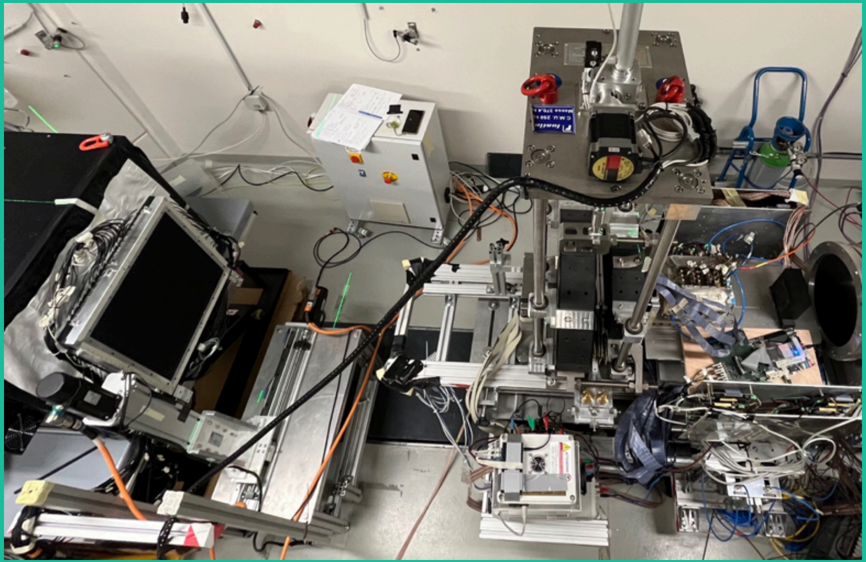
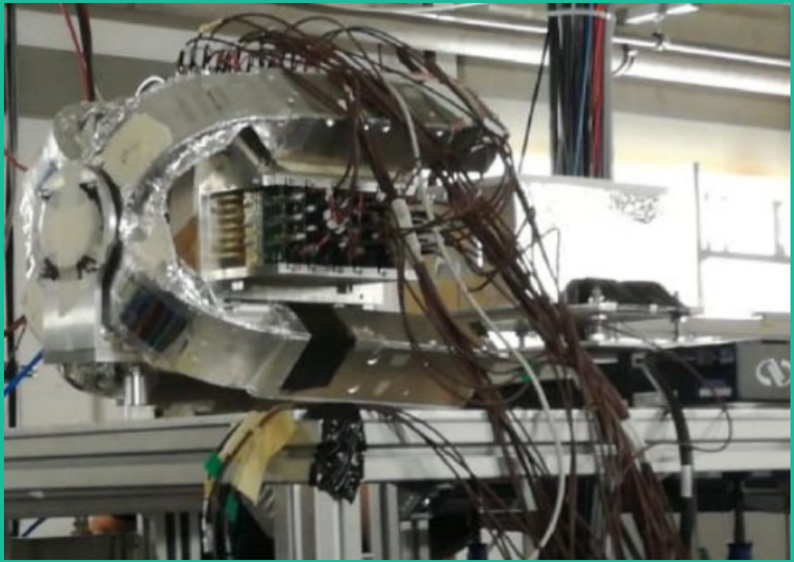
 

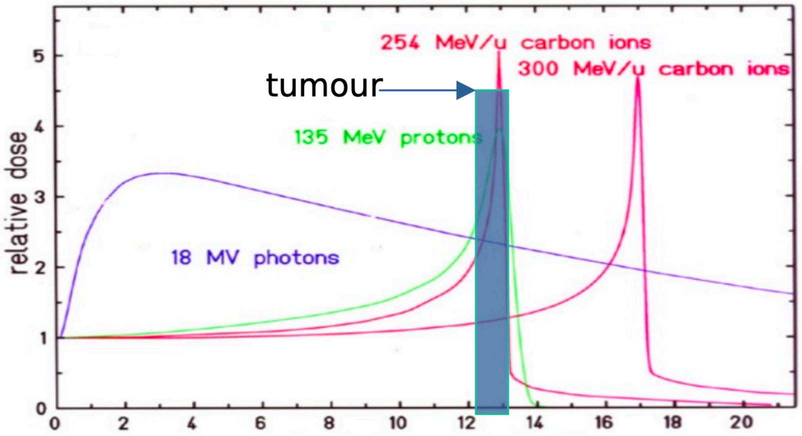
Nuclear fragmentation cross sections measurements: the FOOT experiment

Yunsheng Dong

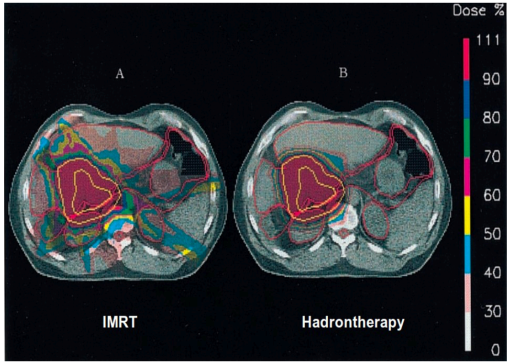
INFN Milano

Sesto Incontro Nazionale di Fisica Nucleare
28/02/2024

Particle therapy



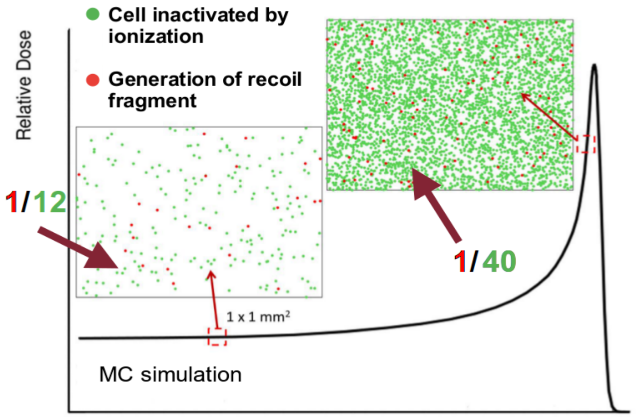
Durante M. And Paganetti H., reports on progress in physics, 79(9):096702, 2016



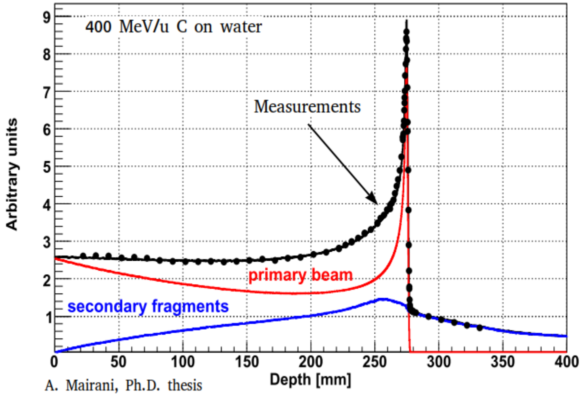
Particle therapy (PT): a form of radiotherapy conducted with hadrons (mainly ^{12}C and H)

- Max dose release in the Bragg peak
- Better dose conformation over the tumour volume, minimising the damage in healthy tissues
- Enhanced biological effectiveness in ^{12}C therapy

Particle therapy



F. Tommasino and M. Durante. Proton radiobiology. Cancers, 7(1):353-381, 2015.



A. Mairani, Ph.D. thesis

Particle therapy (PT): a form of radiotherapy conducted with hadrons (mainly ^{12}C and H)

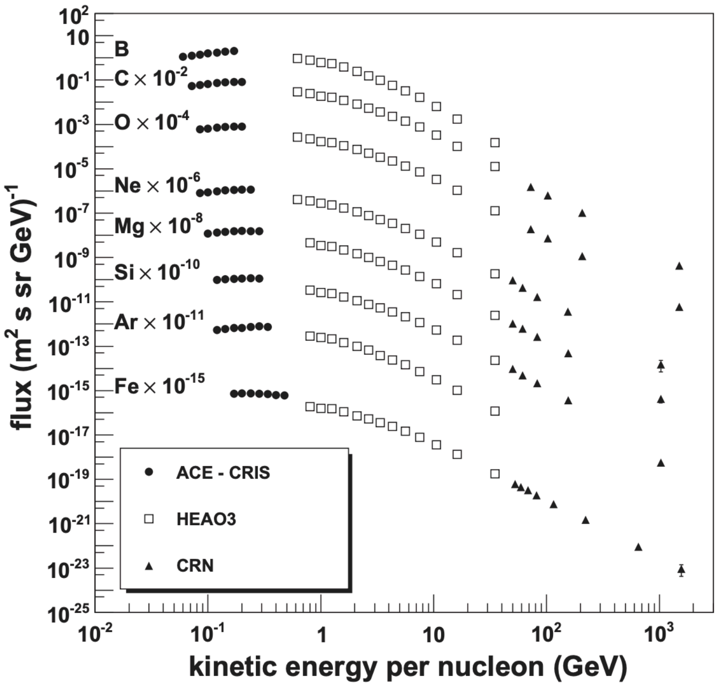
- Max dose release in the Bragg peak
- Better dose conformation over the tumour volume, minimising the damage in healthy tissues
- Enhanced biological effectiveness in ^{12}C therapy

Nuclear interactions in PT

- Target fragmentation in proton therapy
- Projectile fragmentation in heavy ion therapy

Need of differential cross section data to improve the nuclear models adopted in PT and explore new particles such as ^{16}O and ^{4}He

Radioprotection in space

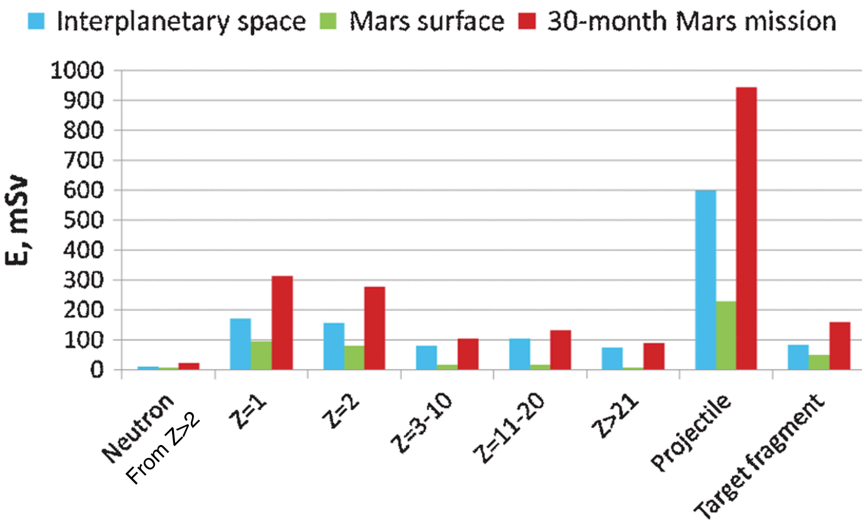


Boezio M. and Mocchiutti E., Astroparticle Physics, 39-40, 2012

Main radiation hazards in future space missions:

- Galactic cosmic radiations ($E<10^{20}$ eV) with H~85-90%, He~10-14%, Z>2~1%
- Solar particles events ($E<10^{5}$ eV), mainly protons

Radioprotection in space



Durante M. and Cucinotta F.A., Reviews of modern physics, 83, 2011

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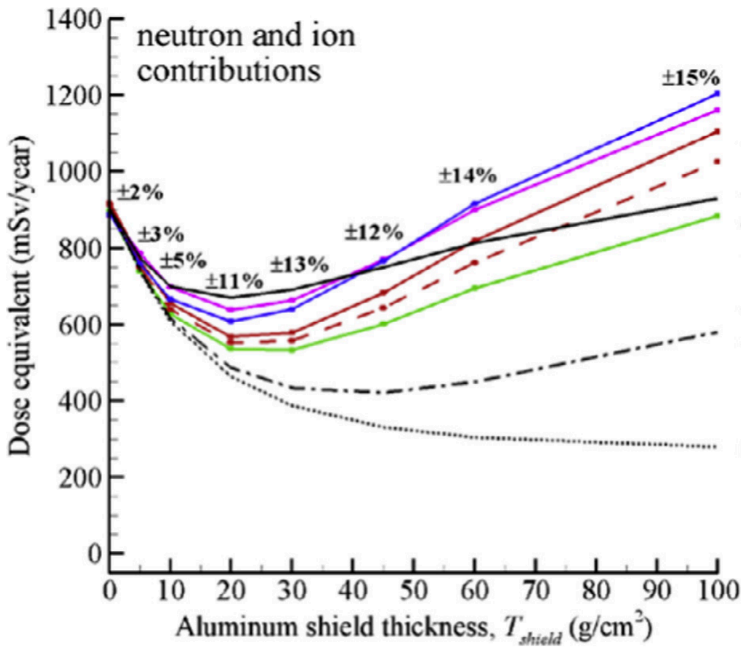
High contribution to the equivalent dose from:

- Primary light ions (mainly H and He isotopes) and fragments produced by primary high Z and Energy particles
- Secondary neutrons that can penetrate deeply

Radioprotection in space



Slaba T. et al, Life science in space research, 12, 2017

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High contribution to the equivalent dose from:

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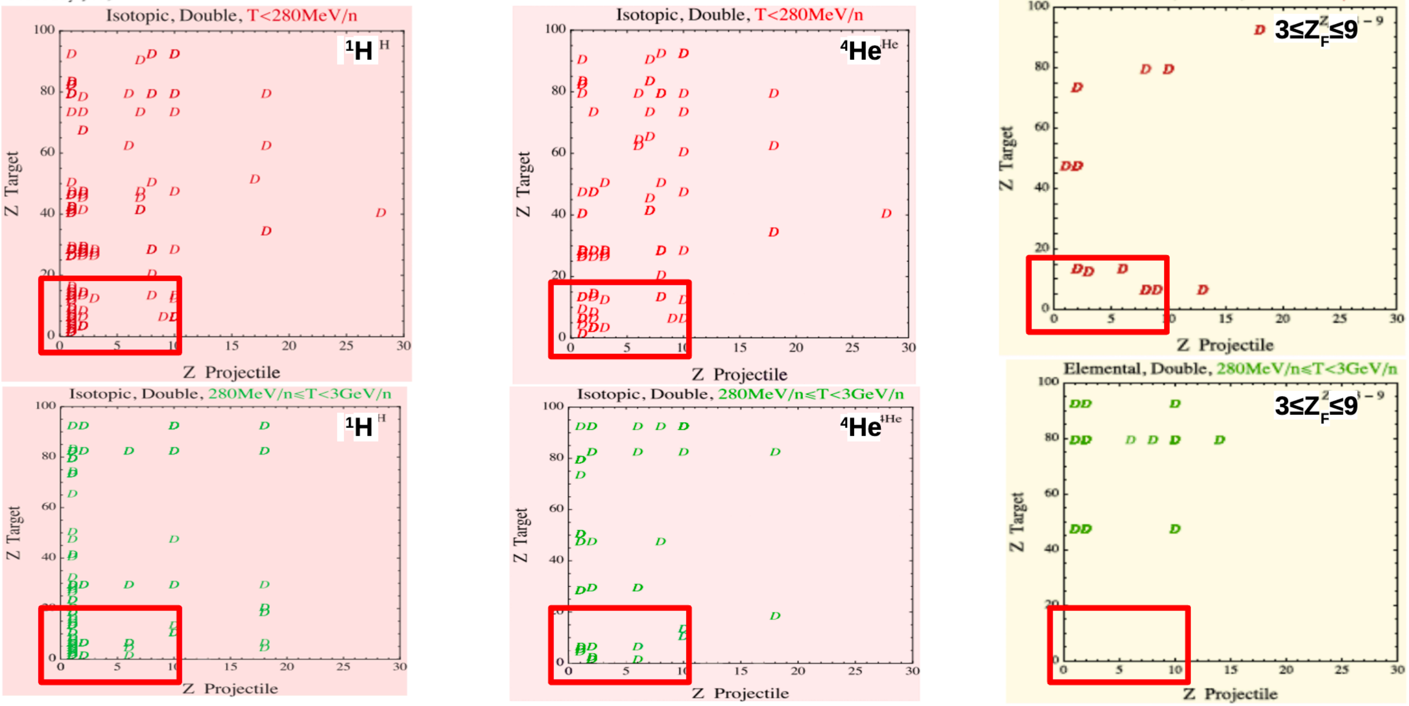
- Secondary neutrons that can penetrate deeply

Large discrepancies between transport codes, mainly for light fragments and neutrons.

Need of nuclear interaction differential cross section data to optimize the MC models, the space shielding design and strategy for shielding

Differential cross section data

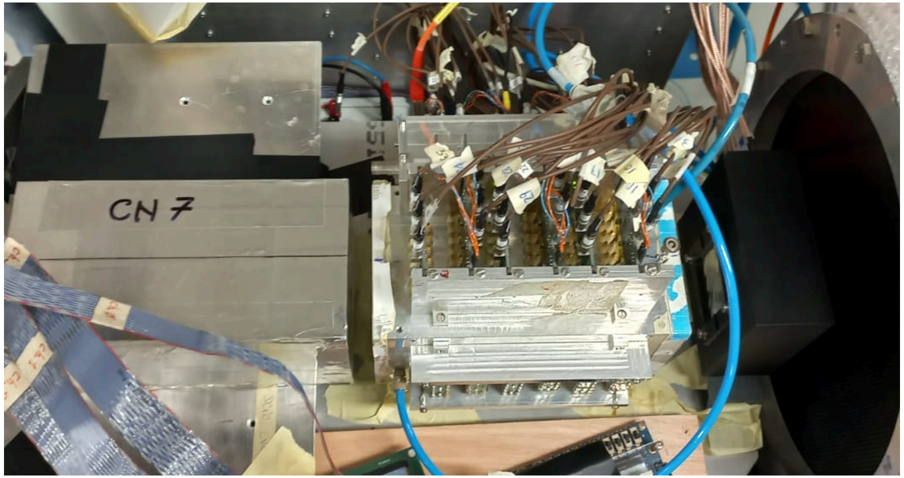
Norbury JW, *Radiat Meas.* (2012) 47:315–63. doi:10.1016/j.radmeas.2012.03.004.



Double differential cross section data available in literature

- In the red square: data of interest for particle therapy
- Lack of data, especially for heavy fragments (z≥3)
- Scarcity of data at large angles
- Double differential cross section of interest for particle therapy:
  - ^{12}C @ 50 and 95 MeV/u on $_{nat}C$ and CH_2 @ Ganil
    J. Dudouet et al, Physical Review C, 88, 08 2013

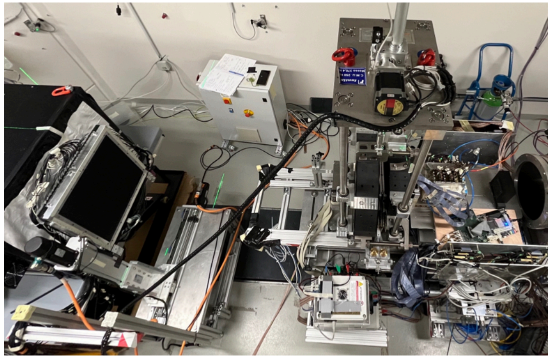
The FOOT (FragmentatiOn Of Target) experiment



Measuring the Impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT Experiment

Giuseppe Battistoni[1], Marco Toppi[2,3*], Vincenzo Patera[3,4] and The FOOT Collaboration

★Battistoni G. et al, Frontiers in Physics 2021 (8) doi.org/10.3389/fphy.2020.568242



FOOT aims to measure the fragmentation differential cross sections ($d^2\sigma/d\Omega \cdot dE$) of particles involved in PT and space radioprotection with two experimental setups

The FOOT data will be adopted:

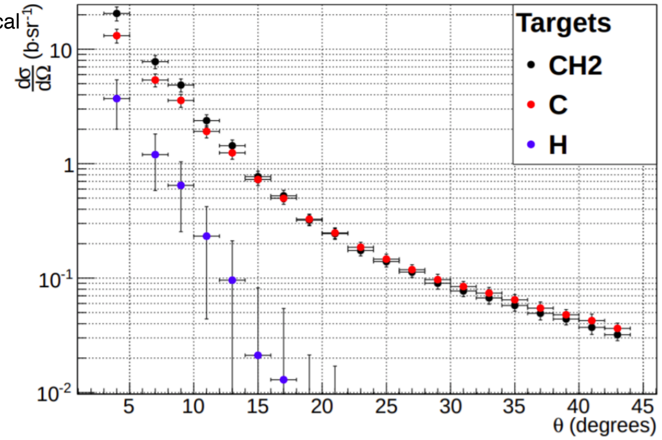
- As benchmark for MC simulation tools
- To improve the TPS and study new particles species in PT (e.g.: ^{16}O and ^{4}He)
- To develop new space shielding materials

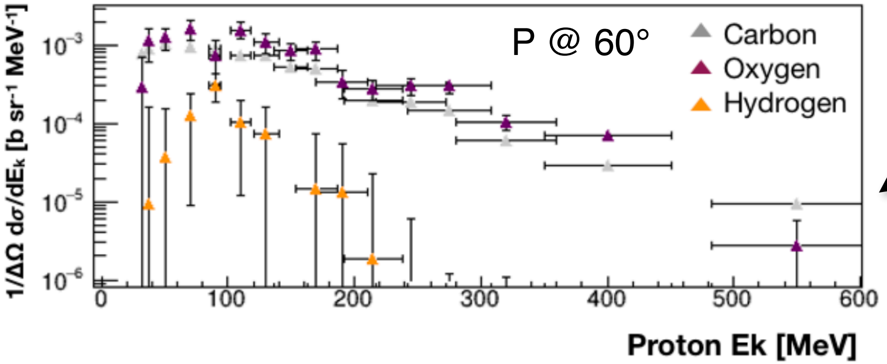
Radiobiological desiderata (from PT):

- $d\sigma/dE$ for target fragm. in PT ~ 10%
- $d^2\sigma/d\Omega dE$ for projectile fragm. in PT ~ 5%
- ΔZ ~ 2-3% ; ΔA ~ 5%

Measurement strategy: choice of target

J. Dudouet et al, Physical Review C, 88, 08 2013





Stoichiometric subtraction of cross sections

- Human body composition: ^{16}O(61%), ^{12}C(23%), H(10%)
- Targets of pure H or O are difficult to be installed and managed (gaseous targets with undefined initial P and inflammable)

$$\sigma(H) = (\sigma(CH_2) - \sigma(C))/2$$

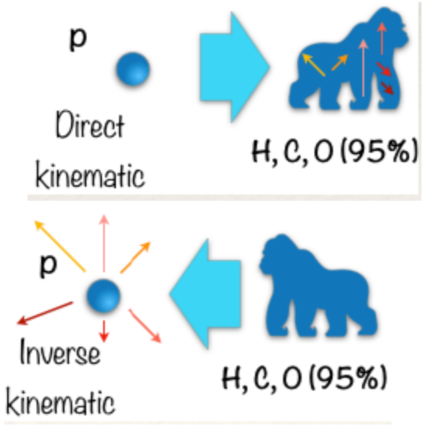
- Performed @ GANIL with ^{12}C @ 95 MeV/u
- **Performed @ CNAO with a "preliminary" FOOT setup**
  ★Mattei et al., IEEE Transactions on Radiation and Plasma Medical Sciences, 4(2):269–282, 2020, 10.1109/TRPMS.2020.2972197
- The subtraction results are an order of magnitude smaller with respect to the initial measured cross section values: **large statistical uncertainties**
- **Use of $_{nat}C$, C_2H_4 and PMMA targets**

Measurement strategy: inverse kinematic approach

Expected average physical parameters for target fragments produced in water by a 180 MeV proton beam

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

GoodHead D.T., Radiation protection dosimetry, 122, 2006



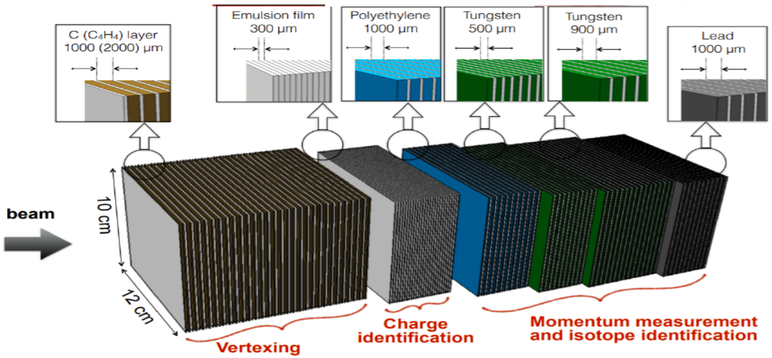
Target fragmentation measurements

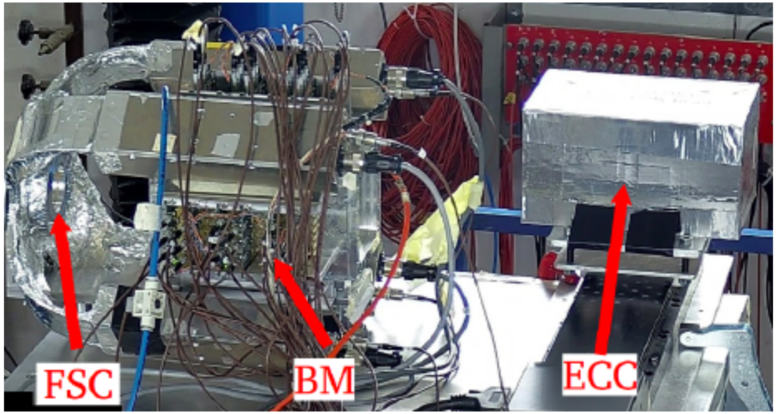
- Target fragments produced from 60 - 200 MeV protons have ranges of ~ μm
- Technical difficulties for a direct detection with common detectors
- Use of an inverse kinematic approach for the target fragmentation measurements

Two experimental setup to fulfil the FOOT experimental program:

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+C
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

Emulsion spectrometer





Emulsion Cloud Chamber (ECC) detector to measure the fragments with Z≤3 and θ<70°

ECC composition:

- Vertexing region: nuclear emulsion films alternated with target layers to identify the interaction vertices
- Charge id. region: only emulsion films exploited for the charge id. with a refreshing procedure
- Absorbing region: emulsion and absorber layers for the momentum and mass id., exploiting the track length and the Multiple Coulomb Scattering effect

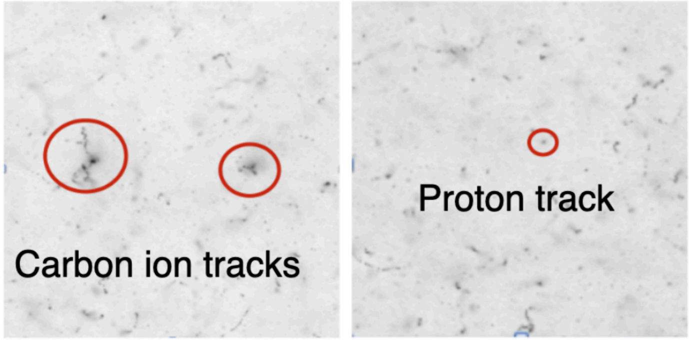
ECC setup:

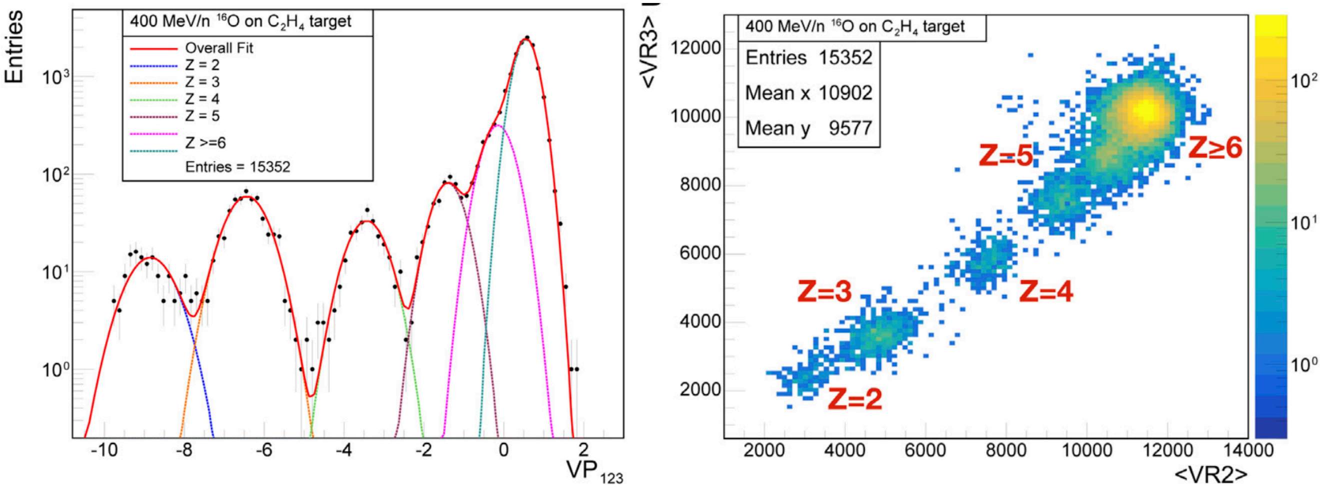
- Plastic scintillator to count the number of primaries
- Drift chamber to check the incoming beam position
- ECC detector with nuclear emulsion films for the cross section measurements

Emulsion spectrometer: charge identification

Charge identification:

- Z ∝dE/dx ∝ grain density ∝ track volume
- Refreshing: applying thermal treatments with increasing temperatures, the tracks from less ionizing particles are gradually deleted
- Combining volumes and angles of the tracks calculated after each treatment, the charge id. is reached
- Saturation effect for Z ≥ 6
- Charge mis-identification (1-5%)



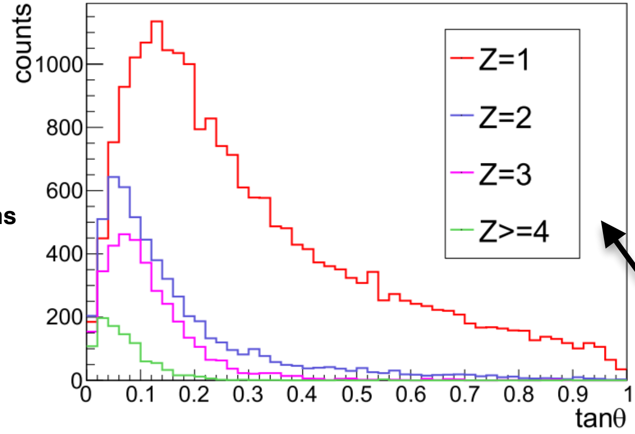


★ Galati et al., Frontiers in Oncology, 11, 2023, 10.3389/fphy.2023.1327202

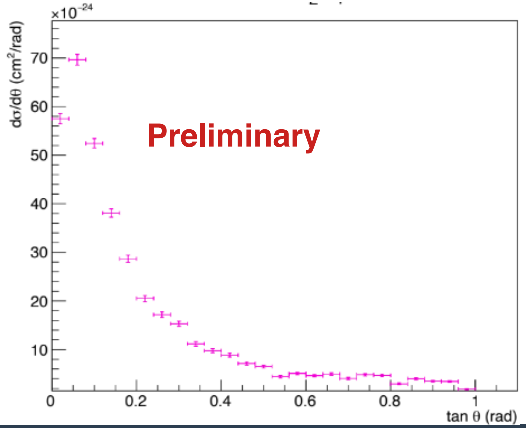
Emulsion spectrometer: measurements

^{16}O @ 200 MeV/u onC_2H_4:

Fragments angular distributions



Angular differential cross section:



Concluded campaigns:

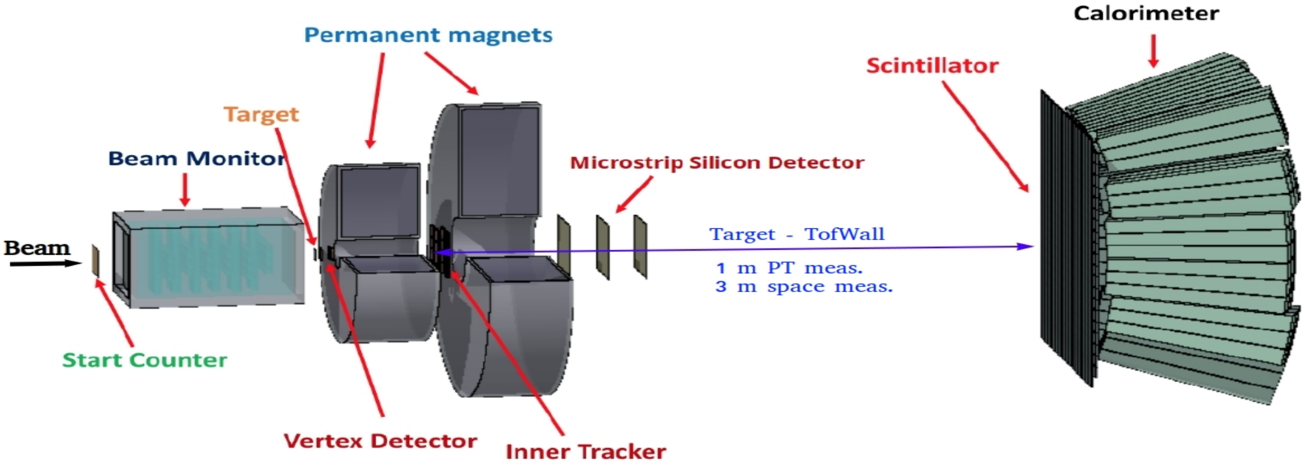
- Characterisation with P, ^{4}He and ^{12}C at 80 MeV/u completed
  - ★ Montesi et al., Open Physics, 17(1):233–240, 2019, 10.1515/phys-2019-0024
- ^{16}O @ 200 - 400 MeV/u and ^{12}C @ 200-700 MeV/u on $_{nat}$C and C_2H_4 targets, analysis ongoing
  - ★ Galati et al., Open Physics, 19(1):383–394, 2021, 10.1515/phys-2021-0032
  - ★ Galati et al., Frontiers in Oncology, 11, 2023, 10.3389/fphy.2023.1327202

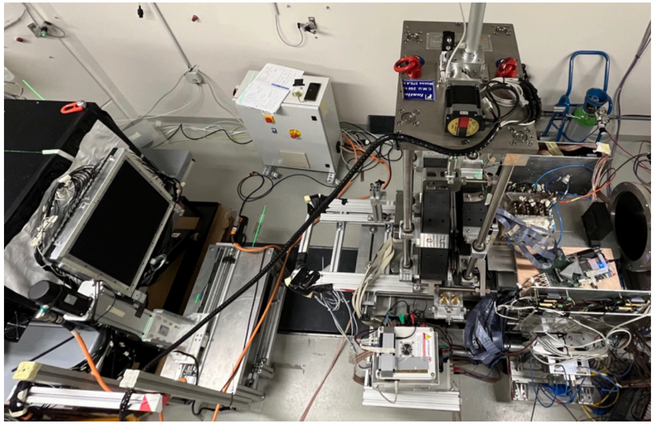
Next measurements:

- Study of a novel kind of emulsions to measure the target fragmentation process with direct kinematics
- First tests in 2023 @ Trento and CNAO with P

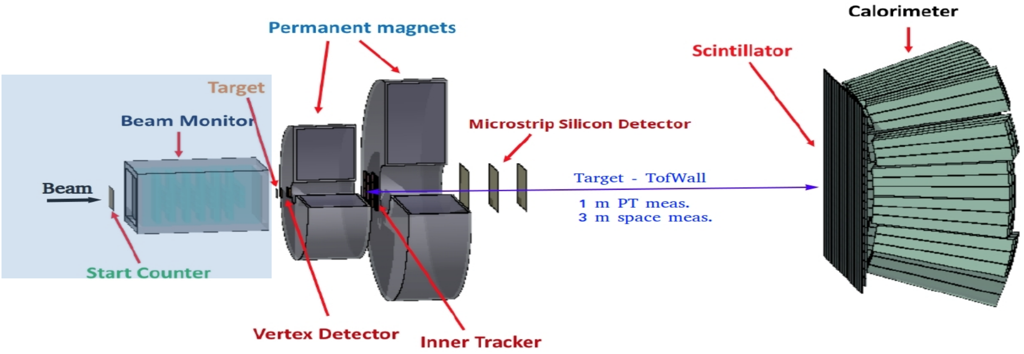
Electronic spectrometer

Electronic spectrometer to detect the fragments with Z≥3 and θ<6°~10°

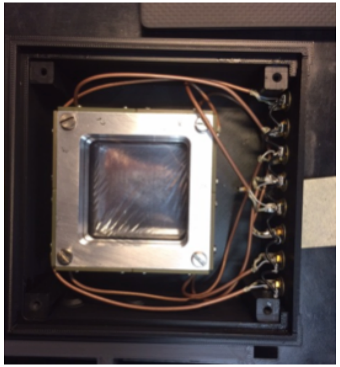




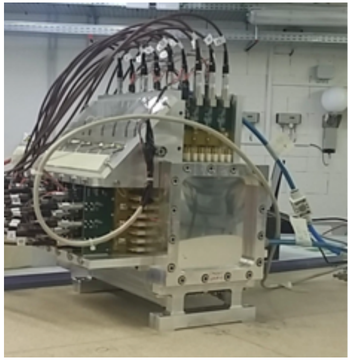
Electronic spectrometer: experimental setup

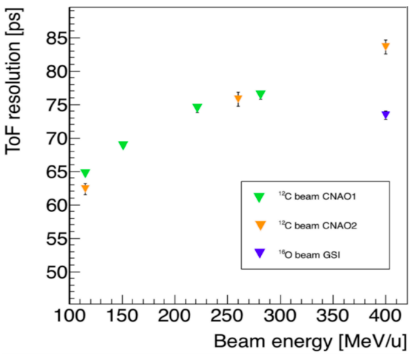


Start counter

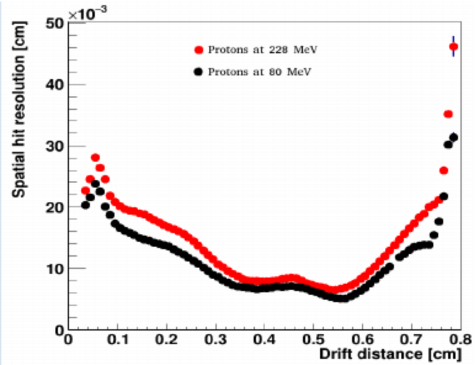


Beam Monitor





★Morrocchi M. et al, NIM A, 2018, 10.1016/j.nima.2018.09.086

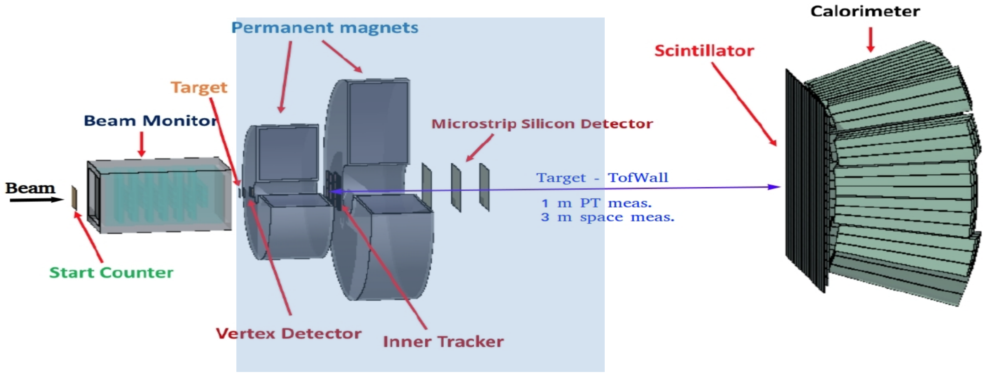


★Dong Y. et al, NIM A, 2021,10.1016/j.nima.2020.164756

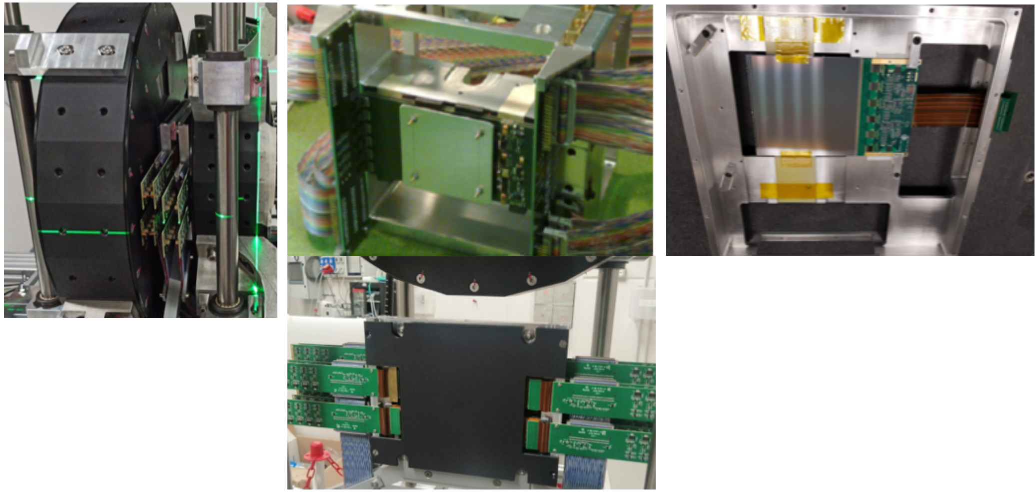
Pre target region:

- Start Counter: plastic scintillator for TOF and trigger measurements
- Beam Monitor: drift chamber for the beam direction and position measurements

Electronic spectrometer: experimental setup



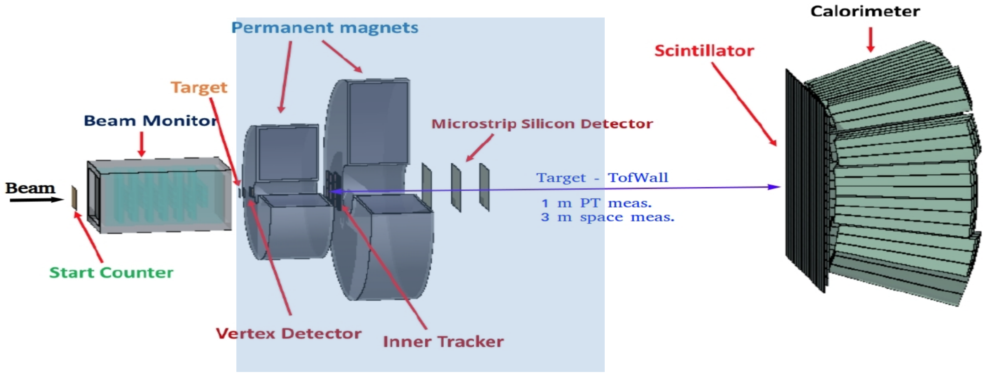
Magnet | Vertex + Inner tracker | MSD



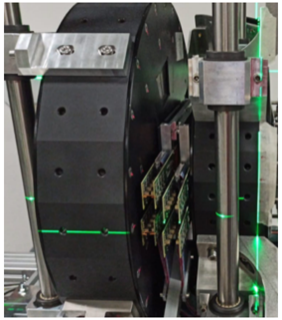
Tracking region:

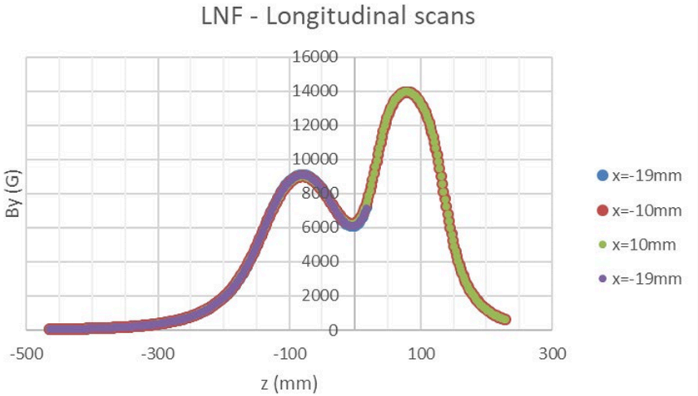
- Particle track and momentum reconstruction

Electronic spectrometer: experimental setup



Magnet

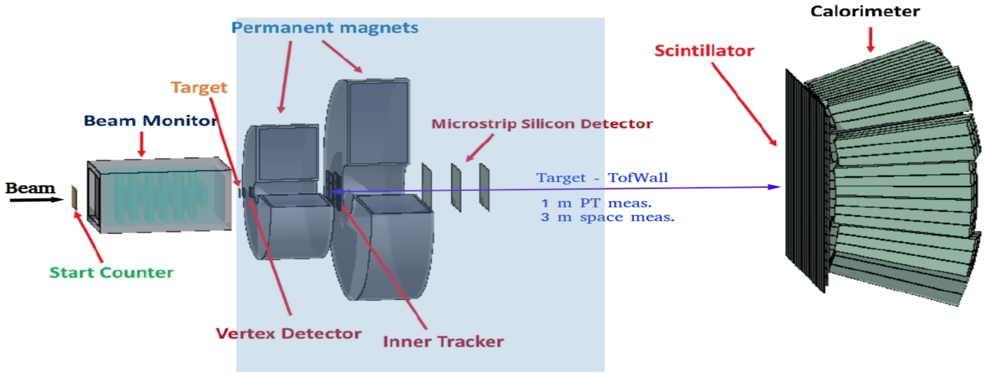




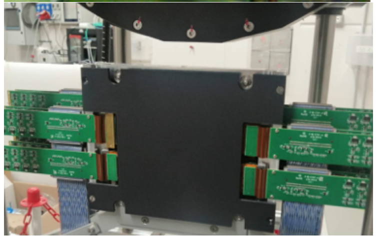
Tracking region:

- Particle track and momentum reconstruction
- Permanent magnets: two magnets in Halbach configuration B_{max}~1.4T ⊥ the beam axis, delivered in autumn 2023

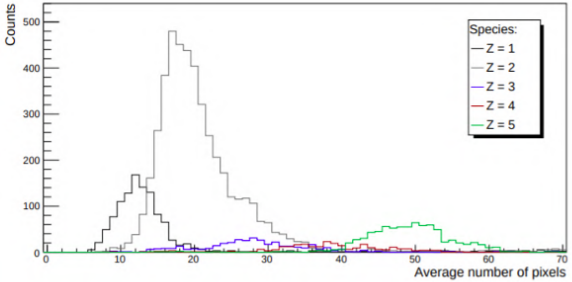
Electronic spectrometer: experimental setup

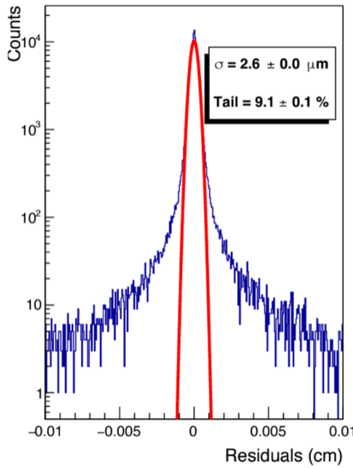


Vertex + Inner tracker



Spiriti E. et al, NIM A,2017, 10.1016/j.nima.2017.08.058

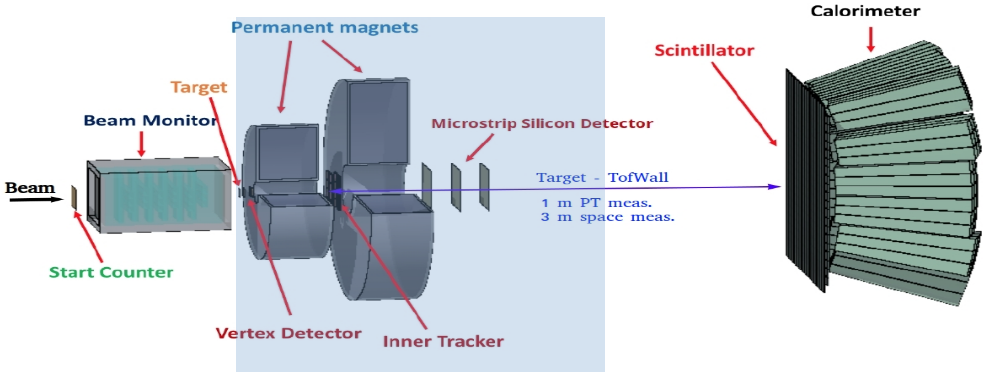




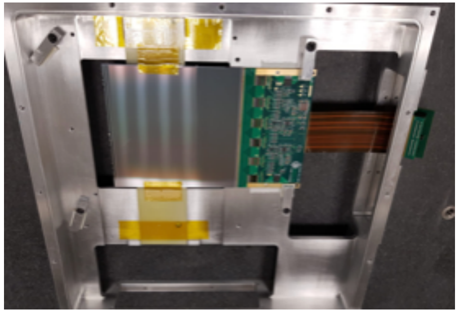
Tracking region:

- Particle track and momentum reconstruction
- Permanent magnets: two magnets in Halbach configuration B_{max}~1.4T ⊥ the beam axis, delivered in autumn 2023
- Vertex and Inner Tracker: Silicon pixel detectors (M28), IT under study

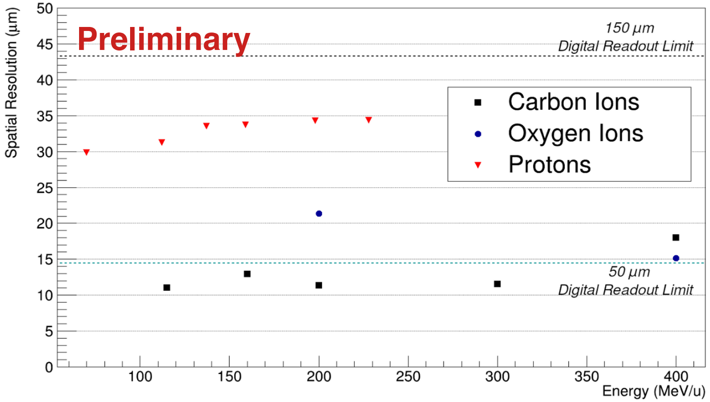
Electronic spectrometer: experimental setup



Microstrip Silicon Detector



★ Silvestre G. et al, JINST, 17, 2022, 10.1088/1748-0221/17/12/P12012



Tracking region:

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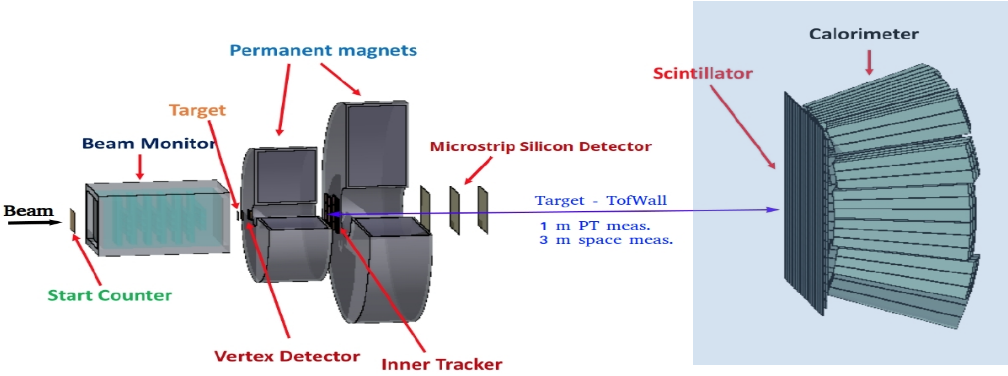
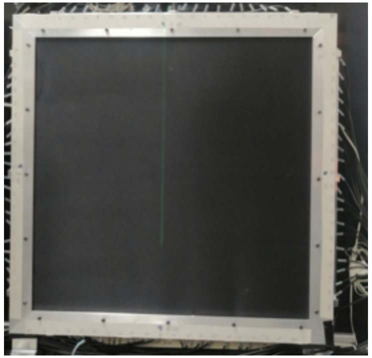
- Vertex and Inner Tracker: Silicon pixel detectors (M28), IT under study
- MSD: Microstrip Silicon Detector, characterisation ongoing

Electronic spectrometer: experimental setup



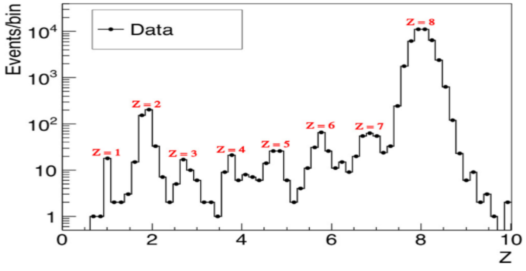
Tof Wall



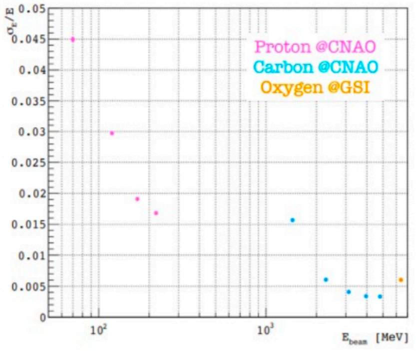
Calorimeter

Downstream region:

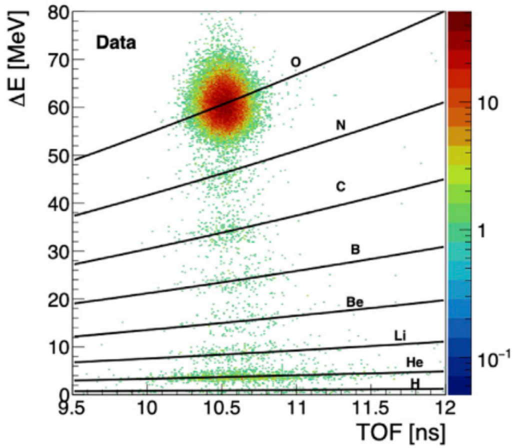
- TofWall: Plastic scintillator bars for the TOF and dE/dx measurements, necessary for the charge identification
- Calorimeter: 320 $Bi_4Ge_3O_{12}$ (BGO) crystals dedicated to the E_{kin} measurement, characterisation ongoing

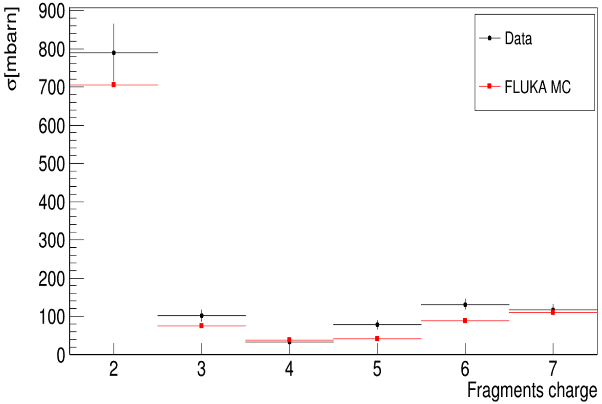


★Kraan A.C. et al, NIMA, 1001:165206, 2021, 10.1016/j.nima.2021.165206



Electronic spectrometer: measurements





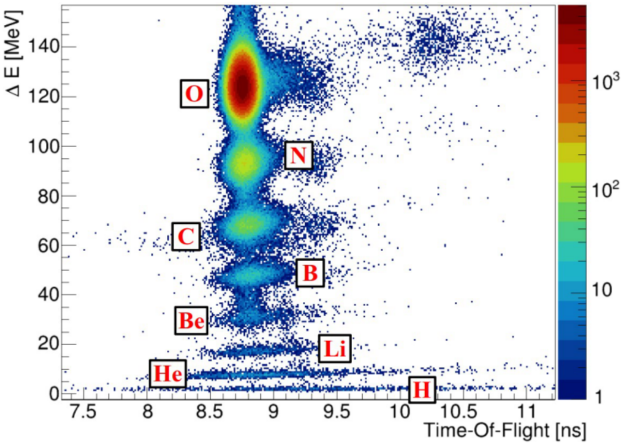
Elemental cross section measurements

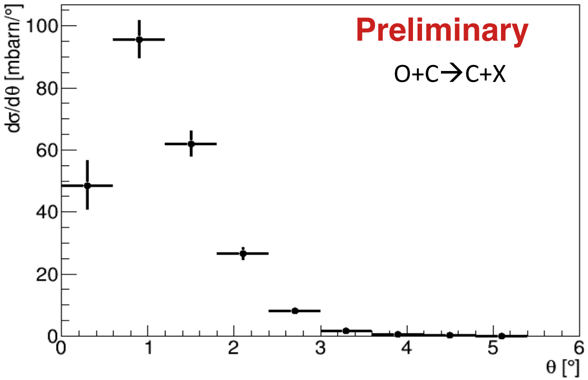
- Different campaigns concluded with half of the setup:
  ^{16}O @ 200 – 400 MeV/u on C and C_2H_4 (GSI)
  ^{4}He @ 100 – 220 MeV/u on C (Hidelberg)
  ^{12}C @ 100 – 400 MeV/u on C, C_2H_4 (CNAO)

- Elemental fragmentation cross section of ^{16}O @ 400 MeV/u on $_{nat}C$ target published (SC+BM+TW)

★Toppi M. et al, Frontiers in Physics, 10, 2022, 10.3389/fphy.2022.979229

Electronic spectrometer: measurements





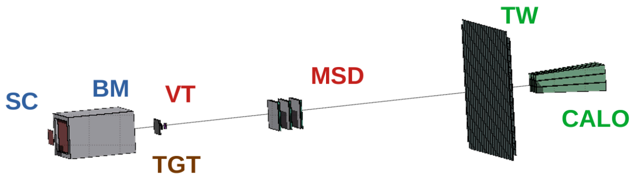
Elemental cross section measurements

- Different campaigns concluded with half of the setup:
  ^{16}O @ 200 – 400 MeV/u on C and C_2H_4 (GSI)
  ^{4}He @ 100 – 220 MeV/u on C (Hidelberg)
  ^{12}C @ 100 – 400 MeV/u on C, C_2H_4 (CNAO)
- Elemental fragmentation cross section of ^{16}O @ 400 MeV/u on $_{nat}C$ target published (SC+BM+TW)

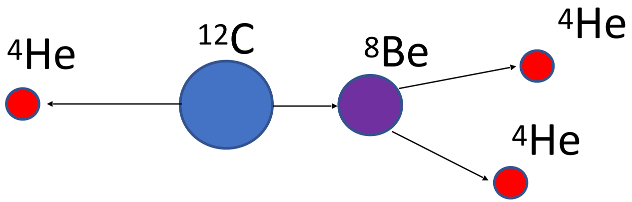
★Toppi M. et al, Frontiers in Physics, 10, 2022, 10.3389/fphy.2022.979229

Differential cross section measurements

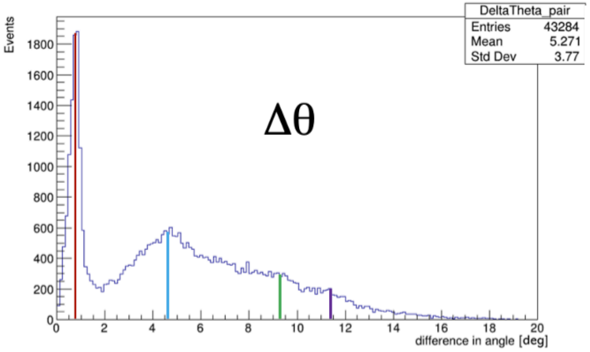
- Analysis of angular cross section of ^{16}O @ 400 MeV/u on $_{nat}C$ target, with partial setup ongoing

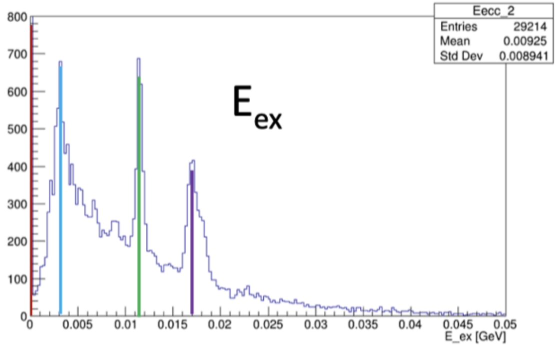


α clustering measurements



MC



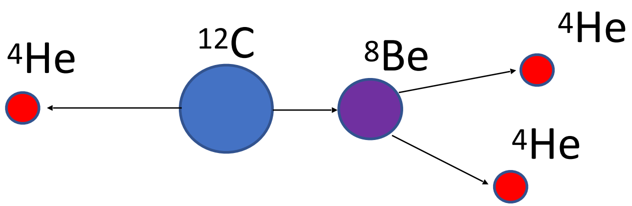


- Different experiments investigated nuclear clustering phenomena, mainly at the Coulomb barrier and Fermi energy range (<100 MeV/u)
- FOOT can measure α clustering phenomena in ^{12}C—>3α and ^{16}O—> 4α @ 200-400 MeV/u
- Measure the formation of intermediate state with the α particle angular correlation and excitation energies

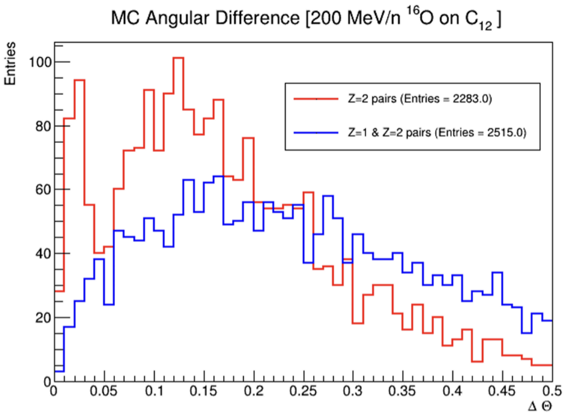
Preliminary studies conducted

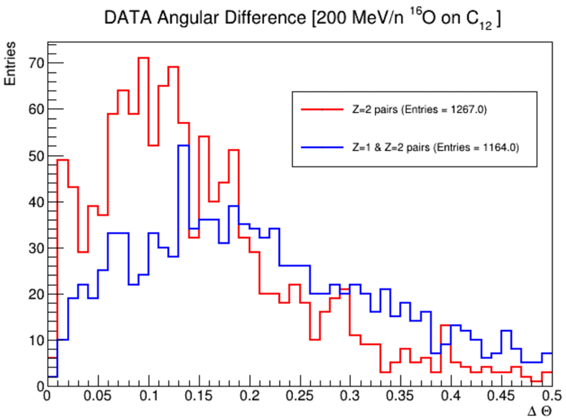
- Electronic spectrometer: high statistics, low resolution (^{12}C @ 200 MeV/u on $_{nat}$C, MC sample)

α clustering measurements



- Different experiments investigated nuclear clustering phenomena, mainly at the Coulomb barrier and Fermi energy range (<100 MeV)
- FOOT can measure α clustering phenomena in $^{12}C \rightarrow 3\alpha$ and $^{16}O \rightarrow 4\alpha$ @ 200-400 MeV/u
- Measure the formation of intermediate state with the α particle angular correlation and excitation energies





Preliminary studies conducted

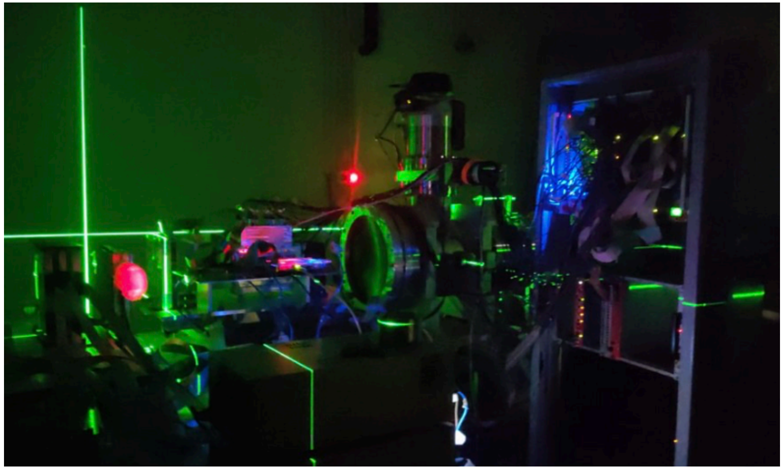
- Electronic spectrometer: high statistics, low resolution (^{12}C @ 200 MeV/u on $_{nat}C$, MC sample)
- Emulsion spectrometer: low statistics, high resolution (^{16}O @ 200 MeV/u on $_{nat}C$, MC and Data)

α clustering measurements

Conclusions and future perspectives

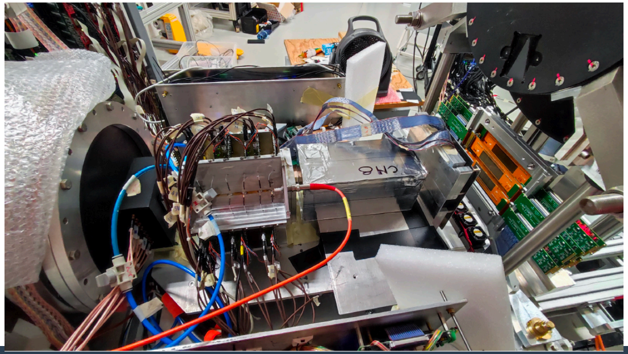
Present status

- Emulsion setup is fully characterised and the cross section data analysis on the past campaigns is ongoing
- Full electronic setup completed in late 2023 (first full setup data taking at CNAO with ^{12}C @ 200 MeV/u)
- Detector performance assessment are almost completed
- Elemental and differential cross section studies on data collected with partial experimental setup are ongoing

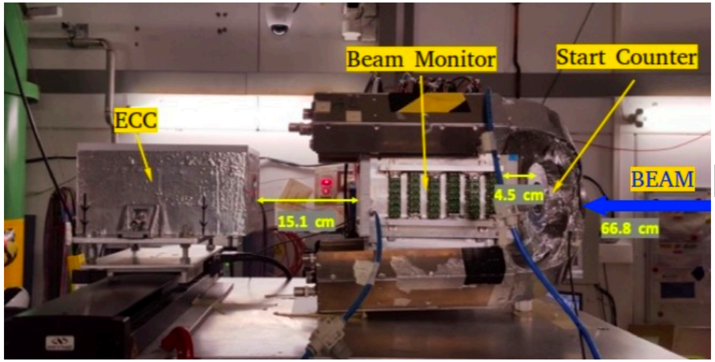


Future perspectives

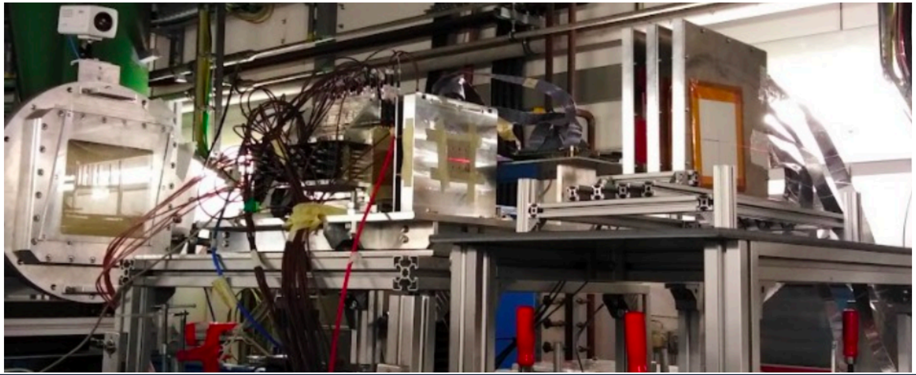
- 2024: first “true” physics run @ CNAO with ^{12}C beam
- 2024-2025: physics run @ GSI with ^{16}O with E_{kin}>400 MeV/u
- 3 PRIN projects related to FOOT approved

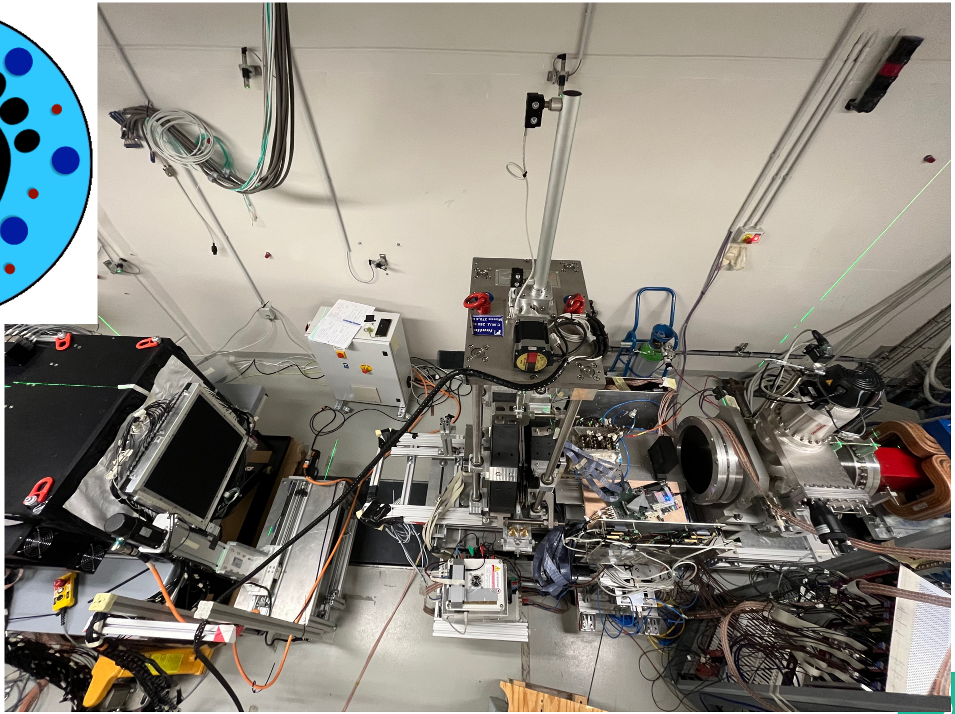


Thank you for your attention



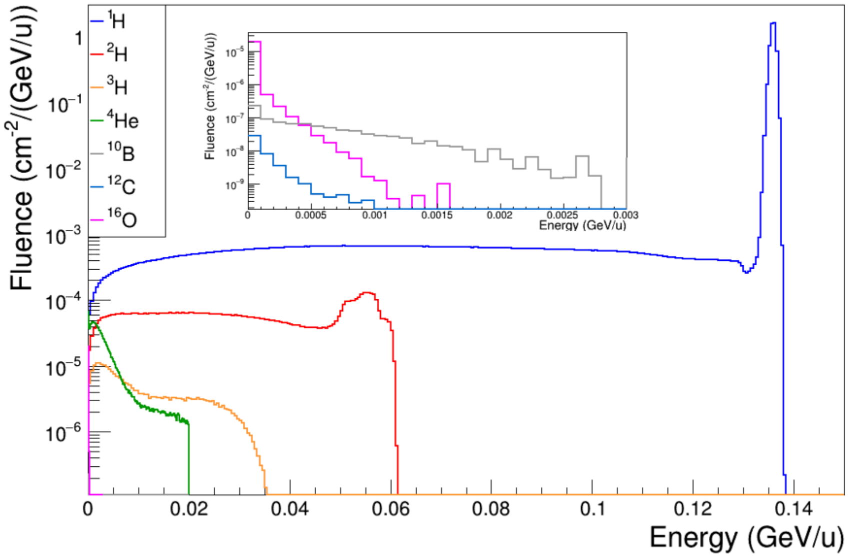
FOOT

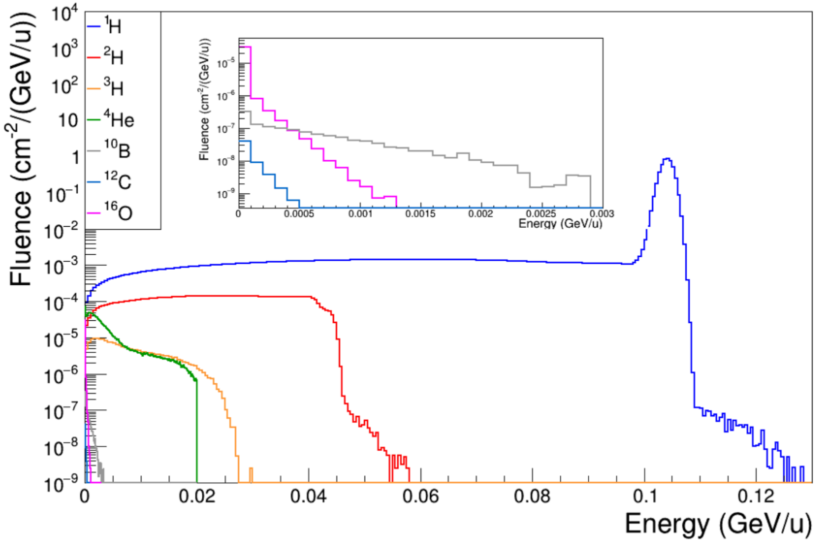




Back up

Fluence



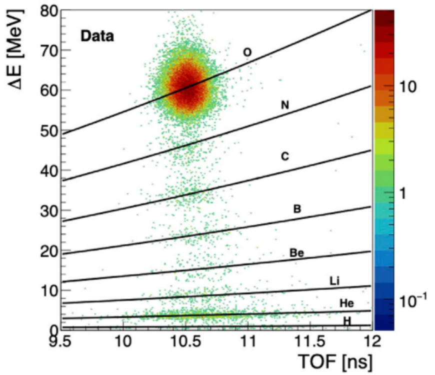


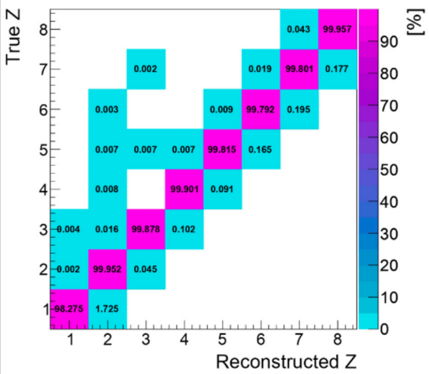
Fluence of target fragments induced by 150 MeV protons in water at z=2.5 (left) and 7.5 cm (right)
The Bragg Peak is at 15.8cm

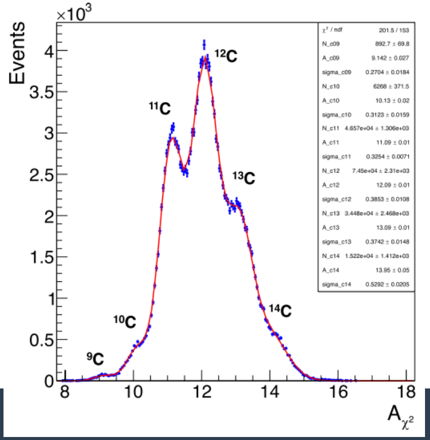
A. Embriaco et al. "FLUKA simulation of target fragmentation in proton therapy" Physica Medica, 80 (2020), doi:10.1016/j.ejmp.2020.09.018

Electronic spectrometer

Toppi et al, Elemental fragmentation cross sections for a 16 O beam of 400MeV / u kinetic energy interacting with a graphite target using the FOOT Δ E-TOF detectors, Frontiers in physics, 2022







★Toppi et al, Frontiers in physics, 2021

Charge identification

- Combine ΔE and TOF measurements: $\frac{dE}{dx} \sim z^2 \cdot f(\beta)$ $\beta = \frac{L}{c \cdot TOF}$
- Charge misidentification < 2%

Mass identification

- Combine TOF, P and E_{kin} with three methods

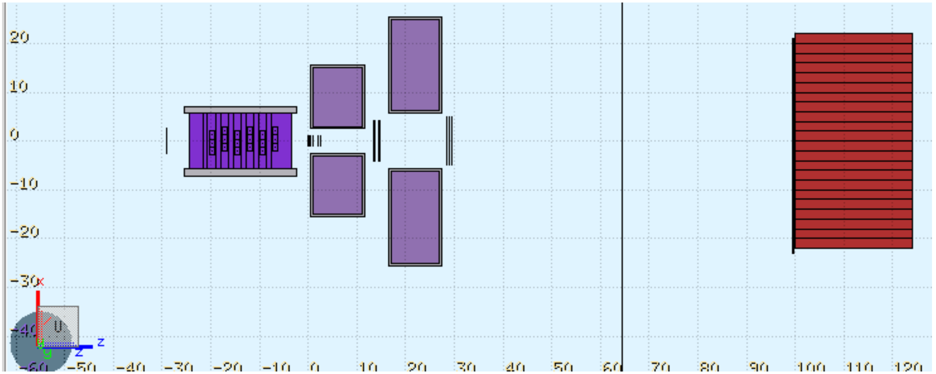
$$A_1 = \frac{m}{u} = \frac{1}{u}\frac{p\sqrt{1-\beta^2}}{\beta} \qquad A_2 = \frac{m}{u} = \frac{E_{kin}}{u}\frac{1+\sqrt{1+\gamma^2\beta^2}}{\gamma^2\beta^2} \qquad A_3 = \frac{m}{u} = \frac{E_{kin}^2 - p^2}{2E_{kin}}$$

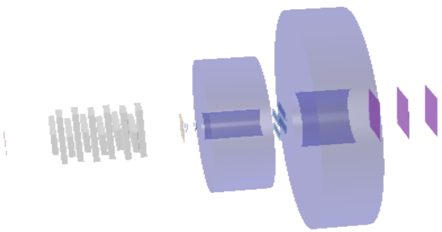
- Final mass estimate with χ2 fit combined with an augmented Lagrangian method

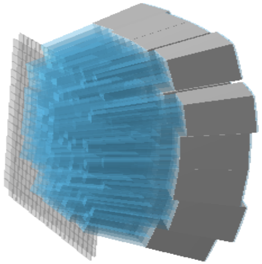
Performances with ^{12}C and ^{16}O @ 100-400 MeV/u:

- σ_{TOF} ~ 70 ps
- σ_p/p ~ 5%
- $\sigma(\Delta E)/\Delta E$ ~ 6 – 14%
- $\sigma_{E_{kin}}/E_{kin} \leq 2\%$

Simulation and reconstruction software





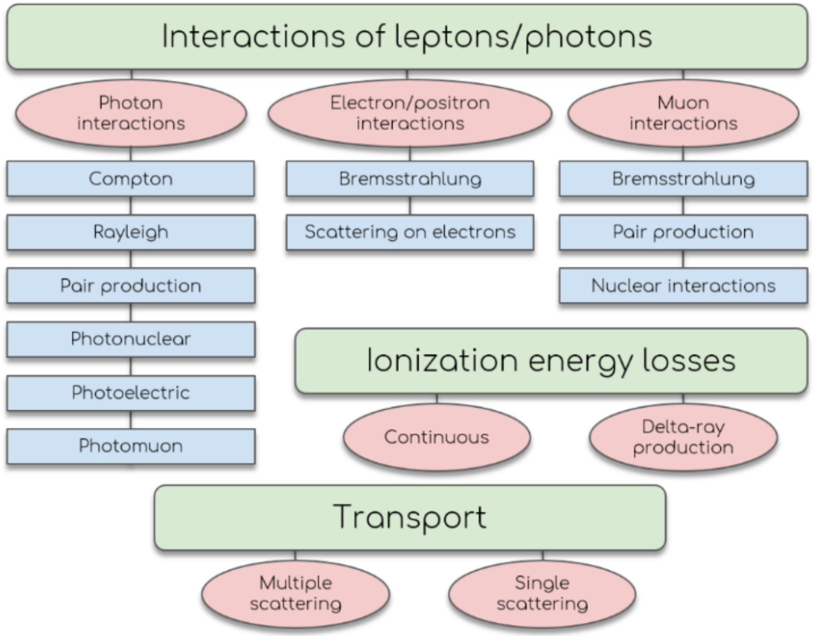


The simulations are made by means of FLUKA MC tool with a dedicated output scheme

The FOOT reconstruction software: SHOE (Software for Hadrontherapy Optimization Experiment)

- Handles both MC and experimental data
- Provides the input files for the FLUKA simulations
- Divided into two levels:
  -local level: to reconstruct the relevant physics quantities of each sub-detector
  -global level: to finalize the analysis combining the sub-detectors informatio

FLUKA Monte Carlo models of interest for FOOT



Electromagnetic interactions models in FLUKA

Handron-nucleus interactions:

- PreEquilibrium Approach to NUclear Thermalization (PEANUT) model for particles with P<3-5 GeV/c based on Generalized Intra-Nuclear Cascade (GINC) model
- Pre-equilibrium emission of light nuclei (A<5)
- Evaporation, Fission, Fragmentation and γ de-excitation

Nucleus-nucleus interactions

- Boltzmann-Master Equation model (E<100 MeV/u): Thermalization of composite nuclei by means of two-body interactions and secondary particles emissions
  Cavinato et al, Nuclear Physics A 643 (1998)
- Relativistic Quantum Molecular Dynamics (0.12-5 GeV/u): Collision simulated minimizing the Hamiltonian equation of motion considering the Gaussian wave functions of all the nucleons in the nucleus overlapping region
  H. Sorge et al., Annals of Phys. 192 (1989) 266