

# EUPRAXIA: ACTIVITY REPORT 2025

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## 1 Introduction

EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) represents Europe's most ambitious initiative in advanced accelerator technologies. Included in the ESFRI Roadmap in 2021, EuPRAXIA aims to establish a distributed research infrastructure, see Fig. 1, centered on plasma-based acceleration and its applications to photon science, high-energy physics and interdisciplinary research.

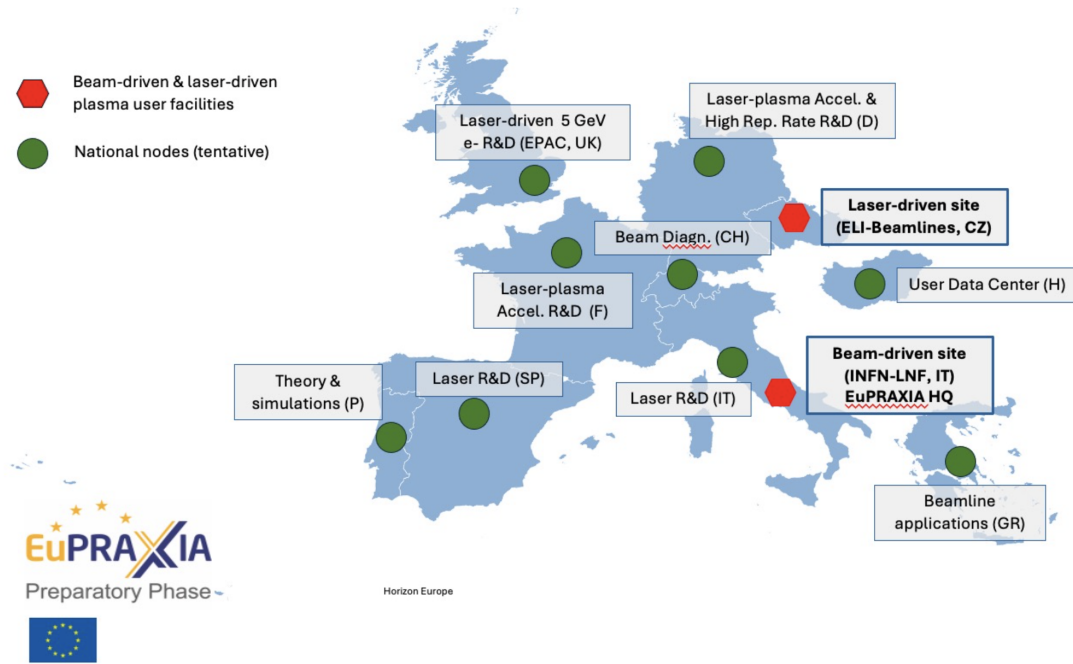


Figure 1: Geographical distribution of the EuPRAXIA Research Infrastructure, showing the two User Sites (Italy and Czech Republic) and the network of contributing Nodes.

EuPRAXIA@SPARC-LAB constitutes the Italian Pillar of this infrastructure under construction at LNF, see Figure 2, and is the first EuPRAXIA user site to reach full technical definition. Its mission is clear: to demonstrate that plasma wakefield acceleration (PWFA) can transition from experimental demonstration to reliable user-facility operation while delivering beam parameters compatible with Free-Electron Laser (FEL) requirements. The year 2025 was devoted to

transforming this vision into a consolidated Technical Design Report (TDR), integrating scientific objectives, accelerator physics, plasma technology, FEL performance, civil engineering, safety, cost and schedule into a unified and implementation-ready document that has eventually been published in February 2026. The full Technical Design Report (TDR) of EuPRAXIA@SPARC.LAB is publicly available at: <https://www.openaccessrepository.it/records/k57qz-5qk09>



Figure 2: Architectural rendering of the EuPRAXIA@SPARC.LAB building at the INFN - LNF campus, which will host the 1 GeV accelerator and the AQUA FEL beamline.

EuPRAXIA@SPARC.LAB is designed as a compact accelerator-based light source capable of delivering a 1 GeV electron beam to an undulator line producing soft X-ray radiation in the water window (3–5 nm).

The water-window spectral range enables high-contrast imaging of biological samples in aqueous environments, while also supporting ultrafast spectroscopy in chemistry, catalysis, battery research and high-energy-density physics. The facility therefore addresses a scientifically mature and societally relevant domain.

A defining element of the concept is the availability of two operational modes:

- Full-RF Mode: in this configuration, the X-band linac accelerates the beam directly to 1 GeV. This mode provides a commissioning baseline, risk mitigation and operational flexibility.

- Hybrid RF+PWFA Mode: in hybrid configuration, a 550 MeV beam from the linac is energy-doubled in a 60 cm plasma module. This represents the technological core of the project and the key innovation of EuPRAXIA@SPARC.LAB.

## 2 EuPRAXIA@SPARC.LAB Machine Performances and Layout

The machine architecture integrates high-gradient accelerator modules, precision magnetic optics, state-of-the-art diagnostics, and photon transport systems into a coherent infrastructure optimized for both performance and flexibility. Each segment of the machine has been designed to preserve emittance, minimize energy spread, and support high-repetition-rate (100 Hz) FEL operation in both Full RF and PWFA modes. The layout of the EuPRAXIA@SPARC.LAB machine is schematically illustrated in Fig. 3.

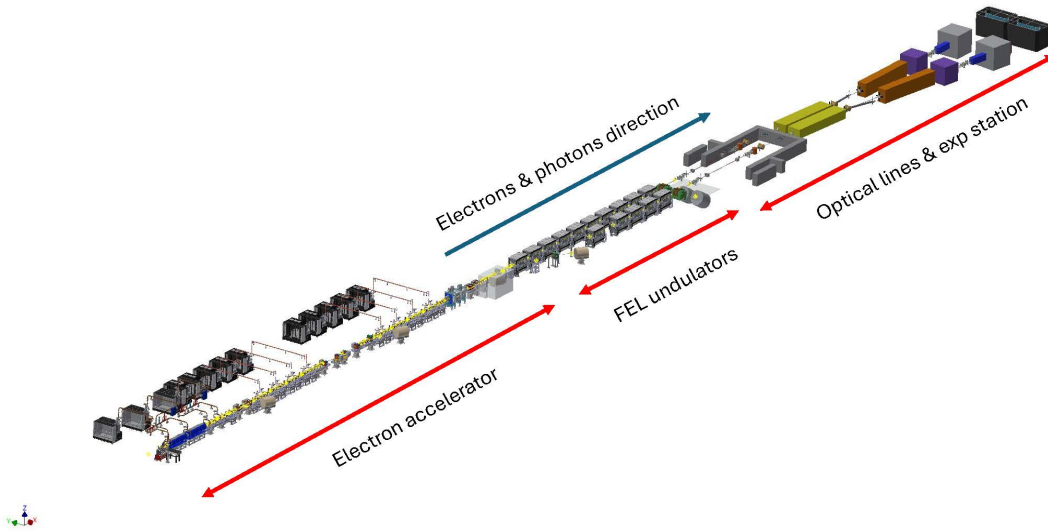


Figure 3: Layout of the accelerator and beamlines

The main sections and components of the facility are briefly outlined below:

- RF Photo-Injector** : The injector comprises a 1.6-cell S-band (2.99855 GHz) RF gun equipped with a copper photocathode and a solenoid, capable of producing low-emittance electron bunches with initial energies of 5.5 MeV. Both the driver and witness bunches are generated within the same RF bucket and accelerated by four S-band accelerating structures up to the injection in the X-band Linac. By operating the first two structures off-crest, the bunches can be velocity-compressed reaching energies of approximately 120 MeV that is actually the current operating mode of the SPARC.LAB photo-injector. If all four structures are run on-crest, as possibly required in the case of using magnetic compressions only, the beams can be accelerated up to a maximum energy of about 250 MeV.

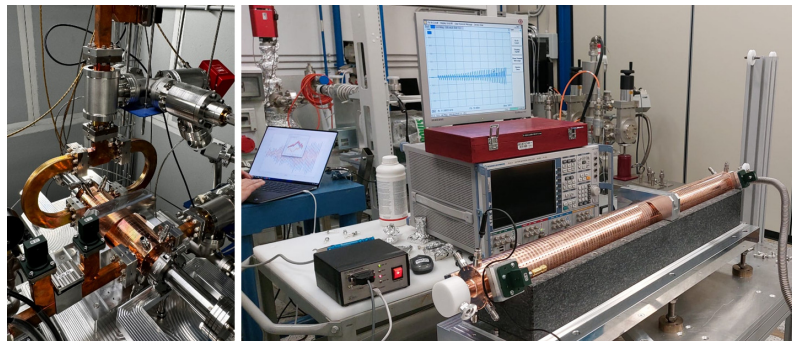


Figure 4: X-band accelerating structure prototypes: 20 cell structure under high power testing at the LNF TEX test facility (left); full scale rf structure under low power rf characterization (right).

- X-band Linac** : The linac comprises 16 high-gradient 90 cm long accelerating structures operating at X-band (11.9942 GHz). At their maximum power, these structures operate at an accelerating field of 60 MV/m, enabling acceleration of the beam up to 1 GeV, sufficient to directly drive the FEL without the use of the plasma stage. When the plasma module is employed, the linac can be operated at a reduced gradient of 30 MV/m, delivering a total beam energy of  $\sim 550$  MeV, including  $\sim 120$  MeV from the injector, which is subsequently boosted by the plasma stage to meet the nominal 1 GeV FEL energy requirement. A 20-cell X-band short RF prototype (shown in Figure 4) has been tested, successfully reaching the nominal parameters. The beamline is equipped with essential components including quadrupoles, beam diagnostics, trajectory correctors and a magnetic bunch compressor.
- Plasma Module** : Positioned downstream of the X-band linac, the plasma stage consists of a 60 cm long plasma channel, including 10 + 10 cm of in/out density ramp, generated within a gas filled (Nitrogen) discharge capillary (operating at 10-50 mbar gas pressure and a voltage of 5-25 kV). In this section, the plasma wakefield boosts the witness bunch from  $\sim 550$  MeV to energies reaching the nominal 1 GeV with an accelerating field of  $\sim 1$  GV/m (and possibly beyond) in the 40 cm active length. Critical components includes a dedicated vacuum chamber, plasma diagnostics, electron spectrometers, and appropriate radiation shielding. Driver and witness are separated in a dispersive section of a dedicated magnetic chicane with a septum magnet at the exit of the plasma vacuum chamber.

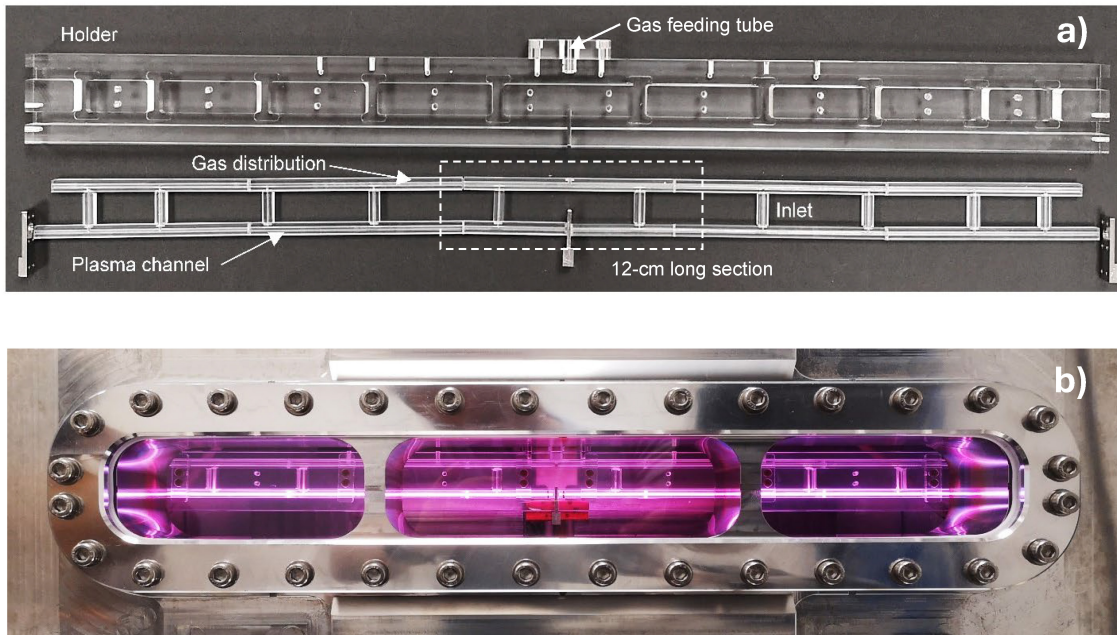


Figure 5: 60 cm-long gas-filled discharge capillary. a) Single components before the capillary assembly. b) Plasma discharge generated after the assembly.

- Transport and Matching Sections** : Upstream and downstream the Plasma Module beam matching is achieved using Permanent Magnet Quadrupoles, providing focusing gradients up to 510 T/m. Downstream Transport section ensures proper beta function and phase-space matching into the undulator while maintaining beam trajectory within tight tolerances ( $\leq 10$

μm).

- **Undulator Line** : The design foresees 10 planar undulator modules on the APPLE X permanent magnet configuration, each module is 2 m long interleaved with a 60 cm long sections hosting diagnostics and quadrupoles. The baseline undulator has an 18 mm period, 1.5 mm minimum gap, and consists of Neodymium-Iron-Boron magnets arranged to allow both linear and circular polarization with tunable wavelengths.
- **Photon Beamlines and End-Stations** : The radiation emitted in the SASE process is extracted and directed via grazing-incidence optics to the experimental stations. Beamlines include focusing mirrors, attenuators, shutters, and diagnostics for intensity, spectrum, and profile measurements. Experimental end-stations are equipped for coherent imaging, time-resolved spectroscopy, and sample manipulation with sub-micron precision.

This modular beamline layout allows for staged commissioning, ease of maintenance, and future upgrades such as seeding schemes, higher energy plasma stages, or additional user beamlines. The baseline performance are reported in Tab. 1.

Table 1: Electron beam and FEL radiation main parameters at the undulator entrance for the two considered machine configurations: plasma acceleration (PWFA) and conventional (Full RF) one. For both the two configurations we reach saturation inside the undulator length at  $\lambda_r = 4$  nm with the expected number of photons per second.

	Units	PWFA	Full RF
		Velocity bunching	Velocity Bunching + Magnetic Compression
Electron Energy	GeV	1	1
Repetition Rate	Hz	100	100
Bunch charge	pC	30	200
Peak current	kA	3.3	3.4
RMS bunch length	μm	1.4	16.9
RMS normalized emittance (x,y)	mm mrad	0.7, 0.7	2.1, 1.0
RMS energy spread	%	0.5	0.2
Slice length	μm	0.5	0.5
Slice normalized emittance (x,y)	mm mrad	0.7, 0.7	0.3, 0.3
Slice energy spread	%	0.04*	0.02
$\rho$ 3D	$\times 10^{-3}$	0.77	1.49
Radiation wavelength	nm	4.06	4.06
Saturation length	m	20.5	20.0
Photon Pulse Energy	μJ	16	150
Photon per pulse	$\times 10^{11}$	3.2	31.3
Photon pulse length (FWHM)	fs	2.33	33.0
Photon bandwidth	%	0.4	0.5
Average photon brilliance	$\# \times 10^{30}$	0.12	2.1

### 3 FEL Scientific Case and Applications

The AQUA beamline of EuPRAXIA@SPARCLAB will open a scientific window onto the ultra-fast world of atoms, molecules, and soft condensed matter. Able to operate in the **3.2–10 nm**

spectral region with the current foreseen hardware, with **nominal performance in the 3.2–5.2 nm water-window range** as supported by start to end simulations, AQUA will deliver intense, femtosecond soft X-ray pulses ideally suited to probe matter on its natural spatial and temporal scales. With pulse durations **shorter than 10 fs** and more than  **$10^{11}$  photons per shot**, the beamline will provide the essential conditions to explore electronic and structural dynamics with high temporal resolution, complementing existing soft X-ray FELs and enabling studies not feasible at synchrotron sources.

AQUA will adopt a **phased approach** that supports both the scientific program and the accelerator development goals:

- **Phase 0:** commissioning on fixed, calibration samples, to allow beam and detectors characterization and alignment.
- **Phase 1:** first user experiments in the gas phase, focused on Atomic, Molecular, and Optical (AMO) physics and simple model systems.
- **Phase 2:** expansion to condensed-phase samples, including liquid jets and aerosol injectors, enabling Warm Dense Matter (WDM) studies and imaging of hydrated biological specimens.

This roadmap ensures that the scientific program evolves coherently with the technological readiness of the facility while maintaining a clear focus on experiments that are tightly linked to the accelerator’s performance evolution.

AQUA’s scientific reach is enabled by an extensive set of experimental techniques. Among these are:

- **Coherent Diffraction Imaging (CDI)** for lensless, native conditions reconstructions of biological and soft-matter samples.
- **Ion and electron spectroscopies**, such as velocity-map imaging and momentum-resolved detection, to study fundamental processes in isolated molecules and clusters.
- **X-ray Absorption and Emission Spectroscopies (XAS/XES)** for element-specific probing of ultrafast electronic and structural dynamics (on a longer time scale in phase 2).

This combination of approaches enables researchers to investigate systems ranging from isolated atoms to complex biological assemblies, all within a unified, flexible beamline architecture.

The main foreseen application areas are:

- **Atomic and Molecular Physics and Gas-phase Systems:** In its first phase of operation, AQUA will primarily support experiments in **AMO physics** with a particular focus on **gas-phase systems**, an area in which soft X-rays and ultrafast temporal resolution provide powerful and versatile tools. Using techniques such as time-resolved soft X-rays absorption, photoemission, ion and electron momentum spectroscopy, and Coulomb explosion imaging, it will be possible to track the evolution of excited molecular states, map ultrafast charge migration, and resolve fragmentation pathways with elemental and site specificity. These studies take full advantage of the coherence and peak brilliance of the AQUA FEL, allowing researchers to observe the evolution of electronic wavepackets or transient molecular structures with femtosecond precision. This class of experiments forms the natural starting point of the scientific program, requiring limited infrastructure while offering high scientific impact.
- **Warm Dense Matter:** As the facility matures, AQUA will extend its reach to the study of **WDM**, a regime of extreme temperature and density relevant to planetary interiors, inertial confinement fusion, and ultrafast solid–plasma transitions. In this domain, soft X-ray

absorption and emission spectroscopies, performed with femtosecond pump–probe sequences (using a dedicated **Ti:sapphire femtosecond laser system** (30 fs,  $\sim 10$  mJ), with an OPA tunable from 200 nm to 20  $\mu\text{m}$ ), offer a uniquely sensitive probe of the transient structural and electronic changes that occur as materials pass through non-equilibrium states. The brightness of AQUA and its tunability within the water-window make it possible to study electron-ion equilibration, short-range order, and the evolution of local atomic environments on sub-picosecond timescales. These experiments, identified as Phase-2 activities will contribute to bridging the gap between theoretical models and experimental measurements in this challenging and technologically relevant regime.

- **Biology and Soft Matter:** Within the water window, carbon-rich biological samples exhibit strong natural contrast against their aqueous environment, making coherent diffraction imaging (CDI) an exceptionally powerful technique. Using the “diffraction-before-destruction” principle demonstrated at several FELs worldwide, AQUA will enable high-resolution imaging of biological specimens such as viruses, macromolecular assemblies, and hydrated cellular structures.

In later phases, the facility may also support time-resolved imaging of radiation damage, membrane dynamics, or conformational changes, although these more advanced biological studies will be developed progressively as beam stability and diagnostic capabilities are refined.

#### 4 EuPRAXIA Preparatory Phase

The EuPRAXIA Preparatory Phase is a Horizon Europe funded project (Grant Agreement No. 101079773) aimed at establishing the strategic, technical, and organisational foundations for the future EuPRAXIA as a European distributed research infrastructure. Launched in 2022 and scheduled for completion in 2026, the project brings together 38 partner institutions and is structured into 16 interconnected Work Packages covering governance, technical design, implementation planning, and sustainability aspects. During 2025, the activities were primarily concentrated on the selection process of the second implementation pillar, namely the *Laser-Driven Pillar*. This process represented a key milestone for the project, as it directly impacts the future configuration and strategic development of the infrastructure. The selection was conducted by an internal evaluation panel, which assessed the proposals submitted by the bidders in accordance with a predefined and agreed evaluation template. The procedure ensured transparency, consistency, and alignment with the project’s technical objectives and long-term vision, ultimately leading to the identification of the preferred implementation pathway for the Laser-Driven Pillar. The outstanding candidates to host the 2nd pillar were:

- ELI-ERIC
- STFC-RAL (UK)
- CNR-INO (IT)

The panel indicated a possible ranking of the bidders based on several parameters:

- Technical and scientific solidity of the proposal
- Existing infrastructures and know-how
- Alignment with their current activities
- Manpower available

The ranking resulting from the evaluation process was presented to the Collaboration Board in March 2025. Following a thorough discussion, the Board formally endorsed ELI-ERIC as the second implementation pillar of EuPRAXIA. Subsequent activities focused on defining the next strategic and operational steps required to ensure continuity beyond the Preparatory Phase. In particular, partners engaged in discussions aimed at establishing a common Memorandum of Understanding to frame the long-term collaboration and to pave the way for the creation of a dedicated legal entity (e.g. an AISBL). These elements were consolidated into a comprehensive milestone entitled “Legal and Financial Package”, which was formally approved during the Collaboration Board meeting hosted at the premises of ELI-ERIC in October 2025.

Another major achievement within the EuPRAXIA Preparatory Phase was the submission of a proposal under Horizon Europe INFRADEV 2025-01-02, entitled “EuPRAXIA Early Implementation Phase”. The proposal was submitted in September 2025, and the positive evaluation outcome was communicated in February 2026. The newly awarded grant is designed to build upon the results of the Preparatory Phase, with a stronger focus on legal, governance, and organisational aspects, ultimately supporting the establishment of the new legal entity and the transition towards the implementation phase of the research infrastructure.

## 5 Conclusions and Future Outlook

The completion of the TDR in 2025 marks the transition from design consolidation to implementation readiness. The coming phase will focus on final approval, civil engineering tender preparation, continued X-band and plasma R&D and progressive commissioning milestones. The scientific and technological ecosystem developed for EuPRAXIA@SPARC\_LAB is designed not only to meet the immediate performance objectives of a compact soft X-ray FEL but also to establish the foundations for the next generation of high-brightness, plasma-enabled accelerators. Several enabling technologies are central to this long-term vision, with significant implications for both fundamental research and applied innovation.

Among the key innovations, the integration of high-gradient **X-band** accelerating structures, delivering fields of  $\sim 60$  MV/m, allows for a dramatic reduction in the RF linac footprint while preserving beam brightness and stability. The use of **plasma channels** for wakefield acceleration represents a transformative step toward ultra-compact energy boosting, offering gradients in excess of 1 GV/m and paving the way for reproducible, beam-quality-preserving plasma stages. Advances in **ultrafast synchronization**, with sub-10 fs rms timing jitter between lasers and electron bunches, are essential enablers for pump-probe experiments and for precise control of beam-plasma interactions. The undulator system introduces additional flexibility through the adoption of **APPLE-X** variable-polarization undulators, enabling on-axis generation of tunable linear, circular, and elliptical polarization states with high stability, an essential capability for a broad class of soft-X-ray spectroscopy and imaging experiments. In **diagnostics and control**, the facility introduces real-time, non-invasive beam monitoring, machine learning assisted predictive tuning, and scalable, modular data acquisition systems, tools that support high repetition rate user operation and that are readily transferable to other infrastructures such as FELs, Linear Colliders, Compton sources, or medical accelerators.

Looking ahead, EuPRAXIA@SPARC\_LAB has been conceived with clear upgrade and diversification pathways. These include the addition of new beamlines such as **ARIA** for VUV radiation, implementation of seeded FEL schemes for improved spectral purity, and expansion of the plasma module to higher energies or multi-stage acceleration. R&D toward operating at **400 Hz** repetition rate - enabled by the forthcoming **C-band photo-injector** - is already underway, in particular in the framework of the PACRI project.