ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPS009

ADVANCING PLASMA ACCELERATOR SCIENCE: INSIGHTS FROM THE EUPRAXIA DOCTORAL NETWORK*

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Abstract

The EuPRAXIA Doctoral Network (EuPRAXIA-DN) trains the next generation of scientists in plasma-based accelerator technologies, addressing challenges in laser-plasma interactions, advanced beam diagnostics, and novel applications. This contribution highlights progress made in three critical areas: (i) real-time characterization of capillary discharge plasmas to stabilize laser-wakefield acceleration, (ii) femtosecond-precision X-band low-level RF (LLRF) control for a compact injector, and (iii) active-plasma-lens (APL)-based beam transport enabling extreme-ultraviolet free-electron-laser (EUV-FEL) operation within four meters of undulator. The innovative training elements within the network, such as the EuPRAXIA School on Plasma Accelerators held in Rome in April 2024 and upcoming EuPRAXIA Camps, are also discussed. It is shown how these foster knowledge exchange and skill development for the network's Fellows and the wider plasma accelerator community.

INTRODUCTION

Plasma-based accelerators promise to drastically reduce the size and cost of particle acceleration infrastructure while offering new opportunities for scientific discovery, industry, and medicine. EuPRAXIA, the European Plasma Research Accelerator with eXcellence in Applications [1], is the first European project to develop a compact multi-GeV accelerator based on these novel concepts. The project was added to the European Strategy Forum on Research Infrastructures (ESFRI) roadmap in 2021, marking its strategic significance.

EuPRAXIA-DN, launched in 2023, contributes directly to the preparation and delivery of this large-scale infrastructure [2]. With 12 Doctoral Candidates (DCs) recruited by institutions across Europe, the network targets critical scientific and technological questions through a coordinated research program structured around three Work Packages (WPs): Laser and Plasma science, Facility Design and Optimization, and Applications.

This paper presents research outcomes from three Fellows. Their work is framed within the broader scientific strategy of EuPRAXIA-DN, emphasizing how targeted R&D projects contribute to the realization of a user-ready, compact plasma accelerator infrastructure. In addition, this paper also highlights training, communication, and outreach actions, which form the backbone of the network's innovative approach to researcher development.

* Work supported by the European Union´s Horizon Europe research and innovation programme under grant agreement no. 101073480 and the UKRI Guarantee Funds.
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RESEARCH

The following research results are examples from across the three EuPRAXIA-DN work-packages and collectively span the EuPRAXIA acceleration chain. Alex Whitehead (WP2) reports the first fully mapped, time-resolved electron-density profiles of hydrogen capillary discharges, demonstrating <3 % rms stability over 6 mm and delivering the input data needed for matched laser-wakefield simulations. Phani Deep Meruga (WP3) presents an 11.994 GHz X-band LLRF prototype that achieves 0.011 % amplitude noise and 0.0105° phase jitter (2.4 fs), satisfying the targeted injector-synchronization specifications. Finally, Mihail Miceski (WP4) models an active-plasma-lens capture beamline that transports 1 GeV, 1 kA LPA beams into a 19 mm-period undulator and predicts EUV FEL saturation within 4 m. Together, these three studies tackle some of the highest-priority technical risks and showcase the network's integrated, cross-sector approach to plasma-accelerator R&D.

Electron Density in Capillary Discharge Plasma

To accurately measure electron density profiles in capillary discharge plasmas is essential for optimizing laser-plasma acceleration and producing high-quality electron beams. EuPRAXIA-DN Fellow Alex Whitehead (ELI ERIC) employed emission spectroscopy, specifically: the analysis of Stark broadening in hydrogen emission lines, to retrieve both, longitudinal and transverse electron density distributions [3]. This approach allowed investigating how capillary geometry and discharge parameters influence the plasma characteristics.

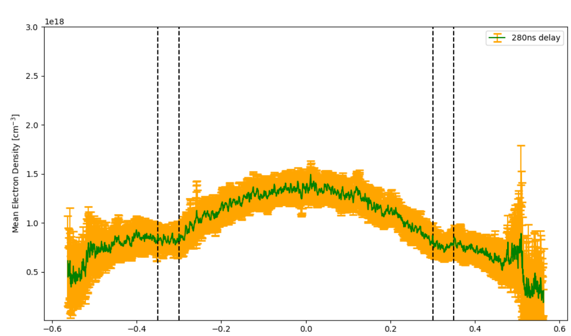

Figure 1: Longitudinal electron density measurement using a 10 mm long, 500 µm cross-section capillary at 25 kV, with an H_2 flow of 0.150 mg/s.

The electron density n_e was determined by measuring the Stark broadening of the hydrogen H_α line at 656 nm, using the relation $\Delta\lambda_{Stark} \propto ne^{(2/3)}$. This method takes advantage of the direct proportionality between the spectral line width

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and the plasma density. The plasma was generated by a high-voltage discharge through a capillary filled with pure hydrogen, with discharge currents peaking at approximately 300 A. Emitted light from the plasma was then collected with a lens and focused onto a spectrometer.

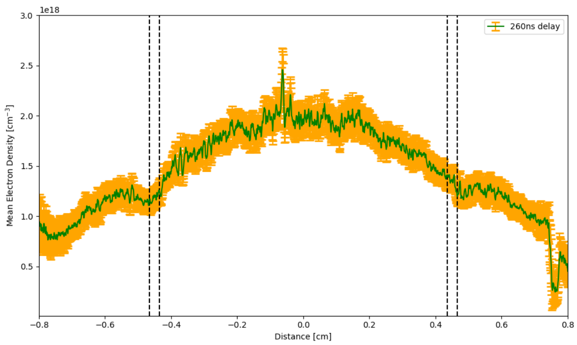

Figure 2: Longitudinal electron density measurement using a 15 mm long, 300 µm cross-section capillary at 25 kV, with an H_2 flow of 0.150 mg/s.

Longitudinal electron density profiles were then obtained via emission spectroscopy, and the effects of capillary geometry including length, cross-sectional area, and gas pressure on the measured electron density studied. Figures 1 and 2 show the results from measurements performed under identical gas flow and discharge conditions, with only the capillary geometry varied. It can be seen that the electron density measured in Fig. 2 is higher, but the plateau region exhibits greater fluctuations compared with Fig. 1. These fluctuations could potentially increase the divergence of the accelerated electron beam.

Additionally, the results highlight the importance of capillary length for effective acceleration. In both cases, the plateau region - where the electron density is suitable for acceleration - is shorter than the total capillary length, thereby limiting the effective acceleration distance. In a next step, real-time, high-repetition-rate electron density measurements using a Mach-Zehnder interferometer will be carried out. This will enable continuous monitoring of the plasma properties, facilitating further optimization of laser-plasma acceleration experiments.

X-Band LLRF Prototype for the EuPRAXIA SPARC_LAB Linac

EuPRAXIA@SPARC_LAB at INFN-LNF in Frascati, Italy is part of the broader EuPRAXIA project. It includes an X-band RF injector for high-gradient acceleration of up to 60 MV/m, enabling a significant reduction in the overall accelerator length. At the core of this advancement is the development of a novel X-band LLRF control system, which monitors and stabilizes the amplitude and phase of the accelerating cavity's RF fields to achieve femtosecond-level beam stability.

Currently, no commercial X-band LLRF systems are available to meet the pulse-based control needs of such a high-performance Linac. The R&D of Phani Deep Meruga (Instrumentation Technologies) is addressing this gap by developing a custom prototype tailored to the requirements of EuPRAXIA@SPARC_LAB [4]. The prototype consists of front-end and back-end modules, featuring single-stage down-conversion and double-stage up-conversion architecture. On the front-end, the input signals are digitized with 250 MSps using high-speed ADCs, performing real-time signal processing with an integrated FPGA, both implemented within the KADC-8 module.

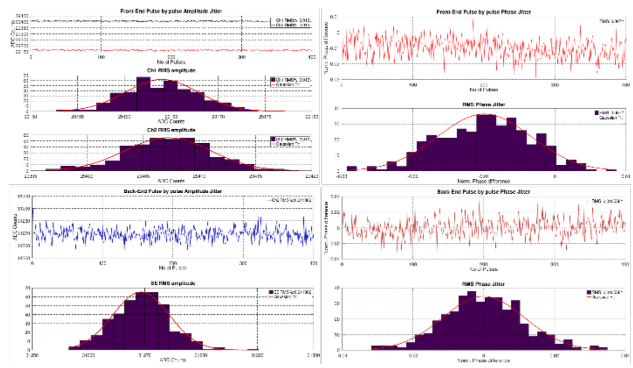

Figure 3: Measured pulse-by-pulse amplitude noise and phase jitter for front-end and back-end.

The X-band LLRF prototype was successfully tested in two phases, focusing separately on front-end and back-end performance, processing over 400 pulses of 150 ns duration as shown in Fig. 3. The demonstrated front-end amplitude noise of 0.013–0.014% RMS and phase jitter of 0.009° RMS are well within the EuPRAXIA requirements. The back-end was evaluated using a loopback configuration, in which the drive signal was connected to one of the front-end RF input chains for analysis. The system produced stable 11.994 GHz pulsed signals, achieving an amplitude noise of 0.011% RMS and a phase jitter of 0.0105° RMS (<2.5 fs). These results confirm the excellent signal fidelity and system stability in open-loop operation. Histogram analysis with Gaussian fitting confirms data reliability and repeatability. Overall, the prototype meets all performance targets and is ready for validation on the TEX facility test bench at INFN-LNF. These tests will validate system performance under realistic operating conditions, before moving toward system industrialization and commercial deployment.

Integration of Active Plasma Lens for Compact EUV Free-Electron Laser Beamline

The project of Mihail Miceski (ELI ERIC) investigates the design and simulation of a compact Free-Electron Laser (FEL) beamline powered by Laser-Plasma Accelerator (LPA) beams, integrating an Active Plasma Lens (APL) for effective electron beam capture and transport [5]. LPAs offer ultrahigh acceleration gradients, generating high-current, low-emittance electron beams ideal for FELs. However, their large energy spread and divergence hinder transport and coherent X-ray generation.

To address this, a beamline architecture that incorporates an APL to mitigate chromatic emittance growth and facilitate beam matching into the undulator section has been proposed. A beamline was designed using initial

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beam parameters of 400 MeV, 0.3 π mm·mrad normalized emittance, 0.2% energy spread and 5 kA peak current. This was modeled after experimental results from the Shanghai Institute of Optics and Fine Mechanics (SIOM). The APL, operating in the linear focusing regime with an 77 T/m gradient and 1 mm aperture radius, is placed 23 cm downstream of the plasma target to minimize emittance degradation. A subsequent quadrupole-based matching section ensures proper Twiss parameter matching for injection into the undulator.

The undulator section employs SwissFEL-type U19 modules with $\lambda_m = 19$ *mm* and $Ku = 1.4$, arranged in a FODO lattice with interspersed quadrupoles. The beamline is optimized to achieve FEL saturation in the extreme ultraviolet (EUV) range. Using Xie's 3D FEL scaling laws, the design predicts a gain length consistent with saturation within a 4 - 4.5 meter undulator length. Time-dependent simulations using GENESIS confirm saturation with pulse energies reaching ~40 µJ and peak powers of ~9 GW, see Fig. 4. Multiparticle tracking with TraceWin shows minimal emittance growth, validating the viability of APL integration. The total beamline length from source to undulator end is several meters.

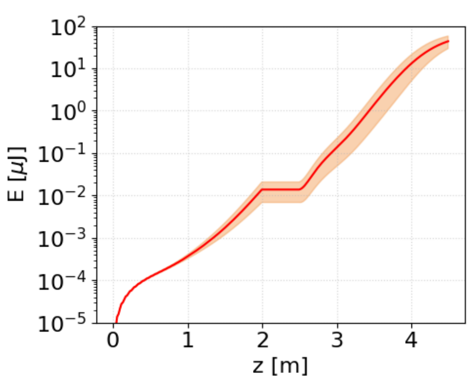

Figure 4: Radiation gain over the undulator length. The solid line represents the mean of the 15 shots with different shot noises, and the shaded region is the standard deviation.

This initial work demonstrates that an APL-enhanced LPA-FEL system is capable of producing high-brightness EUV pulses in a compact layout, supporting next-generation light source development at ELI-ERIC and within the EuPRAXIA framework.

TRAINING

EuPRAXIA-DN delivers a blended training program that combines local activities with network-wide events. Alongside established formats, such as its international seminar series, the network introduces novel opportunities which no single partner could provide, most notably hands-on accelerator-facility sessions that lie beyond the scope of typical university PhD schemes.

A joint, interdisciplinary researcher-skills school for EuPRAXIA-DN and the LIV.INNO Centre for Doctoral Training [6] ran in Liverpool between 13–17 November 2023, and a similar training was provided to the Fellows who were unable to join the first school between 20 – 24 January 2025 [7]. Tailored to the needs of two major training initiatives, the five-day courses balanced project-specific content with transferable-skills workshops. Topics ranged from project management, presentation and science communication to mental-health awareness, intellectual-property protection and knowledge transfer. A follow-up "final-year" school focused on entering the global job market is scheduled for Liverpool in July 2026.

This collaborative model was praised at the European Commission's MSCA Coordinators' Day that was held in Brussels on 8/9 November 2023, livestreamed to over 1,000 attendees. In its first session on cross-network synergies, the EuPRAXIA-DN Coordinator presented the consortium's strategies and highlighted resulting benefits for partners and Fellows.

Further specialized trainings followed: during a Media Training Week in Manchester's *MediaCity* between 20–24 November 2024, partner Carbon Digital coached the Fellows through storyboarding, scripting, filming and editing. The outcome, a short film introducing the Fellows, their research and the network's training offer, now streams on YouTube with subtitles in 13 languages [8]. The film was highlighted as excellent practice in project communication by the European Commission.

EuPRAXIA-DN also hosted an International School on Plasma Accelerators in Rome between 22–26 April 2024. Featuring lectures by leading scientists and industry experts, including 2023 Nobel laureate Professor Anne L'Huillier, the event's full lecture archive is available via the school's indico page [9], providing a lasting resource to the wider community. Finally, the network has started to organize EuPRAXIA Camps – scientific workshops that focus on the technologies [10], science [11] and applications of EuPRAXIA. Information about all past and future events can be obtained via the network's homepage [12]. EuPRAXIA-DN also publishes a quarterly newsletter that goes out to the wider plasma accelerator community.

CONCLUSION AND OUTLOOK

In its first two years EuPRAXIA-DN has removed several of the most pressing technical uncertainties on the road to a compact, user-ready plasma accelerator: sub-3 %-rms stability maps of hydrogen capillary discharges now feed matched LWFA simulations; an X-band LLRF prototype has achieved <0.012 % amplitude noise and <2.5 fs phase jitter, meeting injector specifications ahead of forthcoming TEX-bench validation, and active-plasma-lens transport studies predict EUV-FEL saturation within 4 m of undulator for 1 GeV, 1 kA LPA beams, confirming the viability of meter-scale light sources. These results, produced by Fellows embedded in a deliberately cross-sector research ecosystem, underline the effectiveness of EuPRAXIA-DN's integrated R&D and training strategy. With real-time plasma-diagnostics upgrades, full-system LLRF commissioning and experimental APL tests, the network is well on course to deliver the technology and talent base required for EuPRAXIA and the wider adoption of plasma-based accelerators in science, industry and medicine.

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