The FOOT experiment

Riccardo Ridolfi
on behalf of the FOOT collaboration
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FAIR next generation scientists - 6th Edition Workshop

FOOT goals

Hadrontherapy

Target fragmentation

dσ/dE and dσ/dΩ with 5% precision of the fragment production cross sections in inverse kinematics with C, O beams at 200-400 MeV/u

Projectile fragmentation

same measures in direct kinematics

⇩

The dose to the planning target volume (PTV) in the patient should be delivered with an uncertainty of less than 5% at the 2σ level (ICRU Report 24 1976).

Space radioprotection

dσ/dE and dσ/dΩ with 5% precision of the fragment production cross sections in inverse and direct kinematics with He, C, O beams at around 700 MeV/u

⇩

NASA limits: the Risk of Exposure-Induced Death (REID) from cancer must not exceed the 3%, at a 95% confidence level (C.L.).

The FOOT collaboration

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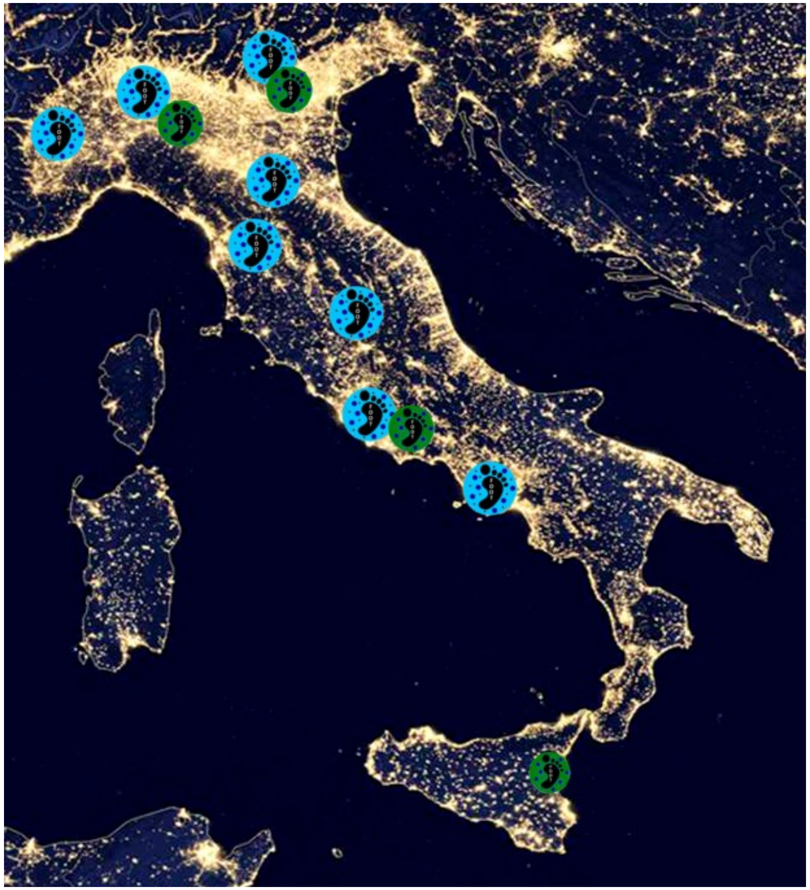
FOOT approved by INFN on September 2017 (CSN3)



~ **100** members:

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

Physics program:

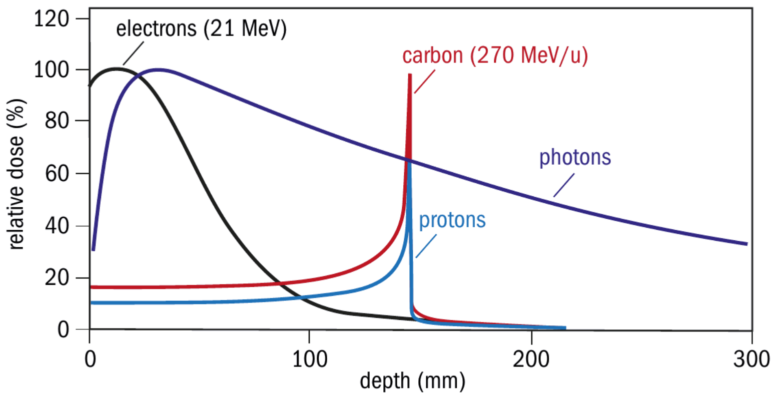
- Nuclear fragmentation @200 MeV/u for **Hadrontherapy;**
- Nuclear fragmentation @700 MeV/u for **space radioprotection.**

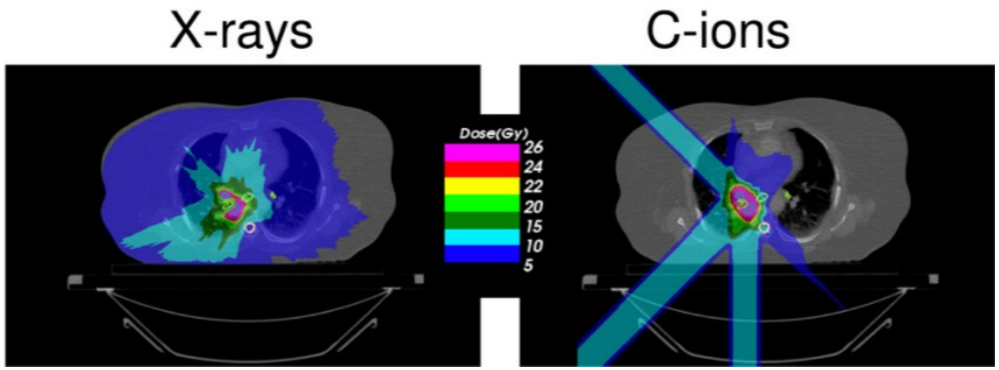
Pros and cons of Hadrontherapy

The FOOT experiment

Riccardo Ridolfi

High **conformity** to the tumour volume ✓





Pros and cons of Hadrontherapy

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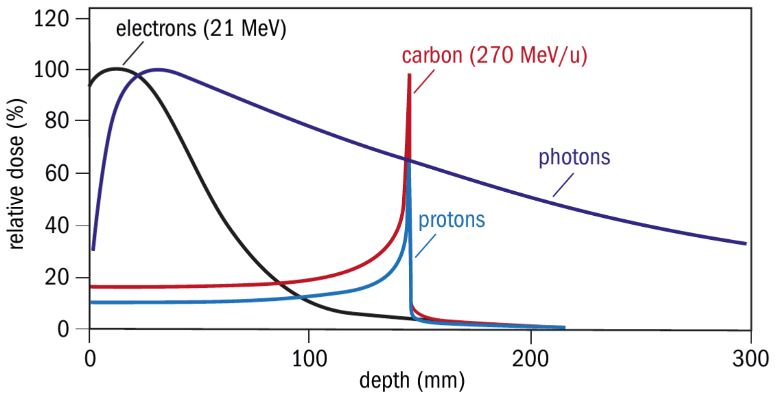
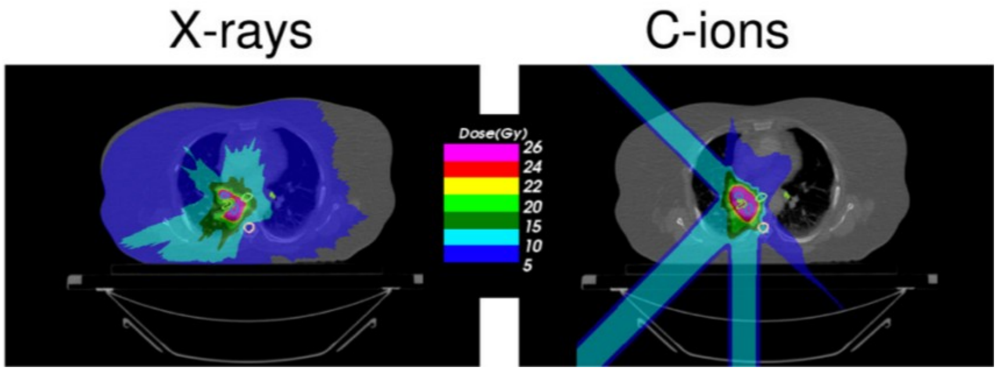
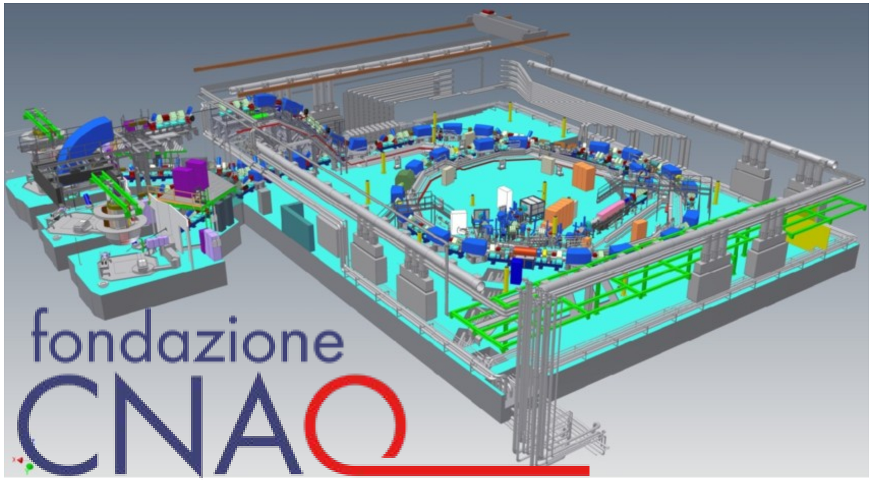




High-cost treatment ✗



Pros and cons of Hadrontherapy

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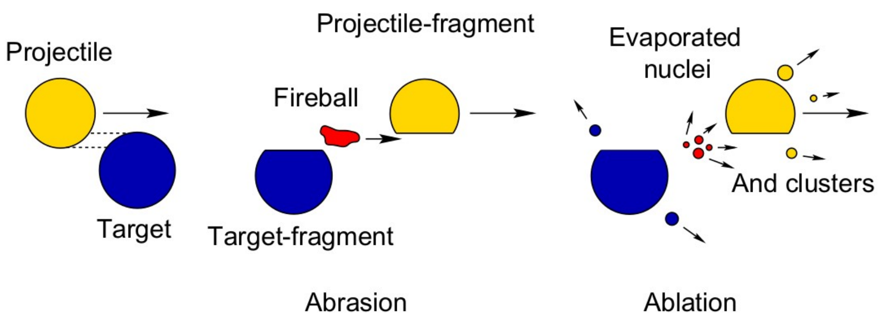
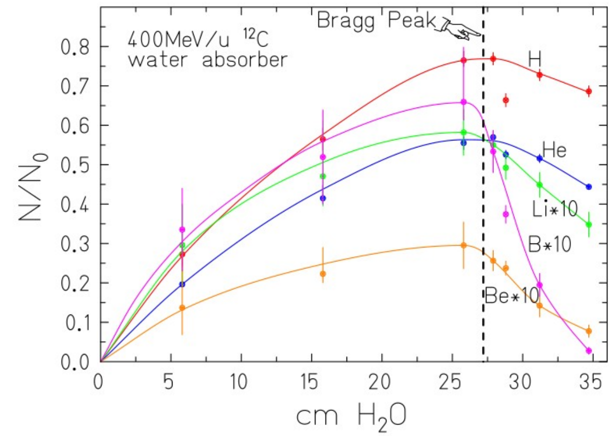
Nuclear fragmentation of the **projectile** and of the **target**





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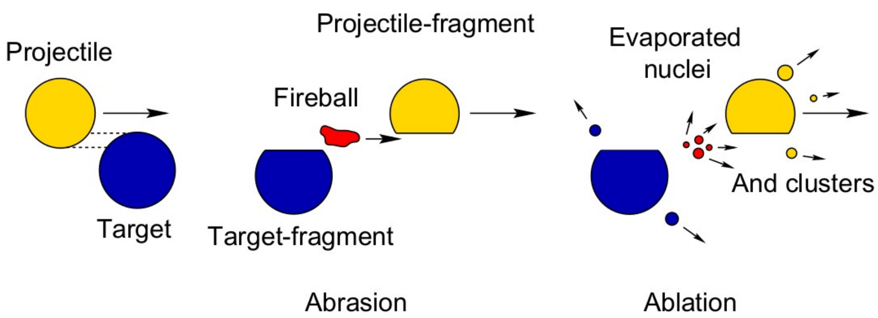

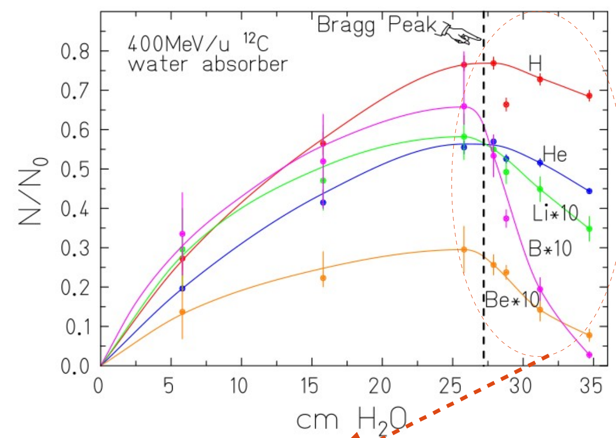

Dose beyond the Bragg peak, possible damage to Organs At Risk!

Pros and cons of Hadrontherapy

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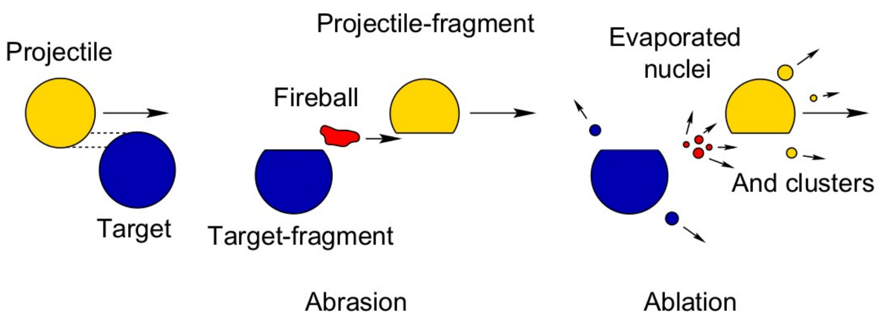
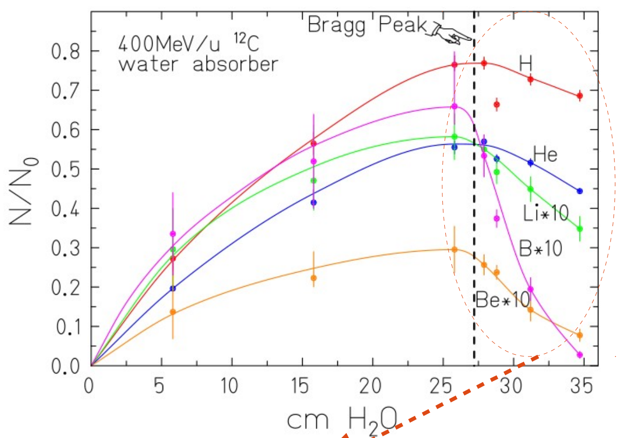
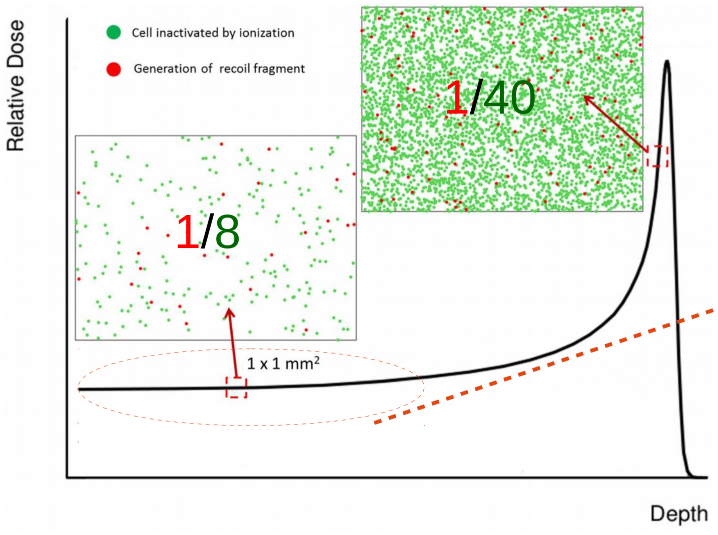
Nuclear fragmentation of the **projectile** and of the **target**





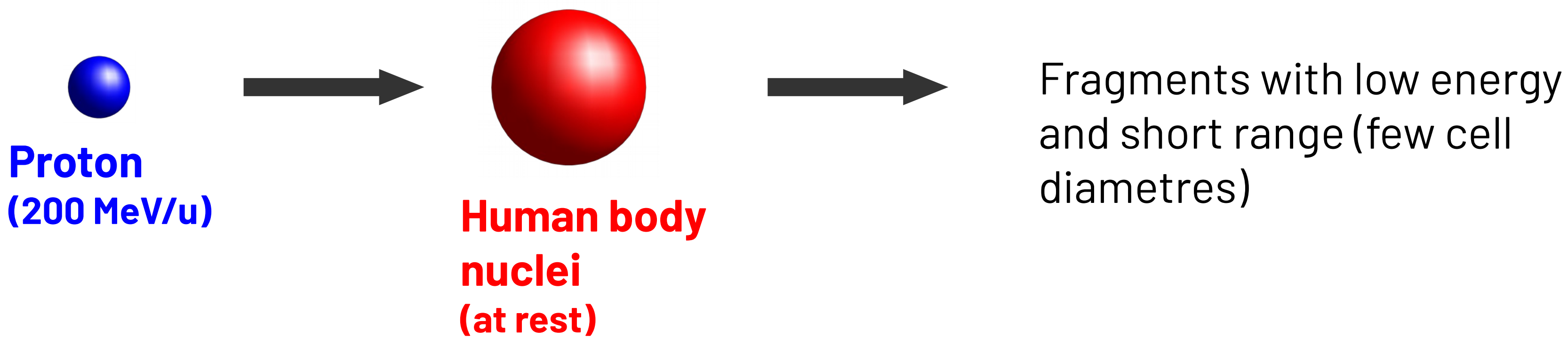
Dose beyond the Bragg peak, possible damage to Organs At Risk!



Target fragmentation contributes to the dose in the entrance channel, at present not considered

The FOOT experiment

With the FOOT experiment we aim to measure fragmentation cross sections relevant for **hadrontherapy** and for space **radioprotection**.
At present there is a lack of experimental data at these energies (200-350 MeV/u and 700 MeV/u).



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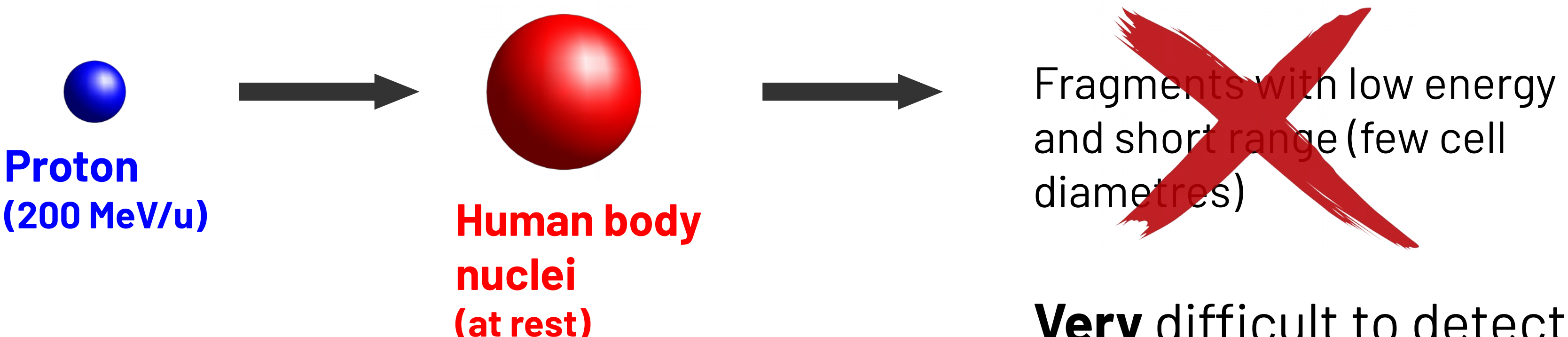

Very difficult to detect!

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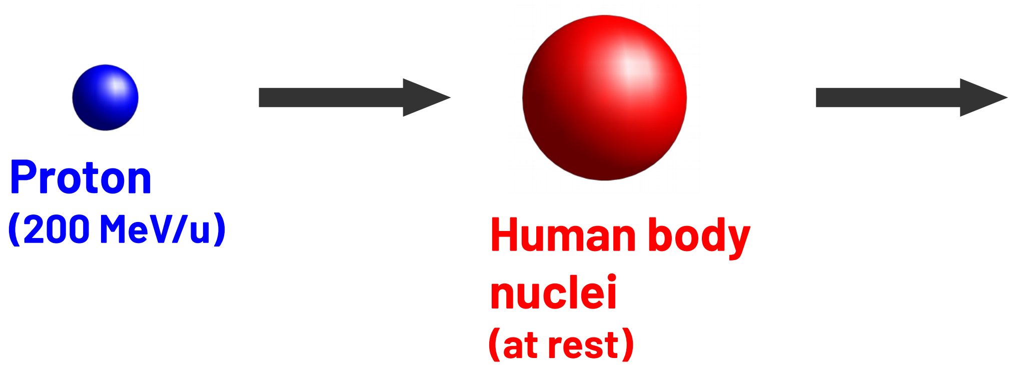
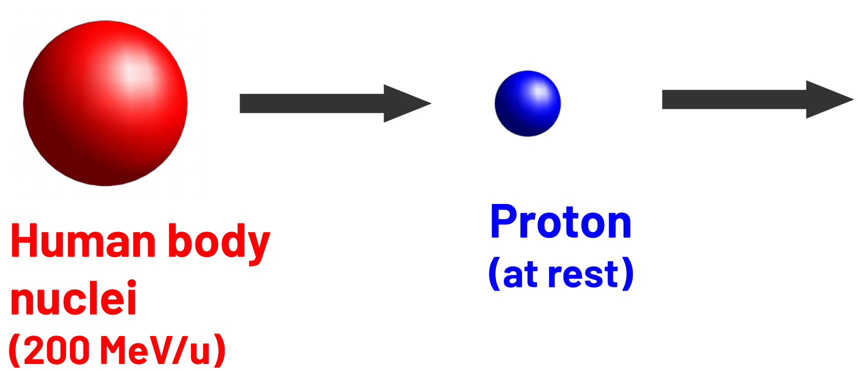


Fragments with low energy and short range (few cell diametres)

Very difficult to detect!



Fragments with **higher** energy and **longer** range!

Inverse kinematics approach (cross sections are invariant)

The FOOT experiment

Problem: hydrogen target

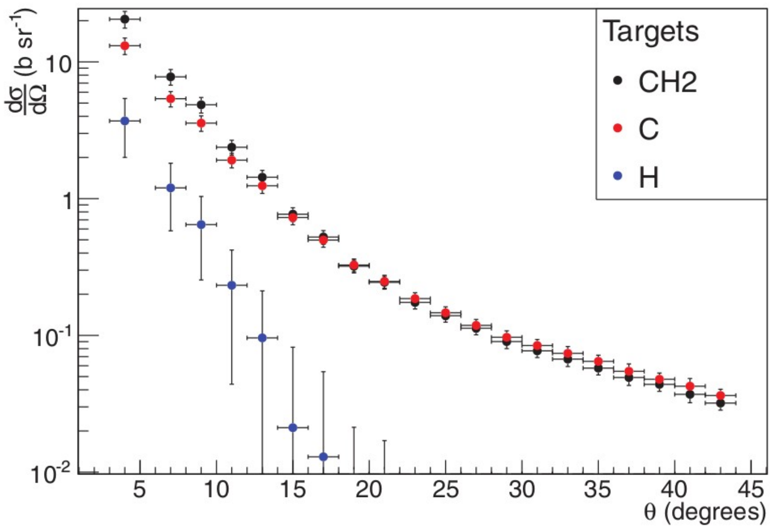
- ✗ gas is not allowed in all experimental rooms
- ✗ gas is too sparse (low interaction probability)

The FOOT experiment

Problem: hydrogen target

- ✗ gas is not allowed in all experimental rooms
- ✗ gas is too sparse (low interaction probability)

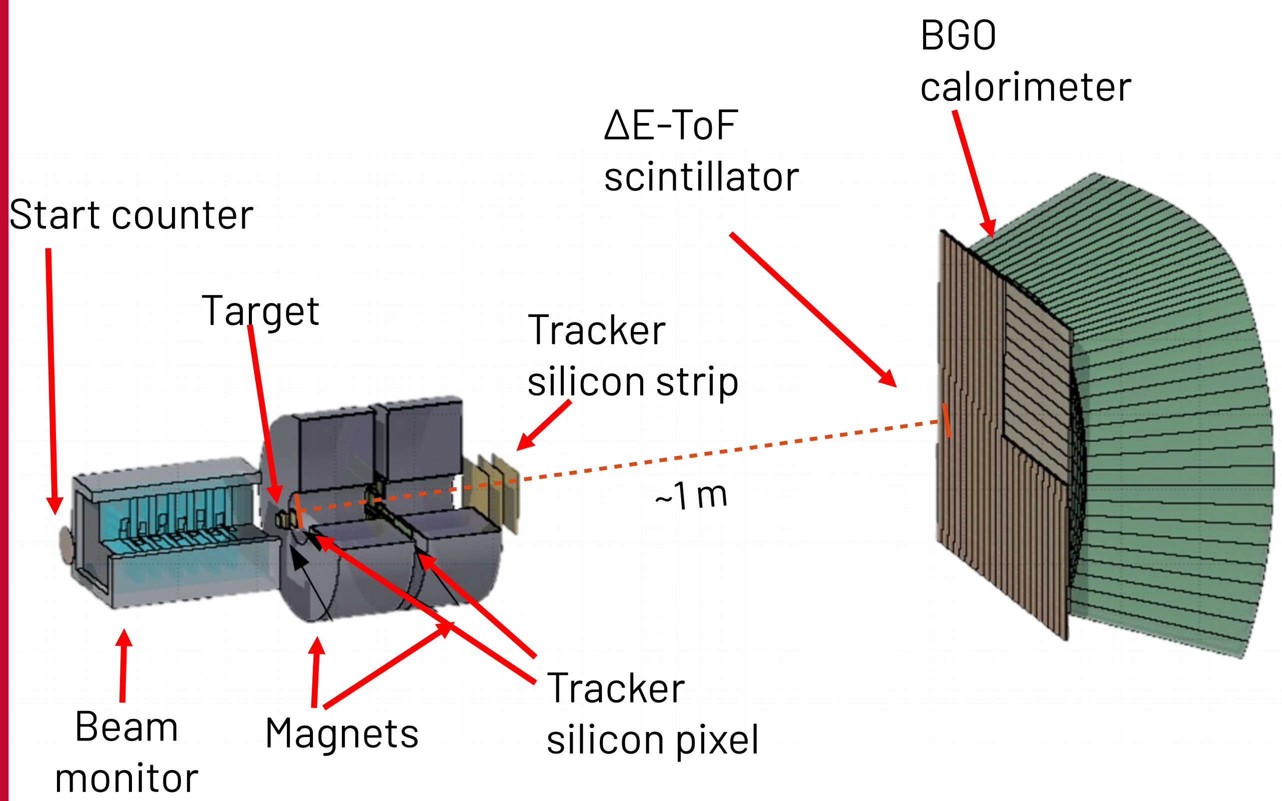
Solution: polyethylene target $(C_2H_4)_n$ and Carbon target



arXiv:1306.0378

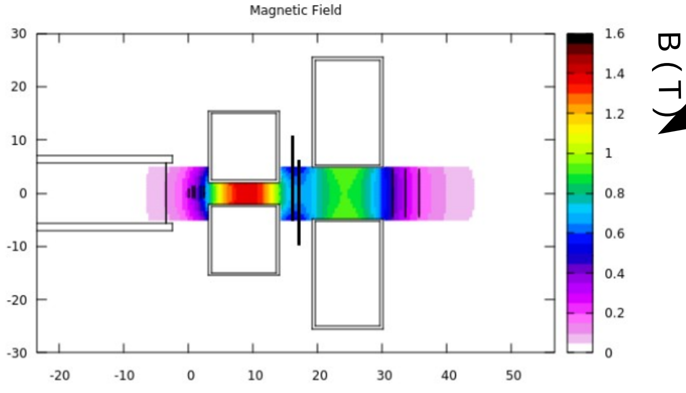
$$\frac{d\sigma}{d\Omega}(H) = \frac{1}{4} \cdot \left(\frac{d\sigma}{d\Omega}(\mathrm{C_2H_4}) - 2 \cdot \frac{d\sigma}{d\Omega}(\mathrm{C}) \right)$$

The electronic setup



Designed for **"heavy"** fragments (**Z>2**)

Angular acceptance up to **10°**



Magnetic field map

The electronic setup

The FOOT experiment

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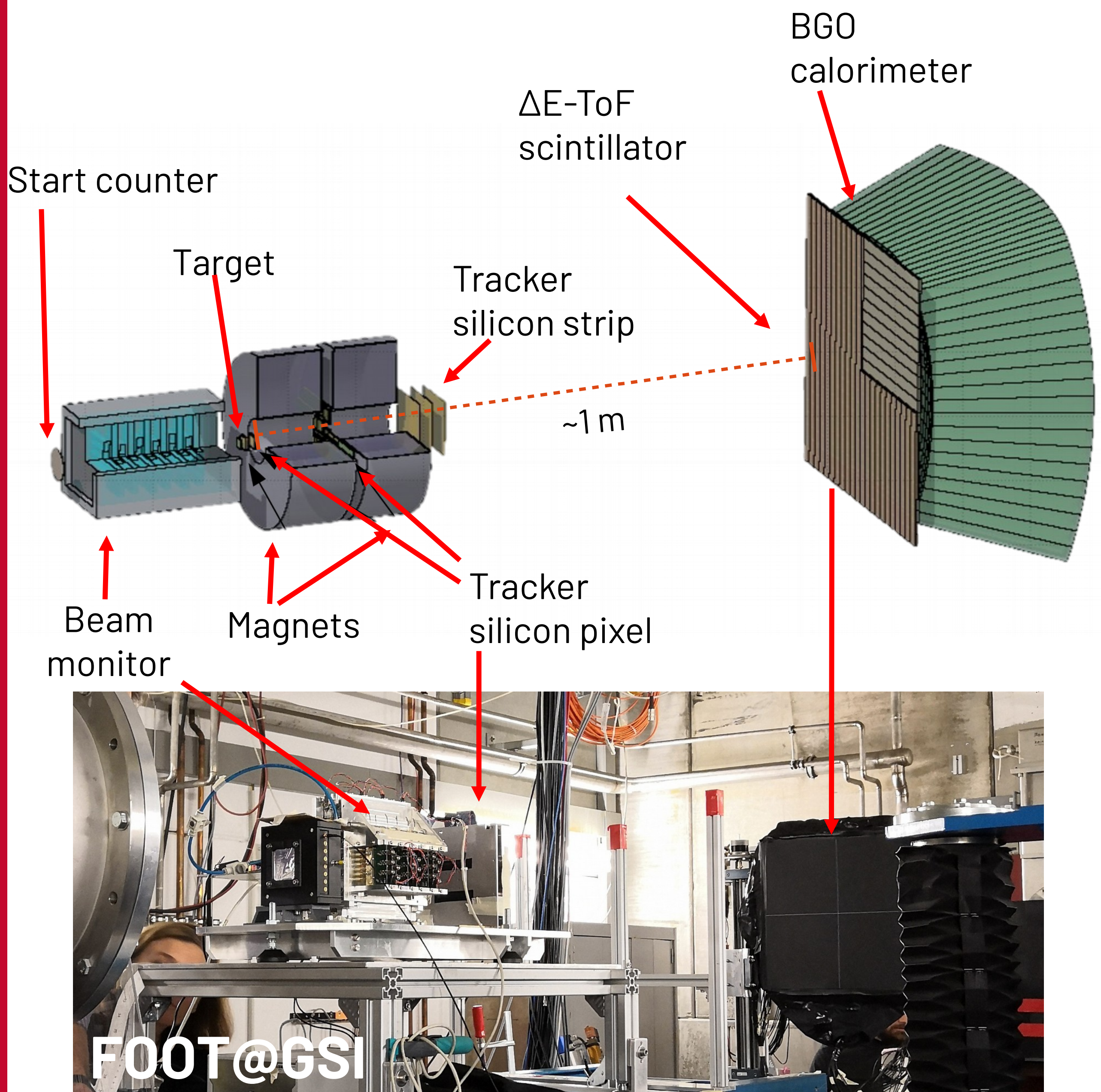
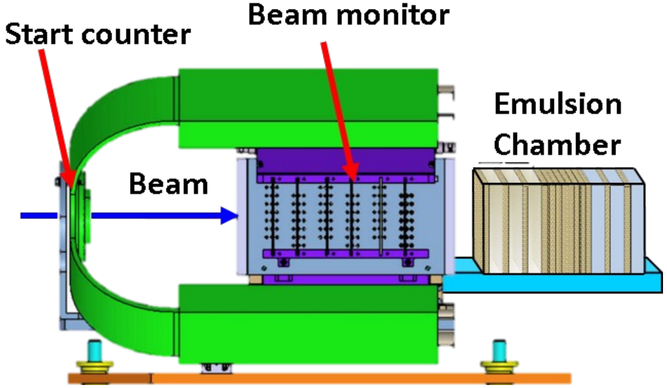


Designed for **"heavy"** fragments (**Z>2**)

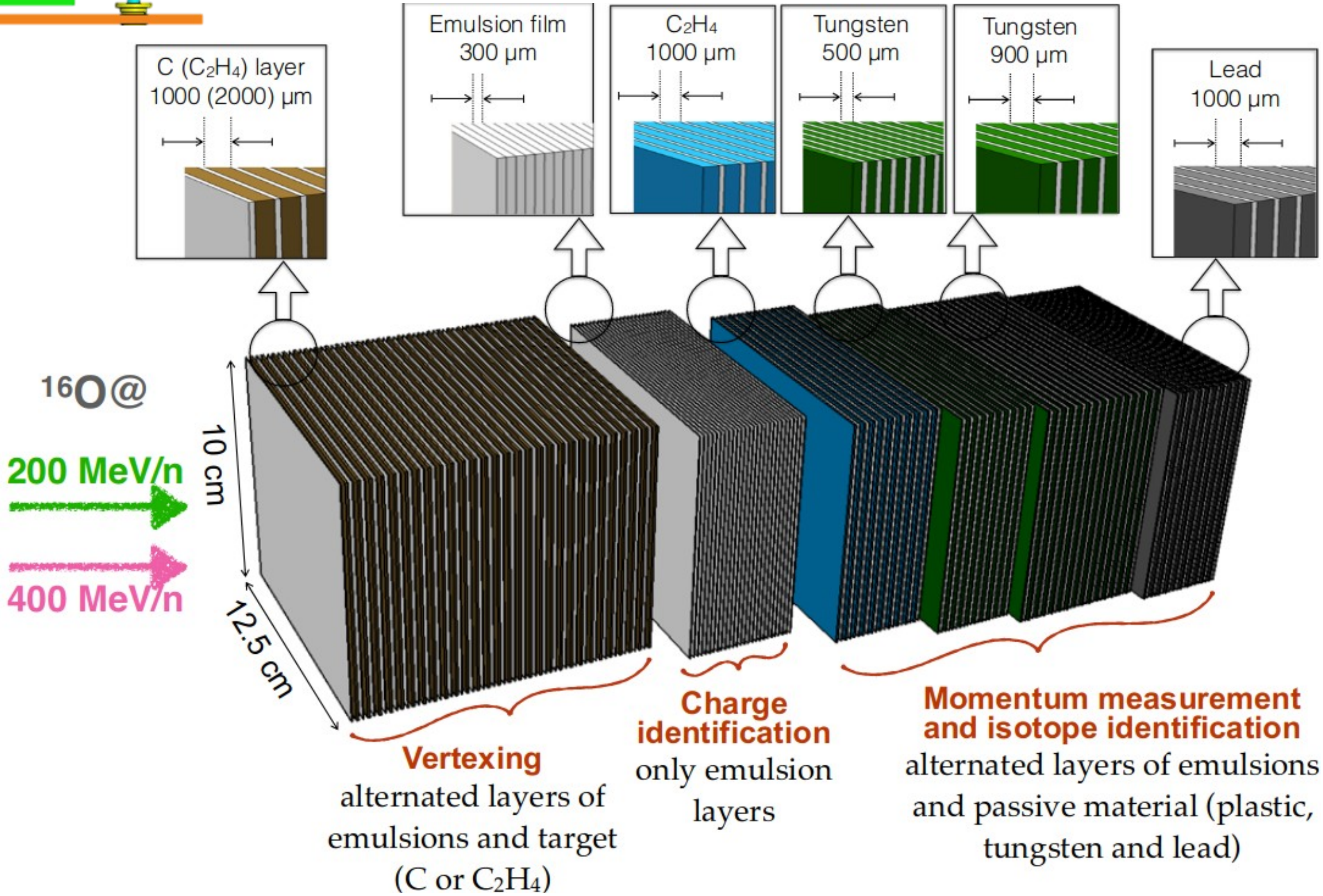
Angular acceptance up to **10°**

The emulsion setup



Designed for **light** fragments (**p,He**)

Angular acceptance up to **70°**



The emulsion setup

The FOOT experiment

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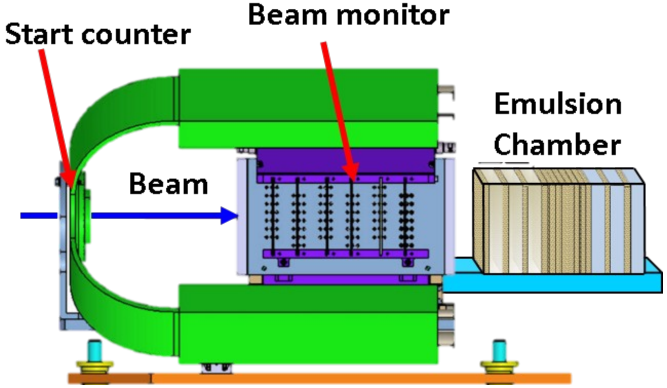
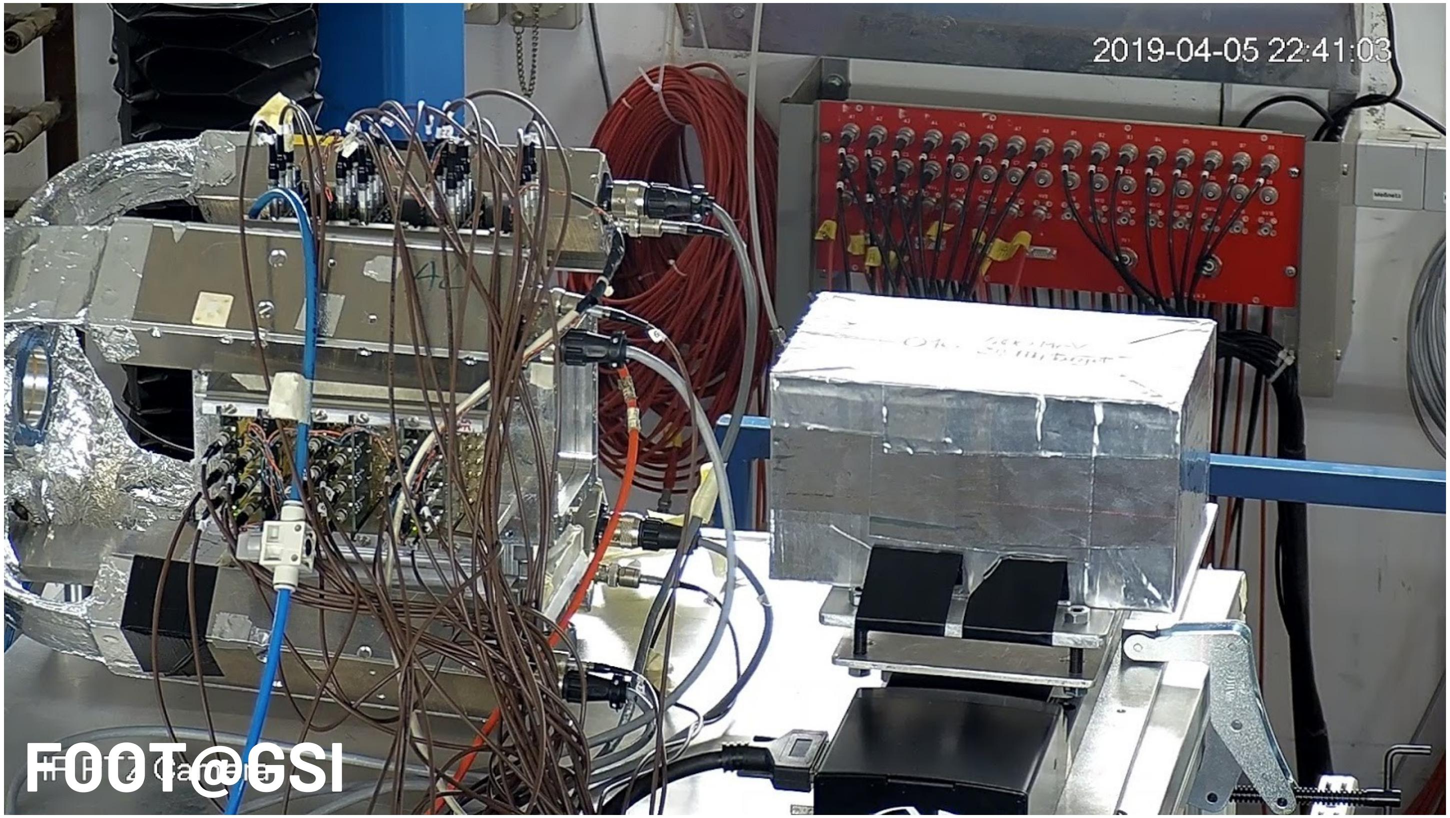
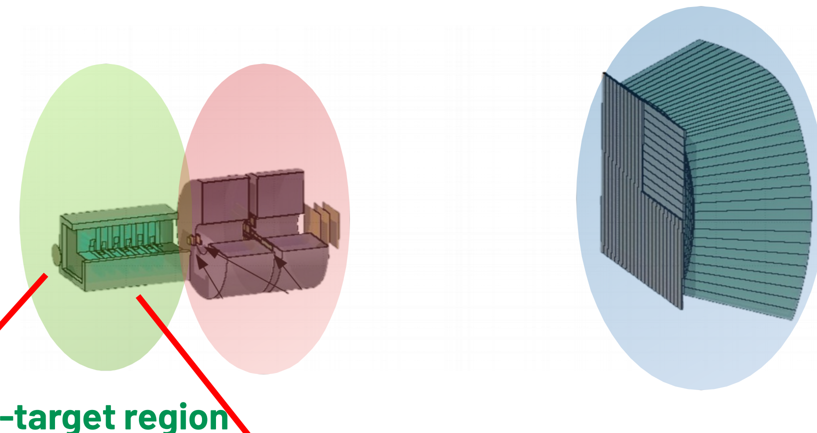


Designed for **light** fragments (**p,He**)

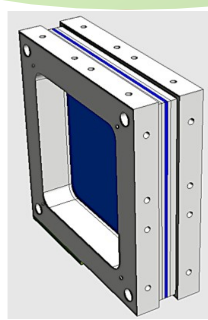
Angular acceptance up to **70°**



Pre-target region

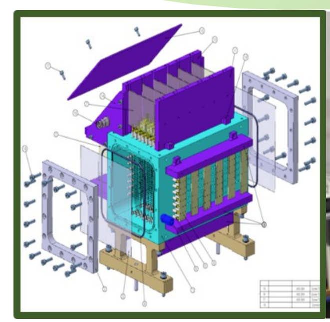


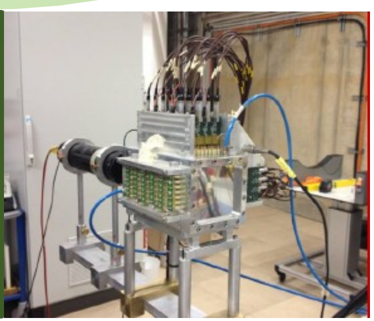
Start Counter (SC)



250 μm–1 mm thick plastic scintillator (depending on E beam)

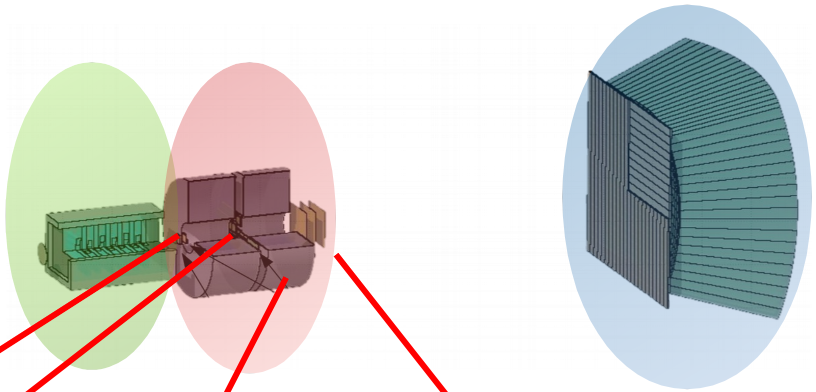
Beam monitor (BM)



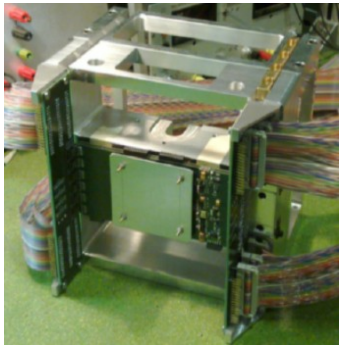


Drift chamber
Gas: Ar/CO_2 (80/20%)

Tracking region

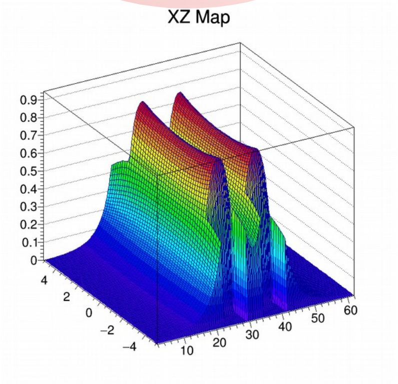


Vertex (VTX) and Inner Tracker (IT)



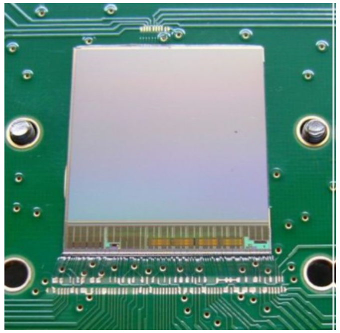
VTX: 4 layers of Si pixel (20 x 20 μm)
IT: 2 layers of Si pixel (20 x 20 μm)

Magnet



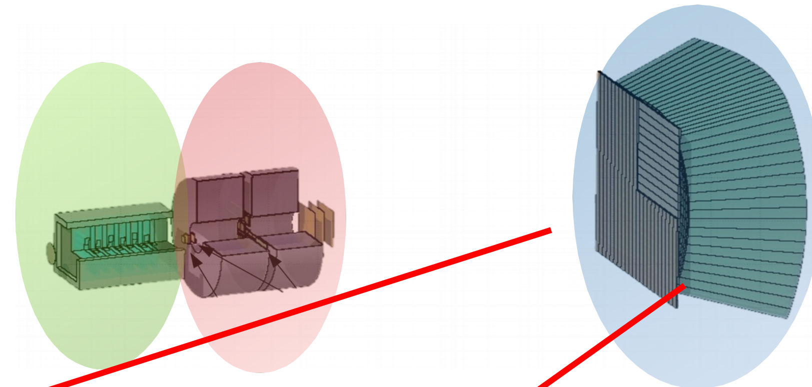
2 permanent magnets
Hallbach geometry
B field in y direction (max 1.3 T)

Micro Strip Detector (MSD)



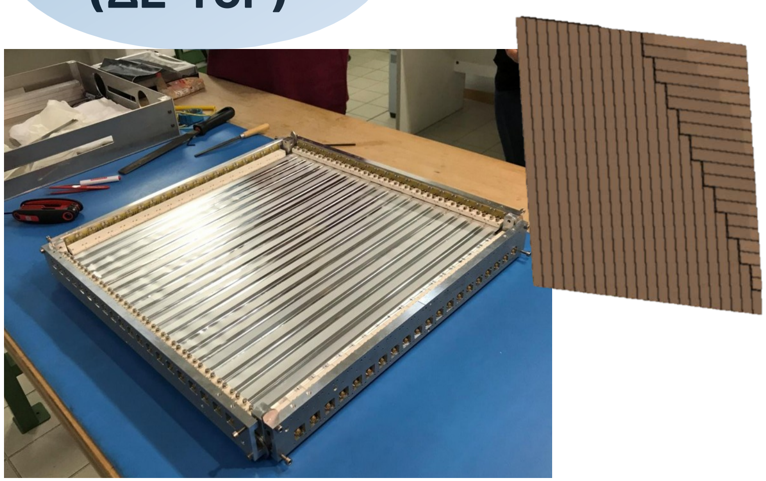
3 layers of Si strips
(120 μm x 9 cm)

Downstream region



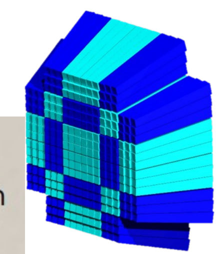
Downstream region

Scintillator (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
$Z_{Bi} = 83$

Density BGO = 7.13 g/cm^3
Weight = 1.027 kg
320 BGO crystals
Total weight 330 Kg

Test beam results

The FOOT experiment

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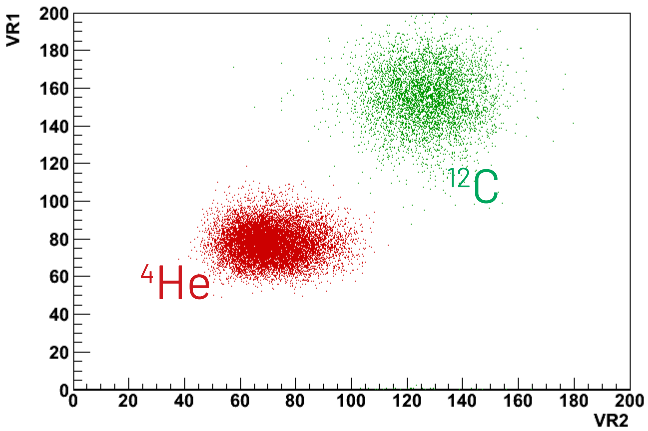
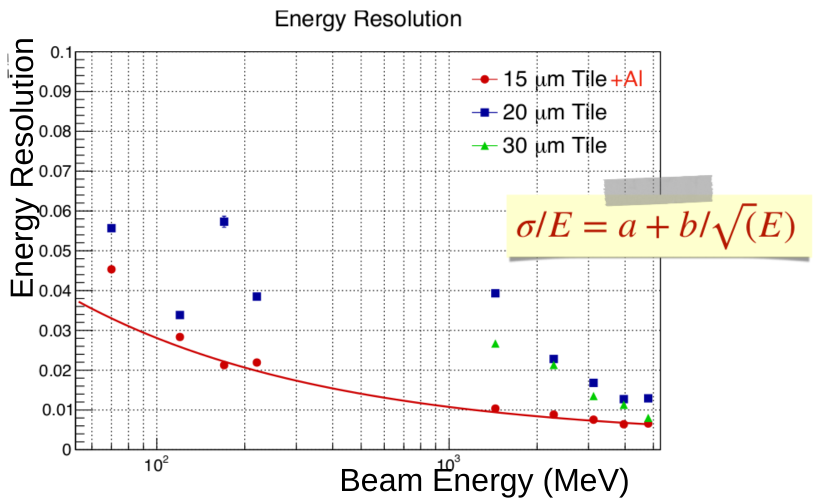
Emulsion chamber test beam@LNS



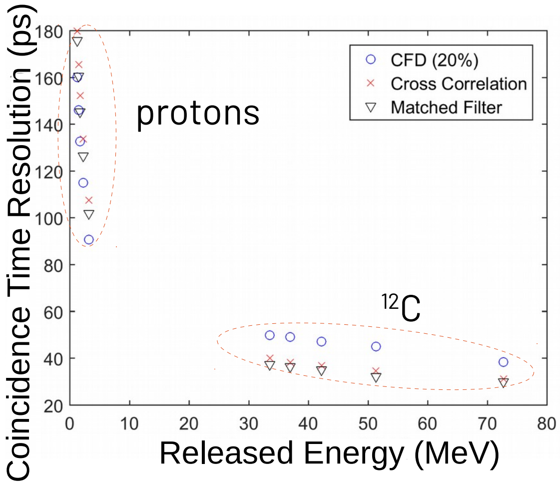
Good charge **separation** after development

Calorimeter test beam@CNAO



Energy resolution for p < 3%
for C < 1%

Scintillator test beam@CNAO



Standard performance used in analysis:

Quantity	Resolution
ToF (ps)	**70** for C, **140** for protons
E_{kin} (%)	**1.5**
p (%)	**3.2**

Charge reconstruction performance @200MeV/u

The FOOT experiment

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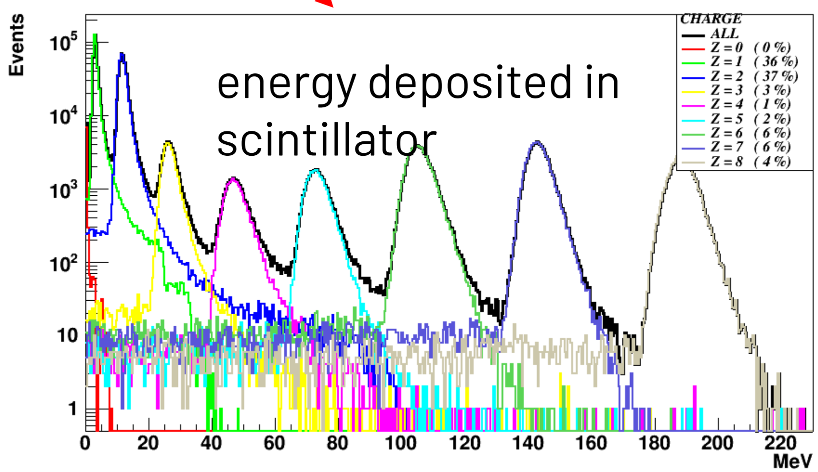
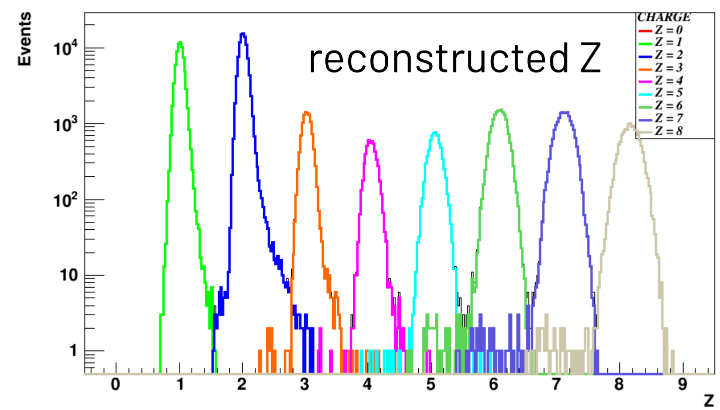
Charge identification (Z)

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

TOF





	1H	4He	7Li	9Be	11B	12C	14N	16O
True charge	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Reco charge	1.01±0.09 (9%)	2.01±0.06 (3%)	3.03±0.08	4.05±0.09	5.06±0.10	6.09±0.12	7.11±0.14	8.15±0.15 (2%)

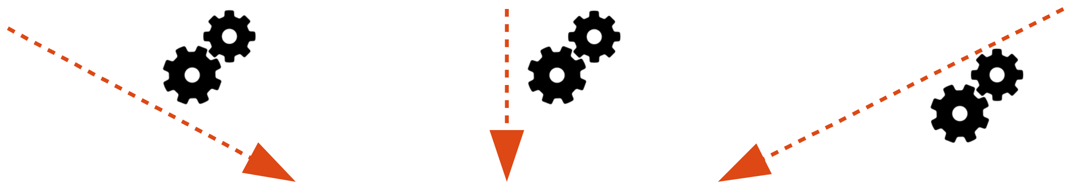
wrong charge assignment < 1%

Fragment identification

Mass identification (A)

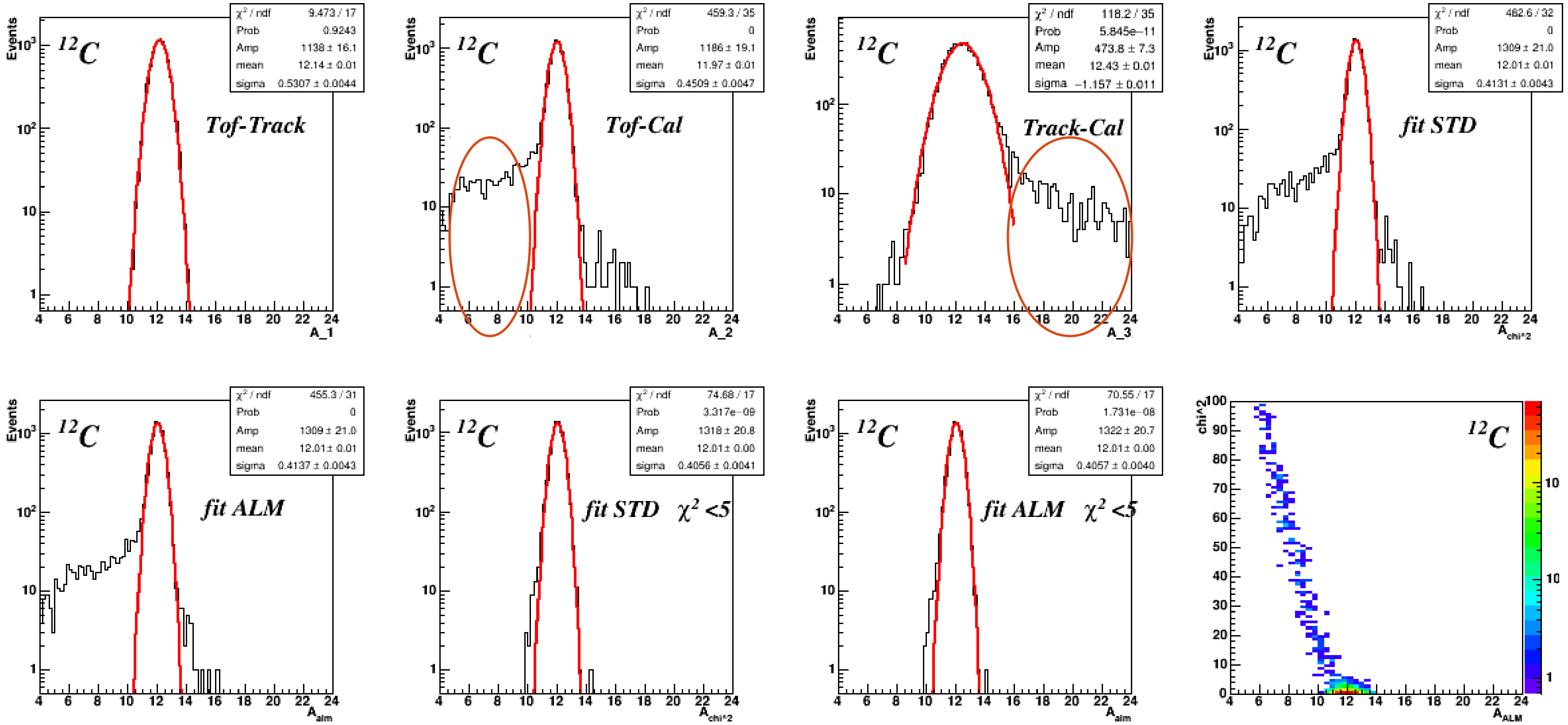
$$A_1 = \frac{p}{u\beta c\gamma} \qquad A_2 = \frac{E_k}{uc^2(\gamma - 1)} \qquad A_3 = \frac{p^2c^2 - E_k^2}{2uc^2 E_k}$$

tracker + ToF | calorimeter + ToF | tracker + calorimeter



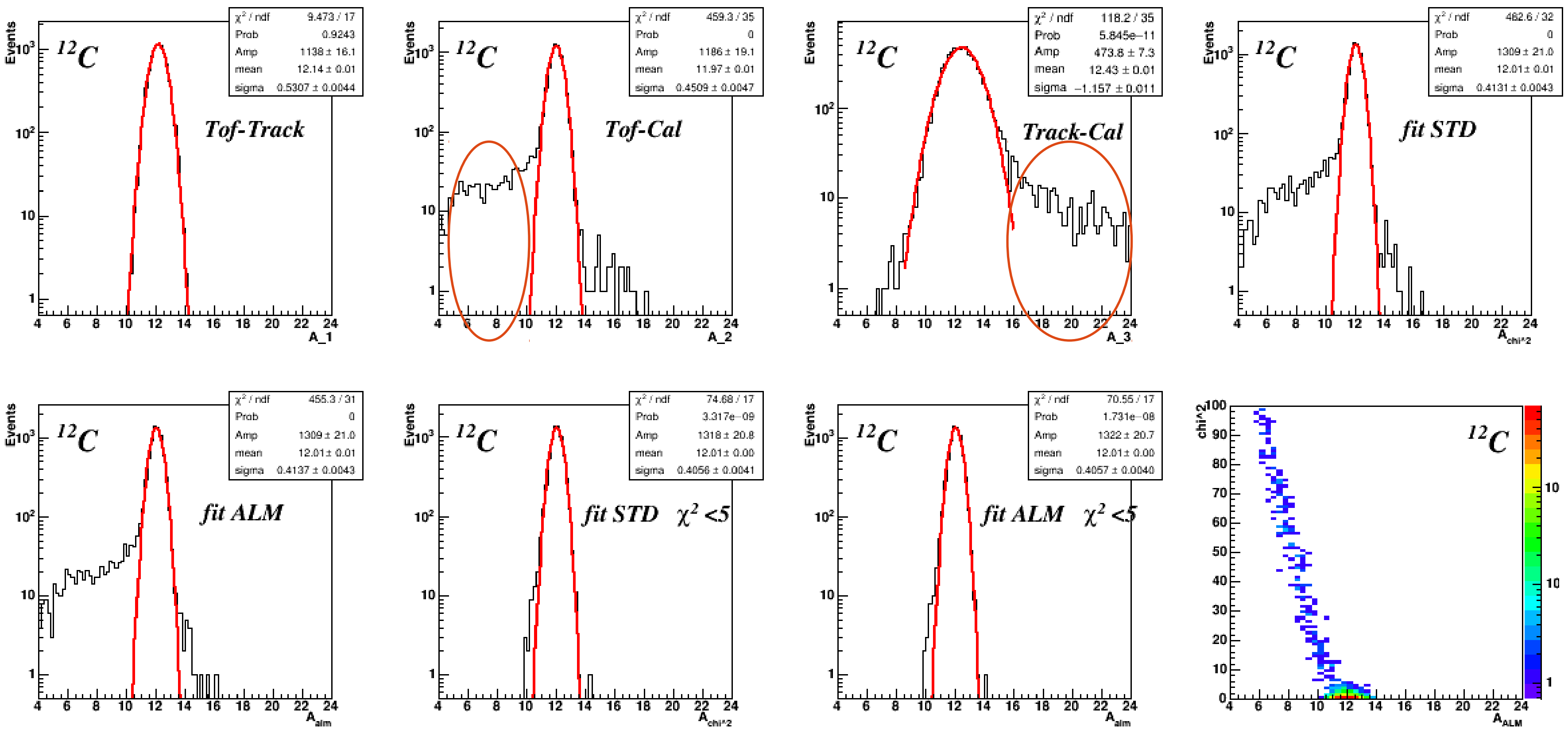
Standard χ^2 and
Augmented Lagrangian
Method (ALM)

Determination of A @200 MeV/u



~17% of fragments undergo nuclear interactions in the calorimeter producing **neutrons** escaping from the detector!

Determination of A @200 MeV/u



~17% of fragments undergo nuclear interactions in the calorimeter producing **neutrons** escaping from the detector!

FOOT redundancy allows to remove these events with a χ^2 cut

FOOT performances on mass reconstruction

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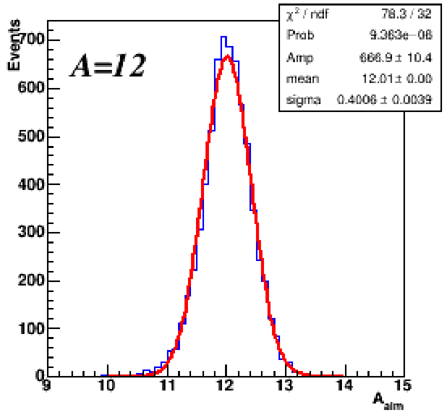
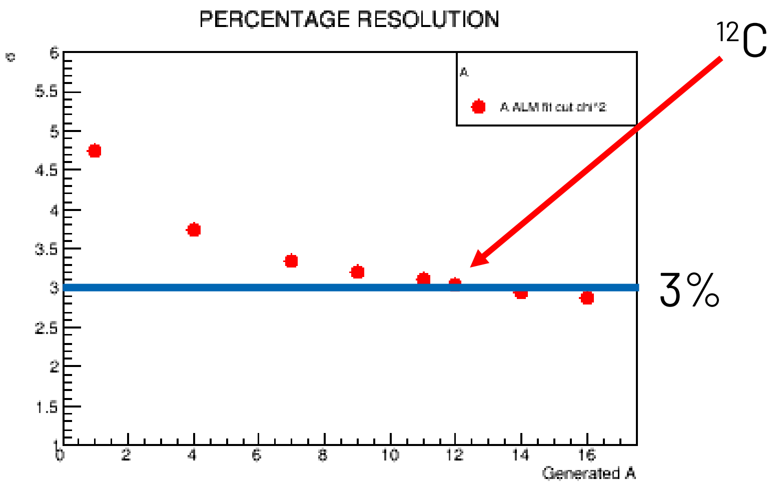
Simulation by FLUKA
^{16}O @200MeV/u → C_2H_4

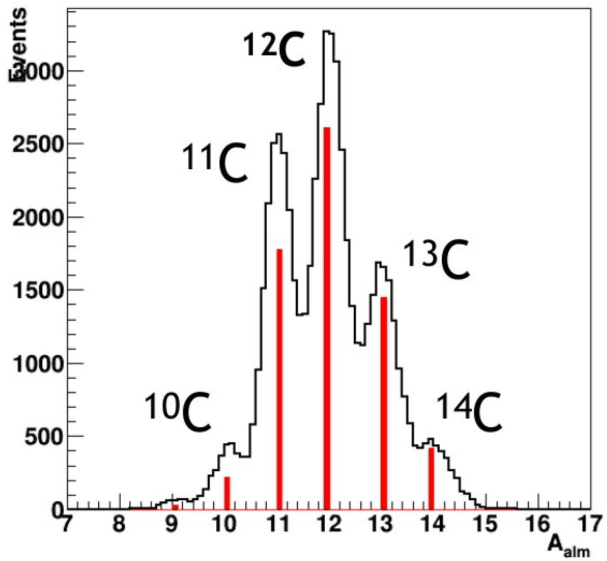


Analysis example on Carbon

Recalling that:

Quantity	Resolution
ToF (ps)	**70** for C, **140** for protons
E_{kin} (%)	**1.5**
p (%)	**3.2**





Resolution for heavy fragments **< 3%**

Possible to **disentangle** isotopes!

Space radioprotection

The FOOT experiment

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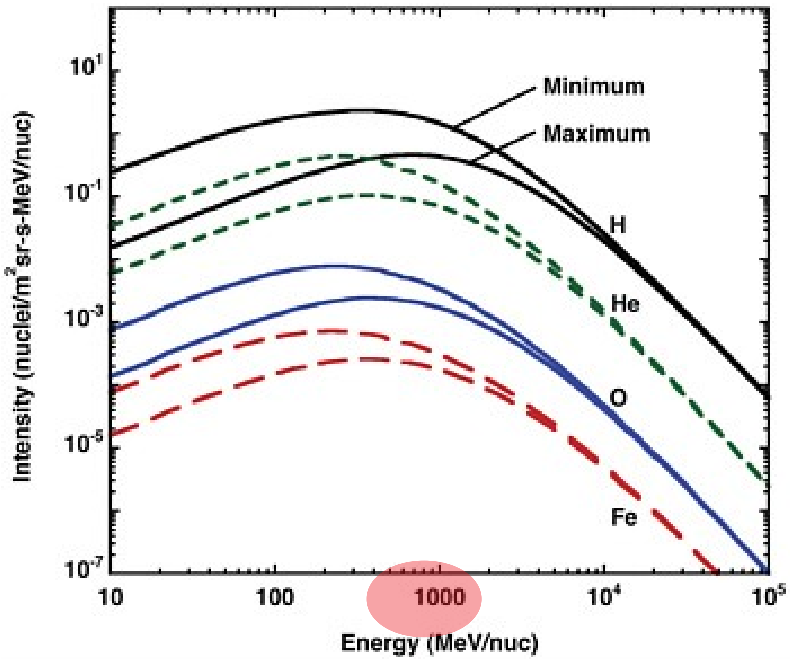
Mars has **NO magnetosphere** and a **very thin** atmosphere → **NO protection** against GCR and SPE

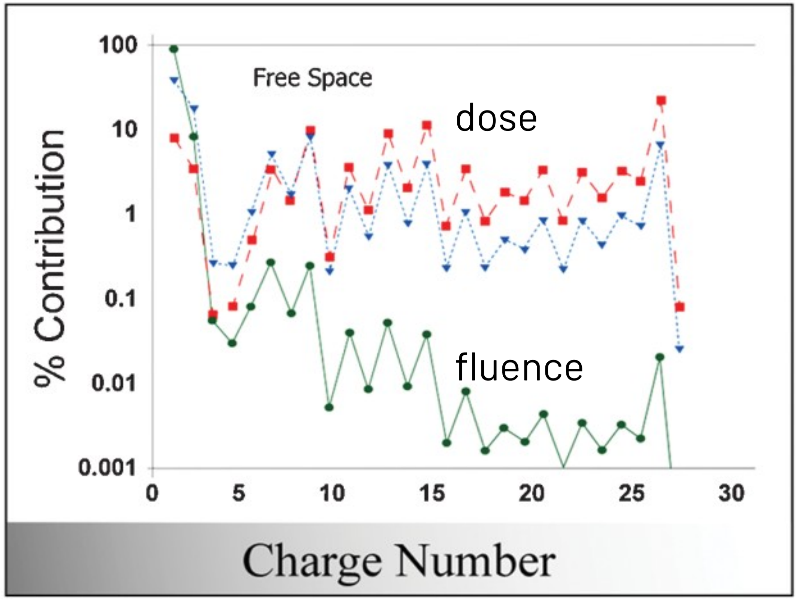
Travel: 1.8 mSv/day (GCR + SPE)
On Mars: 0.64 mSv/day → ~ 1 Sv (increase the cancer probability of ~3%)

On Earth: 2.64 mSv/year

Passive shielding is needed as active seems not feasible!

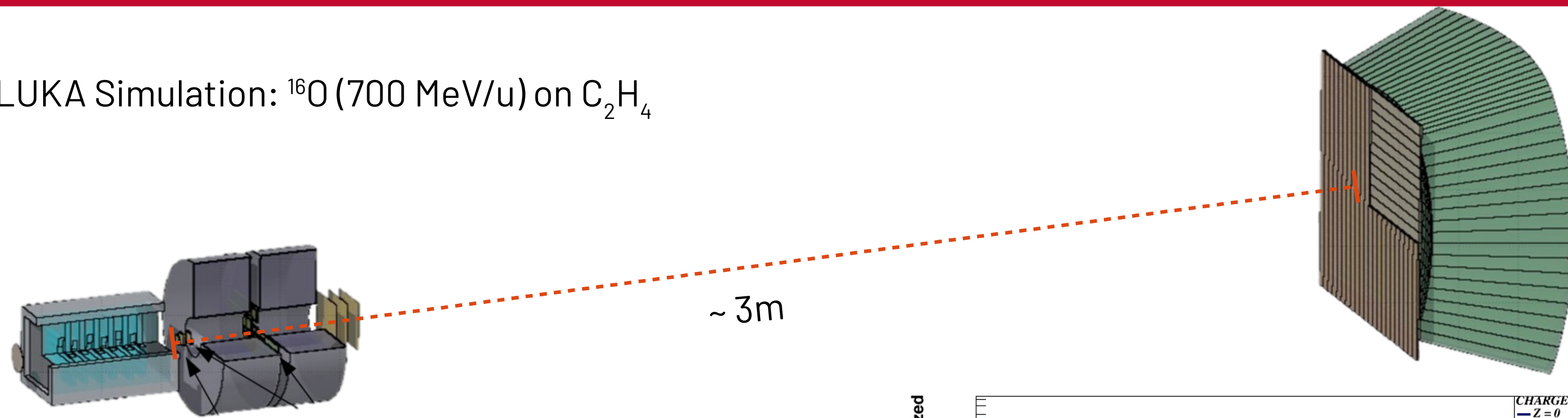


10.1103/RevModPhys.83.1245

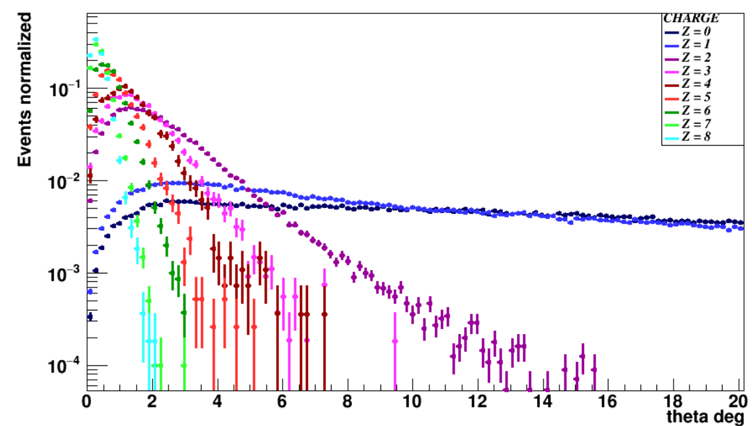


The FOOT setup for higher energy

FLUKA Simulation: ^{16}O (700 MeV/u) on C_2H_4

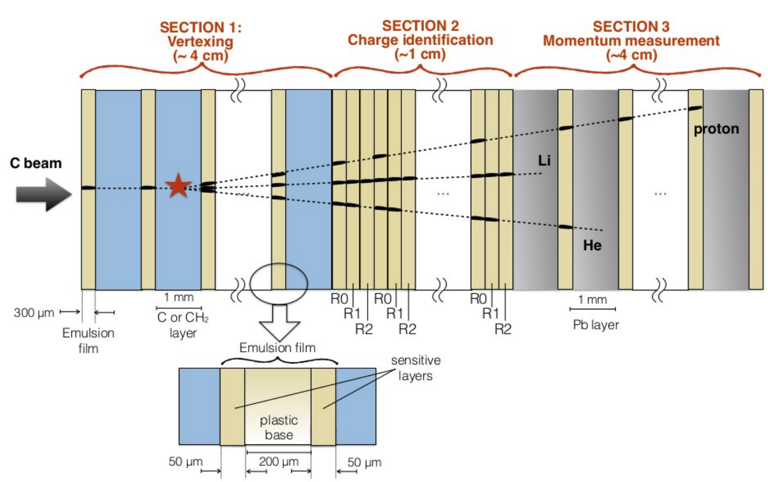


Same acceptance as @ 200 MeV/u
High resolution on β
Crucial for **Z,A determination**



Z>2 fragments inside 4°

Emulsion Chamber
Different geometry and number of layers



Charge reconstruction performance @700MeV/u

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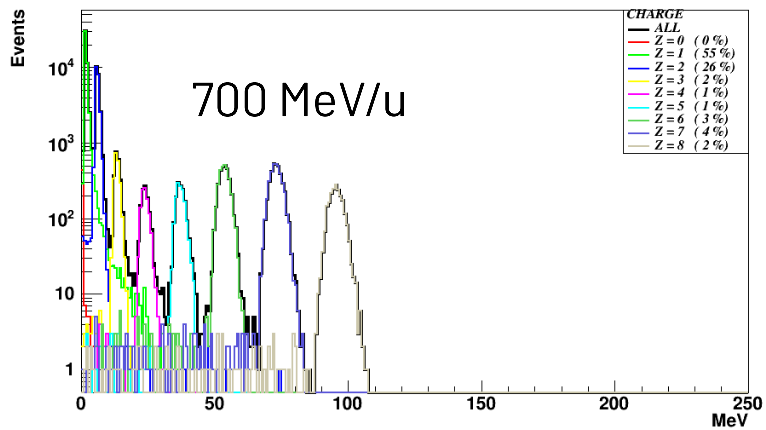
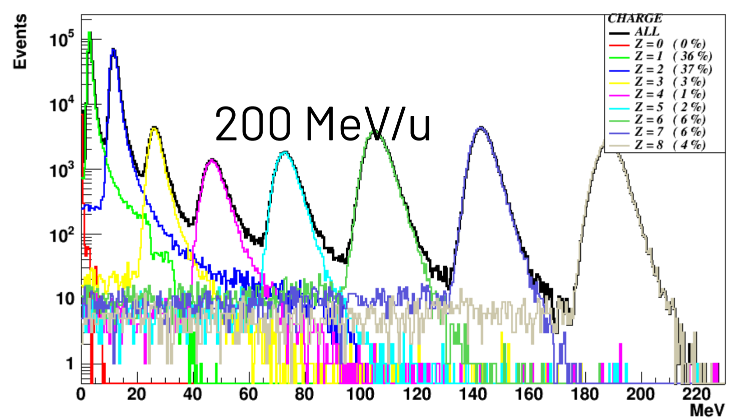
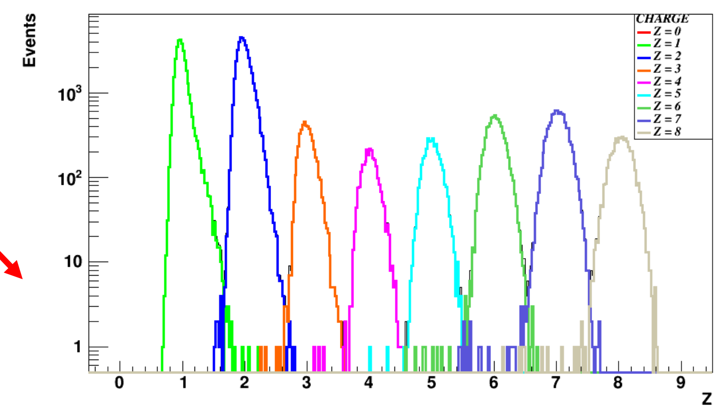


TOF





wrong charge assignment < 1%

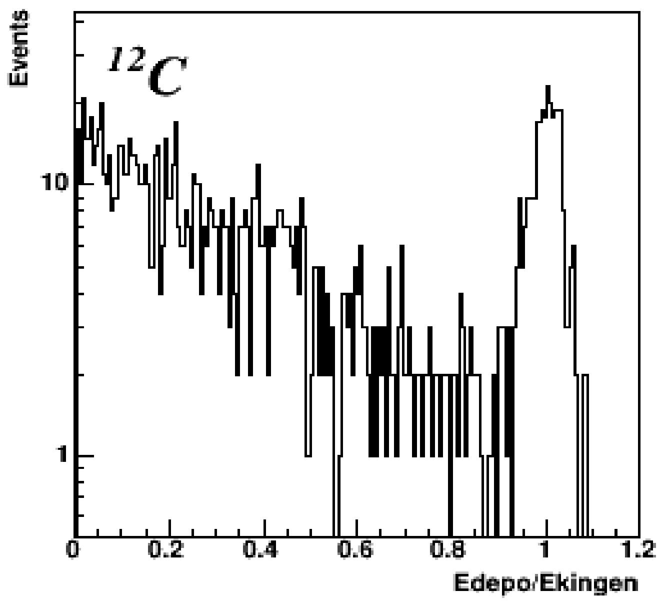
	1H	4He	7Li	9Be	11B	12C	14N	16O
True charge	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Reco charge	0.97±0.08 (9%)	1.99±0.09 (4.5%)	3.00±0.11	4.01±0.12	5.01±0.13	6.03±0.14	7.03±0.16	8.04±0.17 (2.1%)

Determination of A @700 MeV/u

The FOOT experiment

Riccardo Ridolfi

When beam energy increases a major problem arises:
bigger nuclear fragmentation tail



~77% of fragments undergo nuclear interactions in the calorimeter and fit methods are less powerful

Determination of A @700 MeV/u

The FOOT experiment

Riccardo Ridolfi

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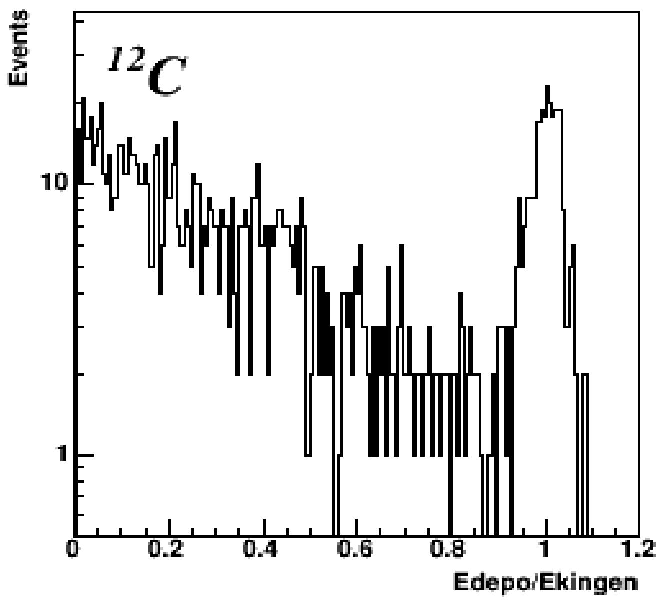


~77% of fragments undergo nuclear interactions in the calorimeter and fit methods are less powerful

Tracking system becomes more **important**!

Momentum resolution @700 MeV/u

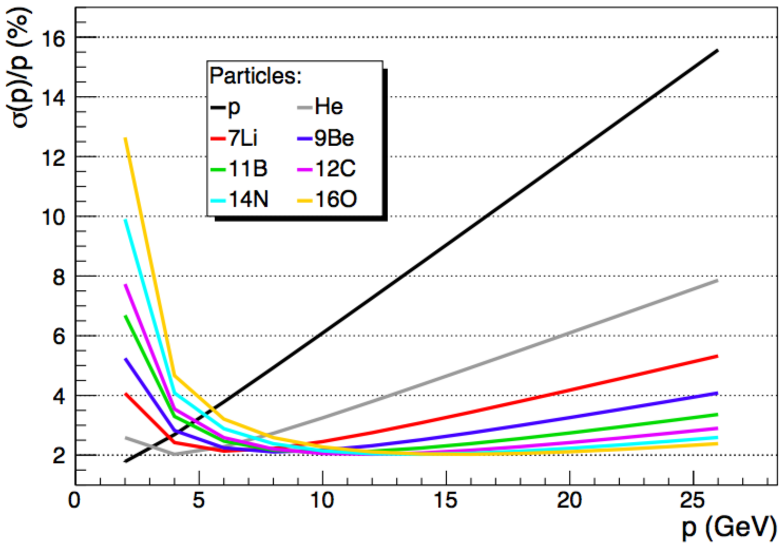
The FOOT experiment

Riccardo Ridolfi

Momentum resolution **improves** at higher energy!

Recall that:

$$\left(\frac{\sigma_p}{p}\right)^2 = \underbrace{\text{const} \cdot \left(\frac{p}{BL^2}\right)^2}_{\text{spectrometer contribution}} + \underbrace{\text{const} \cdot \left(\frac{1}{B\beta\sqrt{LX_0}}\right)^2}_{\text{Multiple Scattering contribution}}$$



Look at the trend, not values!

Momentum resolution @700 MeV/u

Riccardo Ridolfi

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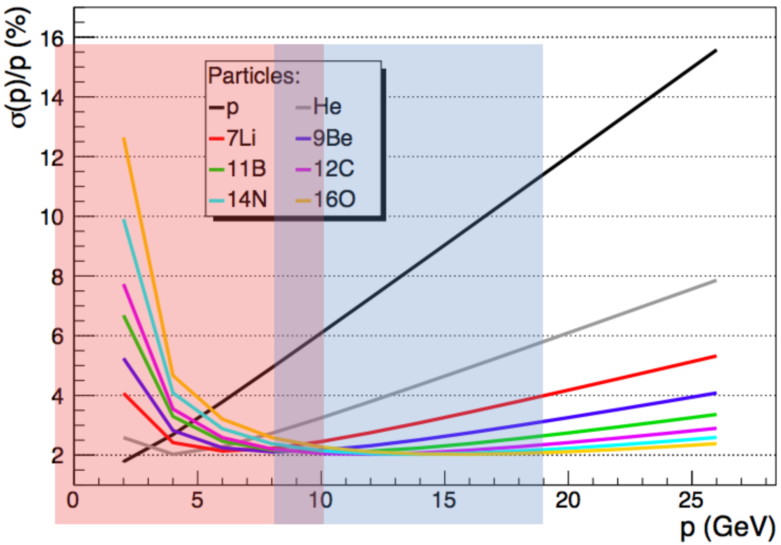


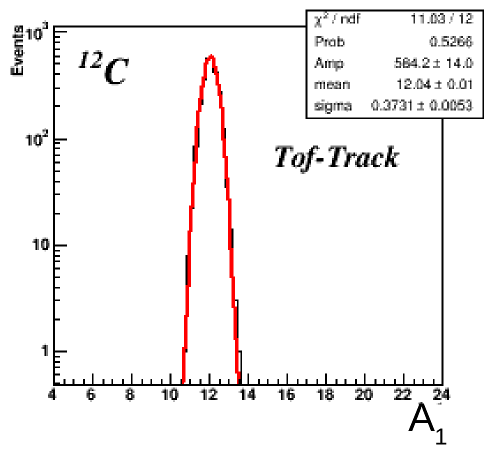
Look at the trend, not values!

FOOT performances on mass reconstruction

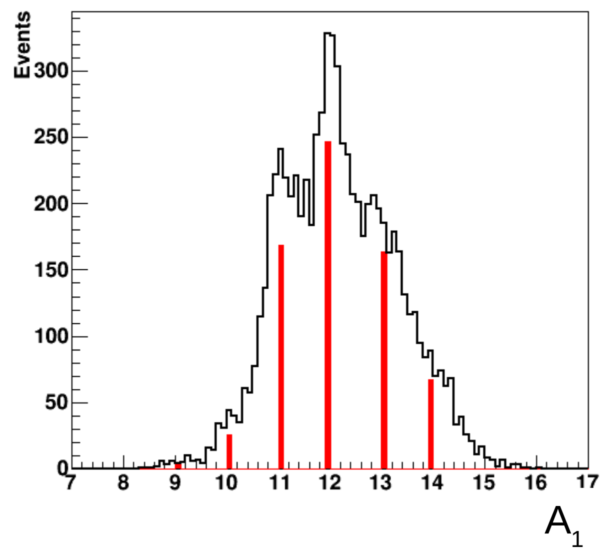
The FOOT experiment

Riccardo Ridolfi

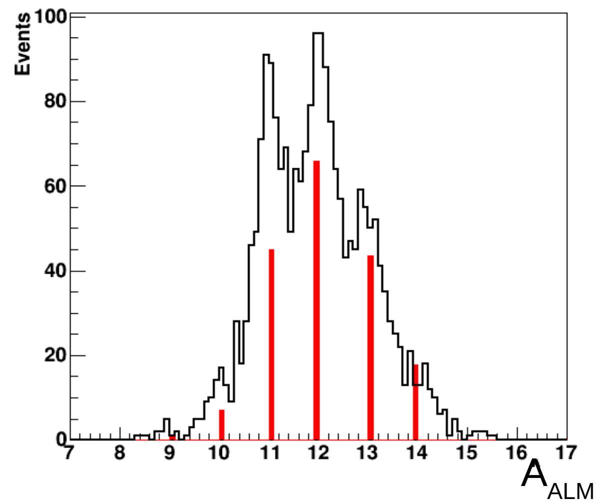
Using only A_1 method (TOF + tracker): $A_1 = \frac{p}{u\beta c\gamma}$



Resolution ~ 3%



In ~20% of events cross-check with ALM is possible



Conclusions

FOOT will measure fragmentation cross sections relevant for **hadrontherapy** and for space **radioprotection**;

the mass of the fragments can be determined with a **resolution better than 3%** , both @200 MeV/u and @700 MeV/u;

some detectors and magnets still under construction;

general test beam with a reduced setup performed in **April at GSI** and analysis is still ongoing;

first **measurements:** first half of 2020.

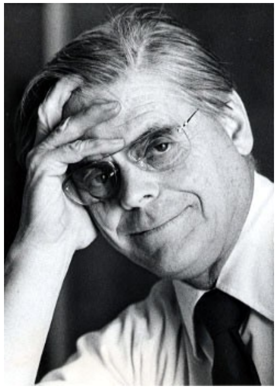
Thank for your attention!

Thank for your attention!

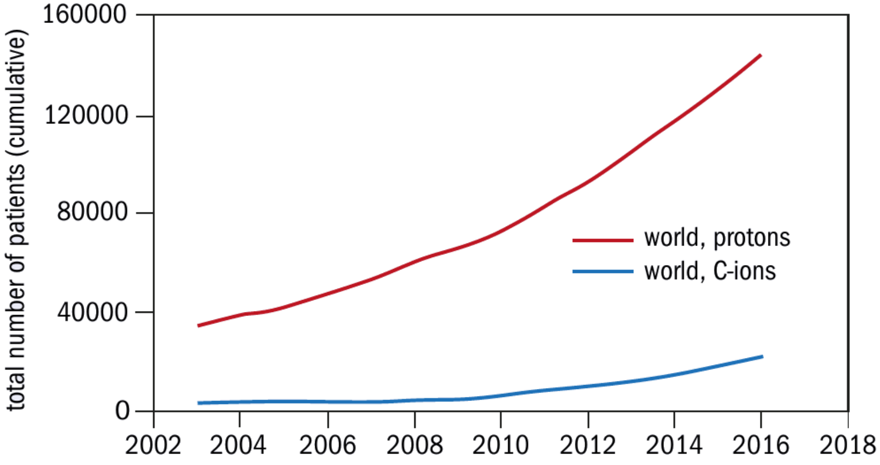
Backup slides

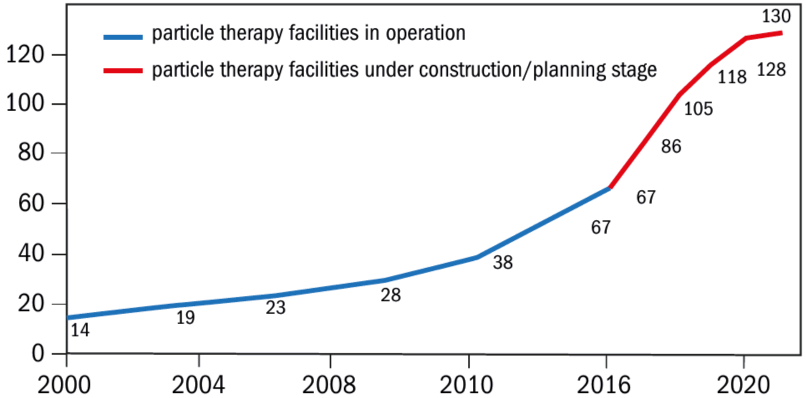
Past, present and future of Hadrontherapy

Robert R. Wilson (1914-2000) wrote
Radiological Use of Fast Protons
(*Radiology. 1946 Nov;47(5):487-91*)



In the World: 1954 Berkeley, 1957 Uppsala, 1967 Dubna, 1979 Chiba, 1985 PSI (...)
In Italy: 2002 LNS (Catania), 2011 CNAO (Pavia), 2015 Centro di Protonterapia (Trento)

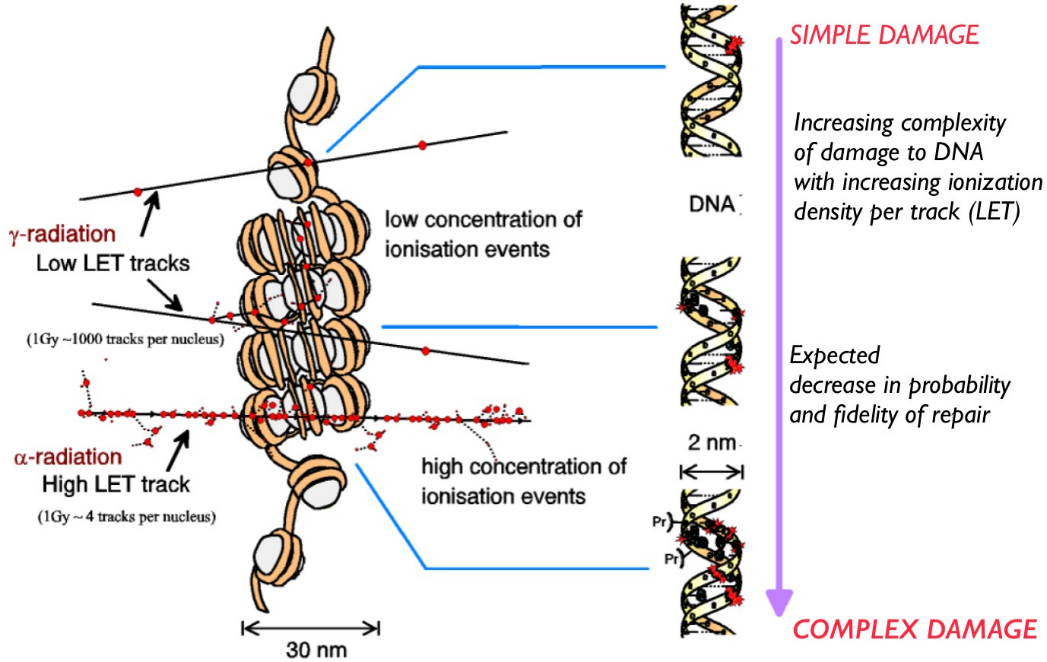


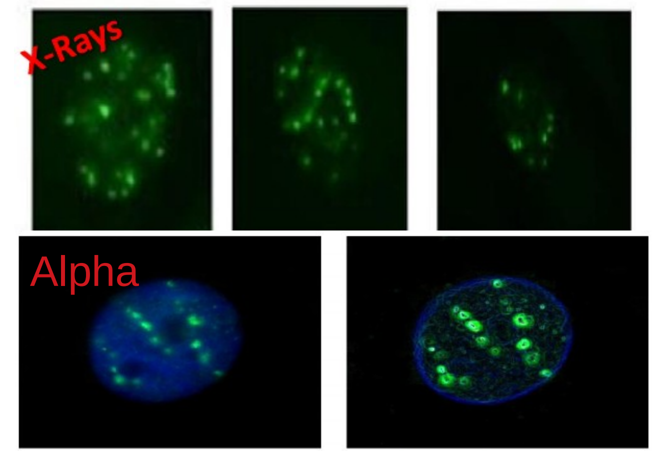


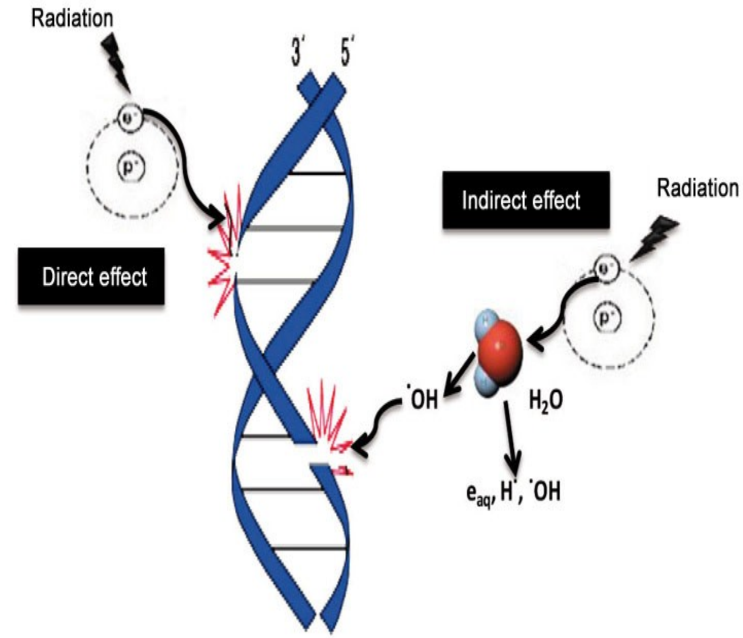
From March 2017 Hadrontherapy in Italy is included in LEA

DNA as target

DNA in cell nuclei is the most sensitive **target** for radiation

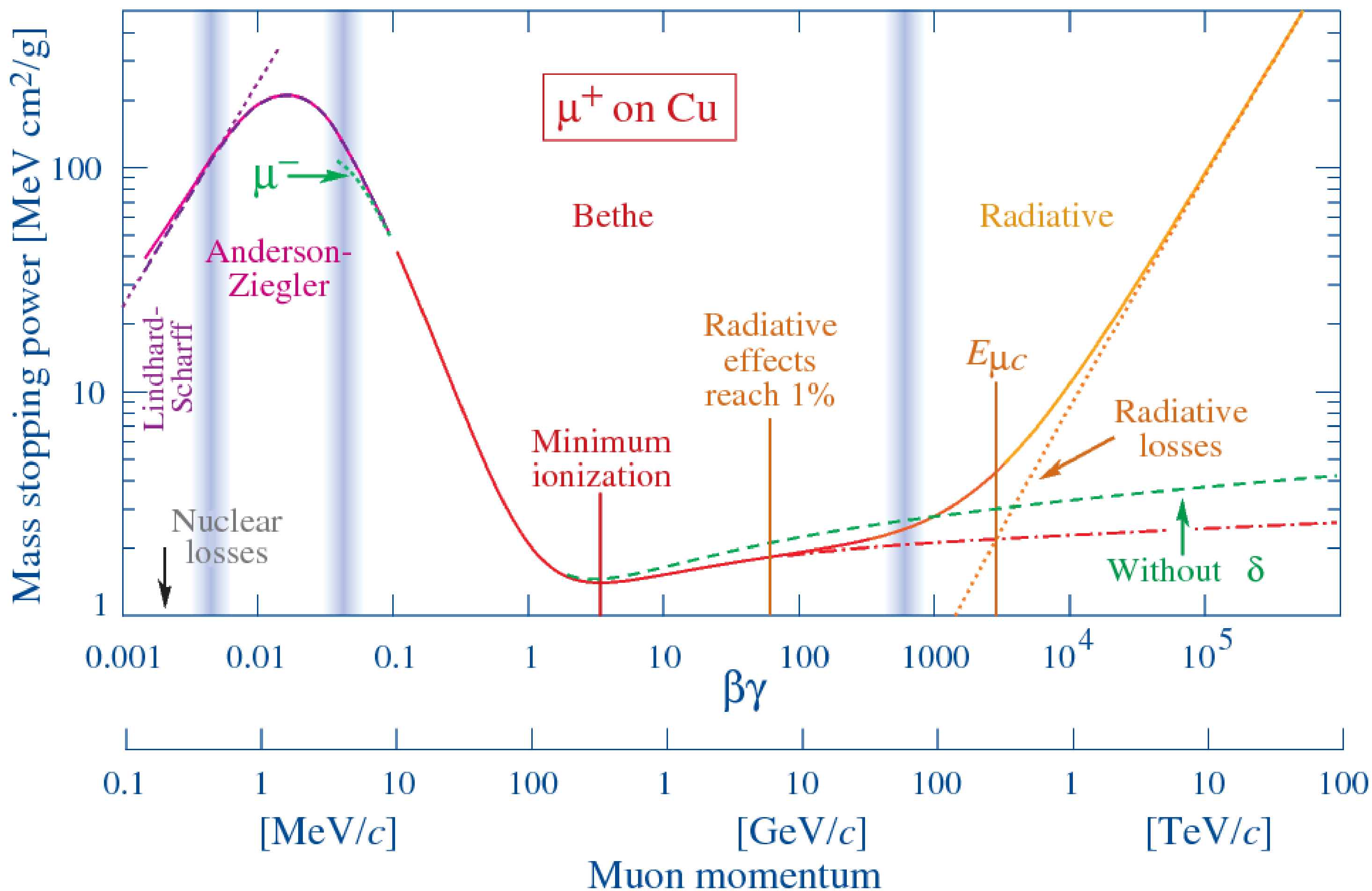






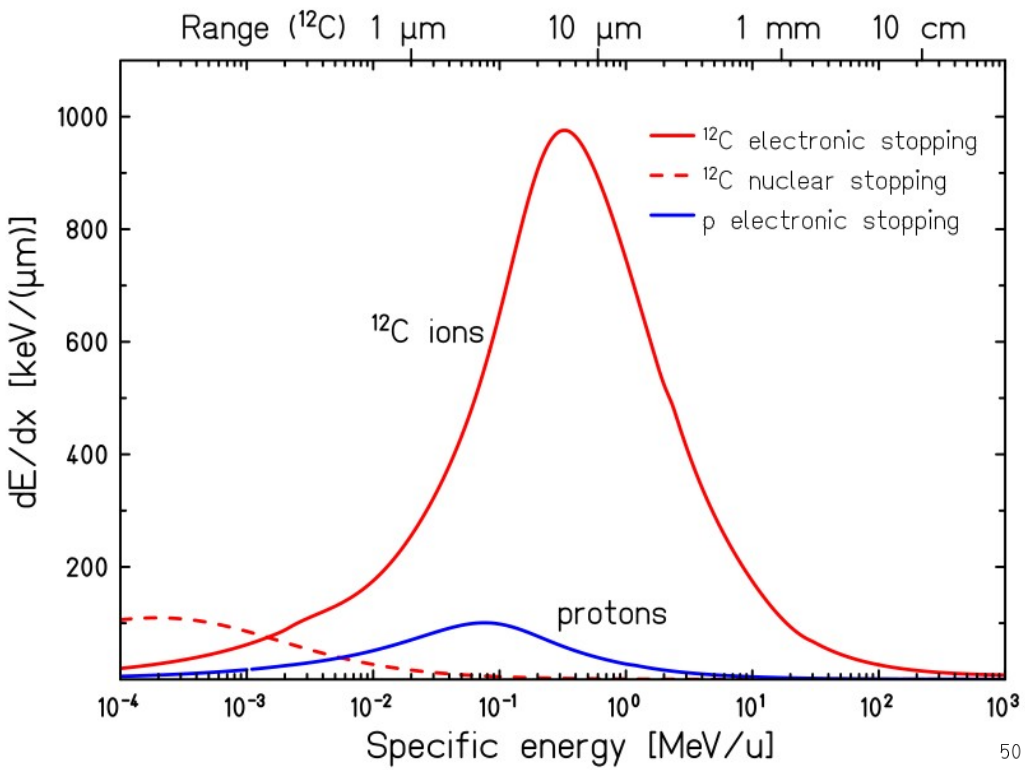
Indirect effect accounts
for **65%** of DNA damages
in **low LET** radiation

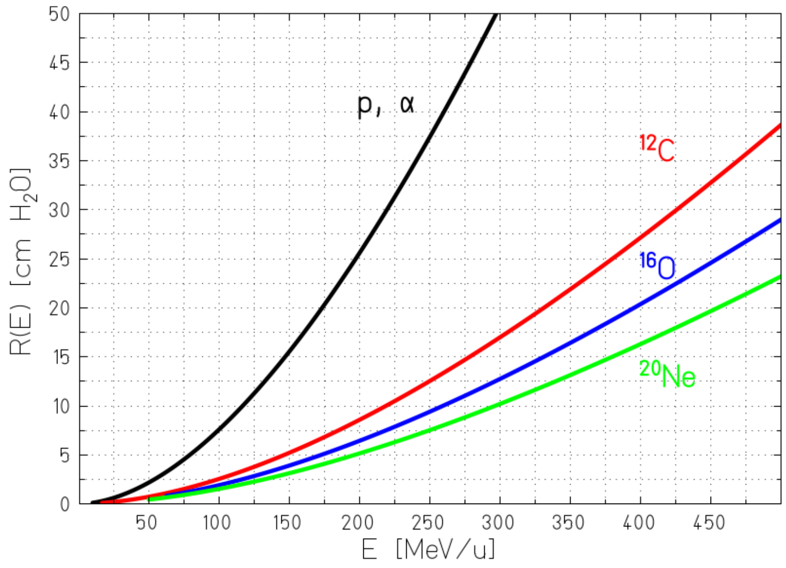
Riccardo Ridolfi



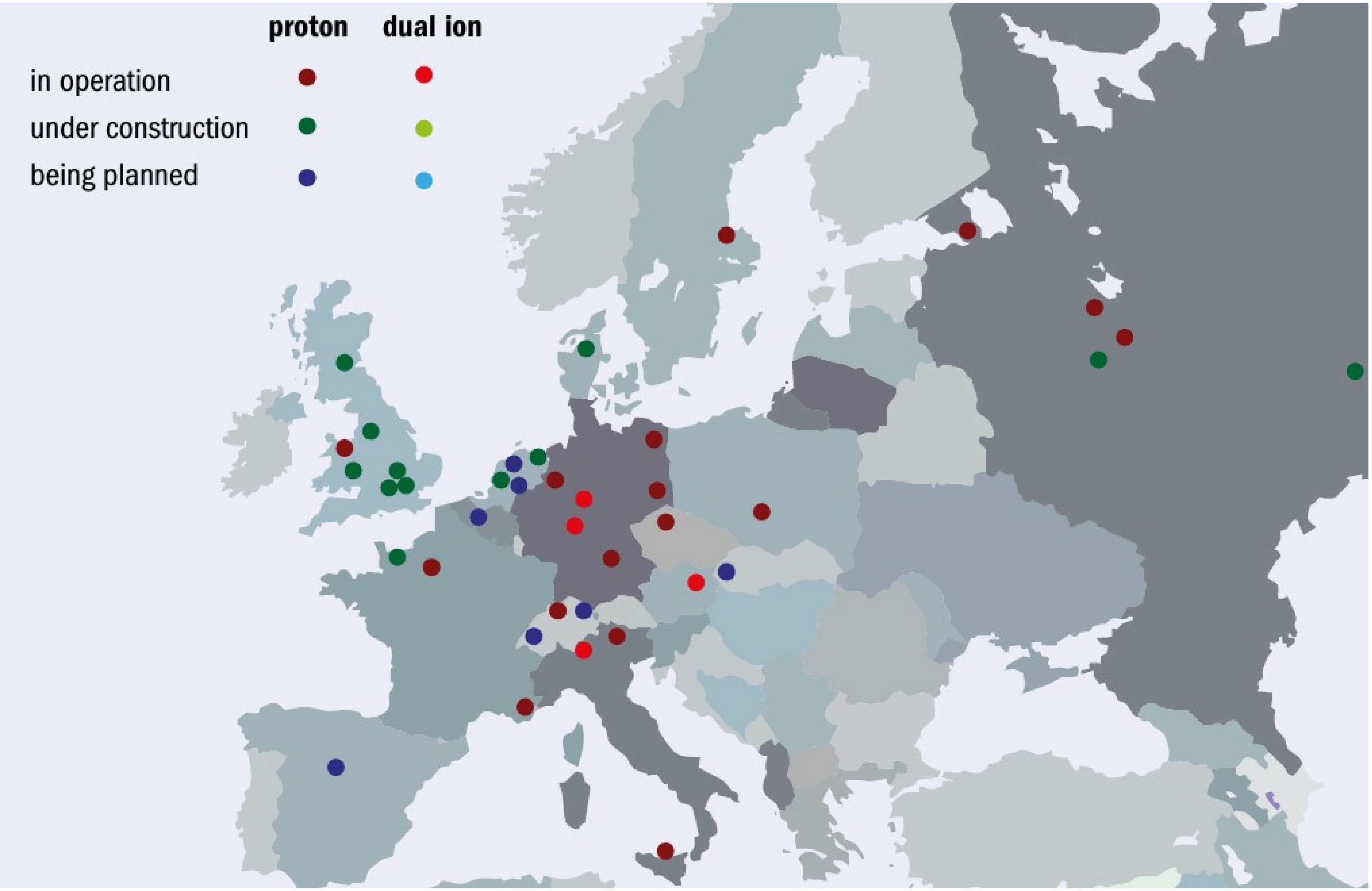
$$-\left\langle \frac{dE}{dx} \right\rangle = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[ln\left(\frac{2m_e \gamma^2 v^2 W_{\max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

Riccardo Ridolfi





Riccardo Ridolfi



Riccardo Ridolfi

The standard approach uses a χ^2 minimization method based on a function f defined as:

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

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. The evaluation of the uncertainties associated to A_1, A_2 and A_3 has to take into account their correlation which is generically expressed by the matrix B, related to the correlation matrix C by the function $B = \left(C \cdot C^T\right)^{-1}$. The correlation matrix C is expressed as:

$$C = \begin{pmatrix} \frac{\partial A_1}{\partial T} dT & \frac{\partial A_1}{\partial P} dP & 0 \\ \frac{\partial A_2}{\partial T} dT & 0 & \frac{\partial A_2}{\partial K} dK \\ 0 & \frac{\partial A_3}{\partial P} dP & \frac{\partial A_3}{\partial K} dK \end{pmatrix} \tag{10}$$

Riccardo Ridolfi

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:

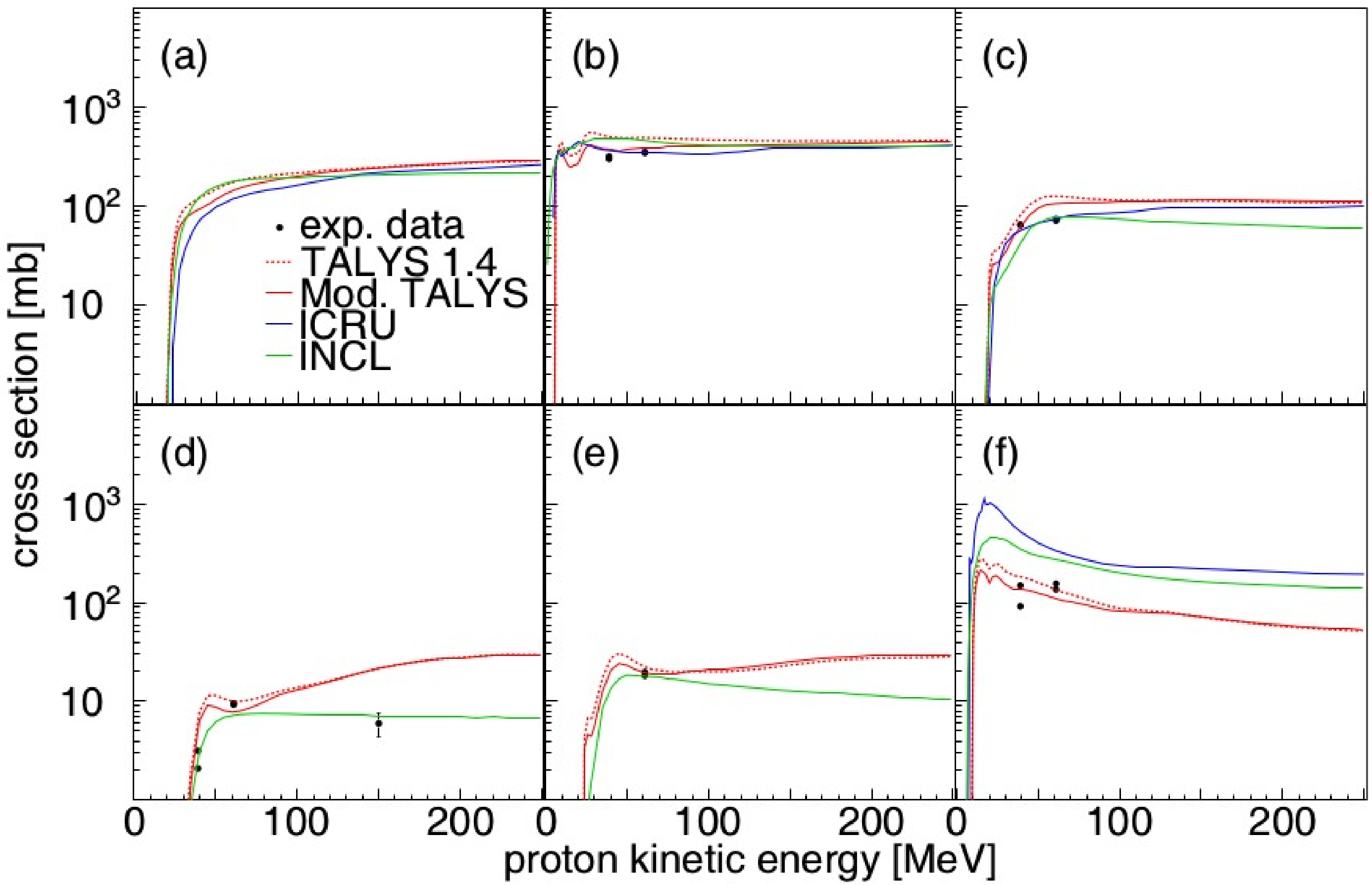
$$f(\vec{x}) = \left(\frac{TOF - T}{\sigma_{TOF}}\right)^2 + \left(\frac{p - P}{\sigma_p}\right)^2 + \left(\frac{E_k - K}{\sigma_{E_k}}\right)^2 \tag{12}$$

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

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

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.

Riccardo Ridolfi



10.1140/epjp/i2015-15153-x

Riccardo Ridolfi

FOOT GOAL:

- differential cross sections (E_{kin}, θ) of each produced fragment

$$\frac{d\sigma_f}{dE_{kin}} = \frac{(Y_f - Bkg_f)^U}{N_{Prim} \,.\, N_t \,.\, \Omega_{Ekin}\ \epsilon_f}$$

PhD thesis of Serena dott.sa Valle Marta

- f — fragment: all Carbon Isotopes
- $(Y_f - Bkg_f)^u$ — Unfolded (Yield – Bkg) of the fragment
- N_{prim} — number of primary events
- N_t — number of scattered center per unit area $N_t = \frac{\rho \cdot N_A \cdot depth}{A}$
- ε_f — efficiency
- Ω_{Ekin} — phase space $\Omega_{Ekin} = Ekin^f_{max} - Ekin^f_{min}$

Performed wrt $E_{kin,n}$ in direct kinematics

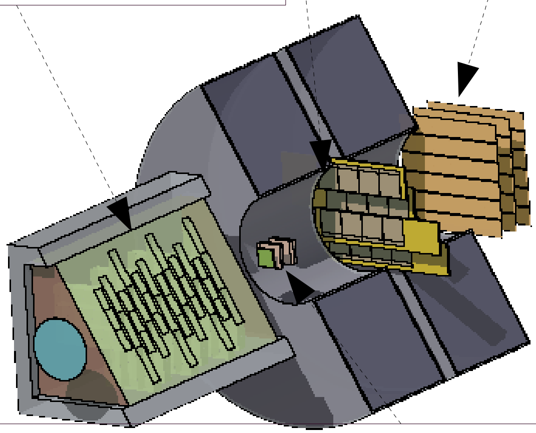
The FOOT experiment

Riccardo
Ridolfi

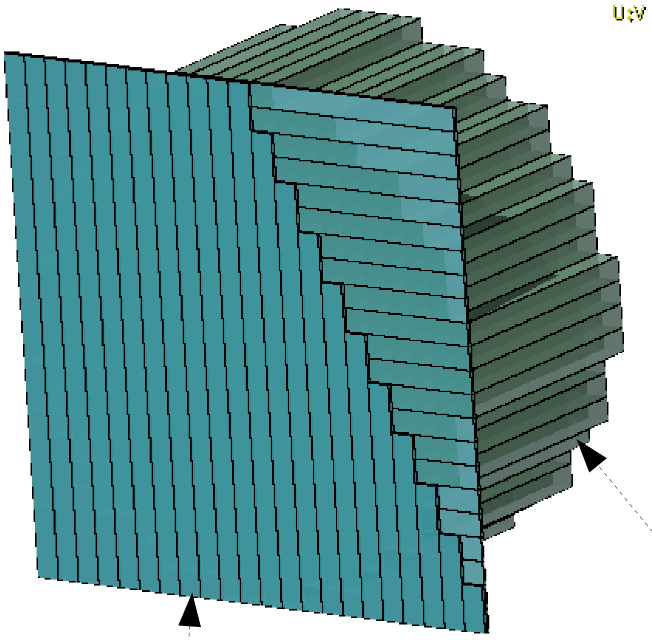
2 planes of 16 M28 pixel sensors, each sensor covering 2x2cm^2

3 x-y planes separeted by 2cm gaps, the covered area is 9x9cm^2

12 layers of wires with three drift cells per layer (16mm x 10mm cell dimension)



4 tracking layers plus the MIMOSA28 chip as final sensor (20.22mm x 22.71mm chip dimension)



BGO crystals calorimeter (bismuth germanate)

2 layers of 20 plastic scintillator rods covering an area of 40x40cm^2