

BREAKTHROUGHS IN EUPRAXIA-DN ON THE PATH TO NEXT-GENERATION PLASMA ACCELERATORS*

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Abstract

The EuPRAXIA Doctoral Network (EuPRAXIA-DN) has delivered major advances over the past year in laser-plasma physics, beam diagnostics, and compact radiation-source concepts. Experiments demonstrated superradiant nonlinear Thomson scattering, showing collective enhancement of radiation from relativistic electron bunches interacting with azimuthally polarized laser pulses. Diagnostics developments include new methods to retrieve femtosecond longitudinal bunch profiles from coherent THz transition-radiation images, as well as preliminary shot-to-shot charge measurements in high-EMP environments using diamond detectors, supported by high-precision characterization of the detector.

This contribution presents these important results in the context of the broader EuPRAXIA-DN project. It highlights how coordinated R&D, structured training, cross-sector international secondments, EuPRAXIA Schools and Camps, as well as hands-on training at world-class research facilities accelerate the technological progress and talent pipeline required for compact, user-ready plasma accelerators.

INTRODUCTION

Plasma-based accelerators show excellent potential to reduce the size and cost of research infrastructures 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 with reliable beam quality. The project was added to the European Strategy Forum on Research Infrastructures (ESFRI) roadmap in 2021.

The 3.2 M€ EuPRAXIA-DN was launched in 2023, funded by the European Union and the UKRI Guarantee Fund. It contributes directly to the preparation and delivery of the EuPRAXIA infrastructure [2] and trains 12 Doctoral Candidates that are based at institutions across Europe and supports a coordinated research program. The network features three scientific Work Packages (WPs) on Laser and Plasma science, Facility Design and Optimization, and Applications.

This paper gives an overview of the research outcomes from three Fellows and puts their results into the wider context of the network. In addition, key results from the network's training, communication, and outreach activities are also described.

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RESEARCH

The following section presents results from the interdisciplinary research within EuPRAXIA-DN. This includes advanced beam diagnostic and sensor development, as well as a key application in the generation of superradiant single-cycle light pulses.

Ultra-short Bunch Length Measurements with fs Resolution

Ultrashort electron bunches produced in the femtosecond (fs) range in plasma accelerators require high-resolution longitudinal diagnostics, with the added challenge of making them cost-effective while maintaining a compact size compatible with the reduced footprint of future plasma accelerator facilities. Polarization radiation such as transition, diffraction or Smith-Purcell radiation is a suitable source of information for recovering the particle distribution from its longitudinal form factor. By analyzing its coherent spectral components across frequencies from the THz to the optical region, bunch lengths ranging from a few hundred fs to sub-fs can be measured.

EuPRAXIA-DN Fellow Ana Maria Guisao Betancur at the Cockcroft Institute/University of Liverpool in the UK develops a diagnostic that is based on imaging the source of transition radiation by placing a broadband camera at the image plane to capture the point-to-point spatial distribution of the coherent transition radiation (CTR). A monitor prototype has been designed, installed, and is currently being tested at the MAX IV facility in Sweden, in the THz to near infrared range, to study bunch lengths down to their operating limit of $\tau_{FWHM} \approx 10$ fs [3]. The spatial features of the broadband image contain information about the original profile that generated the radiation. Image analysis allows for the determination of an apparent bunch length, the description of some particle distribution features [4], and, with deep learning, even the reconstruction of the full bunch profile [5].

Data taken at the MAX IV Short Pulse Facility have shown promising results. Two acquisitions are taken at each datapoint: (a) bunch profile reference data from a Transverse Deflecting Structure (TDS) and (b) corresponding CTR images. A sample parameter scan is shown in Fig. 1, varying the current at the sextupoles (SX01) at the bunch compressor (BC1). Using the second moment to estimate an apparent length metric, it is shown how the size of the CTR image follows the equivalent change in the bunch length for this particular operation on the bunch compressor.

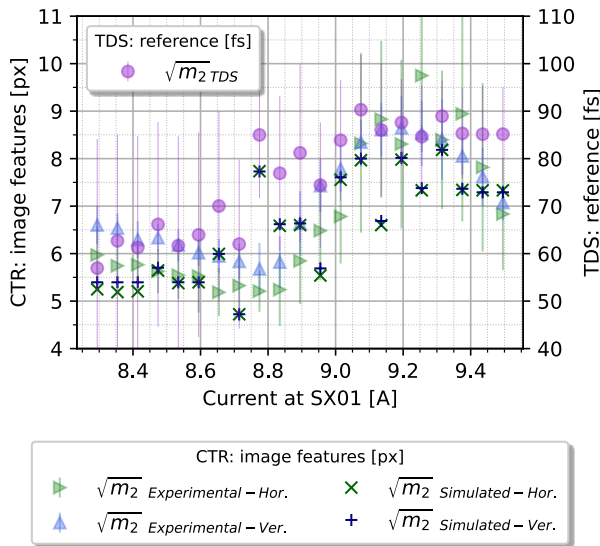


Figure 1: Comparison between effective bunch profile lengths from the TDS and corresponding image features from experimental and simulated CTR spatial images.

The data shows a complex relationship between the bunch profile length and features, and the resulting image. The complexity of the measurement makes a full analysis challenging. Current efforts focus on attempting to reconstruct the full profile using deep learning powered by a mixture of simulated and experimental data.

Development of Integrated Diagnostics for Plasma Accelerators

Single-crystal chemical vapor deposition (sCVD) diamond detectors are widely known for their robustness, fast response, and excellent charge collection efficiency. Within EuPRAXIA-DN, they are being studied for use in shot-to-shot charge measurements in plasma accelerators by Divya, based at CIVIDEC GmbH, Austria. In recent measurements 500 μm -thick sCVD diamond detectors achieved an energy resolution of (16.7 ± 0.2) keV FWHM for 5.485 MeV alpha particles, representing one of the best reported resolutions. This performance was obtained without offline signal processing or peak fitting, demonstrating the intrinsic signal quality of the detector. The measured ^{241}Am alpha spectrum showed that four distinct peaks corresponding to characteristic alpha energies can be clearly resolved, see [6] for details.

Several experimental campaigns were carried out at the Lund High Power Laser Facility [7, 8] to evaluate the suitability of sCVD diamond detectors for real-time beam monitoring in high-intensity fs laser-plasma environments. A 43 μm -thick sCVD diamond sensor with a 4×4 mm² active area, biased at $1.2 \text{ V } \mu\text{m}^{-1}$, was used. Preliminary results show an excellent detector response without requiring digital filtering or signal amplification. The signals were recorded using a 50 Ω -terminated data acquisition system. Fig. 2 shows the raw detector pulses recorded over 50 consecutive shots at a beam axis offset of -5 mm. The signals exhibit a highly stable pulse shape for ultrashort electron bunches with a consistent pulse width

of (1.6 ± 0.03) ns FWHM, reaching peak currents of up to 200 mA. The excellent shot-to-shot reproducibility demonstrates the detector's capability for single shot beam diagnostics in plasma accelerator environments.

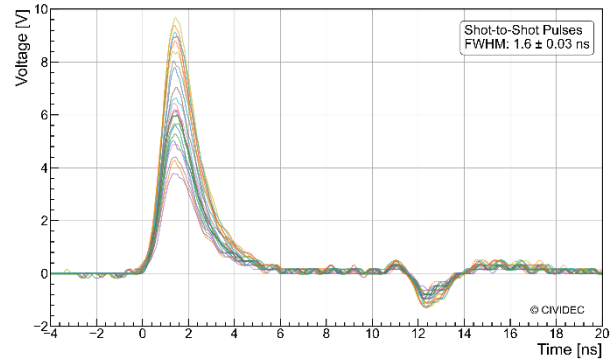


Figure 2: Raw detector pulses from 50 consecutive shots at a beam axis offset of -5 mm, demonstrating stable signal shape and reproducibility.

In a next step, bunch charge reconstruction from the detector signal was performed based on energy deposition and electron-hole pair creation energy in diamond. This allowed to successfully reconstruct the transverse intensity profile, yielding a maximum charge of 0.27 pC at the beam core. These results provide insight into the detailed beam dynamics and shot-to-shot charge and pointing stability. As each bunch originates from an independent laser-plasma interaction, the data inherently reflects the stochastic nature of the beam. These results establish a baseline for future experiments where an impedance-matched readout will be installed closer to the in-vacuum interaction point, enabling improved bunch capture.

Superradiance from Non-linear Thomson Scattering

While plasma accelerator-based light sources are intrinsically ultra-short and collimated, they typically produce incoherent radiation where the peak intensity grows linearly with the number of emitters. Achieving superradiance, characterized by a quadratic scaling of the intensity [9, 10], is a critical goal for making these sources competitive with large-scale facilities. The work of EuPRAXIA-DN Fellow Bhushan Thakur at IST, Portugal explores using structured laser pulses to induce the necessary electron bunching for such coherent emission.

The interaction is modeled using the 3D particle-in-cell (PIC) code Osiris [11], with radiation analyzed via the RaDiO diagnostic tool [12]. The setup involves a relativistic electron bunch having flat-top distribution co-propagating and interacting with an azimuthally polarized laser pulse with a wavelength of 1,000 nm and pulse duration of 109 fs. These pulses feature electric field vectors forming circular loops around the beam axis, creating a strong magnetic field along the optical axis [13]. As the electron bunch co-propagates with the laser in vacuum, it undergoes micro-bunching at approximately the laser period. The majority of the radiation is emitted at small angles with respect to the propagation axis.

To confirm superradiant behavior, the scattering process was analyzed at multiple charge densities. Superradiance is characterized by the electric field amplitude scaling linearly with density, leading to a quadratic scaling of radiation intensity as can be seen in Fig. 3. With increasing density, the interparticle distance becomes smaller than the radiation wavelength. At this stage the particles begin to radiate in phase leading to coherent emission.

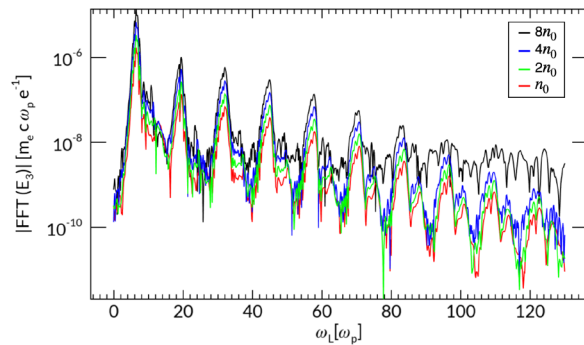


Figure 3: Higher harmonics in the radiation spectrum can be observed at different electron densities.

As the density doubles, the electric field amplitude at the fundamental frequency doubles proportionally, resulting in a quadratic intensity relation with respect to the electric field. The results confirm this linear scaling of the electric field strength for the first 13 harmonics. Beyond this order, the predictable scaling begins to deviate, and the spectrum becomes dominated by noise, most likely due to reduced bunching efficiency at higher densities or the influence of bunch substructures. The resulting single-cycle light pulses and their harmonics span the soft X-ray and EUV ranges, offering a compact route to high-brightness coherent sources. Future work will characterize the micro-bunching mechanism, different polarizations and spatiotemporal field structures, and fully determine the polarization and angular momentum of the emitted radiation.

TRAINING

The EuPRAXIA-DN training program combines local supervision and specialist instruction with network-wide activities that foster interdisciplinary collaboration and transferable skills development. Beyond traditional doctoral training, the network offers its Fellows access to hands-on experience at leading accelerator laboratories and coordinated international activities that no individual institution could provide independently.

A central element of the program is the development of broad researcher competences alongside scientific excellence. To support this, EuPRAXIA-DN and the LIV.INNO Centre for Doctoral Training jointly organized an interdisciplinary Researcher Skills School in Liverpool between 13-17 November 2023, followed by an additional training week for Fellows unable to attend the first event between 20-24 January 2025 [14, 15]. The school combined scientific and professional-skills training tailored to the needs of the doctoral network. Sessions covered areas including project management, scientific

writing, presentation techniques, communication, teamwork, intellectual property, knowledge transfer, and researcher wellbeing. A further advanced career-skills school, focusing on career development, will take place in Liverpool in July 2026.

Complementing these activities, EuPRAXIA-DN organized a Media Training Week at Manchester's MediaCity between 20-24 November 2024 in collaboration with award-winning company Carbon Digital. The Fellows received practical training in storyboarding, scripting, filming, and editing scientific outreach content. The resulting short film, showcasing the Fellows, their projects, and the network's training environment, is available online with subtitles in 13 languages [16]. The initiative was recognized by the European Commission as an example of effective project communication and outreach.

Specialist scientific training was further strengthened through the EuPRAXIA-DN School on Plasma Accelerators, organized in Rome from 22-26 April 2024 in partnership with INFN. The interdisciplinary school introduced the fundamentals of plasma acceleration, beam and plasma diagnostics, laser- and beam-driven acceleration concepts, injection techniques, and high-impact projects such as EuPRAXIA and AWAKE. Lectures were delivered by leading scientists and industry experts, including 2023 Nobel Laureate Professor Anne L'Huillier. Lecture materials remain publicly available via the school [indico page](#) [17]. To promote scientific exchange across the three Work Packages, the network also launched a series of EuPRAXIA Camps focusing on technologies [18], science [19], and innovation [20] using plasma accelerators. These events brought the Fellows together in smaller workshop-style meetings to strengthen collaboration and encourage interdisciplinary discussion. Information on all past and future activities is available through the network website [2]. In parallel, EuPRAXIA-DN continues to engage the wider accelerator community through its quarterly newsletter and coordinated outreach activities.

CONCLUSION AND OUTLOOK

In its first three years the EuPRAXIA-DN Fellows have made major progress in their research. Novel diagnostics with superior time resolution, versatile sCVD diamond detectors and improved ways to generate high-quality radiation are just three examples that were discussed in this paper. All these technologies and techniques will benefit EuPRAXIA directly, whilst also showing excellent potential for application at other short-pulse facilities. The structured training program of this doctoral network is seen as one of the best postgraduate schemes in Europe, and the network coordinator was invited to speak at the European Commission-hosted special event on "More than a PhD: The added value of MSCA doctorates" celebrating the 30th anniversary of the MSCA in Brussels on 24/54 June 2026. Many of the EuPRAXIA-DN Fellows will graduate later this year and there is strong interest in establishing a follow-up project which trains the next generation of PhD candidates focusing on the applications that EuPRAXIA will enable.

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