UNIVERSITÀ DI PISA

Improving hadrotherapy with FOOT experiment

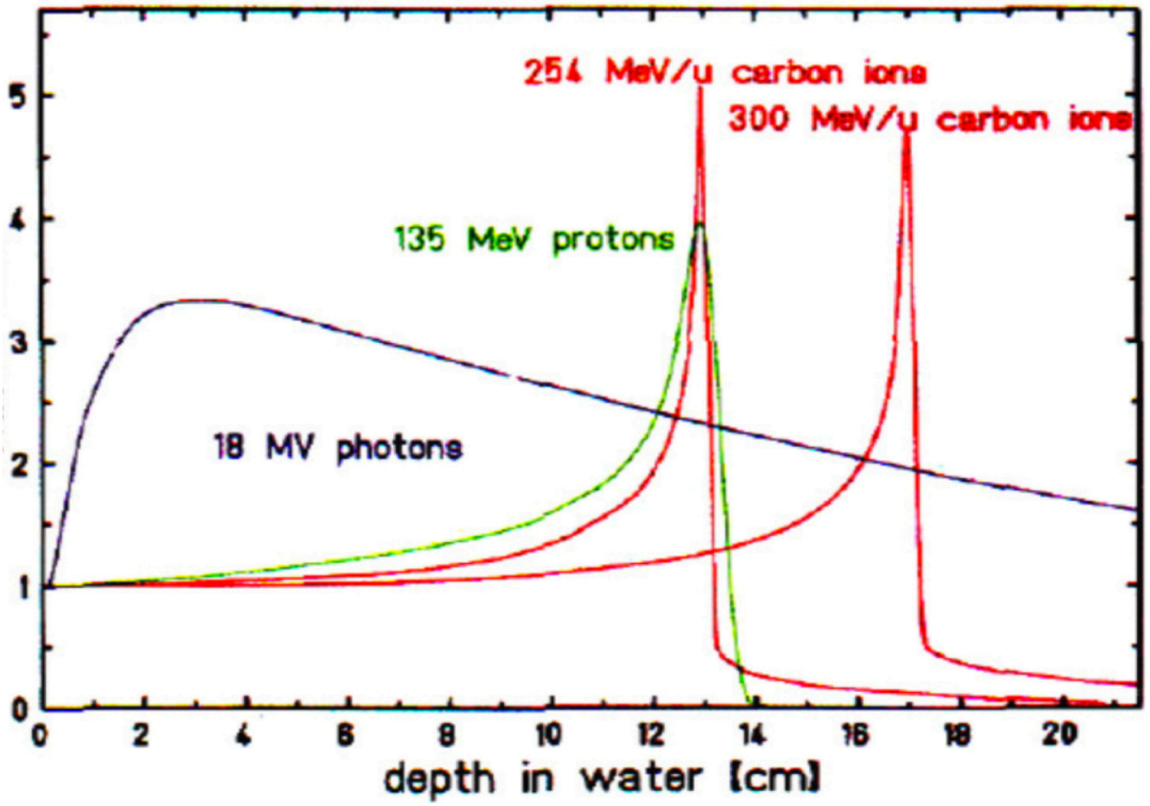
Marco Francesconi

First year seminar, Pisa 21-09-2017

Summary

- What is hadrotherapy
  - How it compares to conventional external radiotherapy treatments
- The problem of nuclear fragmentation
  - its effect on hadrotherapy
- The FOOT Expetiment
  - Experimental setup
  - Expected results

Interaction with matter



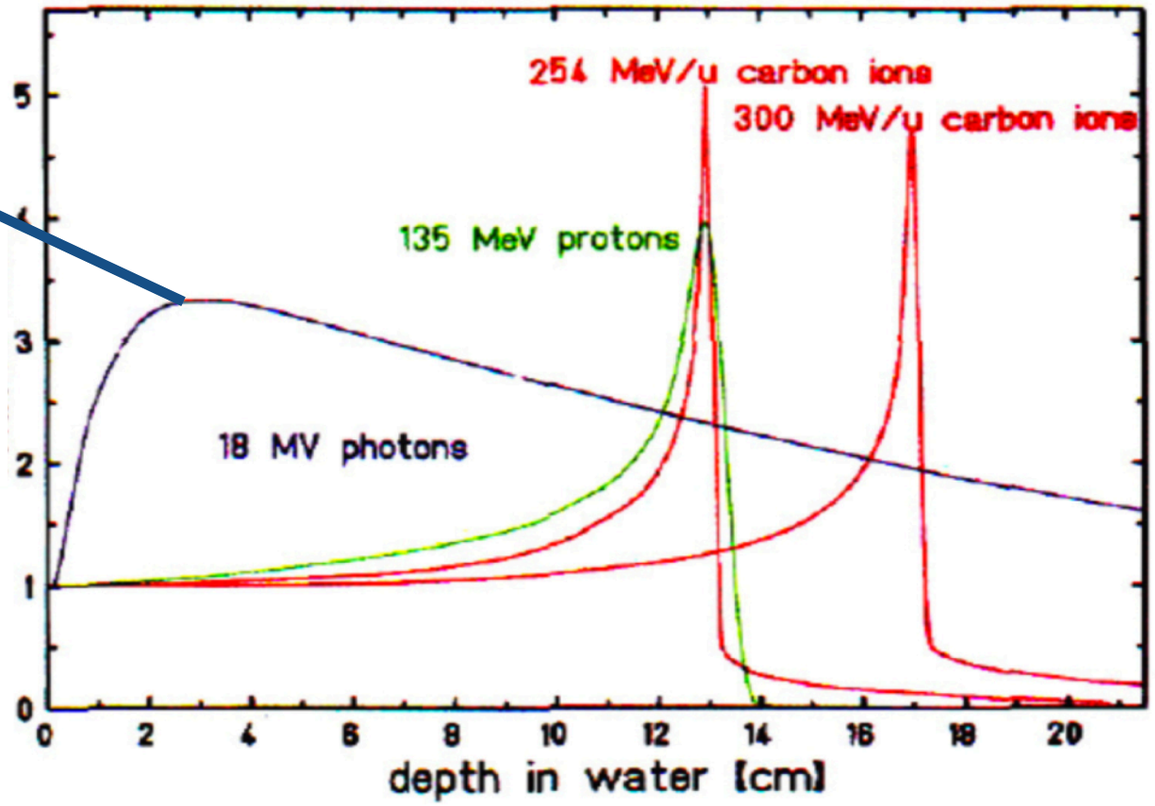
Linear Energy Transfer

$$LET = \frac{dE}{dx}$$

Interaction with matter

Photons:

- Compton Scattering
- Pair Production



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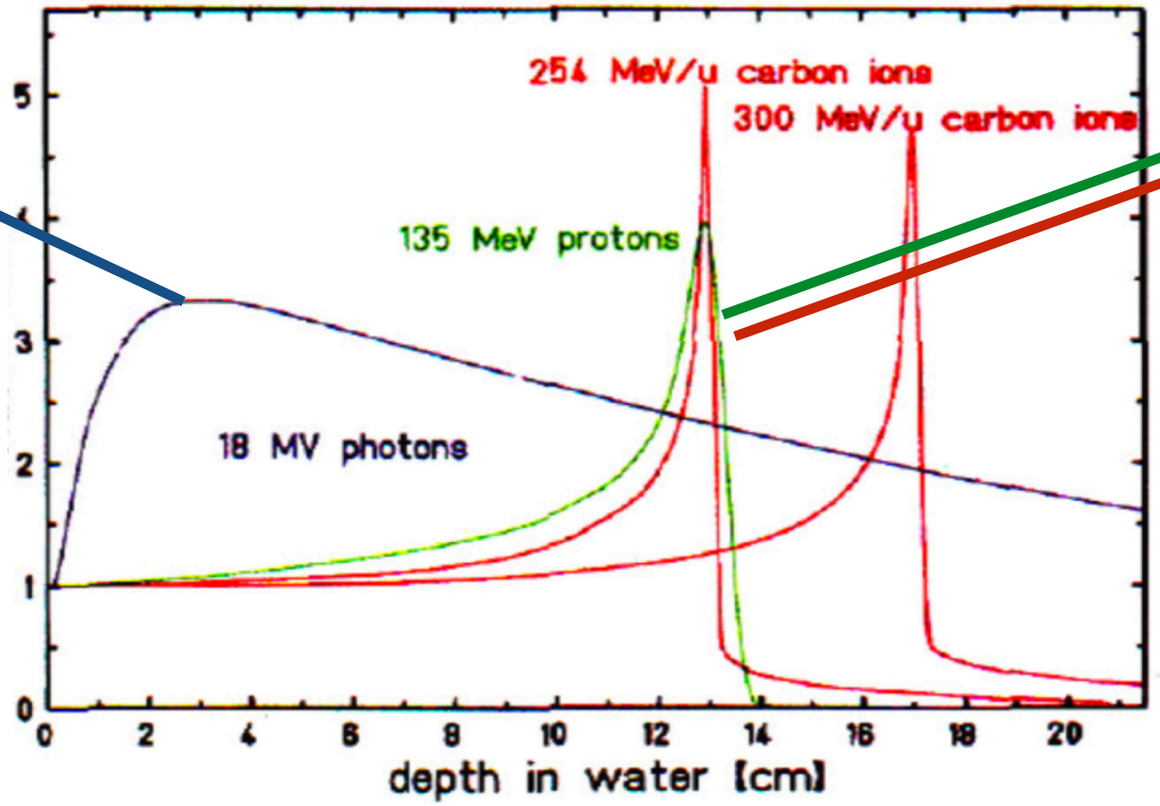

Proton/charged ion:

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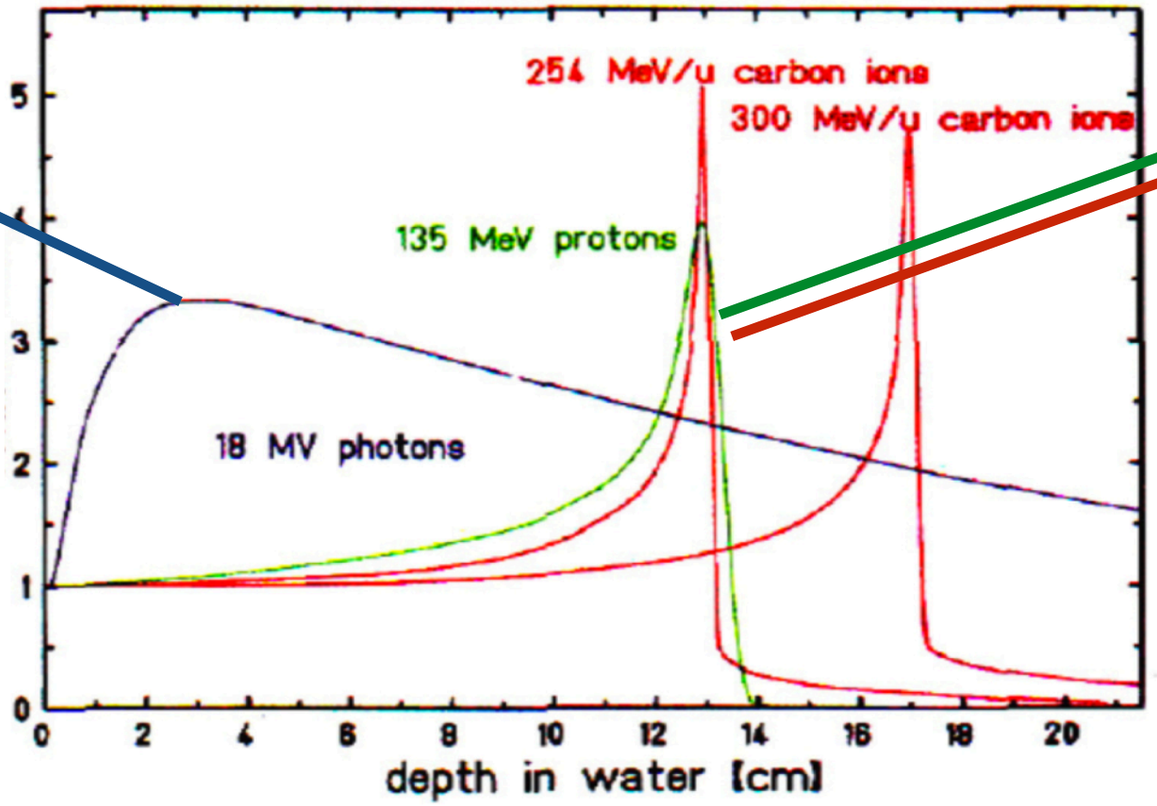

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- Excitation
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Bragg Peak

- Most of the energy is deposited in a small region
- Less deposit in surface
- Can be tuned by changing the energy of the incoming beam

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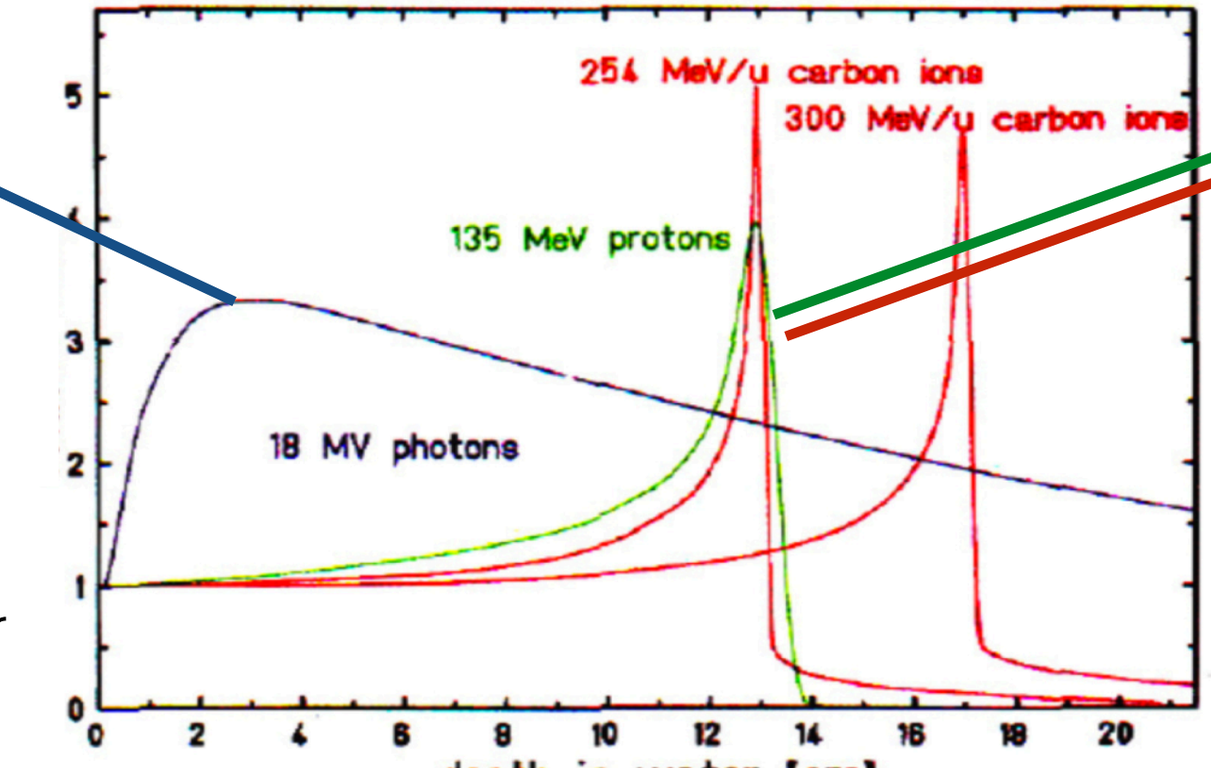

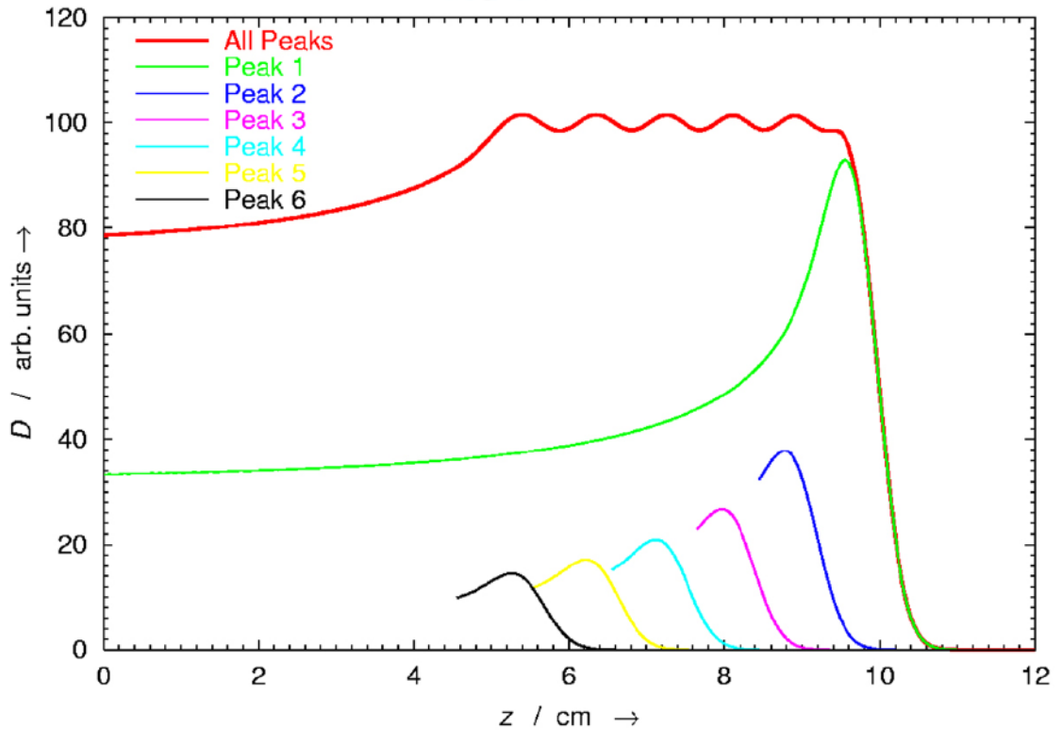

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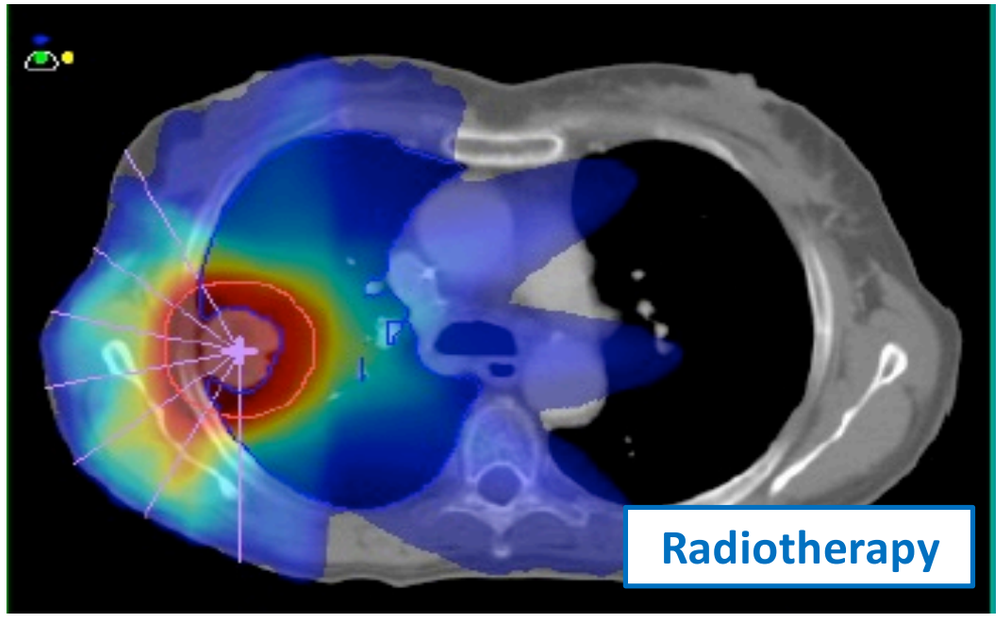
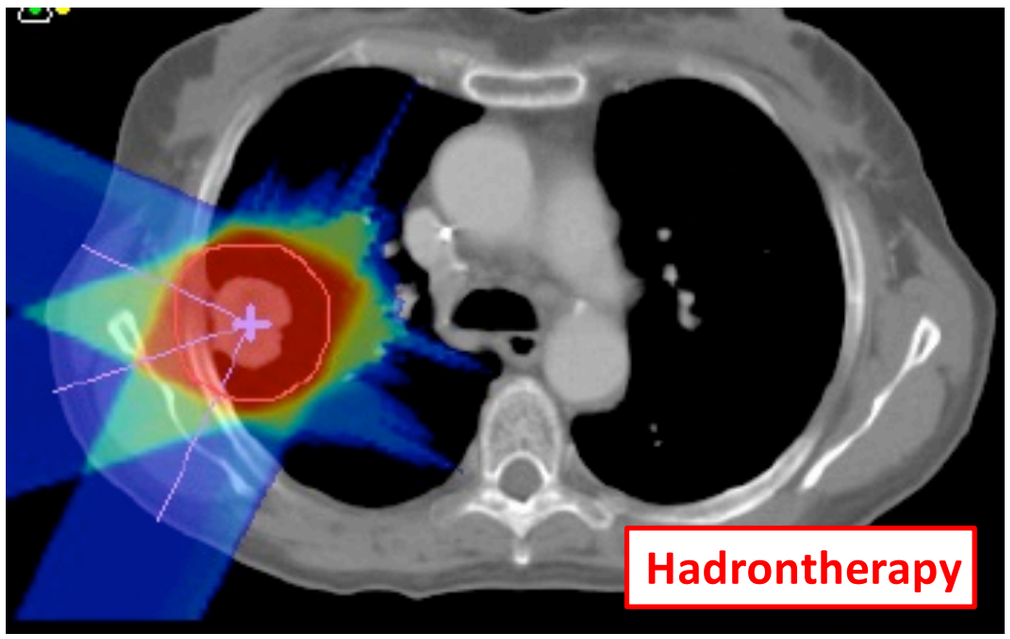
Spread-Out Bragg Peak

Hadrotherapy and conventional radiotherapy

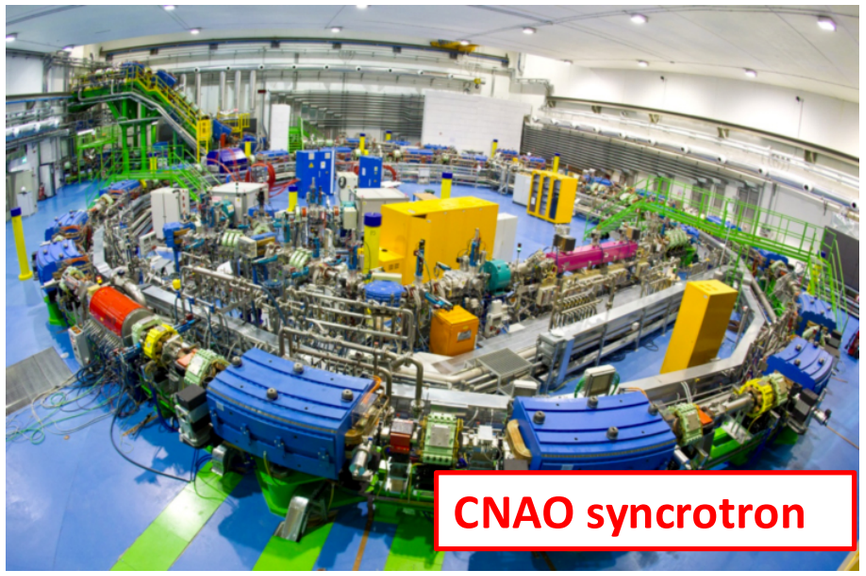


Tens thousands euros



Hundreds millions euros

Treatments costs
~ 5-10 radiotherapy



Hadrotherapy showed capable of addressing cases of radiation resistant tumor
But is worth the economical effort?

Hadrotherapy in Italy

At least yes in Italy!!!!

4th position in the world (ex-aequo with China)

CATANA
Catania

Proton beam up to 60 MeV
Active since 2002
specialized on eye tumor
363 patients

CNAO
Pavia

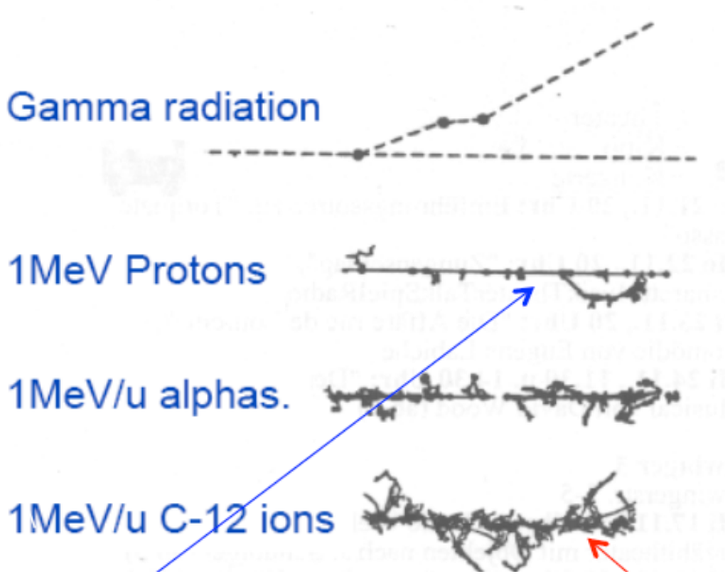
Proton Beam up to 250MeV
Carbon Beam up to 480MeV/u
Active since 2011
1200 patients

Proton Therapy Center
Trento

Proton Beam up to 230MeV
Active since 2015

Still experimental treatments but recognized by Italian sanitary system in 2017

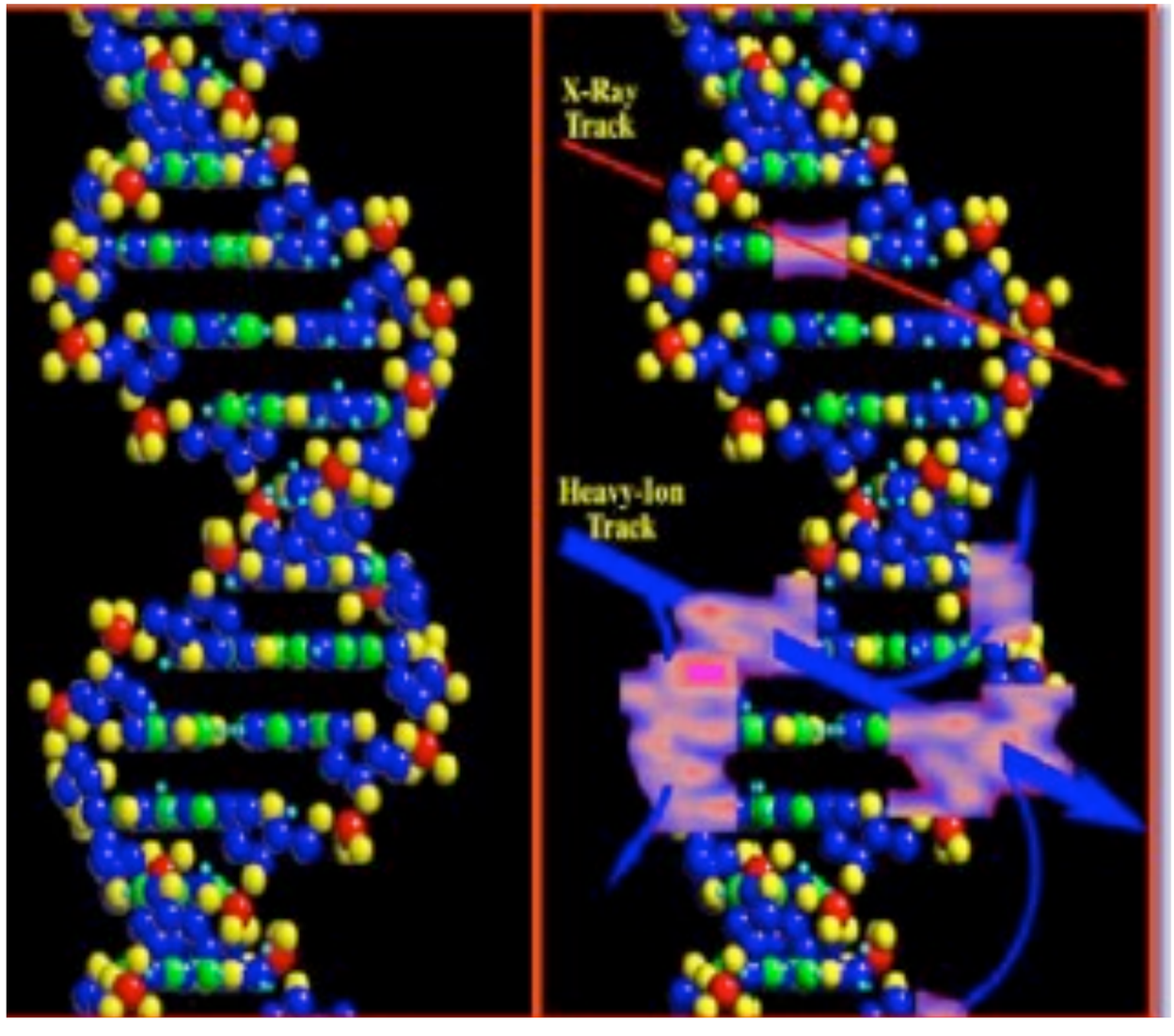
RadioBiological Effectiveness



$$R.B.E = \left(\frac{D_{X-ray}}{D_H}\right)_{Same\ effect}$$

Dose

$$D = \frac{dE}{dm}$$

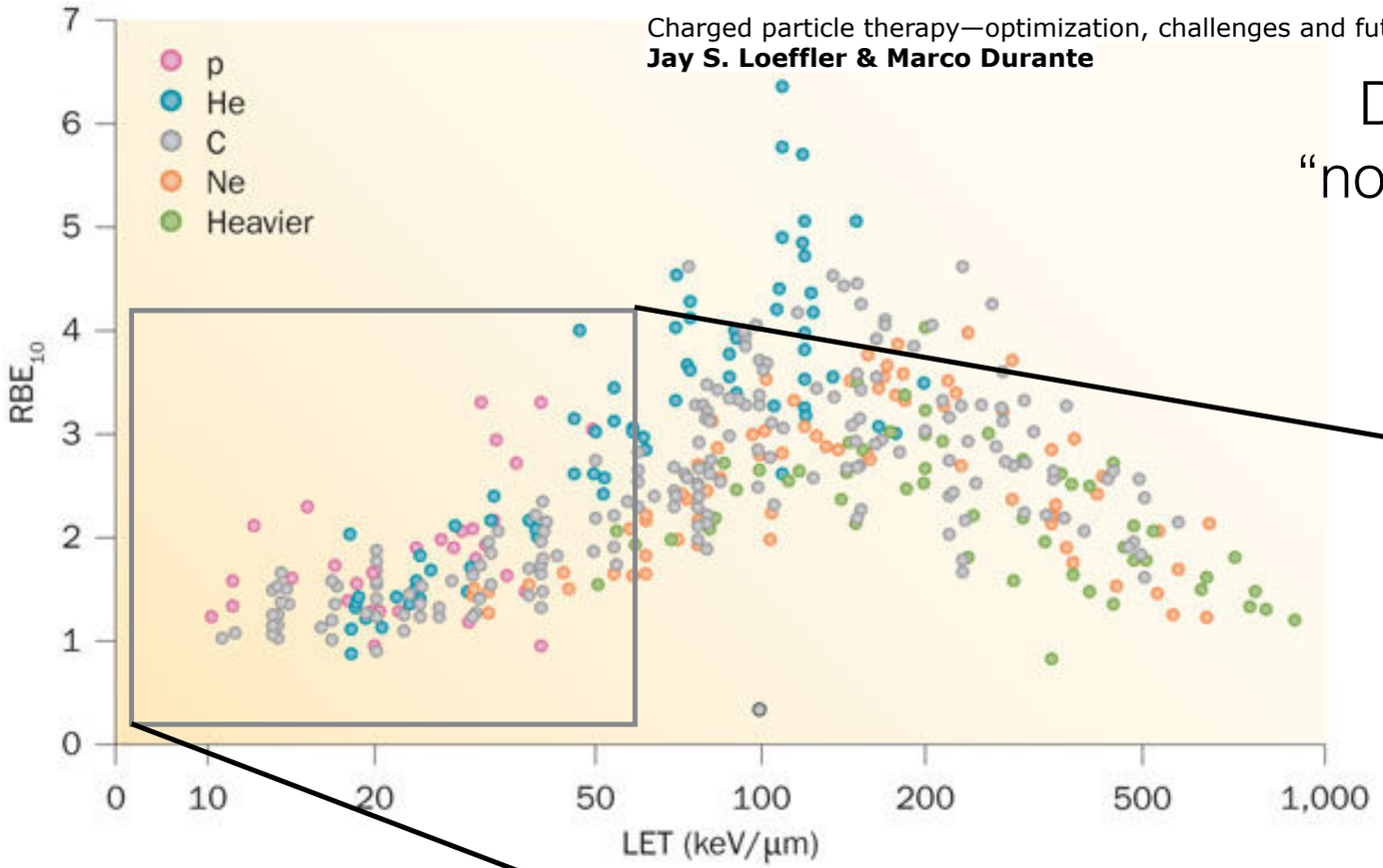


Particle with **bigger charge** tends to cause more ionization clusters

↓

Higher possibility to cause irreparable damage to the tumor cell

RBE values



Charged particle therapy—optimization, challenges and future directions
Jay S. Loeffler & Marco Durante

Difficult to evaluate correctly due to "non objective" nature of the observable

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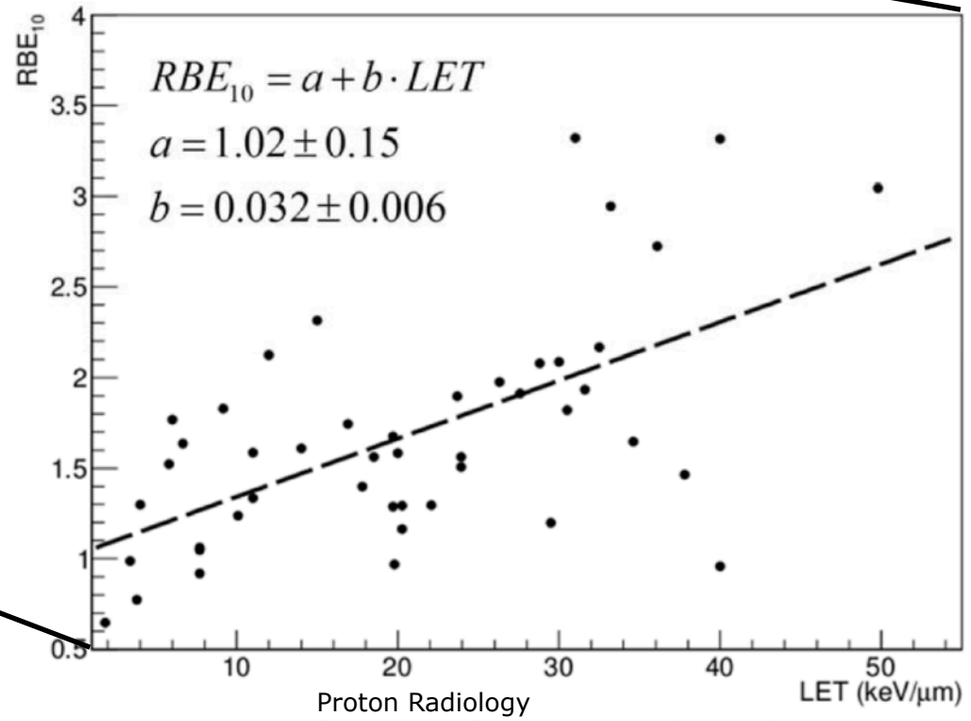

Proton Radiology
Francesco Tommasino & Marco Durante

RBE values

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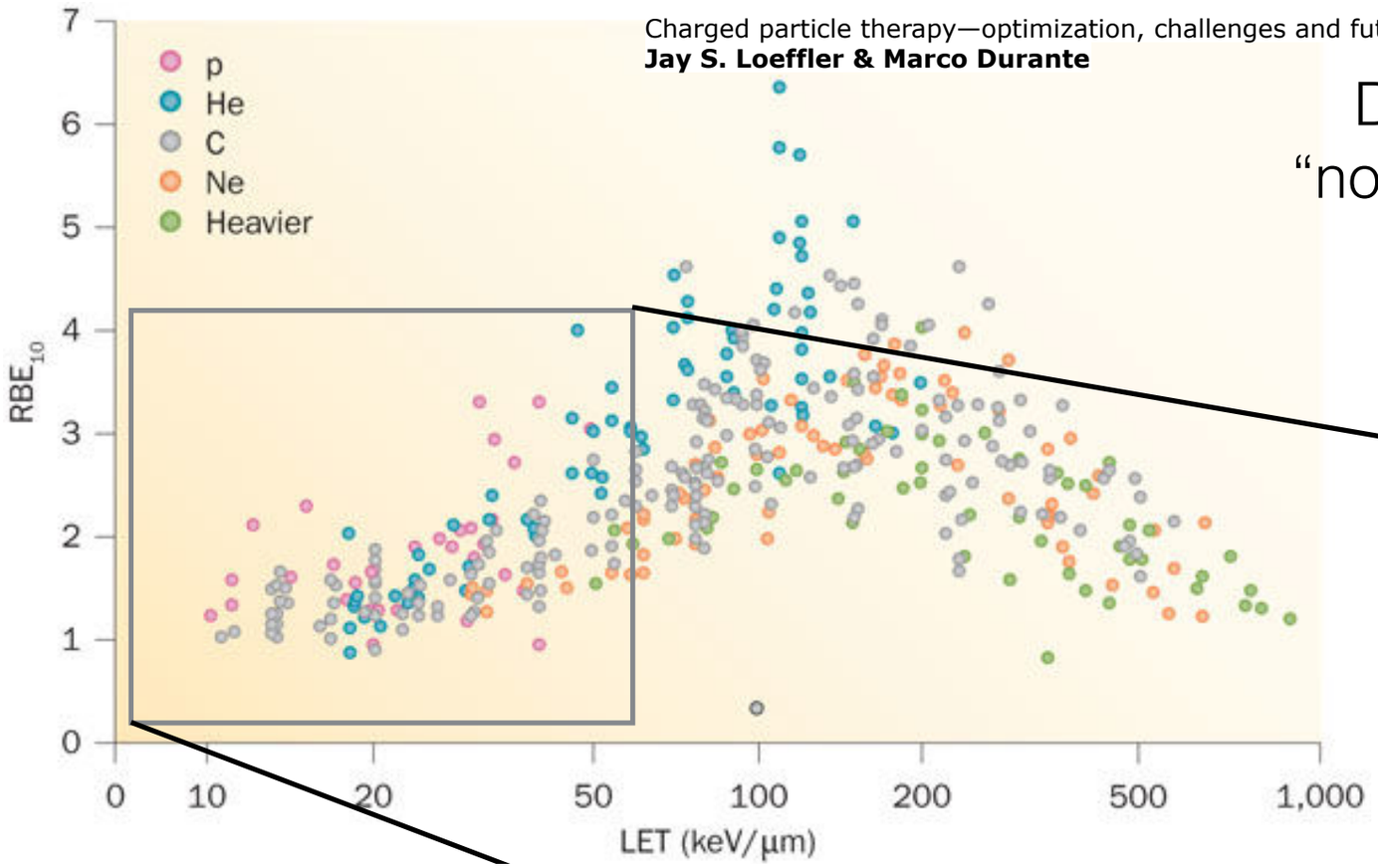

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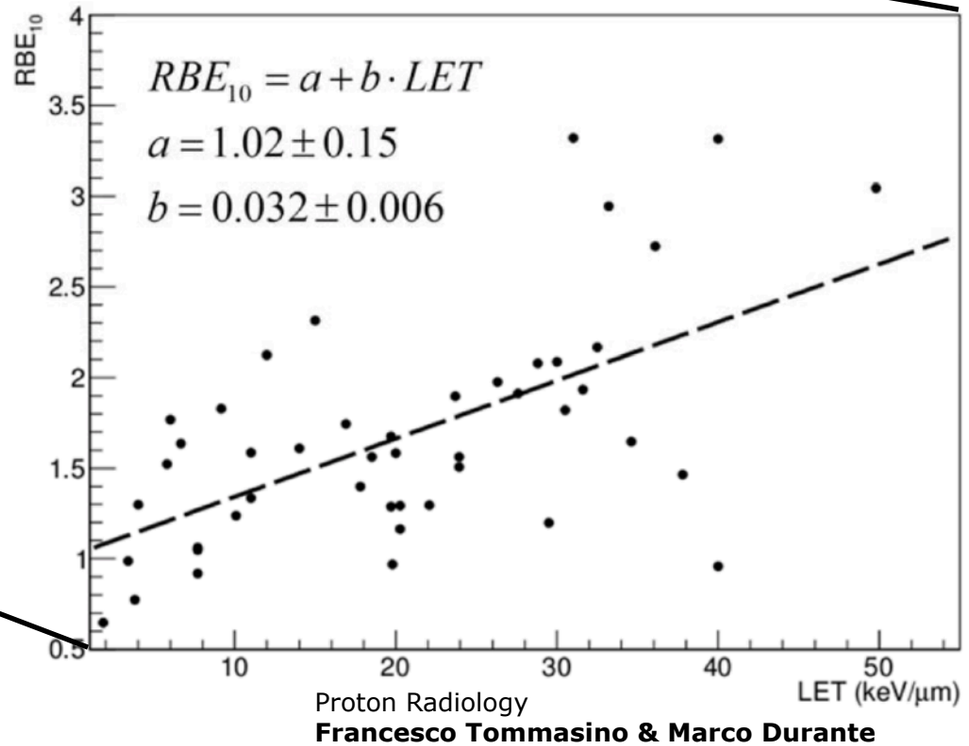

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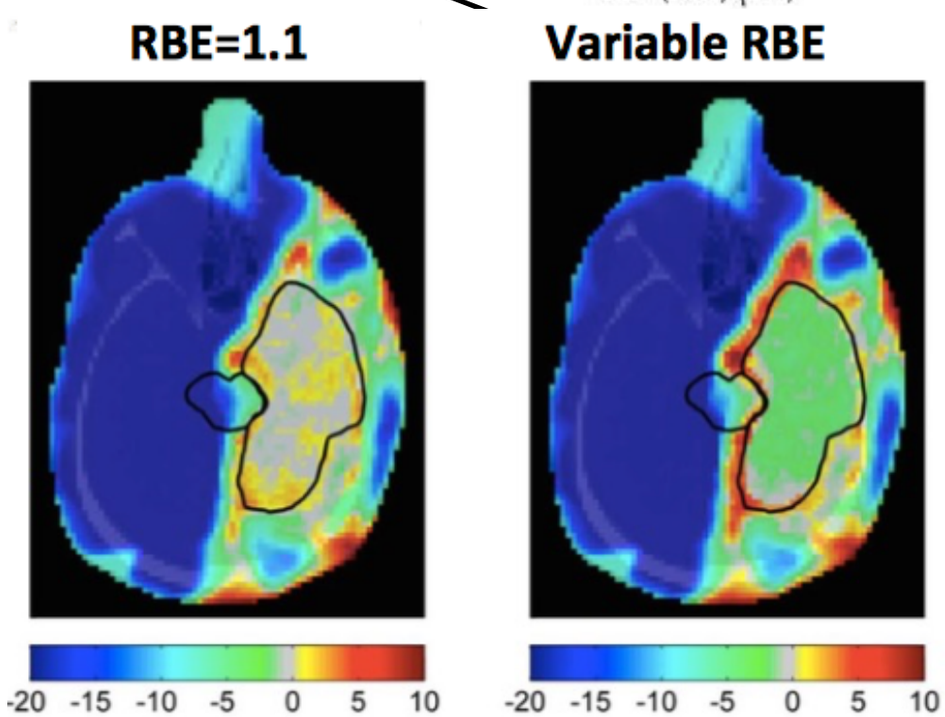
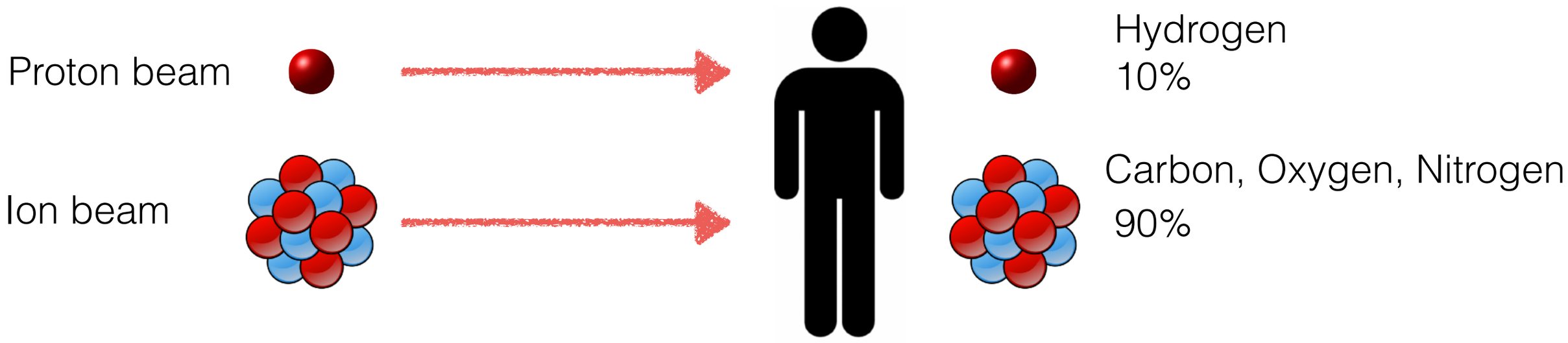


Target/projectile fragmentation is a source of such variations??

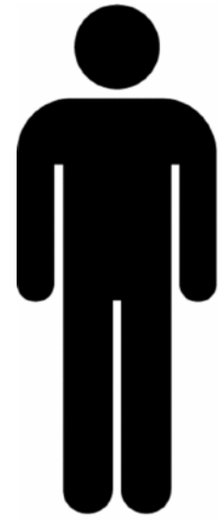
Fragmentation



Fragmentation

Proton beam

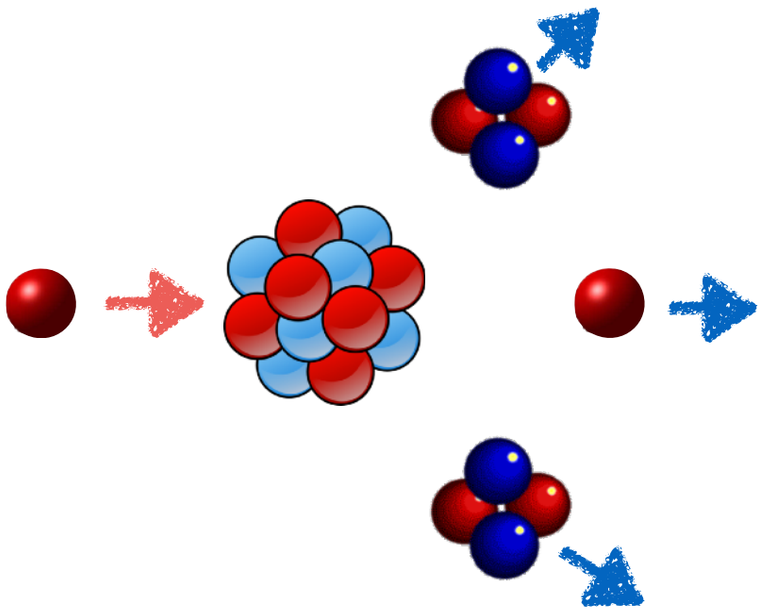
Ion beam



Hydrogen
10%

Carbon, Oxygen, Nitrogen
90%

Target Fragmentation



Low energy fragments

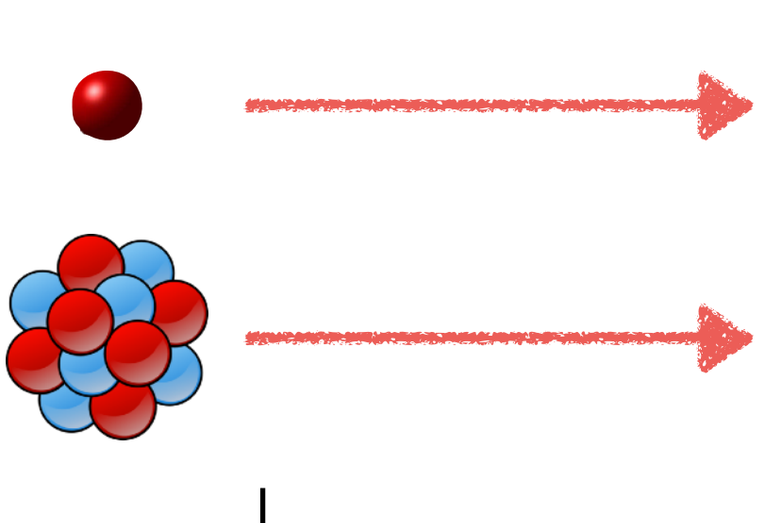
↓

Small Range

Fragmentation

Proton beam

Ion beam



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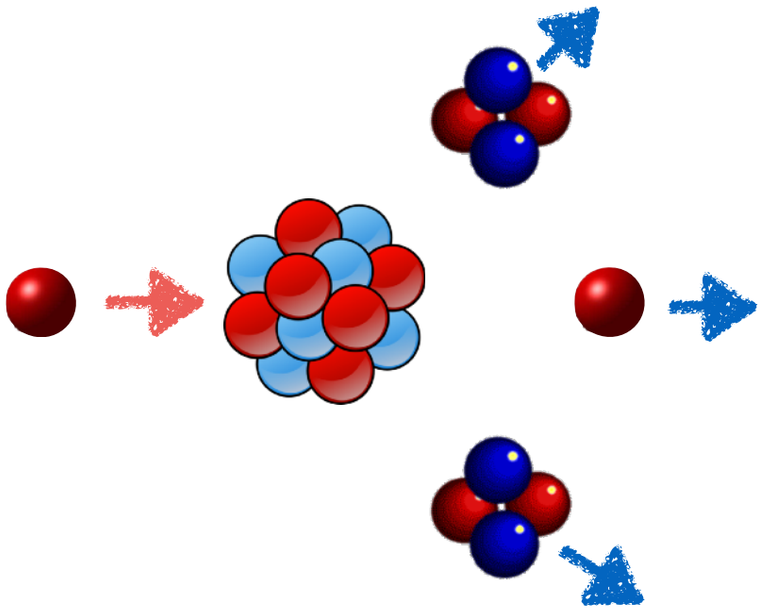
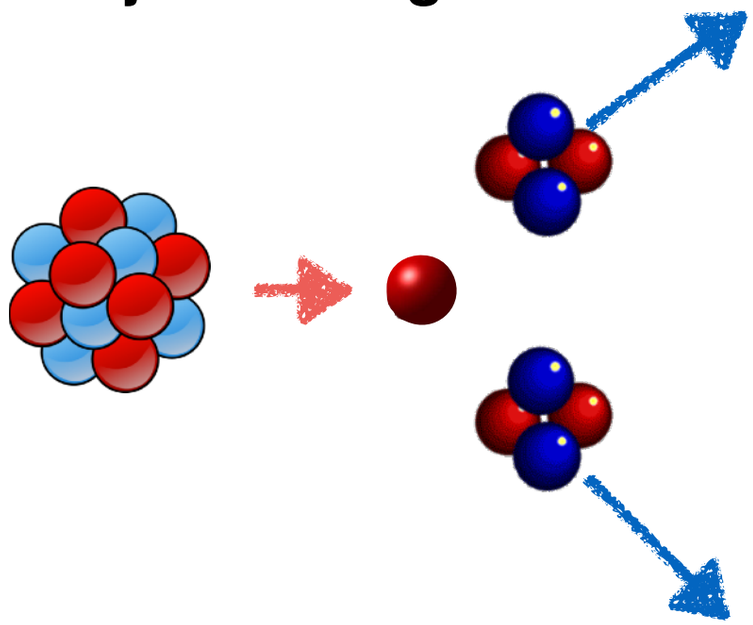


Low energy fragments

↓

Small Range

Projectile Fragmentation



High energy fragments

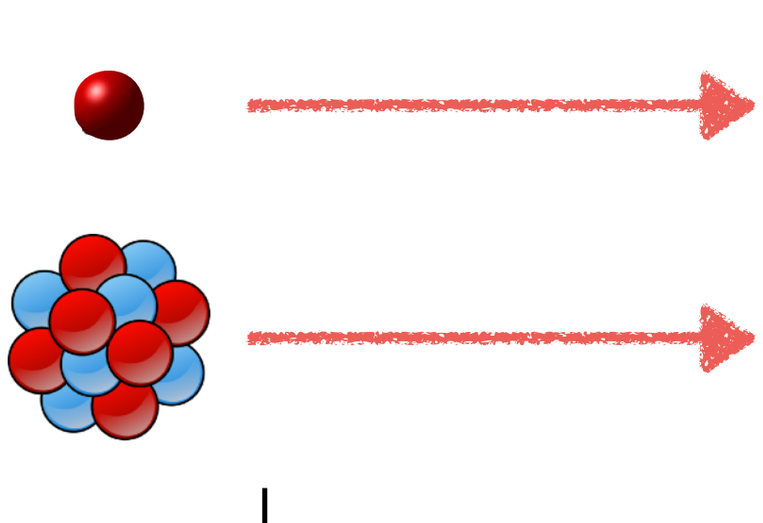
↓

Long Range

Fragmentation

Proton beam

Ion beam



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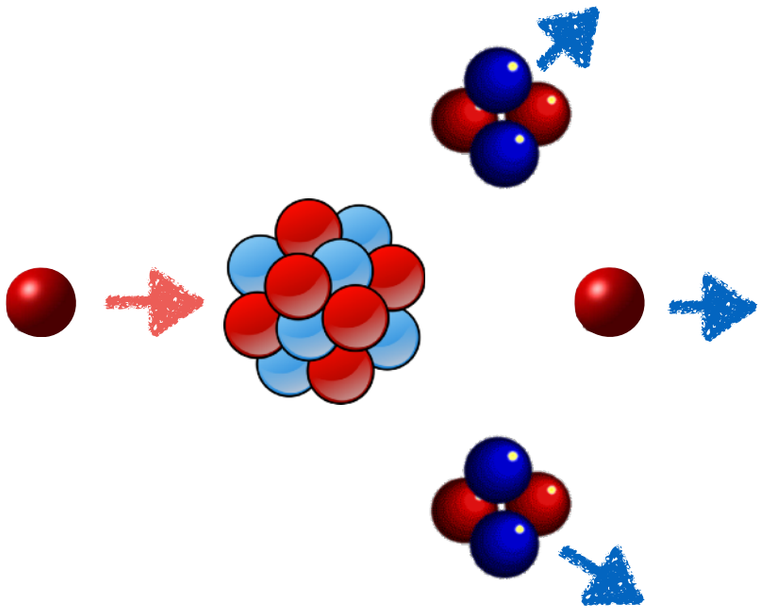

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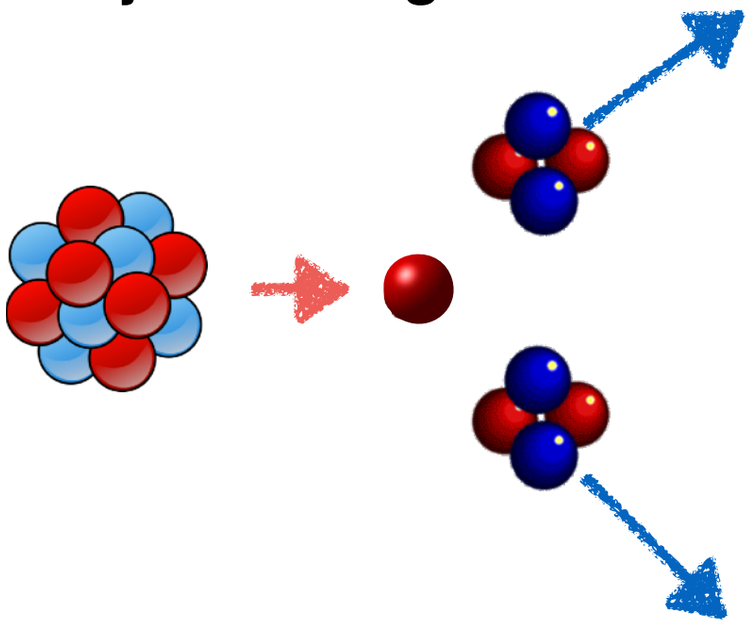
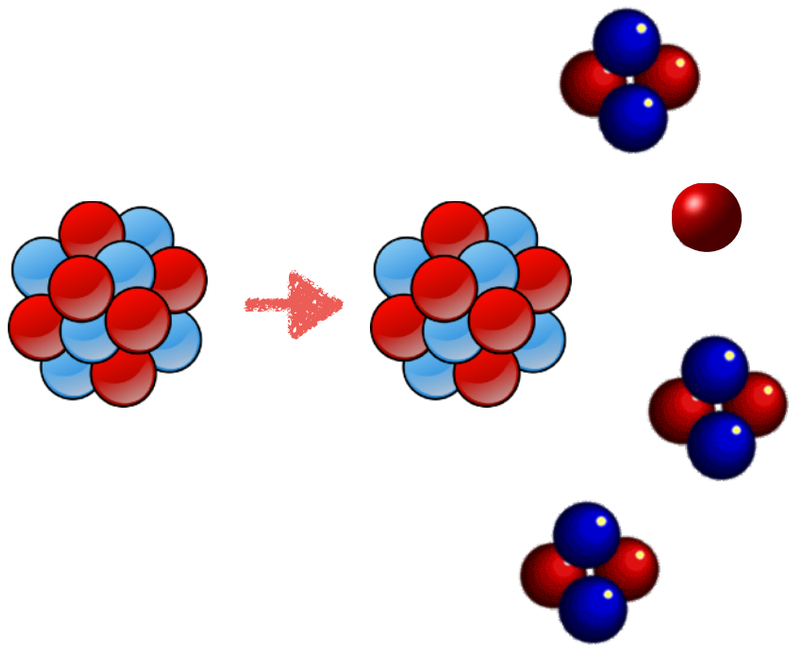


High energy fragments

↓

Long Range

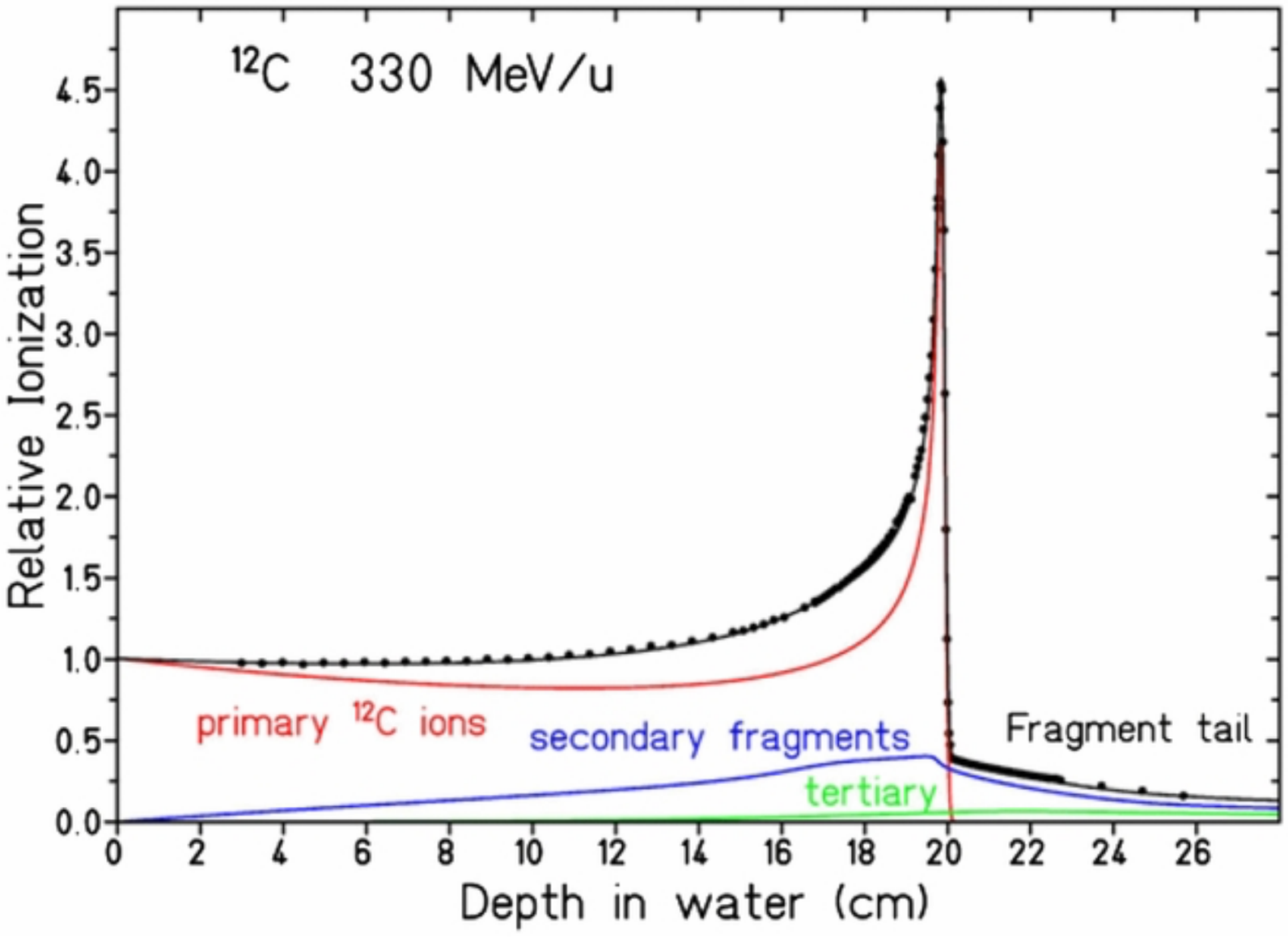
Taget+Projectile Fragmentation

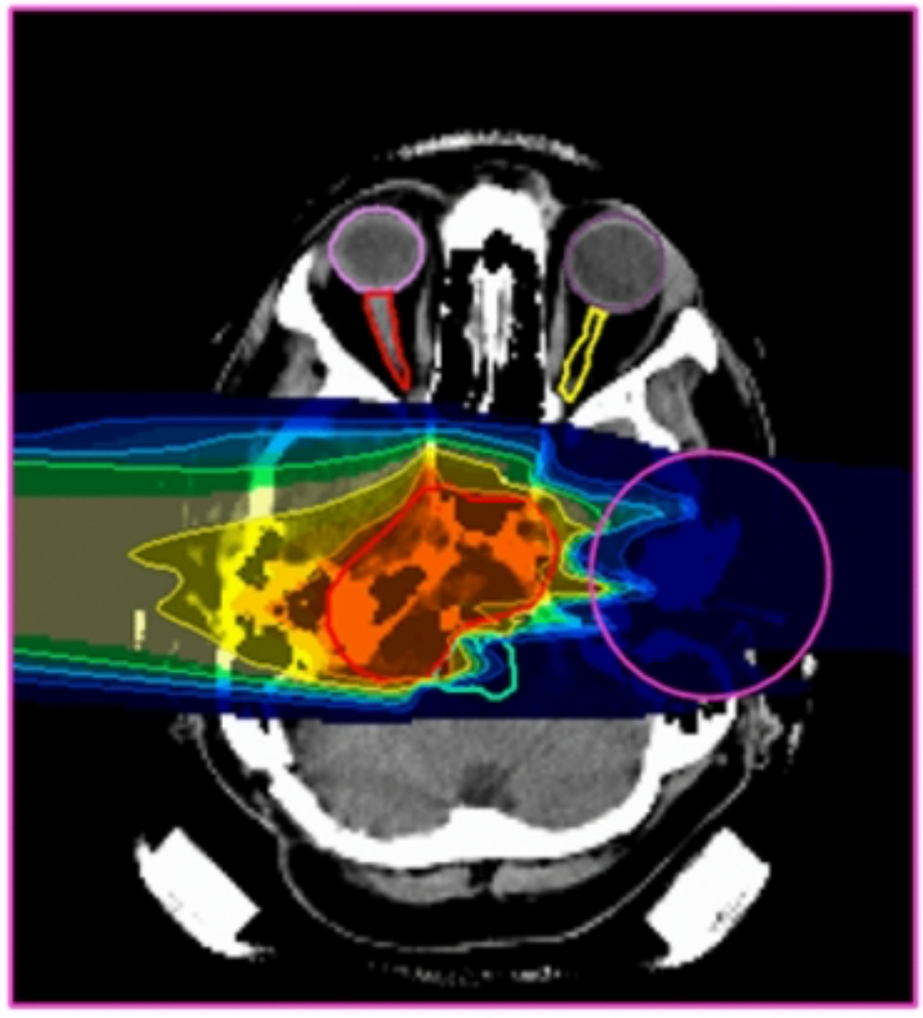


Both

Effect

E Haettner et al 2013 Phys. Med. Biol. 58 8265





Increased energy deposit in the entry channel (Target Fragmentation)
long tail after the tumoral target (Projectile Fragmentation)

Effect

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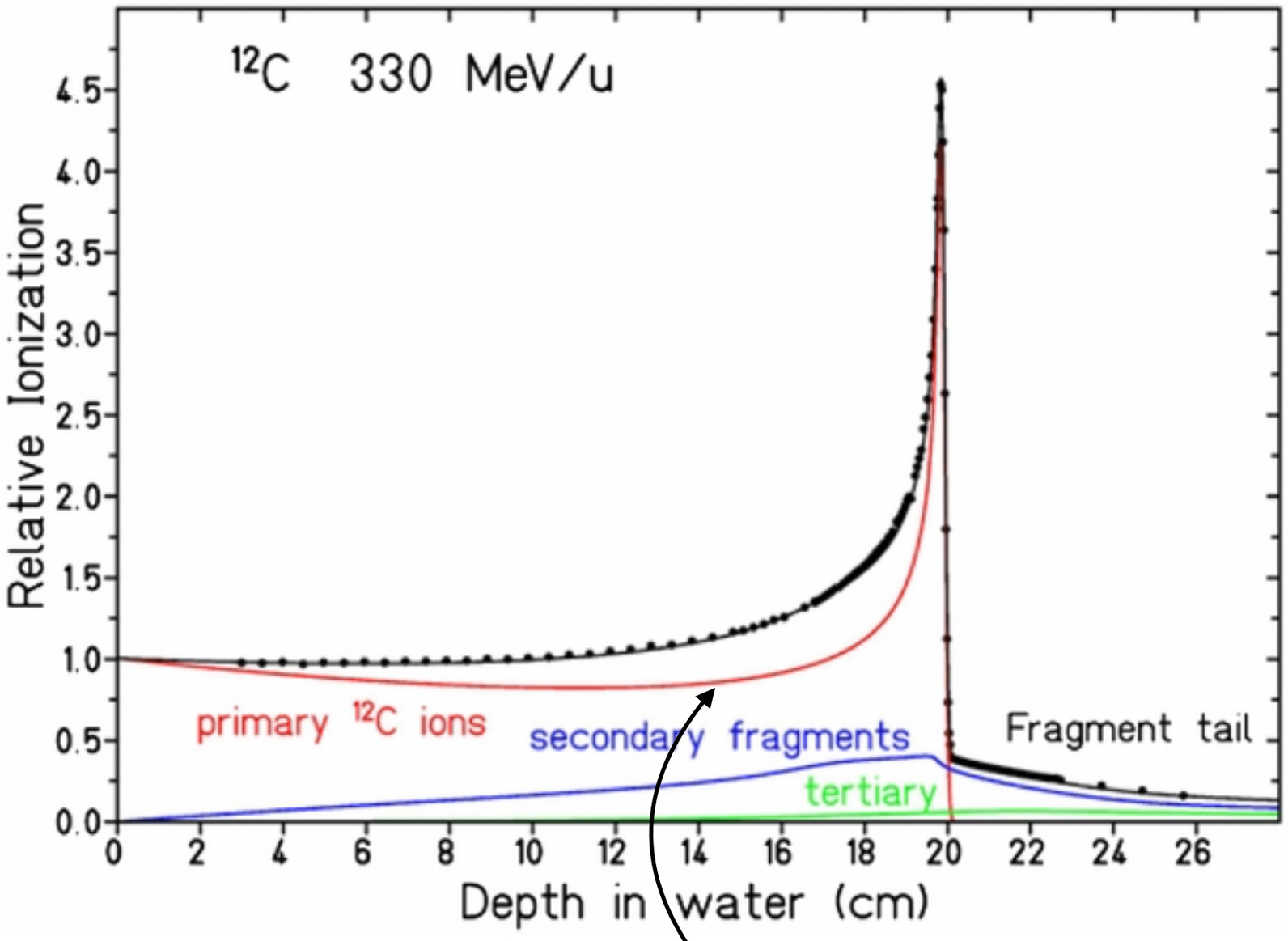

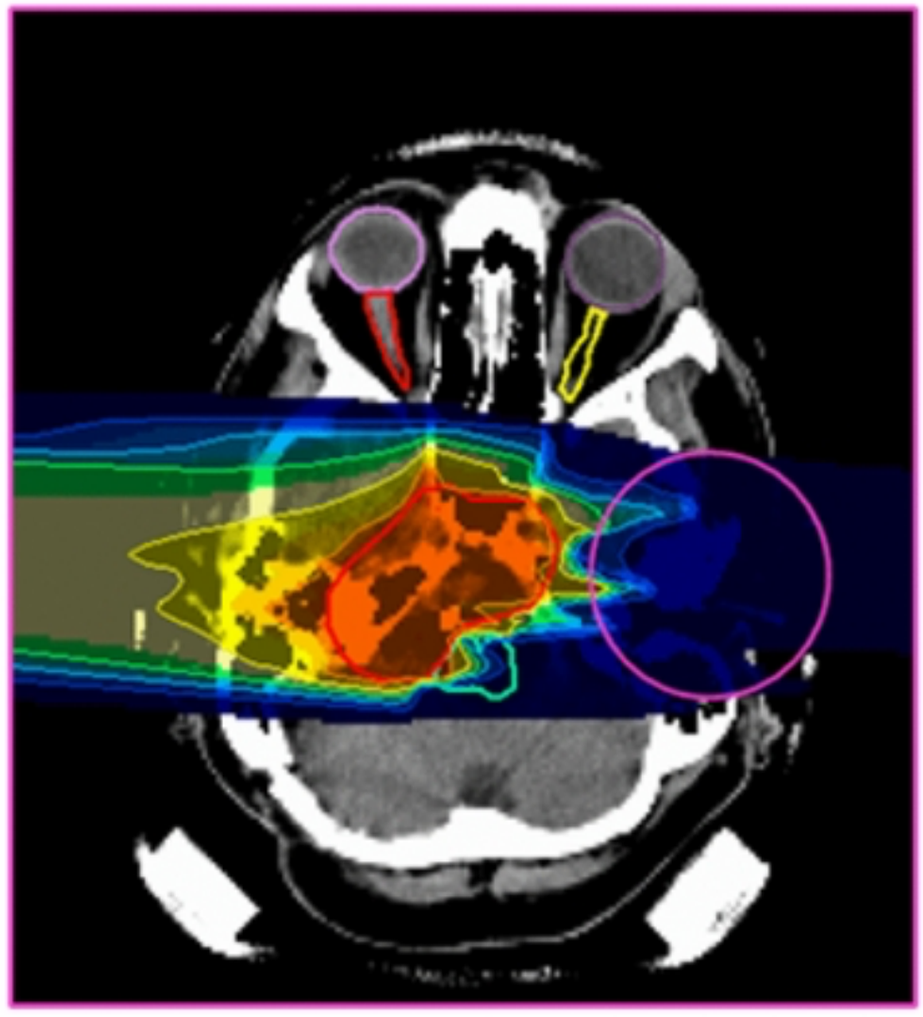

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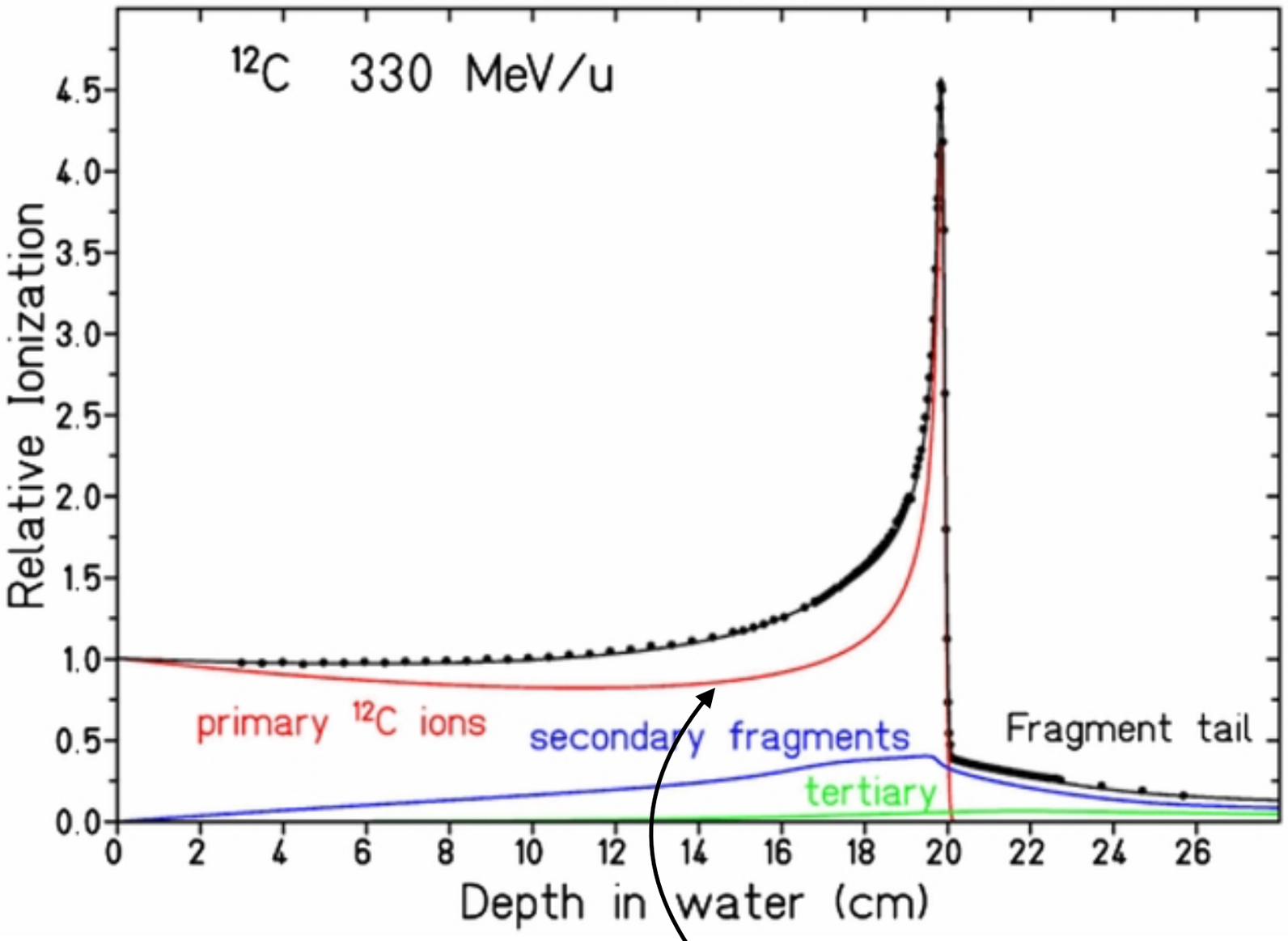

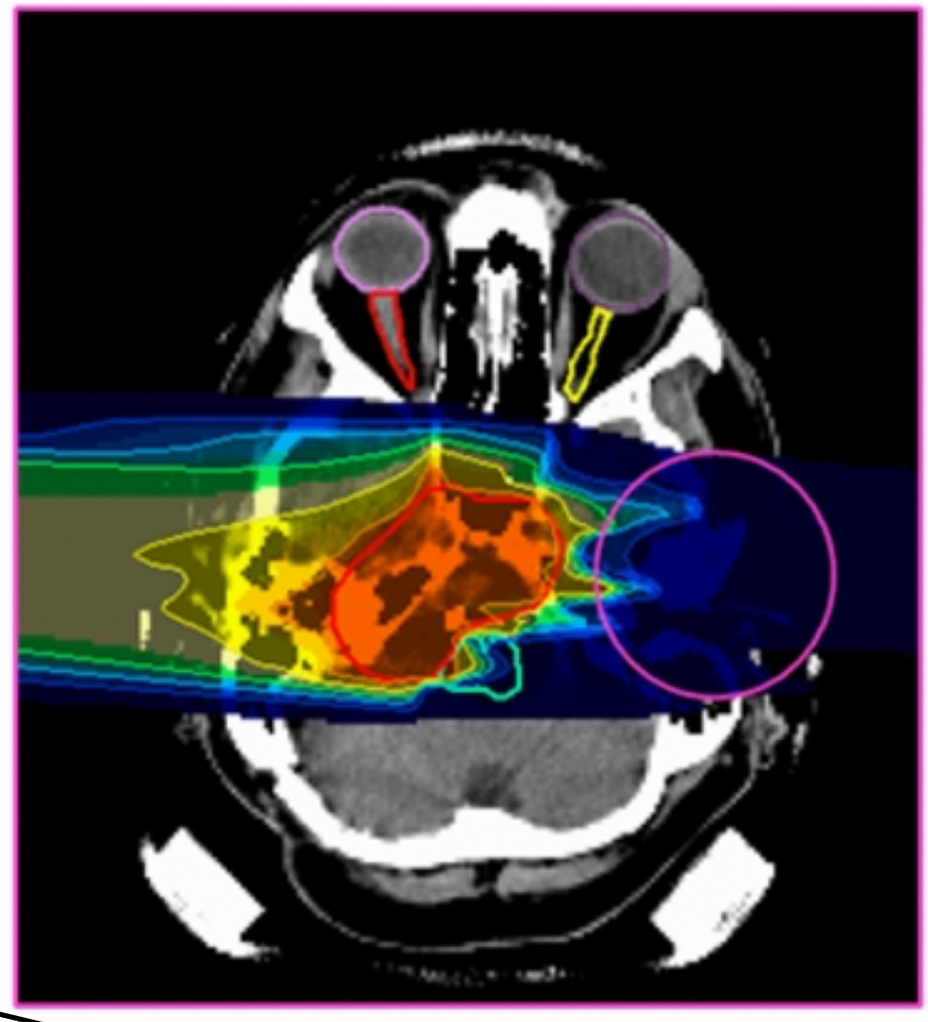

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Experimental challenge

Detect low-energy products from target fragmentation

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

Range from MC Simulation ~um

Fragments remains inside production target

Very difficult to detect almost impossible to characterize

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Proton 100-250MeV

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Proton 100-250MeV

DIRECT KINEMATIC

Ion 100-250MeV/u

INVERSE KINEMATIC

The FOOT Goal

Measure $\frac{d\sigma}{dE, d\theta}$ with 5% uncertainty for 200MeV ions for various ion (H, He, C, O…) impinging on different targets (C, C_2H_2,PMMA…)

with isotopic identification

with 1-2MeV/u resolution in the fragment energy

with ~10 mrad accuracy in angles

9 INFN section (Pisa included)

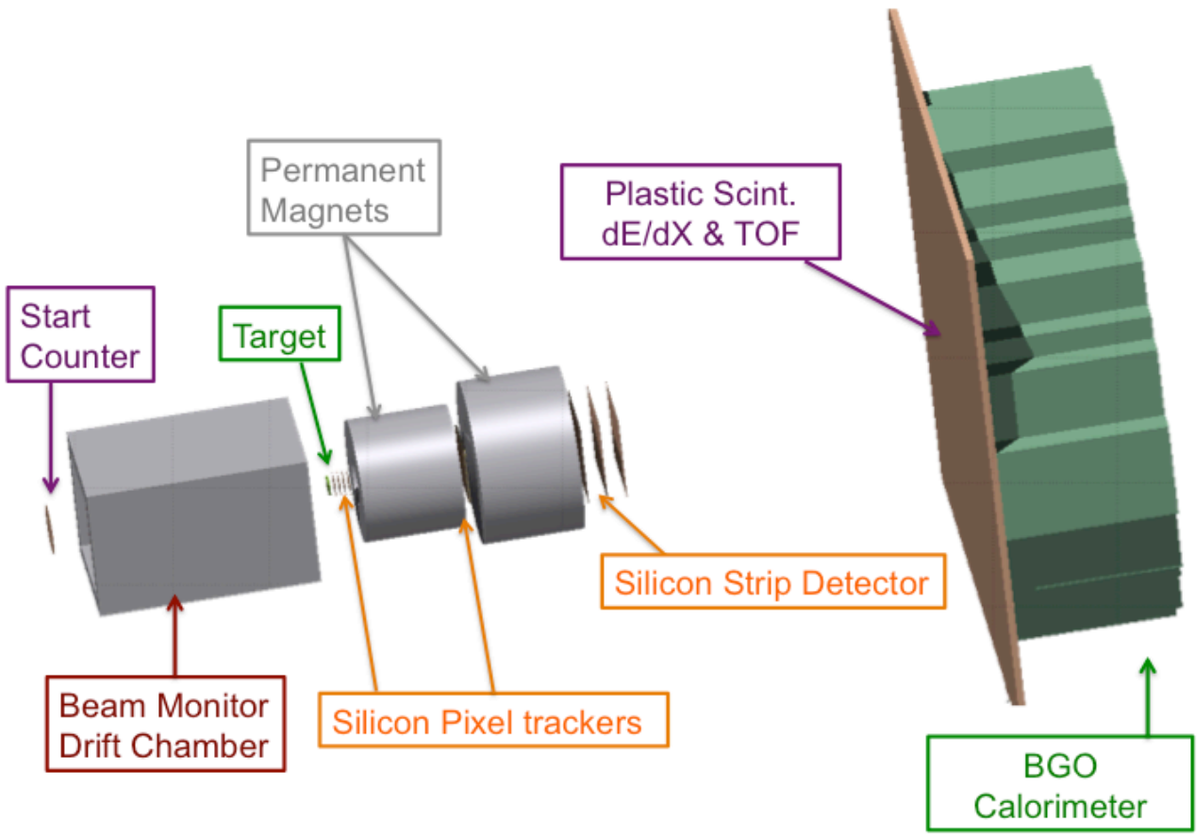
Almost all national labs:
CNAO, TIFPA, LNS, LNF

International collaboration with:

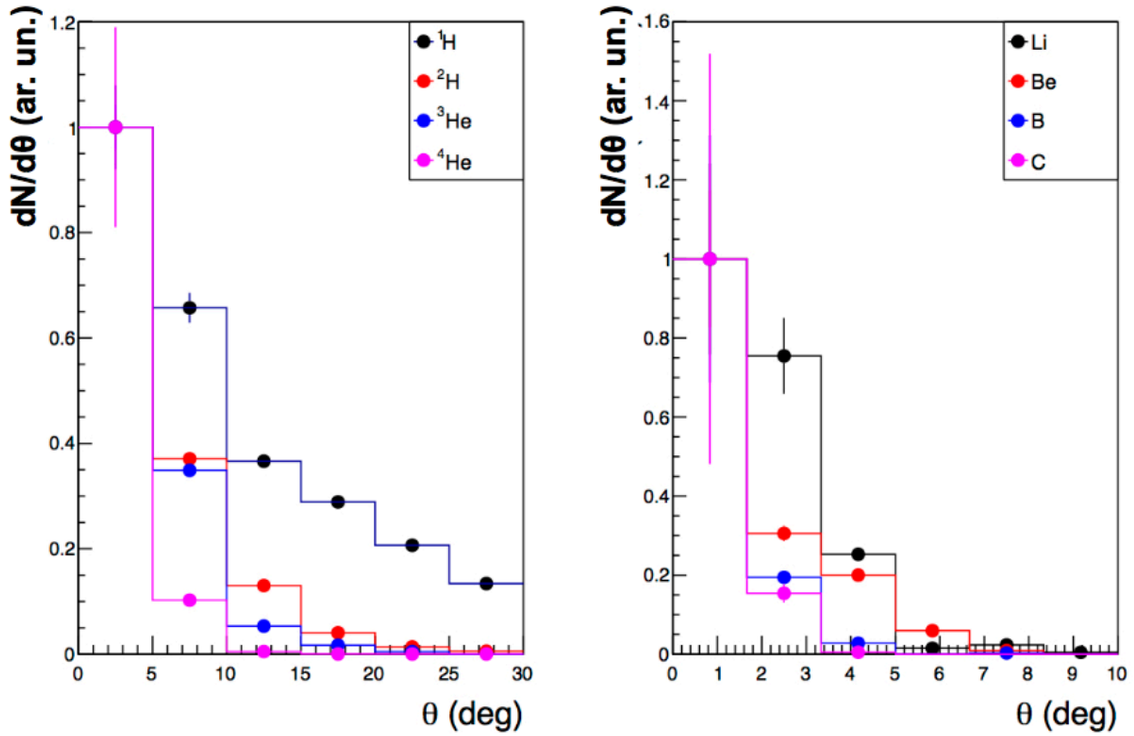
- Nagoya University (Japan)
- GSI (Germany)
- Aachen University (Germany)
- IPHC Strasbourg (France)

The FOOT "Double" Experiment

Measure $\frac{d\sigma}{dE, d\theta}$ down to He^4



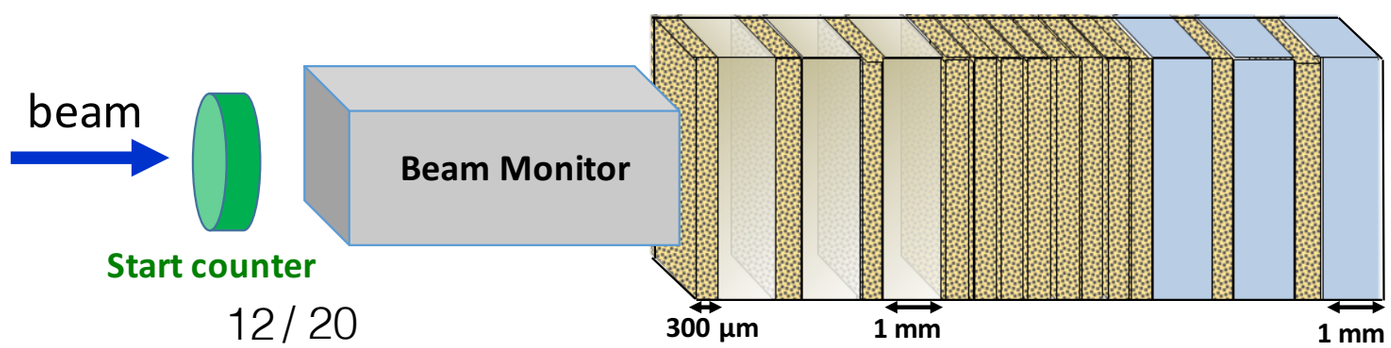
acceptance in 10° cone



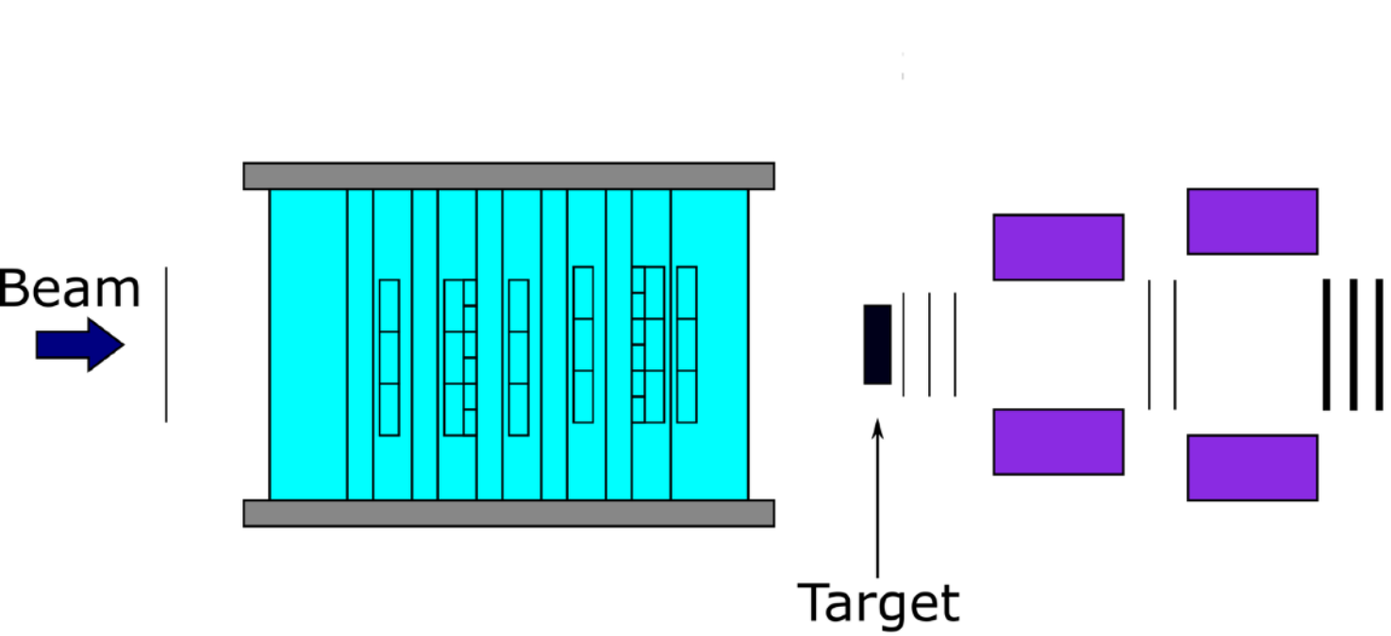
O(200 MeV) -> C_2H_2

Performance	required
Δp/p	5%
ΔK/K	2%
ΔTOF	100 ps
Δ(dE)/(dE)	2%

Complementary setup using emulsion film for light nuclei (large angle)

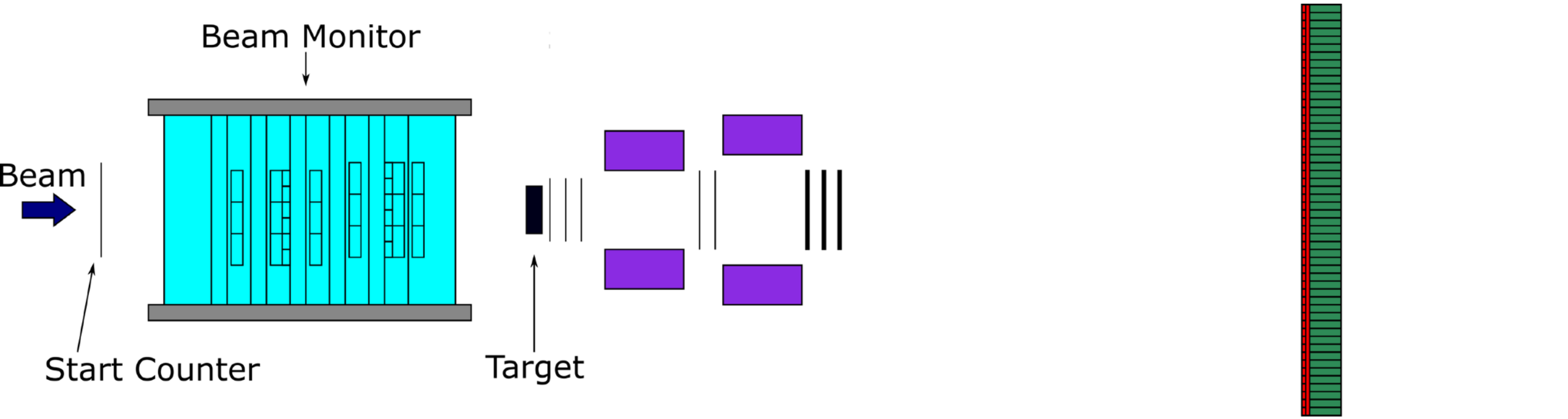


The FOOT spectrometer



Sub-detector	Main Characteristics

The FOOT spectrometer



Sub-detector	Main Characteristics
Start Counter	Plastic scintillator 250 μm
Beam monitor	Drift chamber (12 layers of wires)

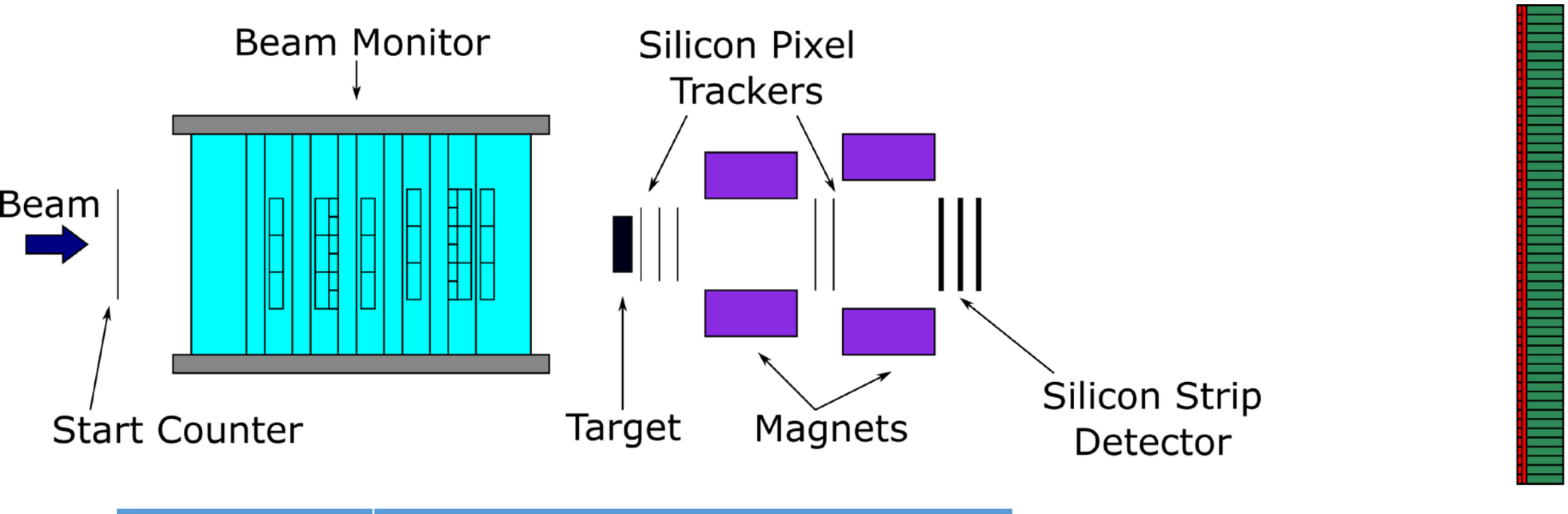
Start Counter

- Measure incoming Beam flux (Normalization)
- Provide Start Time

Beam Monitor

- Check Beam is fine (no Fragmentation)
- Provide track of the incoming particle

The FOOT spectrometer



Sub-detector	Main Characteristics
Start Counter	Plastic scintillator 250 μm
Beam monitor	Drift chamber (12 layers of wires)
Target	C + C_2H_4 (2 mm)
Vertex	4 layers silicon pixel (20x20 μm)
Magnet	2 permanent dipoles (Halbach geometry 0.8 T)
Inner Tracker	2 layers silicon pixel (20x20 μm)
Outer Tracker	3 layers of Silicon strip (125 μm pitch)

Vertex & Inner Tracker(Silicon Pixel)

- Track outgoing fragments
- Locate vertex of fragmentation
- ultra-low material budget
- first estimation of momentum

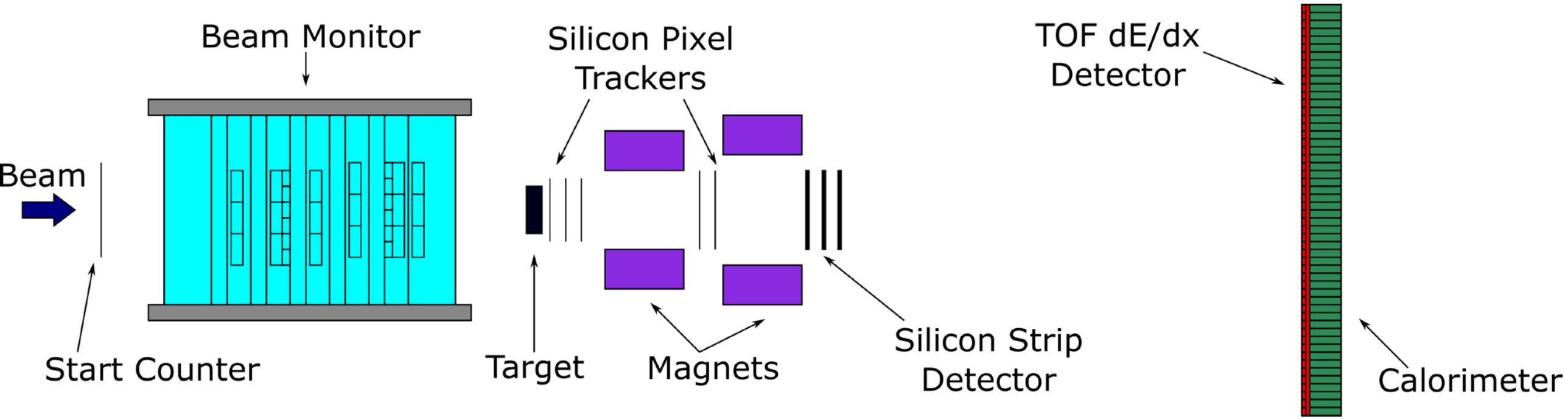
Magnet

- Double dipolar magnet
- non superconducting, easier to maintain

Strip detector

- Very good tracking on wider surface
- Provide dE/dx information (particle identification)
- Allow extrapolation of track to next detectors

The FOOT spectrometer



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Vertex	4 layers silicon pixel (20x20 μm)
Magnet	2 permanent dipoles (Halbach geometry 0.8 T)
Inner Tracker	2 layers silicon pixel (20x20 μm)
Outer Tracker	3 layers of Silicon strip (125 μm pitch)
Scintillator	2 layers of 20 bars (2x40x0.3 cm)
Calorimeter	360 BGO crystals (2x2x14 cm)

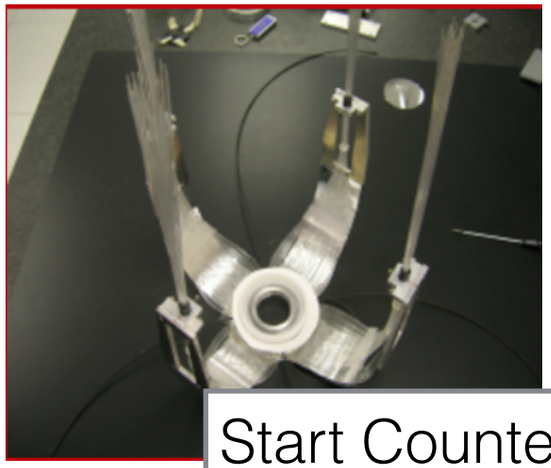
TOF-dE/dx

- Provide timing of fragments
- measure dE/dX
- Locate hit point in far detector

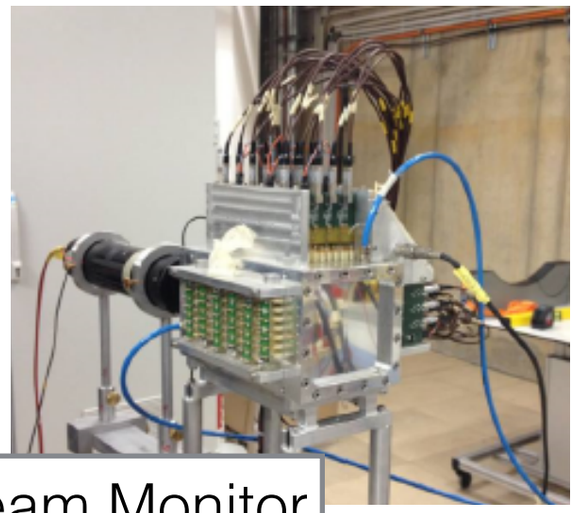
Calorimeter

- Energy measurement
- No timing information required

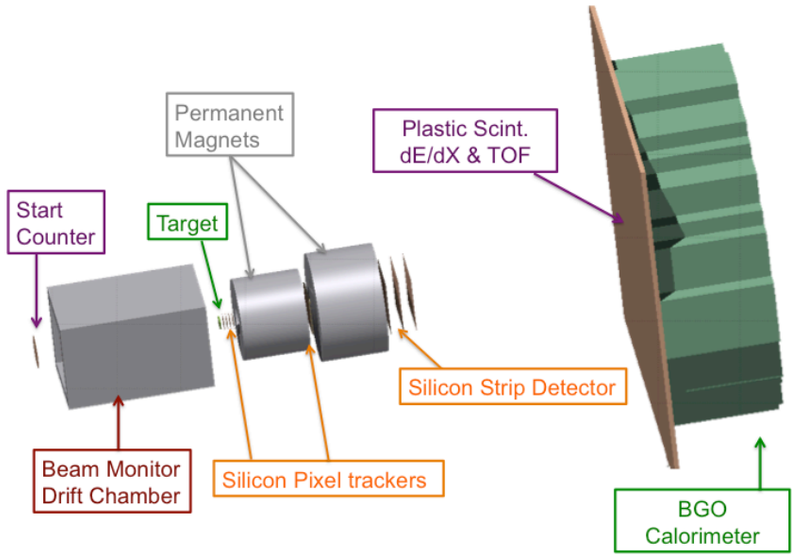
Prototypes in progress



Start Counter



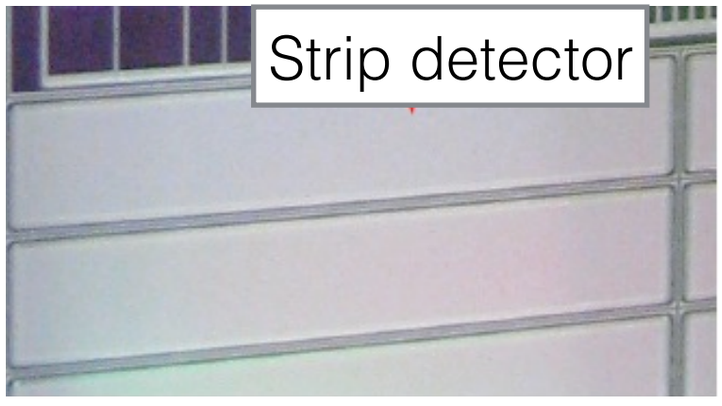
Beam Monitor



Target & Vertex

Calorimeter

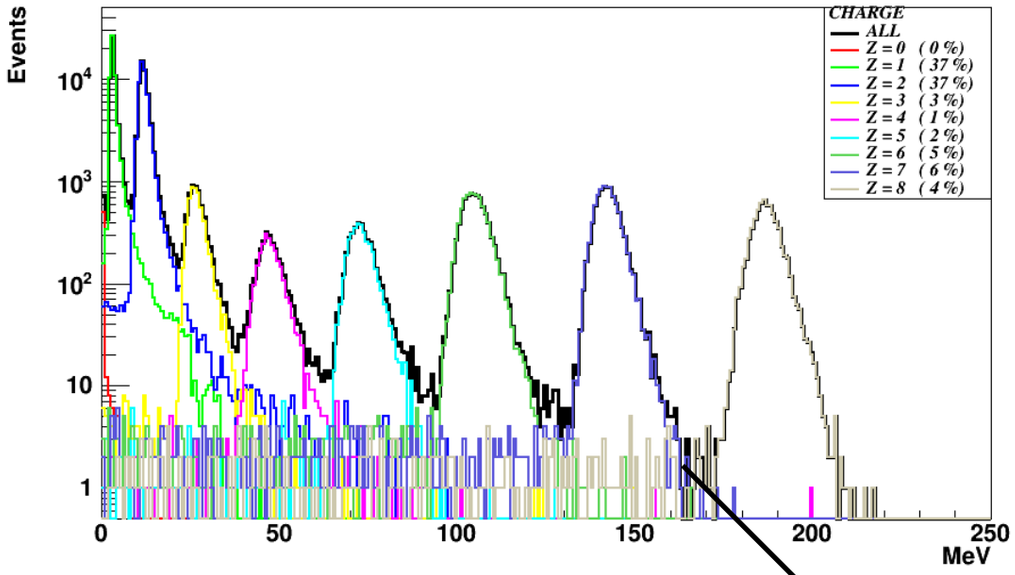
TOF-dE/dx

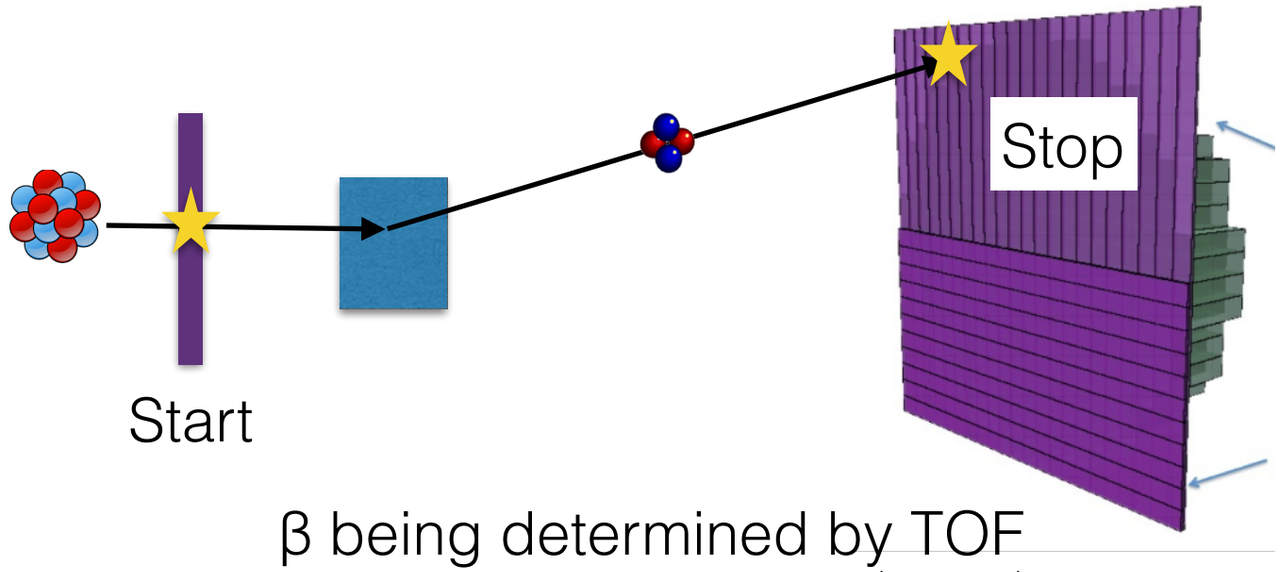


Strip detector

Fragment Identification (Z)

Dedicated Time of Flight detector -> determination of Z

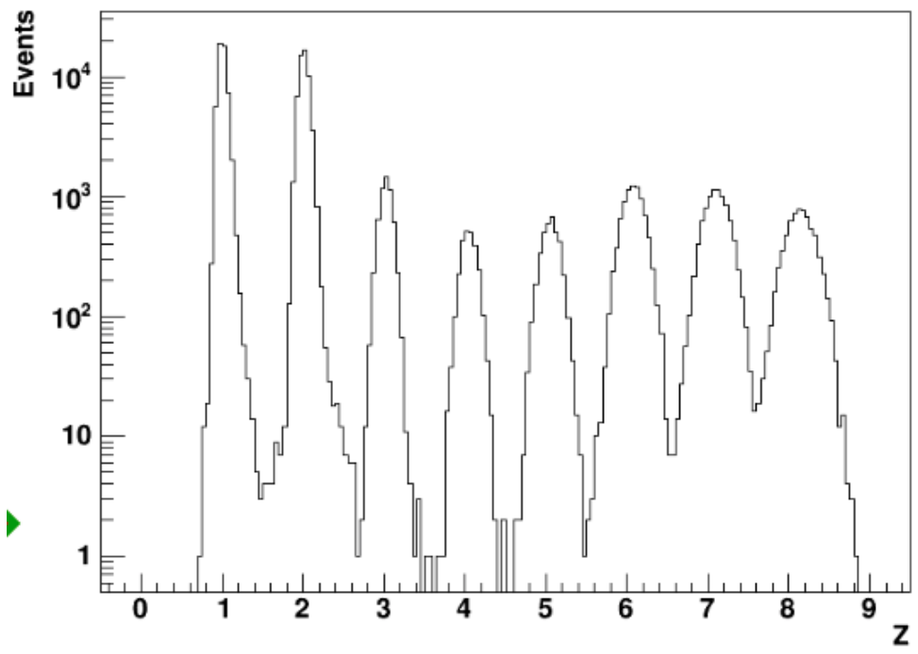




β being determined by TOF

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

Bethe-Bloch Formula



from 5% to 2% resolution across H to O

Possible improvement considering:
such as dE/dx in silicon trackers
feasible but not yet studied

Fragment Identification (A)

FOOT is a redundant experiment

Mass value can be extracted using multiple detectors

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

Tracker-TOF

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

Calorimeter-TOF

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

Calorimeter-Tracker

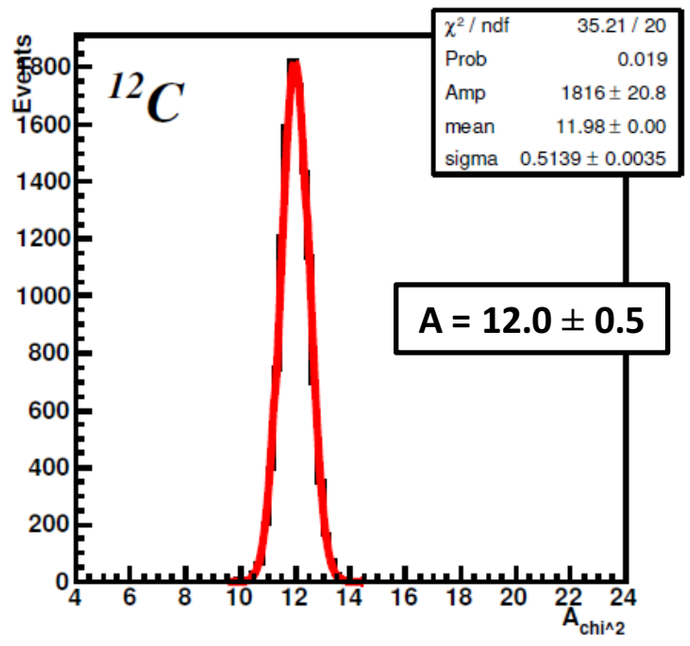
Both σ(A)/A below 7%

σ(A)/A~11%

combining such measurements σ(A)/A ~ 5%

<u>By imposing that A and Z are integer the energy and impulse resolution get better</u>

i.e.: improves by factor 2 σ(P)/P

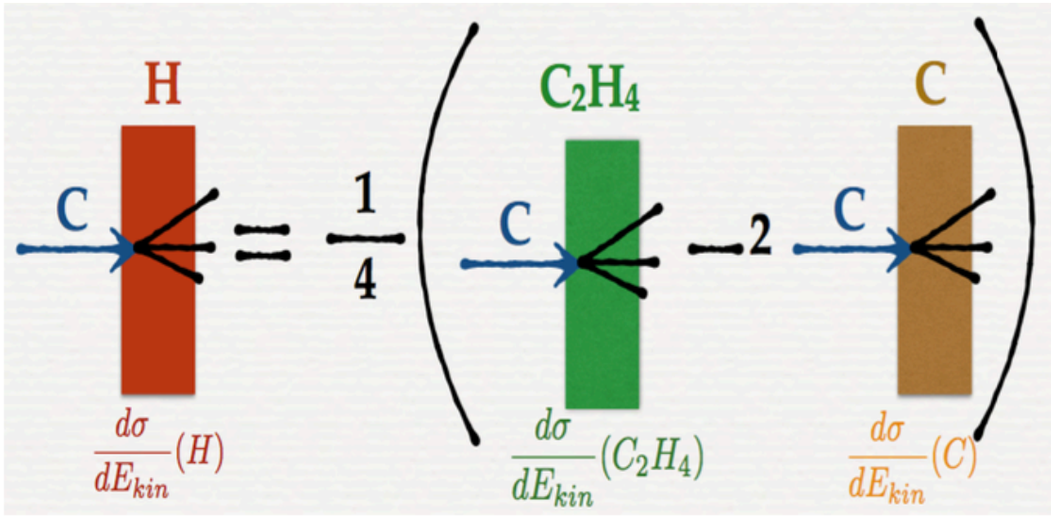


Montecarlo simulation of differential cross section

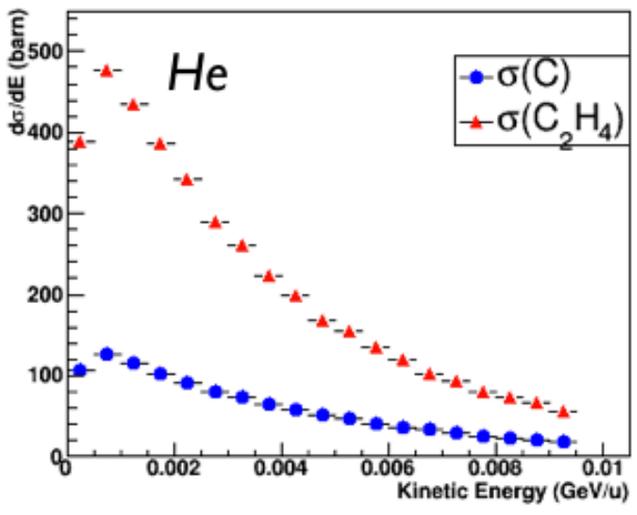
FOOT may use different target

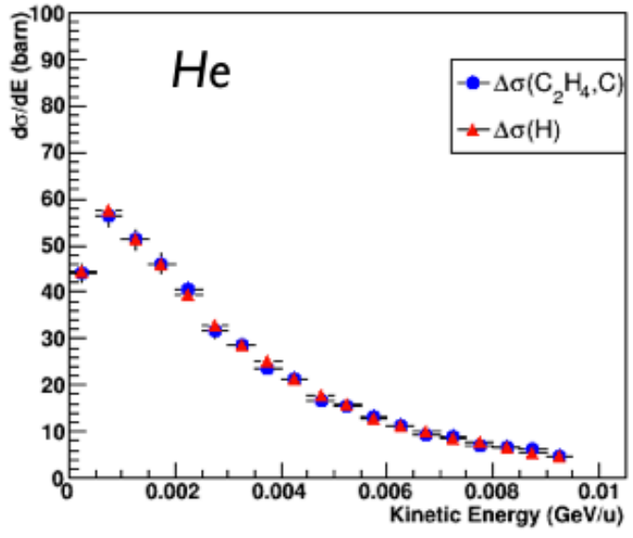
Extract cross section of protons by comparing carbon and polyethylene

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



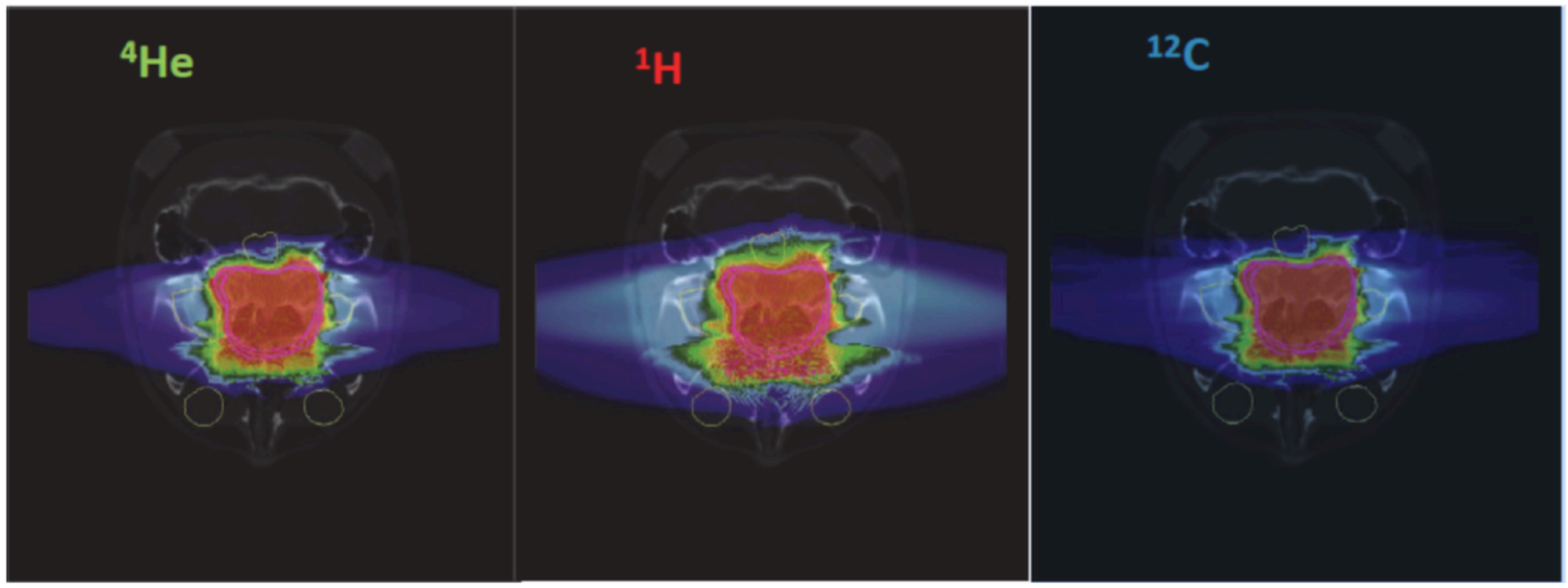
this procedure have been validated with Montecarlo





Other experimental activities in FOOT

- **Helium or Oxygen as possible ions to be used in therapy?**



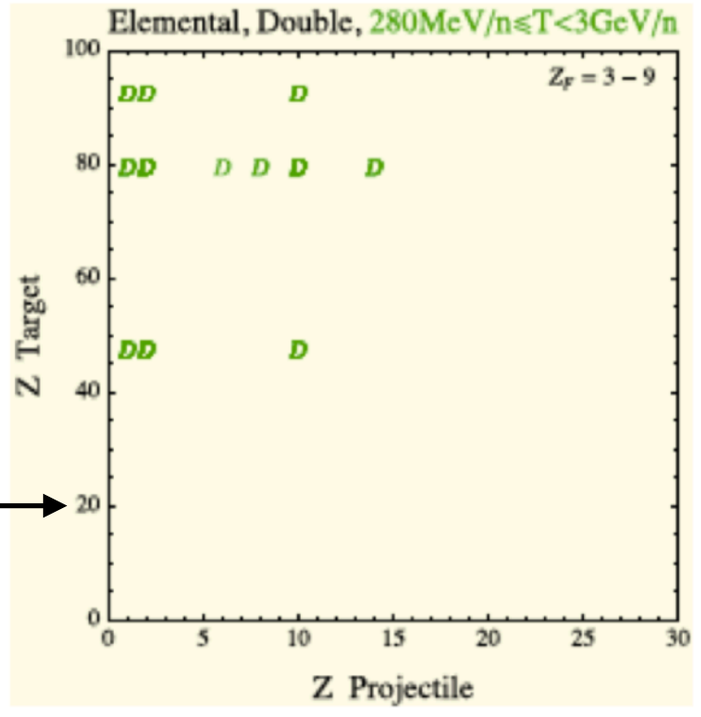
Balance between lateral dispersion immunity and fragmentation probability

- **Measure cross section for Cosmic Ray particle that may be armful to astronauts**

  Higher energies (up to 700 MeV/u)

  Also with on bigger projectiles (Si, Fe)

  This is an example of known combination of projectile-target for non-hydrogen fragments →



References

Everything concerning FOOT:

FOOT Collaboration, **FOOT Conceptual Design Report**, https://web.infn.it/f00t/index.php/it/public-links, Being pushed to Arxiv soon

in an handy 94 pages size

Francesco Tommasino and Marco Durante, **Proton Radiobiology**, Cancer 2015

Jay S. Loeffler and Marco Durante, **Charged particle therapy - optimization. challenges and future directions**, Nature Reviews 2013

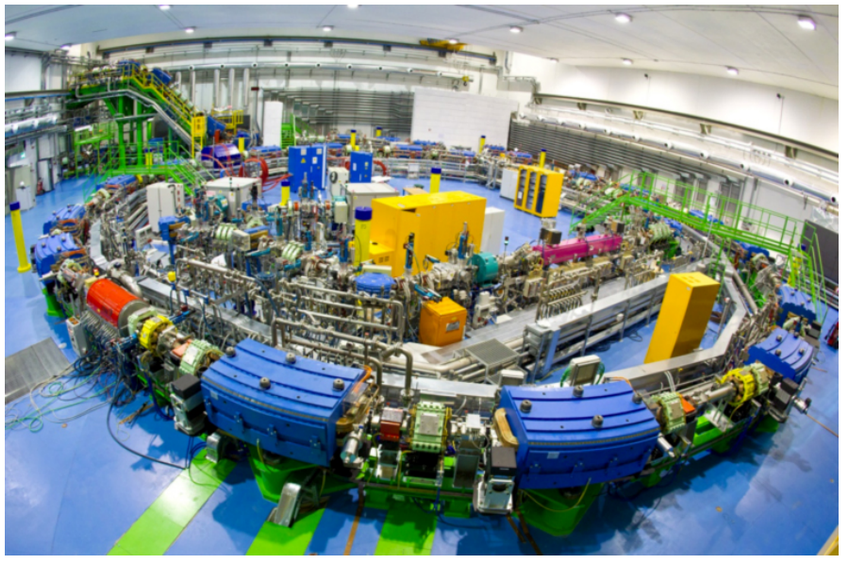
E. Haettner *et al,* **Experimental study of nuclear fragmentation of 200 and 400 MeV/u ^{12}C ions in water for applications in particle therapy**, Phys. Med. Biol. 2013

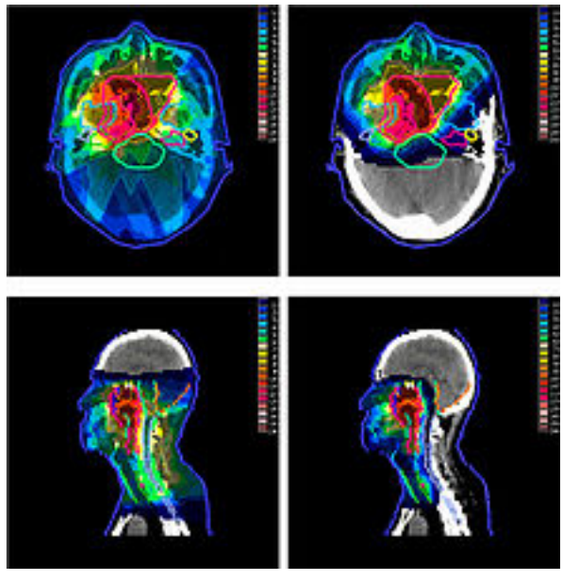
Conclusion

FOOT experiment aims to measure fragmentation cross section of ions interesting for therapy applications

Design phase have been almost completed,
waiting for final approval by INFN

This is a very multicultural experiment involving people and knowledges from Particle, Nuclear and Medical Physics

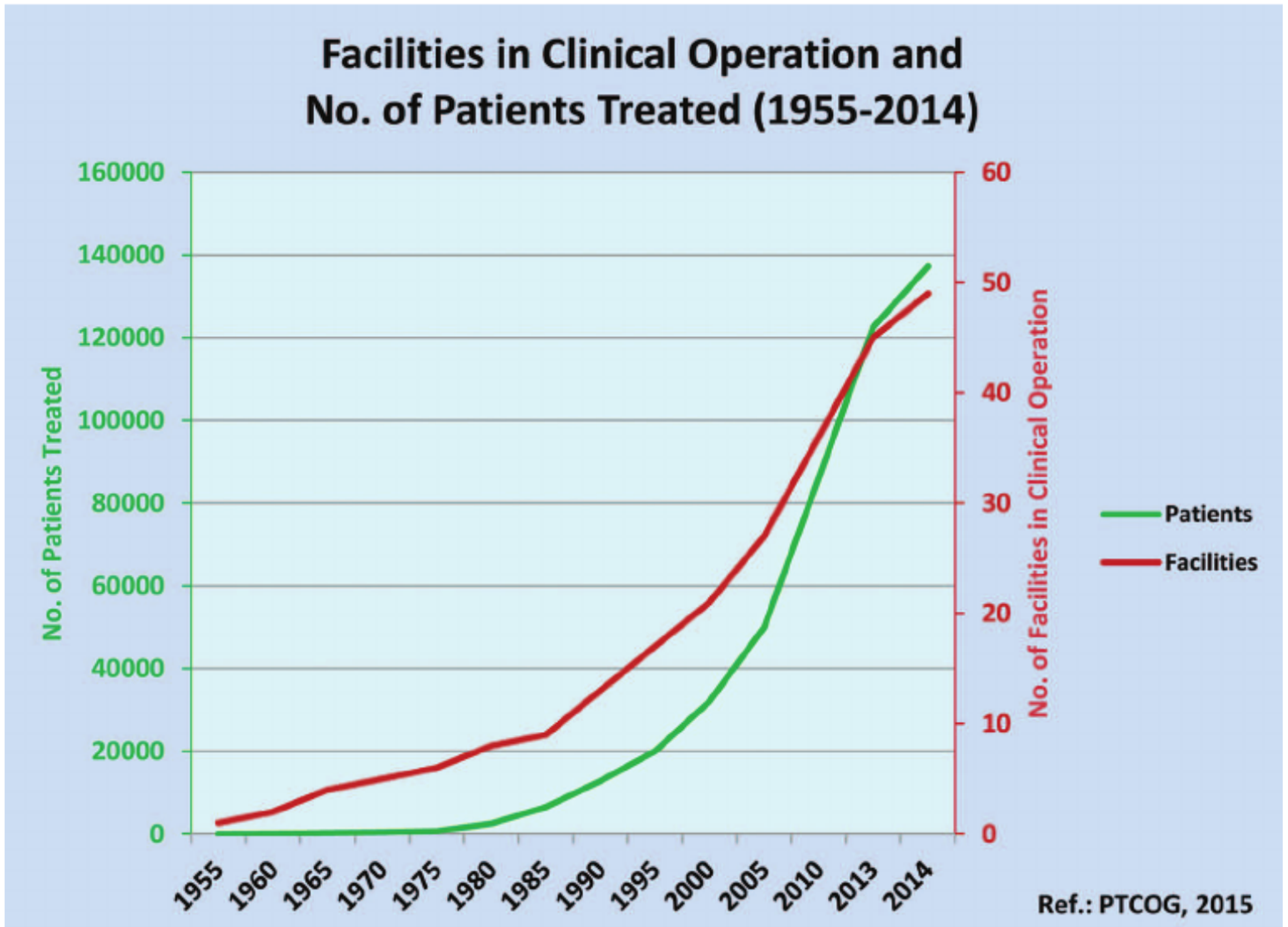




… and world is looking forward to FOOT results!

Backup

Hadrotherapy history



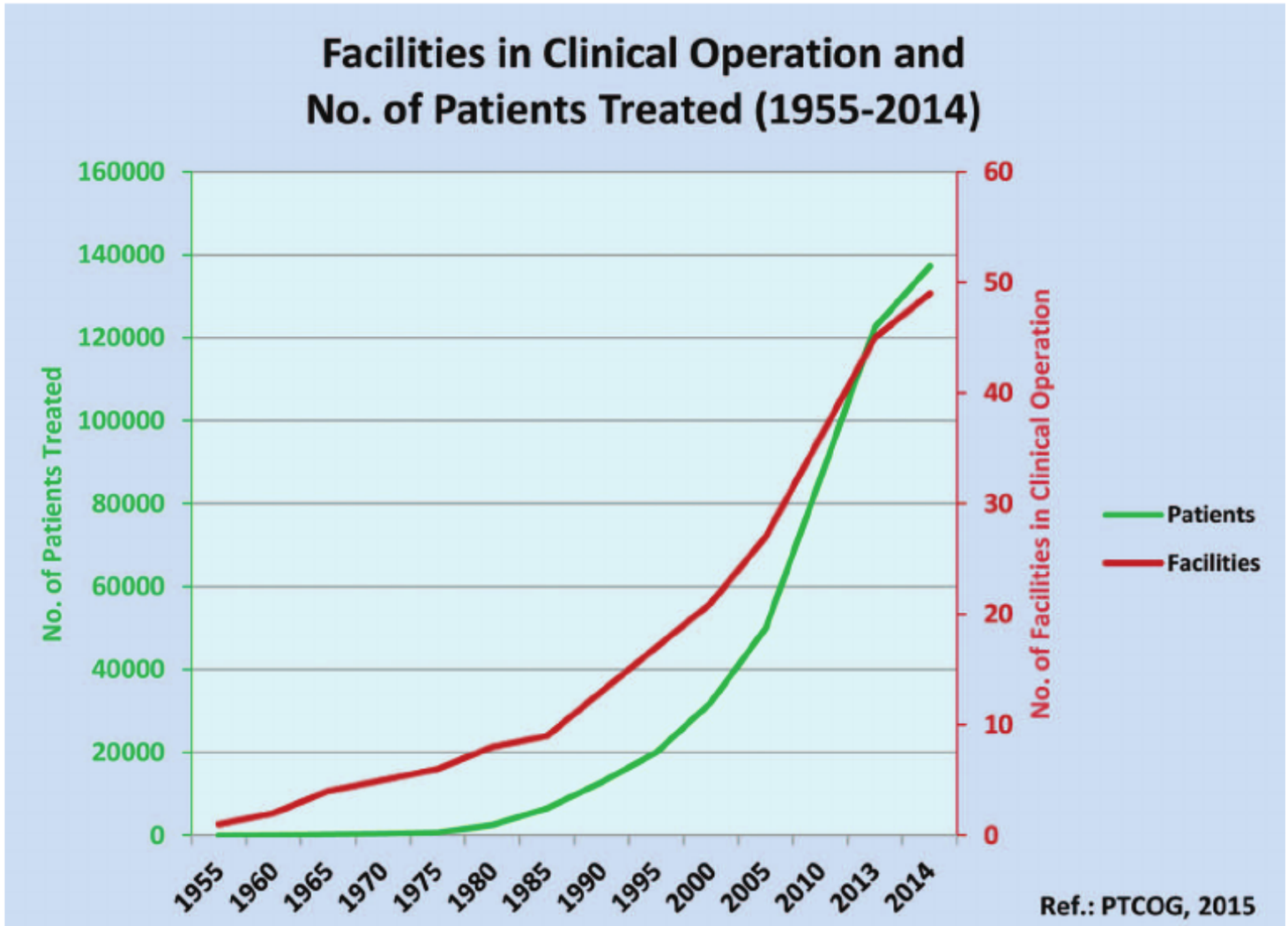
Steadily growing

2017 data (PTCOG):

- 75 operating facilities
- out of them 11 are ion-therapy
- 41 being built

154203 patients
by the end of 2015
(20000 with carbon ions)

Hadrotherapy history



Steadily growing

2017 data (PTCOG):

- 75 operating facilities
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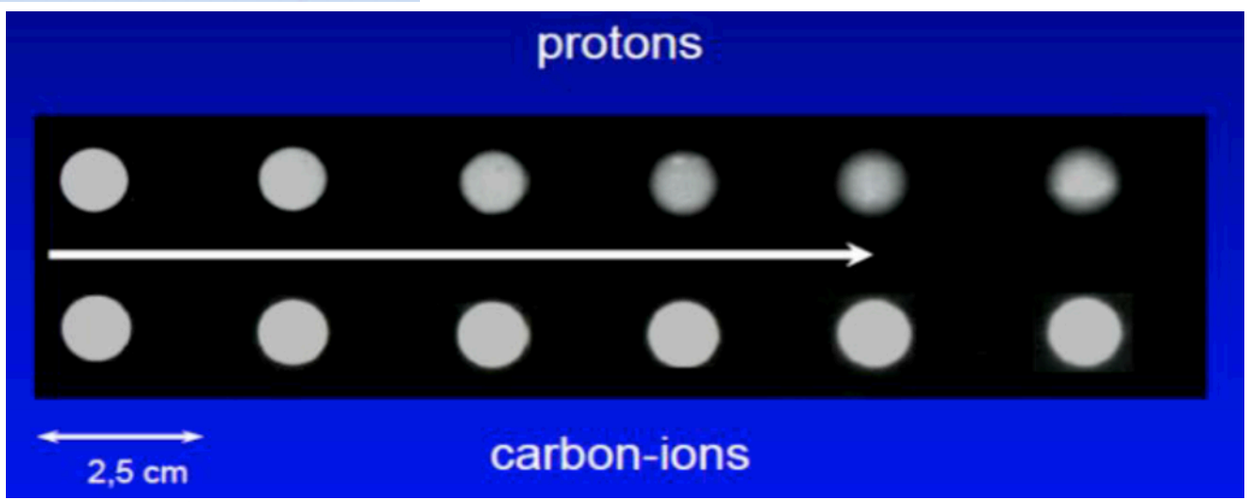
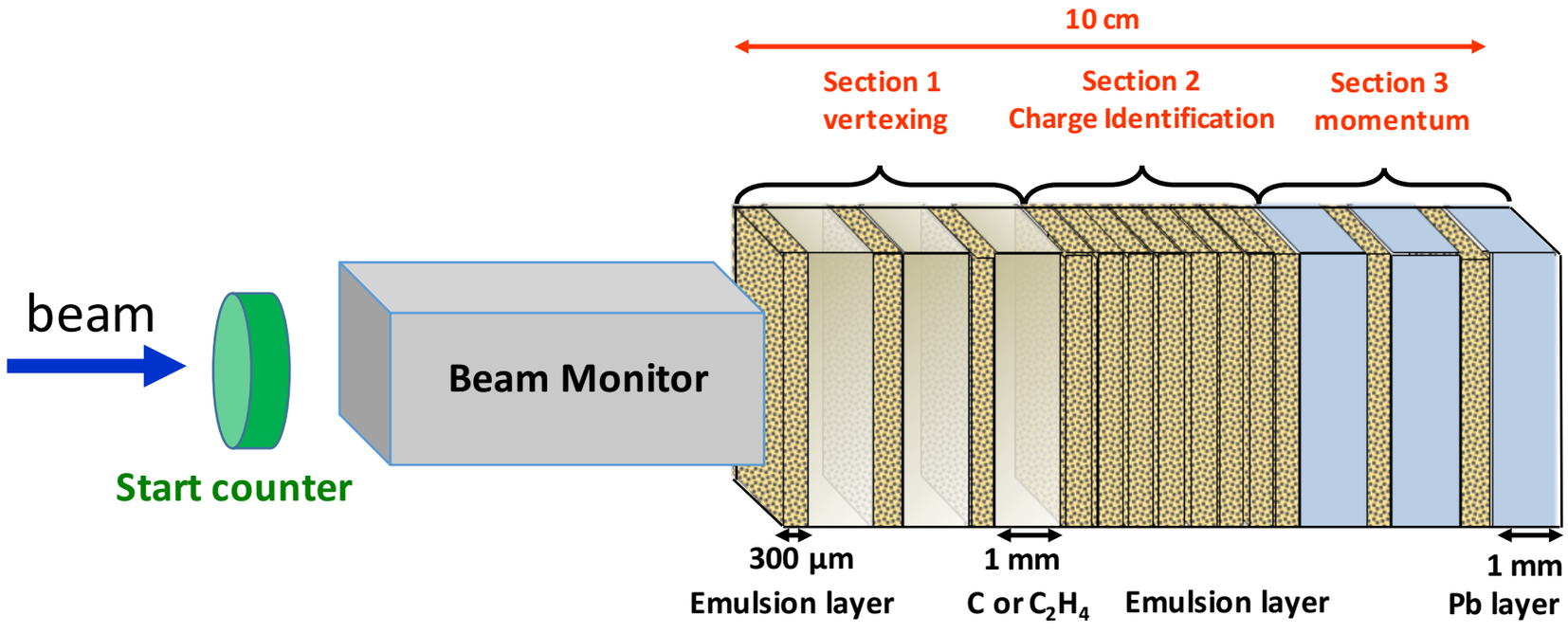
154203 patients
by the end of 2015
(20000 with carbon ions)

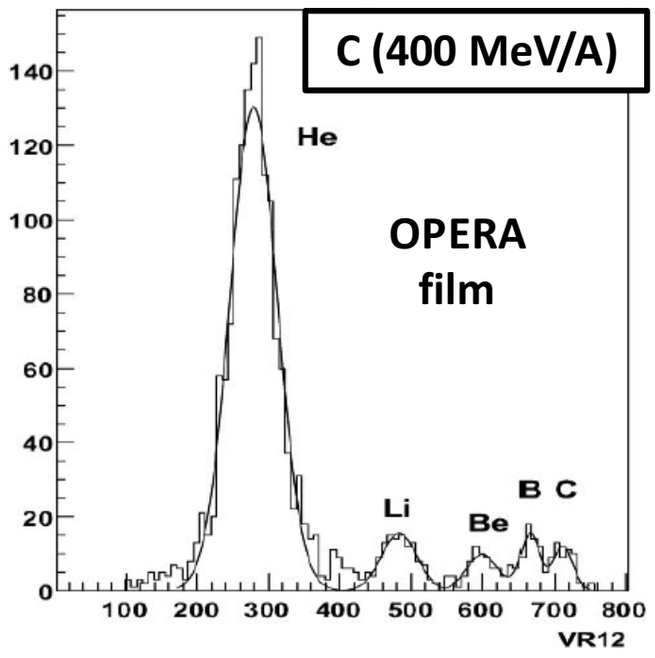
The future is ion beam?

- higher relative Bragg peak
- less lateral dispersion
- more “effective”
- … more susceptible to a problem described later…



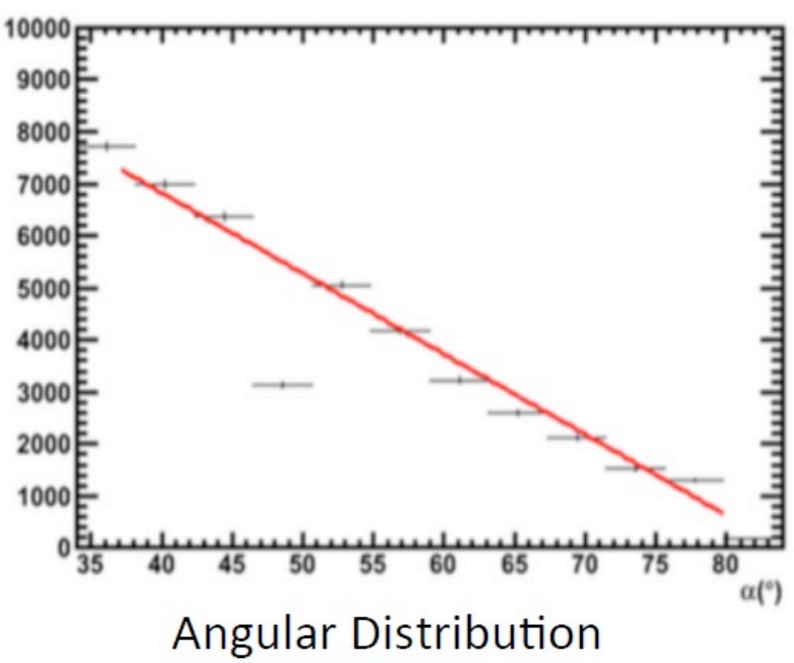
The emulsion spectrometer





Integrate target, Particle Identification and spectrometer

- Good to separate low mass isotopes
- Big angular acceptance due to compactness ± 70°



Angular Distribution