Status of the FOOT Experiment

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Consiglio di Sezione INFN Milano

5th July 2023

Outline

Present status of FOOT

- Physics case and collaboration
- Status of apparatus
- Results (and publications)

Future Programs

- Next data takings
- Financial requests for 2024

FOOT Purposes

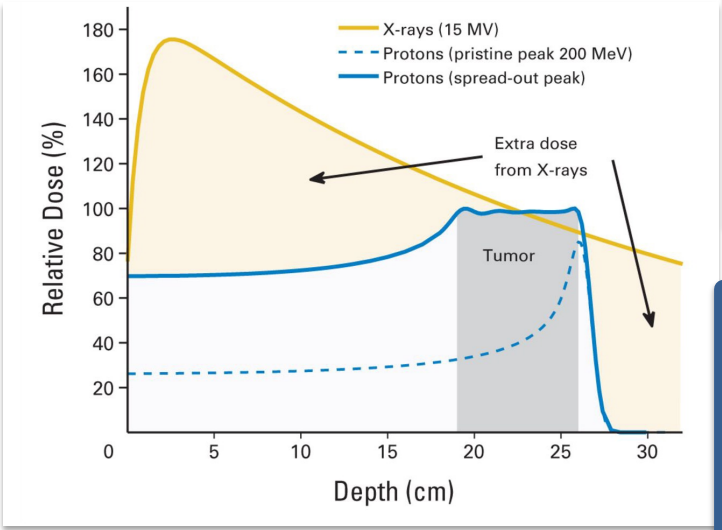
Measurement of fragmentation cross sections for **Hadrontherapy** and **space radioprotection**

p +
C +
He +
} C, O, H, (Si, Al)

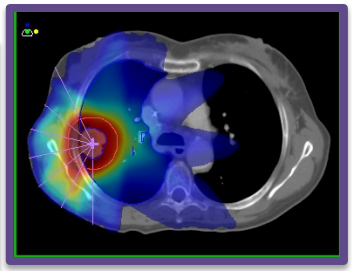
$\frac{d\sigma}{d\Omega}, \frac{d\sigma}{dE_{kin}}$

Goal accuracy <5%

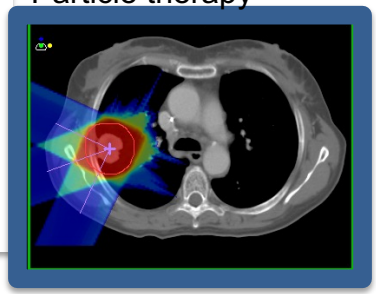
$80\ \mathrm{MeV/}u < E_{kin} < 400\ \mathrm{MeV/u}$



Traditional radiotherapy

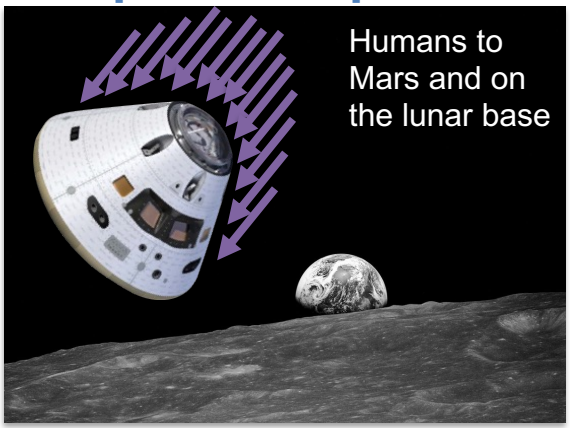


Particle therapy



$E_{kin} > 0.5\ \mathrm{GeV/u}$

Spacecraft shielding
Radio-protection in Space



The FOOT Priority Physics Program

Specific measurements related with Particle Therapy & Radioprotection in Space

target C, C_2H_4, PMMA ($C_5O_2H_8$) ➔ cross sections on C, O and H

Phys	Beam	Target	Energy (MeV/u)	Inv/direct kinematics
Target Frag. PT	^{12}C	C, C_2H_4	200	inv
Target Frag. PT	^{16}O	C, C_2H_4	200	inv
Beam Frag. PT	^{12}C	C, C_2H_4, PMMA	350	dir
Beam Frag. PT	^{16}O	C, C_2H_4, PMMA	400	dir
Beam Frag. PT	^{4}He	C, C_2H_4, PMMA	250	dir
Rad. Prot.space	^{4}He	C, C_2H_4, PMMA	700	dir
Rad. Prot.space	^{12}C	C, C_2H_4, PMMA	700	dir
Rad. Prot.space	^{16}O	C, C_2H_4, PMMA	700	dir

The FOOT Collaboration (2023)

93 Authors

33 Institutions

Italy, France, Germany, Japan, Cuba

3 Continents (Europe, Asia, America)

G. Galati [1] V. Boccia [2,3] A. Alexandrov [3] B. Alpat [4] G. Ambrosi [4] S. Argirò [5,6]
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F. Cavanna [6] P. Cerello [6] E. Ciarrocchi [8,9] S. Colombi [10,11] A. De Gregorio [12,13]
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Y. Dong [7] M. Durante [2,3] R. Faccini [12,13] V. Ferrero [6] C. Finck [16] E. Fiorina [6]
M. Francesconi [8,9] M. Franchini [11,10] G. Franciosini [12,13] L. Galli [9] E. Iarocci [17]
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C. Massimi [10] I. Mattei [7] A. Mengarelli [10] A. Mereghetti [15] T. Minniti [23,24]
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C. Sanelli [17] A. Sarti [21,12] O. Sato [31] S. Savazzi [15] L. Scavarda [32] A. Schiavi [21,12]
C. Schuy [30] E. Scifoni [18] A. Sciubba [17,21] L. Servoli [4] G. Silvestre [4,28] M. Sitta [29,6]
A. Sood [16] R. Spighi [10] E. Spiriti [17] V. Tioukov [3] S. Tomassini [17]
F. Tommasino [18,19] M. Toppi [21,12] G. Traini [12] A. Trigilio [12,13] G. Ubaldi [11,10]
A. Valetti [5,6] M. Vanstalle [16] M. Villa [11,10] U. Weber [30] R. Zarrella [11,10]
A. Zoccoli [11,10]

INFN:

10 units (Bo, LNF, Mi, Na, Pg, Pi, Rm1, Rm2, TIFPA, To)

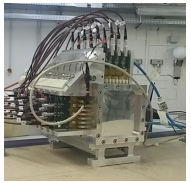
65 researchers & 9 technologists

28.55 FTE (26.5 researchers, 2.05 technologists)

2024:

Add Bari and maybe University of Miami

The FOOT experiment: the electronic spectrometer

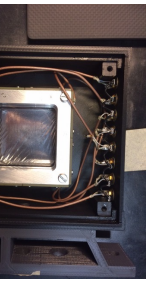


Permanent magnets

Target

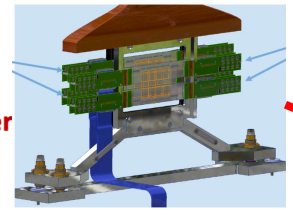
Beam Monitor

Start Counter

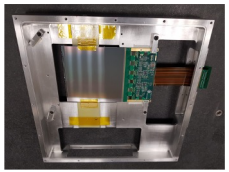


Silicon Pixel
Vertex Detector

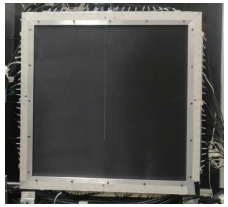
Silicon Pixel
Inner Tracker



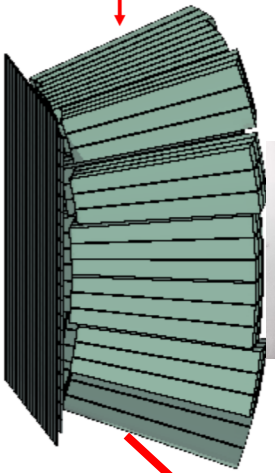
Si microStrips

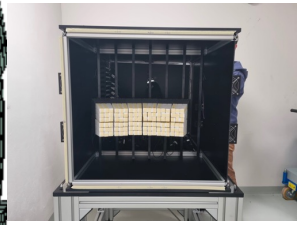


ΔE & TOF
Scintillation Bars



BGO Calorimeter





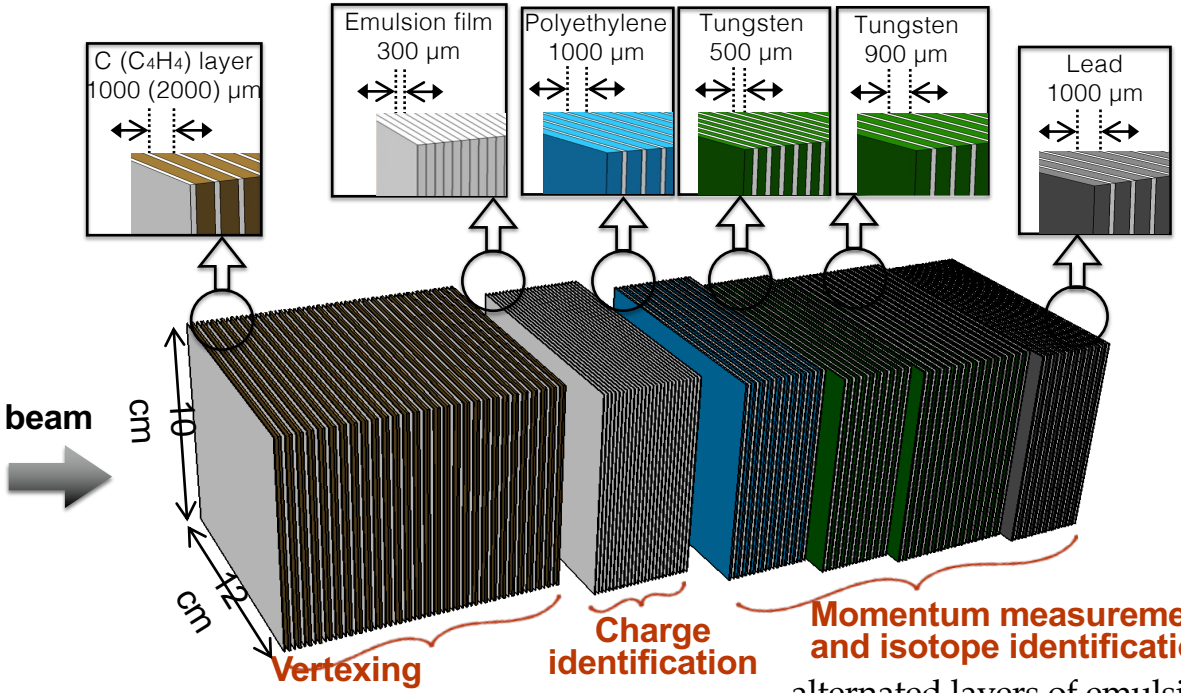
Z ≧ 2
10° angular acceptance

To be completed

The FOOT experiment: the emulsion spectrometer

$Z \leqq 3$

Wide angular acceptance



Vertexing

alternated layers of emulsions and target (C or C_2H_4)

Charge identification

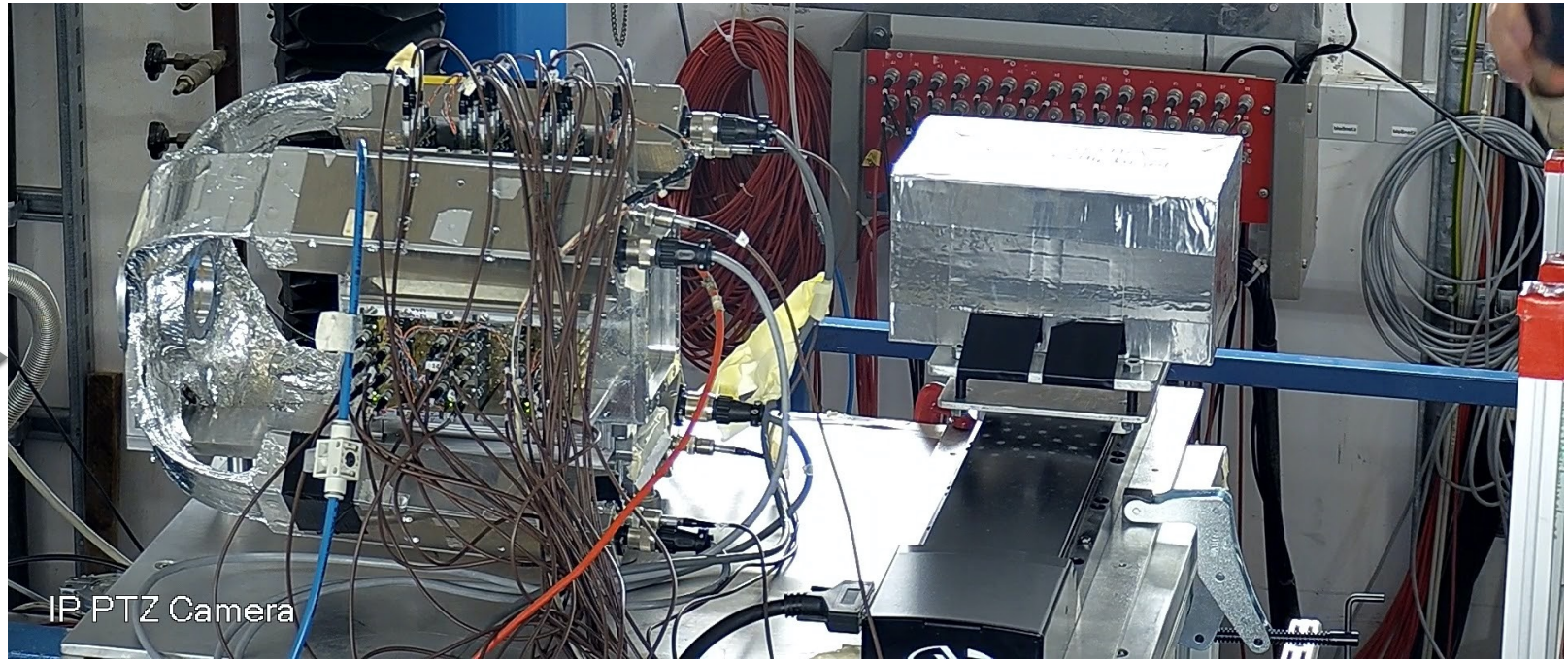
only emulsion layers

Momentum measurement and isotope identification

alternated layers of emulsions and passive material (plastic, tungsten and lead)

The FOOT experiment: the emulsion spectrometer

beam



FOOT Highlights 2022-2023

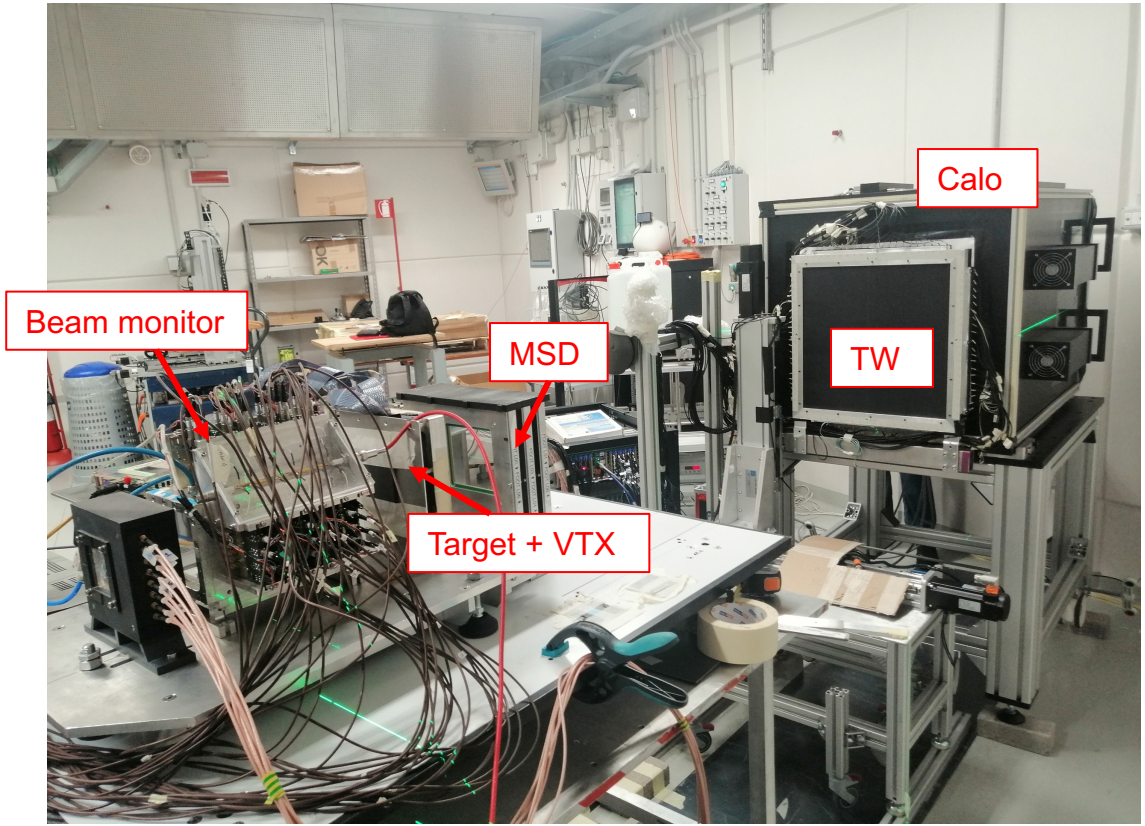
Pandemic hit FOOT delaying key components and reducing data taking time. We are recovering from this situation.

Data takings at GSI in 2021, Heidelberg and CNAO in 2022.

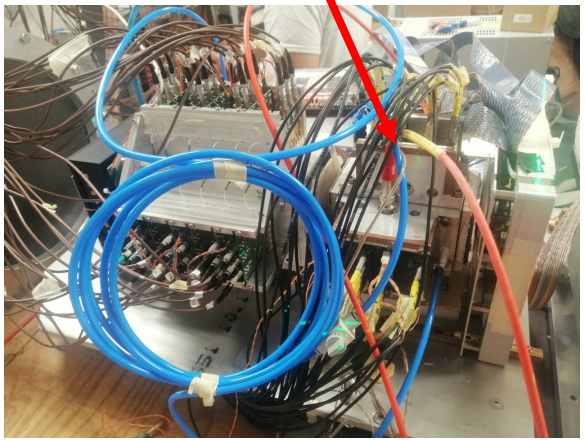
Working for CNAO in autumn 2023 (with ^{12}C beam)

- ✓ Acceleration on **calorimeter** module production. Completion for this summer → already working on spares
- ✓ Biggest critical element: **permament magnet**. Changed the magnetic elements. Delays due to many reasons. Assembly started last week. Delivery expected for mid september
- ✓ Tests on **Drift Chamber** to stand high rates; tested a second smaller Drift chamber (Milano)
- ✓ **DAQ system** has been tested on all detectors
- ✓ Several significant progresses on **reconstruction software**; several analyses in parallel
- ✓ GSI Emulsion data analyses near the end. NIT emulsions tested in Trento

FOOT @CNAO Dec. 2022

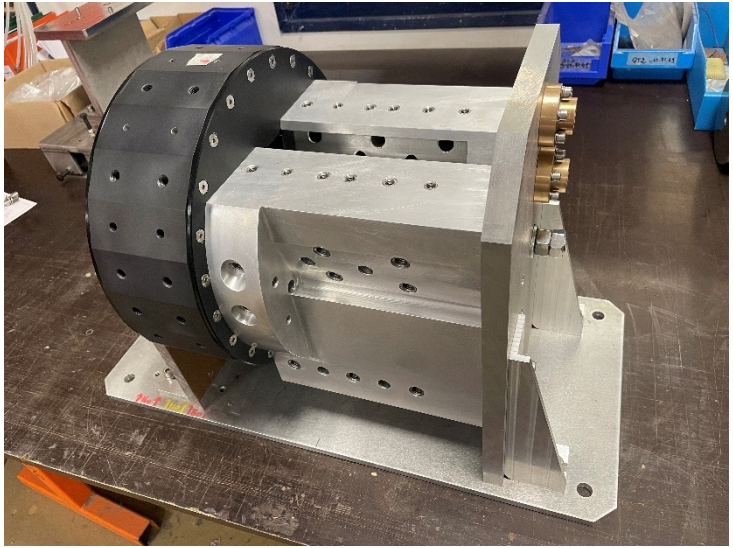


Test of spare small drift chamber for beam monitoring



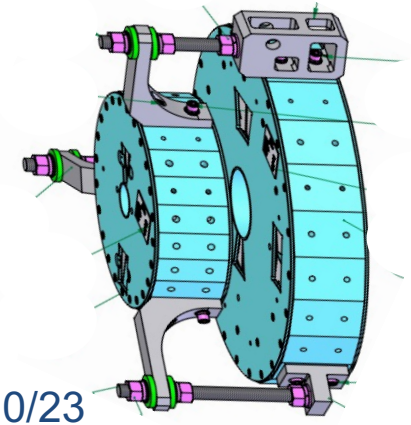
Status of Magnet

- New design
- Full analysis done
- Yokes, tools and elements ready



Schedule:

- Manifacturing M1: up to 27/06/23
- Manifacturing M2: up to 19/07/23
- Assembly M1+M2: up to 26/07/23
- Measurements @ SigmaPhi: up to 02/08/23
- Assembly and packing: from 03/08 to 30/08/23 (vacation time)
- **Shipment: 31/08/23**
- **Arrival at LNF: 13/09/23**



Measurements at LNF:

- one week from 13/09 to 15/10/23

Calorimeter

Modules:

- 22 modules (198 crystals) assembled, 17 of them already calibrated in temperature
- 40 crystals ready at CERN
- gluing at CERN (last 82 crystals) to be completed at the beginning of July

Temperature calibration:

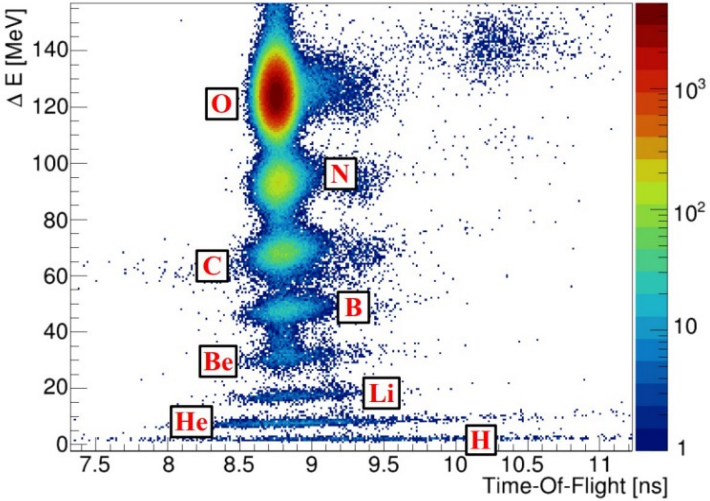
to be completed by the end of July (beginning of September)

Some results on GSI 2021 data

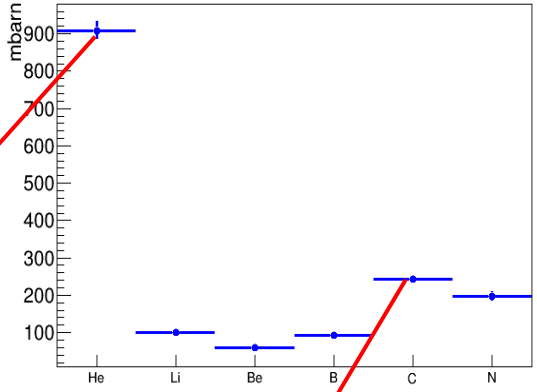
Measurements at GSI, Beam: ^{16}O, 400 MeV/n, Target: C

Results from first engineering runs

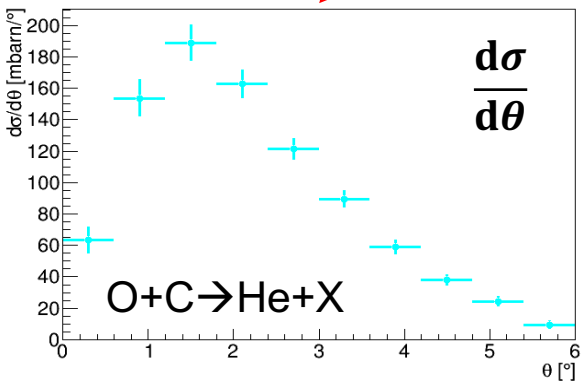
Particle Z identification

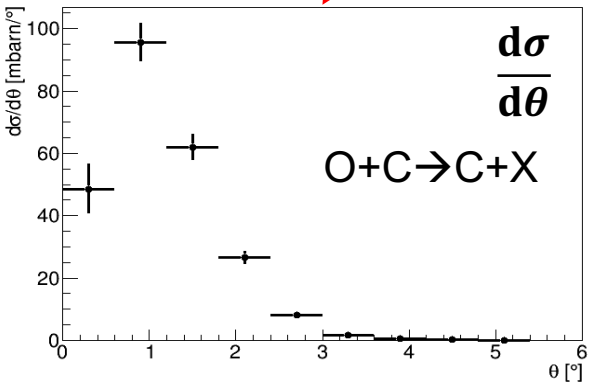


Production cross section for specific elements

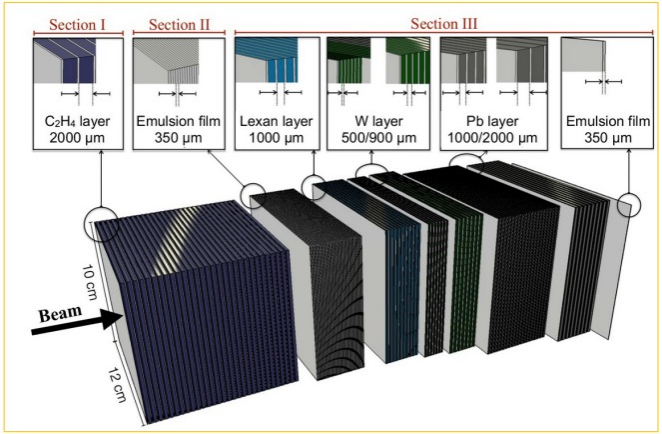


First angular cross section measurements

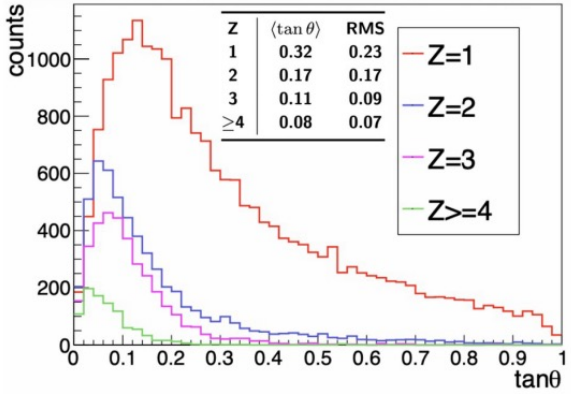




Emulsion results, GSI 2019/21 data

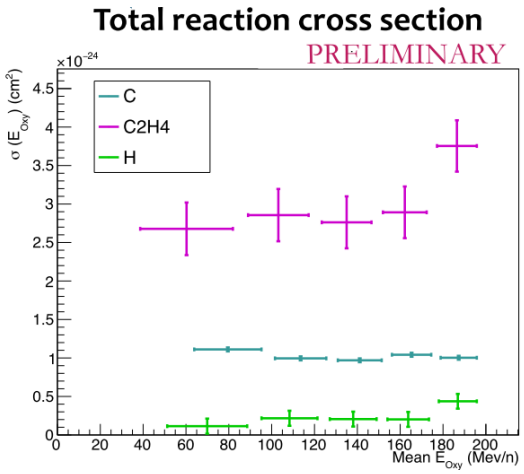


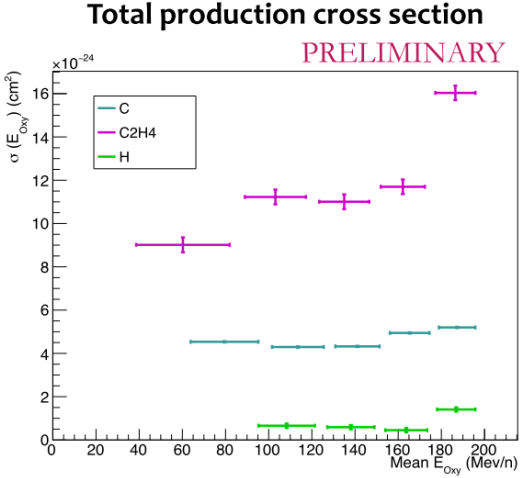
Beam: ^{16}O, 200 MeV/N
Target: C, C_2H_4



Two target technique to extract cross sections on H

$$\sigma|_H = \frac{1}{4}(\sigma|_{C_2H_4} - 2\sigma|_C)$$





Papers published in 2022

1. M. Toppi, et al, *Elemental fragmentation cross sections for a 16O beam of 400 MeV/u kinetic energy interacting with a graphite target using the FOOT ΔE-TOF detectors*, Front. Phys., 2 November 2022, Sec. Medical Physics and Imaging, Research Topic: Breakthrough in Particle Therapy: At the Edge of Physics, Biology and Medicine, See https://doi.org/10.3389/fphy.2022.979229
2. G. Silvestre et al, *Characterization of 150 micrometer thick silicon microstrip prototype for the FOOT experiment*, accepted in JINST 2022 https://jinst.sissa.it/jinst/author/docPage.jsp?docPgType=work&docId=JINST_070P_0922

Proceedings published:

1. K. Kanxheri6,1 et al, *The Microstrip Silicon Detector (MSD) data acquisition system architecture for the FOOT experiment* 2022, Journal of Instrumentation, Volume 17, March 2022 DOI 10.1088/1748-0221/17/03/C03035 (Topical Workshop on Electronics for Particle Physics 2021, 20–24 September, 2021)
2. L. Galli, et al, *The fragmentation trigger of the FOOT experiment*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 1046, 2023, 167757. 15th Pisa Meeting on Advanced Detectors, Elba, 2022, https://doi.org/10.1016/j.nima.2022.167757
3. A.C. Kraan et al, *Calibration and performance assessment of the TOF-Wall detector of the FOOT experiment*, NIMA:,Volume 1045, 2023, 167615, 15th Pisa Meeting on Advanced Detectors, Elba, 2022, https://www.sciencedirect.com/science/article/abs/pii/S016890022200907X
4. A. De Gregorio, *Measurements of the ^{16}O cross section on a C target with the FOOT apparatus, Nuovo Cim.C* 45 (2022) 6, 194, Contribution to: SIF 2021, 194

Papers published in 2023

Proceedings:

1. R. Zarrella, *Nuclear fragmentation cross section measurements with the FOOT experiment*, EPJ Web of Conferences 284, 10001 (2023)
2. Gianluigi Silvestre , *Characterization of the Microstrip Silicon Detector for the FragmentatiOn Of Target experiment*, Nuclear Instruments and Methods in Physics Research Section A: Volume 1047, February 2023, 167717 https://www.sciencedirect.com/science/article/pii/S0168900222010099
3. Riccardo Ridolfi, *Nuclear fragmentation cross section measurements with the FOOT experiment*, proceeding from EuNPC conference in 2022, publication to come.
4. Giacomo Ubaldi, *The FOOT experiment: a first measurement for nuclear fragmentation cross section for hadrontherapy*, proceeding from SIF 2022, publication to come.

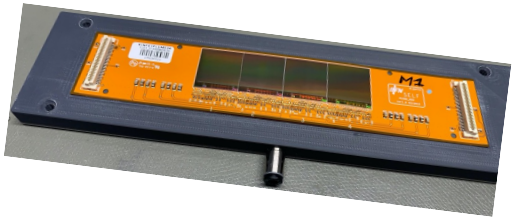
In writing stage

FOOT for the Moon, Mars and beyond: current status and first cross section measurements for space radioprotection

Charge identification of fragments produced by interaction of 16-O beam at 200 and 400 MeV/u on C and C_2H_4 target , emulsion group, to be submitted to frontiers

A new photon calibration method for silicon microstrip sensors

Data takings and tests in 2023



- July 2023

Tests and DAQ Integration of IT & VTX

- October / November 2023 – 52 h, ^{12}C @ 200 – 400 MeV/n

Goal: electronic apparatus fully completed! (Doubts on magnet)

Emulsions

Beam test goals:

- Calibration of new modules of calorimeter
- Integration, tests and calibration of VTX & IT
- Measurement of the production cross sections for light & «heavy» fragments

Year 2024 and beyond

CNAO (2024)

Base laboratory for FOOT set-up.
We plan to start measuring the processes declared in the CDR

In the future we expect to use the new ion species available from the new sources @CNAO (^{16}O, ^{4}He, ^{56}Fe, … ^{6}Li,)

Need of GSI or other similar labs for kinetic energies in the range 0.5 - 2.0 GeV/N.

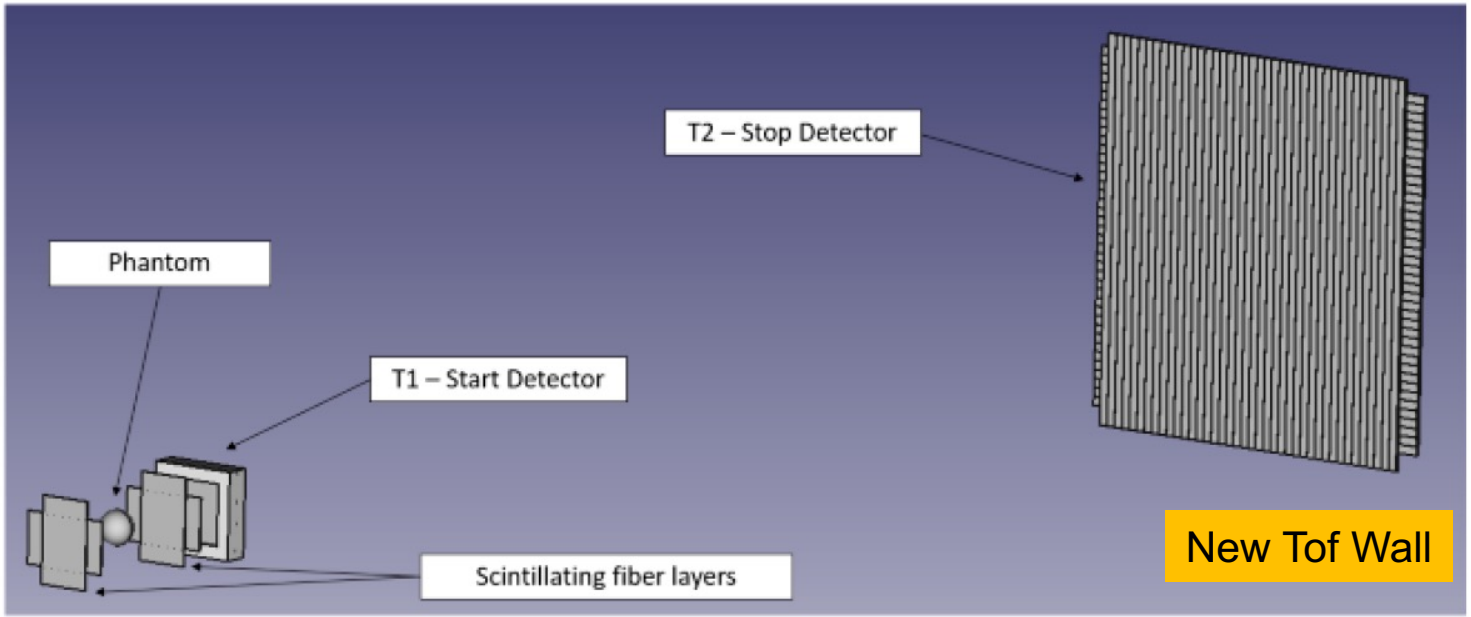
We'll continue to ask travel money and beam to ESA, NASA, or to access to transnational laboratory access programs.

9 prins won by FOOT people
3 are a direct extension of FOOT physics program

PRIN 2022: TOFpRad

PI (M. Morrocchi, UNIPI),
Roma 1 (G. Traini),
MI (S. Muraro)

The goal is to produce a more segmented TofWall (bar width: 1 cm wrt 2 cm), same overall dimensions, to be able to perform proton radiography.
A new TofWall can be easily integrated in the FOOT detector

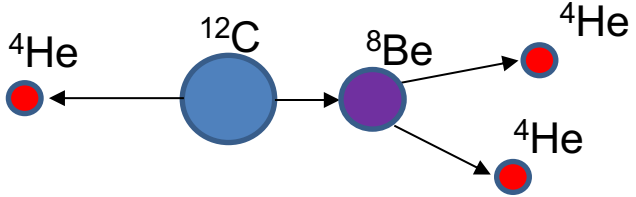


Milano activity

- Management, maintenance and operation of Beam Monitor (Drift Chamber)
- Co-coordination of data taking at CNAO in Nov. Dec. 2022
- Responsability of MC simulation for the whole experiment
- Software development (Y. Dong now the deputy software coordinator since Jan. 2023)
- Data analysis. New proposal by Milano group:

analysis of FOOT data in terms of **α-clustering.**

Study of exclusive channels $^{12}C \rightarrow 3\ \alpha$; $^{16}O \rightarrow 4\ \alpha$.



There are a lot of data at Coulomb barrier and

Fermi energies, but not enough around 200 MeV/u

- Organization of Collaboration Meeting in June 2023 (thanks to local CSN3 for financial support)

FOOT Milano: Anagrafica 2024 e richieste

A) Missioni (meeting e prese dati): 26 k€
B) Consumo (Gas, cavi e connettori, metaboliso di laboratorio): 3.0 k€
C) Trasporto gas: 1.5 k€
D) Pubblicazioni: 2.5 k€

Richiesta servizi Milano: eventuale assistenza su richiesta del Servizio Elettronica

		%
S. Muraro	Ric. III Livello	80
I. Mattei	Ric. III Livello	70
Y. Dong	AR INFN	80
G. Harki	AR INFN	40
S. Brambilla	Primo Tecnologo	10

2,8 FTE

Conclusions

We are on the edge of completing the electronic detector.

Detector comprehension is constantly increasing.

Some physics results published, other almost ready to be published.

We're facing another «engineering run» in oct/nov 2023.

For 2024 we foresee mainly physics runs.

For the future:

We are looking forward to perform fragmentation cross section measurements with different beams, targets and energies, both for electronic and emulsion set-up. We'll focus on this in the next year at CNAO, but we are also open to new options (e.g. NIT emulsions, ESA/NASA measurements).

We are also considering other nuclear physics measurements.