



UNIVERSITÀ
DEGLI STUDI DI BARI
ALDO MORO



Study of target and hadron beam fragmentation for Charged Particle Therapy

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on behalf of the FOOT and DAMON Collaborations



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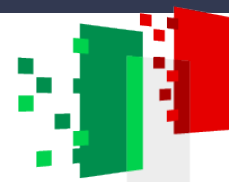
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**Ministero
dell'Università
e della Ricerca**

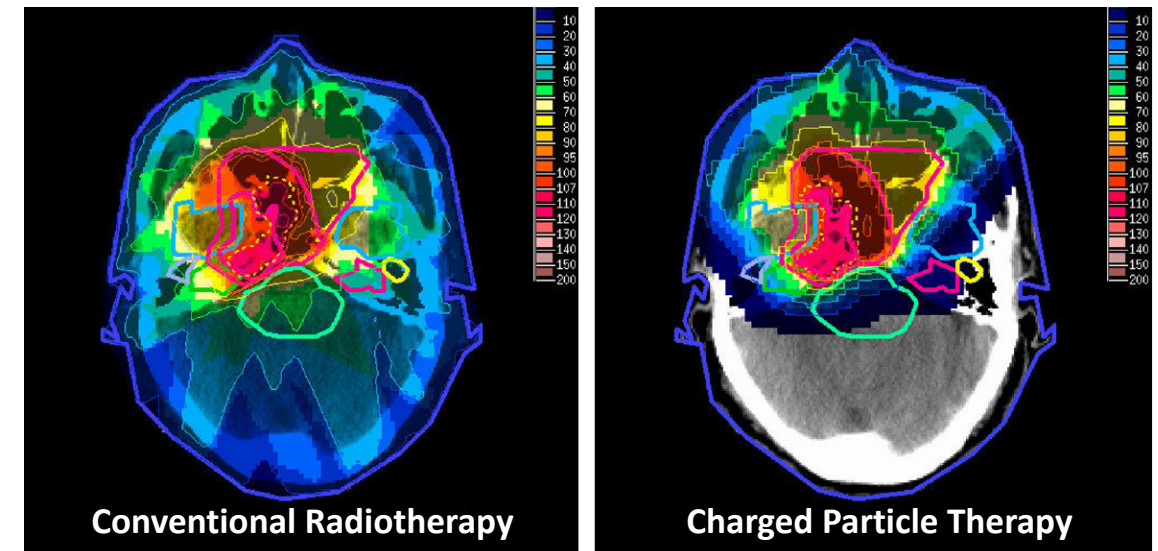
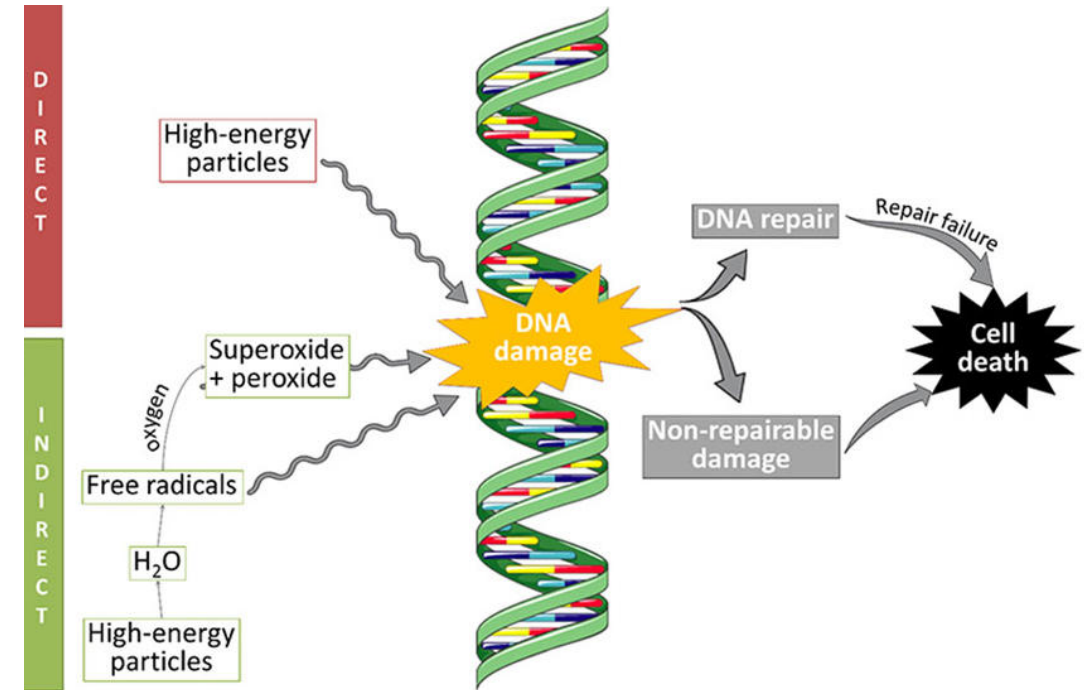
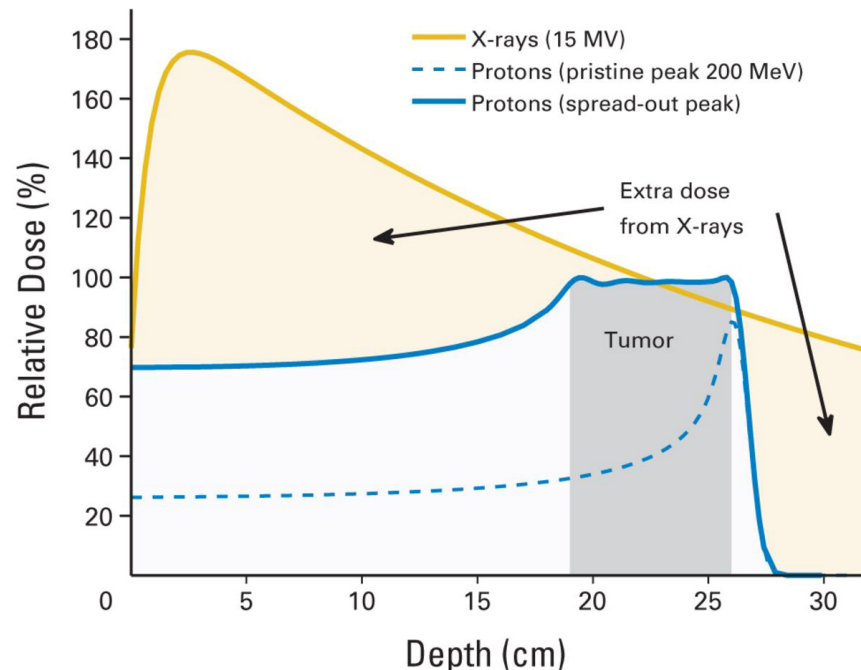


Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



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
- Peak of dose released at the end of the track (Bragg Peak), allows sparing the healthy tissues



The open issue of beam and target fragmentation

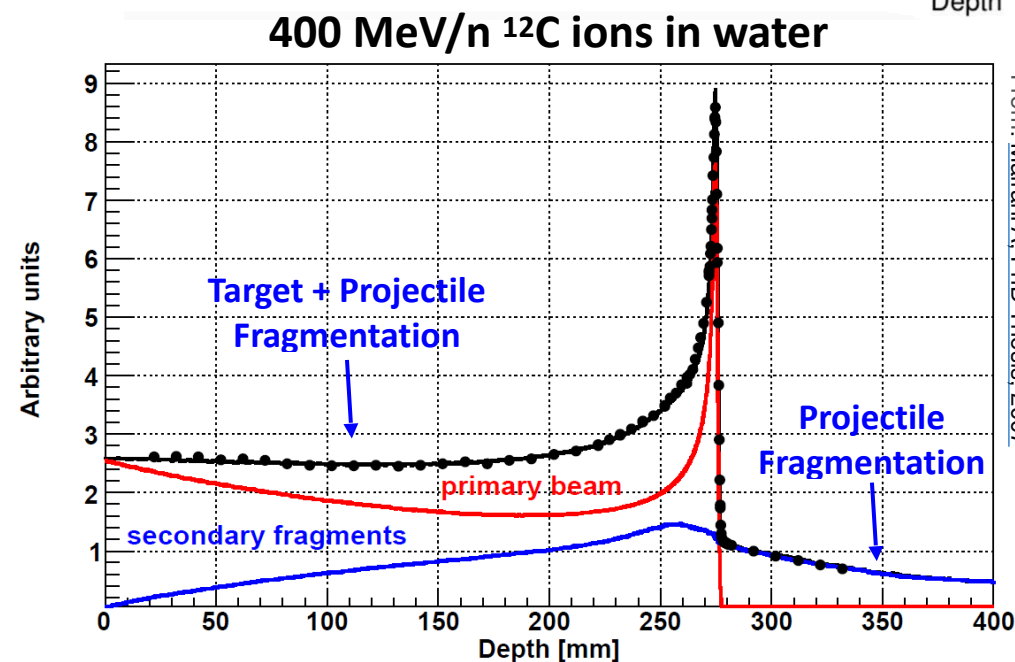
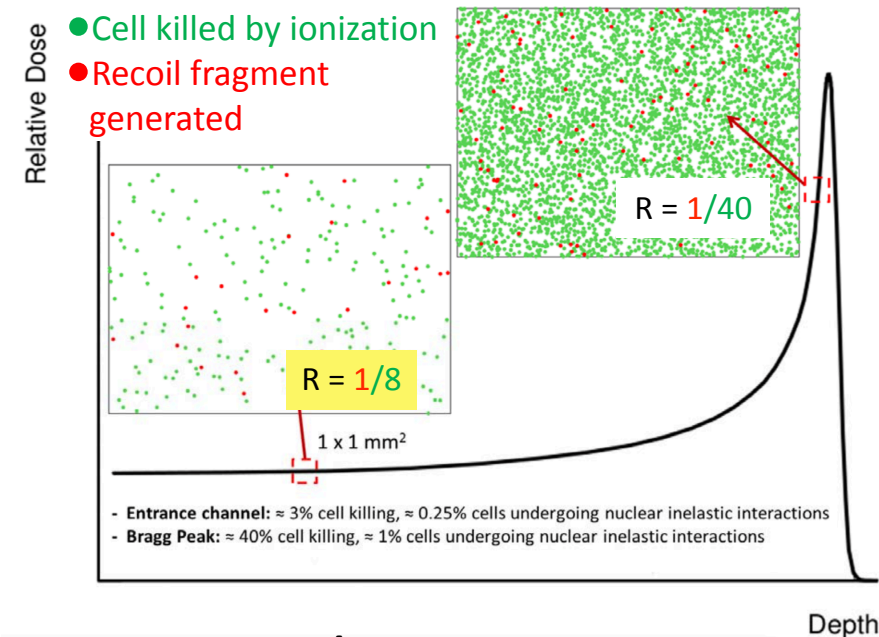
The nuclear fragmentation of the target and beam particles is still an open issue

Proton beam (Target fragmentation):

- Small range fragments (down to $\sim \mu\text{m}$)
- Missing experimental data for heavy fragments having significant contribution to the dose
- Increase of biological damage ($\sim 10\%$) in the entrance channel

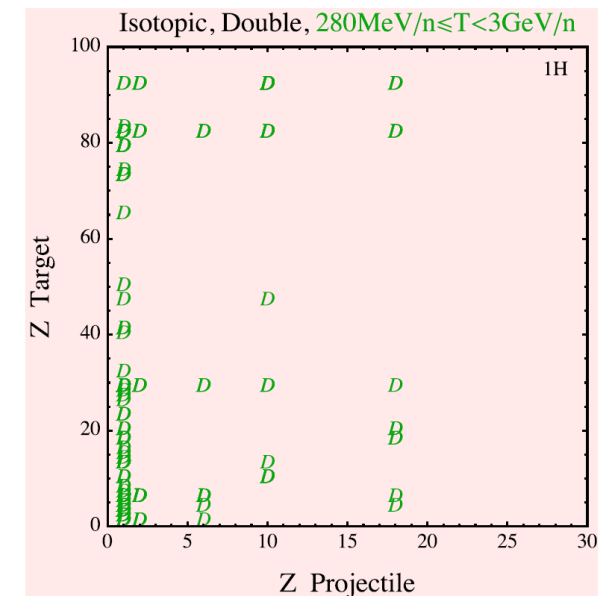
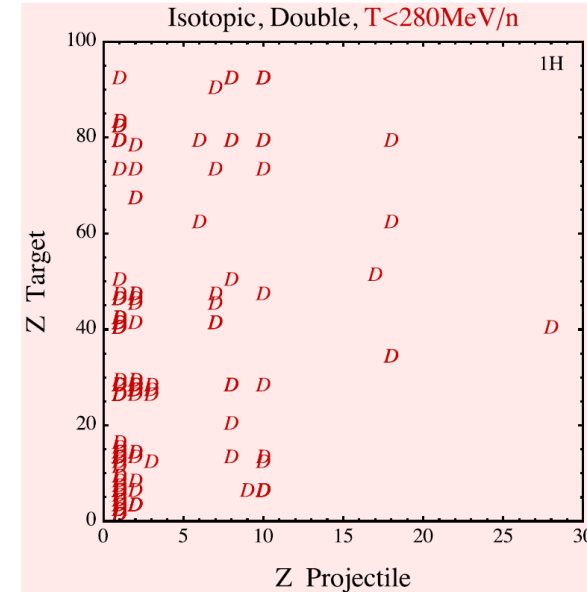
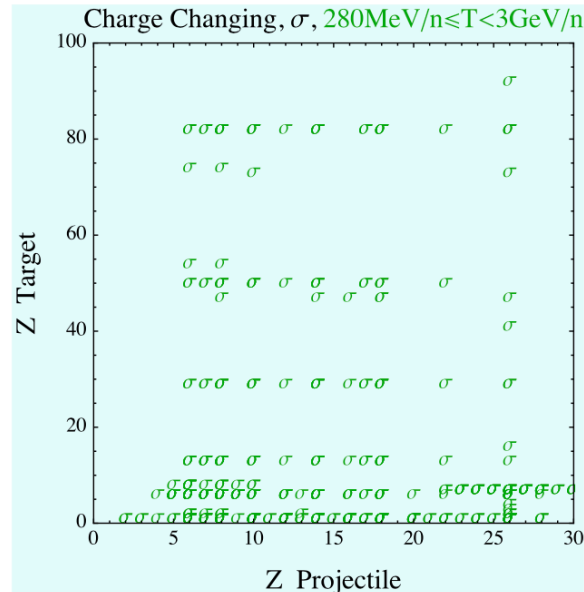
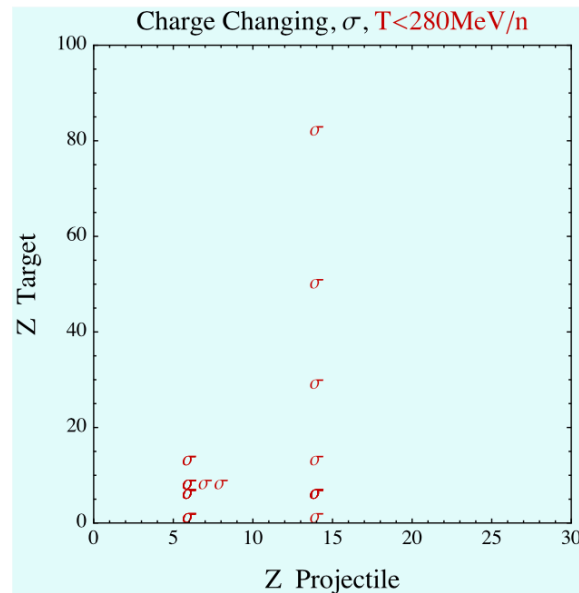
Heavy Ions (Beam and target fragmentation):

- 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 (^4He and ^{16}O) to be studied



Missing Fragmentation Cross Sections

- Each marker represents at least one measurement for a given projectile-target pair and energy range.
- Charge-changing cross sections provide the overall probability that the projectile changes charge, but do not identify the produced fragments.
- Double-differential isotopic cross sections describe proton production as a function of two kinematic variables, typically energy and angle.
- These data are much scarcer, especially below 280 MeV/n.

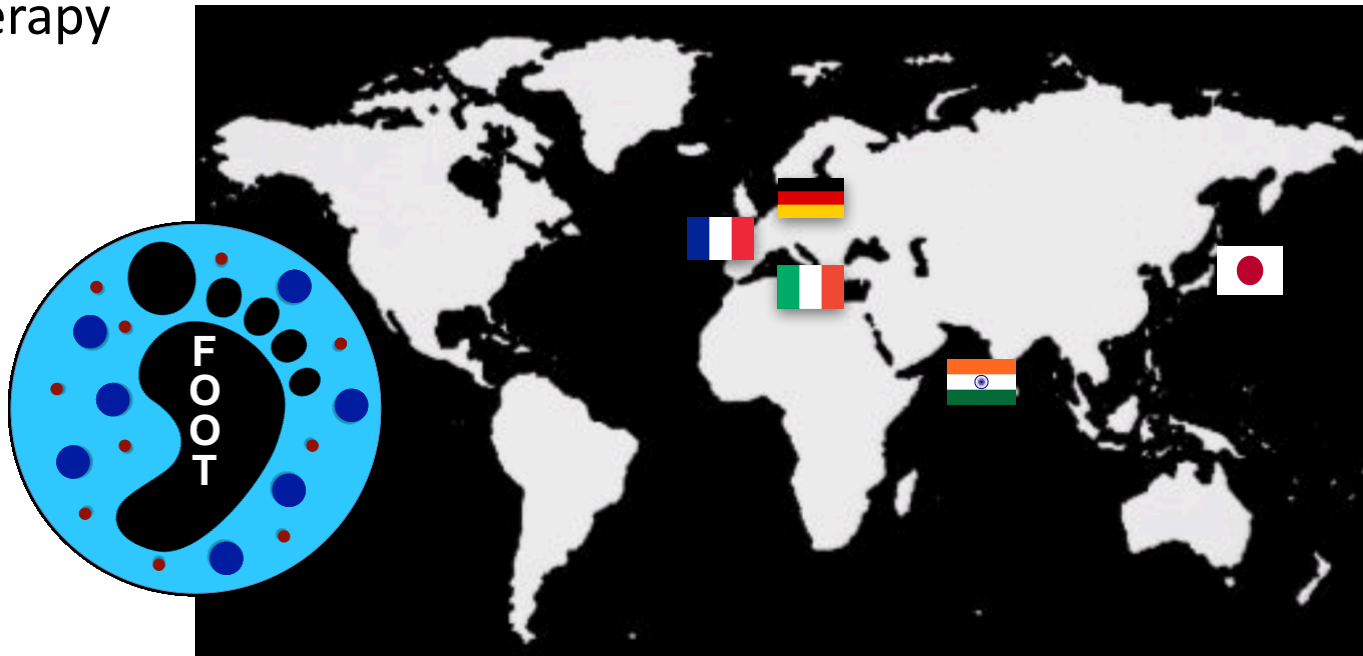


Radiation Measurements 47 (2012) 315-363 <https://www.sciencedirect.com/science/article/pii/S1350448712000686>

It is important that these measurements, which have never been done before, are carried out

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

- 16 universities Italy, Japan, France, Germany, India
- 3 laboratories: CNAO, GSI, IPHC
- INFN (National Institute for Nuclear Physics): 11 units (Milano, Roma Sapienza, Roma TorVergata, Bologna, TIFPA, Pisa, Torino, Napoli, Perugia, LNF, Bari)

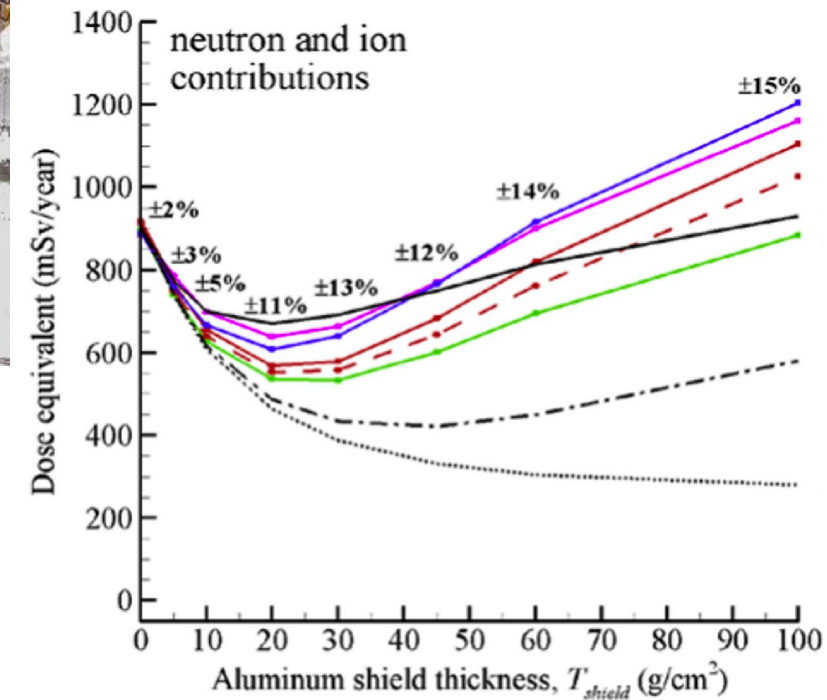
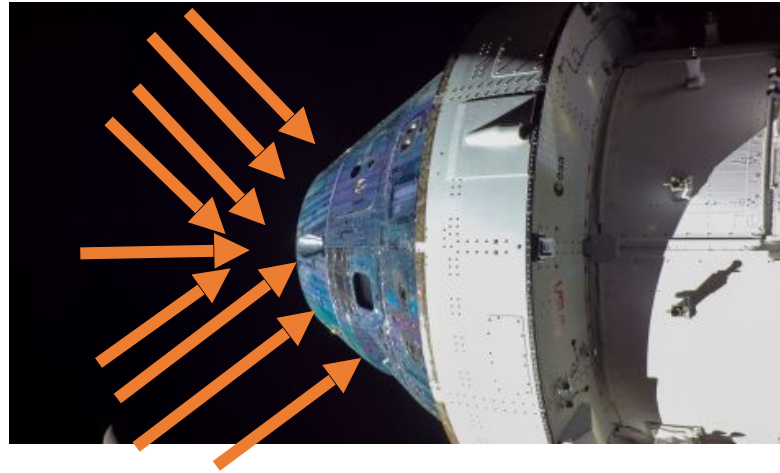
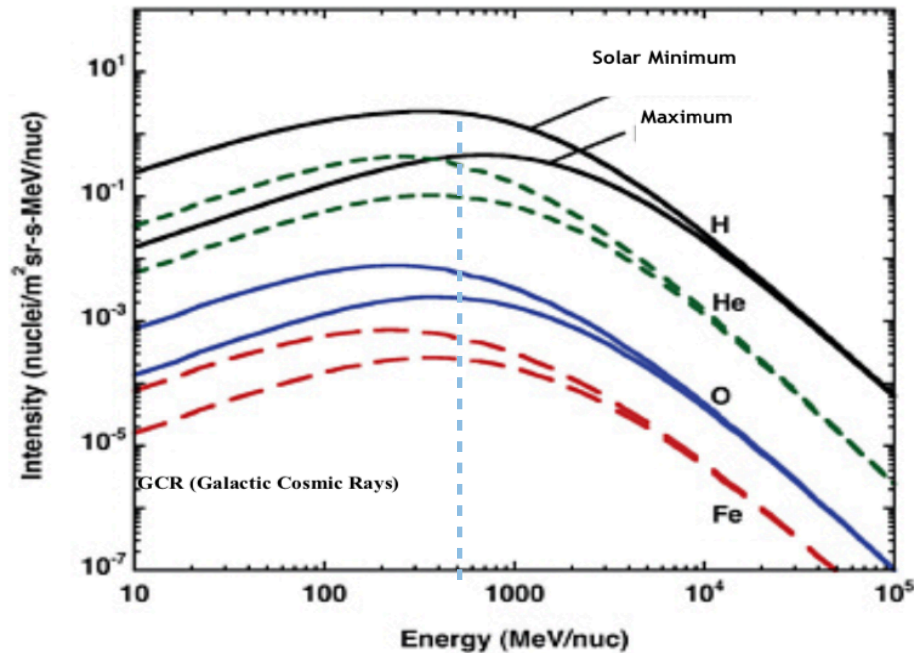
FOOT Physics Program

- ➔ 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
- ➔ ^4He , ^{12}C , ^{16}O beams of 200-400 MeV/u on ^{12}C , C_2H_4 and $\text{C}_5\text{O}_2\text{H}_8$ targets

Physics	Application field	Beam	Target	Upper Energy (MeV/nucleon)	Kinematic approach	Interaction process
Target fragmentation	PT	^{12}C	$\text{C}, \text{C}_2\text{H}_4$	200	inverse	p+C
Target fragmentation	PT	^{16}O	$\text{C}, \text{C}_2\text{H}_4$	200	inverse	p+O
Beam fragmentation	PT	^4He	$\text{C}, \text{C}_2\text{H}_4, \text{PMMA}$	250	direct	$\alpha+\text{C}, \alpha+\text{H}, \alpha+\text{O}$
Beam fragmentation	PT	^{12}C	$\text{C}, \text{C}_2\text{H}_4, \text{PMMA}$	400	direct	$\text{C}+\text{C}, \text{C}+\text{H}, \text{C}+\text{O}$
Beam fragmentation	PT	^{16}O	$\text{C}, \text{C}_2\text{H}_4, \text{PMMA}$	500	direct	$\text{O}+\text{C}, \text{O}+\text{H}, \text{O}+\text{O}$
Beam fragmentation	Space	^4He	$\text{C}, \text{C}_2\text{H}_4, \text{PMMA}$	800	direct	$\alpha+\text{C}, \alpha+\text{H}, \alpha+\text{O}$
Beam fragmentation	Space	^{12}C	$\text{C}, \text{C}_2\text{H}_4, \text{PMMA}$	800	direct	$\text{C}+\text{C}, \text{C}+\text{H}, \text{C}+\text{O}$
Beam fragmentation	Space	^{16}O	$\text{C}, \text{C}_2\text{H}_4, \text{PMMA}$	800	direct	$\text{O}+\text{C}, \text{O}+\text{H}, \text{O}+\text{O}$

FOOT for space

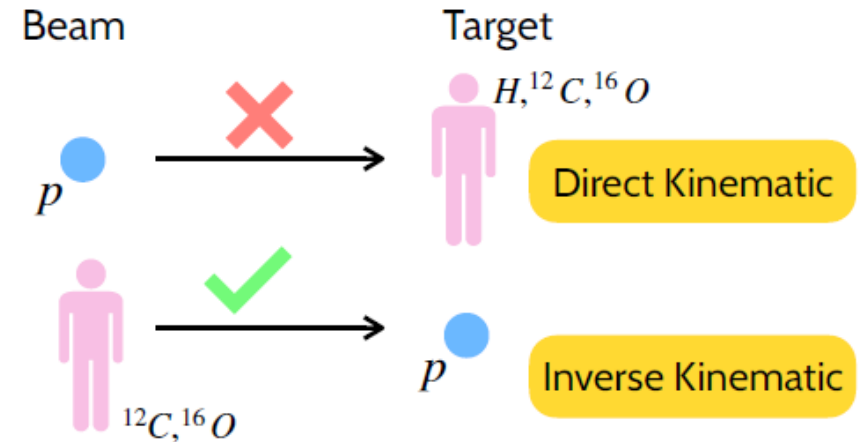
- Charged particles in space: Solar Particles Events (SPEs), Galactic Cosmic Rays (GCRs), geomagnetically trapped particles
- Interaction with walls/shielding of spacecraft produce secondary fragments



From: doi.org/10.1016/j.lssr.2016.12.003

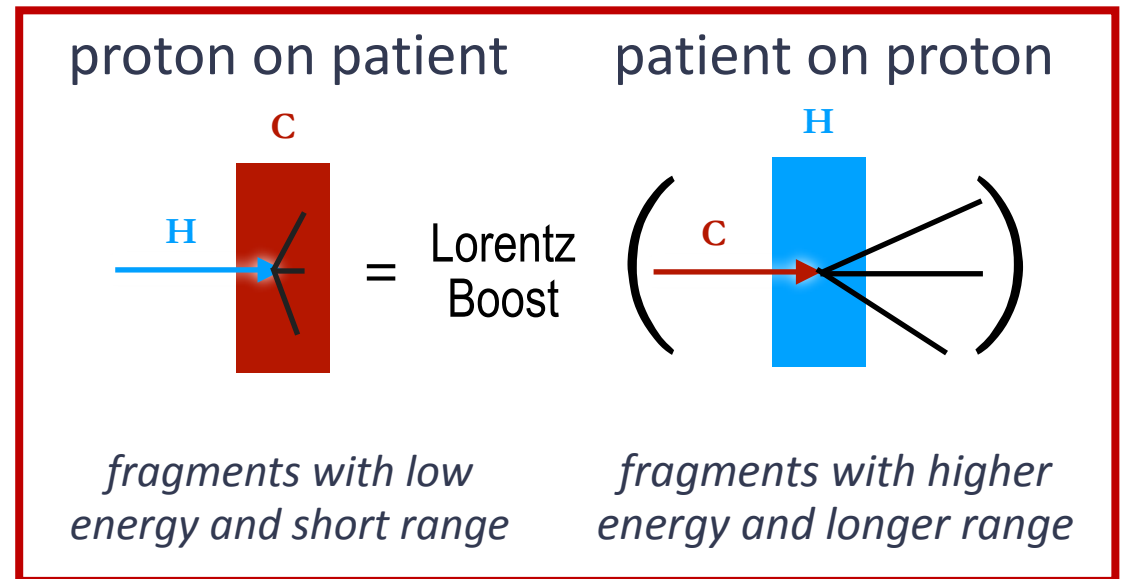
Inverse kinematic approach

- Protons on “patient” (98% C, O, and H nuclei) 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



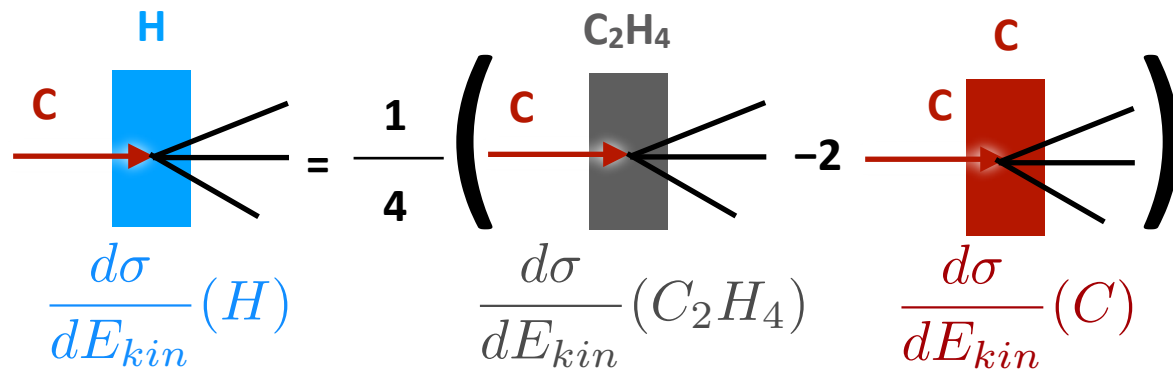
p (180 MeV) on H_2O : range of fragments

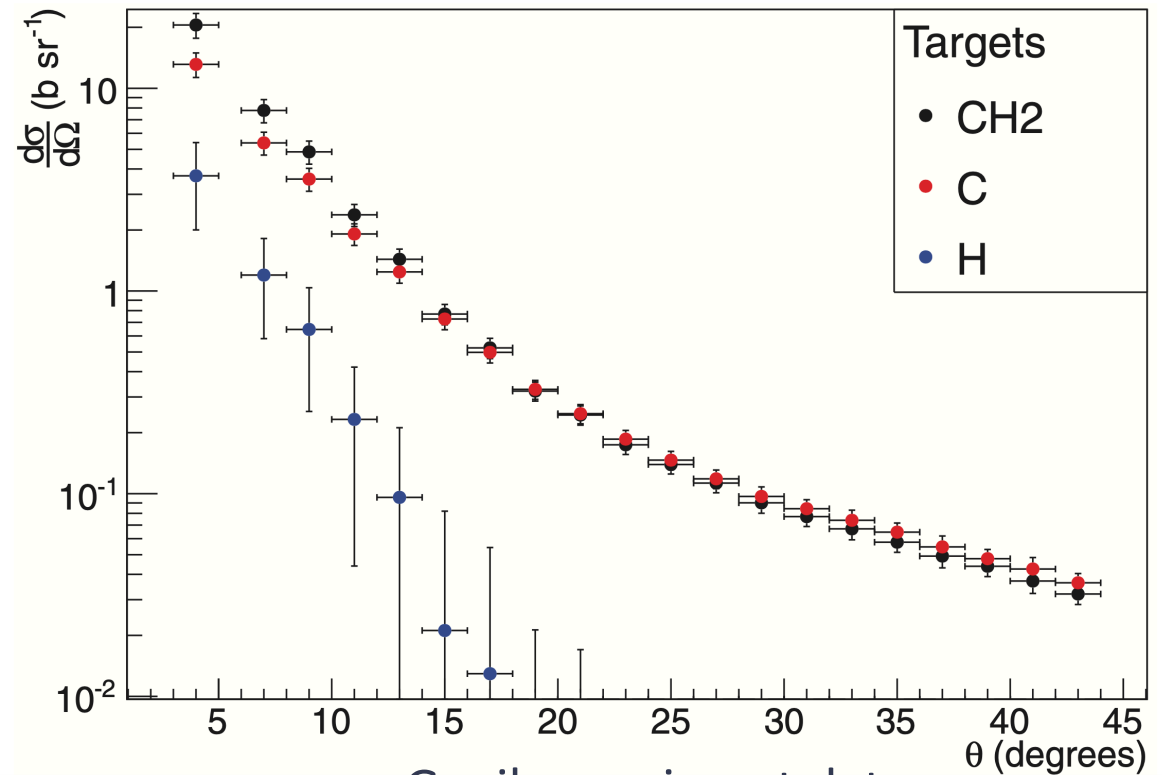
Fragment	E (MeV)	LET (keV/ μm)	Range (μm)
^{15}O	1.0	983	2.3
^{15}N	1.0	925	2.5
^{14}N	2.0	1137	3.6
^{13}C	3.0	951	5.4
^{12}C	3.8	912	6.2
^{11}C	4.6	878	7.0
^{10}B	5.4	643	9.9
^8Be	6.4	400	15.7
^6Li	6.8	215	26.7
^4He	6.0	77	48.5
^3He	4.7	89	38.8
^2H	2.5	14	68.9



The experimental challenge of measuring H cross section

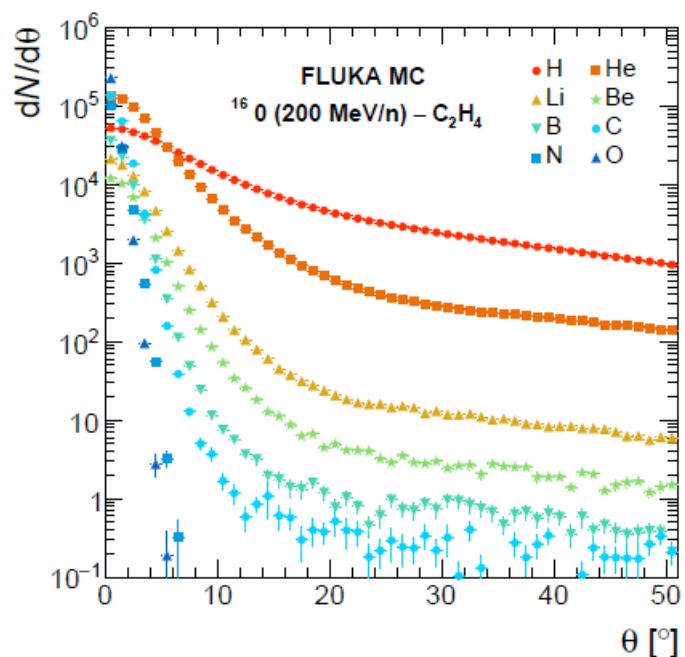
- Gas target: Low Cross-Section
- Difficulty to make a H target
- Variations in target temperature and density can significantly affect the cross-section

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


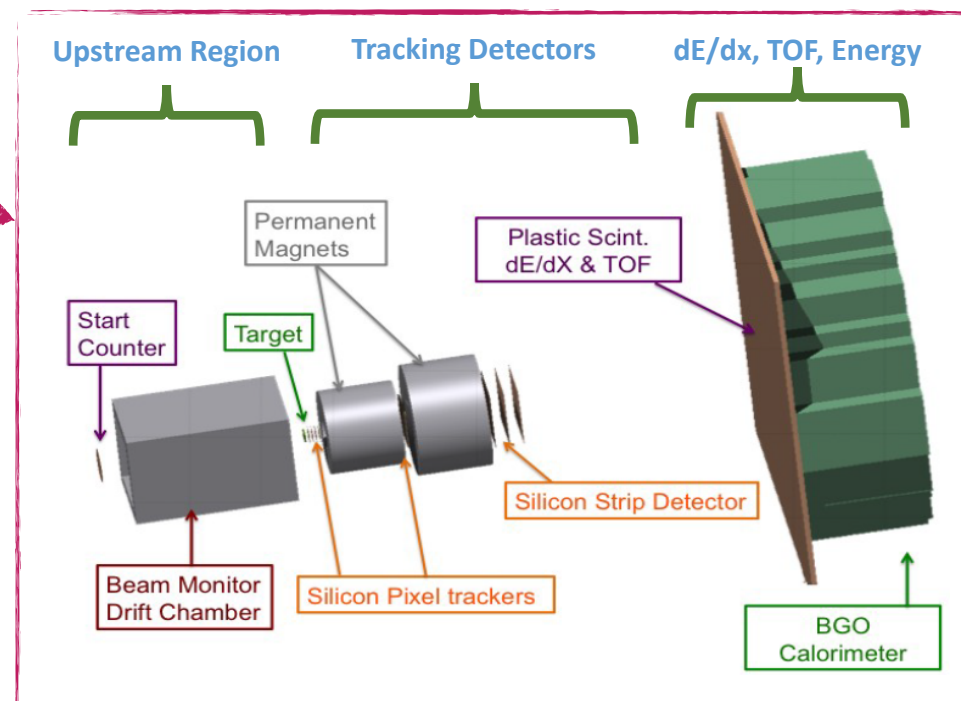
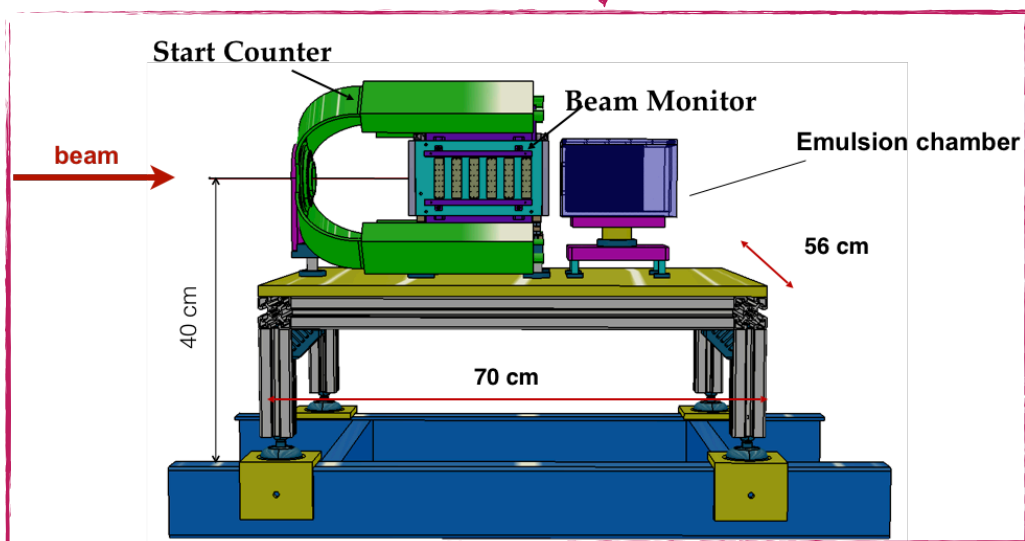


Ganil experiment data:
C(95 MeV/n) on C and C₂H₄ target

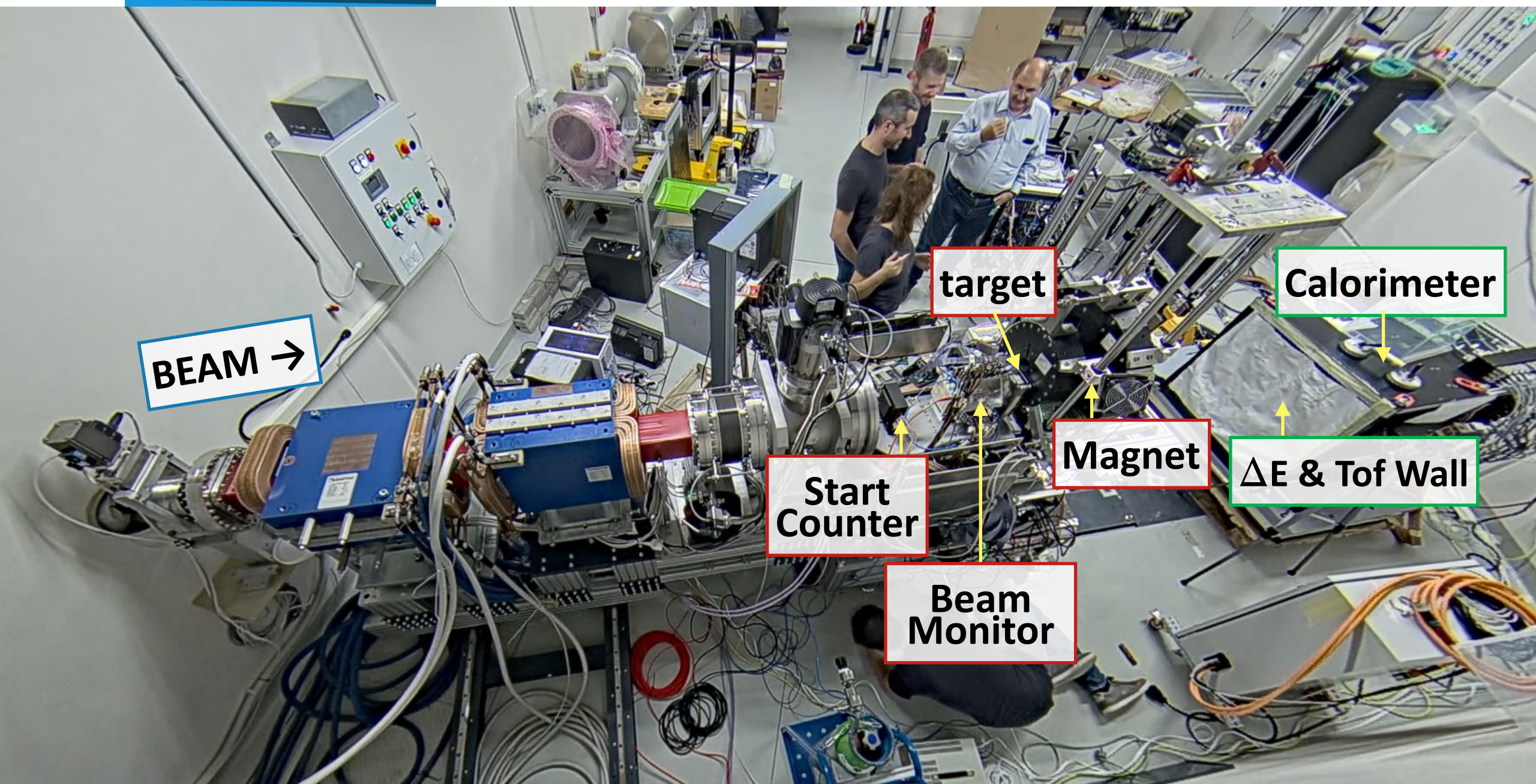
The setups



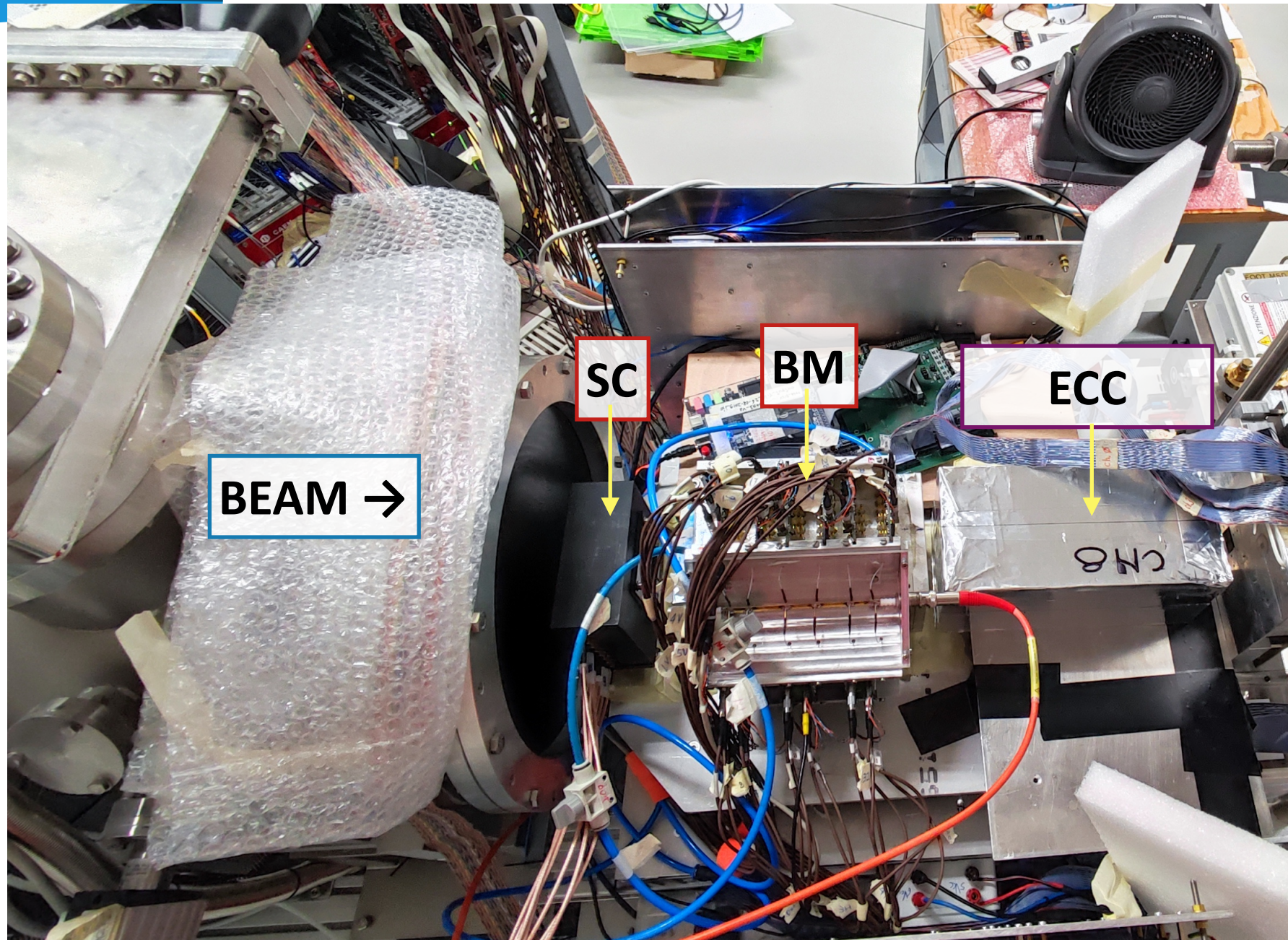
- Table-top experiment: small dimensions of the experimental halls of treatment centres
- Two complementary setups:
 - **nuclear emulsion spectrometer** to measure light charged fragments ($Z \leq 3$)
 - **magnetic spectrometer** with electronic detectors to measure the higher Z fragments ($Z \geq 3$)



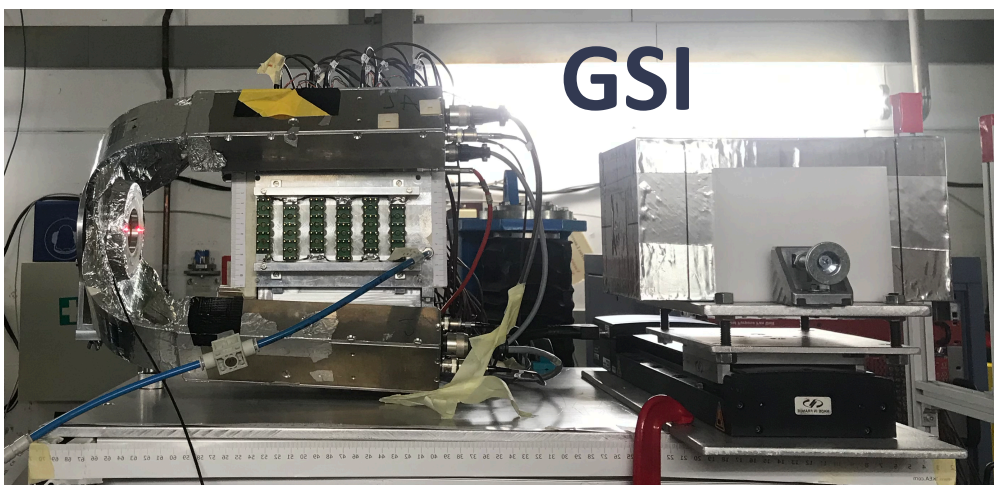
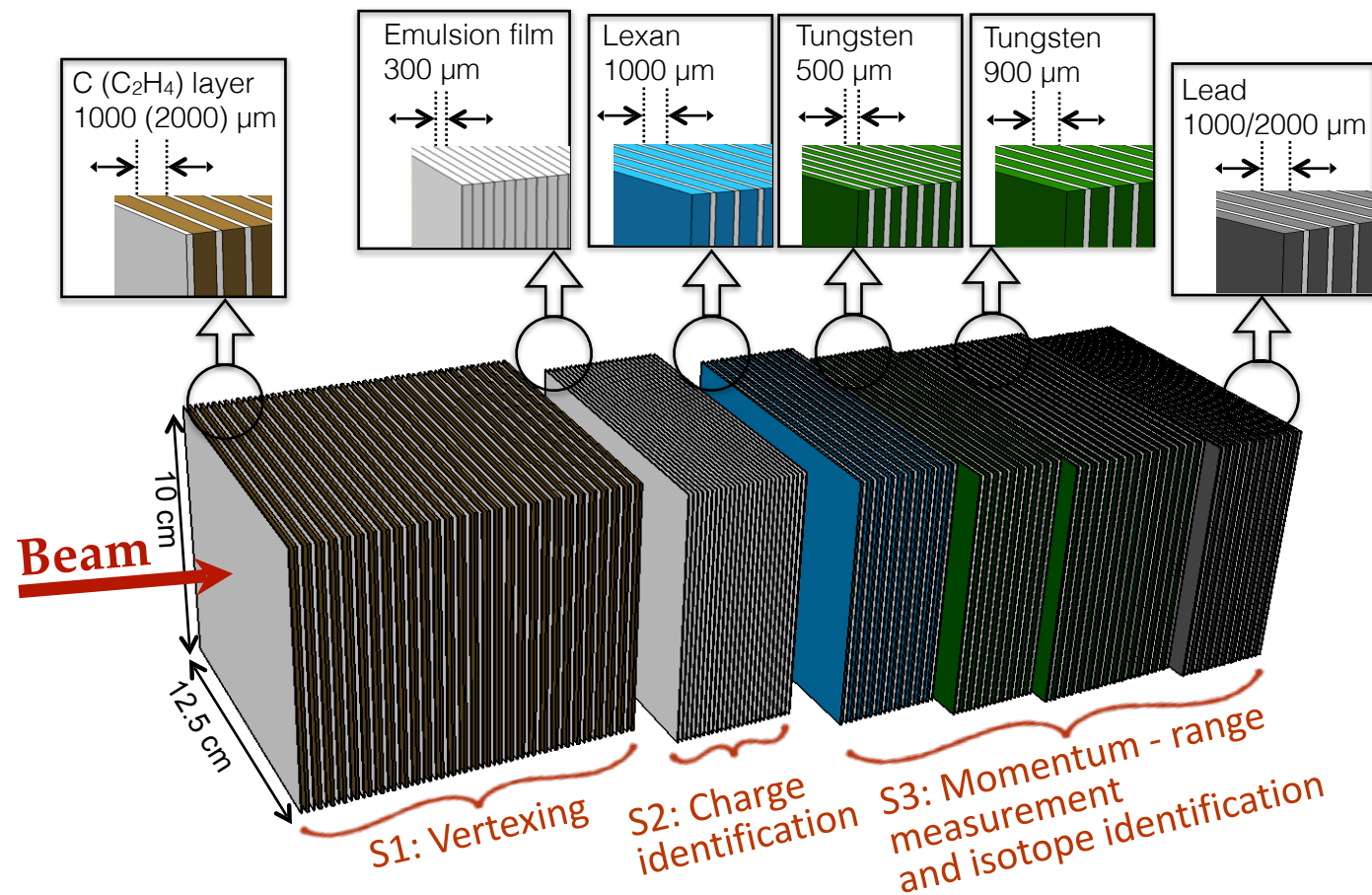
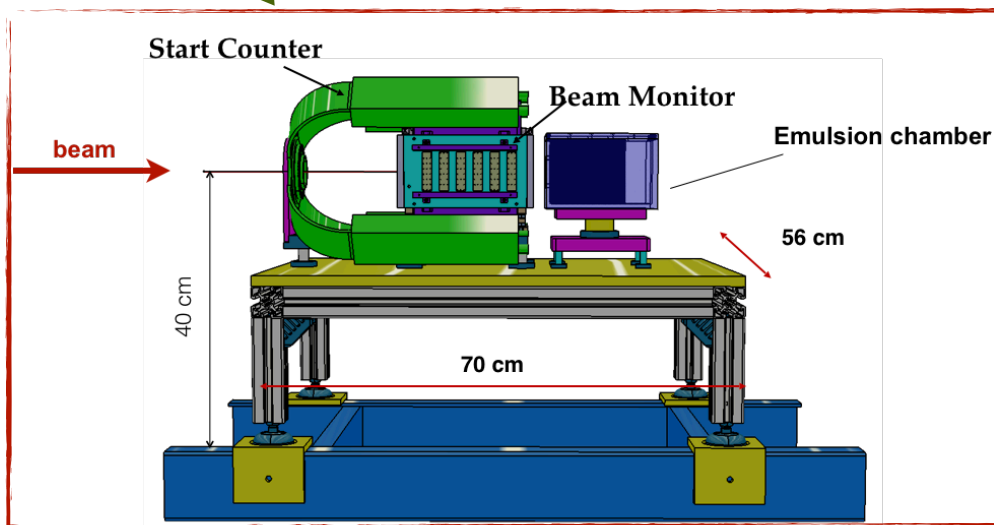
Magnetic spectrometer at CNAO (Pavia, Italy)



Nuclear emulsion spectrometer at CNAO (Pavia, Italy)

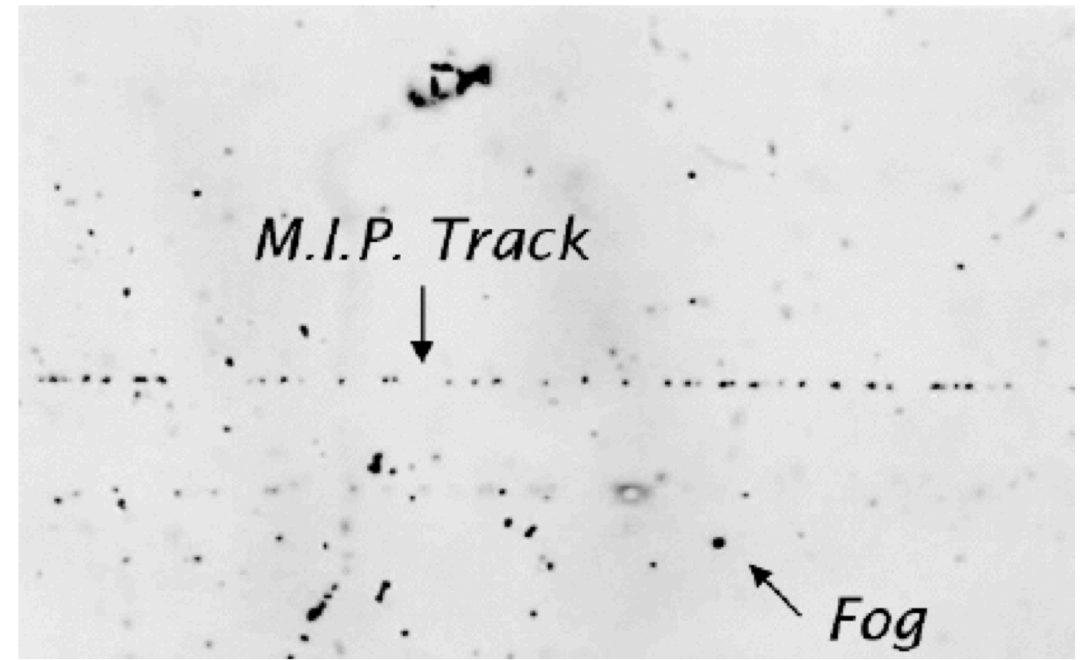
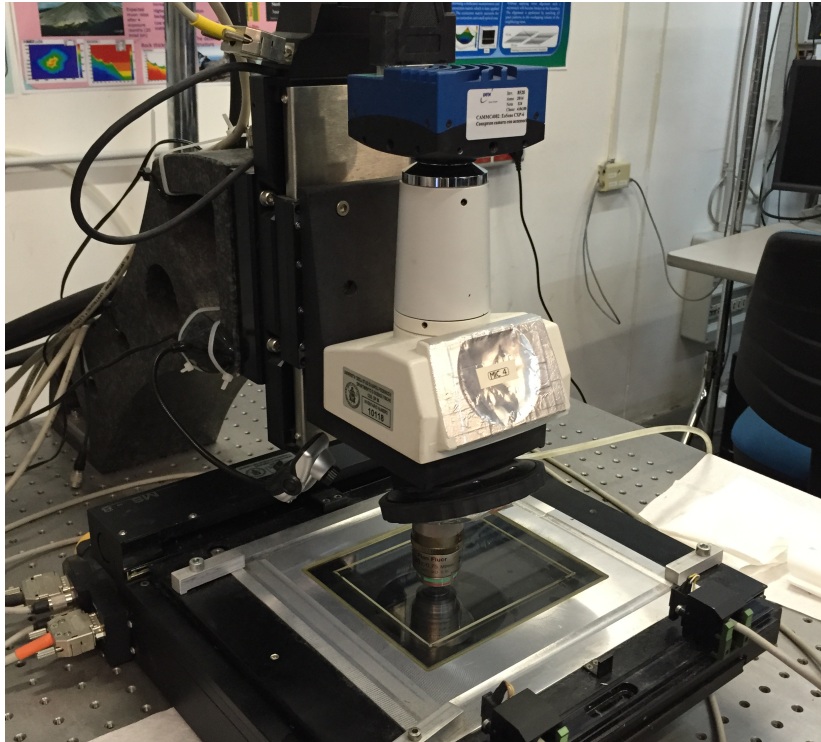


The nuclear emulsion spectrometer



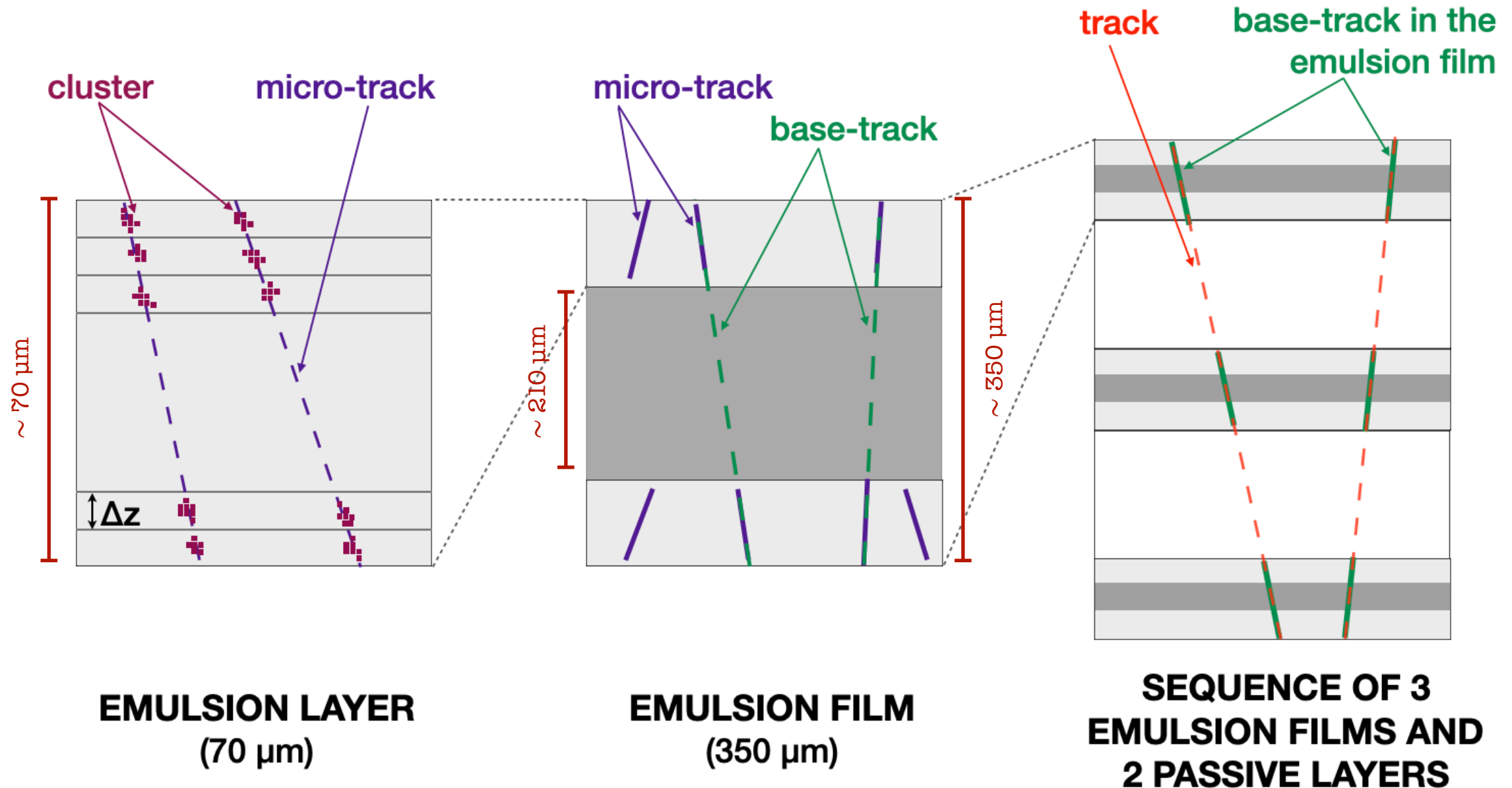
Nuclear emulsion films

Thanks to nuclear emulsion films it is possible to detect tracks with a resolution of $\sim 1 \mu\text{m}$!



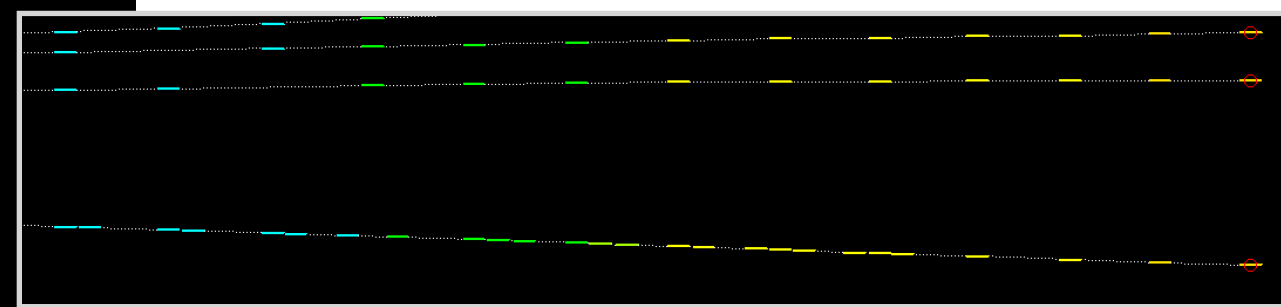
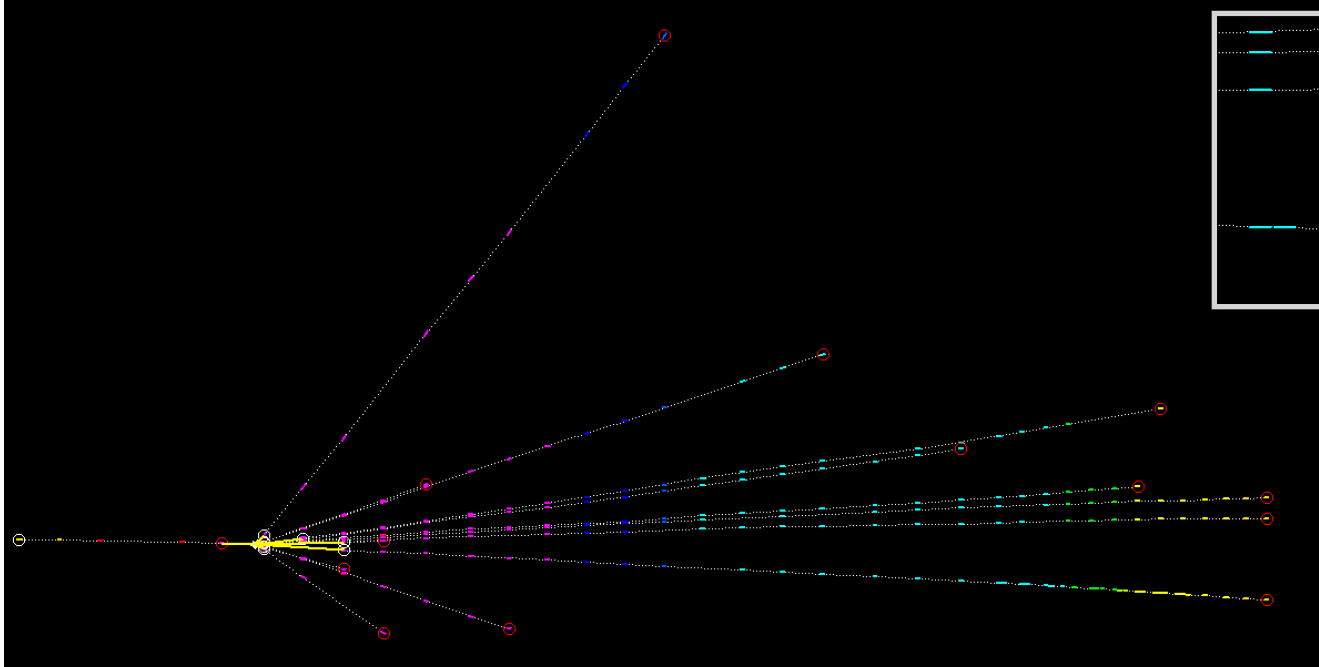
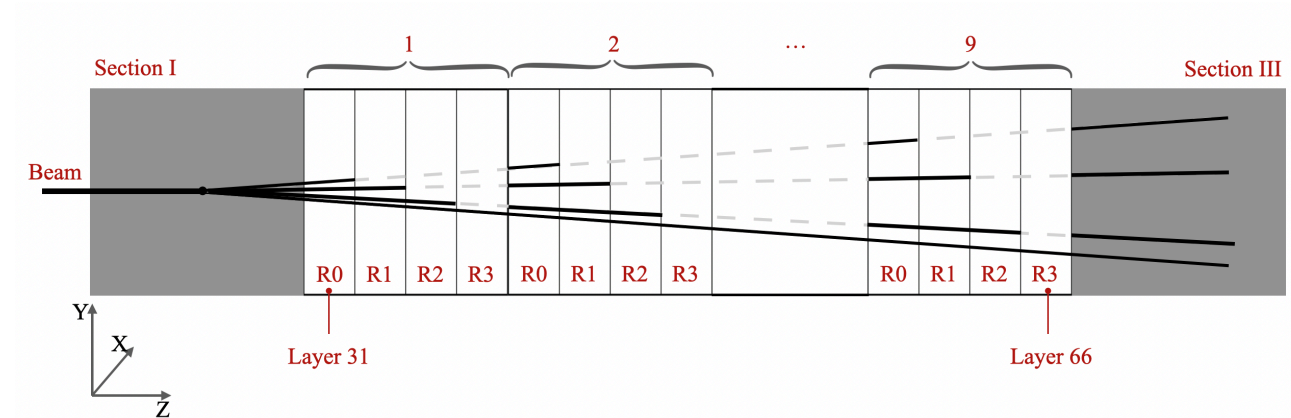
$100 \mu\text{m}$

Tracks reconstruction in nuclear emulsions



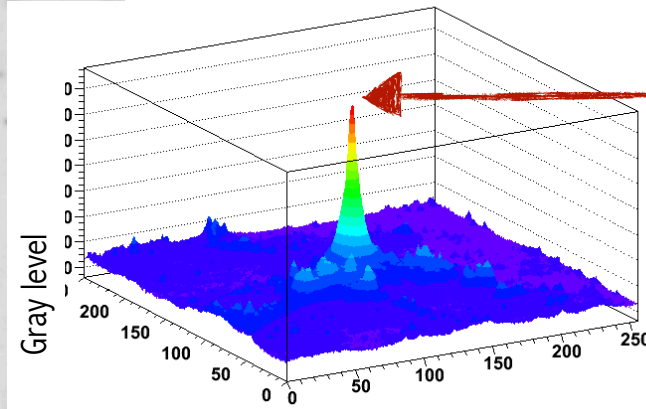
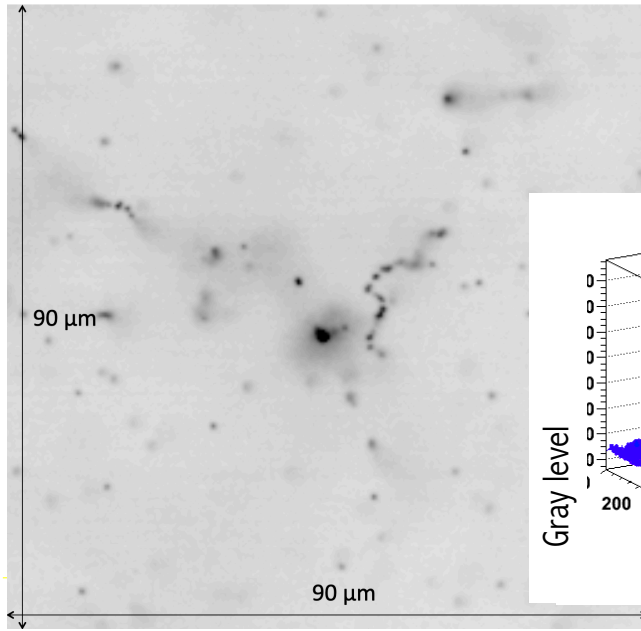
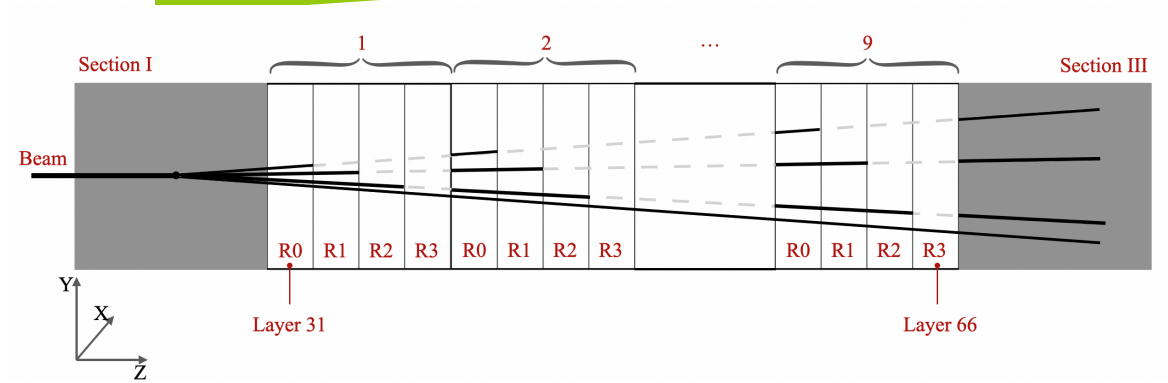
Charge identification with Nuclear Emulsions spectrometer

- Section 2 was divided into 9 cells, each containing 4 nuclear emulsion films that underwent different thermal treatments inducing a controlled fading
- Each thermal treatment erase totally or partially track's segments, depending on its ionisation



O@200MeV/n interaction in the Emulsion Spectrometer

Charge identification with Nuclear Emulsions spectrometer



For each track the following variables are evaluated:

- $\tan\theta$: the tangent of the inclination of most upstream fitted track segment w.r.t. the Z axis
- NR_x : the number of segments belonging to the track for each set of thermal treatments R_x , with $x \in \{0,1,2,3\}$
- VR_x : for each segment, a variable named "volume" is defined as the sum of the pixel brightness and expressed in arbitrary units related to particles' ionisation

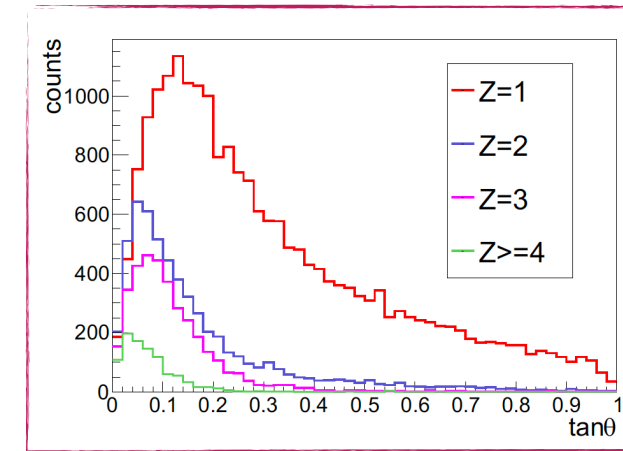
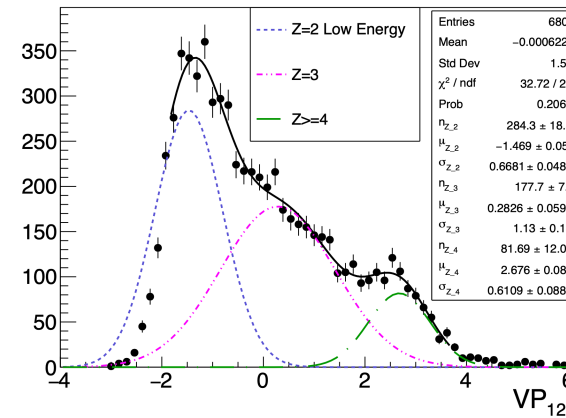
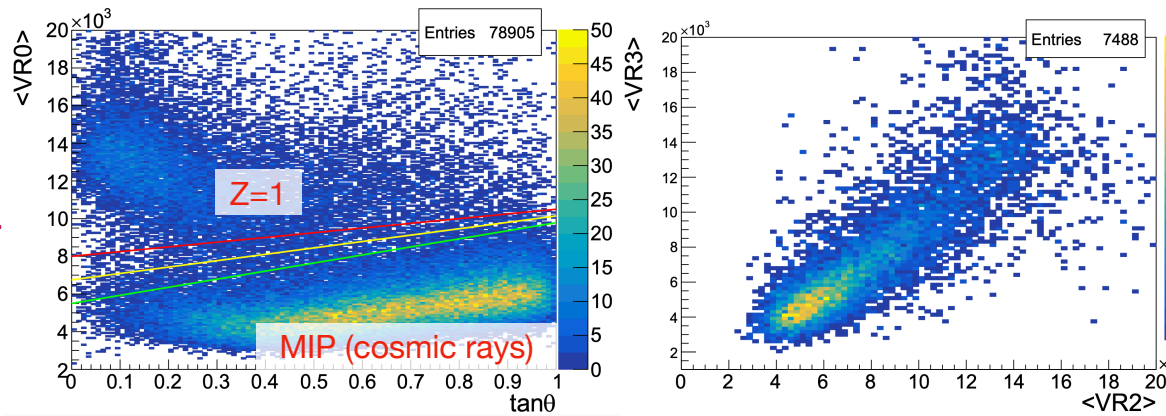
$$\langle VR_x \rangle = \frac{\sum_{NR_x} VR_x}{NR_x}$$

Charge identification with Nuclear Emulsions spectrometer

Two complementary methods:

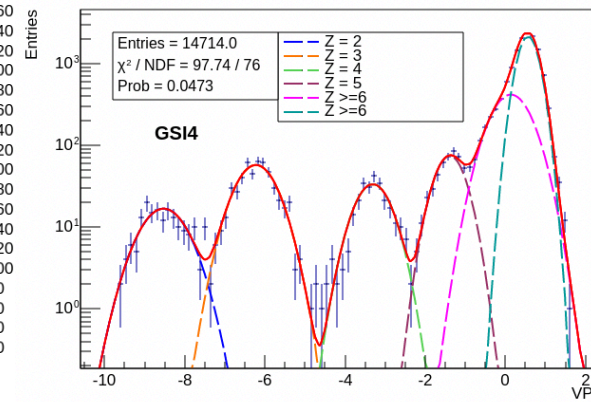
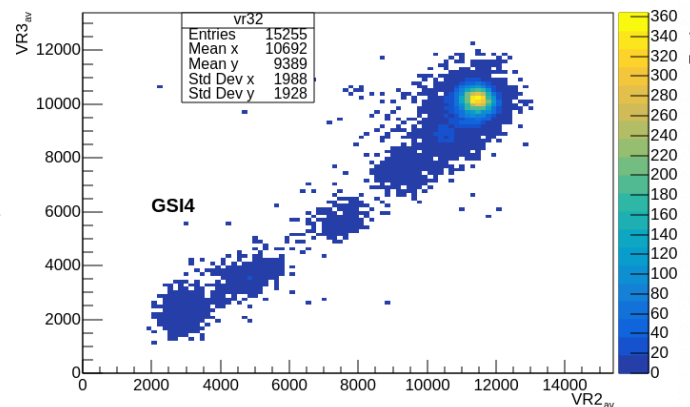
- Cut based-analysis to distinguish cosmic rays, $Z=1$ and $Z=2$ (high energy) fragments
- Principal Component Analysis to separate $Z=2$ (low energy), $Z=3$ and $Z \geq 4$ fragments

O@200MeV/n on C₂H₄



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

O@400MeV/n on C₂H₄



G. Galati, V. Boccia
doi.org/10.3389/fphy.2023.1327202

Total Cross Section Measurement

$$\sigma|_{C \text{ or } C_2H_4} = \frac{Y}{N_B N_{TG} \epsilon_{reco}}$$

$$\sigma(x)_H = \frac{1}{4} \left[\sigma(x)_{C_2H_4} - 2\sigma(x)_{C_{nat}} \right]$$

Results from O@200 MeV/n
campaign (CNAO, Italy) on
C and C₂H₄ targets



[arXiv:2607.00743](https://arxiv.org/abs/2607.00743)

- Y = # of vertices (total CC xsec) or fragments (production xsec)
- N_B = # of ions colliding on the target (includes the efficiency on beam reconstruction)
- N_{TG} = # of particles in the target: $\frac{\rho d N_A}{A}$, with:
 - ρ = target density:
 $\rho_C = 1.73 \text{ g/cm}^3$
 $\rho_{C_2H_4} = 0.94 \text{ g/cm}^3$
 - d = target thickness:
 $d_C = 0.1 \text{ cm}$ per layer
 $d_{C_2H_4} = 0.2 \text{ cm}$ per layer
 - $N_A = 6.022 \cdot 10^{23} / \text{mol}$
 - A = molar mass:
 $A_C = 12 \text{ g/mol}$
 $A_{C_2H_4} = 28 \text{ g/mol}$
- ϵ_{reco} = reconstruction factor

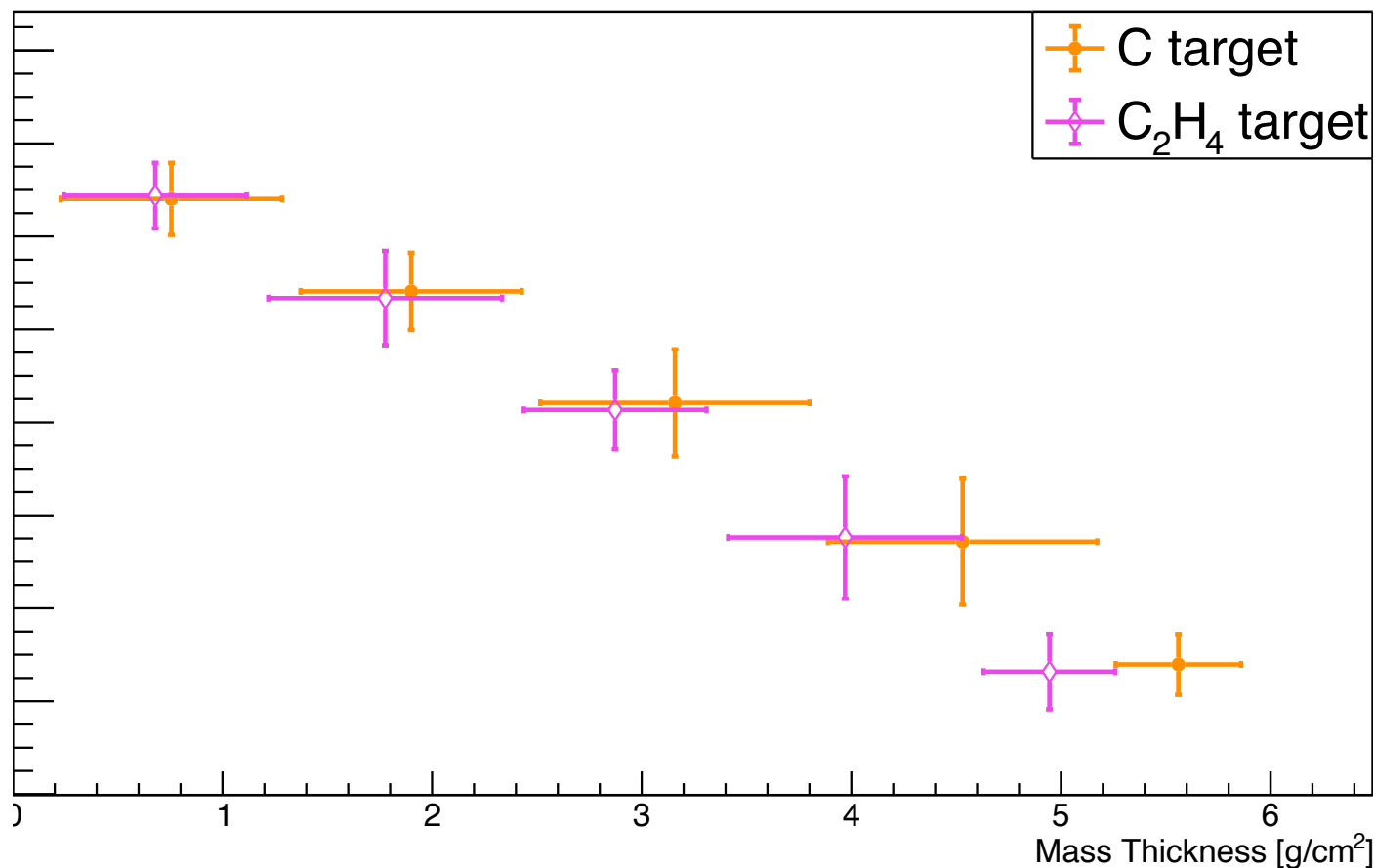
One detector... many measurements!

arXiv:2607.00743

- The energy loss within S1 is not negligible
- We divide S1 into sub-sections
- x denotes the sub-section

$$\sigma(x)_{C \text{ or } C_2H_4} = \frac{Y(x)}{N_B N_{TG} \epsilon_{\text{reco}}(x)}$$

FOOT Oxygen@200MeV/n



C:

- (188 ± 8) MeV/n
- (168 ± 8) MeV/n
- (144 ± 11) MeV/n
- (114 ± 13) MeV/n
- (88 ± 13) MeV/n

C₂H₄:

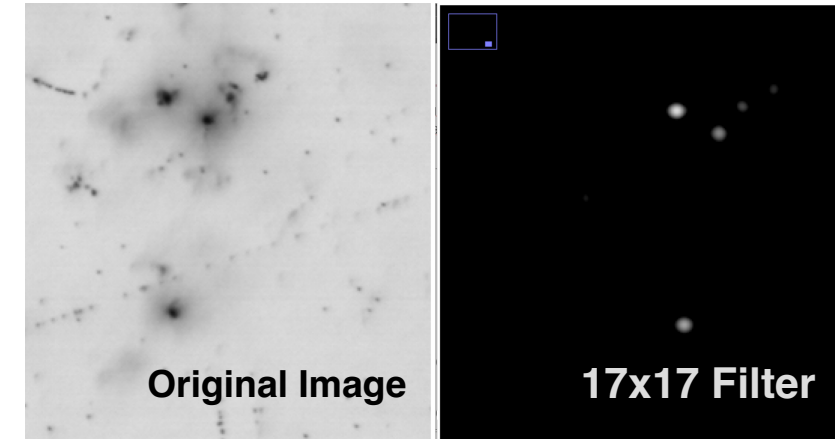
- (188 ± 7) MeV/n
- (167 ± 10) MeV/n
- (143 ± 8) MeV/n
- (116 ± 13) MeV/n
- (88 ± 8) MeV/n

H:

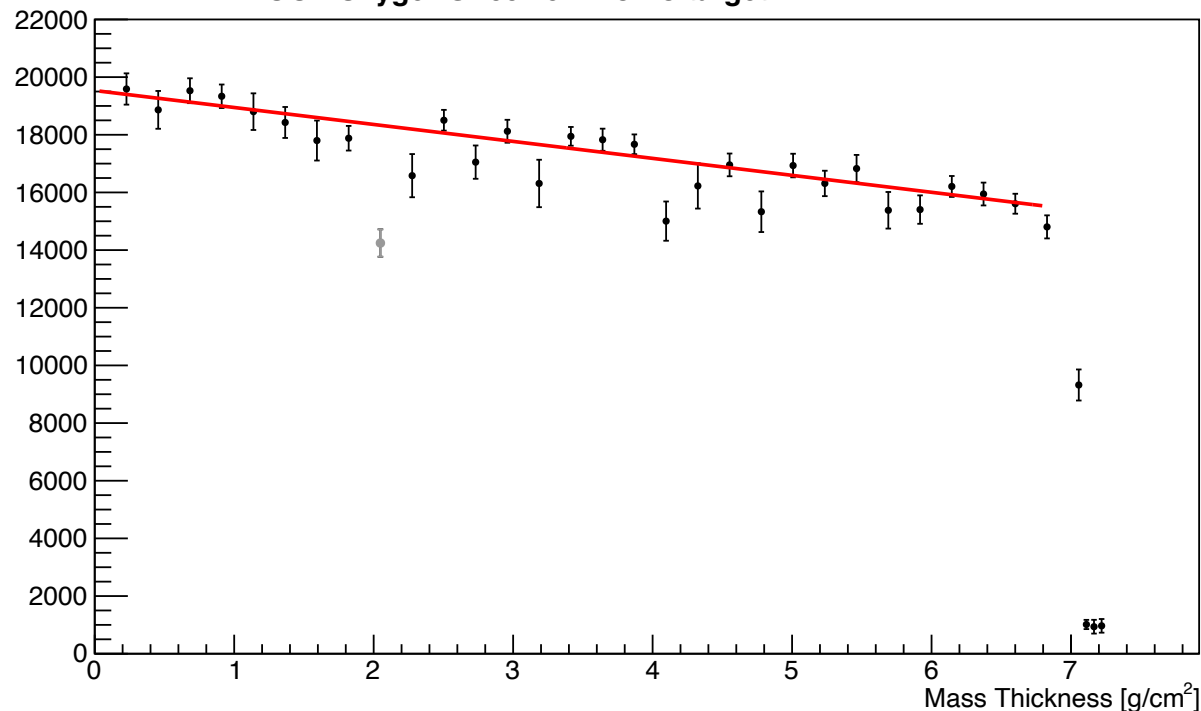
- (188 ± 8) MeV/n
- (168 ± 10) MeV/n
- (144 ± 11) MeV/n
- (115 ± 13) MeV/n
- (88 ± 8) MeV/n

Evaluation of the number of beam particles for each subsection

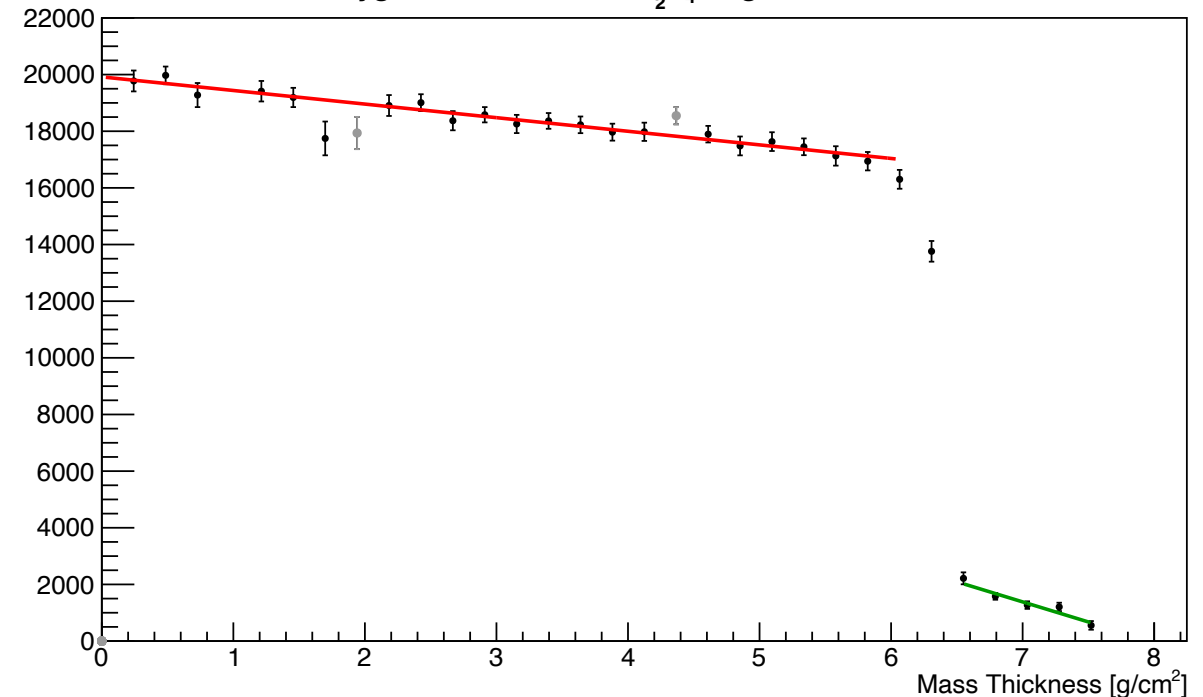
- To determine the number of ions colliding with each target, optical microscope images were processed using a high-pass Gaussian filter, whose kernel size (17x17) was optimized to match the typical dimensions of oxygen-induced pixel clusters.



FOOT Oxygen@200MeV/n on C target



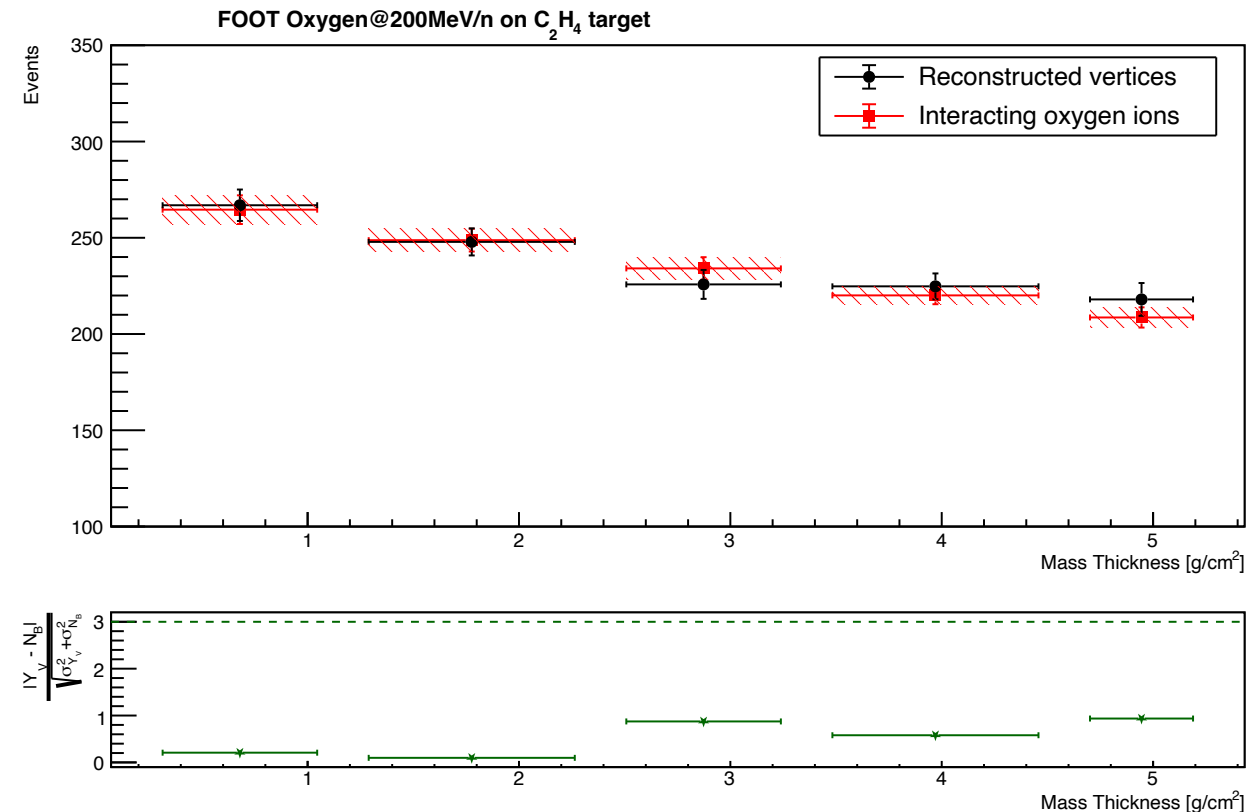
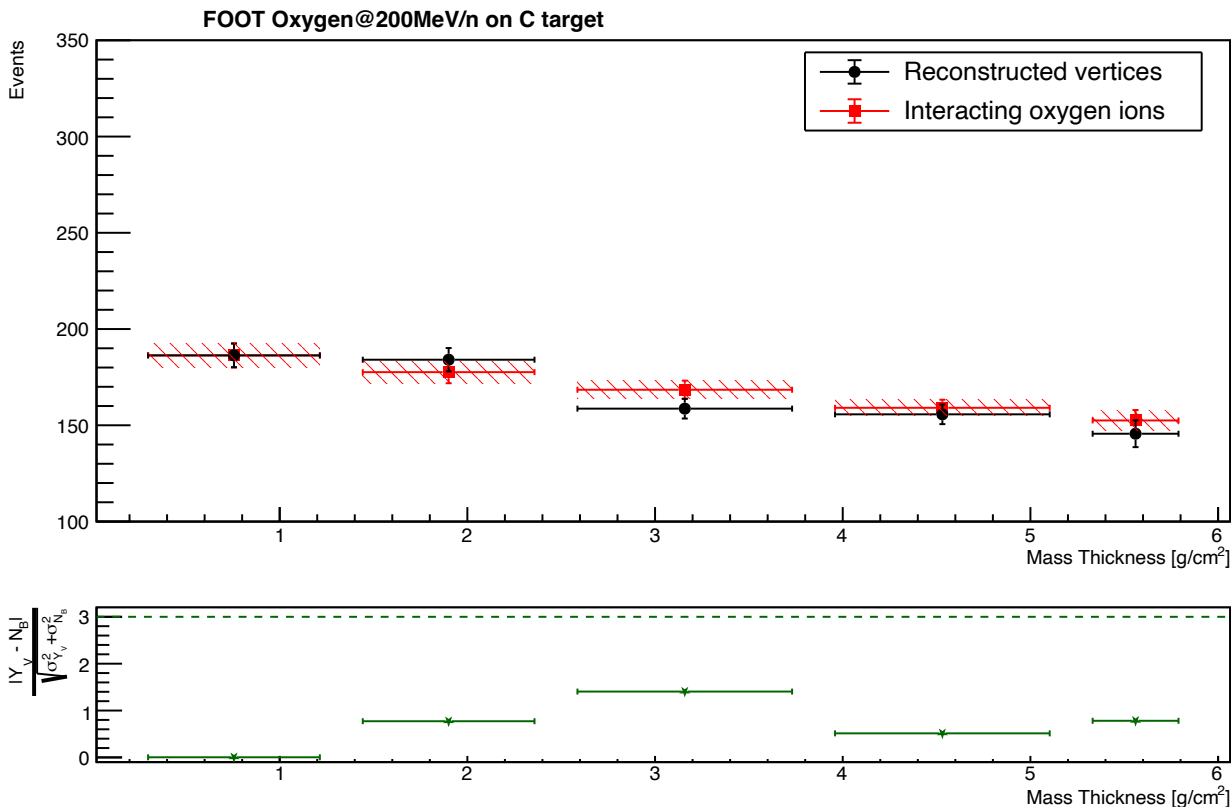
FOOT Oxygen@200MeV/n on C₂H₄ target



Systematic error evaluation

arXiv:2607.00743

- Comparison of the number of disappearing beam oxygens and the number of reconstructed vertices
- Double check for cross section with **completely independent methods** (both in terms of hardware and software)
- Normalized difference between the two measurements is always below 3, indicating that the systematic uncertainty is smaller than the statistical one and can thus be considered negligible

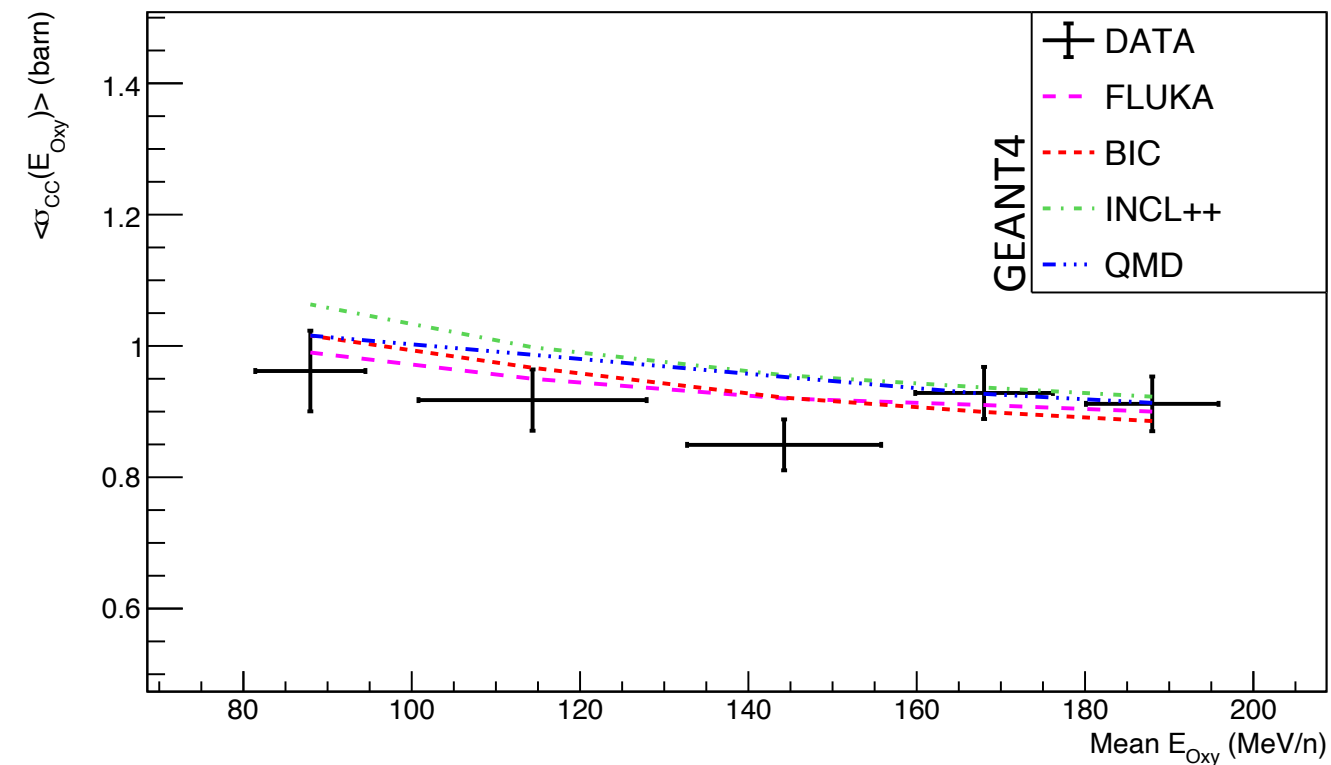


Total charge-changing cross section on C

arXiv:2607.00743

$$Y = \langle \# \text{ of vertices} \rangle$$

FOOT Oxygen@200MeV/n on C target



Angular acceptance: 45°

Beam E_{kin} (MeV/n)	σ_{CC} on C (barn)	σ_{CC} on C_2H_4 (barn)	σ_{CC} on H (barn)
188 ± 7	0.91 ± 0.04	3.0 ± 0.1	0.31 ± 0.06
167 ± 10	0.93 ± 0.04	3.0 ± 0.1	0.28 ± 0.05
143 ± 11	0.85 ± 0.04	2.7 ± 0.1	0.25 ± 0.06
115 ± 14	0.92 ± 0.05	3.2 ± 0.1	0.33 ± 0.06
87 ± 8	0.96 ± 0.06	3.1 ± 0.2	0.30 ± 0.08

TABLE IV. Available results from other experiments for σ_R on C.

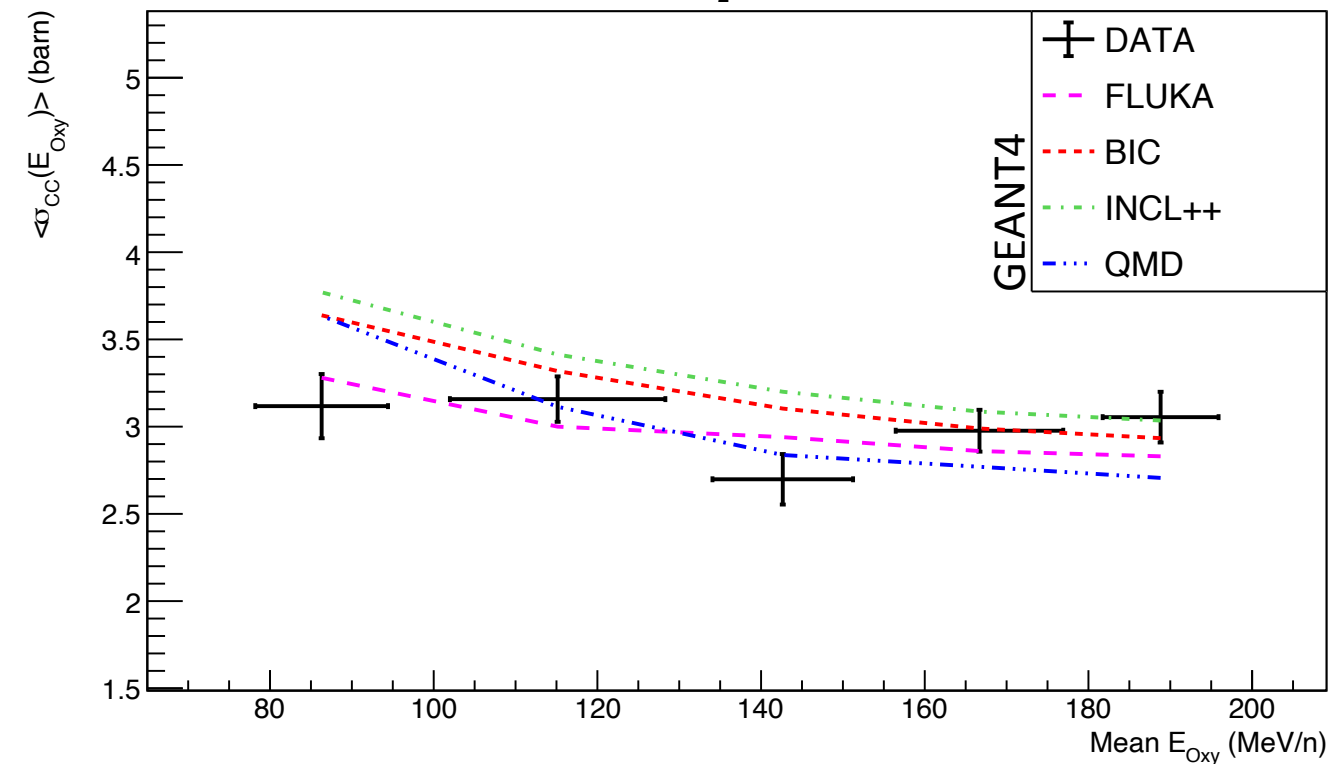
Ref.	Beam E_{kin} (MeV/n)	Angular Acceptance	σ_R on C ($cm^{-2} \cdot 10^{-24}$)
Yamaguchi [31]	288	10°	0.852 ± 0.017
Zeitlin [32]	290	5.7°	0.863 ± 0.020
Zeitlin [32]	400	5.7°	0.842 ± 0.022

Total charge-changing cross section on C₂H₄

arXiv:2607.00743

$$Y = \langle \# \text{ of vertices} \rangle$$

FOOT Oxygen@200MeV/n on C₂H₄ target



Angular acceptance: 45°

Beam E_{kin} (MeV/n)	σ_{CC} on C (barn)	σ_{CC} on C ₂ H ₄ (barn)	σ_{CC} on H (barn)
188 ± 7	0.91 ± 0.04	3.0 ± 0.1	0.31 ± 0.06
167 ± 10	0.93 ± 0.04	3.0 ± 0.1	0.28 ± 0.05
143 ± 11	0.85 ± 0.04	2.7 ± 0.1	0.25 ± 0.06
115 ± 14	0.92 ± 0.05	3.2 ± 0.1	0.33 ± 0.06
87 ± 8	0.96 ± 0.06	3.1 ± 0.2	0.30 ± 0.08

TABLE V. Available results from other experiments for σ_R on CH₂.

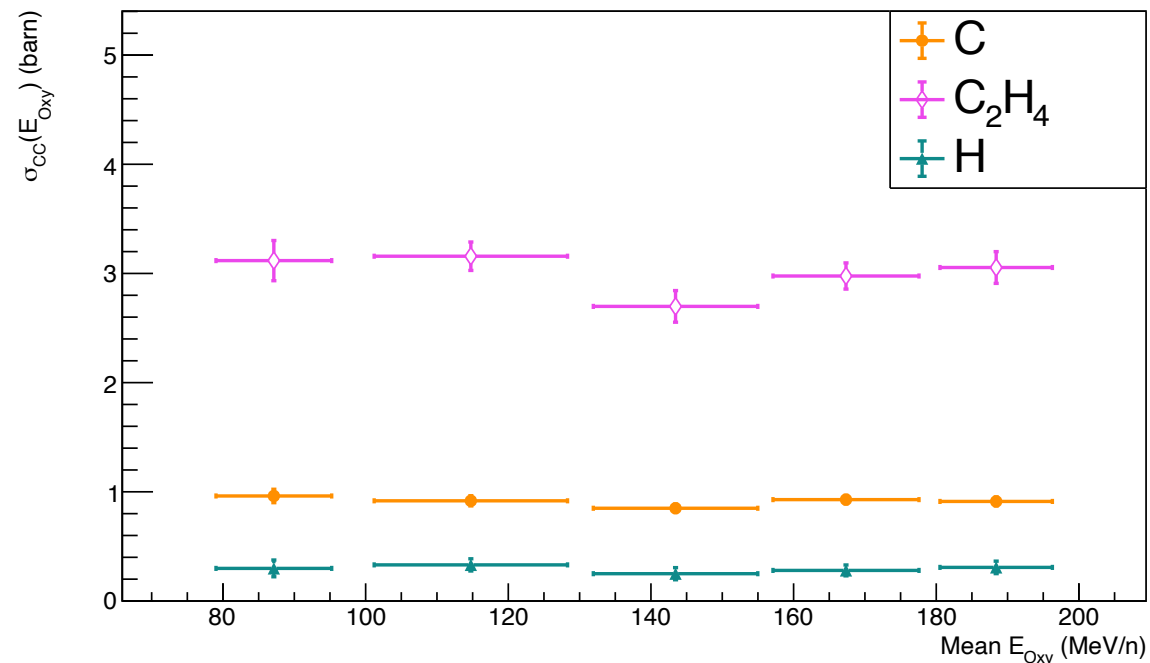
Ref.	Beam E_{kin} (MeV/n)	Angular Acceptance	σ_R on CH ₂ (cm ⁻² · 10 ⁻²⁴)
Webber [33]	441	7.7°	1.260 ± 0.013
Webber [33]	591	7.7°	1.316 ± 0.013
Webber [33]	669	7.7°	1.328 ± 0.013

Note that the cross section on C₂H₄ is twice that on CH₂

Total charge-changing cross section

$$Y_i = \langle \# \text{ of vertices} \rangle$$

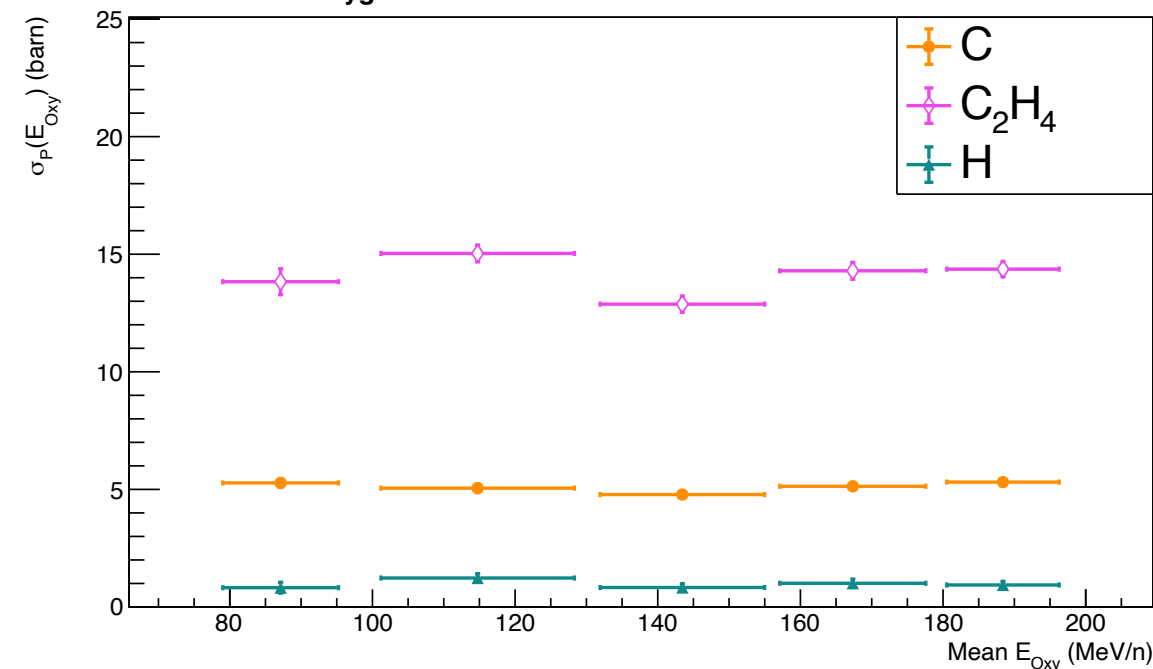
FOOT Oxygen@200MeV/n



Total production cross section

$$Y_i = \langle \# \text{ of fragments} \rangle$$

FOOT Oxygen@200MeV/n

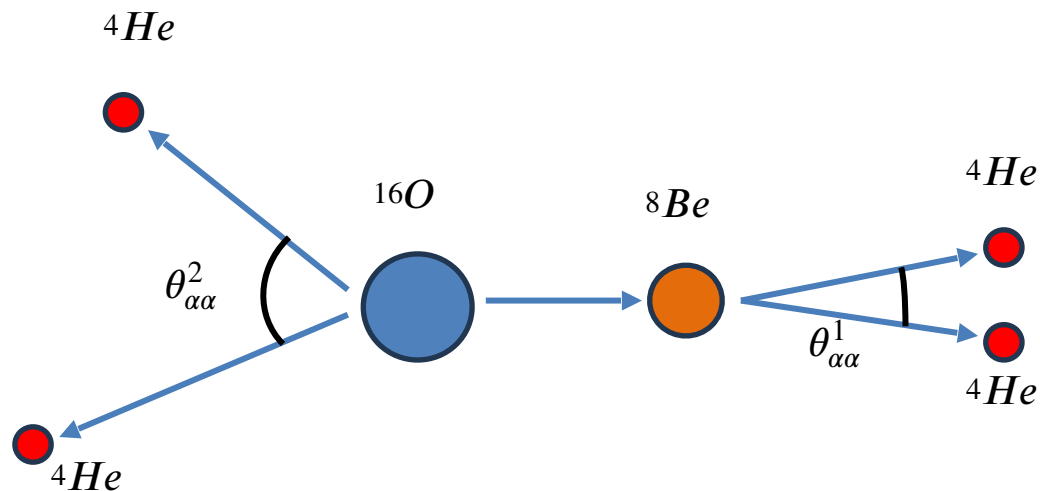
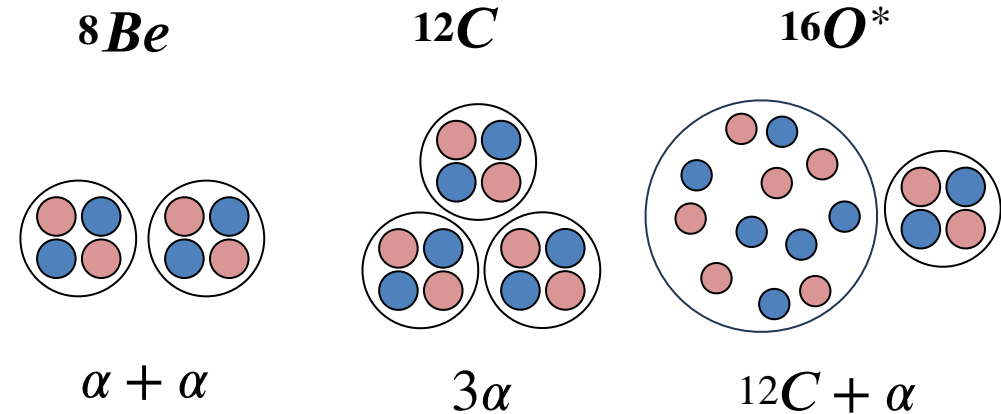


Beam E _{kin} (MeV/n)	σ_{CC} on C (barn)	σ_{CC} on C ₂ H ₄ (barn)	σ_{CC} on H (barn)
188 ± 7	0.91 ± 0.04	3.0 ± 0.1	0.31 ± 0.06
167 ± 10	0.93 ± 0.04	3.0 ± 0.1	0.28 ± 0.05
143 ± 11	0.85 ± 0.04	2.7 ± 0.1	0.25 ± 0.06
115 ± 14	0.92 ± 0.05	3.2 ± 0.1	0.33 ± 0.06
87 ± 8	0.96 ± 0.06	3.1 ± 0.2	0.30 ± 0.08

Beam E _{kin} (MeV/n)	σ_P on C (barn)	σ_P on C ₂ H ₄ (barn)	σ_P on H (barn)
188 ± 7	5.3 ± 0.1	14.4 ± 0.3	0.93 ± 0.14
167 ± 10	5.1 ± 0.2	14.3 ± 0.4	1.01 ± 0.17
143 ± 11	4.8 ± 0.1	12.9 ± 0.3	0.83 ± 0.18
115 ± 14	5.1 ± 0.2	15.0 ± 0.4	1.23 ± 0.18
87 ± 8	5.3 ± 0.2	13.8 ± 0.6	0.82 ± 0.23

Alpha clustering studies

- Alpha clustering is one of the most remarkable manifestations of nuclear structure in light nuclei
- The ground state of ${}^8\text{Be}$ is the simplest example of such a configuration, consisting of two weakly unbound α particles separated by only 92 keV from the two- α threshold, and represents a sensitive benchmark for nuclear reaction models
- Experimental studies of cluster phenomena at intermediate energies are still scarce



- Because of its short lifetime ($\sim 7 \times 10^{-17}$ s), ${}^8\text{Be}_{\text{g.s.}}$ cannot be observed directly
- The small decay energy results in a characteristic opening angle of approximately 13 mrad at the energies considered in this work

Alpha clustering studies

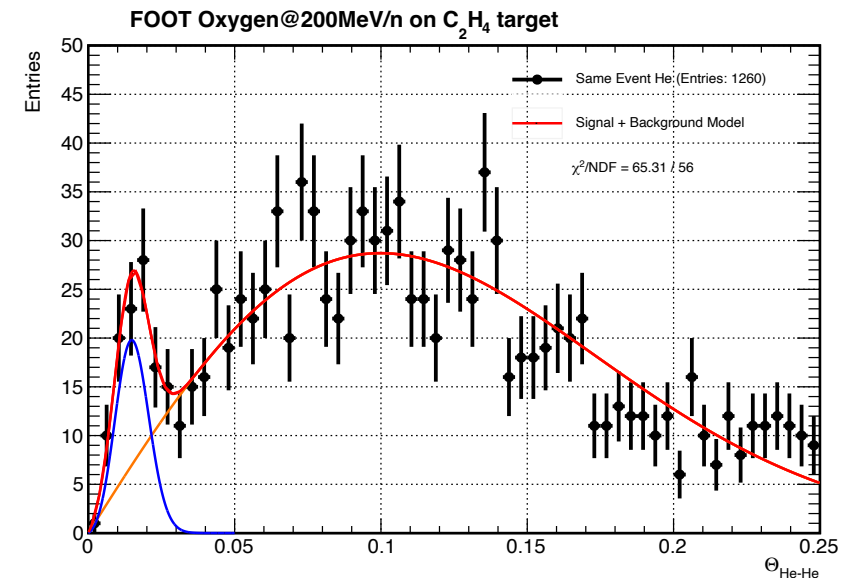
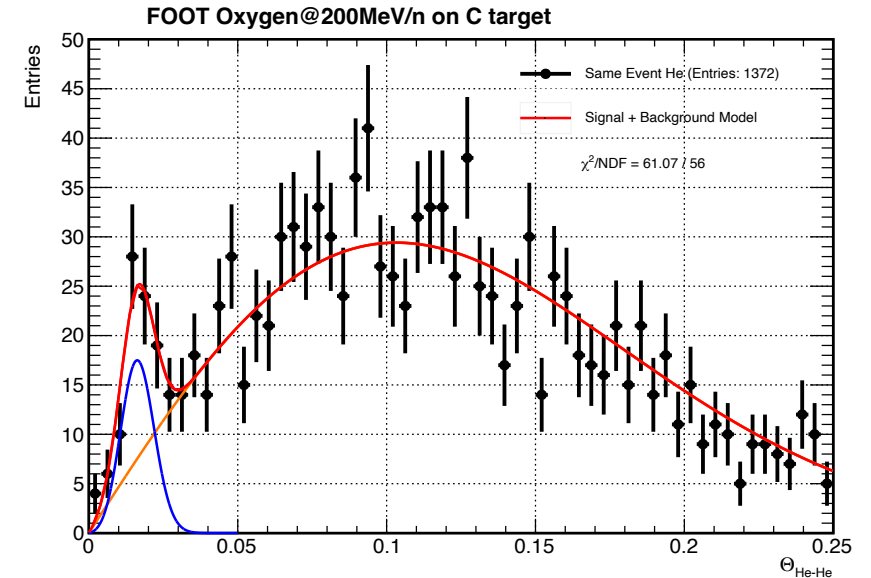
- Interaction vertices containing at least two helium fragments were selected, and the opening-angle distribution of all He-He pairs was analysed to identify the ${}^8\text{Be}_{g.s.}$ signal

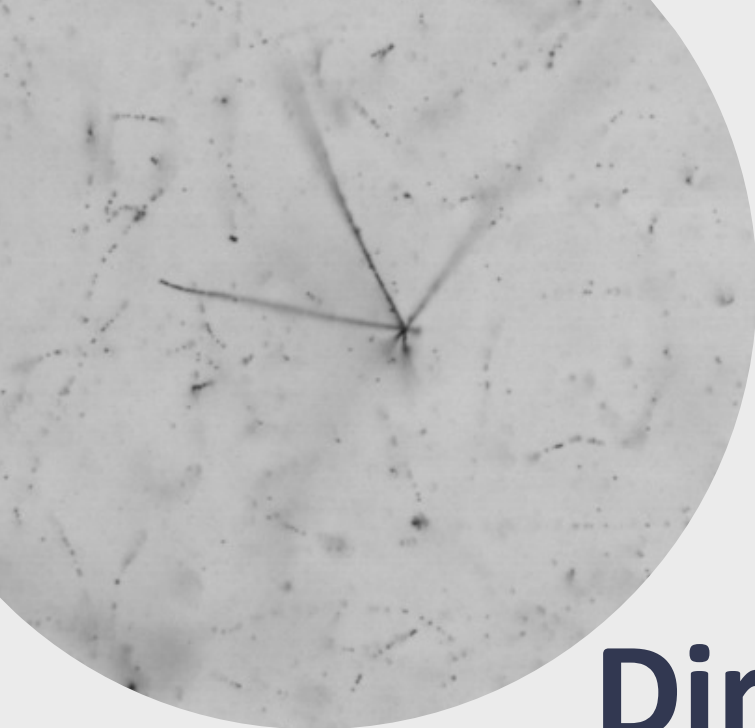
$$\sigma^{8\text{Be}_{g.s.}}(C) = (25 \pm 6 \pm 2) \text{ mb}$$

$$\sigma^{8\text{Be}_{g.s.}}(C_2H_4) = (70 \pm 6 \pm 6) \text{ mb}$$

Simulation	$\sigma_{8\text{Be}_{g.s.}}$ (mb)	Data/MC	Simulation	$\sigma_{8\text{Be}_{g.s.}}$ (mb)	Data/MC
FLUKA	47 ± 1	$53\% \pm 15\%$	FLUKA	155 ± 2	$45\% \pm 11\%$
Geant4, INCL++	48 ± 1	$52\% \pm 14\%$	Geant4, INCL++	178 ± 2	$39\% \pm 10\%$
Geant4, BIC	43 ± 1	$57\% \pm 16\%$	Geant4, BIC	156 ± 2	$45\% \pm 12\%$
Geant4, QMD	48 ± 1	$53\% \pm 14\%$	Geant4, QMD	152 ± 2	$46\% \pm 12\%$

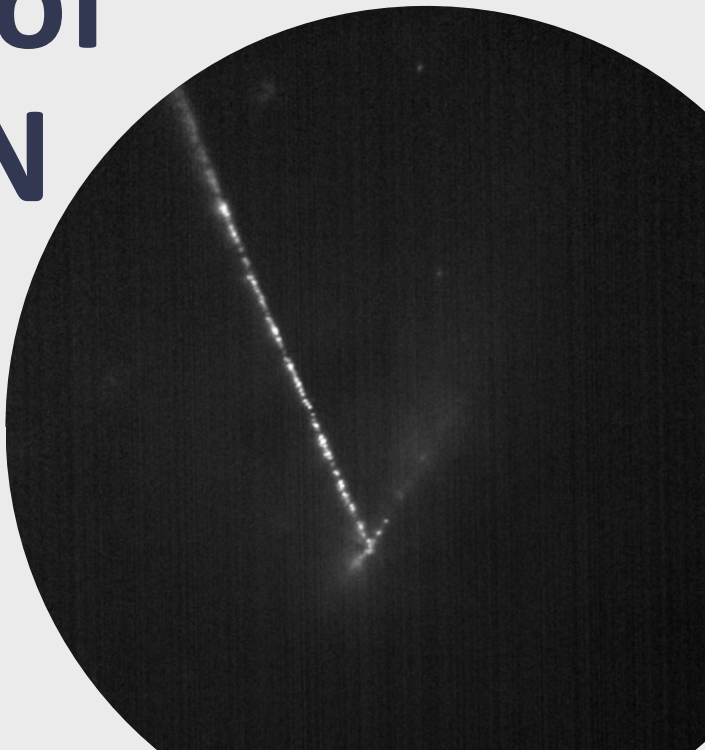
- This first measurement of ${}^8\text{Be}_{g.s.}$ production in ${}^{16}\text{O}$ fragmentation at intermediate energies shows that current transport models systematically overestimate the production cross section



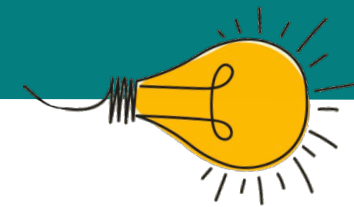


DAMON

**Direct meAsureMent of
target fragmentatiON**



The idea



- The main experimental difficulty for a direct measurement of target fragmentation induced by a proton beam is the short range of produced fragments
- Fragments so short do not exit the target: target and the tracking device should coincide
- Very high resolution: novel kind of nuclear emulsion, called Nano Imaging Tracker (NIT), with grains at the nanometric scale allows to detect path lengths shorter than 100 nm

p (180 MeV) on H₂O: range of fragments

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

References:

- [Asada, T. et al. The development of a super-fine-grained nuclear emulsion. Prog. Theor. Exp. Phys. 6, \(2017\)](#)
- [Alexandrov, A. et al. Super-resolution high-speed optical microscopy for fully automated readout of metallic nanoparticles. Sci. Reports 10, 18773 \(2020\)](#)

PRIN 2022 (Projects of Significant National Interest)

Codice progetto: **2022PXWR5J**

Titolo: **DAMON: Direct meASureMent of target fragmentation**

Coordinatore: **GALATI Giuliana**

Contributo MUR per Ricerca: **207.615**

Cofinanziamento Ateneo/Ente: **46.845 €**

Costo totale: **254.460 €**

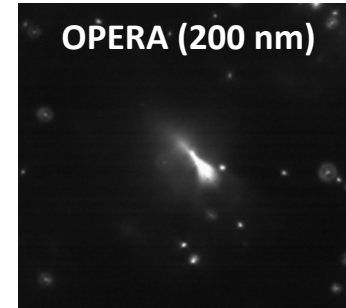
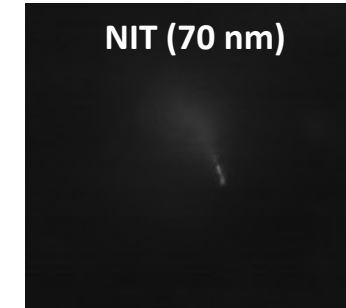
ERC: **PE2_6**

n°	Associated Investigator	Qualification	University/ Research Institution
1.	GALATI Giuliana	Ricercatore a t.d. - t.pieno (art. 24 c.3-a L. 240/10)	Università degli Studi di BARI ALDO MORO
2.	LAURIA Adele	Professore Associato (L. 240/10)	Università degli Studi di Napoli Federico II
3.	D'AMBROSIO Nicola	Dirigente tecnologo	Istituto Nazionale di Fisica Nucleare



NIT for target fragmentation measurements

- NIT act both as target and tracking devices
- The average crystal size is 70 nm (instead of 200 nm of OPERA-like emulsion films)
- Production facilities available in Nagoya (*Japan*) and Laboratori Nazionali del Gran Sasso (LNGS, *Italy*)

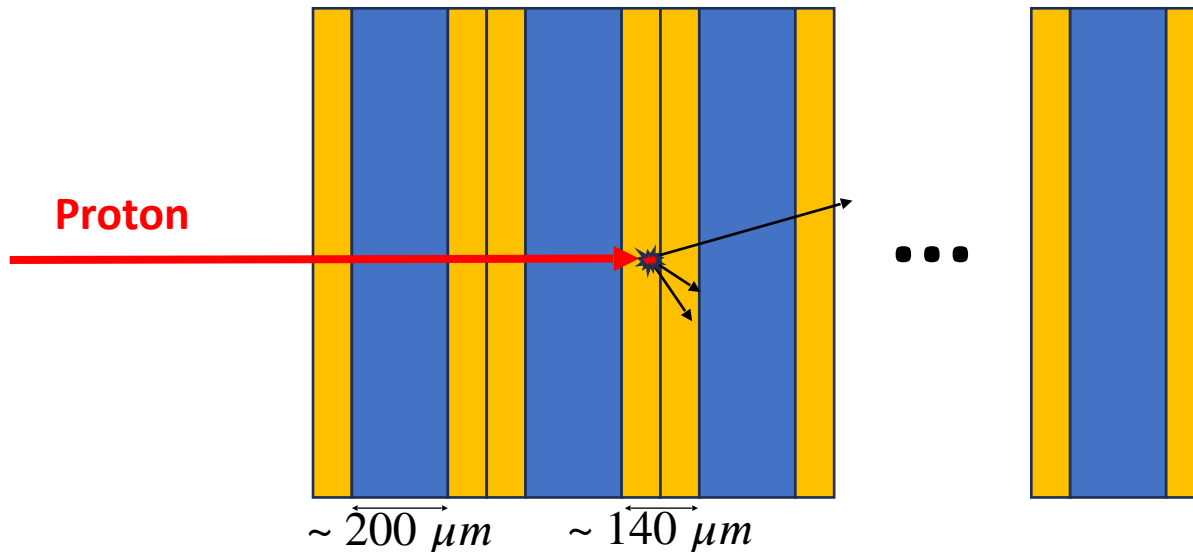


NIT sensitive layer

AgBr(I) crystals dispersed in organic gelatine (H, C, O, N)

Plastic Support

Polystyrene or PMMA (H, C, O)



LNGS Production Facility (ISO 5 Clean room)



NIT Read out

- Optical microscopes
- Challenge: detect tracks with lengths comparable/shorter than optical resolution

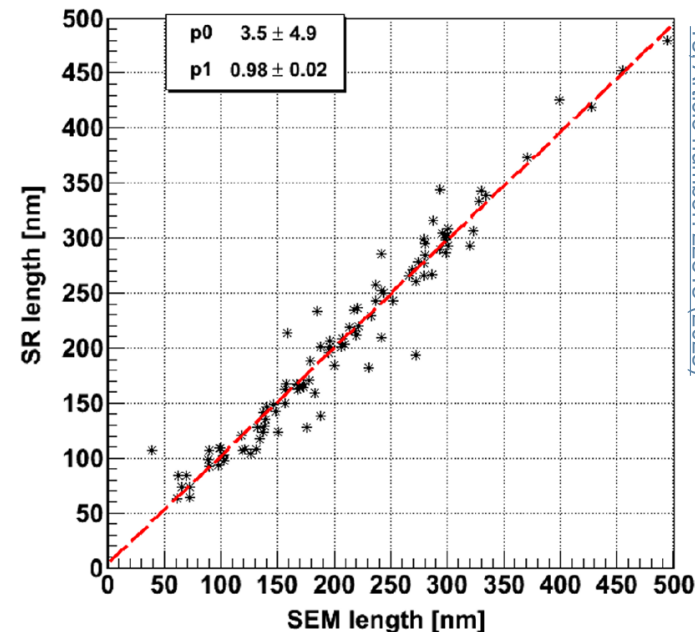
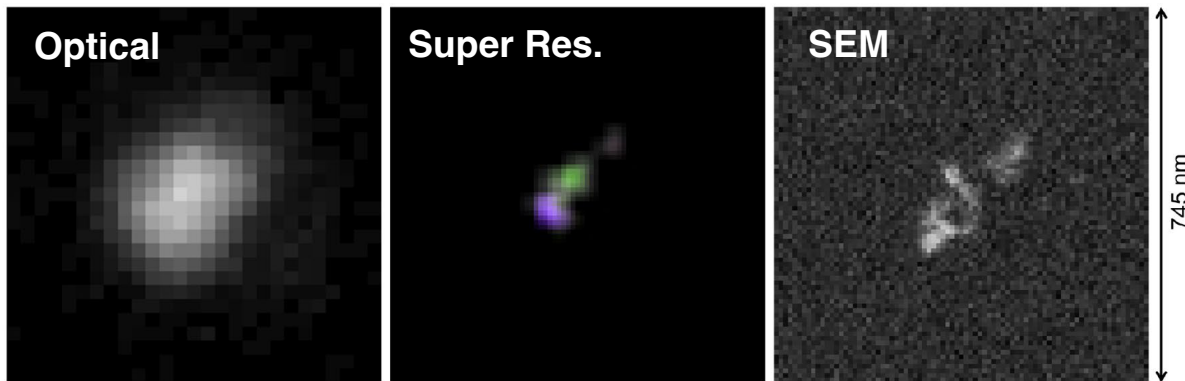
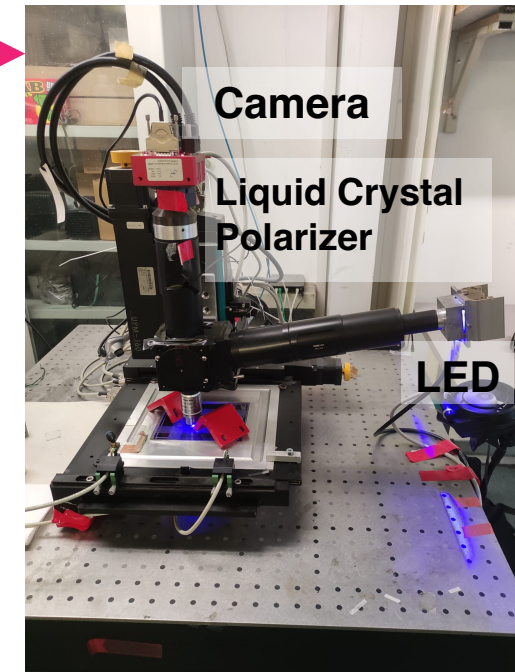
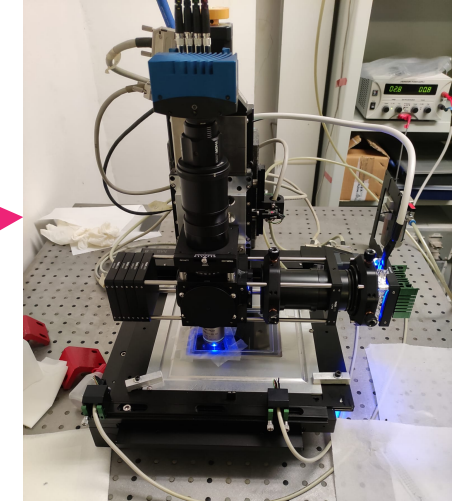
STEP 1: CANDIDATE IDENTIFICATION

Pros: Fast scanning profiting of the improvements driven by the OPERA experiment

Limit: Resolution: ~ 200 nm (Optical diffraction limit)

STEP 2: CANDIDATE VALIDATION (Resonant light scattering)

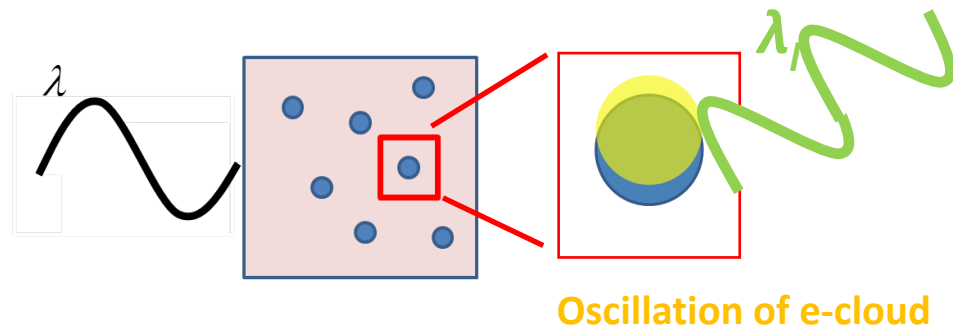
Pros: Super resolution: ~ 50 nm



From: Alexandrov et al. Scientific Reports volume 13, Article number: 22813 (2023)

Step 2: Resonant Light Scattering

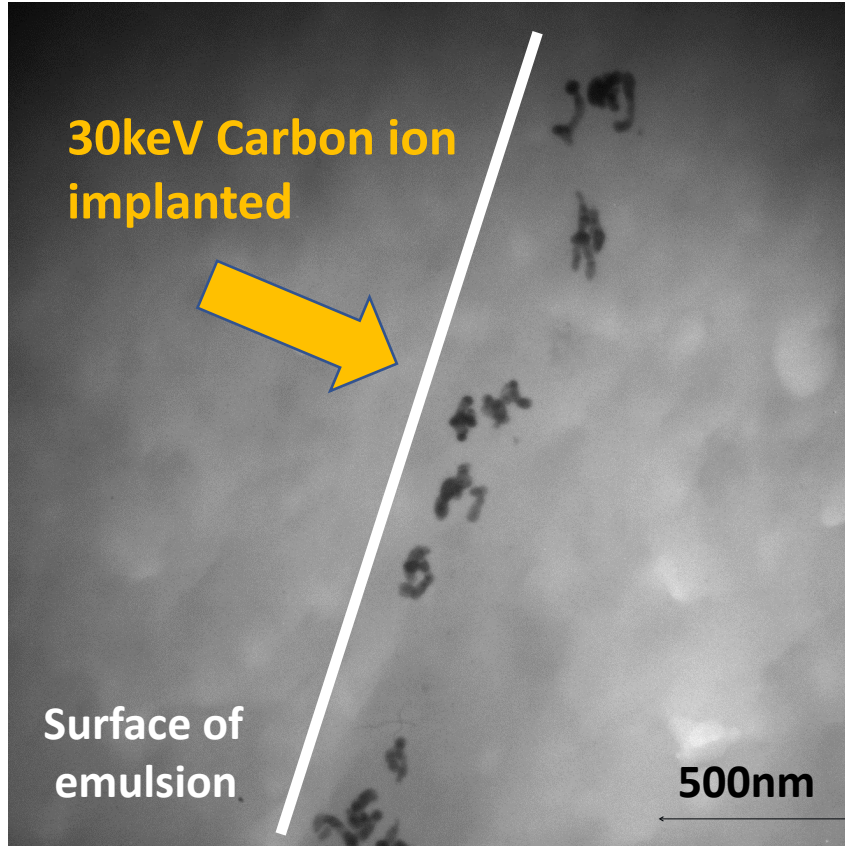
- The Localized Surface Plasmon Resonance (LSPR) phenomenon occurs when the light is scattering off a nanometric metallic (silver) grain dispersed in a dielectric medium ([Applied Phys Letters 80 \(2002\) 1826](#))
- Sensitive to the shape of nanometric grains: when silver grains are **not spherical**, the resonant response depends on the polarization of the incident light.
- Each grain is emphasized at different polarization values



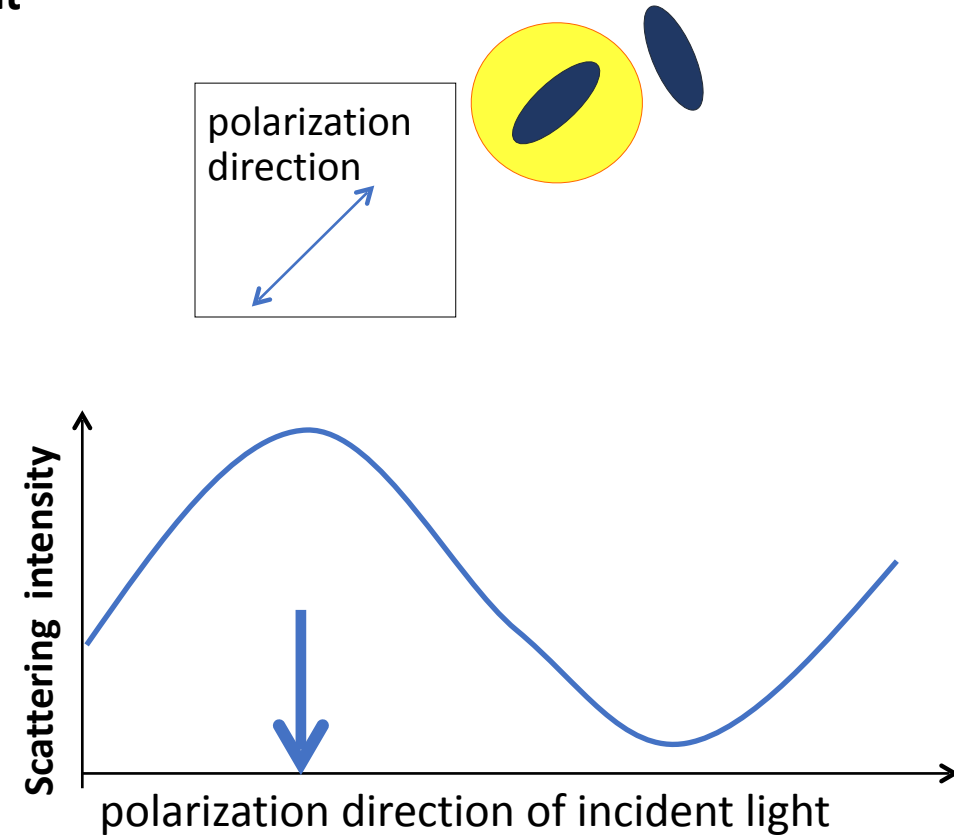
- Taking multiple measurements over the whole polarization range produces a displacement of the barycenter of the cluster
- Measure the displacement of cluster barycentre as a function of polarization angle (dx, dy)

Beyond the limits of diffraction with Plasmon Analysis

TEM image of Carbon track after development



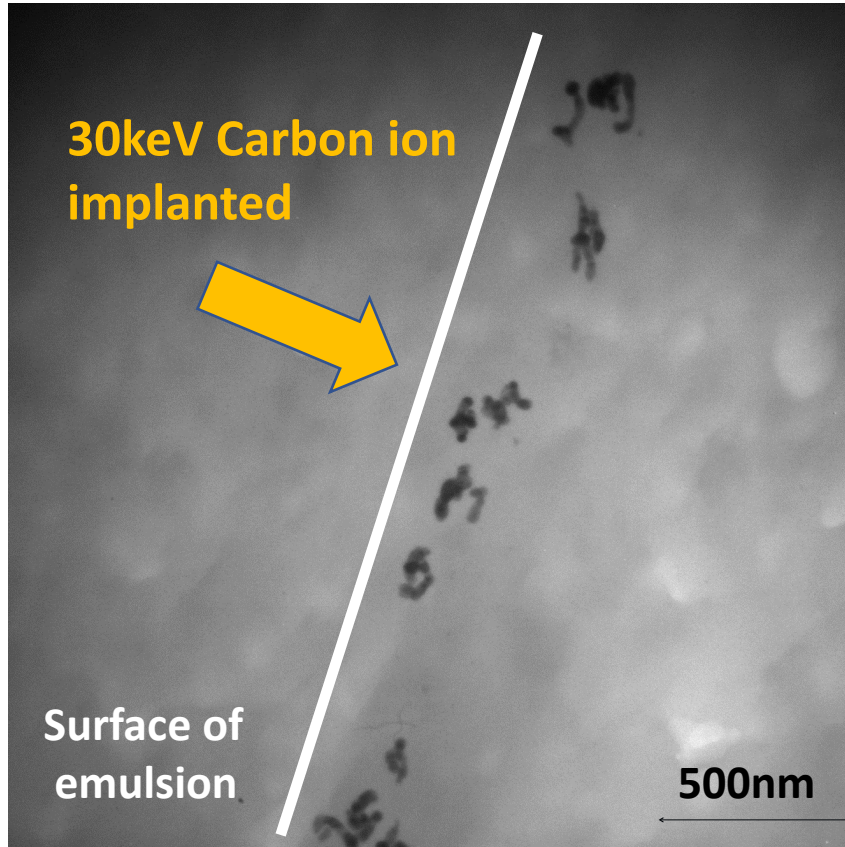
Different orientation



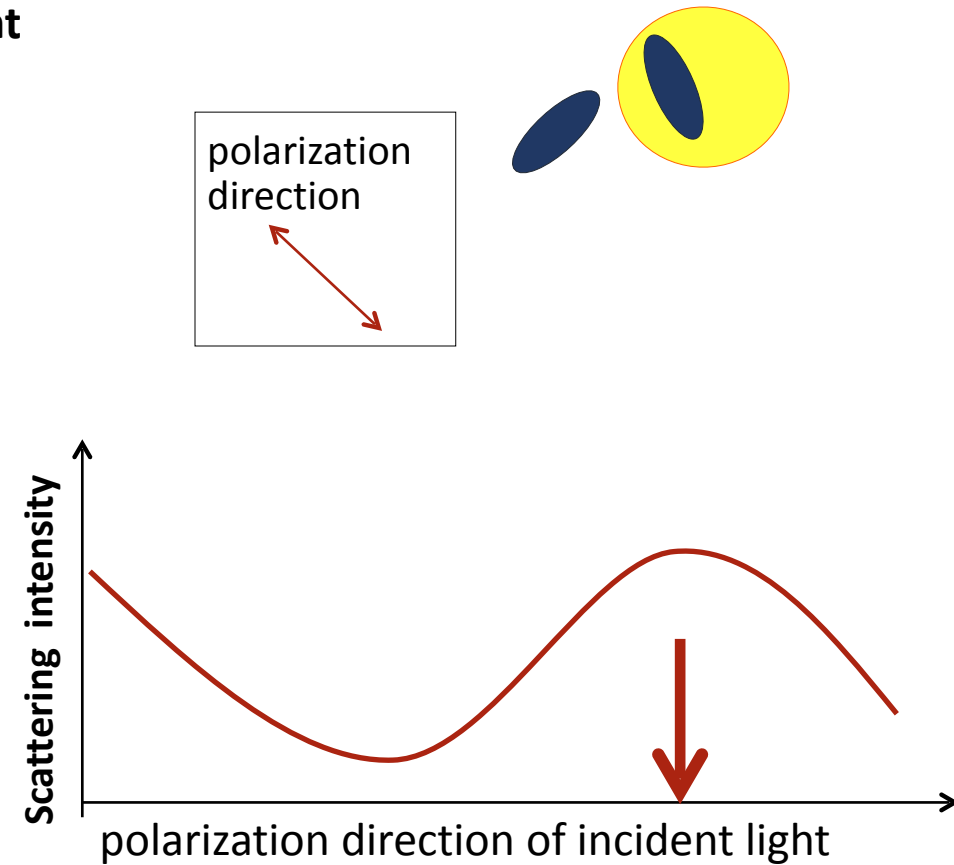
Optical response strongly depends on the polarization of incident light

Beyond the limits of diffraction with Plasmon Analysis

TEM image of Carbon track after development



Different orientation



Optical response strongly depends on the polarization of incident light

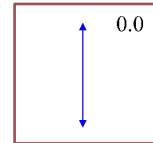
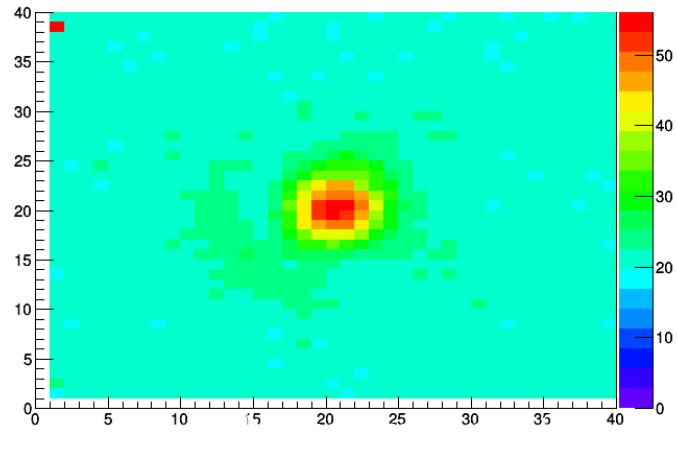
Beyond the limits of diffraction with Plasmon Analysis

Background grain



Barycenter of the cluster

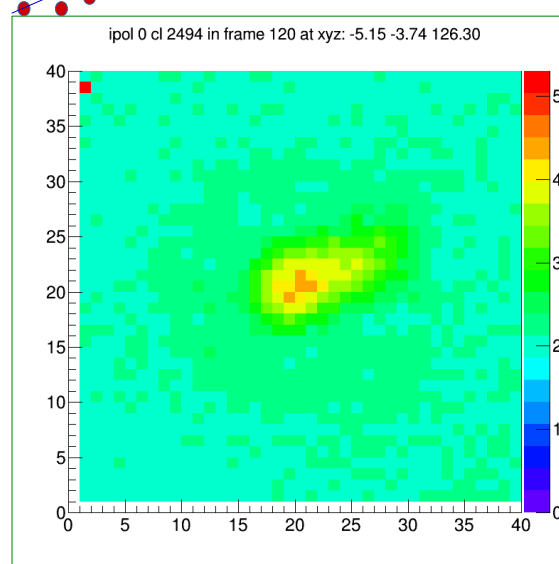
cl 872 in frame 420 at xy: 12.65 -3.84



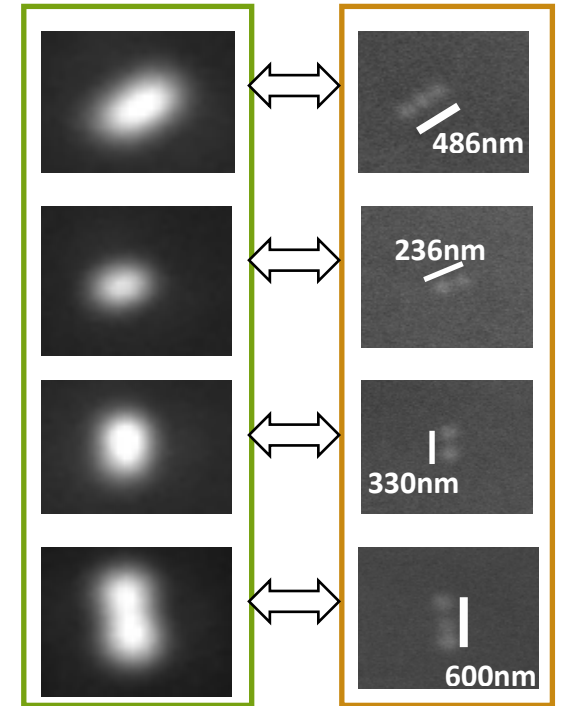
Polarization
angle

Signal-like events
(100keV C ion)

Max barshift



OPTICAL MICROSCOPE



X-RAY MICROSCOPE

Color representation

Resolved event (npeaks)

$L = 213 \text{ nm}$

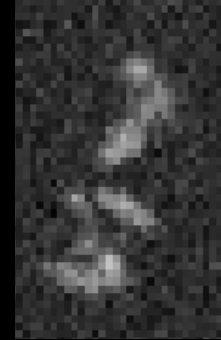


Reconstructed image

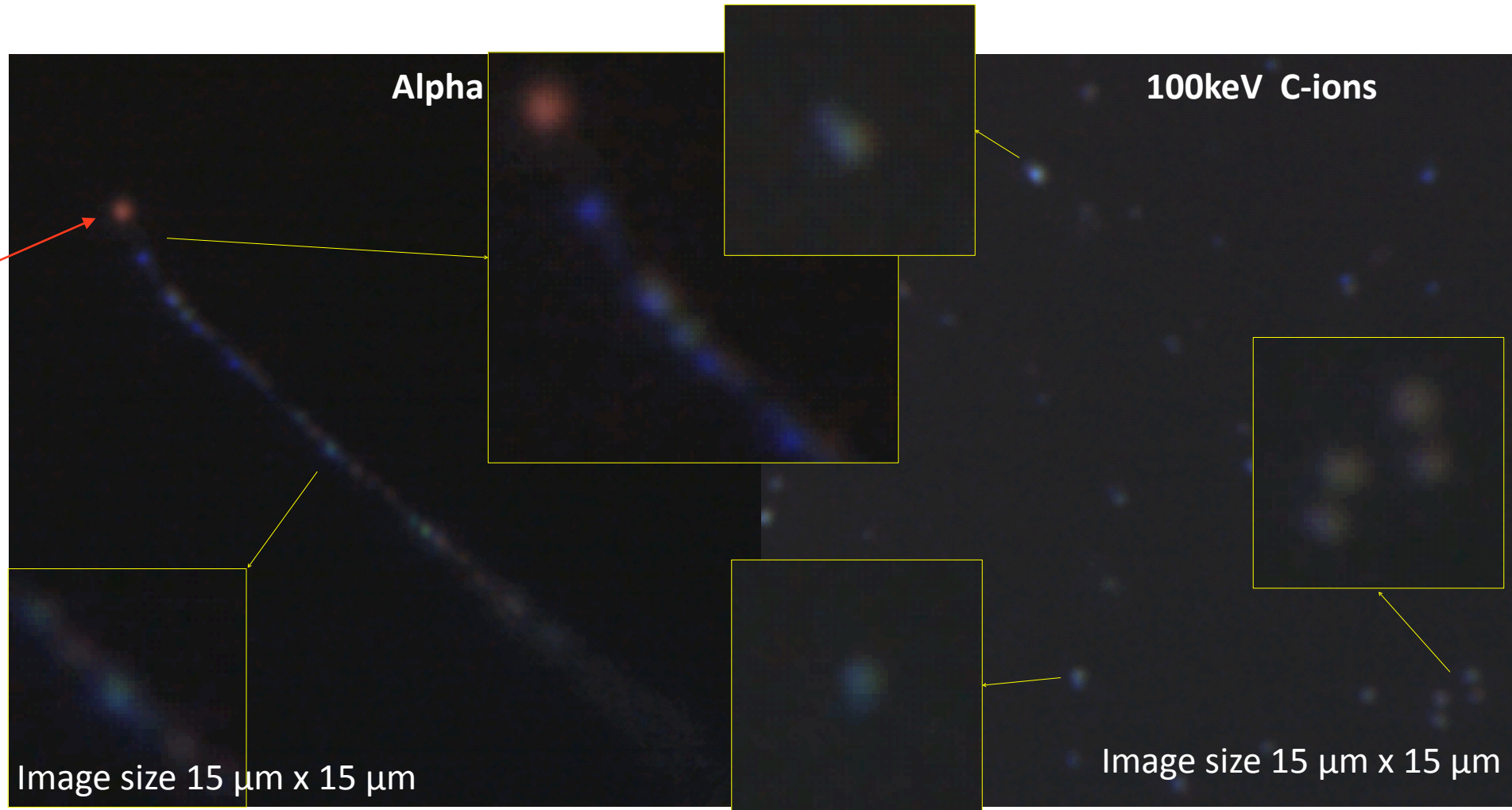
200 nm



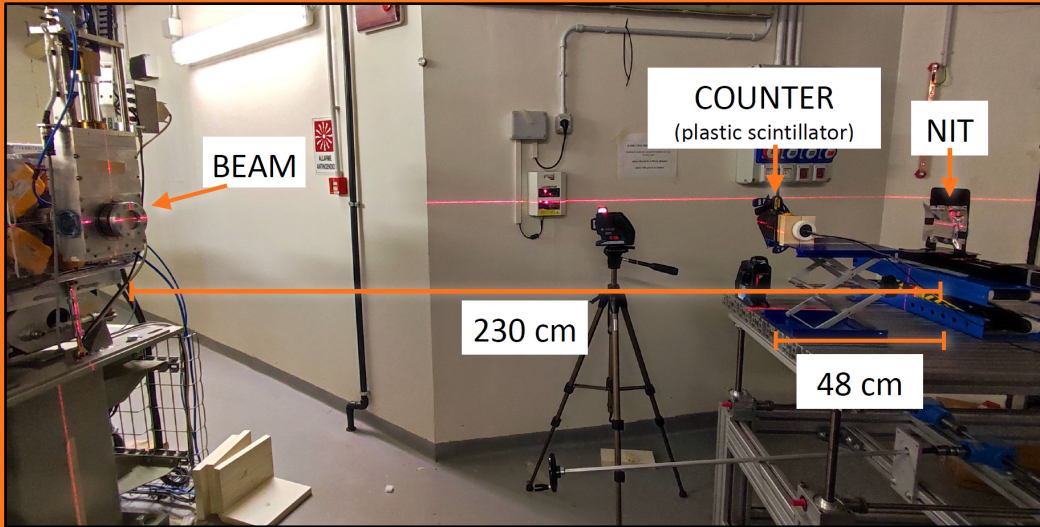
SEM image



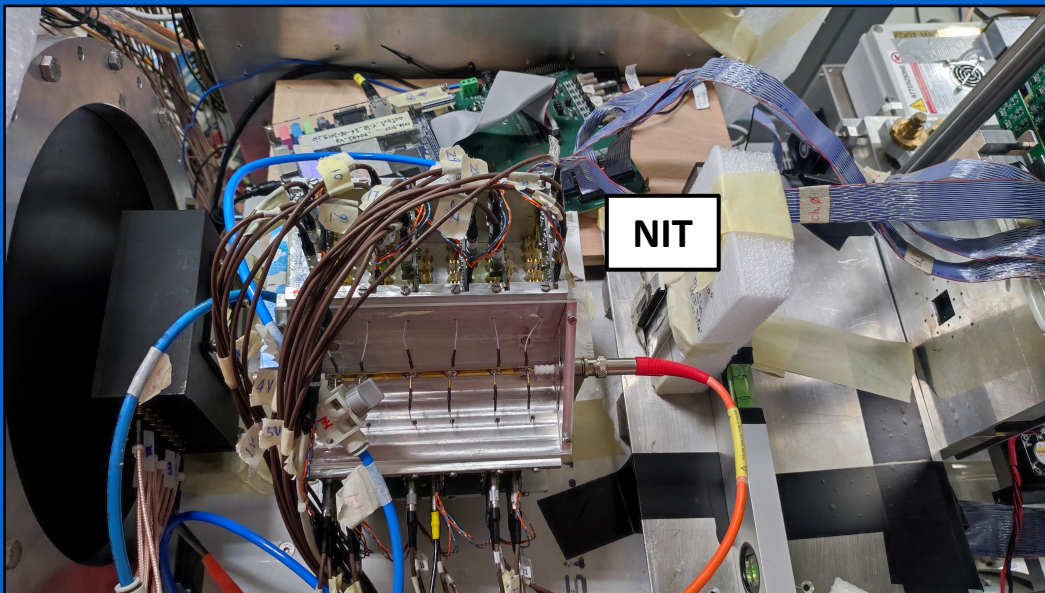
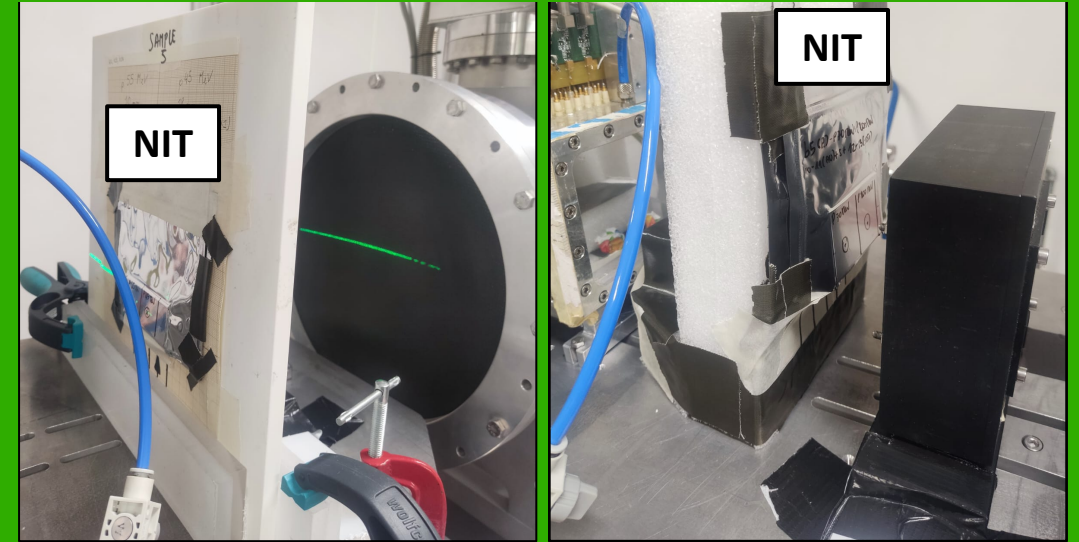
Color representation



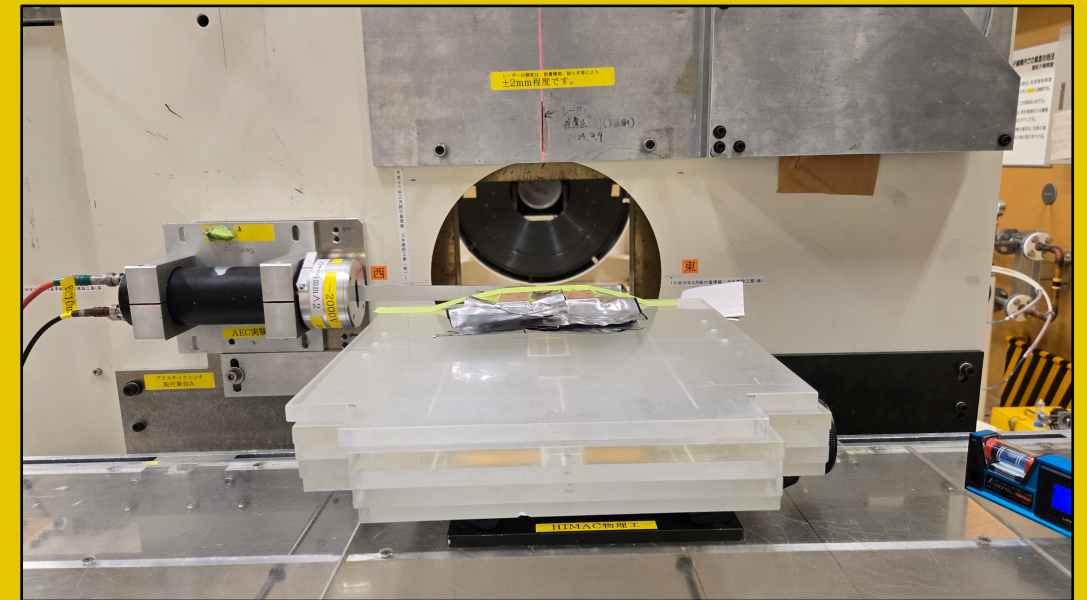
Trento Proton Therapy Center (2023): pilot test with 211 MeV protons



CNAO (2024): several exposures to protons (energies ranging from 15 MeV to 200 MeV) and carbon ions (200 MeV/n and 400 MeV/n)



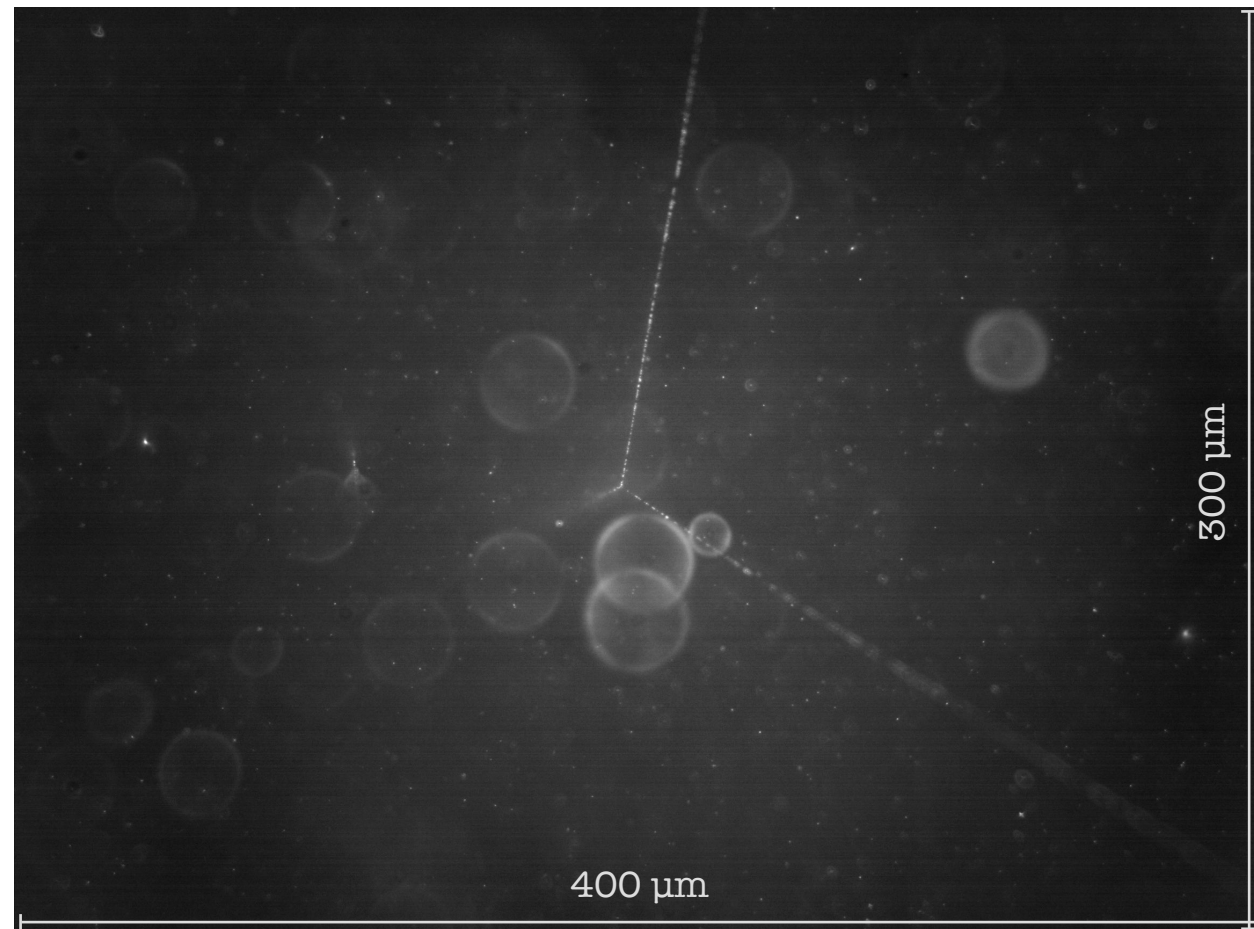
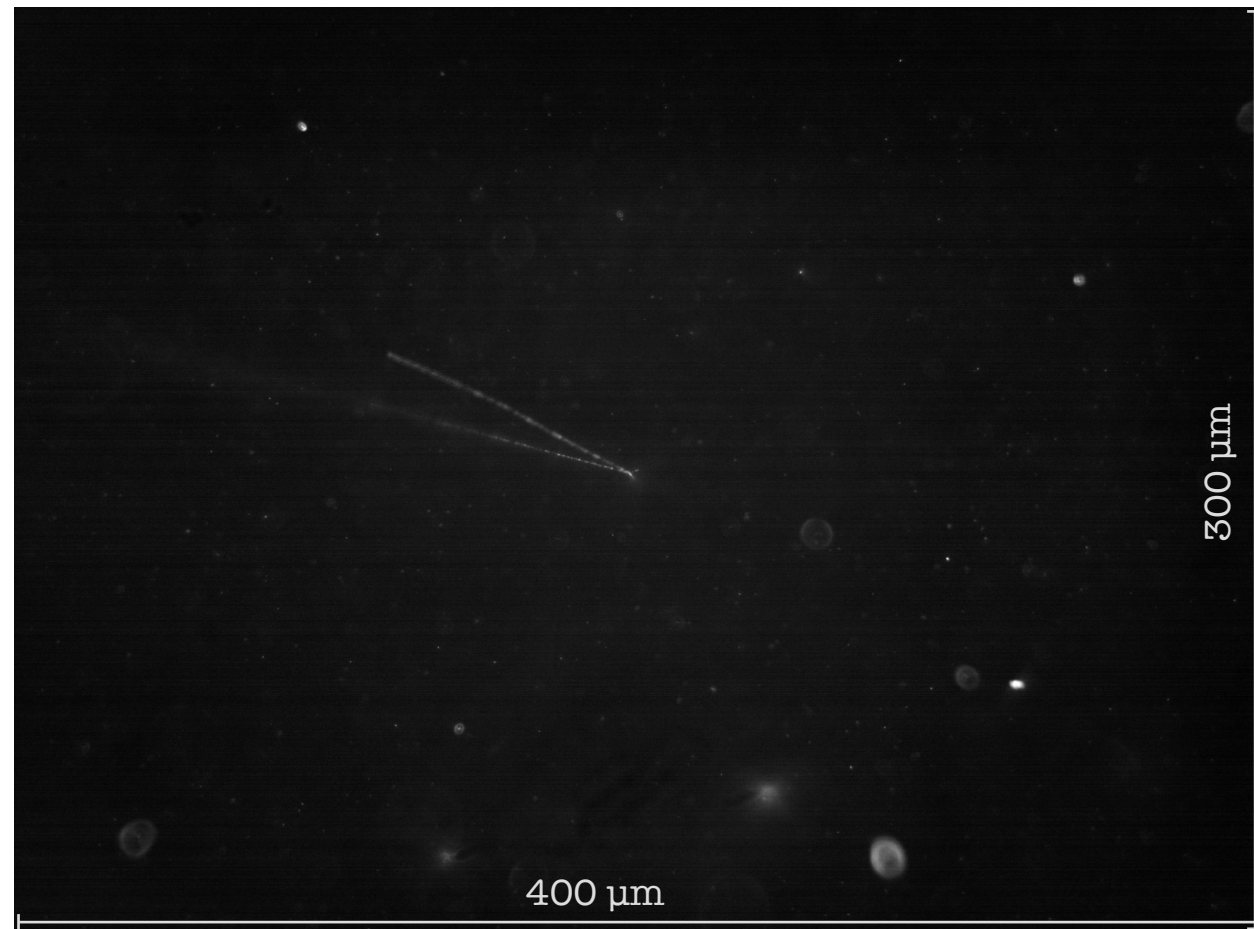
CNAO (2023): single high intensity spot (10^7 protons) to test the sensitivity at 70 MeV



HIMAC (2024): Carbon ions (290 MeV/n) to test crystal efficiency with different gel sensitizations

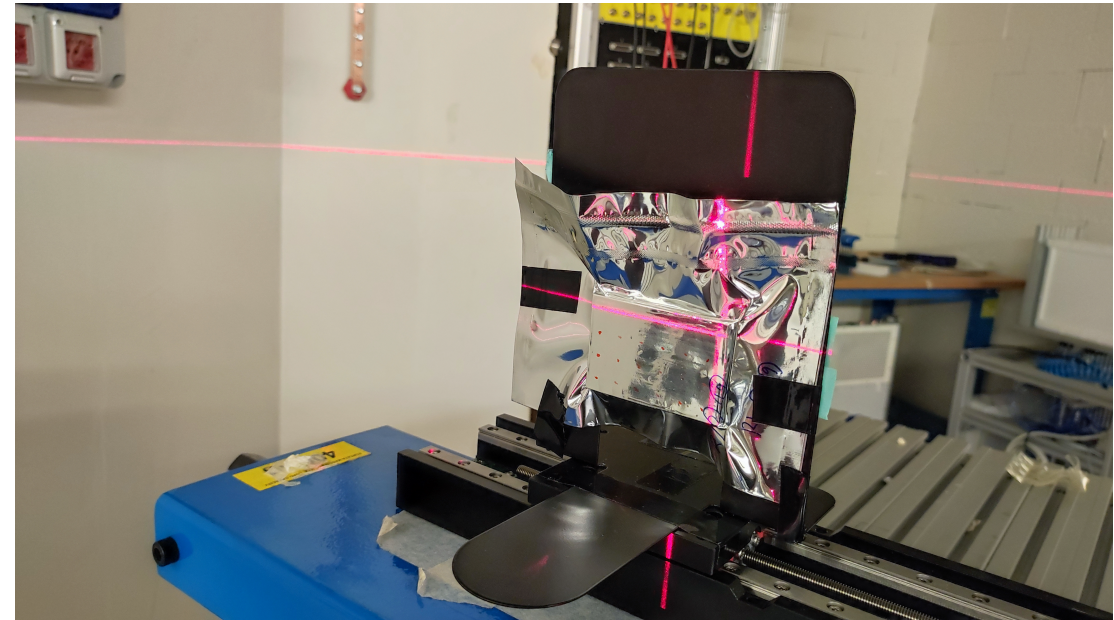
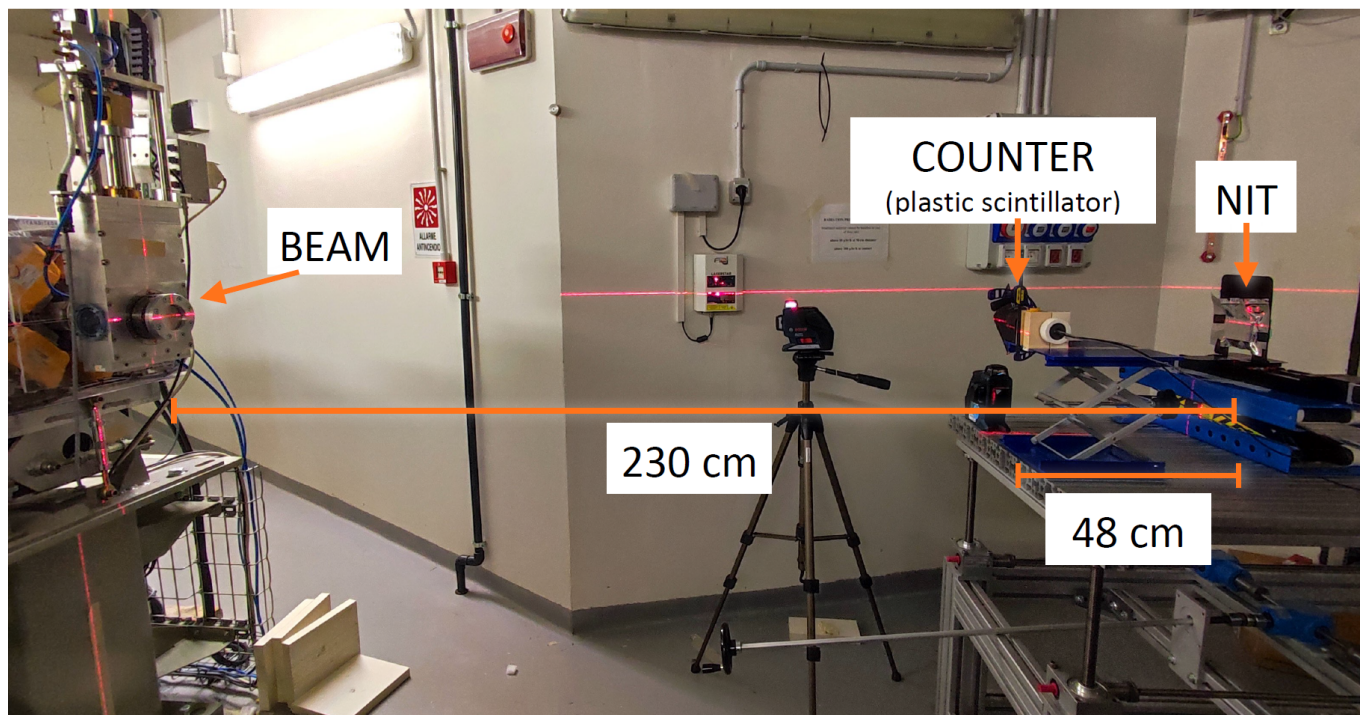
Examples of interactions seen in NIT

Fast Scanning System
Naples University



First pilot test at Trento Institute for Fundamental Physics and Applications

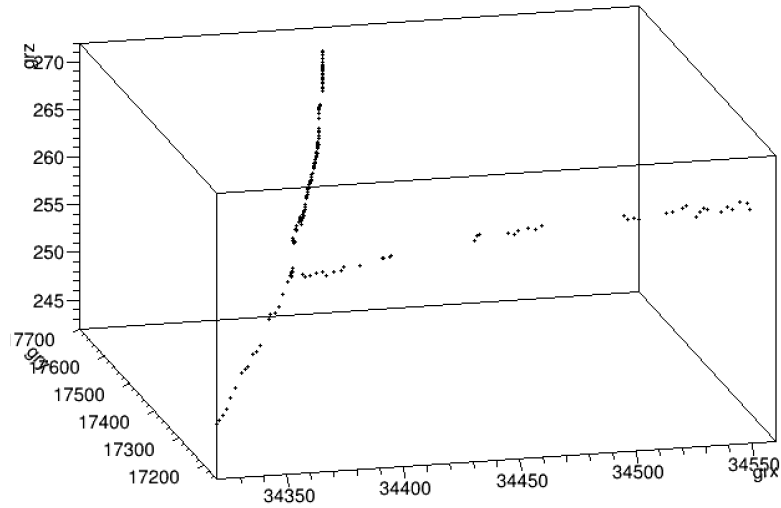
- 19 NIT films ($\sim 6.4 \times 4 \text{ cm}^2$) for the brick, 1 film for sensitivity tests
- Fixed pencil beam @211 MeV (FWHM $\sim 1.5 \text{ mm}$)
- 6x4 grid for a uniform exposure of the NIT emulsions (about 11.000 protons per spot)



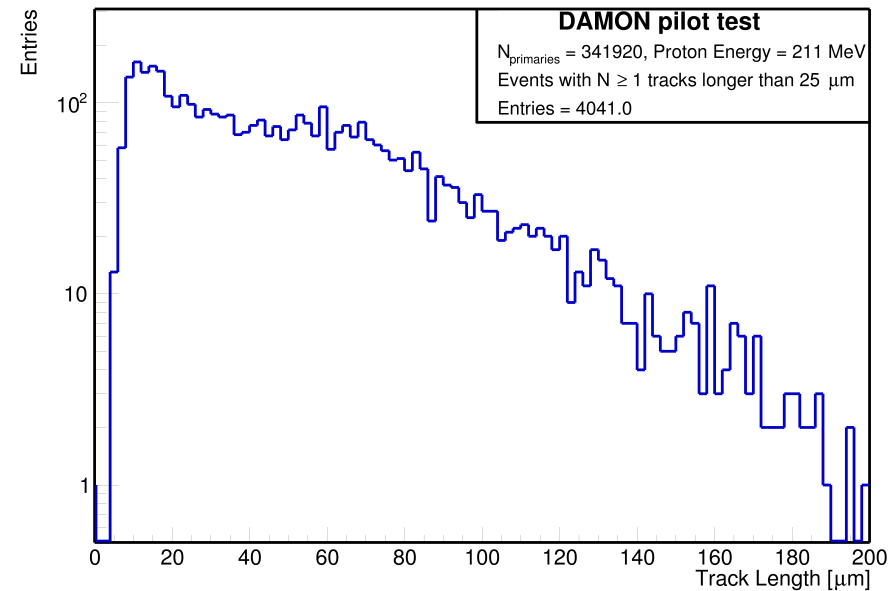
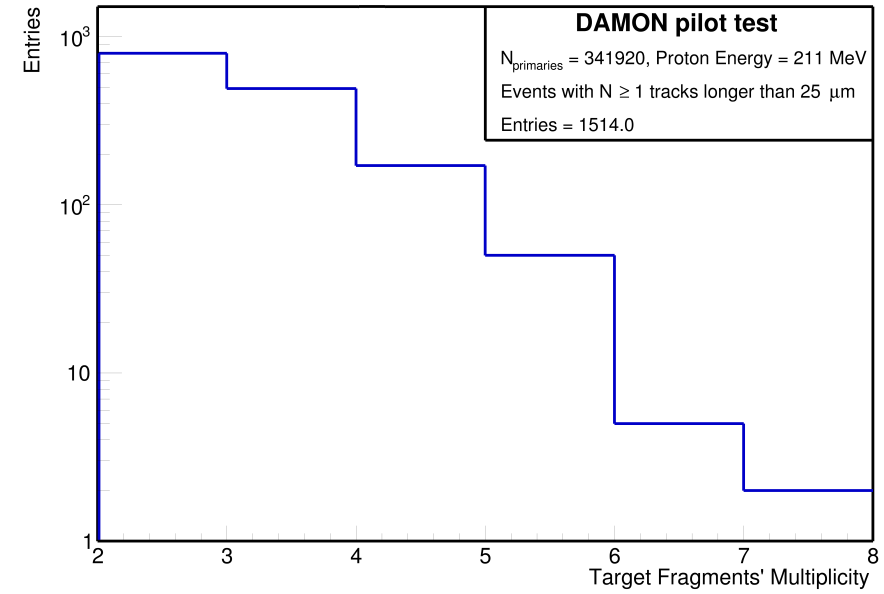
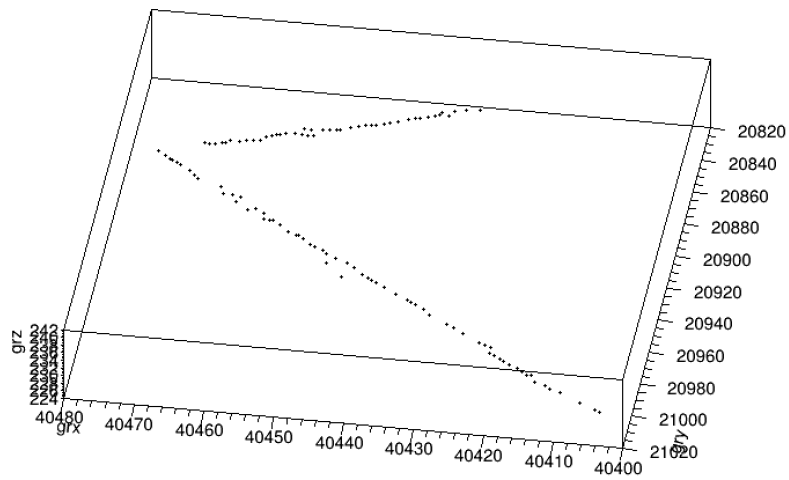
Some Results

[10.1016/j.nima.2024.170006](https://doi.org/10.1016/j.nima.2024.170006)

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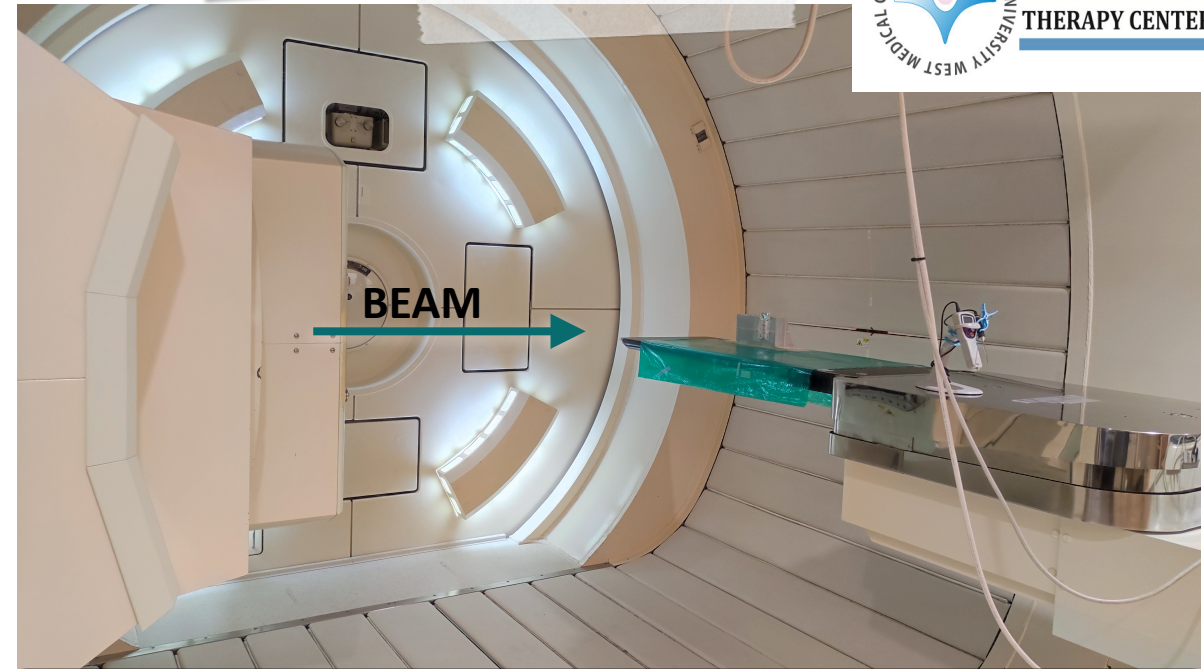


grz:gry:grx {id==7552||id==7591}



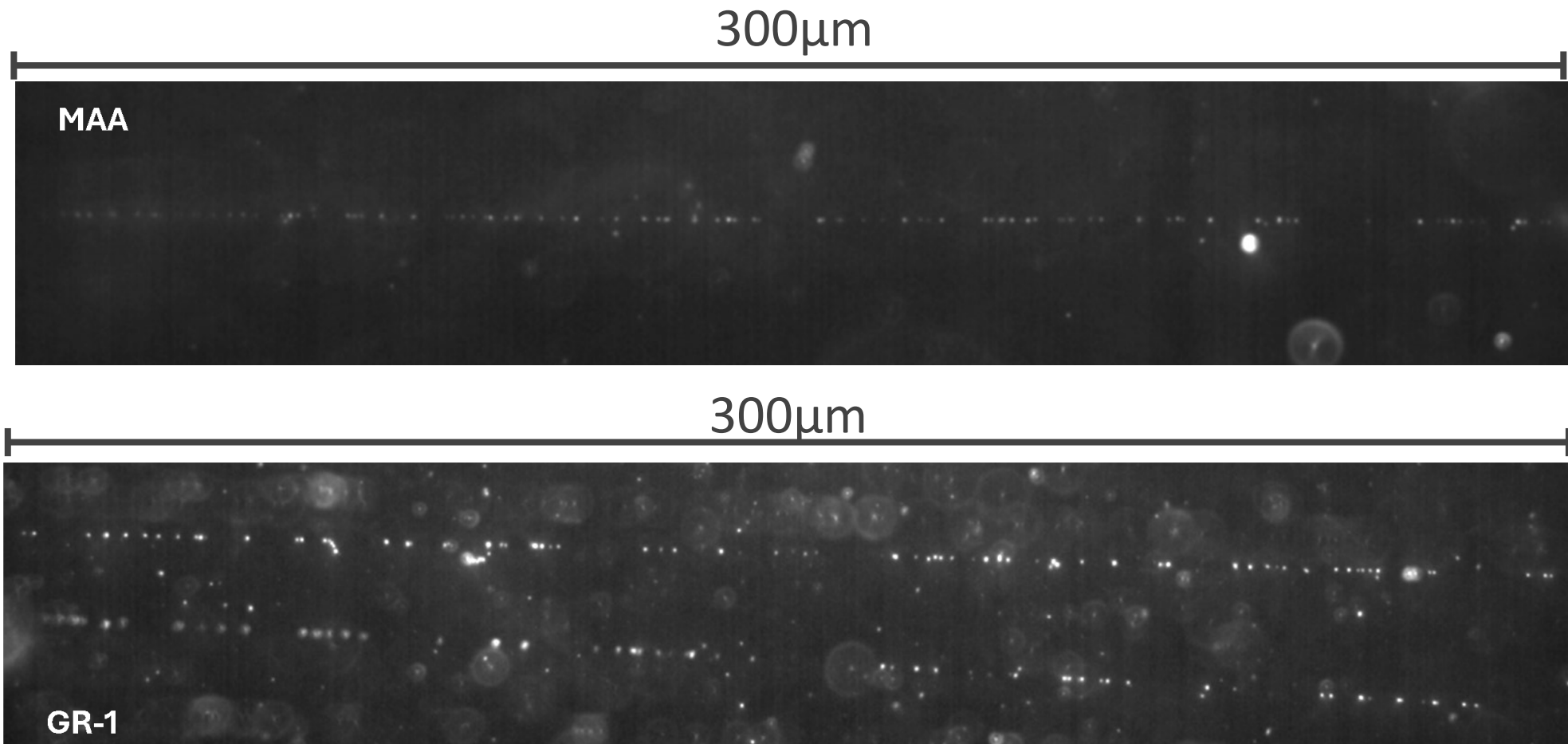
R&D with Toho and Nagoya Universities

- Jan-March 2025: 3 exposure slots at **Nagoya Proton Therapy Center**
- R&D to improve 200 MeV proton reconstruction on:
 - gel sensitization
 - development recipe and temperature
 - support material (Polystyrene, PMMA)
- Physics measurement: expose a NIT brick to protons to reconstruct interactions



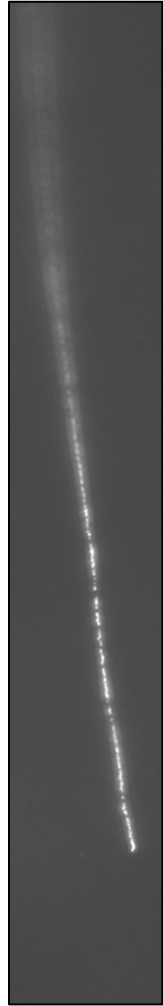
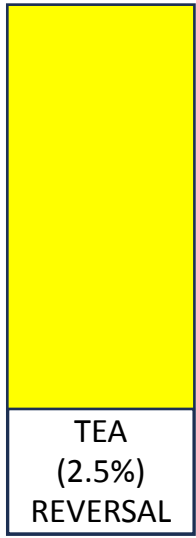
NIT chemical development

70 MeV proton tracks recorded with 70nm NIT developed with old “MAA” (left) and new “GR-1” (right) recipe:

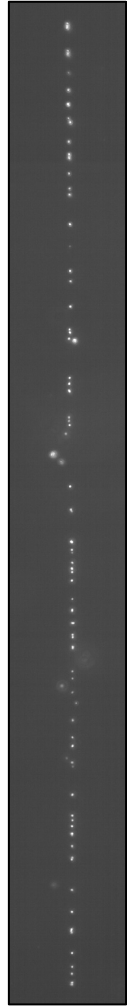


Grain Density Calibration

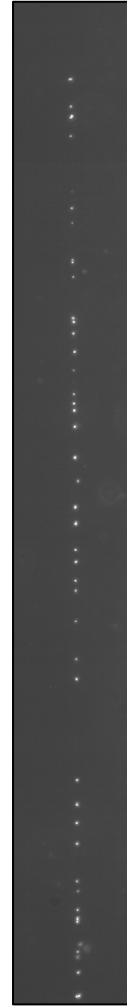
Proton
Beam



End of range



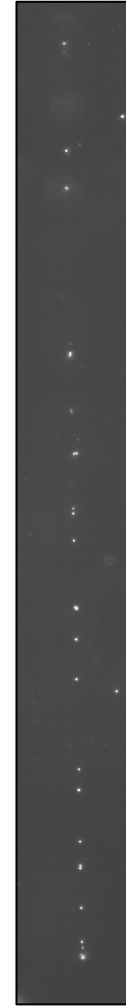
$\sim 26 \text{ MeV}$



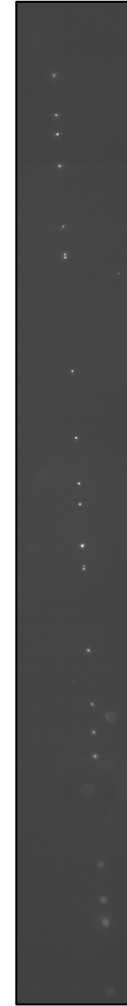
$\sim 68 \text{ MeV}$



$\sim 96 \text{ MeV}$



$\sim 126 \text{ MeV}$

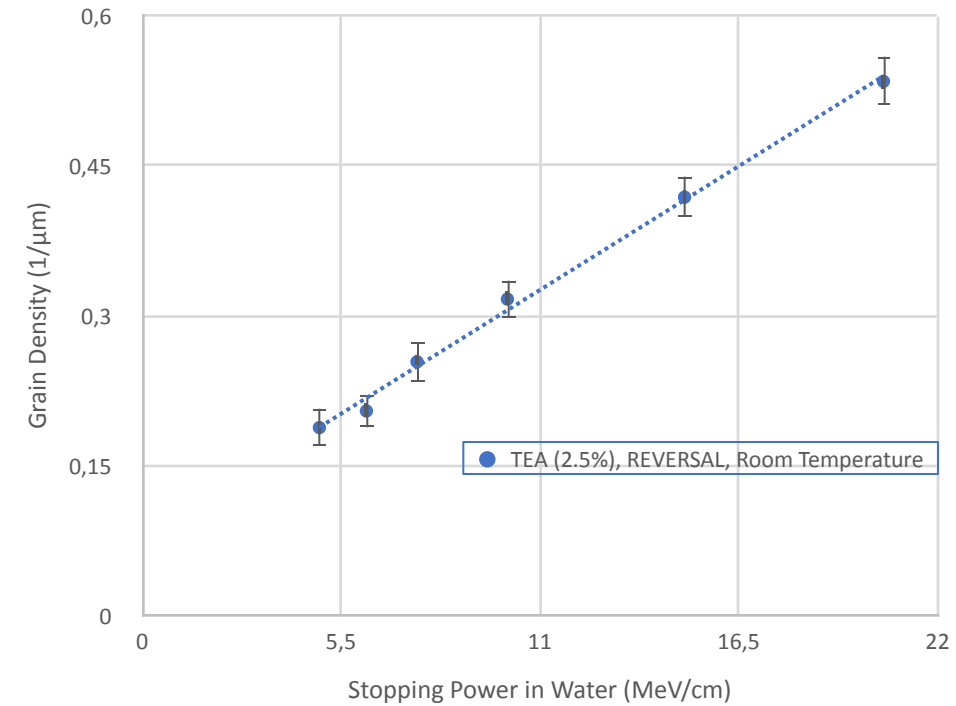


$\sim 179 \text{ MeV}$

Proton Energy



Proton Grain Density vs Stopping Power



Conclusions

- **FOOT** is designed for the measurement of fragmentation differential cross sections of interest in Particle Therapy and radio protection in space with an accuracy better than 10%
 - Data takings performed at GSI, HIT and CNAO with nuclear emulsion setup and electronic detectors setup
 - First cross section measurements provided with nuclear emulsion setup for ^{16}O @200 MeV/n on C and C_2H_4 targets ($\text{O}\rightarrow\text{C}$, $\text{O}\rightarrow\text{H}$)
 - First measurement of $^8\text{Be}_{\text{g.s.}}$ production in ^{16}O fragmentation at intermediate energies: evidence of alpha-clustering effects and a systematic overestimation by current transport models
- **DAMON**: Nano Imaging Trackers (NIT) allows us to set an experiment with 100 nm threshold for tracks reconstruction. The direct measurement of target fragmentation due to proton beam seems feasible



Other relevant publications

- M. Dondi et al. (FOOT Collaboration). “Nuclear fragmentation cross section measurements for a 400 MeV/nucleon ^{16}O beam on polyethylene and hydrogen targets with the FOOT experiment”. In: Phys. Rev. C 113 (6 June 2026), p. 064620. doi: [10.1103/17nq-3ddt](https://doi.org/10.1103/17nq-3ddt)
- Y. Dong, I. Mattei et al. (FOOT Collaboration). “Cross section measurements of large angle fragments production in the interaction of carbon ion beams with thin targets”. In: Eur. Phys. J. A 62.55 (2026). doi: [10.1140/epja/s10050-025-01693-4](https://doi.org/10.1140/epja/s10050-025-01693-4)
- R. Ridolfi et al. (FOOT Collaboration). “Angular differential and elemental fragmentation cross sections of a 400 MeV/nucleon ^{16}O beam on a graphite target with the FOOT experiment”. In: Phys. Rev. C 112 (1 July 2025), p. 014610. doi: [10.1103/nmw9-ldrm](https://doi.org/10.1103/nmw9-ldrm)
- M. Toppi, A. Sarti et al. (FOOT Collaboration). “Elemental fragmentation cross sections for a ^{16}O beam of 400 MeV/u kinetic energy interacting with a graphite target using the FOOT ΔE -TOF detectors”. In: Frontiers in Physics 10 (2022). issn: 2296-424X. doi: [10.3389/fphy.2022.979229](https://doi.org/10.3389/fphy.2022.979229)
- G. Battistoni et al. (FOOT Collaboration). “Measuring the Impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT Experiment”. In: Frontiers in Physics 8 (2021), p. 555. issn: 2296-424X. doi: [10.3389/fphy.2020.568242](https://doi.org/10.3389/fphy.2020.568242)

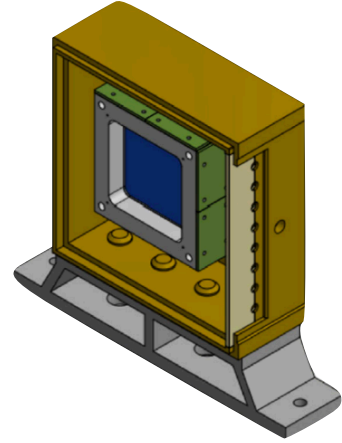
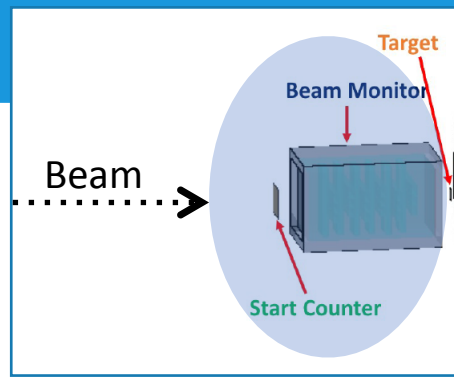


THANK **Y**OU!



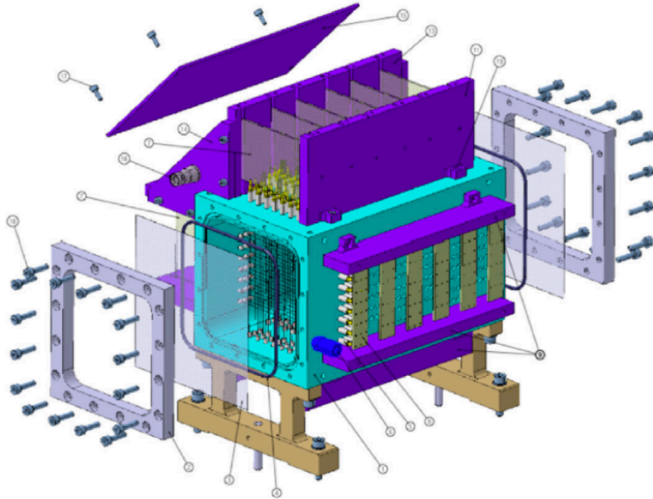
Back up slides

Upstream Region



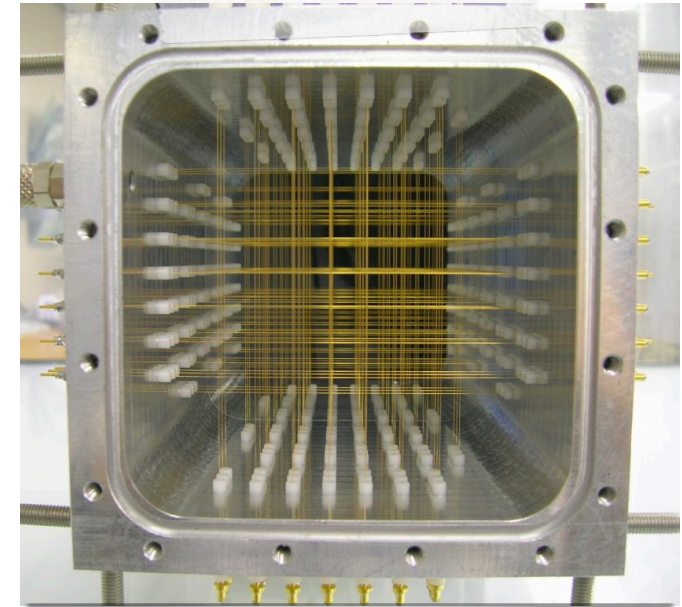
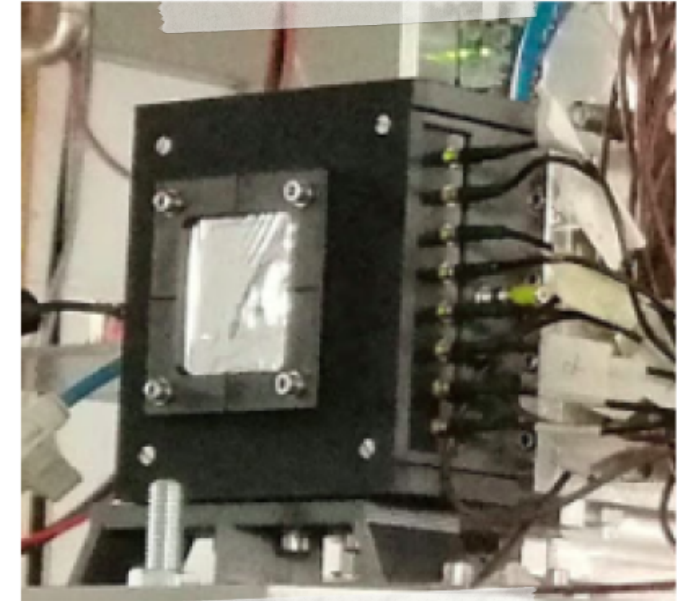
- **Start Counter:** Plastic Scintillator
Trigger signal + incoming ion flux

- 5x5 cm² squared foils of EJ-228
- 250 μ m thickness
- Light collected by 48 SiPM
- Trigger and TOF start

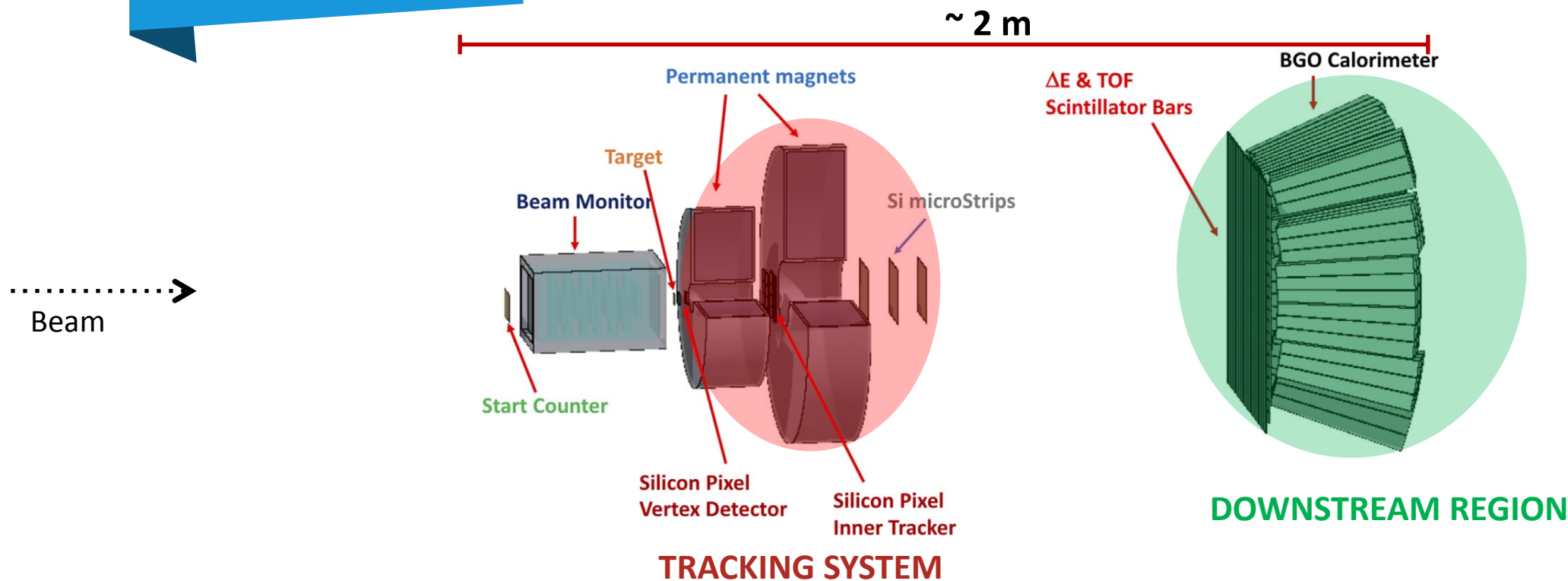


- **Beam Monitor:** drift chamber
Beam position measurement

- 12 wire layers, 3 drift cells per layer
- rectangular cell 16mm×10mm
- 80/20% gas mixture of Ar/CO₂
- spatial resolution of 100 μ m



The electronic setup



- Large variety of detectors
- Designed for heavier fragments ($3 \leq Z \leq 8$)
- Angular acceptance of 10°
- Possible online analysis
- First data taking with the complete setup in Oct-Nov 2023

- $\sigma(p)/p$ at level of 4-5%
- $\sigma(\text{TOF})$ at level of 100 ps
- $\sigma(E_{\text{kin}})/E_{\text{kin}}$ at level of 1-2%
- $\sigma(\Delta E)/\Delta E$ at level of 5%

Improvements in oxygen reconstruction

Challenges in oxygen reconstruction with nuclear emulsions:

- Non-linear response to particles' ionization (saturation effects)
- Scanning and reconstruction system optimized for Minimum Ionizing Particles (MIPs) but not for highly ionizing particles
- Efforts to design a new method with higher efficiency for oxygen reconstruction

