EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

Progress report: WP10

Kevin Cassou and Rob Shalloo

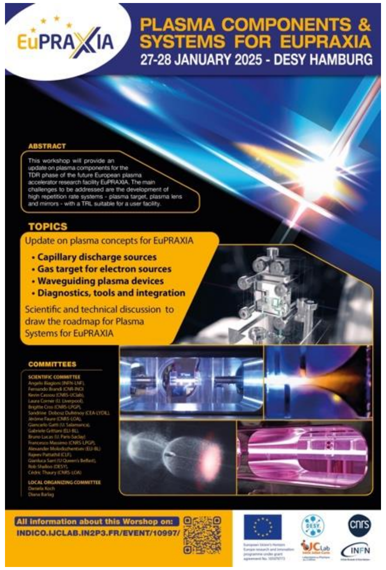
This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Last update on WP10 - plasma systems

Funded by the European Union

Workshop on plasma system and components for EuPRAXIA 27-28/01/2025

- 25 attendees on-site and up to 6 online
- Presentation of the WP10 review work
- The discussion group tried to evaluate the TRL level of various plasma components for EuPRAXIA.



Technical Status Report on Plasma Components and Systems in the context of EuPRAXIA [1] **has been accepted to PoP**.

Milestone M10.1 has been delivered.

Last deliverable **on TRL level of plasma component and system** in preparation for the end of the year based on workshop inputs.

📍Activities slowly being merged with **WP4 of PACRI INFRATECH**


Technical Status Report on Plasma Components and Systems

Technical Status Report on Plasma Components and Systems in the context of EuPRAXIA

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(Dated: 24 December 2024)

arXiv:2412.16910v1 [physics.plasm-ph] 22 Dec 2024

The EuPRAXIA project[1] aims to construct two state-of-the-art accelerator facilities based on plasma accelerator technology. Plasma-based accelerators offer the possibility of a significant reduction in facility size and cost savings over current radio frequency (RF) accelerators. The two facilities - one laser-driven one a beam-driven - are envisioned to provide electron beams with an energy in the ...

I. INTRODUCTION

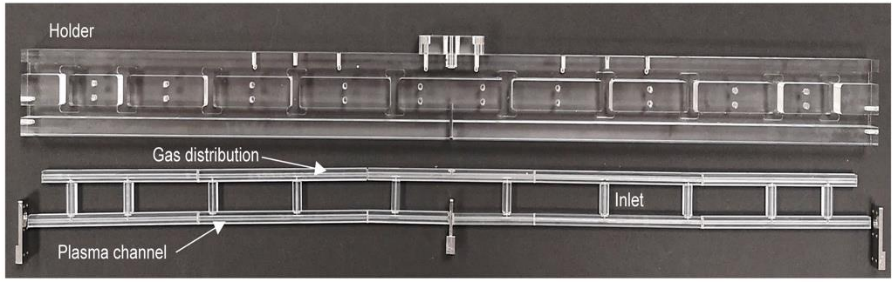
With regards to plasma components and systems relevant for EuPRAXIA, the plasma within these devices is generated either via a high-voltage discharge or by a suitable laser pulse / particle beam. The generation of the plasma can be initiated from a few microseconds before up to just prior to the desired ...

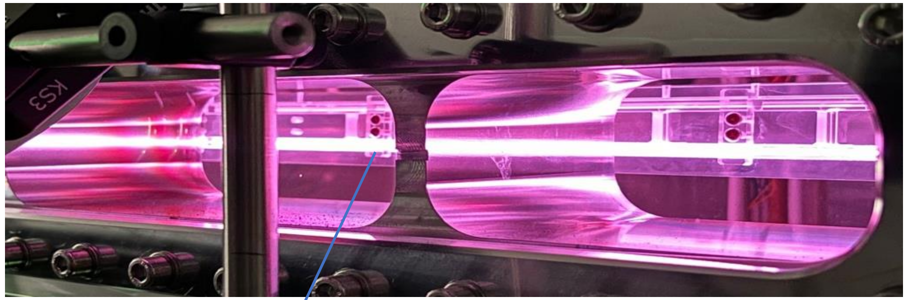
[1] https://arxiv.org/abs/2412.16910

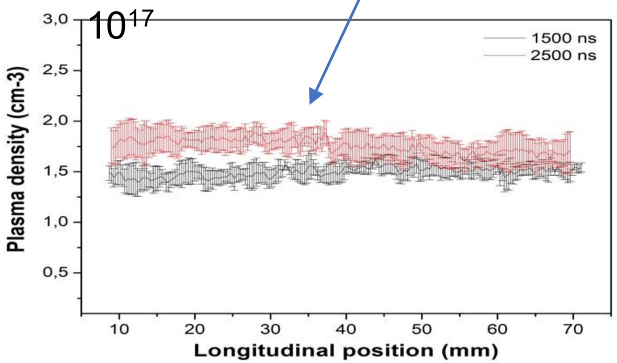
Beam driven plasma components

Test of meter-scale plasma discharge structure

Potentially ~ 1 GeV energy gain @ 10^{16} cm^{-3}

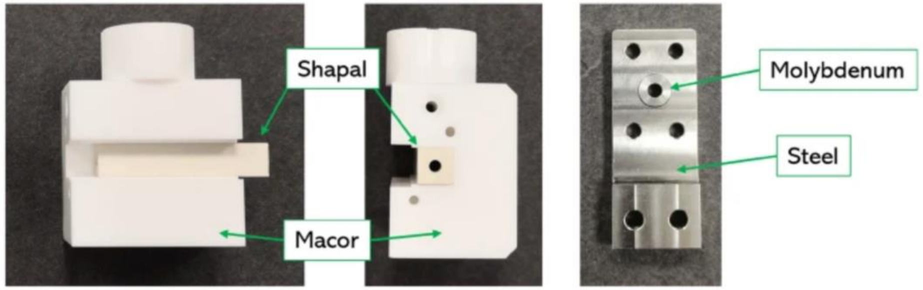


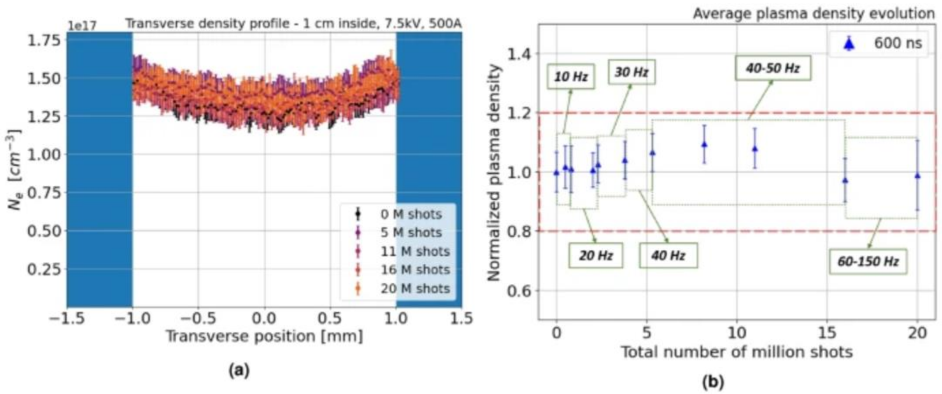




Advanced short plasma discharge for high repetition rate

up to 150Hz using ceramic [1]

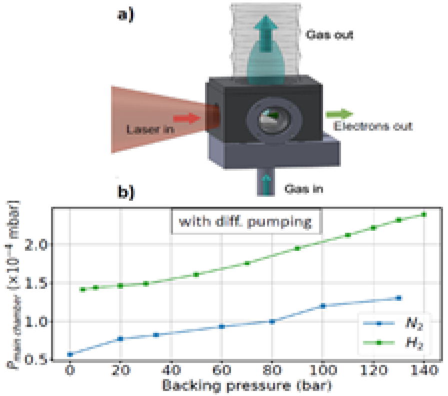


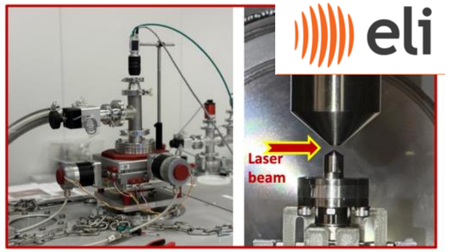


[1] . L. Crincoli et al. Scientific Reports volume 15, 12456 (2025)

High repetition rate operation gas target

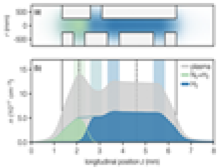
Continuous gas flow jet of H_2 and N_2 [1,2]

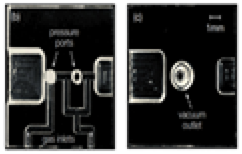


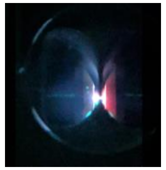


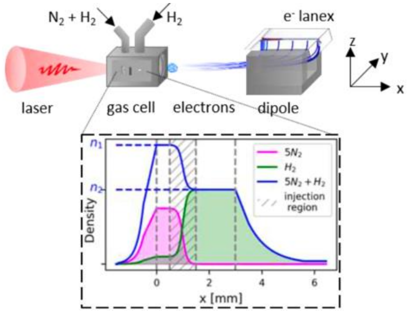
[1] J. Monzac et al. *Rev. Sci. Instrum.* 96, 043302 (2025)
[2] S. Lorenz, ELI-BL LPAW2025

Pulsed and continuous gas flow gas cell target [3,4,5]





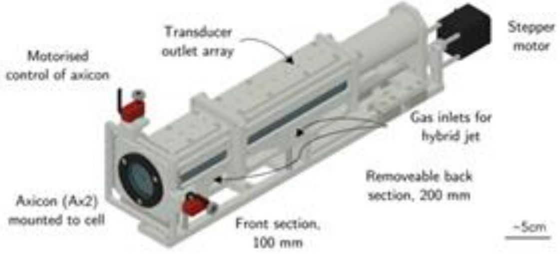


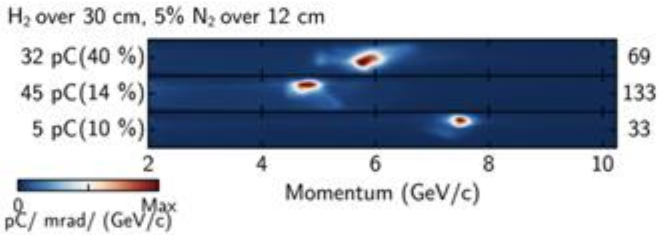


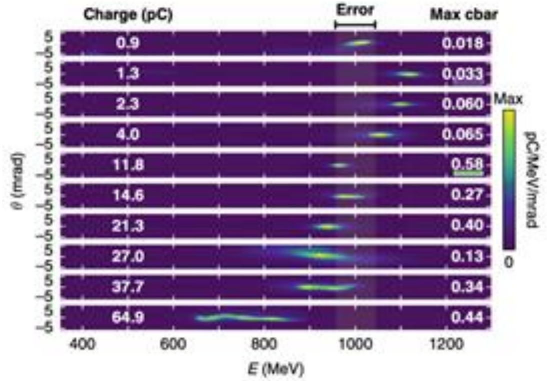
[3] M. Kirchen, PhD Thesis University of Hamburg (2021)
M. Kirchen et al PRL 126, 174801 (2021) S. Jalas et al PRAB 26, 7, 071302 (2023)
[4] P. Drobniak et al. *Rev. Sci. Instrum.* 96, 033304 (2025)
[5] L. Steyn et al. arxiv:2506.18047v1 (2025)

GeV laser-plasma injector scheme

HOFI plasma waveguide [6-11]







[6] R. J. Shalloo et al., PRAB **22**, 041302 (2019
[7] B. Miao et al., PRX **12**, 031038 (2022)
[8] K Oubrerie et al., Light Sci. Appl. **11**, 180 (2022)
[9] A. Picksley et al., PRL **131**, 245001 (2023)
[10] A. Picksley et al., arXiv:2408.00740 (2024)
[11] E. Rockafellow, et al. Phys. Plasmas 32, 053102 (2025)

potential contribution for R&D in plasma modules interferometric diagnostics

Funded by the European Union

Density Stability requirement in plasma modules <1 % → appropriate real-time diagnostics have to be deployed.

This requirement, together with the actual geometrical design in terms of plasma dimensions and optical accesses, dictates the decision of the best optical diagnostics to monitor and control the plasma module in a **high-quality HRR laser-plasma accelerator**.

Main open issues:

1. accurate real-time measure plasma density at the **<10^{16} cm^{-3}** level;
2. accurate real-time measure of the neutral particle density for low dispersive gas/targets (e.g., **mm-sized helium jets**);

Requirements for the laser-plasma accelerator

target type	jet	cell	unit
gas flow	supersonic	transonic	-
access	open	limited	
length	0.100 – 100	2 – 100	mm
density	$10^{18} - 10^{20}$	$10^{17} - 10^{19}$	cm^{-3}
density control	1	0.3	%
repetition rate$^{(*)}$	1 – 1000	1 – 10	Hz
driver average power	∼ 2	∼ 2	W
density tailoring	yes, sharp	yes, smooth	-
species distribution	yes	yes	-
multi- driver beam	yes, any angle	yes, co-linear	-
gas load	high	moderate	
wear part	nozzle	aperture / channel	

Scenario:

1. *LPA EuPRAXIA set an **integrated approach with commonly defined goals on plasma module and their diagnostics in operative HRR laser-plasma accelerators**;*
2. *Existing interferometric approaches have limited capabilities when considering the necessary sensitivity with proper deployability in operative accelerators, and further **R&D of innovative and robust interferometric diagnostics solution is needed;***
3. *At CNR-Pisa there is a **deep knowledge and long-term proven experience** in **developing and deploying robust and high sensitivity interferometric diagnostics in large laboratories/infrastructure;** some preliminary R&D activity is already on going concerning innovative interferometric approaches aiming specifically at solving the existing issue for a real-time high-sensitivity density diagnostics.*

*CNR-Pisa is interested in **R&D on plasma modules interferometric diagnostics** and **is willing to participate and contribute** to the activities in **innovative interferometric** diagnostics for the plasma modules **to be deployed in the HRR laser-plasma accelerator facility.***

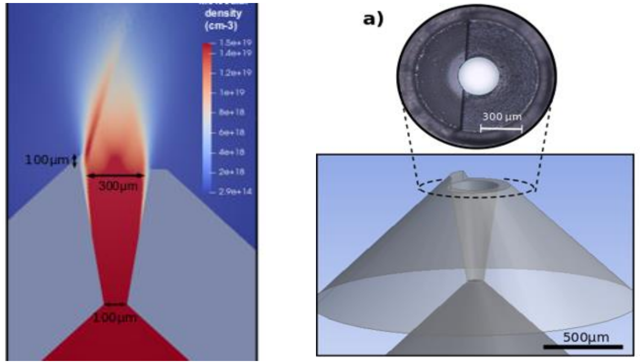
LOA contribution on high repetition rate gas jet targets

Already achieved

5-10 MeV kHz beam using 5 W average power laser, *Monzac et al., Phys. Rev. Research 6, 043099 (2024)*

Shocked jet for stable injection, *Rovige et al., RSI 92, 083302 (2021)*

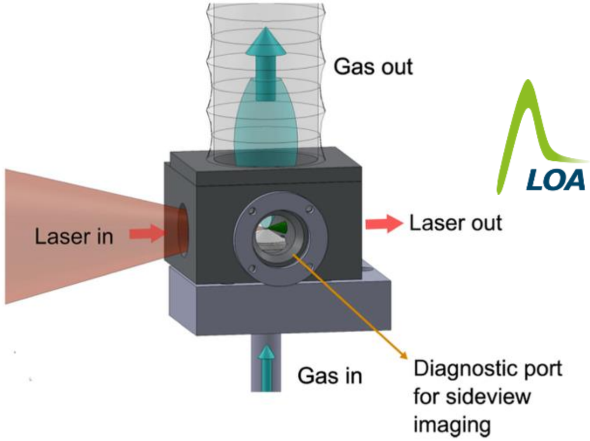
Differential pumping for kHz operation, *Monzac, et al., Rev. Sci. Instr. 96, 043302 (2025)*

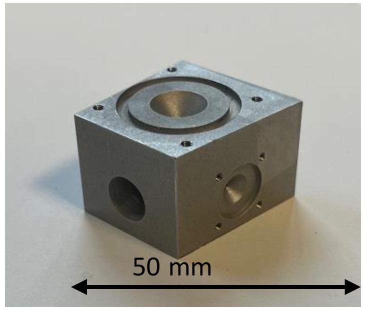


Asymmetric shocked micro-nozzles

Future work in PACRI

1. **100s MeV beam** using **100 W** average power laser in **LAPLACE-HC**
2. **Differential pumping** for 100 Hz operation
3. Testing and **improving nozzle resistance to 100 W laser power** and plasma heat





H_2 jet in differential chamber

IJClab gas cell type target development

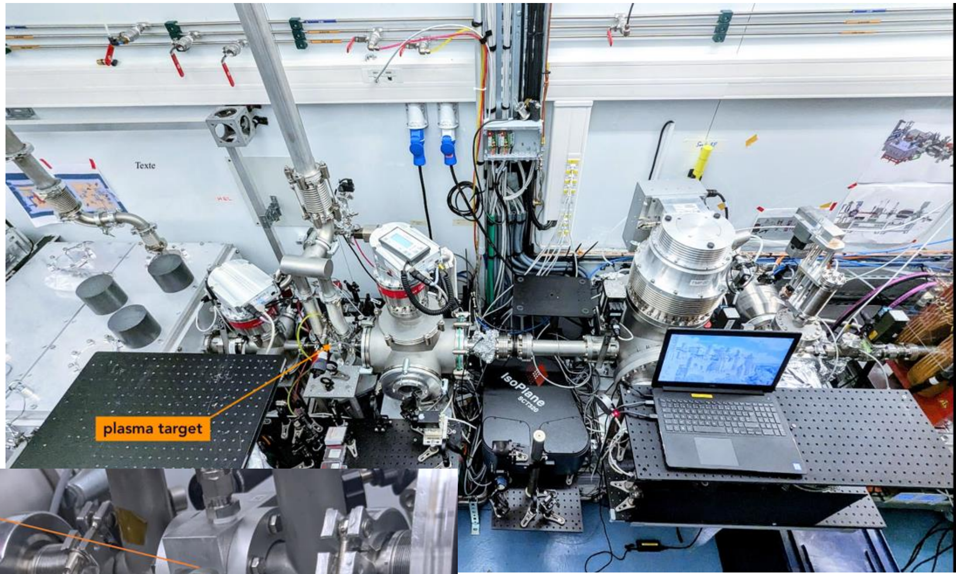
Various approach

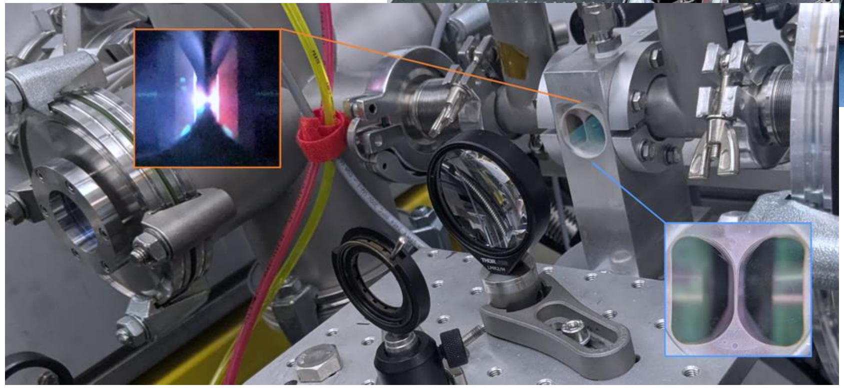
gas cell with multi chamber cell type, *P. Drobniak et al., RSI* 96, 033304 *(2025)*

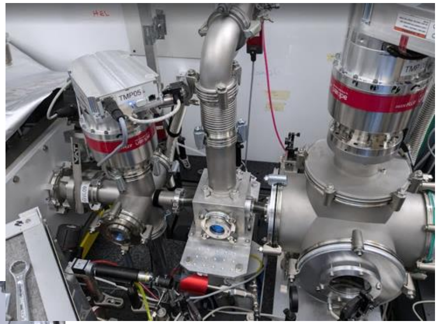
gas cell channel type (DESY/LUX-like) *P. Drobniak et al. in preparation (2025)*

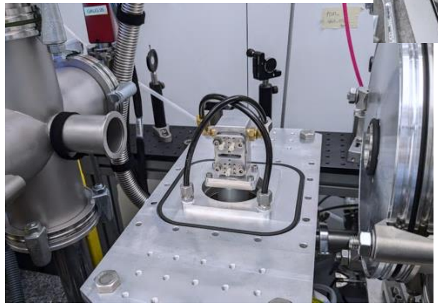
Differential pumping system for **continuous gas flow** with pressure range **1-100mbar** (multi species)

Beamline-integrated double cell target for laser-plasma electron injector, *Serhal et al., in preparation (2025)*









Future work in PACRI

1. Push **development of gas cell** for continuous gas flow **for HRR LPA**
2. **PALLAS beamline allow test various gas cell target test up to 15 W on target**
3. Collaborate to and **improve gas cell resistance to 100 W laser power** and plasma heat

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Preparatory Phase

Potential FRANCE CNRS LPA national node

Kevin Cassou on behalf CNRS involved labs

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Funded by the European Union

CNRS labs involved (EuPRAXIA)

4 labs (IJClab, LLR, LOA, LPGP) in the south Paris area gathering various expertise:

- **Simulations:** PIC, start to end modelling,), laser input GSA-MD, lasy, optimisation, AI/ML (Artifact network)
- **Facilities:** LAPLACE, PALLAS
- **Current project:** exploring HRR LWFA electron source, single stage GeV electron source, high quality electron, stability and control for applications, contribution to hybrid project

Current resources on accelerator and LWFA: ~ 35 FET

Preliminary : LPA French roadmap

French research network for accelerator R&D (SCIPAC) is in the process of defining a roadmap for 2028-2035.

Approach: Build on national expertise, unify the community, and align with **EuPRAXIA** challenges. The strategic objectives are:

1. Increase **reliability and control** of laser-plasma accelerator.
2. Increase the **average current** of laser-plasma accelerator ≥ 200 Hz.
3. Demonstrate **multi-stage** laser-plasma LINAC delivering **10 GeV, 100pC** with intermediate step matching **EUPRAXIA** phase 2

LPA French roadmap extract

🎯 Strategic Objectives

1. **Reliability and performance** of LPA
2. Achieve **≥ 200 Hz** repetition rate
3. Demonstrate **multi-stage LPA**

⚙️ Project Vision

- Build on French laboratory expertise and ongoing initiatives
- Federate the national laser–plasma acceleration community
- Develop an **electron source** tailored **to industrial and medical needs**
- Ensure complementarity with and contribute to the **EUPRAXIA** program
- Grow the community by involving experts **from conventional accelerator science**

📍Rationale & Impact

- Establish technological credibility and pave the way to societal and industrial applications
- Reinforce major French efforts (**LAPLACE**, **PALLAS**)
- Enable demonstration in **pilot applications**, including **FLASH radiotherapy**
- Transfer reliability advances directly to **EUPRAXIA**
- Support future high-repetition-rate operation (≥ 20 Hz initial phase)

⚡ Path to High-Energy LPA

- Long-term goal: laser–plasma linear accelerator beyond **100 GeV**
- Key milestone recognized internationally (ESPPU, SnowMass, Allegro): **10 GeV, 100 pC electron beams**
- High technical risk due to technological immaturity and limited community size

Phased approach: (1) Reduce technological risks via combined experimental + numerical studies **(2)** Multi-stage, high-energy implementation

LPA EuPRAXIA France national node

Funded by the European Union

LAPLACE HC

LOA

Development of **robust and stable HRR electron source in the 50-200 MeV** energy

- A 80 m^2 clean room (iso 6) to host the laser
- A **high-repetition rate Ti:sapphire laser developed by Thales. phase I (2024-2025)** : **100 Hz** repetition rate, **200mJ** laser energy on target, < 25 fs pulse duration FWHM.

phase II (starting 2026): the goal will be to reach **1 J** at 100-200 Hz, reaching **100 W** of average power

- A 50 m^2 radiation shielded area for the LPA is setup

LAPLACE HE

LOA

investigation of novel laser-plasma based accelerators in the GeV range

- A 180 m^2 clean room (iso 6) to host the laser
- A **350 TW Ti:sapphire laser system 6J, 25fs, 1 Hz**
- 2×200 m^2 radiation shielded area where up to 6 dedicated beamlines will be set-up

🚧 construction starting in 2026

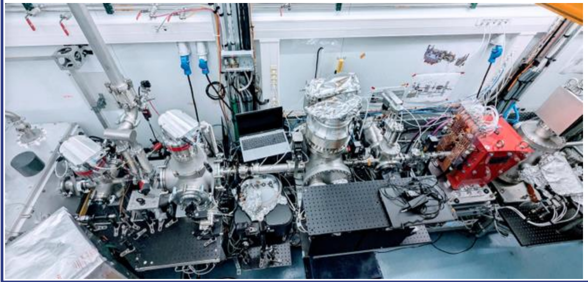
PALLAS

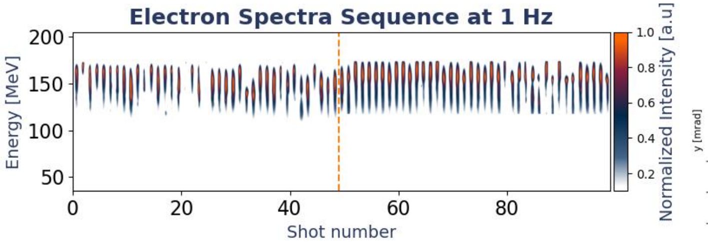
Laboratoire de Physique des 2 infinis Irène Joliot-Curie

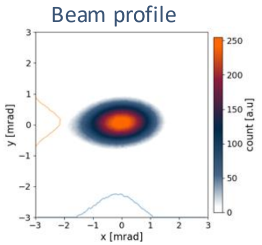
laser-plasma injector test facility aiming to achieve **reliability and control** comparable to conventional RF accelerator standards. Laser system 3.5J, 10Hz, 40 fs.

- advanced laser control
- plasma target development
- beam optimisation

⚡ **Commissioning has started** in spring 2025, first beam end of June with 1.5J, 1Hz delivering 160MeV beam, down to dE <12MeV, 20pC, ~ 1mrad – no stabilisation







LPA TDR contribution phase 1

laser development

Area of Collaboration	Interest (✓)	Scope of Contribution
Laser beam stabilization utilizing closed-loop feedback systems	✓	Active beam pointing stabilisation with high speed SiC mirror
Real-time Laser Diagnostics	✓	
Control system	✓	Tango control command, archiving, integration of standard laser diagnostics
AI and Machine Learning	✓	Application of AI/ML for automated and reliable laser operation.

Current status

At least one contact person per CNRS lab has actively joined the TDR working group lead by Alexander Molodozhentsev

- the collaboration must **define realistic phasing** for the TDR and setting the first FEL at EUPRAXIA@ELI-BL
- Coordination between national nodes is mandatory
- CNRS rely on **limited resources** (PACRI) and **no specific fund** for travel for the **TDR**

LPA scheme

Area of Collaboration	Interest (✓)	Scope of Contribution
Technical Design of the Laser Beam Transport and the entire setup	✓	Design of the phase 1 and 2 LPA beamline
Laser diagnostics in focus	✓	Integration of laser diagnostics for laser monitoring in the interaction region (focus region) from low to high energy. Multispectral camera. Laser wavefront control. Laser diags linked to modelling.
Plasma Source and real-time Plasma Diagnostics	✓	Tailored plasma target for various injection scheme, truncated ionisation injection, shock injection. Density out ramp for beam divergence mitigation. Gas jet, gas cell, differential pumping
Electron Injection and Beam Quality Control	✓	Simulation studies
Modelling, Online tuning and Control Algorithms	✓	**XOPT** library feedback experience. Development and test of implementing MOBO for LPI, surrogate models, multi-agents.
Control system (scalable control architecture) with feedback	✓	**Tango4LPA** initiative, simplification of installation and management for LPA setup. Archiving, investigation of feedback loop.
AI and Machine Learning	✓	Test of cloud deploy MLOps/feature store plug to control system with low latency for "real time" inference.
Experimental Demonstration (available beamline)	✓	Various possible beamtime in **PALLAS, LAPLACE** and programmatic laser beam time campaign on European laser facilities.
Others		Tools development (**GSA-MD**) and PIC input files for 1 GeV scheme single and 2-stage; dev and test for modelling of gas cell and long plasma code development for HOFI long channel modelling.