EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

# Recent Progress on the EuPRAXIA Project

**Antonio Falone | INFN-LNF**

**European Advanced Accelerator Conference 2025 - La Biodola (IT)**
**24/09/2025**

Funded by
the European Union

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773. It is supported by in-kind contributions by its partners and by additional funding from UK and Switzerland.

# Introduction

Funded by the European Union

- The EuPRAXIA project is advancing towards the establishment of a distributed European Research Infrastructure, as outlined in the ESFRI 2021 Roadmap.
- Significant progress has been achieved in recent years from scientific, technical, and organizational perspectives.
- This presentation will provide an overview of the progress made and offer an outlook on the upcoming challenges

European Plasma Research Accelerator with eXcellence In Applications

# EuPRAXIA Concept

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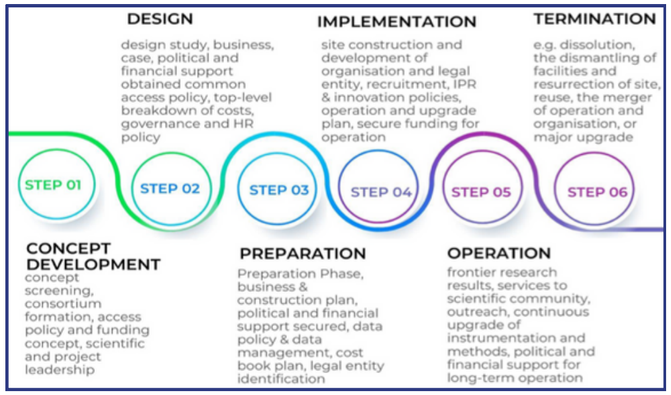
the European Union

The **EuPRAXIA project** envisions a **distributed European user facility** offering open access to advanced **plasma-based accelerators and beamlines.** Beyond serving the **scientific community**, it acts as a **hub for innovation**, fostering collaboration between academia, industry, and technology developers. A key feature is its commitment to **open innovation**, driving the joint development and application of **next-generation accelerator concepts.**

# EuPRAXIA Roadmap

Funded by the European Union

R&D Program




START Conceptual Design

CDR Published

DESIGN PHASE

START Preparatory Phase

PREPARATORY PHASE

START Pre-Implementation Phase

END Preparatory Phase

PRE IMPLEMENTATION PHASE

END Pre-Implementation Phase

LEGAL ENTITY ESTABLISHED

PROCUREMENT & INSTALLATION

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031

ESFRI APPLICATION

ESFRI Roadmap Inclusion

TDR EuPRAXIA@SPARC_LAB Ready
EuPRAXIA@ELI-ERIC - Selected

TDR EuPRAXIA@ELI-ERIC -Ready

EuPRAXIA@SPARC_LAB Starts installation - Building Ready

Transition to Landmark

# EuPRAXIA Distributed architecture

Funded by the European Union

Emerging architecture to be fully explored and detailed in the Early Implementation Phase Project

2 Implementation Pillars
@ INFN – LNF & @ ELI-ERIC

Several National Nodes. Roles to be fully defined

Project Clusters

# EuPRAXIA Program

Funded by the European Union

Set of correlated projects each of them contributing to the implementation of the EuPRAXIA Concept as distributed research infrastructure.

| PROJECT NAME | TOPIC |
|---|---|
| **EuPRAXIA@SPARC_LAB** | Implementation Beam Driven Pillar (including ARIA BeamLIne recently Funded) |
| **EuPRAXIA@ELI-ERIC** | Implementation Laser Driven PIllar |
| **EuPRAXIA Advance Photon Sources – EuAPS** | Betatron Radiation Source + High Power and High Rep.Rate laser development |
| **EuPRAXIA Doctoral Network** | Training |
| **EuPRAXIA Preparatory Phase** | Preparation of the distributed infrastructure – Legal, Governance, Finance and main WPs |
| **EuPRAXIA Early Implementation Phase** | Consolidation of the distributed infrastructure – towards the legal entity |
| **PACRI** | R&D on Plasma, Laser & X-Band technology |

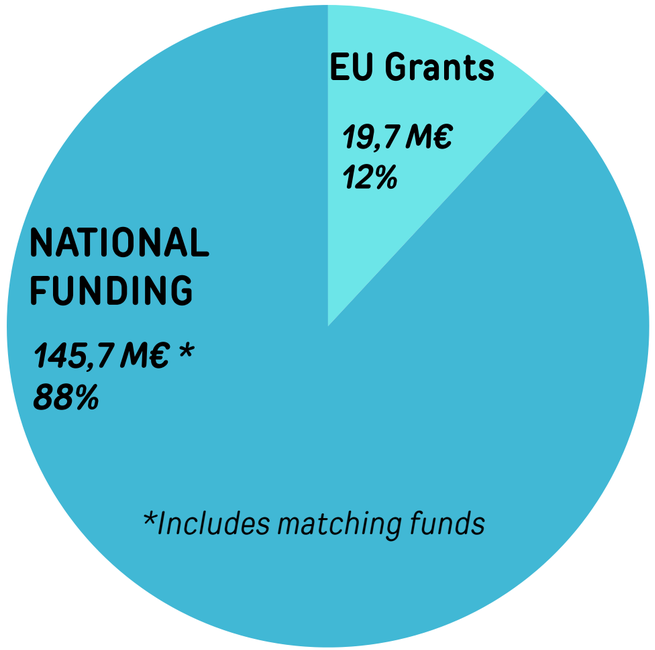
# EuPRAXIA Funding stats

Funded by the European Union

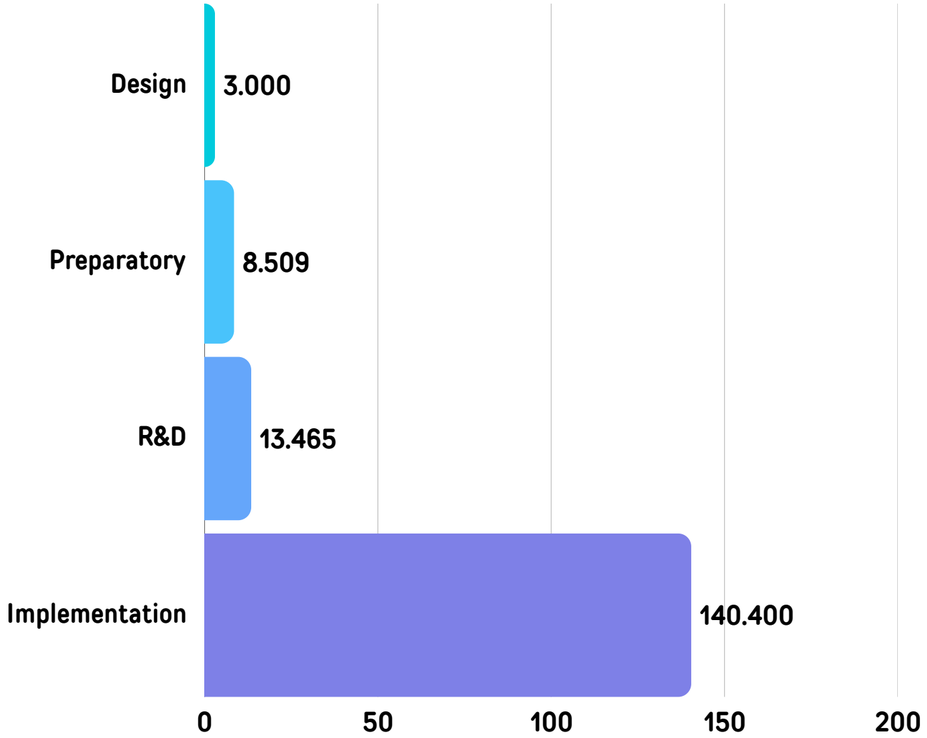
After the successfull inclusion in the ESFRI Roadmap 2021 EuPRAXIA has gained a remarkable funding attractiveness.

Around 165 M€ raised so far.

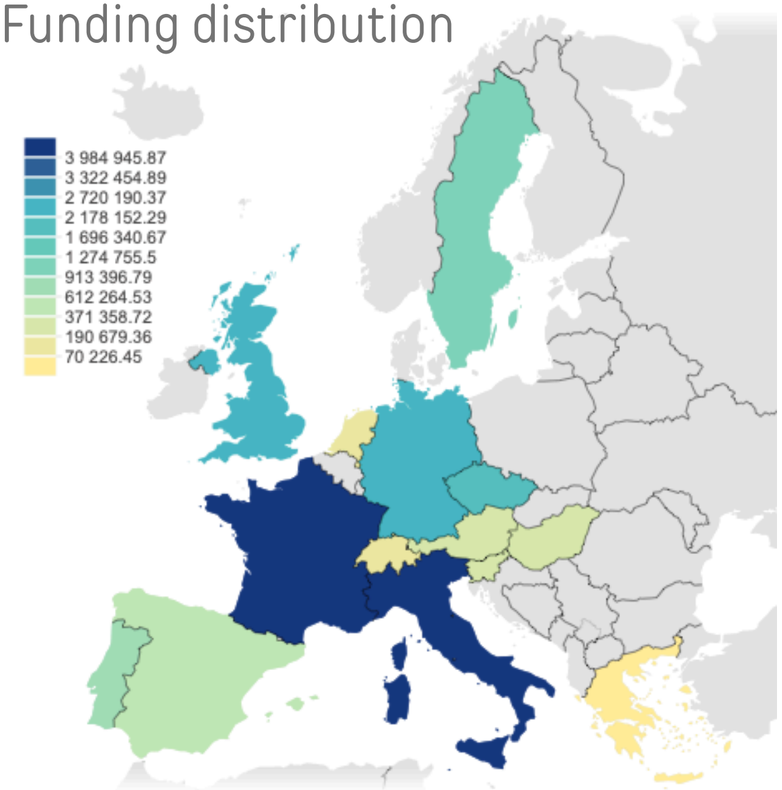
## Funding sources




## Distribution per life-cycle phase




## EU Funding distribution



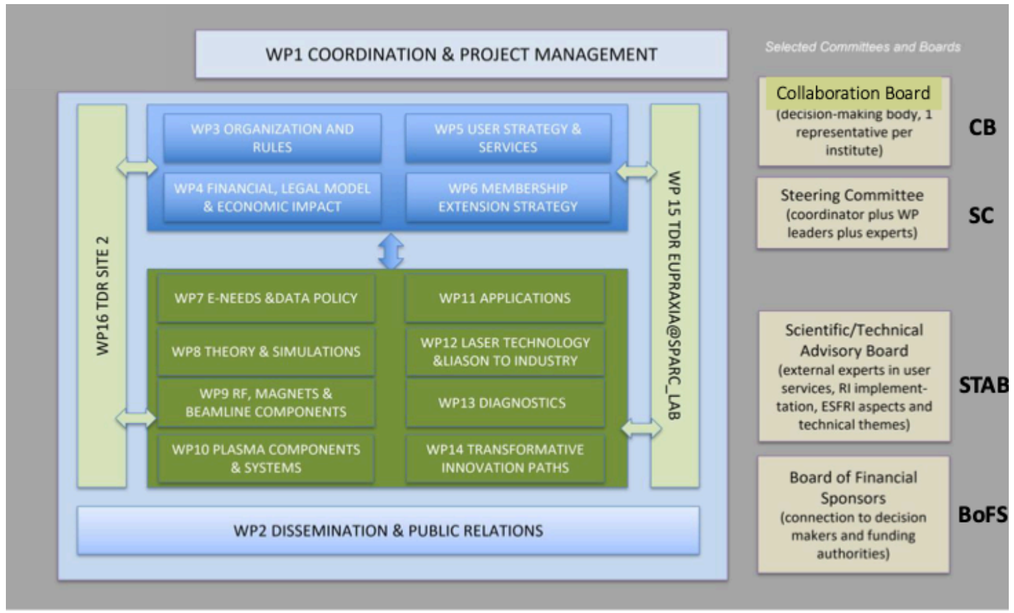
# EuPRAXIA Preparatory Phase

Funded by the European Union

28 EU institutions beneficiaries, 10 associated partners, 8 observers. 16 workpackages.
1/11/2022 to 31/10/2026 – Mid term review successfully passed in July 25. Approaching the end of the project in 1 year from now.

Main goal: lay down the foundation of a novel ESFRI distributed research infrastructure.
It addresses a wide range of topics over three main dimensions (Organization, Scientific and communication).

Draft of the legal and financial model – Socio economic impact assessment.




- Managerial WP`s
  - **Outreach** to public, users, EU decision makers and industry
  - **Define** legal model (how is EuPRAXIA governed?), financial model, rules, user services and membership extension for full implementation
  - Works with **project bodies and funding agencies** → Board of Financial Sponsors
- Technical WP's (correspond to Project Clusters):
  - **Update of CDR** concepts and parameters, towards technical design (full technical design requires more funding)
  - Specify in detail **Excellence Centers and their required funding**: TDR related R&D, prototyping, contributions to construction
  - Help in defining funding applications for various agencies
- Output defined in **milestones & deliverables** with dates

# EuPRAXIA Early Implementation Phase

Funded by the European Union

INFRADEV-2025-01-02 . Just submitted!  Kick off (if approved) in spring 2026. 18 beneficiaries + 2 associated partners, 11 countries represented.

In response to the reccommendations outlined in the ESFRI monitoring outcome (April 2025)

In continuity with the preparatory phase, topics focused on:

- Legal, Governance and Organizational model
- Distributed architecture model – National nodes definition
- Financial and business plan
- Data management & User access strategy
- Socio-economic Impact & Industrial engagement strategy.

Transition from funded based collaboration (e.g. DESCA Model) to Legal entity (with all relevant legal tools: Statute, bylaws, rules, Service Level Agreements, In-Kind contribution framework etc.).

## Beam Driven Pillar

1 GeV Electron beam Linac with a plasma stage acceleration module to drive 2 FEL Lines:

- AQUA (water region, around 4nm)
- ARIA (180nm) – Recent funding from Regional Government through ERDF Eu Program.

It includes a brand new building and ancillary utilities.

Major investment and flagship project of INFN-LNF.

Technical Design Report in the approval phase (end of the year).

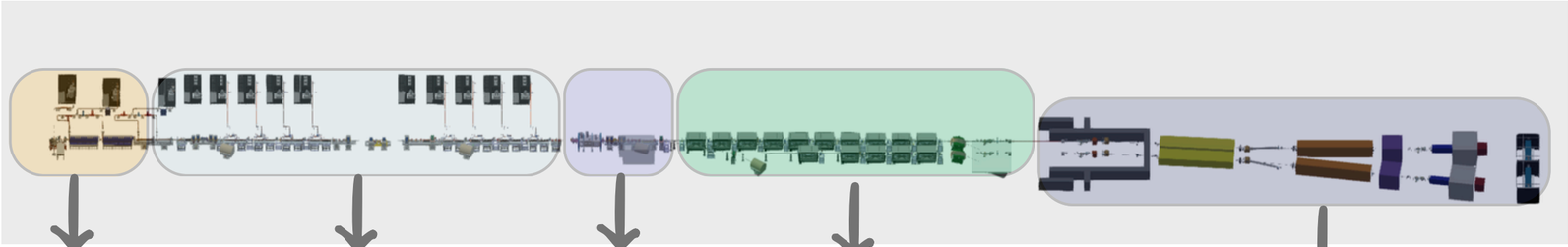
Building tender to be issued soon (hopefully October 2025) expected completion in 2029.


The overall concept is based on two main technological pillars under development

- X-Band Technology
- Plasma acceleration

# EuPRAXIA @SPARC_LAB

Funded by the European Union




2 Operating working points:
Plasma based and Full RF.

| | Units | PWFA | Full RF |
|---|---|---|---|
| | | 30 pC with tapering | Hybrid compression |
| Electron Energy | $GeV$ | 1 | 1 |
| Repetition rate | $Hz$ | 100 | 100 |
| Bunch charge | $pC$ | 30 | 200 |
| Peak current at undulator entrance | $kA$ | 3.3 | 3.4 |
| RMS bunch length at undulator entrance | $\mu m$ | 1.4 | 16.9 |
| RMS normalized emittance (x,y) | $mm\ mrad$ | 0.7,0.6 | 2.1,1.0 |
| RMS energy spread | % | 0.5 | 0.2 |
| Slice length | $\mu m$ | 0.5 | 0.5 |
| Slice Normalized emittance (x,y) | $mm\ mrad$ | 0.7,0.6 | 0.3,0.3 |
| Slice energy spread | % | 0.04* | 0.02 |
| $\rho$ (3D) | $\times 10^{-3}$ | 0.77 | 1.49 |
| Radiation wavelength | $nm$ | 4.0 | 4.0 |
| Saturation length | $m$ | 20.5 | 20.0 |
| Photon Pulse Energy | $\mu J$ | 16 | 150 |
| Photon per pulse | $\times 10^{11}$ | 3.2 | 31.3 |
| Photon Bandwith | % | 0.4 | 0.5 |
| Photon Brilliance per shot | $\times 10^{30}$ | 0.12 | 2.1 |

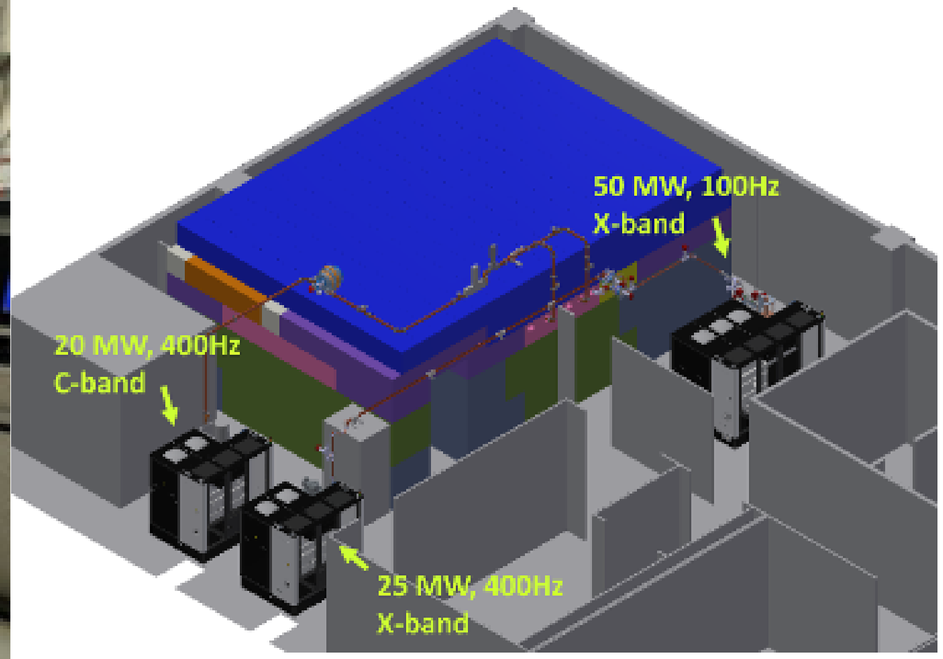
*Courtesy M.Ferrario*

# EuPRAXIA @SPARC_LAB | X-Band

Funded by the European Union

TEX Facility (**TE**st stand for **X**-Band)

High Power lab equipped with 3 RF Systems (2 X-Band and 1 C-Band) and a dedicated bunker for RF accelerating section conditioning



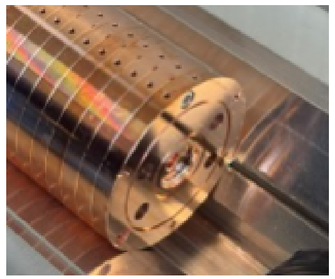

| Parameter | Unit | Canon E37217 | Canon E37119 |
|---|---|---|---|
| Frequency | MHz | 5712 | 11994 |
| Peak RF output Power | MW | 20 | 25 |
| Average RF output power | kW | 21 | 15 |
| Modulator Average power | kW | 752 | 752 |
| RF pulse length | us | 2.5 | 1.5 |
| Repetition Rate | Hz | 400 | 400 |
| Gain | dB | 50 | 47 |
| Efficiency | % | 40 | 40 |

*Courtesy F.Cardelli, S.Pioli*

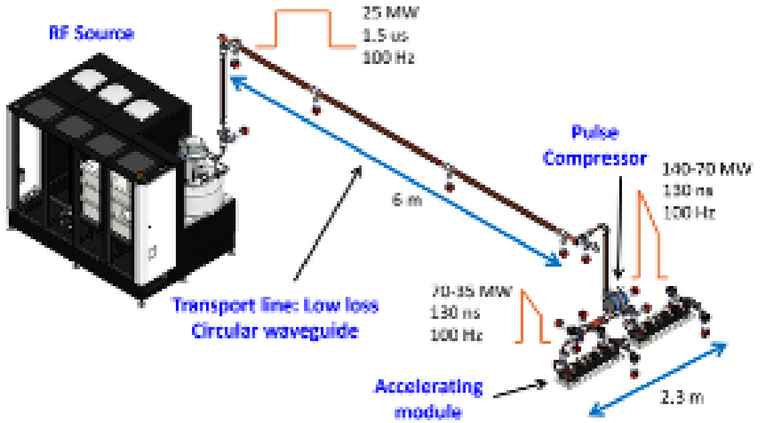
# EuPRAXIA @SPARC_LAB | X-Band

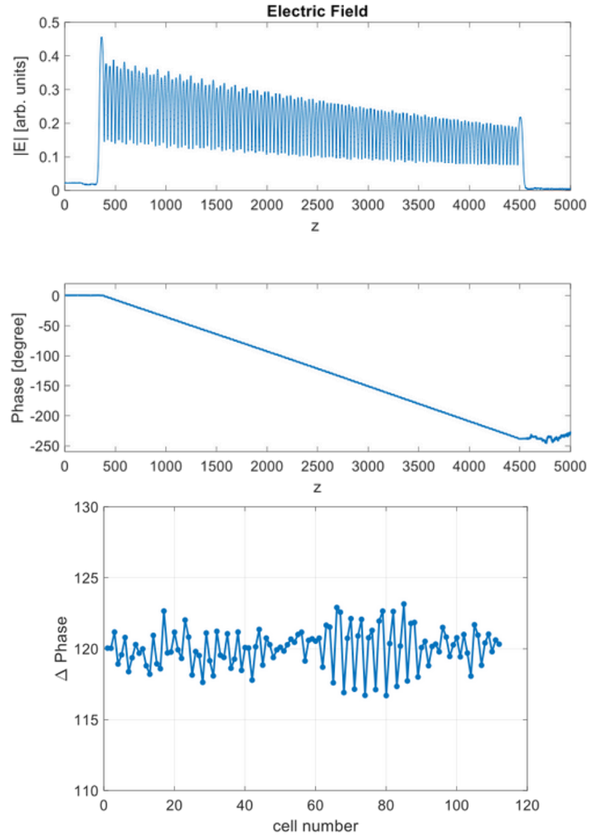
Funded by the European Union

1st full scale X-band prototype section has been realised in house in collaboration with COMEB. Conditioning coming soon.



| Accelerating structures parameter | Symbol | Unit | Value |
|---|---|---|---|
| Frequency | $f_{RF}$ | GHz | 11.9942 |
| Average accelerating field | $E_{acc}$ | MV/m | 60 |
| Iris radius (linear tapered) | $a$ | mm | 3.85-3.15 (3.5) |
| Structure active length | $L_s$ | m | 0.94 |
| Number of cells | $N_{cell}$ | | 112 |
| Shunt impedance per unit length | $R$ | MΩ/m | 93-107 (100) |
| Effective shunt impedance per unit length | $R_s$ | MΩ/m | 350 (347) |
| Peak input power per structure | $P_{peak}$ | MW | 70 |
| Input power per structure averaged over the pulse | $P_{in}$ | MW | 51 |
| $P_{out}/P_{in}$ | | % | 25 |
| Filling time | $\tau_F$ | ns | 130 |
| Peak mod. Poynting Vector | $S_c$ | W/μm$^2$ | 3.6 (4.3) |
| Peak Surf. E field | $E_P$ | MV/m | 160 (190) |
| Quality factor | Q | | 6400 |
| Phase advance per cell | $\phi$ | | $2\pi/3$ |
| Repetition rate | $f_{rep}$ | Hz | 100 |



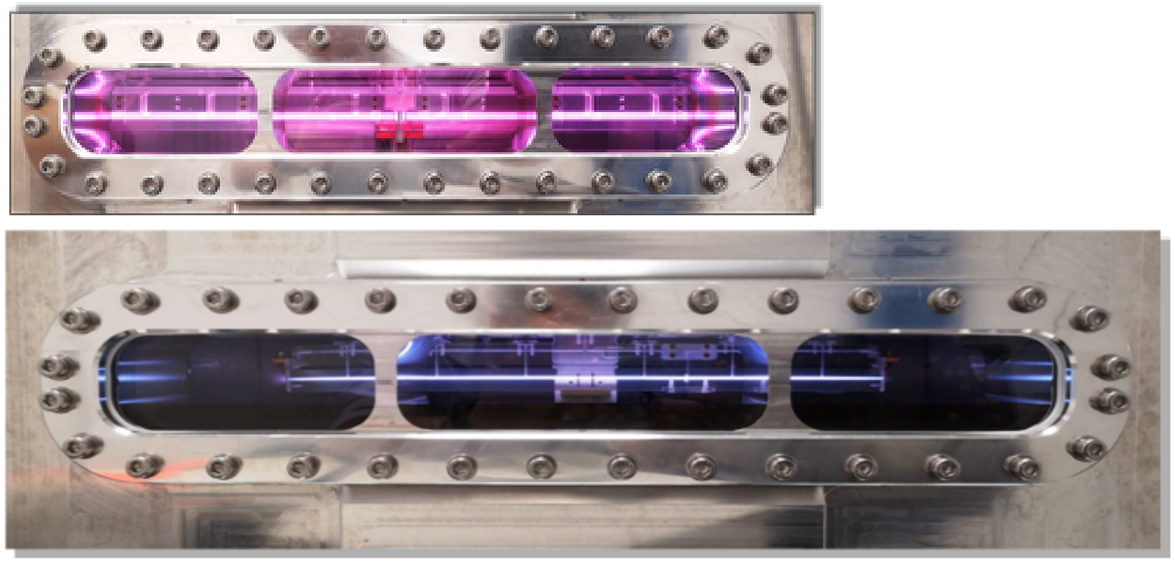




*Courtesy F.Cardelli, D.Alesini*

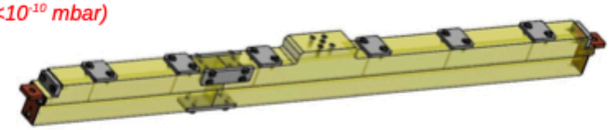
# EuPRAXIA @SPARC_LAB | Plasma

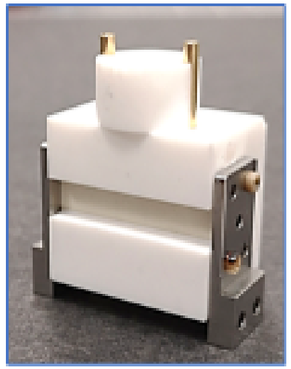
Funded by the European Union

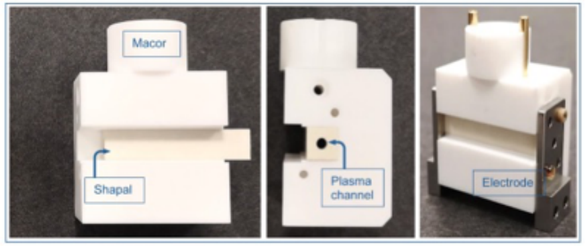
| Key design parameters for the EuPAXIA@SPARC_LAB plasma source | |
|---|---|
| **Source type** | Gas-filled discharge capillary |
| **Geometry** | 60 cm in length<br>2 mm in diameter<br>variable inlets |
| **Gas** | Argon, Nitrogen, Hydrogen |
| **Gas injection system** | Continuous gas injection using a common service channel and several injectors with variable position and size |
| **Repetition rate** | 100 - 400Hz |
| **Discharge circuit parameters** | Voltage: 10÷15 kV<br>Current: 400÷500 A |
| **Materials** | Channel: Sapphire, Shapal<br>Holder: Macor<br>Electrodes: Tungsten |
| **Plasma density** | $10^{16} \div 10^{17}$ cm$^{-3}$ |
| **Lifetime** | $3 \times 10^{8}$ shots |
| **Shot-to-shot stability** | $< 1\%$ with laser stabilization |



- 40 cm long capillary → 1st prototype for the EuPRAXIA facility — A. Biagioni, V. Lollo
  - *Made with special junction to allow negligible gas leaks (<$10^{-10}$ mbar)*
- Operating conditions
  - *1 Hz repetition rate (to be increased up to 100 Hz)*
  - *10 kV – 380 A minimum values for ionization*
  - *6 inlets for gas injection. Electro-valve aperture time 8-12 ms*








- Production of the final prototype (60 cm long Shapal/Macor capillary)
- Further resistance tests on the 60cm capillary in the final plasma chamber
- New electrode materials such as tantalum or tungsten (successfully tested molybdenum)

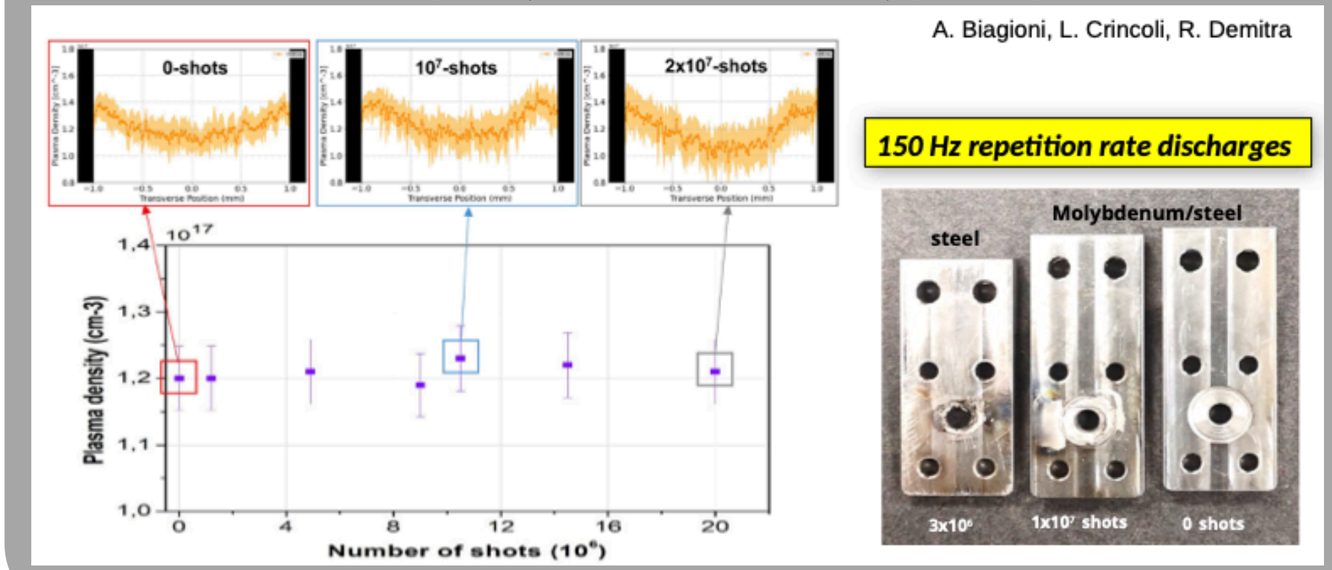
*Courtesy R.Pompili, A.Biagioni*

# EuPRAXIA @SPARC_LAB | Plasma

Funded by the European Union

## Intensive R&D on capillary lifetime and density profile preservation

A. Biagioni, L. Crincoli, R. Demitra

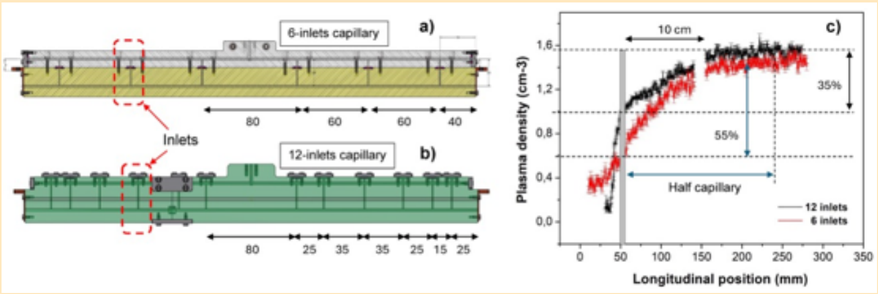



**150 Hz repetition rate discharges**





- Plastic prototype to test different parts of the plasma source
- Laboratory testing for setting plasma formation parameters (voltage, currents, pressure, densities)
- Partial testing of materials (2x10^7 discharges) to work at high repetition rates

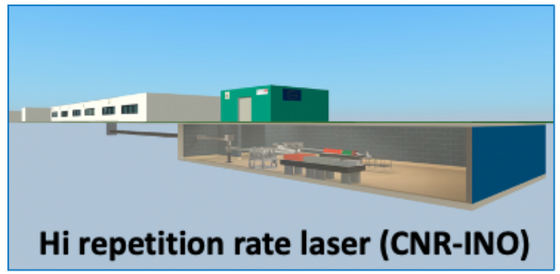


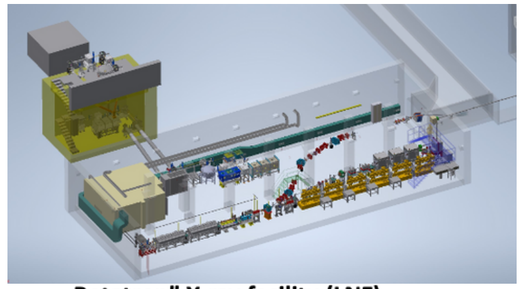

tests on a 40 cm long capillary to control the ramps (plasma channel geometry and gas distribution system) within the capillary as required by beam physics to achieve the acceleration targets (red profile has been used for beam dynamics simulations)

*Courtesy R.Pompili, A.Biagioni*

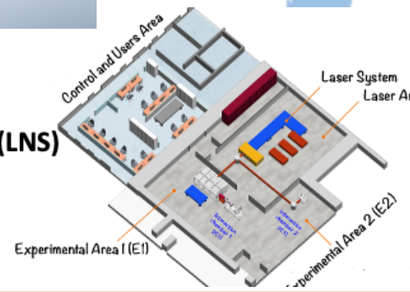
# EuPRAXIA Advanced Photon Sources - EuAPS

**EuAPS** led by INFN with CNR and University of Tor Vergata, plans a laser-driven "betatron" X-ray facility at LNF SPARC_LAB. It also develops high-power (up to 1 PW) and high-rep rate (up to 100 Hz) lasers for EuPRAXIA. EuAPS secured €22.3M funding from PNRR Next-Gen EU Program, and received top scores in the ESFRI Physical Sciences and Engineering area.


Hi repetition rate laser (CNR-INO)


Betatron" X-ray facility (LNF)


High power laser (LNS)




- Budget consumption at 98% (few remaining orders ongoing)
- Instrumentation delivery & installation on going
- Commissioning scheduled Q1-2026
- End of the project 30/04/2026
- 10 years of operation committed (Sustainability analysis ongoing)

## EuAPS@INFN-LNF Betatron Radiation Source

| Parameter | Value | unit |
|---|---|---|
| Electron beam Energy | 100-500 | MeV |
| Plasma Density | 10^17-10^19 | cm-3 |
| Photon Critical Energy | 1 to 10 | keV |
| Number of Photons/pulse | 10^6-10^9 | |
| Repetition rate | 1 to 5 | Hz |
| Beam divergence | 3 to 20 | mrad |

*Courtesy C.Bortolin*

# EuPRAXIA @ ELI-ERIC

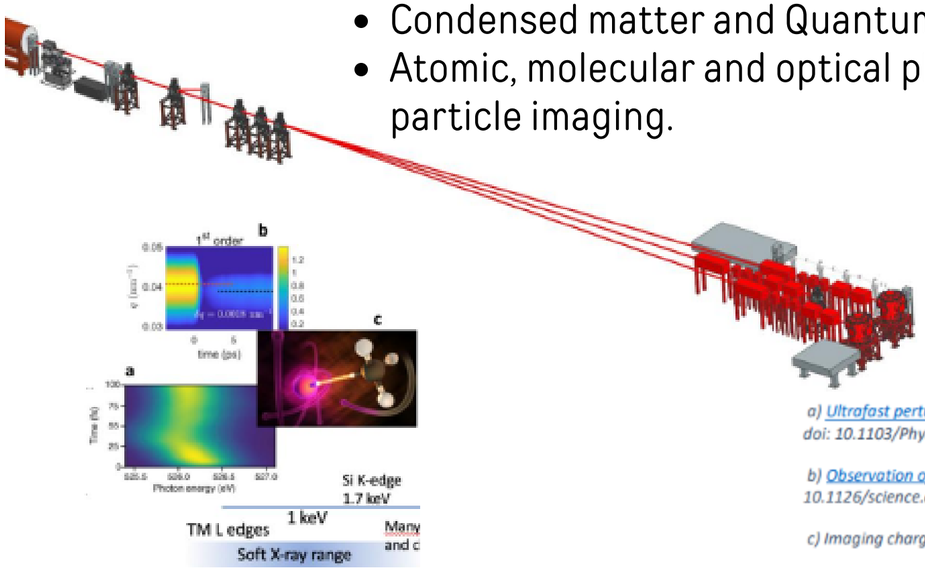
Funded by
the European Union

## Laser Driven Pillar

Selected by the EuPRAXIA Collaboration Board in March 2025 after a competitive and open process among other candidates (EPAC-UK, CNR-IT, CLPU-ES)

The conceptual design of the LPA-based soft X-ray Free Electron Laser (FEL), as part of the EuPRAXIA Phase-1 at ELI Beamlines, has been finalized [IPAC24] based on existing facilities (Swiss-FEL Athos Beamline and FERMI).
**2 end stations planned** – key area of applications:

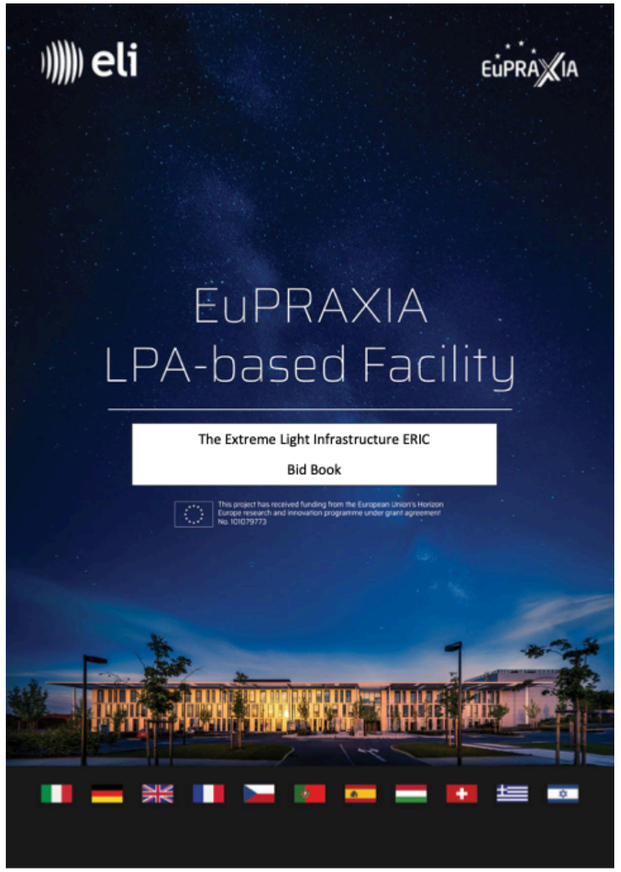
- Condensed matter and Quantum Materials (CQM)
- Atomic, molecular and optical physics (AMO), Chemical sciences and ultrafast single-particle imaging.




a) Ultrafast perturbation of magnetic domains by optical pumping in a ferromagnetic multilayer, Phys. Rev. B 106, (2022) doi: 10.1103/PhysRevB.106.144422;

b) Observation of the fastest chemical processes in the radiolysis of water, Science 367, 179 (2020) doi: 10.1126/science.aaz4740;

c) Imaging charge transfer in iodomethane upon x-ray photoabsorption, Science, 18 July 2014, (10.1126/science.1253607);




*Courtesy A.Molodozhentsev*

# EuPRAXIA @ ELI-ERIC

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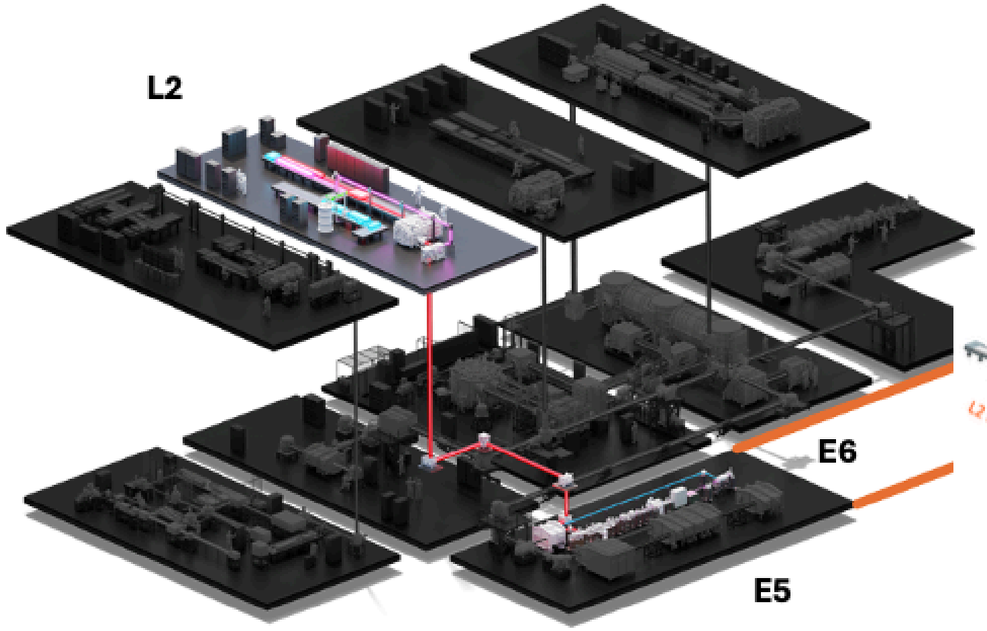
Phase 1 – Soft X-ray FEL laser plasma based, massive use of existing infrastructure + undulator line and user end station

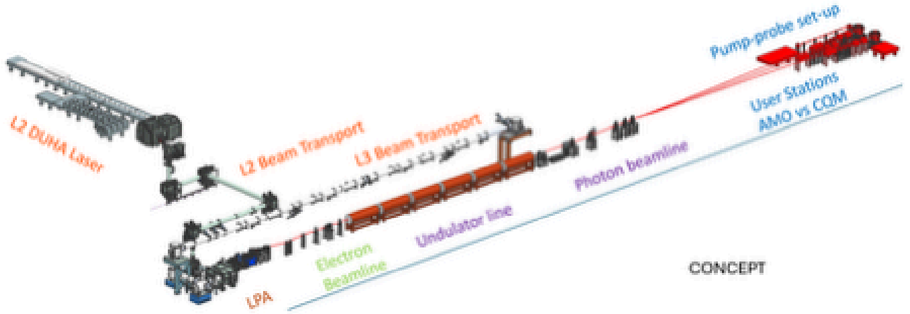
**Phase-1: 1GeV electron LPA soft X-ray FEL**

**+ BETATRON and POSITRON (LE) sources**

**Existing infrastructure**




**Conceptual solution for Phase-1, Integrated into the ELI Beamlines infrastructure**




*Courtesy A.Molodozhentsev*

# EuPRAXIA @ ELI-ERIC

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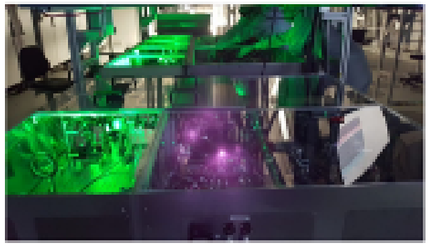
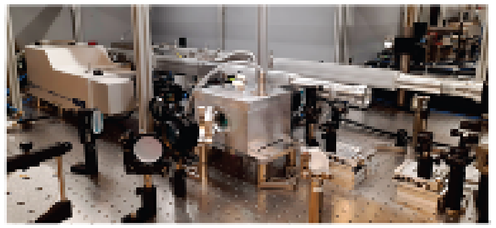
Additional implementation items: High power / high repetition rate laser system and betatron radiation source

❑ High-power high-repetition-rate **LASER development** (L2-DUHA)



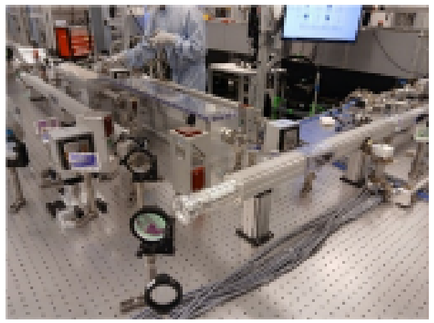
Broadband front end of L2-DUHA



Booster amplifier of L2-DUHA

Brayton cryogenic cooling system integrated into laser

L2-DUHA compressor chamber in L2-hall

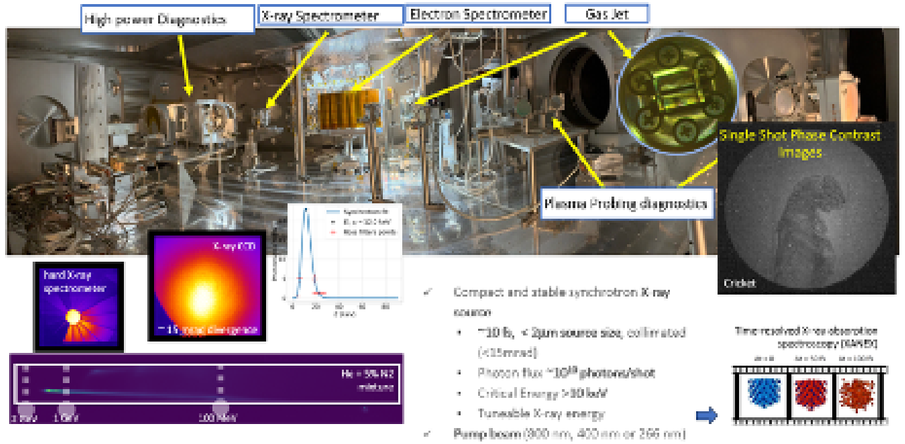


OPCPA system under pre-alignment

*Tyler Green (ELI BL)*

❑ **BETATRON source:**

Commissioning and USER-operation




*Uddhab Chaulagain (ELI-BL*

*Courtesy A.Molodozhentsev*

# EuPRAXIA @ ELI-ERIC

Funded by the European Union

Technical design report working group has just been triggered internally @ ELI-ERIC. To be completed by april 2027.


**I. Executive Summary**

EuPRAXIA at ELI Beamlines
LPA-based soft X-ray FEL in the International Context
Scientific Goals
Detailed Design:
- *Selection of Major System Parameters*
- *Layout of the EuPRAXIA LPA-based soft X-ray FEL User Facility at ELI Beamlines*
- *Main Performance Parameters*

Technical Specifications:
- *Laser and Laser Beam Transport*
- *Laser-Plasma Electron Accelerator*
- *Electron Beam Transport*
- *Undulator Line*
- *Photon Beamlines and End-Stations*
- *Conventional Facilities and Building*

Safety and Risk Analysis
Cost and Schedule
Project Plan with Phases and Milestones
Conclusion

**+ XV chapters**

**ELI Beamlines current status:**

- ✓ Internal team - assigned
- ✓ SoW and Project Tasks - identified
- ✓ R&D budget for 2026 (TDR-oriented) - assigned
- ○ Forming a collaboration with EuPRAXIA through National Nodes → in progress

*Courtesy A.Molodozhentsev*

# EuPRAXIA EU monitoring outcomes

Funded by the European Union

In April 2025 we went through a comprehensive mid-term ESFRI monitoring process.
55 questions – 60 pages questionnaire covering a wide range of topic.

ESFRI MoS

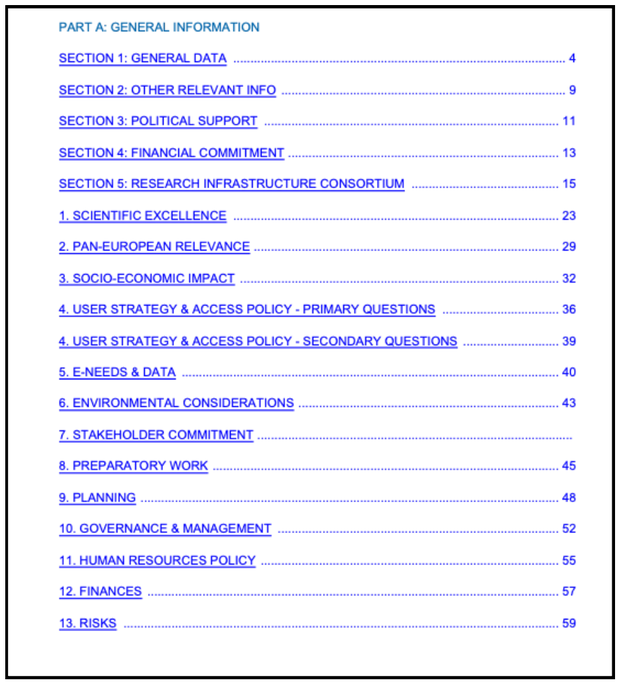
ESFRI Monitoring System

Strategy Report on Research Infrastructures

Project Report
Created at 2025-04-10

PROJECT COORDINATOR:
Antonio Falone

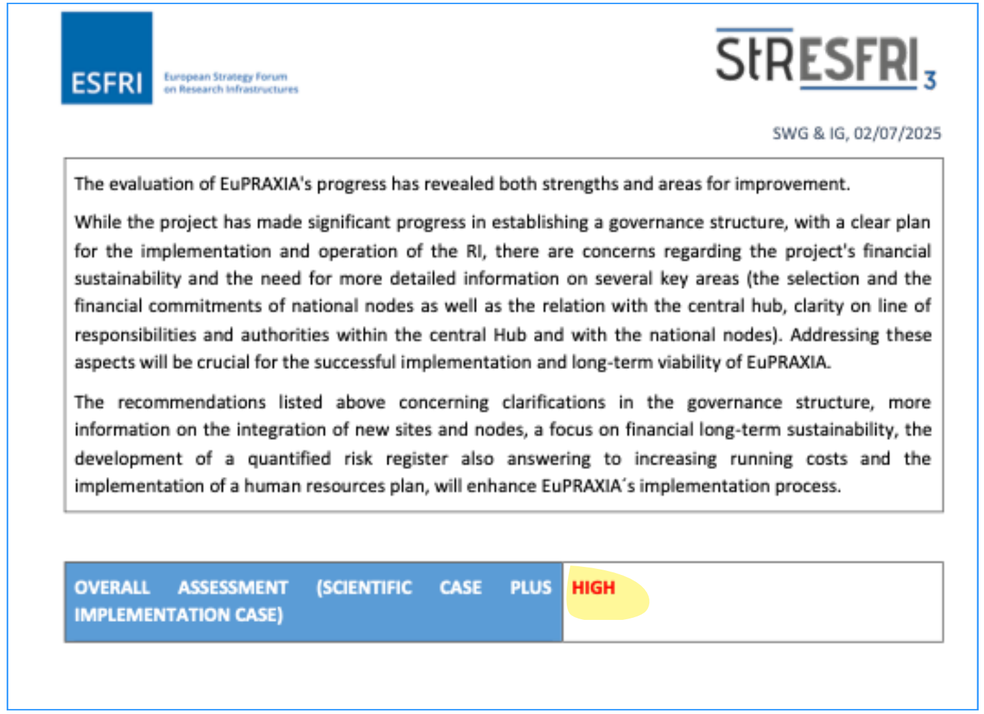
PROJECT NAME:
European Plasma Research Accelerator with Excellence in Applications



PART A: GENERAL INFORMATION



Outcome



ESFRI European Strategy Forum on Research Infrastructures

StRESFRI 3

SWG & IG, 02/07/2025

The evaluation of EuPRAXIA's progress has revealed both strengths and areas for improvement.

While the project has made significant progress in establishing a governance structure, with a clear plan for the implementation and operation of the RI, there are concerns regarding the project's financial sustainability and the need for more detailed information on several key areas (the selection and the financial commitments of national nodes as well as the relation with the central hub, clarity on line of responsibilities and authorities within the central Hub and with the national nodes). Addressing these aspects will be crucial for the successful implementation and long-term viability of EuPRAXIA.

The recommendations listed above concerning clarifications in the governance structure, more information on the integration of new sites and nodes, a focus on financial long-term sustainability, the development of a quantified risk register also answering to increasing running costs and the implementation of a human resources plan, will enhance EuPRAXIA´s implementation process.

| | |
|---|---|
| OVERALL ASSESSMENT (SCIENTIFIC CASE PLUS IMPLEMENTATION CASE) | HIGH |

Solid reccomendations :

Strengthen the national nodes role and secure financial committment for the laser driven pillar, consolidate final governance. Address environmental sustainability.
All topics addressed in the next grant and to be solved in the next years

Next monitoring will be at the end of the roadmap where we will be assessed and evaluated to become “landmark”.

# EuPRAXIA on the path to full maturity

Funded by
the European Union

EuPRAXIA is a well-established community in the middle of the ESFRI roadmap.

Significant progress has already been achieved, and further advances lie ahead, driving EuPRAXIA towards full maturity both organizationally and technically.

## Financial and Organization

- Finalize financial and business plan
- Fund raising and stakeholder engagement
- Definition of the distributed architecture
- Legal & Governance issues
- Secure funding

## Scientific & Technological topics

- Consolidate TRL on plasma technology
- Finalize X-Band development
- Consolidate Laser TRL (high rep.rate & power)

## Implementation

- Start installation works on EuPRAXIA@SPARC_LAB (Building to be procured soon).
- Start procurement of EuPRAXIA@SPARC_LAB Components.
- Finalize EuPRAXIA@ELI ERIC TDR
- Start commissioning of EuAPS (Betatrone Radiation Source and Laser systems at CNR & INFN-LNS)



*Antonio Falone | INFN-LNF*