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EUPRAXIA DOCTORAL NETWORK*

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Abstract

EuPRAXIA is the first European project that develops a dedicated particle accelerator research infrastructure based on novel plasma acceleration concepts and laser technology. It focuses on the development of electron accelerators and underlying technologies, their user communities, and the exploitation of existing accelerator infrastructures in Europe. It was accepted onto the ESFRI roadmap for strategically important research infrastructures in June 2021 as a European priority.

To fully exploit the potential of this breakthrough facility, advances are urgently required in plasma and laser R&D, studies into facility design and optimization, along a coordinated push for novel applications. EuPRAXIA-DN is a new MSCA Doctoral Network for a cohort of 12 Fellows between universities, research centers and industry that will carry out an interdisciplinary and cross-sector plasma accelerator research and training program for this new research infrastructure. This paper gives an overview of this interdisciplinary network and its research.

INTRODUCTION

Several tens of thousands of particle accelerators are in use today with varied applications in research, industry, medicine and other fields. Yet accelerator usage could be more widespread, were it not limited by cost and size constraints, especially in hospitals, universities and small and medium size companies.

A possible solution to this bottleneck is the development of more compact – and consequently more cost-efficient – accelerator technologies, a strategy that has been investigated in the past two decades bringing forth plasma accelerators as one of its most promising candidates. In plasma accelerators, a driver, i.e. a relativistic particle bunch or a femtosecond, high intensity laser pulse – propagates through a plasma target – typically an ionized gas plume – creating a longitudinal plasma wave in its wake. Due to the charge dynamics inside the plasma wave structure, accelerating and focusing electric fields on the order of hundreds of GV/m are generated. These allow the acceleration of particle beams to energies of hundreds of MeV to several GeV within structures approximately two to three orders of magnitude smaller than equivalent RF cavities. With first theoretical predictions of plasma acceleration made in 1979 , corresponding experimental techniques have been developed in particular in recent years reaching both energy records and technological milestones, including the staging of multiple plasma accelerator structures , the generation of plasma-based undulator radiation and the development of first phase-space control mechanisms.

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Funded initially as a Horizon 2020 Design Study between 2015 to October 2019, the EuPRAXIA (European plasma accelerator with excellence in applications) project investigates and compares both, existing and possible new approaches in plasma acceleration to develop a facility design comprising several specialized beamlines and user areas with the most suitable technology. It comprises laser-driven, electron beam-driven, as well as hybrid acceleration approaches. The consortium published a Conceptual Design Report for this breakthrough facility in 2020 [1] which outlines the design of the EuPRAXIA accelerator as a distributed European research infrastructure.

Following a thorough evaluation and selection procedure, ESFRI proudly announced on 30 June 2021 that EuPRAXIA will now be included in its strategic roadmap of priority research infrastructures. This game-changing facility shall produce versatile beams for a range of applications at lower costs and smaller footprint than what can be achieved with more conventional radiofrequency accelerators. On 1 January 2023, the new EuPRAXIA Doctoral Network (EuPRAXIA-DN) was launched [2]. A formal kick-off meeting was held in Brussels on 15-17 January 2023, see Fig. 1. The project has received 3.2 M€ in funding from Horizon Europe and the UKRI Guarantee Funds. The doctoral candidates in this network carry out an interdisciplinary and cross-sector plasma accelerator research and training program that will benefit the EuPRAXIA facility.

Figure 1: Participants in the EuPRAXIA-DN kick-off meeting at the European Parliament in Brussels.

RESEARCH

To advance EuPRAXIA towards user and application readiness, however, beam quality as well as accelerator control and stability must still be improved significantly. The EuPRAXIA Doctoral Network (EuPRAXIA-DN) cap-

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italizes on the existing EuPRAXIA consortium and will address some of the key challenges of this research facility across three scientific Work Packages (WPs):

- **Laser & Plasma**, combining laser shaping and characterization with cutting edge research into plasma formation;
- **Facility Design and Optimization**, studying advanced beam diagnostics methods to fully characterize the beams in EuPRAXIA, along new accelerating technologies that enable high-gradient acceleration and hence more compact schemes;
- **Applications**, studying next-generation compact light sources, medical applications and micro accelerators, driven by THz radiation.

The sections below give one example for the R&D that will be carried out in each of these three work packages.

Laser & Plasma

This WP will tackle an overall optimization of the accelerated electron beam by carrying out comprehensive studies into the optimization of the laser and plasma parameters. The project at CNR-INO will focus on the manipulation and characterization of ultrashort laser pulses for high-quality electron bunch acceleration. The production of high-quality bunches, in terms of key parameters such as energy spectrum and emittance, is currently recognized as one of the main challenges for the development of innovative, plasma-based electron accelerators for applications. In the framework of Laser Wake Field Acceleration (LWFA), the production of high-quality bunches heavily depends on the capability to inject bunches into the plasma wave in a well-localized and controlled manner. While the quality of bunches produced via self-injection in the so-called bubble regime has been steadily increased in recent years, advanced injection schemes have been studied for advanced accelerators, such as injection in density down-ramp and shock, colliding pulses and ionization injection. In the framework of the latter approach, a “two-colour” scheme, envisioning the usage of a long (~10 micron) wavelength pulse to drive the plasma wave and a shorter wavelength pulse for ionization injection, was proposed [3]. More recently, an evolution of this scheme, called “REMPI”, was proposed by the CNR-INO group [4] and predicted to deliver bunches with very high quality, i.e. $\varepsilon<0.1$ mm·mrad and $\Delta E<1\%$ while using a single Ti:Sa laser. Such an approach is based on the usage of a train of ultrashort pulses to resonantly drive the plasma wave while avoiding any electron injection and of a pulse at a harmonic of the laser fundamental frequency to trigger the ionization injection; in contrast to the original proposal, such a scheme allows the usage of a single laser chain, possibly based on the well-consolidated Ti:Sa laser technology, and has been down-selected as one of the possible approaches for the EuPRAXIA laser-driven injector. One of the main challenges is the possibility of generating a train of ultrashort pulses, starting from a single laser chain. A few schemes have been proposed to accomplish this task [5, 6]. Recently, the excitation of plasma wave by multiple pulses was demonstrated [7], using a sequence of pulses obtained via the partial recompression of a sequence of two stretched pulses obtained via a Michelson interferometer. More recently, a scheme based on the usage of delay masks has been proposed by the CNR-INO group [8]. The translation of these methods of pulse train generation to high (average and peak) power laser systems for driving high quality accelerators may be hindered by issues related to the “quality” of the pulse train, as well as to the overall energy efficiency.

Facility Design and Optimization

Ultra-short bunch length measurements with femtosecond resolution are required to fully characterize the beams in EuPRAXIA. A doctoral candidate at the University of Liverpool/Cockcroft Institute will develop a new technique that provides excellent time resolution whilst being non-invasive. Currently, longitudinal diagnostics with such resolution is limited to only a handful of solutions [9-11]. Each one has their strengths and weaknesses, but generally there is a compromise between longitudinal profile resolution, number of shots required, and ease of application. The Fellow will develop a new longitudinal profile monitor based on broadband imaging of coherent radiation which is simple to operate on a shot-to-shot basis, and provides fs-resolution of the bunch profile width and features.

Transition radiation has a broadband spectral distribution, of which a specific bandwidth is typically studied. If this bandwidth contains wavelengths comparable to or exceeding the bunch length of the source bunch, the radiation will be coherent. A THz-based imaging system has been developed by the University of Liverpool to image the source distribution of coherent transition (CTR) or diffraction radiation (CDR) which theory and simulations have shown is dependent on bunch length [12]. A comparison of the bunch lengths obtained with this method and ELEGANT simulations was done and an excellent agreement between the measured CTR and the ELEGANT FWHM bunch length values was found. The Fellow will use this framework to progress the monitor towards a non-invasive single-shot method of measuring detailed longitudinal profile information. They will study optimum integration so the monitor can operate online and non-invasively. They will then integrate machine learning techniques to combine this monitor with existing diagnostic systems to develop a suite of so-called “virtual diagnostics” for EuPRAXIA and beyond. This process will involve implementing several diagnostics upstream and, crucially, away from the interaction point (IP). By using a combination of invasive diagnostics at the IP and machine parameters, a machine learning model will be developed which directly maps beam parameters upstream, to those at the IP. Once this training is complete, the IP diagnostics can be removed, and the measurements upstream will form a robust, online, virtual diagnostic system for the IP.

Whilst targeting the specific parameters of EuPRAXIA, an emphasis will be on developing a technique that can be easily integrated into essentially any short pulse accelerators, i.e. also including Free Electron Lasers or other plasma accelerator schemes such as AWAKE [13].

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Applications

A doctoral candidate at the newly formed ELI ERIC will work on a laser-driven undulator coherent radiation source by optimizing electron beam transport between the laser-plasma interaction chamber and the undulator section where the radiation is generated.

High quality radiation requires preserving the quality of the electron beam by using a combination of advanced all-optical, i.e. active lensing mechanisms based on capillary discharge physics, and more conventional magnetic systems. This work will include updating the existing experimental technologies at the LUIS setup so that operation can be done with high energy electron beams, as well as developing enhancements of the existing electron beam diagnostics in collaboration with the Fellows in WP2.

Established beam transport codes will be used for optimizing the electron beam quality at the location of the undulator. This will form the basis for modeling the FEL mechanics to optimize the undulator sections with at least four in-vacuum undulators with a variable-gap. This is required for reaching the saturation regimes for both, self-amplified-spontaneous-emission (SASE) and seeded FEL regimes. Matrix detectors will then be studied to enable active lensing based on capillary discharge.

TRAINING EVENTS

Training within EuPRAXIA-DN consists of research-led training at the respective host, in combination with local lectures, as well as participation in a network-wide training program that is also open to external participants. This training concept builds on the successful ideas developed through a large number of pan-European networks initiated and coordinated by the author, going back to the initial DITANET project [14].

All Fellows will be enrolled into a PhD program and thus embedded into a structured course program at their host university or, if their work contract is with an industry partner or a research center, with a collaborating university. Courses at the PhD awarding institution include lectures on plasma physics, accelerator science and technology, electronics, detector design, as well as courses on the local language. In addition, network-wide events will be organized that are also open to external participation. All EuPRAXIA-DN Fellows will complete a dedicated researcher skills training at the University of Liverpool in November 2023. This week-long training will include sessions on project management, presentation skills, and communication of research outcomes to diverse audiences, as well as IP rights and knowledge transfer. Directly afterwards, the Fellows will follow a media training at MediaCityUK, Manchester, organized in close collaboration with experts from Carbon Digital. This will teach the Fellows the essential skills of video production and allow them to produce their own project video.

A week-long school, open to Fellows in the network, as well as up to about 50 external participants on ‘Plasma Accelerators’ will be organized in summer 2024. The interdisciplinary event will bring together all research areas within EuPRAXIA-DN. The school will introduce the basic principles of plasma accelerators, including basic plasma physics, laser- and beam-driven acceleration, plasma injection schemes, plasma and beam diagnostics, particle-in-cell codes, as well as specific high impact projects, including EuPRAXIA and AWAKE. Tutorial sessions in smaller problem classes will reinforce content and promote discussion. All participants will be given the opportunity to present their own research in a poster session.

To further enhance knowledge exchange and ensure that all Fellows are exposed to the techniques and methodologies developed in the other WPs, three 2-day training Camps covering two scientific WPs at a time will be organized. They are spaced by 3 months after the School so that Fellows can meet on a very regular basis, supporting the creation of strong bonds within the network.

- **EuPRAXIA-DN Camp I** will cut across WP2 and WP3 and cover laser and plasma technology and relate the physics with advanced beam instrumentation developments and HPC simulations, as well as the integration of all of these technologies into a common accelerator control system.
- **EuPRAXIA-DN Camp II** will target the science enabled by the EuPRAXIA facility and bridge between WP2 and WP4. It will discuss breakthrough measurements that will be enabled by advances in laser and plasma R&D.
- **EuPRAXIA-DN Camp III** will discuss the innovations that EuPRAXIA will enable, combining the new technologies from WP2 and the innovative applications in medicine, biology, chemistry and material science studied in WP4.

Each Camp will be split in sessions and each of the session topics will be led by an invited keynote speaker who will give a talk on the state-of-the-art in that topic area. This will then be followed by presentations given by the network’s Fellows working in this area and selected contributions from other delegates. Discussion time will be included for each session and there will also be more general discussions at the end of each day linking between WPs and defining research requirements on the short and medium term. A special Symposium with a focus on industry collaboration and innovation will be held in Liverpool on Friday, 10 July 2026 and in that same year, a 3-day international conference will be (co)-organized, with a focus on the novel techniques and technologies developed within the network. All events will be announced via the EuPRAXIA-DN home page [2].

SUMMARY AND CONCLUSION

The EuPRAXIA Doctoral Network has started on 1 January 2023 and will train 12 Fellows in cutting-edge plasma accelerator R&D over the next four years. This paper gave examples from the wide-ranging research program and outlined the interdisciplinary training that will be offered to the doctoral candidates. The aim to engage with the wider accelerator community was highlighted.

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