The FOOT Project in the 2025-2027 years

Foot goals

The FOOT experiment was designed to address the topic of nuclear fragmentation in two completely different fields: ion therapy and space radioprotection [1]. It is well known that in the ion kinetic energy range 0.1-1.0 GeV/N several interesting differential fragmentation cross sections are missing and both treatment planning systems and designs of the shielding of deep space missions have to rely on (not accurate) fragmentation models. The FOOT experiment, having two complementary set-up and a flexible design, has already performed several data taking campaigns (in table 1 below) and has started to provide measurements in this field.

Table 1: Data taking campaigns already performed

Beam	Target	Energy MeV/u	Statistics (millions, electronic set-up only)	Integral Differential elemental	Integral Differential isotopic	direct	Inverse	Emul-sions	Cam-paign
O	C C2H4	200 400	0.06	angle	NO	YES	NO	Yes Yes	GSI 2019 GSI 2020
O	C C2H4 C C2H4	200 200 400 400	14.2 12.2 5.5 6.5	angle	NO	YES	NO	Yes	GSI 2021
He	C	100 140 200 220	18.5 19.6 13.5 14.4	angle	NO	YES	NO	No	HEID 2022
C	C	200	4.1	angle	NO	YES	NO		CNAO 2022
C	C C2H4	200 200	3.2 2.0	Angle Energy	YES	YES	YES	Yes	CNAO 2023

Most of the campaign have been performed with a limited electronic set-up. Only the CNAO 2023 had a full set-up as designed and described in the TDR. The data taken up to now have been largely used to understand the detectors [2-4] and only partially processed for the cross section measurements [5-8]. In addition to what initially foreseen, we're experimenting with a new generation of high quality emulsions [9], called Nano Imaging Tracking emulsions (NIT), where the spatial accuracy of track reconstruction allows the detection and identification of fragments from the target fragmentation. These fragment ranges are usually shorter than 100 um and fully contained in a single NIT layer. With the other two set-up the same cross sections are obtained using the inverse kinematic technique.

The FOOT collaboration has weekly analysis meetings, monthly physics meetings and two in-presence general meetings each year. The data analysis is proceeding and monitored continuously. Up to now, we had several technical publications on different detectors [2-4] or software tools and few physics results on the very first data takings [5-8]. Half of the emulsion data taken at the GSI have been already published and the other half is going to be published soon: the analysis is almost finished. Few physics results have been published up to now with the electronic set-up. The understanding of the partial detector first and the accurate controls of the systematics have delayed considerably the analysis. The GSI 2021 O-C data have been fully analyzed and the results are in the publication phase. These are the first fragmentation differential cross sections for several $Z<8$ fragments available as a function of the fragment scattering angle. The tuning of the software tools and the understanding of the background for this sample is now an asset that is used to process the GSI 2021 O-C_2H_4 sample and to extract the fragmentation cross sections on polyethylene first and by difference the difficult O-H fragmentation differential cross sections later.

The Heidelberg 2022 sample is of interest for the use of the helium beam, but the set-up was partial, lacking the vertex, the magnet and having only few calorimeter modules. The data have been used to understand the detectors (mainly the microstrip detector and the calorimeter modules). From the physics the data have not yet been exploited fully. The same happened to the CNAO 2022 campaign: very interesting for the understanding of the detectors, but lacking magnet, inner tracker and part of the calorimeter, the physics analysis has not yet started. We put more effort into the analysis of the CNAO 2023 campaign, which is the first one with the nominal electronic set-up, completed with magnet, inner tracker and calorimeter. Particle identification, particle tracking in the magnetic field and calorimeter calibration are currently the main field of study on this sample. The fragmentation cross section measurements will follow.

Plan for the next three years

For the next three years we plan to fulfill and extend the measurement goals that were at the FOOT origin: study the target fragmentation, with few C+C and O+C campaign with the electronic set-up using the inverse kinematic approach and the isotopic identification of the produced fragments (Table 2). This is the missing part with respect to the campaigns studied up to now (except CNAO 2023).

The plan starts in 2025 at CNAO where we plan to study C+C and C+C2H4 interactions at “low energies”, from 200 MeV/n down. It is well known that during ion therapies, fragmentations happen during all the slowing down of the ions inside the body, from the beam energy down to the region of the Bragg peak (energies below 50 MeV/n). Therefore, the cross sections should be evaluated at different ion energies. This comes easily with the emulsion set-up, where the slowing down of the beam inside the emulsion brick mimics what happens during therapies, but for the electromagnetic set-up, where thin target foils are used, data taking at different energies are needed. One of the interesting reasons to look for low carbon energies is that from the theoretical models the typical Hadrontherapy range is very difficult to study, being well above the region of few nucleons and few energy levels and is not yet in a regime that can be processed with thermodynamics/statistical techniques. Very few studies from first principles are available, all with a beam energy below 100 MeV/n [10].

During 2026 we plan to have two data takings: one at GSI, in the framework of a MAECI joint project with an Oxygen beam and another one at CNAO. The energy of the oxygen beam will be higher than the 2021 samples. We’ll use a 500 MeV/n beam on which we can both have information relevant for Hadrontherapy and space radioprotection. If time and the machine will allow it, a sample at higher energy (700 MeV/n) will be collected. The CNAO data taking will be devoted to C+C at different energies, but there will be the possibility to have a NIT emulsion exposure using protons.

In 2027 we plan to have a data taking at CNAO. The main goal of this data taking should be to finish the C+C energy scan. We plan to add here a third target: PMMA for the extraction of the C+O fragmentation cross sections.

An interesting possibility that has been raised only recently is to have access at the new sources at CNAO. In fact, the CNAO has now the ability to run with ^{4}He and ^{16}O ions. In future, it might have the possibility to run also with a lithium beam (approval pending). If the ^{4}He beam will be available, we plan to repeat and extend the measurements done in Heidelberg with the full magnet spectrometer and with the full calorimeter.

These are the goals we will pursue. Being both the Hadrontherapy and the Space radioprotection an active and dynamic field of research, we are open to additional fund opportunities via PRIN projects, ESA/ASI/NASA agencies or other, that might change our time-schedule or plans also in the near future.

Table 2: Foreseen data taking campaigns

Beam	Target	Energy MeV/u	Integral Differential elemental	Integral Differential isotopic	Direct	inverse	Emul-sions	Cam-paign
C	**C** **C2H4**	**100-200**	**Angle** **Energy**	**YES**	**YES**	**YES**	**YES** **(NIT?)**	**CNAO 2025**
O	**C**	**500-700 (?)**	**Angle** **Energy**	**YES**	**YES**	**YES**	**YES**	**GSI 2026**
C	**C** **C2H4**	**200-300**	**Angle** **Energy**	**YES**	**YES**	**YES**	-	**CNAO 2026**
P	**C**	**100-220**	**Angle** **Energy**	**YES**	**YES**	**-**	**NIT**	**CNAO 2026**
C	**C** **C2H4** **PMMA**	**320-400**	**Angle** **Energy**	**YES**	**YES**	**YES**	**YES**	**CNAO 2027**
He	**C** **C2H4** **PMMA**	**200-400(?)**	**Angle** **Energy**	**YES**	**YES**	**YES**	**YES**	**CNAO 2027**

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