ACCELERATORS ACTIVITIES AT ENEA FOR AEROSPACE

G. Bazzano†[1], A. Ampollini[1], M. D. Astorino[1], A. Doria[1], F. Fortini[1], P. Nenzi[1], E. Pavoni[1]
G. Picardi[1], C. Poggi[2], C. Ronsivalle[2], V. Surrenti[2], E. Nichelatti[2], E. Trinca[2]
[1]ENEA Frascati Research Centre, Rome, Italy
[2]ENEA Casaccia Research Centre, Rome, Italy

Abstract

The ENEA Frascati Particle Accelerators Laboratory operates a set of S-band electron and proton linear accelerators providing beams relevant for radiation-effects studies in the aerospace sector. The TOP-IMPLART proton LINAC delivers low-energy (1–6 MeV) and high-energy (up to 71 MeV) beams, while the REX and TECHEA facilities supply 3.5–5 MeV and 1–3 MeV electron beams, respectively; both can also operate as X-ray sources via removable bremsstrahlung converters. The contribution reviews ENEA activities in aerospace applications, including irradiation of electronic components, material and shielding studies, and radiobiology and astrobiology experiments. ENEA is involved in several national and European projects— such as Cryptomars, Space It Up!, Space-EBC, and Thread — addressing key topics for space exploration. In parallel, ENEA provides irradiation services within infrastructures such as DIANA and ASIF supporting component testing and material qualification. This work highlights ENEA's role in supporting the aerospace community through advanced accelerator capabilities, coordinated research initiatives, and a broad portfolio of irradiation services aimed at enhancing the robustness and space-readiness of technologies for future missions.

INTRODUCTION

The increasing demand for reliable technologies for space missions requires ground-based infrastructures capable of providing controlled, reproducible and well-characterized irradiation conditions. This need is closely related to radiation hardness assurance activities, which address the main radiation effects relevant to space systems, including total ionizing dose, displacement damage and single-event effects [1]. Accelerator-based facilities are particularly relevant in this framework, since they allow the investigation of radiation effects on materials, electronic components and biological systems under selected particle, energy, flux and dose-rate conditions [2,3].

Since ground-based tests cannot reproduce the full complexity of the orbital radiation environment in a single exposure, complementary irradiation facilities are often required to cover different particle species, energies and dose-rate regimes. In this context, multi-source and mixed-field irradiation infrastructures represent an important approach for testing components and systems under controlled yet representative radiation conditions.

This paper presents an overview of ENEA activities for aerospace applications, with emphasis on the accelerator facilities operated at the Frascati Research Centre, their integration with complementary irradiation infrastructures, and selected research programs exploiting these capabilities.

†giulia.bazzano@enea.it

ENEA FRASCATI PARTICLE ACCELERATORS LABORATORY

The ENEA Frascati Particle Accelerators Laboratory (ACP) has developed and operated compact RF linacs since the 1980s, along two main technological lines: electron radiation sources for research and industrial processes, and accelerator prototypes for medical applications. Accelerators currently in operation are one proton linac, TOP-IMPLART, and two S-band electron linacs, REX and TECHEA. Although different in layout, energy range and original purpose, the three machines share a common emphasis on compact RF technology, pulsed operation, and flexible beam delivery.

TOP-IMPLART is a pulsed proton linear accelerator developed as a full-linear prototype for proton therapy, with the original objective of reducing the complexity and cost of proton-therapy systems. The machine is based on a commercial 7 MeV injector, including a duoplasmatron source followed by a 425 MHz RFQ and DTL section, and on an ENEA-designed booster composed of eight S-band Side Coupled Drift Tube Linac modules operating at 2997.92 MHz [4]. The booster modules are grouped in two RF sections each one powered by a 10 MW peak-power klystron. The accelerator provides two lines: a low-energy vertical line in the 1–6 MeV range and a high-energy horizontal line up to 71 MeV [5, 6]. A summary of the beam parameters for the vertical (V) and horizontal (H) lines is reported in Table 1.

Table 1: Beam Parameters of TOP-IMPLART Extraction Lines

Parameter	Line	Value
Pulse length	V	20 - 100 µs
Peak current	V	100 µA
Energy on target	V	1 – 6 MeV
Beam spot size on target (diameter)	V	10 mm
Pulse length	H	2.4 µs
Peak current	H	15 µA
Max energy on target	H	70 MeV
Pencil beam size on target (FWHM)	H	25 mm
Rep. rate	H&V	25 Hz

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REX is a 5 MeV S-band electron linac commissioned at the end of the 1980s as an electron and bremsstrahlung radiation source for technological irradiation processes [7,8]. The accelerator is an RF pulsed standing-wave linac, based on an on-axis coupled accelerating structure and driven by a 2 MW peak-power magnetron. The electron beam is extracted in air through a 50 µm titanium window into a lead-shielded irradiation chamber. A removable high-Z conversion head can be installed at the linac exit to operate the facility in X-ray mode. The electron beam characteristics are summarized in Table 2.

Table 2: Main Beam Parameters of the REX Accelerator

Parameter	Value
Pulse length	3,5 µs
Peak current	160 mA
Rep. rate	20 Hz
Max electron energy	4.8 MeV

TECHEA is a compact S-band electron linac developed within the TECHEA project as the radiation source of a self-shielded device for breast irradiation in prone position [9]. The linac operates at 2998 MHz, has four accelerating cavities with an overall accelerating-structure length of about 20.8 cm, and delivers electrons up to 3 MeV in 3.4 µs pulses powered by a 2 MW peak-power magnetron driven by a solid-state modulator. In the original configuration, the electrons impinge on a tungsten/copper converter to generate a bremsstrahlung photon beam with characteristics analogue to a ^{60}Co treatment unit; electron-mode operation is also available for irradiation studies. The TECHEA system main beam parameters are given Table 3.

Table 3: Main Beam Parameters of TECHEA Accelerator

Parameter	Value
Pulse length	3,5 µs
Peak current	120 mA
Rep. rate	100 Hz
Max electron energy	3 MeV

AEROSPACE APPLICATIONS AND PROGRAMS

Distributed Irradiation Capabilities

The increasing interest in space radiation effects has progressively extended the use of ENEA irradiation facilities from their original nuclear, medical and technological domains toward aerospace-oriented research and qualification activities. In this framework, the ENEA Frascati Particle Accelerators Laboratory provides proton and electron beams through TOP-IMPLART, REX and TECHEA, while the ENEA Nuclear Department operates complementary photon and neutron irradiation facilities originally developed to support component, material and diagnostic studies for nuclear fission and fusion research.

These facilities include the CALLIOPE ^{60}Co gamma irradiation plant [10], the TRIGA RC-1 research reactor [11], the RSV TAPIRO fast reactor [12] and the Frascati Neutron Generator (FNG) [13]. Together with ACP accelerators, they provide a distributed irradiation capability covering photons, neutrons, electrons and protons. This multi-source approach enables experiments on materials, components, detectors and biological systems exposed to controlled radiation fields representative of complex space-related environments [14].

A key national framework for the exploitation of these capabilities in the space sector is ASIF, the ASI Supported Irradiation Facilities program. ASIF aims to establish a coordinated network of irradiation facilities distributed across Italy and serving the national and international space communities [15]. Through the ASIF gateway, users can access irradiation services, beam availability information, TID and TNID dose estimates, dosimetric measurements and experimental support for different radiation fields, including electrons, protons, ions, neutrons and photons. The program also promotes common access rules, operating procedures, test processes and qualification methodologies, taking into account the European ESCC/ECSS reference framework. Within this framework, ENEA facilities contribute to making radiation testing more accessible, traceable and comparable for space-related research and qualification.

Beyond ASIF, ENEA irradiation capabilities are also being integrated in broader international access schemes for technology testing and validation. Within NATO DIANA, the Defence Innovation Accelerator for the North Atlantic, ENEA acts as a test centre, offering irradiation and characterization capabilities for technologies requiring validation under harsh radiation conditions [16]. ENEA is also involved in RADNEXT and in RADNEXT-2030, its forthcoming continuation. While ENEA participation in RADNEXT was based on the Frascati Neutron Generator, RADNEXT-2030 will involve FNG, CALLIOPE, TOP-IMPLART and REX [17]. This extension will provide complementary neutron, photon, proton and electron fields within a European framework for harmonized access, testing methodologies, training and data sharing.

Accelerator-Based Applications in Space Programs

As discussed in the previous section, one of the most common and direct applications of particle accelerators to space research is radiation-hardness assurance of electronic components. At the same time, the renewed emphasis on crewed exploration beyond low-Earth orbit, within current lunar and Moon-to-Mars programs, makes proton radiobiology increasingly relevant to space research, since protons are a major component of several space-radiation fields. The versatility of the TOP-IMPLART horizontal beam-delivery line allows these different application scenarios to be addressed on the same accelerator infrastructure. Figure 1 shows two representative examples of custom set-ups: the irradiation of electronic components for radiation-hardness assurance, and the irradiation of cell

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cultures for proton-radiobiology experiments. In both cases, sample holders, positioning systems, collimation and monitoring arrangements are adapted to the experimental requirements, while the final configuration is supported by dedicated Monte Carlo calculations aimed at optimizing beam transport, field uniformity and dose delivery at the sample position.

Figure 1: Examples of custom irradiation set-ups installed on the TOP-IMPLART horizontal beam-delivery line: (Top) electronic components for radiation-hardness-assurance testing; (Bottom) cell cultures for proton-radiobiology experiments.

Several national and European programs show how ENEA accelerators can support space research beyond the conventional qualification of electronic components. In these activities, controlled proton and electron beams are used as experimental tools for astrobiology, advanced materials, manufacturing processes, radiation shielding, detectors and technology validation for exploration missions. In this perspective, accelerator-based irradiation is not only a means to reproduce radiation damage, but also a flexible tool to tailor dose, dose rate, beam geometry and irradiation protocols to the requirements of different space-related experiments.

CRYPTOMARS, funded by the Italian Space Agency, addresses astrobiology and planetary exploration by investigating Antarctic cryptoendolithic microbial communities as Martian-analog life forms [18,19]. The project adopts a multi-omic approach to study their response to multiple stresses relevant to early and present-day Martian environmental conditions, including ionizing radiation, UV exposure, thermal cycling and hydration-dehydration cycles. In the ionizing-radiation part of the program, TOP-IMPLART and CALLIOPE provided controlled low-dose proton irradiation and gamma exposure, respectively. The proton campaign built on the experience previously developed within the TOP-IMPLART project in radiobiology and dosimetry experiments [20,21], but required a dedicated beam-delivery configuration, including not only dose-driven operation, but accelerator operation at very low current and sample positioning in the beam halo (Fig. 2). These solutions were necessary to obtain reproducible, very-low-dose exposure conditions compatible with the biological objectives of the experiment and with the need to irradiate a relatively large number of heterogeneous rock samples. This campaign demonstrates the adaptability of a proton linac to non-conventional space-biology applications, where beam control and dosimetric reliability are critical for interpreting biological response.

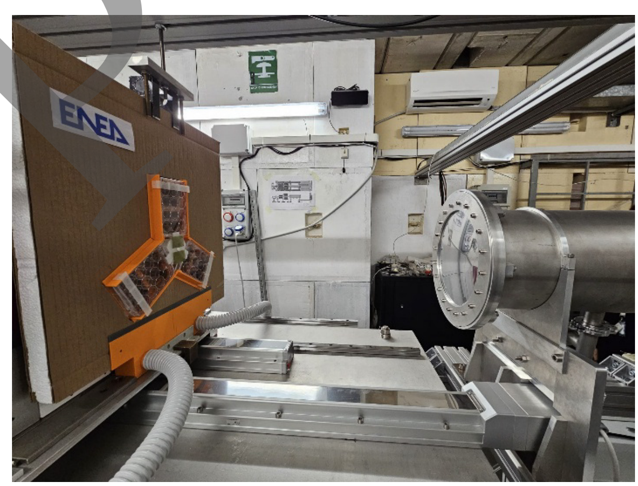

Figure 2: Set-up of the CRYPTOMARS irradiation campaign at TOP-IMPLART.

The SPACE-EBC project, led by the Italian company Vega Composites, is an example of industry-research collaboration promoted by ASI and consistent with the ENEA mission of supporting the industrialization of advanced technologies. The project is devoted to the development of electron-beam curing as an innovative manufacturing process for carbon-fiber reinforced polymer components intended for space applications [22]. It aims to replace conventional thermal curing with room-temperature polymerization of electron-curable resin systems, potentially

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reducing cost, processing time, energy consumption and thermo-mechanical stresses induced by high-temperature curing. The REX electron linac capabilities are used to define irradiation parameters such as beam energy, current, delivered dose and process geometry, supporting the industrial partner in their research towards material formulation, sample manufacturing and process qualification. In this case, the accelerator is not used primarily as a radiation-effects test facility, but as an enabling element of a manufacturing route for space-grade composite structures. A dedicated sample positioning and motion systems had to be realized to allow irradiation of the relatively large samples within the small irradiation chamber (Fig. 3).

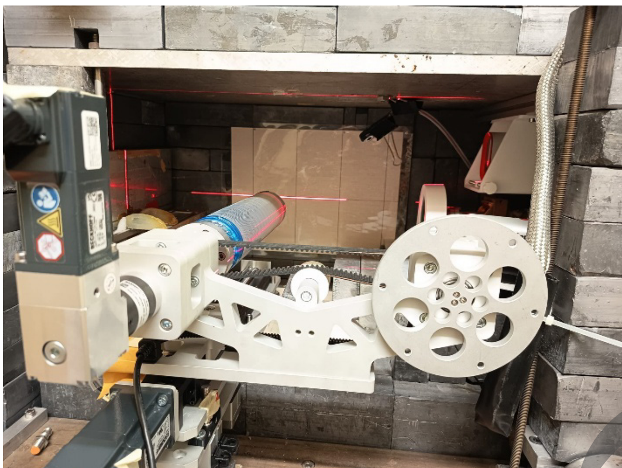

Figure 3: Set-up of the Space-EBC irradiation campaign at REX.

Space It Up! is a national program aimed at strengthening Italian space technologies for exploration and exploitation, while promoting knowledge transfer and collaboration among universities, research institutions, industries and SMEs [23]. The program is organized into nine thematic areas, or Spokes, addressing key upstream and downstream challenges identified by the international space community.

ENEA is involved in Spoke 8, focused on “Robotic and Human Exploration of Extraterrestrial Habitats, Architectures and Infrastructures”, which aims to increase the Technology Readiness Level of enabling solutions for future human and robotic exploration. The experimental activities carried out at ACP Laboratory within Space It Up! focus on radiation-shielding studies of optical coatings and in situ resource utilization (ISRU) materials, such as lunar regolith, the investigation of novel detection concepts for radiation monitoring, and the assessment of advanced composite materials for lightweight shielding applications.

A specific activity concerns the development and testing of optical-readout solid-state ionizing-radiation detectors and dosimeters based on lithium fluoride (LiF) [24]. These devices exploit radiation-induced color-center formation in LiF crystals or films, which can be read optically to provide spatially resolved information on the absorbed dose. Their compactness, passive operation and robustness make them suitable candidates for radiation monitoring in harsh extra-terrestrial environments.

A further activity is devoted to advanced composite materials for radiation shielding, with emphasis on graphene-based polymer composites. The work includes the fabrication of composite samples, their microstructural characterization, and the evaluation of their shielding properties under controlled irradiation conditions. The objective is to optimize material formulation and architecture in order to improve radiation attenuation while preserving the low-mass and functional requirements typical of space applications.

At the European level, ENEA is involved in THREAD, a Horizon Europe EIC Pathfinder project led by Politecnico di Milano and focused on Thermite-for-Demise (T4D), i.e. the use of thermite reactions to assist satellite demise during atmospheric re-entry. The project builds on previous European activities on design-for-demise and investigates whether thermite-based concepts can provide technical and industrial benefits for reducing the survivability of satellites and critical components during uncontrolled re-entry, thereby contributing to space-debris mitigation and ground-risk reduction [25, 26]. Particular attention is given to the survivability of thermite charges over the satellite life cycle, including exposure to vacuum, thermal cycling and radiation, as well as to safety, regulatory and dual-use aspects. In this context, TOP-IMPLART and CALLIOPE will support the assessment of candidate thermite-based materials, shaped charges and representative components exposed to controlled proton and gamma fields relevant to space environmental qualification.

CONCLUSION

The ENEA Frascati Particle Accelerators Laboratory provides proton and electron beams based on linear RF pulsed accelerators available for research and industrial users in the field of aerospace radiation-effects studies. They are operated within a versatile platform managed by the ENEA Nuclear Department which includes also gamma and neutron sources originally developed for nuclear fission and fusion research.

The accelerator-based facilities are used for electronic-component qualification and technology qualification in the framework of national and international access frameworks such as ASIF, DIANA and RADNEXT-2030.

In addition, programs such as CRYPTOMARS, SPACE-EBC, Space It Up! and THREAD demonstrate the use of accelerator-based irradiation also in non-conventional research fields, including astrobiology, advanced materials, manufacturing processes, shielding studies and technologies for sustainable space operations.

By combining accelerator expertise with complementary irradiation sources, beam characterization, dosimetry and coordinated facility-access schemes, ENEA supports the development of robust technologies and experimental methodologies for future space missions operating in complex radiation environments.

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