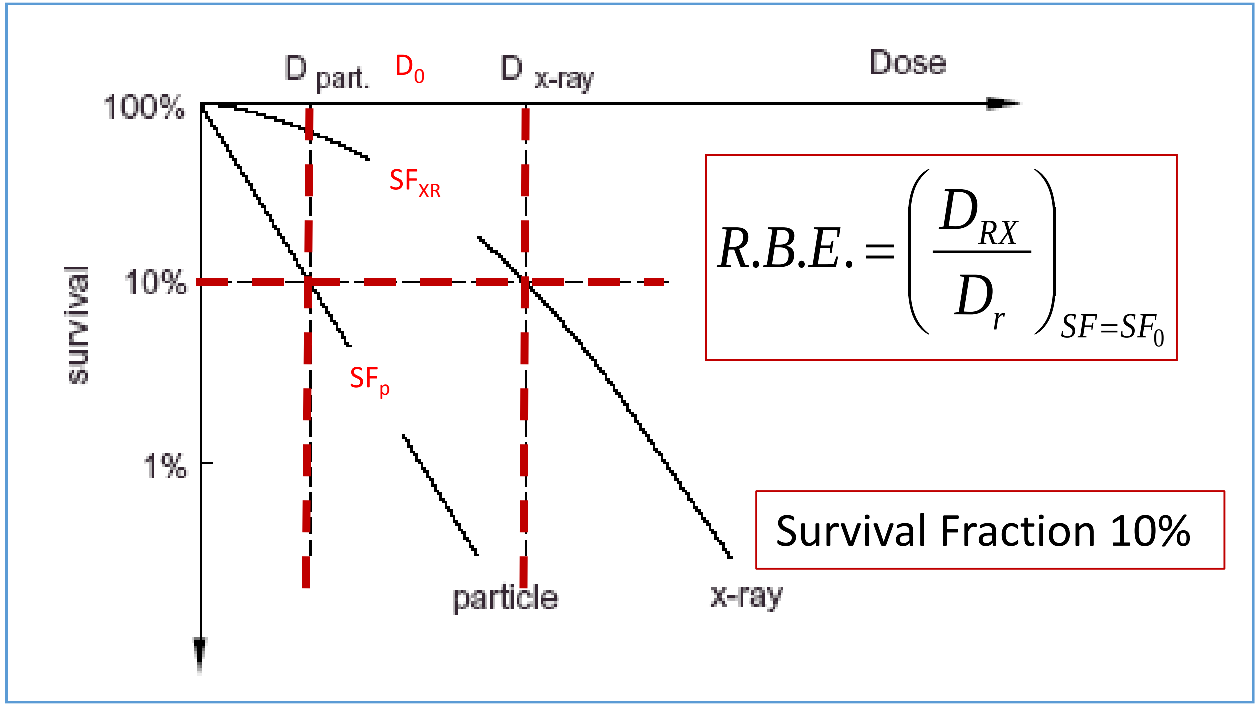
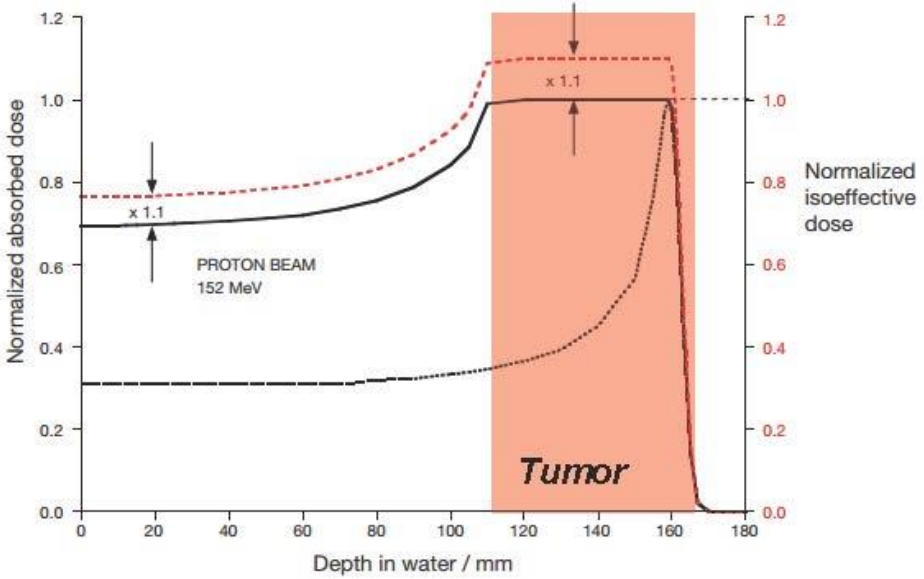
Back-up slides

RBE: Relative Biological Effectiveness



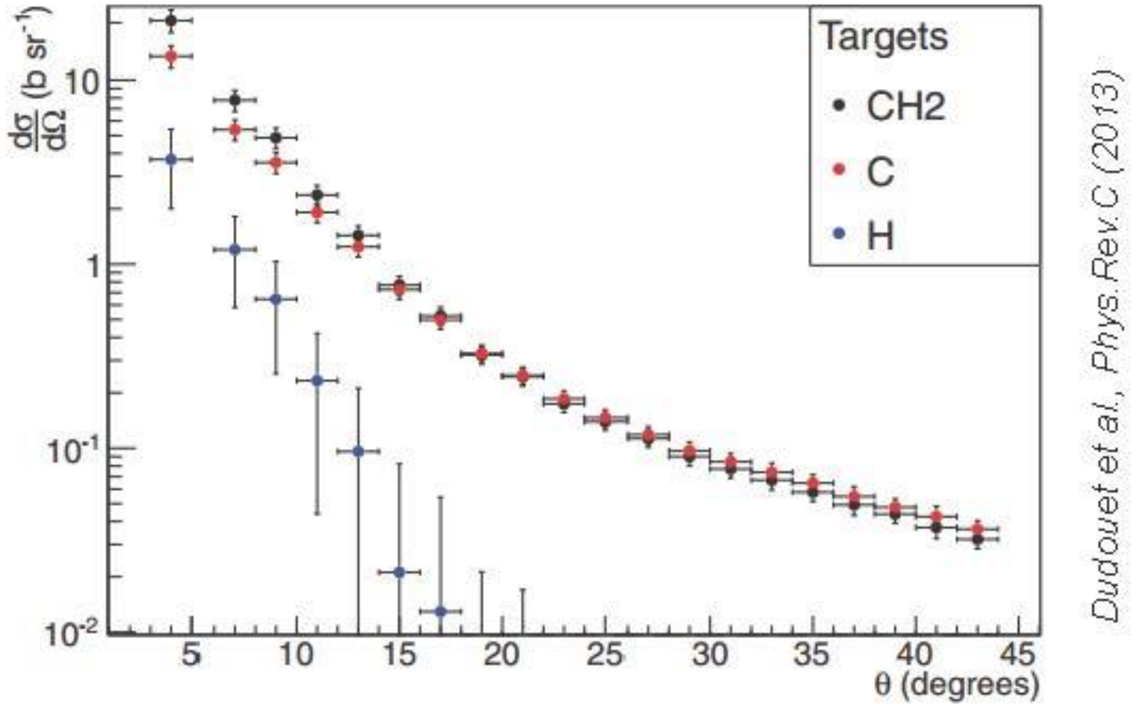
$$D_{BIO} = R.B.E.* D_{phys}$$



In clinical practice protons RBE is a constant equal to 1.1, but experimental data show that RBE varies with Linear Energy Transfer (LET)!

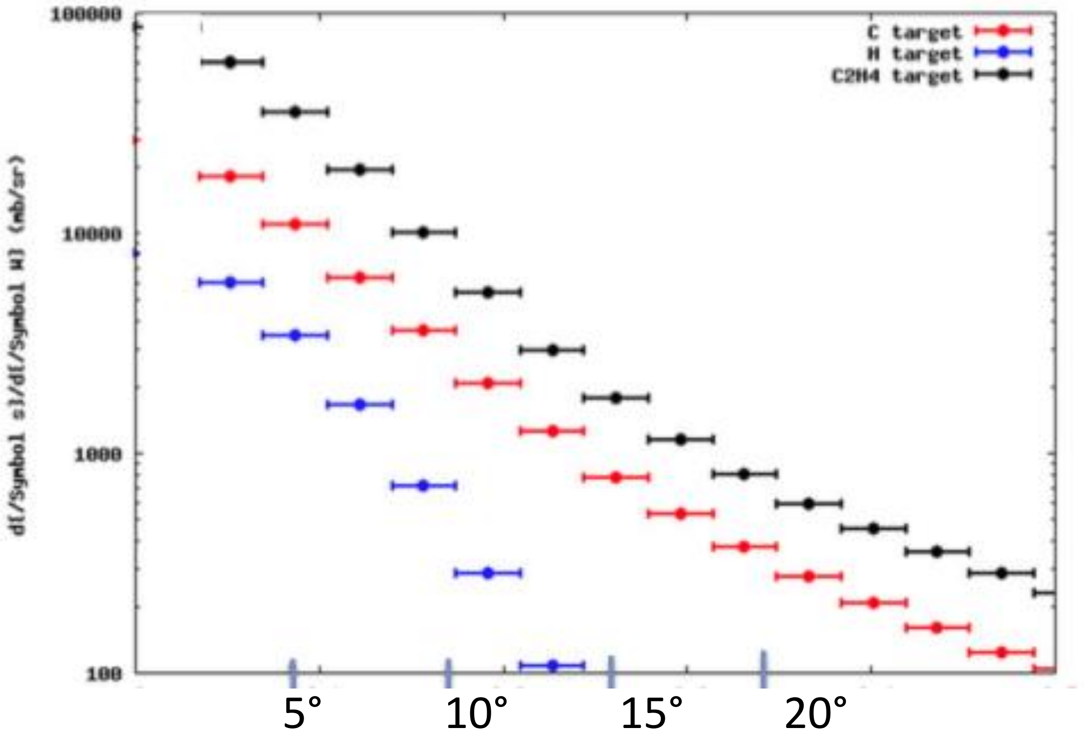
Double target strategy: preliminary results

C @ 95 MeV/n on C and C_2H_4



➢GANIL experimental data

C @ 200 MeV/n on C and C_2H_4



➢Fluka simulation in the FOOT experiment

FOOT Detector: redundancy

1. Simultaneous determination of β and p respectively from the TOF and the magnetic spectrometer:

$$A_1 = \frac{p}{U\beta c\gamma}$$ where $$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$ and U = 931.5 MeV (Unified Atomic Mass)

2. Simultaneous determination of β and E_{kin} respectively from the TOF and the calorimeter:

$$A_2 = \frac{K}{Uc^2(\gamma - 1)}$$

3. Simultaneous determination of p and E_{kin} respectively from the magnetic spectrometer and the calorimeter:

$$A_3 = \frac{p^2c^2 - K}{2\,U\,c^2 E_K}$$

FOOT Conceptual Design Report

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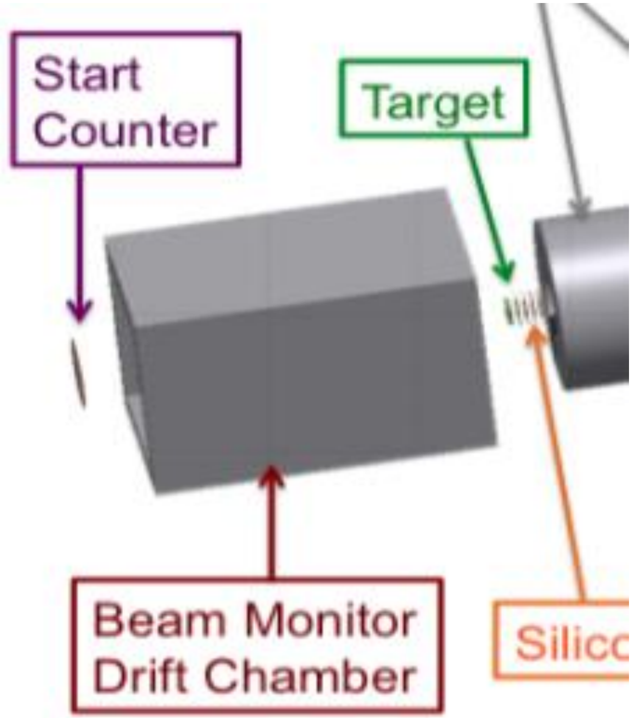
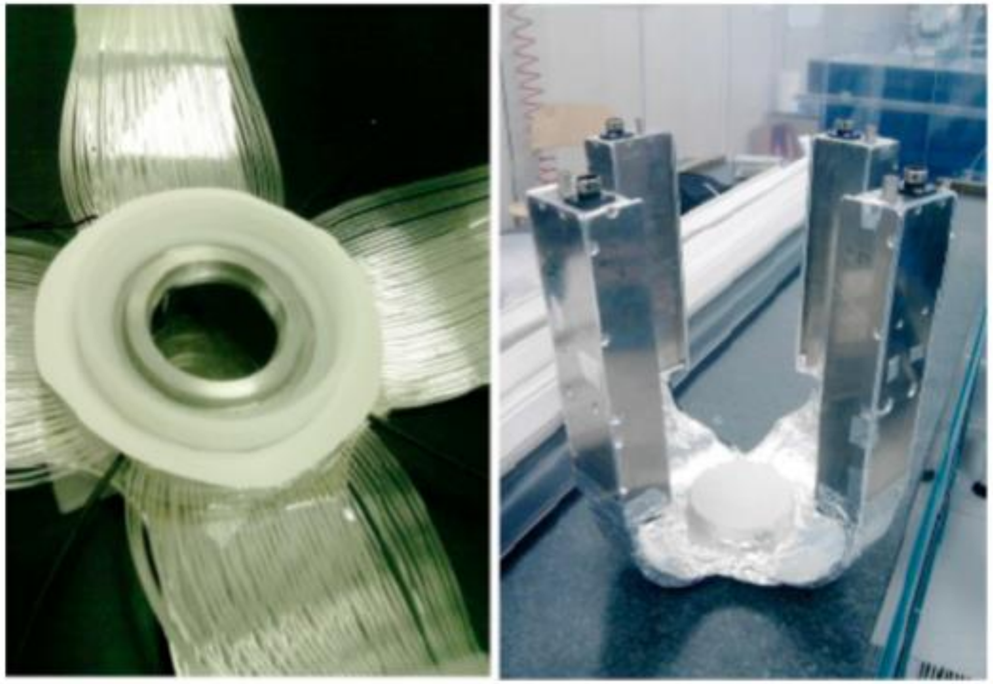
[r] *Università di Roma "Tor Vergata", Italy*
[s] *Università di Napoli "Federico II", Italy*
[t] *Università di Pisa, Italy*
[u] *Università di Bologna, Italy*
[v] *Università di Milano, Italy*
[w] *Università di Perugia, Italy*
[x] *Institut Pluridisciplinaire Hubert Curien (IPHC), Strasbourg, France*
[y] *GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*
[z] *CNAO, Italy*
[†] *RWTH University, Aachen, Germany*

FOOT Detector: upstream/target region

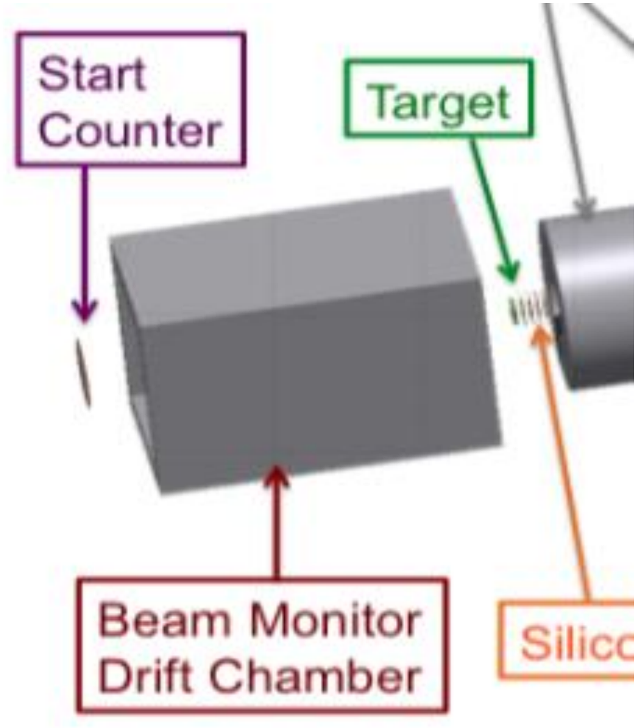


- **Start counter**: thin plastic scintillator (250 μm)
  - start signal of the TOF **(100 ps)**
  - counts primaries

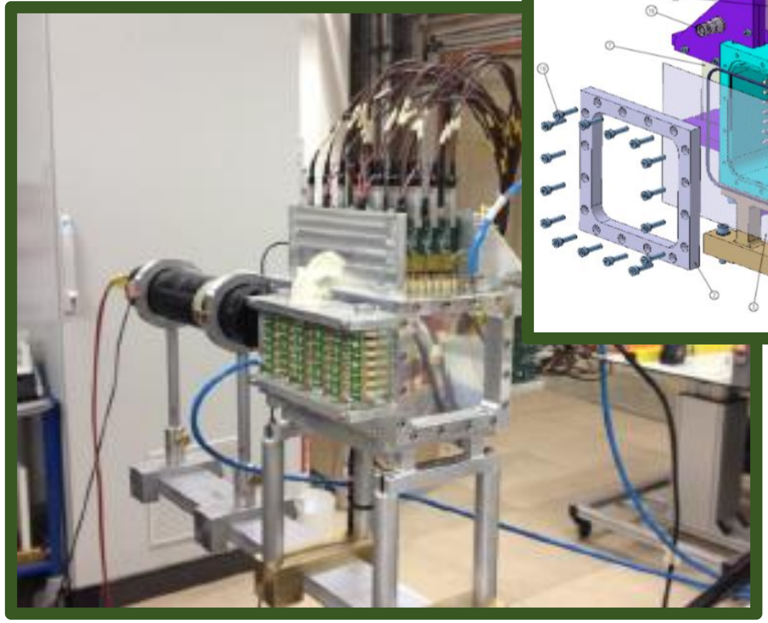


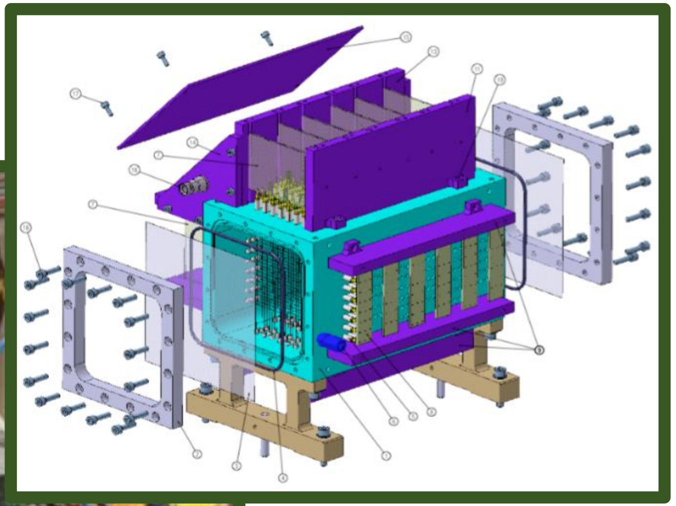
- scintillator foil and 160 optical fibers grouped in four different arms

FOOT Detector: upstream/target region

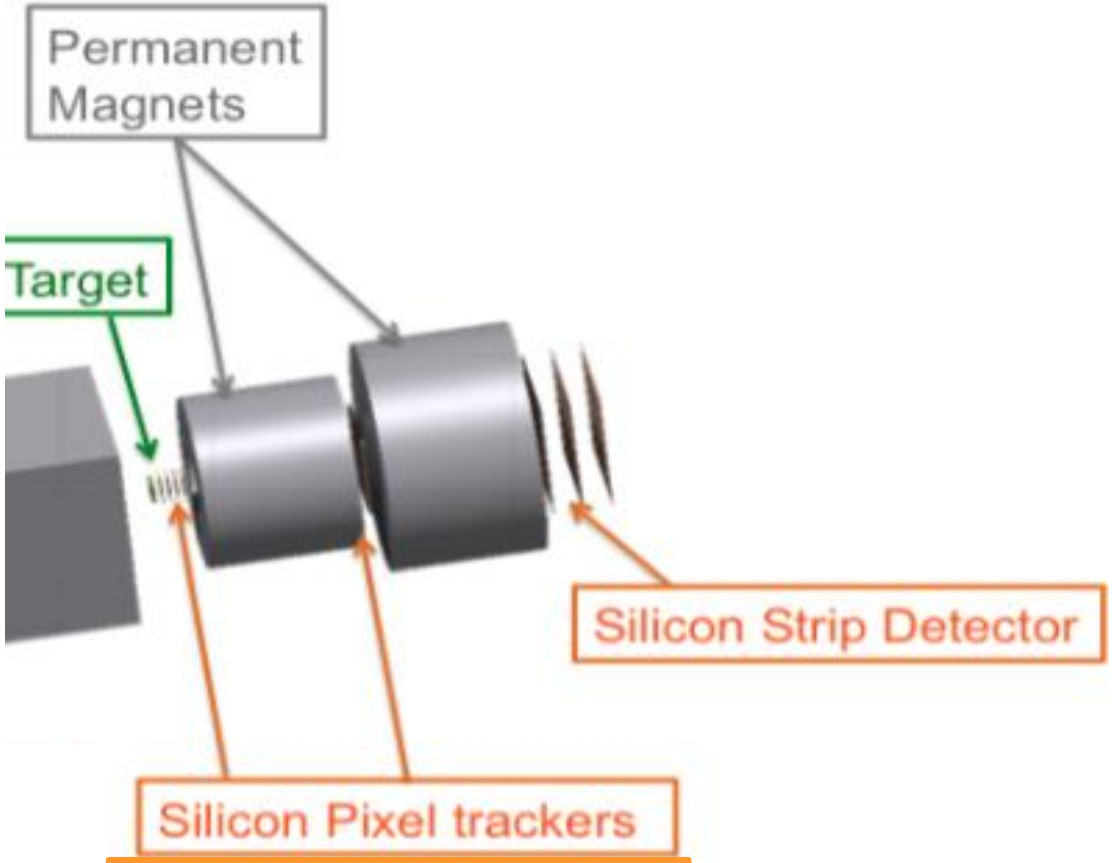


- **Beam monitor**: twelve layers of wires, with three drift cells per layer
- measure the direction and the position (spatial resolution ~140 μm) of the impinging beam on the target
- looks for fragmented primaries





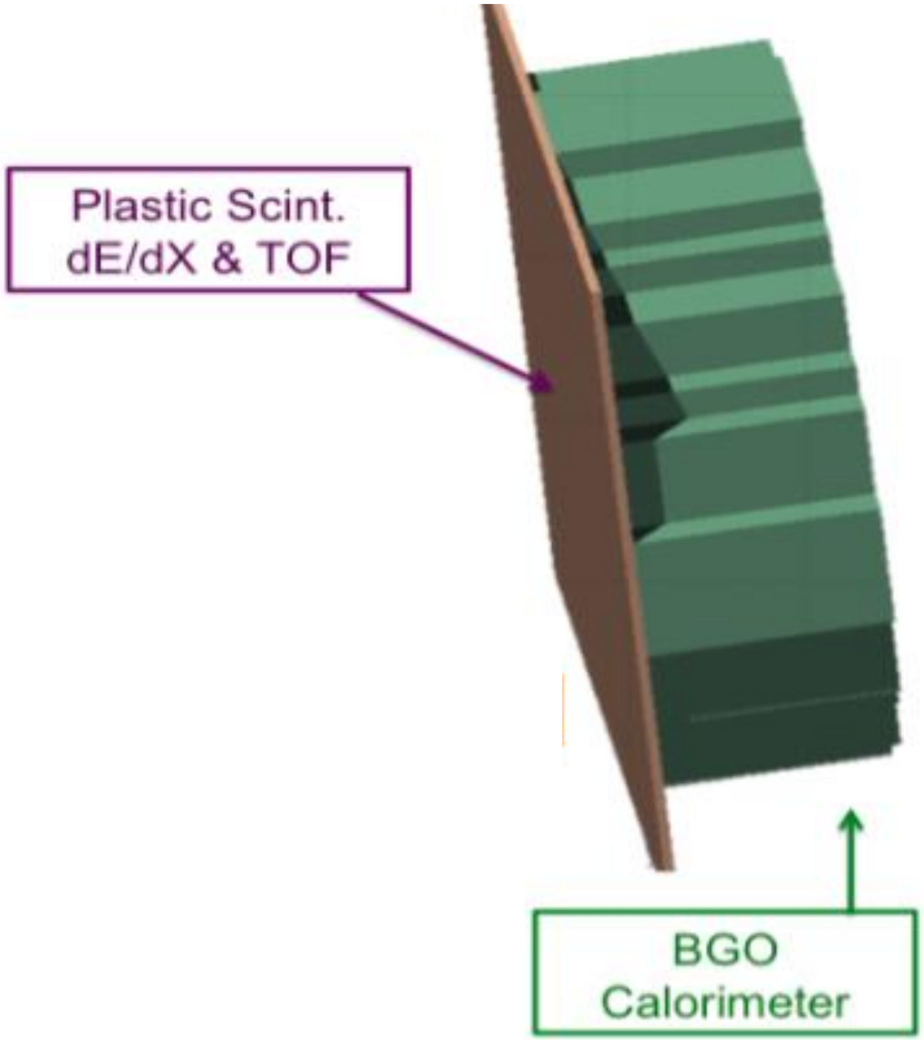
FOOT Detector: magnetic spectrometer



Vertex and Inner tracker

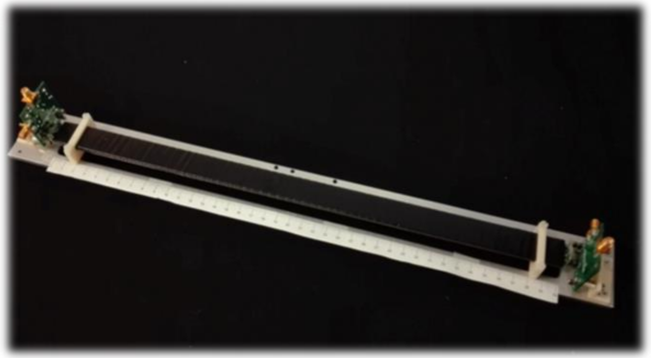
Target and vertex tracker

FOOT Detector: plastic scintillator & calorimeter



- Two orthogonal layers of 20 plastic scintillator rods (2 cm large and 40 cm long for a total area of 40×40 cm^2, tickness 3 mm)
  - the stop signal for the TOF measurement
  - the measurement of the energy loss ΔE to identity the charge of the fragments

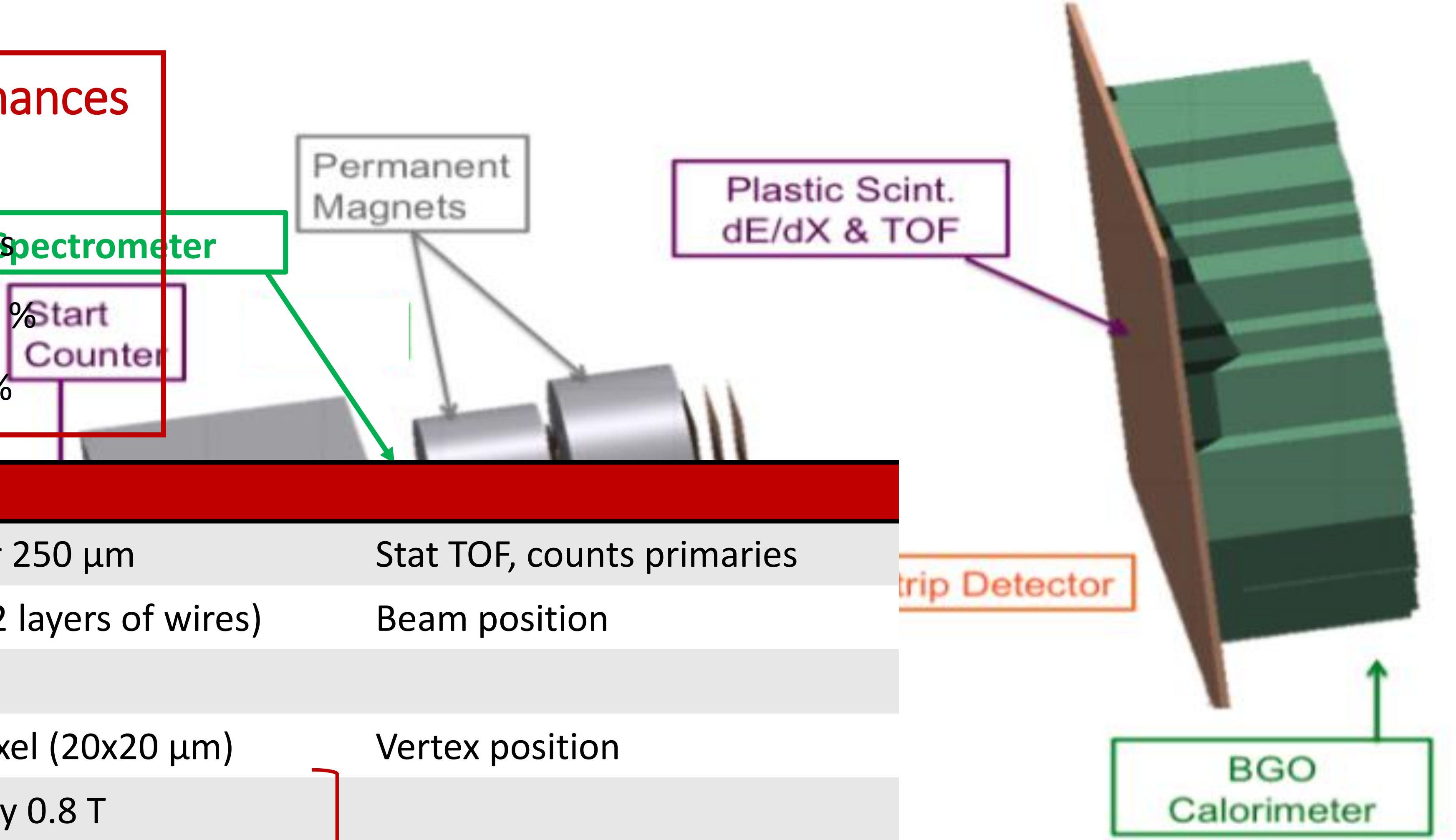
- The calorimeter will be formed by about 360 BGO crystals (2x2 cm^2 transverse size) covering a circular surface of about 20 cm radius
  - fragments kinetic energy



Plastic scintillator detector prototype

Required performances

- $\Delta p/p \sim 5\ \%$
- $\Delta\ TOF \sim 100$ ps
- $\Delta\ E_{kin} / E_{kin} \sim 2\ \%$
- $\Delta(dE)/dE \sim 2\ \%$



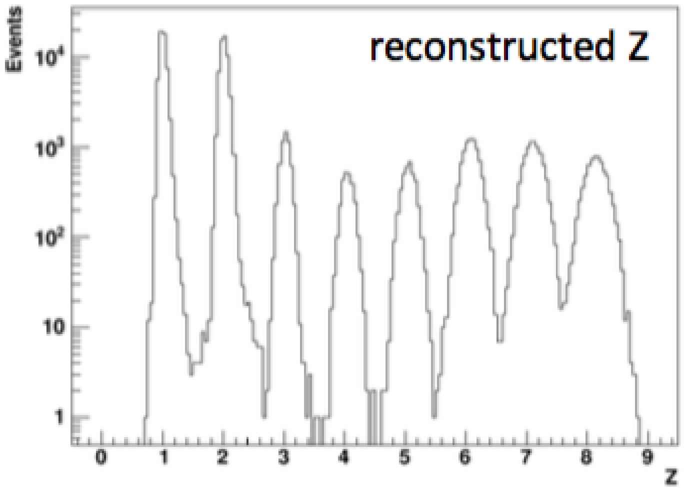
Sub-detector	Main features	
Start counter	Plastic scintillator 250 µm	Stat TOF, counts primaries
Beam monitor	Drift chamber (12 layers of wires)	Beam position
Target	C / C_2H_4	
Vertex	4 layers silicon pixel (20x20 µm)	Vertex position
Permanent Magnet	Halbach geometry 0.8 T	
Inner Tracker	2 layers silicon pixel (20x20 µm)	Magnetic spectrometer: $\Delta p/p$
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

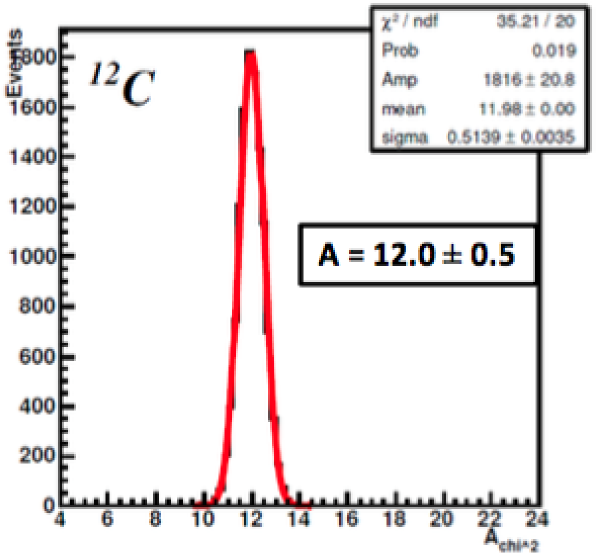
FOOT Detector: redundant measurements

- The Z fragments can be reconstructed by the Bethe-Bloch equation and by measuring the energy deposited in the scintillator detector

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

- The reconstructed Z resolution ranges from 2% (^{16}O) to 5% (^{1}H)

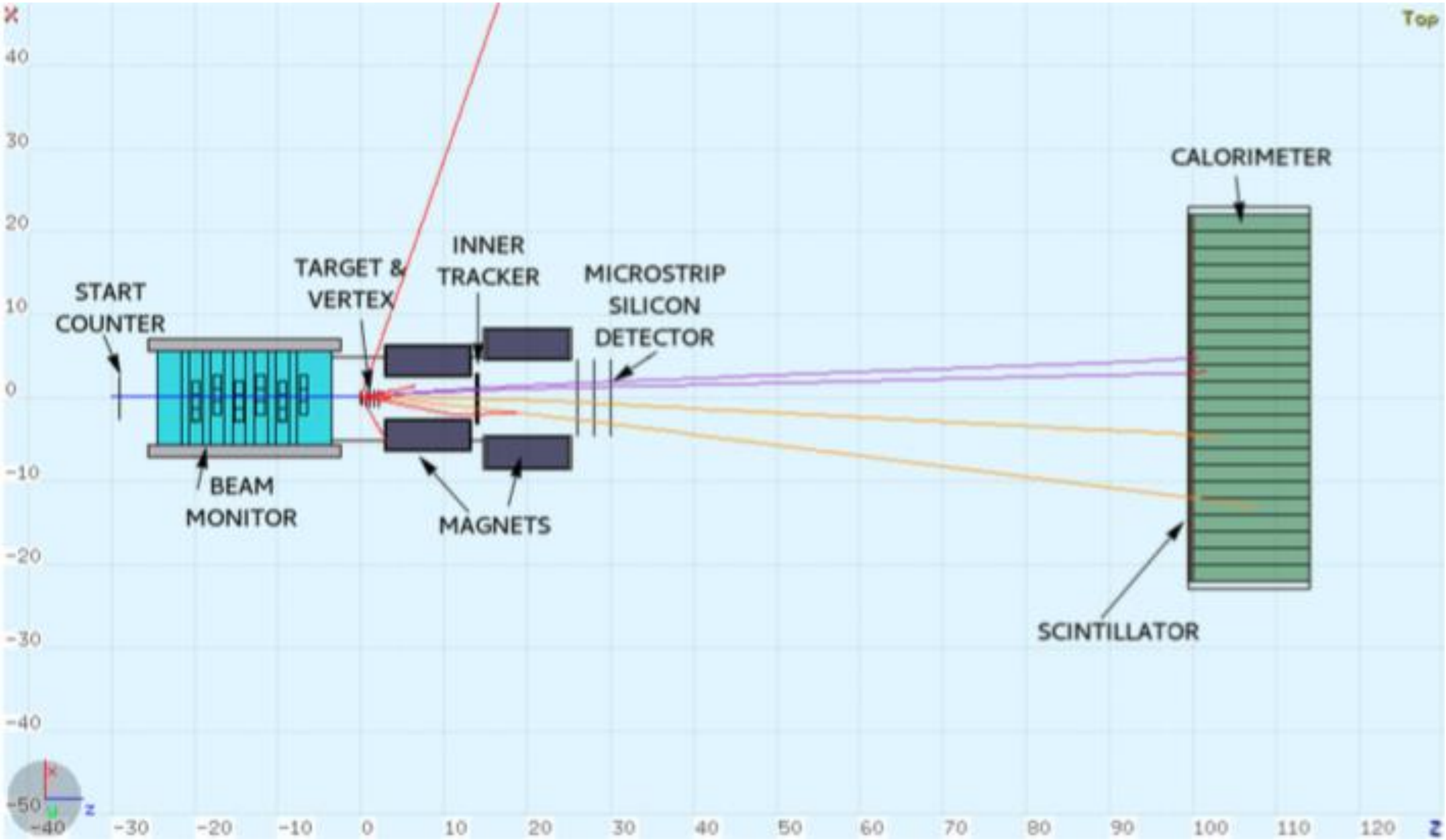




- The fragments mass A can be determined by:
  - measuring β and p respectively from the TOF and the magnetic spectrometer
  - measuring β and E_{kin} respectively from the TOF and the calorimeter
  - measuring p and E_{kin} respectively from the magnetic spectrometer and the calorimeter

- Resolution for heavy fragments 4%

FOOT Detector: simulation with FLUKA



Schematic 2D event display of a primary ^{16}O ion interacting in a polyethylene target