The FOOT experiment

Andrey Alexandrov, Vincenzo Boccia, Giovanni de Lellis, Antonia di Crescenzo, Giuliana Galati, Adele Lauria, Maria Cristina Montesi, Valeri Tioukov

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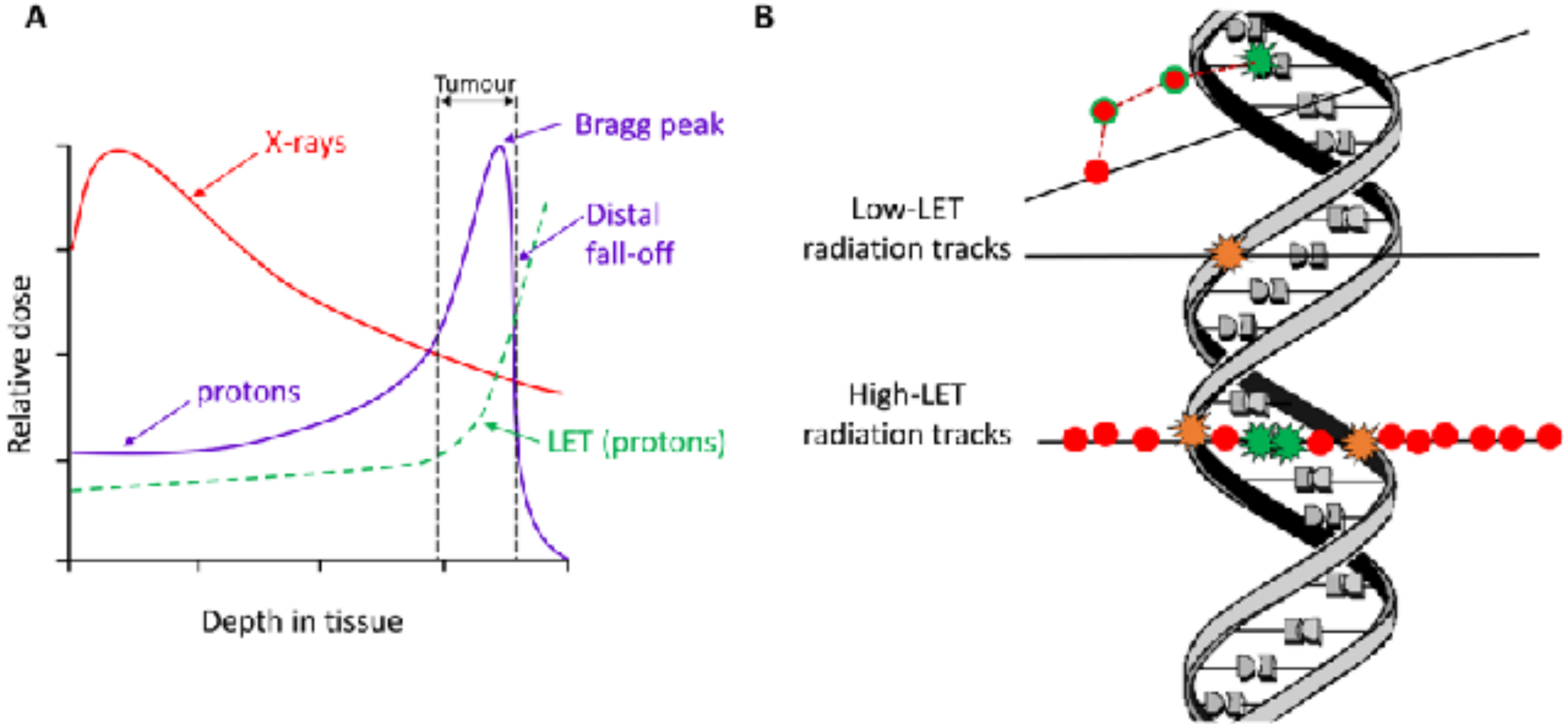
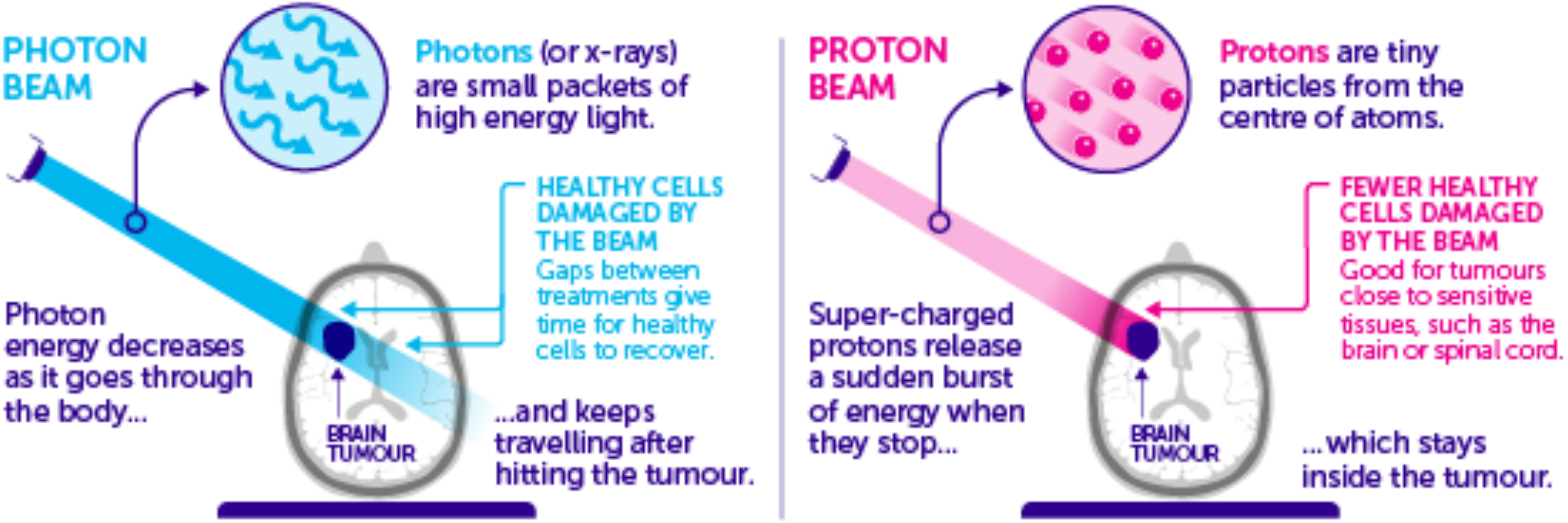
Charged Particle therapy for Cancer Treatments

- Cancer treatment by radiation: use of different kind of radiation to kill cancer cells by direct and indirect damage of DNA cells
- Charged Particle therapy (CPT): uses heavy ions instead of photons and electrons



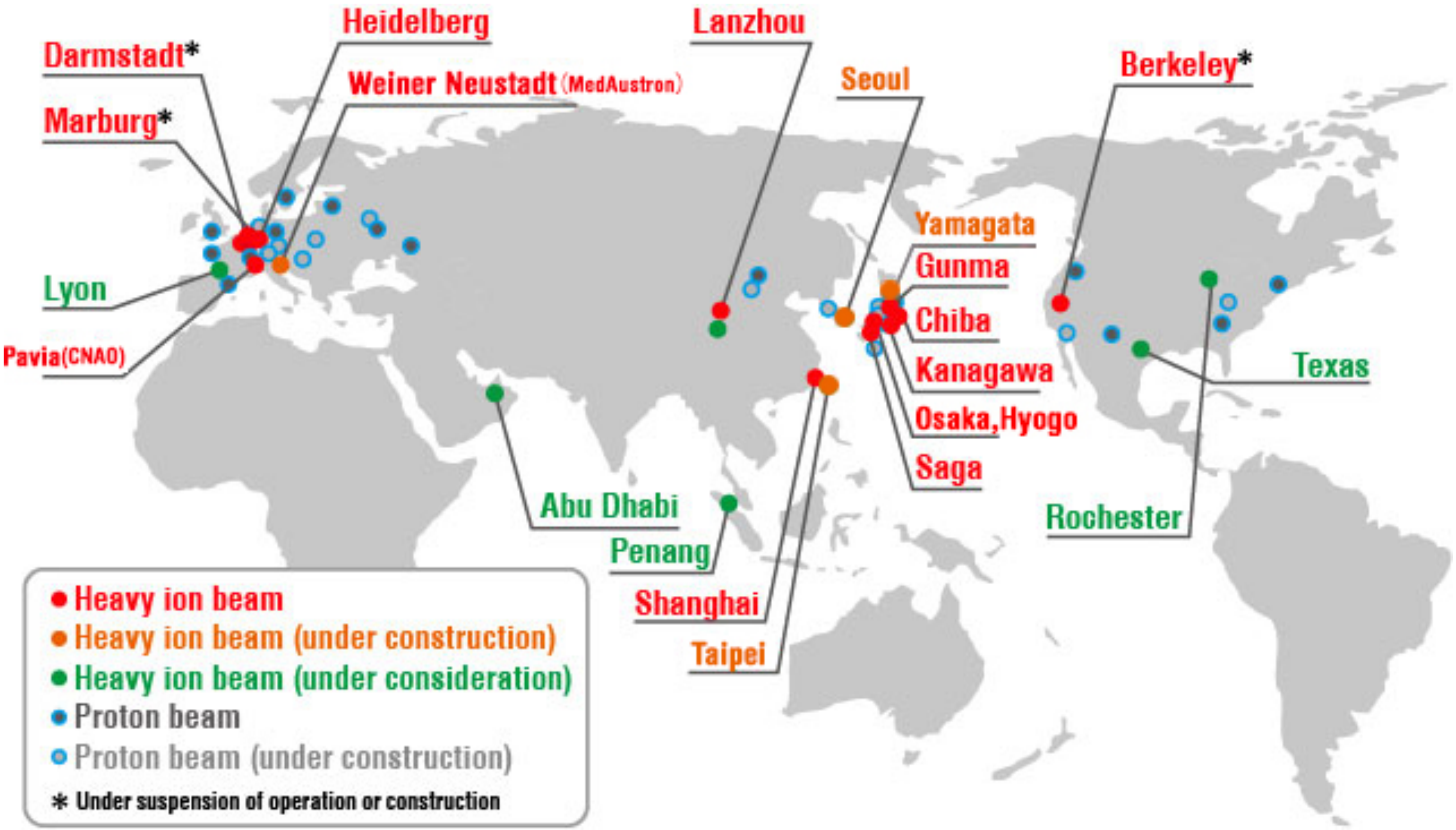
Photons vs Protons



https://news.cancerresearchuk.org/

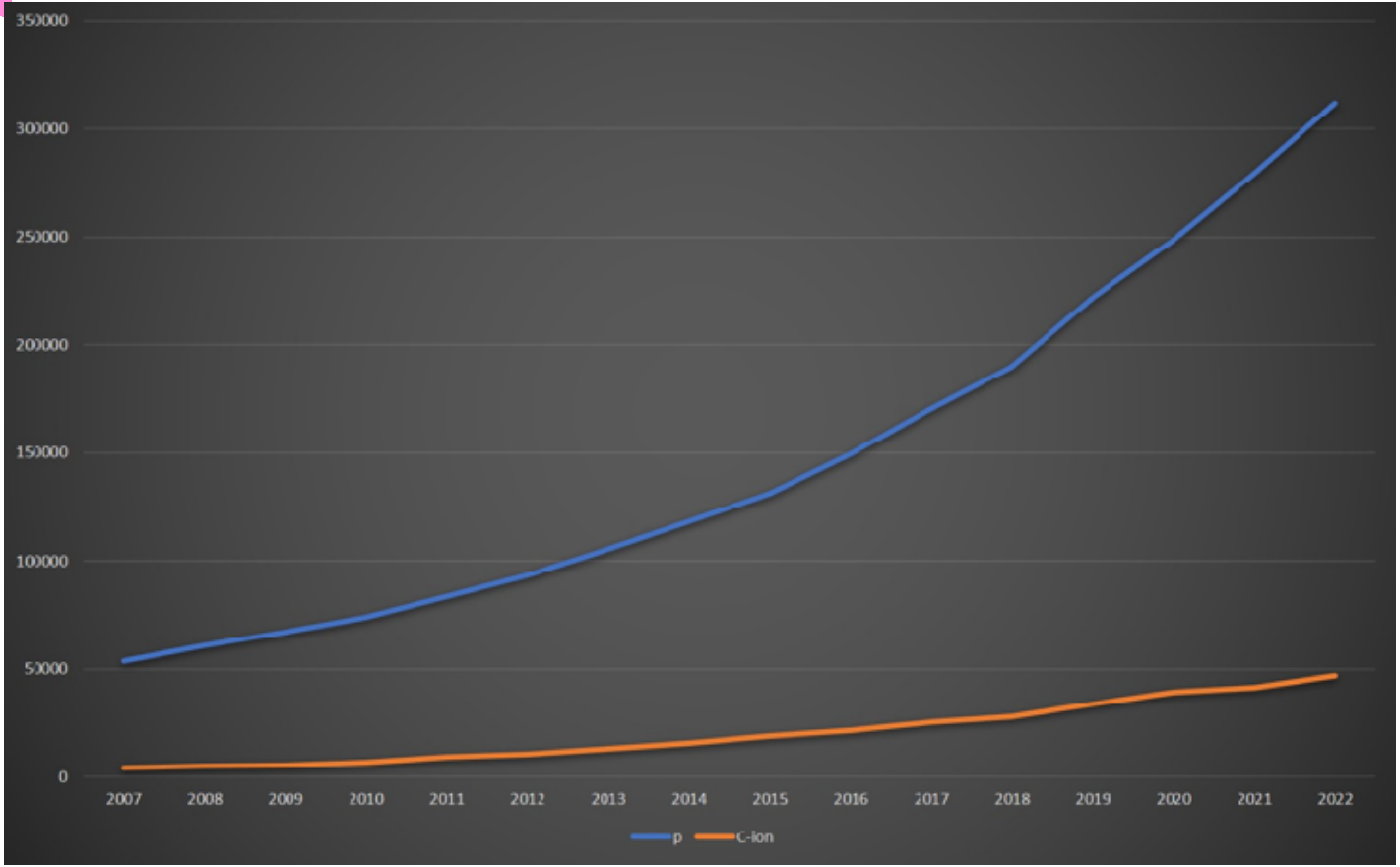
Heavy ion therapy facilities around the world

https://www.particle.or.jp



Patients treated with Protons and Carbons (2007-2022)

https://www.ptcog.site/



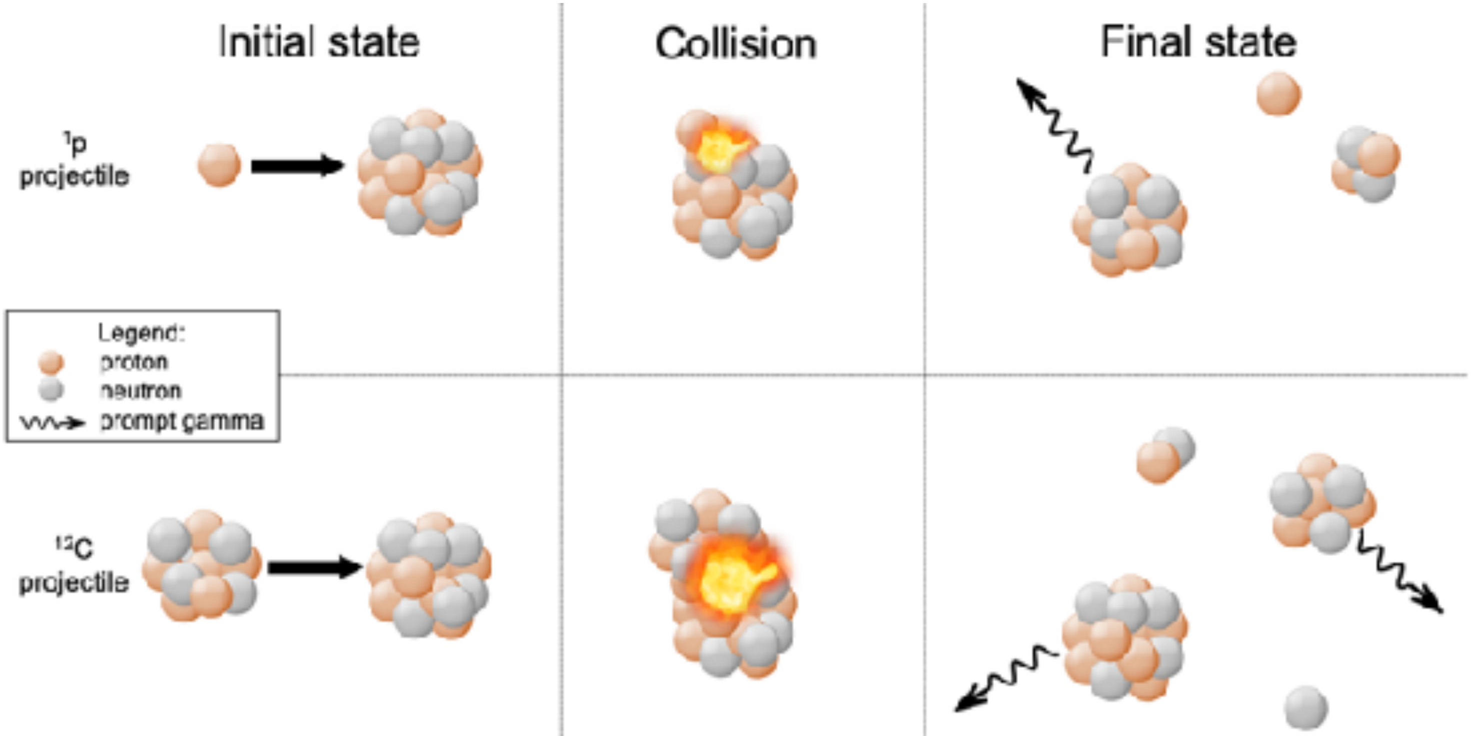
Charged Particle therapy for Cancer Treatments

Target Fragmentation:

- Target fragments have very low energies (short range, hundreds of mm)
- Difficult to detect

(non-proton) Beam Fragmentation:

- Projectile fragments have long range
- Non-zero dose beyond the Bragg peak to address



Particle therapy: fragmentation of the target

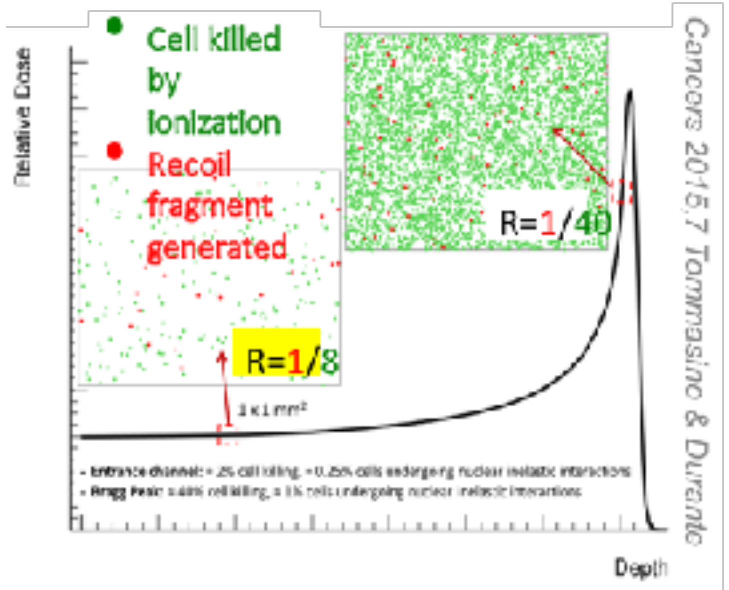
The nuclear fragmentation of the target and beam particles is an open issue

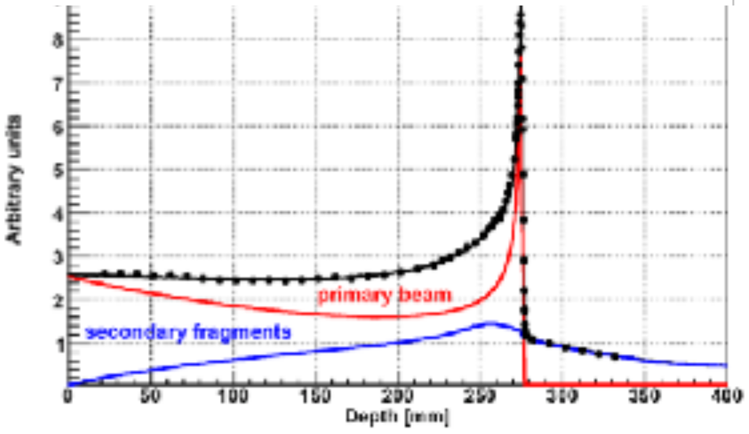
Proton beam (Target fragmentation):

- Small range fragments (~tens of µm)
- Missing experimental data for heavy fragments having the greatest contribution to the dose
- Increase of biological damage (~10%) in the entrance channel

Charged particles (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 studied





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

Measurements of nuclear fragmentation cross sections useful to improve Treatment Planning Systems for ion therapy

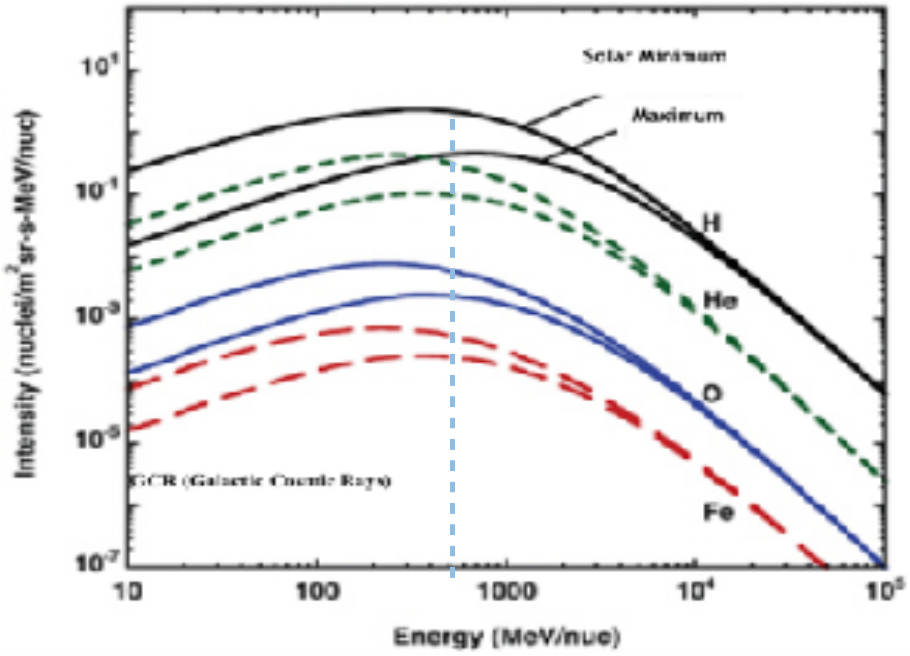
The FOOT (FragmentatiOn Of Target) experiment

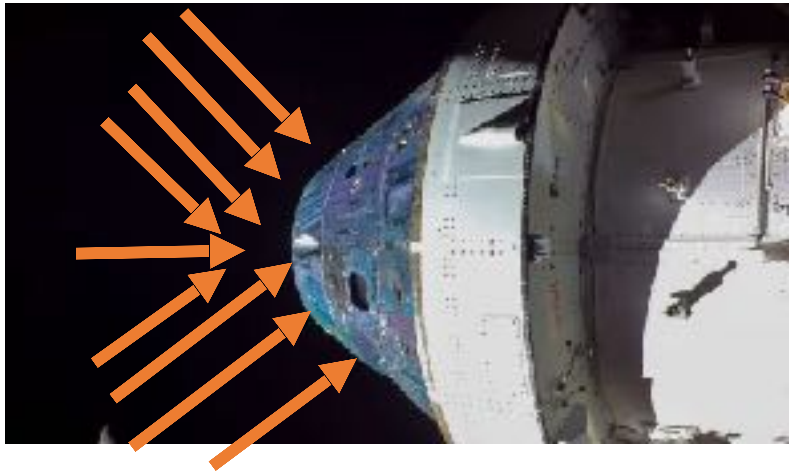
FOOT aims at measuring nuclear fragmentation cross sections to improve Treatment Planning Systems for proton and ion therapy

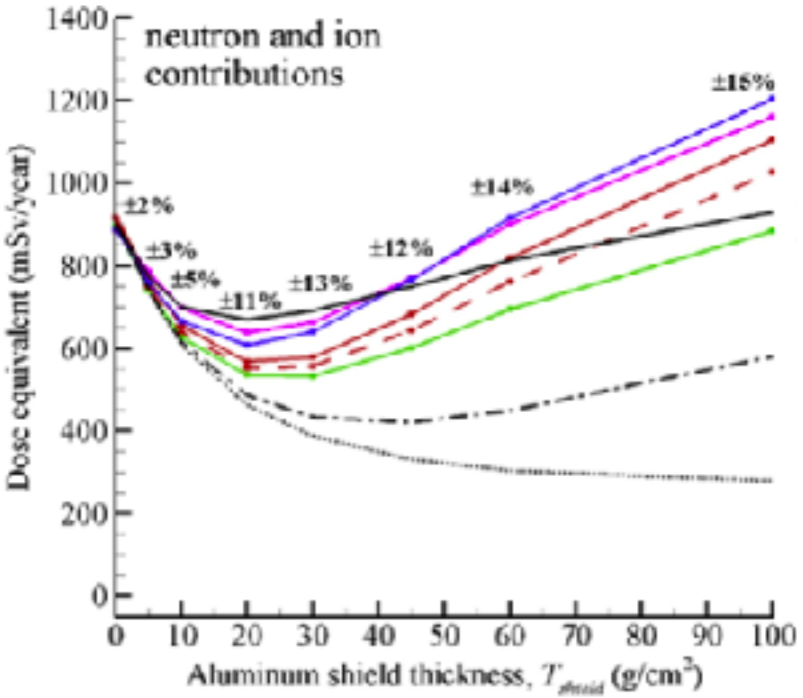
- ~ 100 members
    - INFN: 12 units (Milano, Roma Sapienza, Roma TorVergata, Bologna, TIFPA, Pisa, Torino, Napoli, Perugia, LNF, Bari)
    - 3 laboratories: CNAO, GSI, IPHC
    - 15 universities: France, Italy, Japan, Germany

FOOT for space

- Charged particles in space: Solar Particles Events (SPEs), Galactic Cosmic Rays (GCRs), geomagnetically trapped particles
- Interaction with walls/shielding of spacecraft produce secondary fragments







doi.org/10.1016/j.lssr.2016.12.003

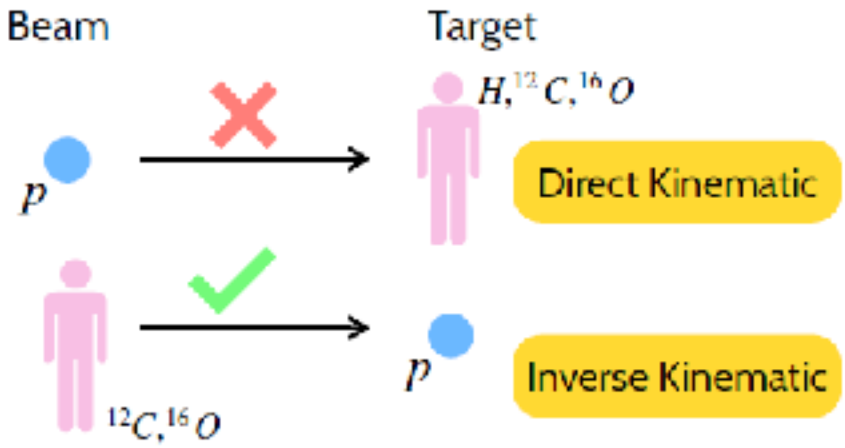
FOOT Physics Program

- Aim: beam and target fragmentation cross sections with 5% accuracy
- Experiment design to perform mass and charge identification at few % accuracy
- Direct/Inverse kinematics approaches
- ^{4}He, ^{12}C, ^{16}O beams of 200-800 MeV/u on ^{12}C and C_2H_4 targets

Physics	Application field	Beam	Target	Upper Energy (MeV/nucleon)	Kinematic approach	Interaction process
Target fragmentation	PT	^{12}C	C, C_2H_4	200	inverse	p+C
Target fragmentation	PT	^{16}O	C, C_2H_4	200	inverse	p+O
Beam fragmentation	PT	^{4}He	C, C_2H_4, PMMA	250	direct	α+C, α+H, α+O
Beam fragmentation	PT	^{12}C	C, C_2H_4, PMMA	400	direct	C+C, C+H, C+O
Beam fragmentation	PT	^{16}O	C, C_2H_4, PMMA	500	direct	O+C, O+H, O+O
Beam fragmentation	Space	^{4}He	C, C_2H_4, PMMA	800	direct	α+C, α+H, α+O
Beam fragmentation	Space	^{12}C	C, C_2H_4, PMMA	800	direct	C+C, C+H, C+O
Beam fragmentation	Space	^{16}O	C, C_2H_4, PMMA	800	direct	O+C, O+H, O+O

Inverse kinematic approach

- Protons on “patient” (98% C, O, and H nucleus) can be replaced by ^{16}O, ^{12}C ion beams impinging on a target made of protons
- By applying the Lorentz transformation (well known β) it is possible to switch from the laboratory to the patient frame



p (200 MeV) on O_2: range of fragments

Tommasino and Durante *Cancers* - 2015

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

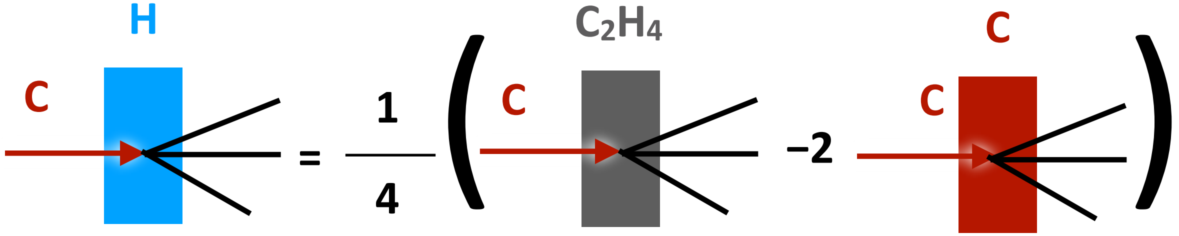
proton on patient | patient on proton

fragments with low energy and short range

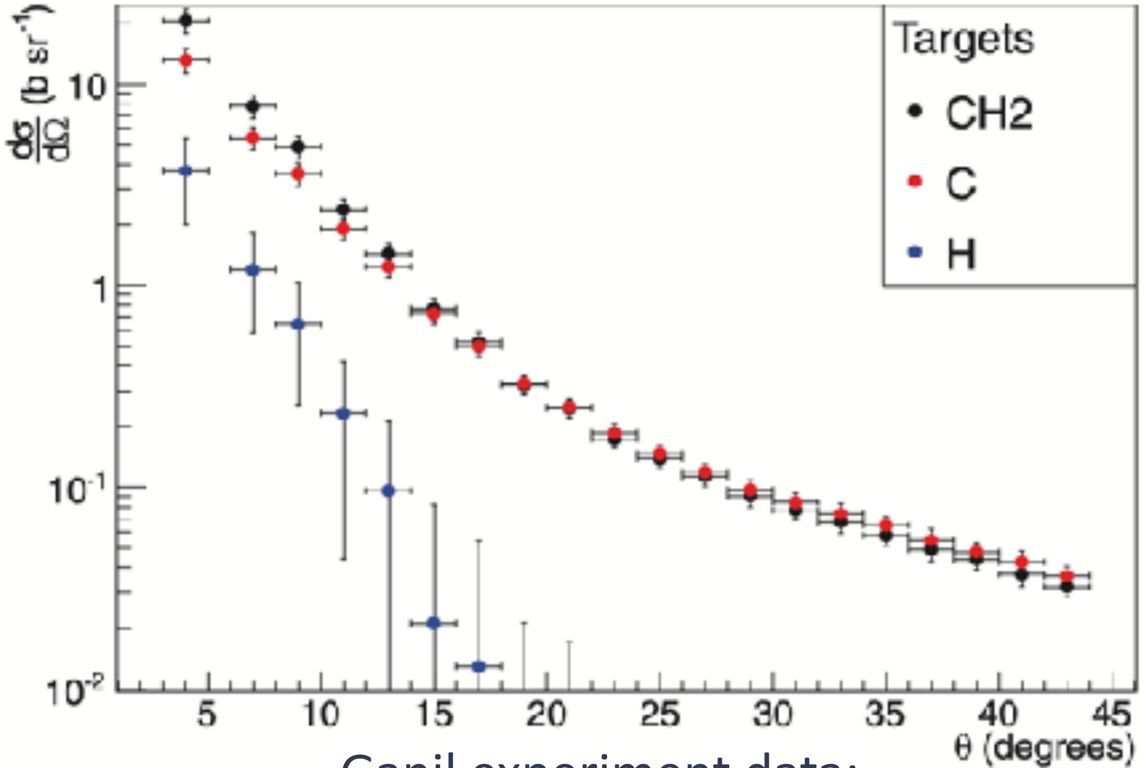
fragments with higher energy and longer range

The experimental challenge of measuring H cross section

- Gas target: Low Cross-Section
- Difficulty to make a H target
- Variations in target temperature and density can significantly affect the cross-section



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



Dudouet et al, Phys. Rev. C (2013)

Ganil experiment data:

C(95 MeV/n) on C and C_2H_4 target

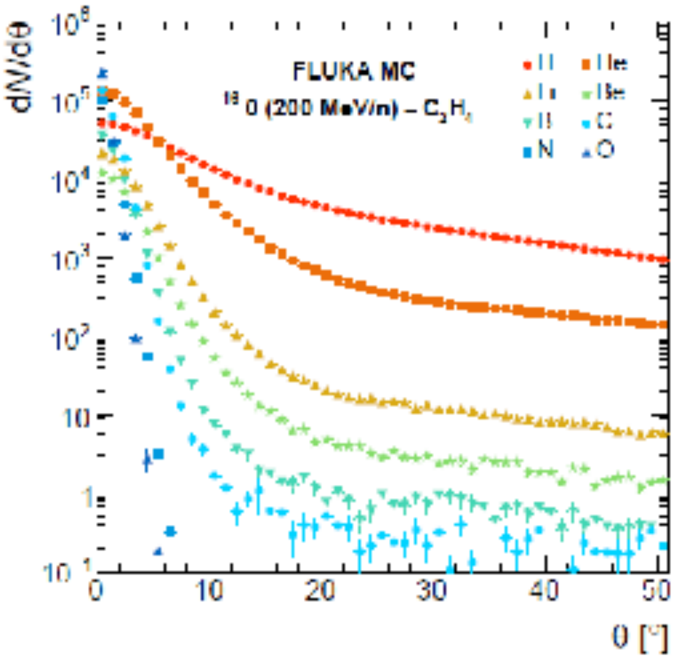
Cross Section Measurement

$$\left.\frac{d\sigma(x)}{dx}\right|_{C\ or\ C_2H_4} = \frac{Y_i(x)}{N_B N_{TG} \Delta x \epsilon^i_{reco}(x)}$$

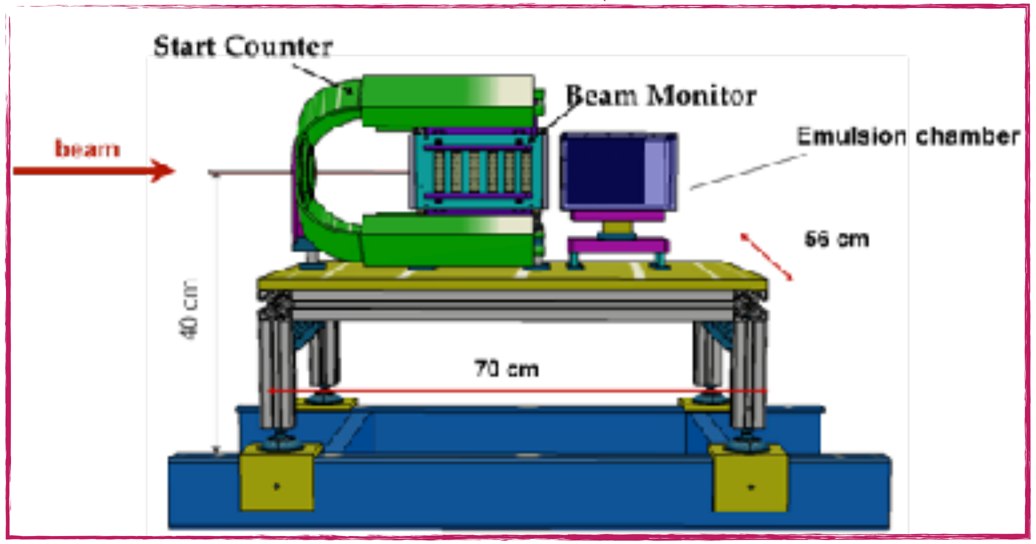
$$\left.\frac{d\sigma(x)}{dx}\right|_{H} = \frac{1}{4}\left(\left.\frac{d\sigma(x)}{dx}\right|_{C_2H_4} - 2\left.\frac{d\sigma(x)}{dx}\right|_{C}\right)$$

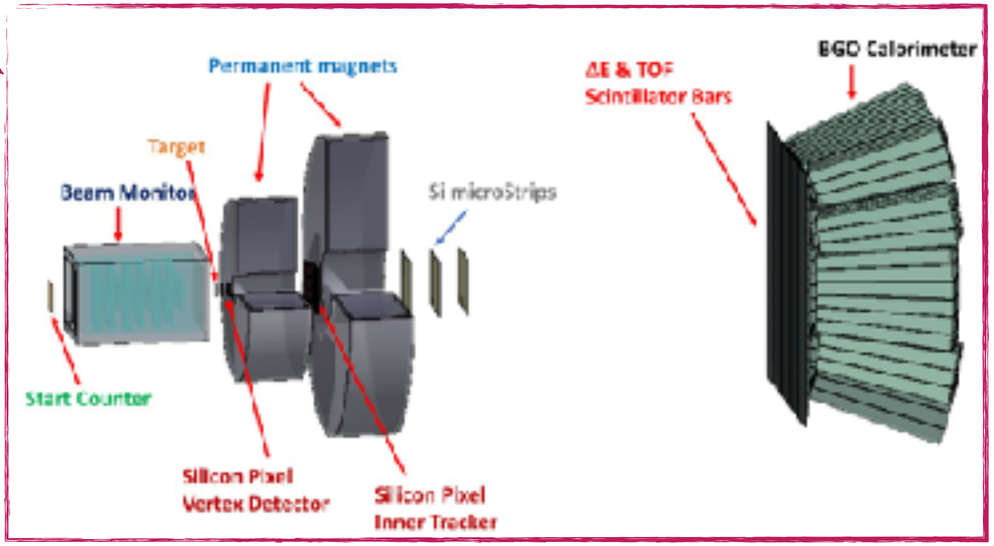
- Y_i = # of fragments in the interval Δx
- N_B = # of ions colliding on the target
- N_{TG} = # of particles in the target: $\frac{\rho d N_A}{A}$, with:
  - ρ = target density:
    - $\rho_C = 2.26 g/cm^3$
    - $\rho_{C_2H_4} = 0.94 g/cm^3$
    - $\rho_H = 0.0708 g/cm^3$
  - d = target thickness:
    - $d_C = 0.1 cm$ per layer
    - $d_{C_2H_4} = 0.2 cm$ per layer
  - $N_A = 6.022 \cdot 10^{23}/mol$
  - A = molar mass:
    - $A_C = 12 g/mol$
    - $A_{C2H4} = 28 g/mol$
    - $A_H = 1 g/mol$
- $\Delta x = x$ bin
- ϵ^i_{reco} = reconstruction efficiency

The setups

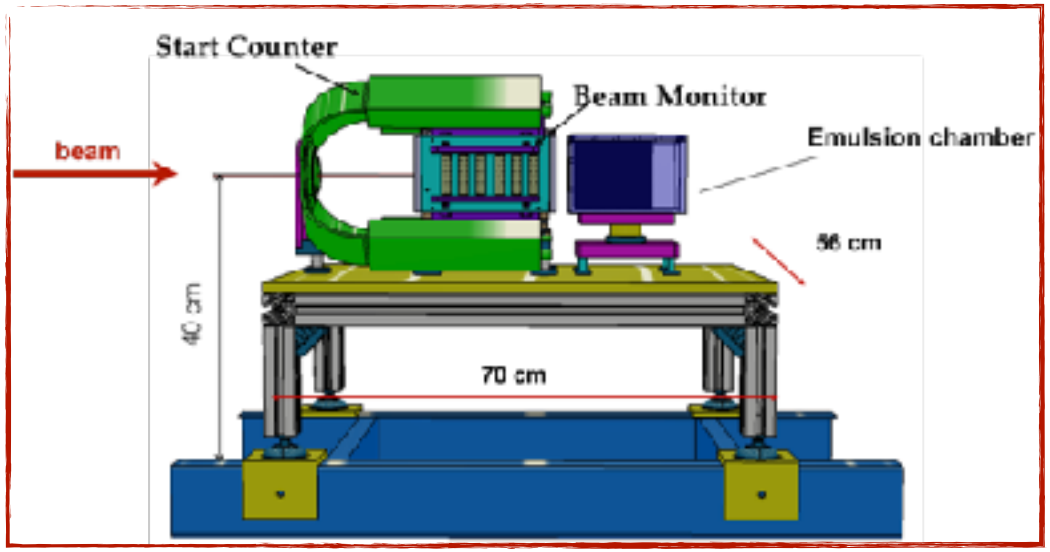


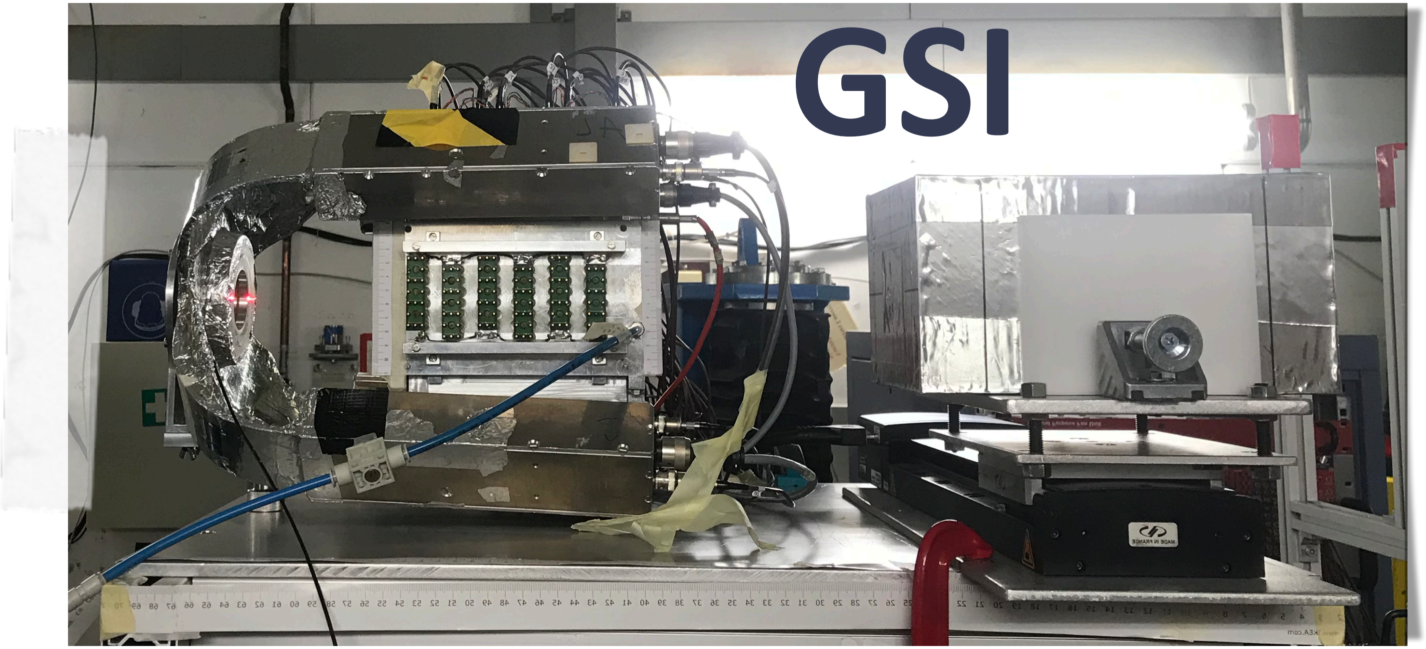
- Table-top experiment: small dimensions of the experimental halls of treatment centres
- Two complementary setups:
  - **nuclear emulsions spectrometer** to measure light charged fragments (Z≤3)
  - **magnetic spectrometer** with electronic detectors to measure the higher Z fragments (Z≥3)



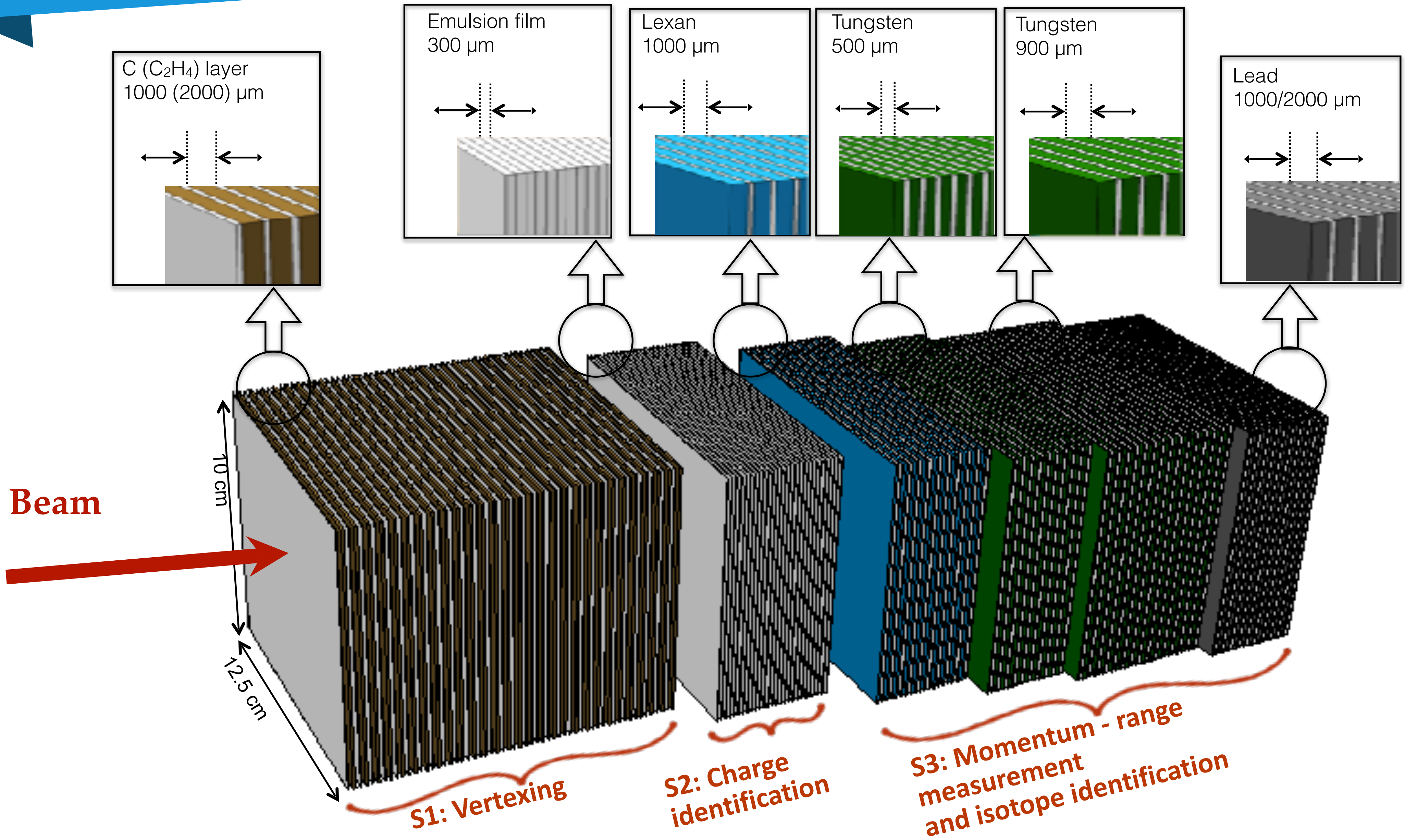


The nuclear emulsion setup





The nuclear emulsion setup



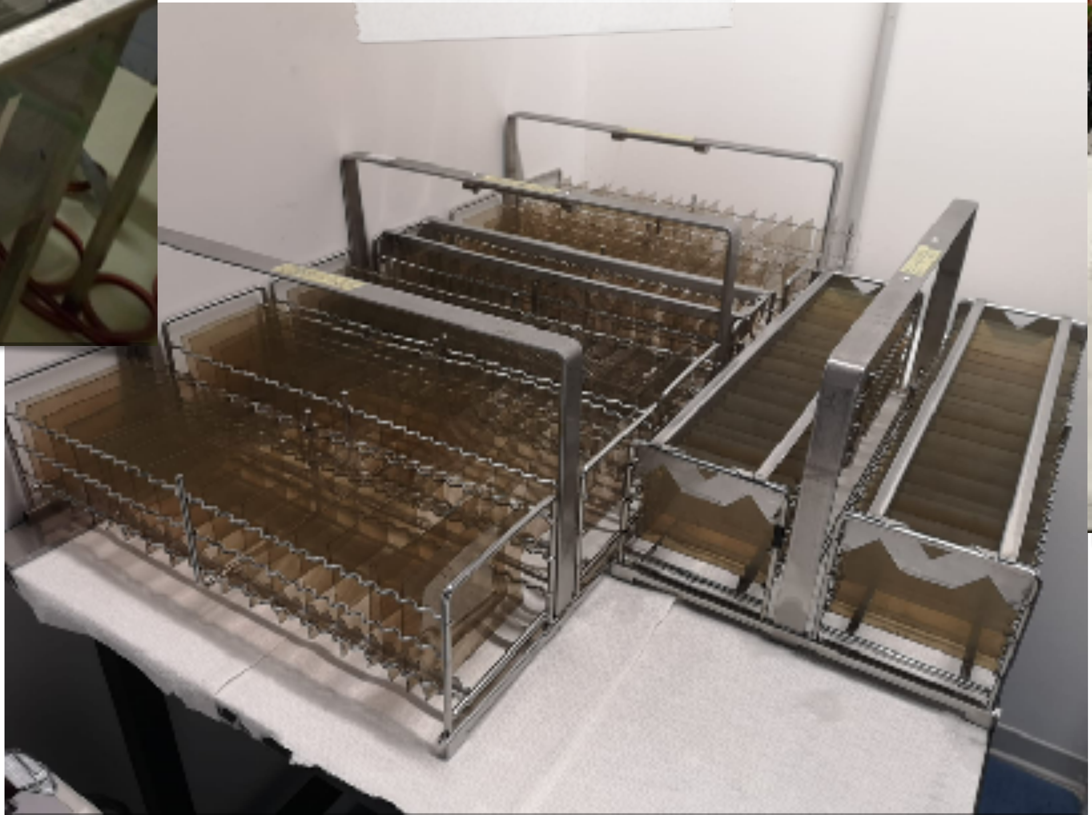
Cross-section measurements with Nuclear Emulsions setup

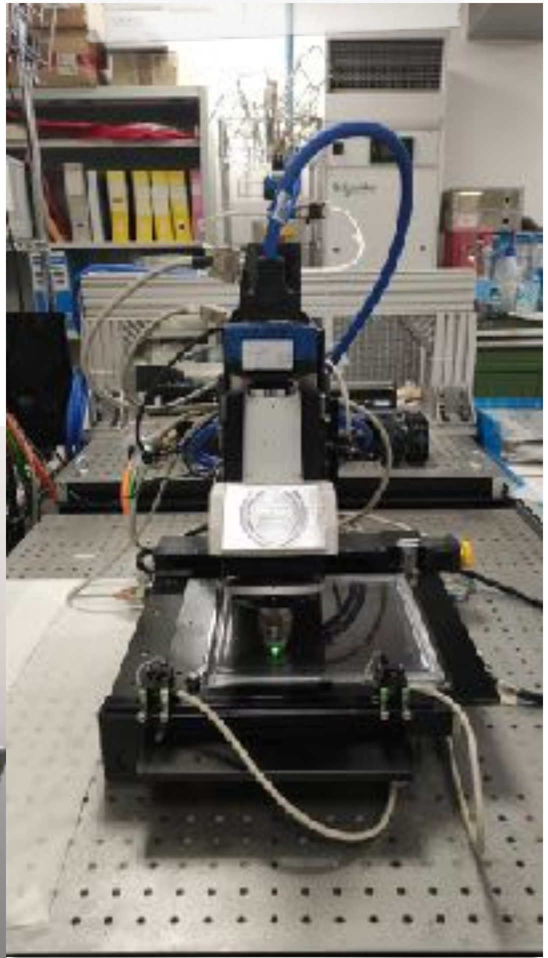
Beam	Facility / Year	Aim	Status
Oxygen @ 200 MeV/n	GSI 2019	Hadrontherapy	Analysis on going
Oxygen @ 400 MeV/n	GSI 2019	Hadrontherapy	Analysis on going
Carbon @ 700 MeV/n	GSI 2020	Radioprotection in space	Data aquired
Carbon @ 221 MeV/n	CNAO 2023	Hadrontherapy	Scanning of Nuclear emulsion films ongoing

Nuclear emulsions development and scanning

1

2





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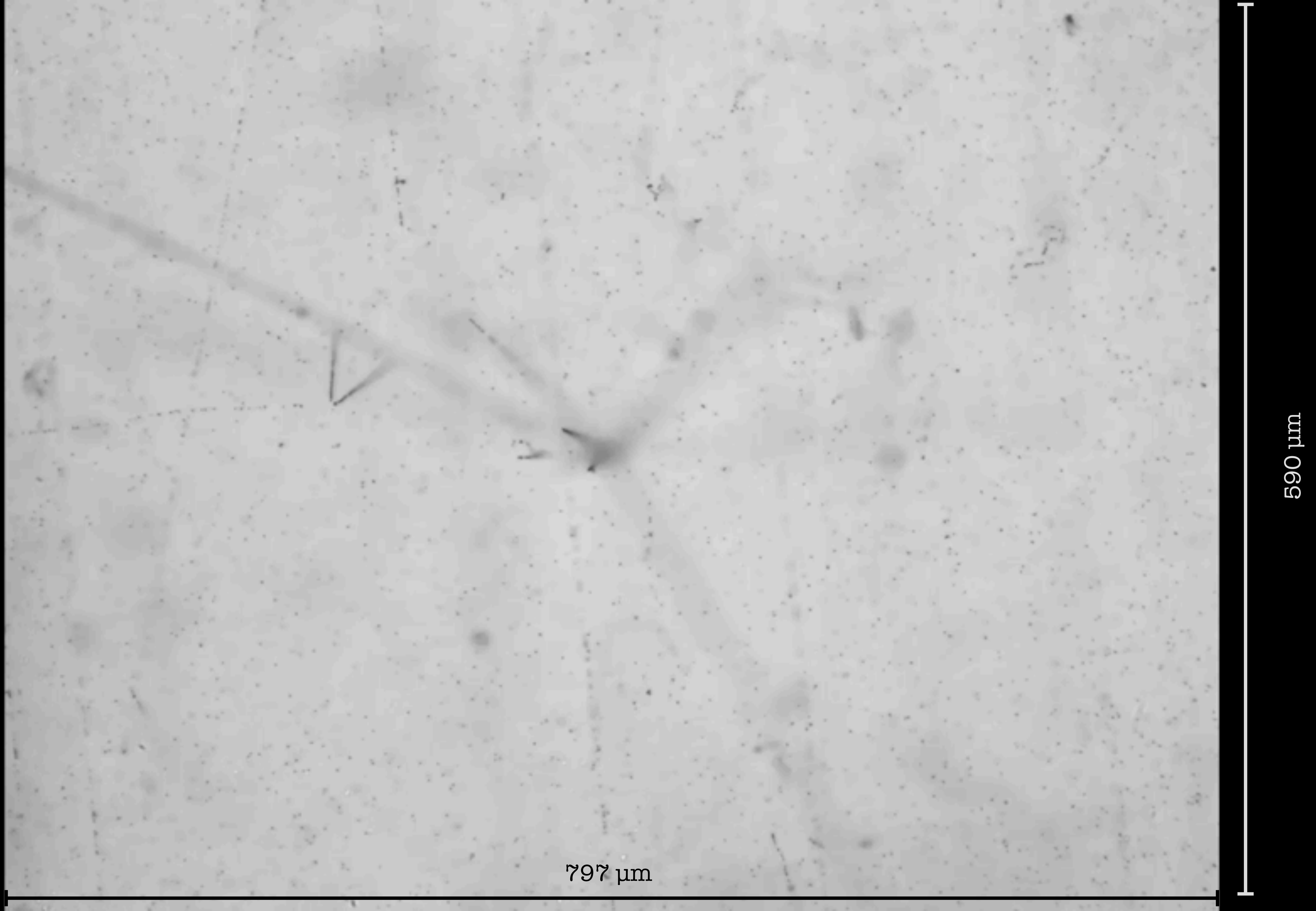

797 µm
590 µm

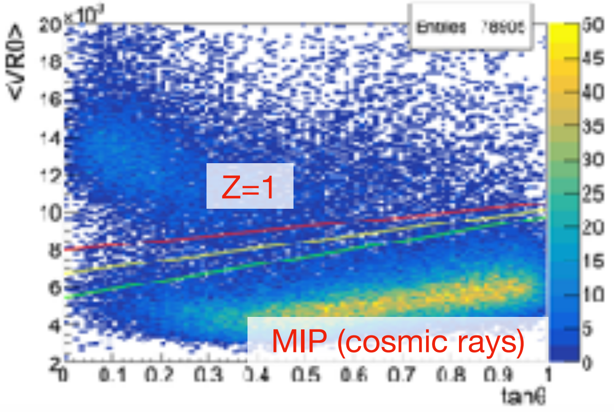

590 µm
797 µm

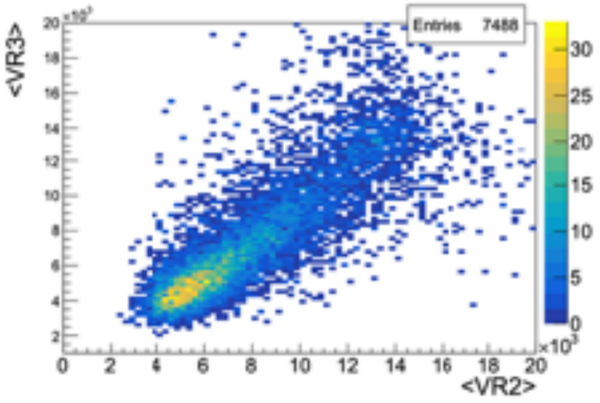
Charge identification with Nuclear Emulsions spectrometer

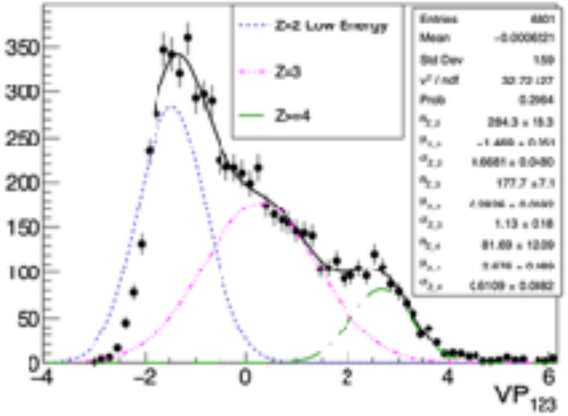
Two complementary methods:

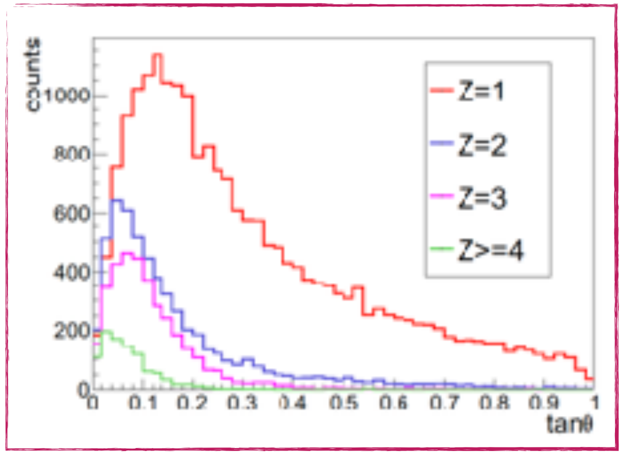
- Cut based-analysis to distinguish cosmic rays, Z=1 and Z=2 (high energy) fragments
- Principal Component Analysis to separate Z=2 (low energy), Z=3 and Z≥4 fragments

O@200MeV/n on C_2H_4



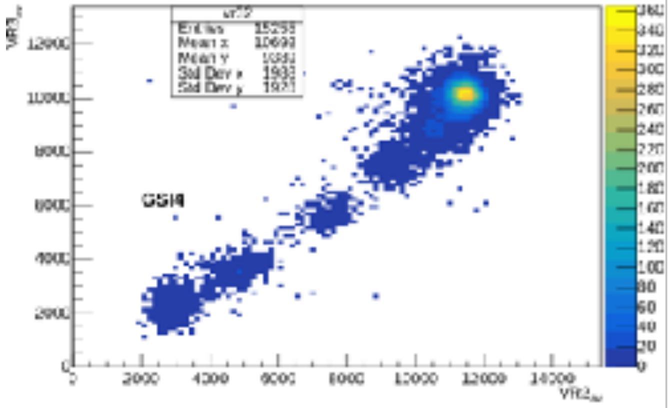


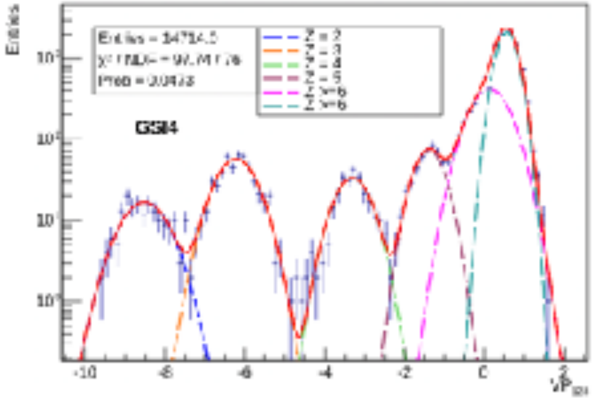




G. Galati doi.org/10.1515/phys-2021-0032

O@400MeV/n on C_2H_4





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doi:10.1016/j.nima.2005.08.109