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FIRST RESULTS FROM THE EUPRAXIA DOCTORAL NETWORK: PAVING THE WAY FOR NEXT-GENERATION PARTICLE ACCELERATORS*

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Abstract

This paper presents initial findings from the 3.2 million Euro EuPRAXIA Doctoral Network. The European Plasma Research Accelerator with eXcellence In Applications (EuPRAXIA) is at the forefront of advanced particle accelerator research, focusing on the development of plasma-based accelerator technologies.

The EuPRAXIA Doctoral Network, a collaborative effort among leading research institutions, is dedicated to exploring and advancing the frontiers of plasma-based particle acceleration. The network's research involves a wide range of topics, from beam diagnostics and optimization techniques to new applications. Here, we present the innovative approaches and methodologies employed to achieve very high acceleration gradients, improve the energy sharpness and overall beam quality. Some of the early research results of this new network are discussed, showcasing the progress made across the network's three scientific work packages. The paper also gives an overview of the initial training provided to the network's Fellows.

OVERVIEW

EuPRAXIA is the first European project that develops a dedicated particle accelerator research infrastructure based on novel plasma acceleration concepts and laser technology [1]. It focuses on the development of electron accelerators and underlying technologies, their user communities, and the exploitation of accelerator infrastructures in Europe. It was accepted onto the ESFRI roadmap for strategically important research infrastructures in June 2021.

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. The 3.2 M€ EuPRAXIA Doctoral Network (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 [2]. The network focuses on scientific and technical innovations and on boosting the career prospects of its Fellows.

The first year of EuPRAXIA-DN has focused on the recruitment of the Fellows, finalizing the research and secondment plans between network partners, as well as effective project communication and establishing the management structure of the project.

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RESEARCH

To advance EuPRAXIA towards user and application readiness, EuPRAXIA-DN addresses some of the key challenges across three scientific Work Packages (WPs):

- Laser and 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 following subsections describe progress made in three out of the twelve research projects in the network to exemplify progress made.

Manipulation and Characterization of Ultra-short Laser Pulses for High-quality Electron Bunch Acceleration

In order to establish EuPRAXIA as a new research infrastructure for industry applications, the generation of high-quality electron beams is essential. One of the reasons for a potential degradation of the quality of the electron beam in plasma accelerators is the quality of the interacting laser pulse itself. This quality can be affected by dispersive and nonlinear effects that occur in refractive optics.

For this reason, Off-Axis Parabolic (OAP) mirrors have become a standard in many high power laser facilities, including the Intense Laser Irradiation Laboratory at CNR-INO in Pisa, Italy, operating a laser system with a peak power of up to 220 TW, <25 fs laser pulses at an energy of more than 5 J [3]. The reason for using this type of mirror is the achromaticity and possibility of transporting extremely high intensities as they do not exhibit the inherent Fresnel losses or absorption of bulk material. However, when dealing with ultra-short and ultra-intense laser pulses, the temporal and spatial structure of the electric fields in the focal region of the OAPs need to be understood in very good detail, especially under tight focusing conditions where $N_f \leq 1$. In order to study ultrashort laser pulses, a broad wavelength spectrum needs to be taken into account. For this reason, EuPRAXIA-DN Fellow David Gregocki, based at CNR-INO, implemented this feature into an existing light transport code written in C++ [4]. He added the imaginary part of the laser pulse's electric field

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to obtain full information in the spectral domain and to retrieve the duration of the pulse in the time domain.

In his simulations, the OAP mirror radius was *R=76.2 mm* with $\theta_{OA} = 6°$, the central wavelength λ_0= *800 nm*, $\sigma_\lambda = 30$ *nm*, and the wavelength spectrum in the range between 618 nm and 1,130 nm in increments of 0.5 nm was considered, i.e. using 1,024 iterations in total. N_f was picked at random, and the parent focal length *f* was calculated using N_f=*f/3D*, where *D=40 mm* is the FWHM of the laser pulse before focusing. Based on the θ_{OA} and information from Fig. 1, it was possible to obtain the parameters *d* and f_{AP}, using the identity $tan(\beta) = cot(\theta_{OA})$. Moreover, the super-Gaussian incident laser pulse was considered. The integration of the real and imaginary parts of the transverse electric field and consequent multiplication by spectral amplitude were performed separately for each wavelength across the chosen spectrum.

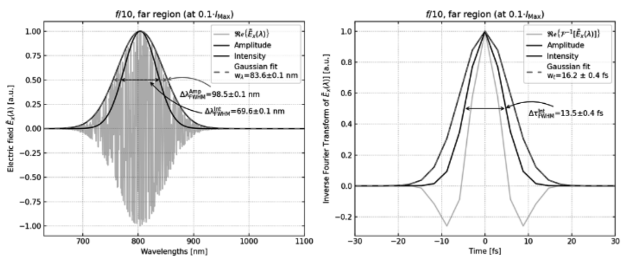

Figure 1: Parent focal length *f=1200 mm* with N_f *=10*. The transverse electric field is observed in the far focal region.

From Fig. 1, pulse duration stretching can be observed further from the central region of the focal plane, i.e., where *I* is 50% of I_{Max}. One of the reasons for this phenomenon can be linked to the different intensity distributions of the focused laser pulses. Further studies assuming tight focusing conditions are currently being conducted.

THz-driven Dielectric Accelerators

Since the first experimental demonstration of high-gradients in dielectric microstructures in 2013 [5], dielectric laser-driven accelerators have caught the attention of the particle accelerator community. Thanks to their compactness, high-gradient capabilities, and the fact that laser technology is already available, they stand as an alternative to conventional particle accelerators. Nevertheless, employing optical lasers poses some new challenges that need to be solved [6]. One way to address these is to use longer wavelengths for both, acceleration and beam manipulation [7, 8]. The fast advancement in the generation of terahertz (THz) radiation, gives rise to Dielectric Terahertz-driven Accelerators (DTAs) [9, 10].

The project of Andrés Leiva Genre at the University of Pécs in Hungary focuses on a symmetric waveguide with an integrated dual-pillar grating dielectric structure for particle acceleration. Two linearly polarized multi-cycle THz pulses are focused onto the waveguides. The pulses propagate through the waveguides until they reach the DTA pillars, which provide the phase mask for net acceleration. Electrons would then be injected perpendicular to the waveguide along the direction of the dielectric accelerating structure. Particle acceleration can be achieved by synchronizing electron injection with the THz pulses and different scenarios have been studied, see Fig. 2.

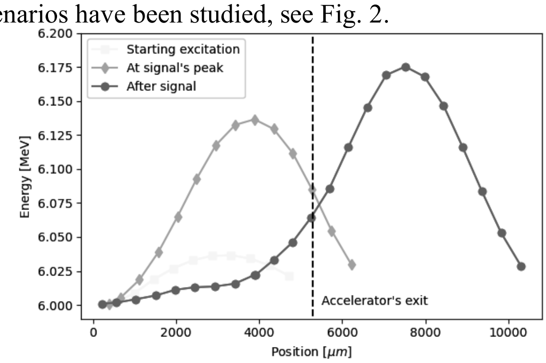

Figure 2: Simulated beam energy as a function of position along the DTA for different operating modes.

The propagation of THz pulses was analyzed, aiming to maximize the amplification factor for the peak electric field while avoiding high reflection. To measure the temporal profile of the electric field, a reflective electro-optical setup using an asymmetric waveguide and periodically-poled Lithium Niobate (ppLN) for multi-cycle THz pulse generation was used. The laser wavelength, pulse duration, energy, and repetition rate were 1030 nm, 170 fs, 1 mJ, and 1 kHz, respectively. In first experiments, the pulse shape for three different configurations was measured:

- without the waveguide,
- with THz focused at entrance of waveguide,
- with THz focused one inch inside of the waveguide.

The multi-cycle THz pulse shape generated by the ppLN was measured in all configurations. The measured pulse shape (1st configuration) was used as the input signal in the simulations. Then, the measured pulse shape was compared in the experiment and the pulse obtained by the simulations after traversing the structure for the second configuration. Both were found to be in good agreement, validating the propagation of the pulse inside the waveguide. This will now allow utilizing the pulse shape from the simulations to optimize the DTA structure for acceleration.

It is next planned to employ higher pump intensities, different schemes for multi-cycle THz pulse generation, different foci inside the waveguide, carry out an overall optimization of the DTA and waveguide, measure the waveguide's coupling efficiency, and ultimately move towards DTA-integrated waveguides.

Theoretical and Experimental Studies of Plasma Formation in Capillary Discharge Waveguides for Plasma-based Accelerators

EuPRAXIA's innovation thrust relies on the development of efficient and resilient plasma sources. A key component of such sources is the capillary through which plasma is channeled. Romain Demitra and co-workers at INFN-LNF in Italy have analyzed a 3 cm long, 1 mm diameter, 3D-printed plastic capillary with dual inlets, filled with hydrogen gas. The endurance of the capillary throughout its operational life is critical for the success of high-frequency applications for next-generation accelerators.

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The setup includes a precision electro-mechanical valve, which introduces hydrogen at variable pressures between 10 and 30 mbar into the capillary. The activation of the valve at a rate of 1 Hz for 5 ms intervals is succeeded by a 7 kV voltage pulse applied to the capillary's copper electrodes 1.4 ms after the valve shuts. This sequence initiates a 300 A plasma current. A spectrometer coupled with an intensified CCD camera acquires the emission spectrum, facilitating plasma density measurements through the Stark broadening observed in the hydrogen Balmer series [11].

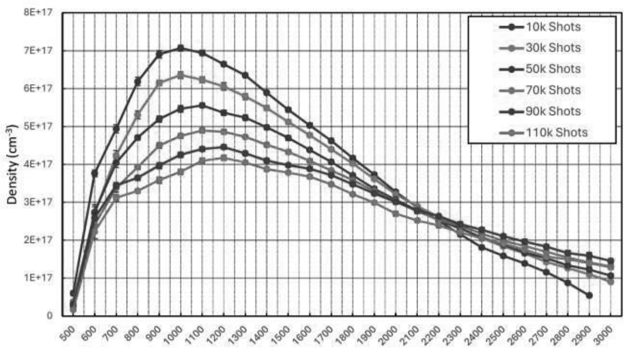

Figure 3: Mean plasma density for different lifetimes.

The measured mean plasma density per delay for different lifetimes shown in Fig. 3 displays a decreasing trend in average plasma density with an increasing number of shots. This demonstrates the capillary's declining efficacy over time. In addition to quantitative measurements, direct visual inspection of the capillary post-operation were done to provide further insight into material degradation.

The observed decline in plasma density and the subsequent effect on the accelerating field highlight the limitations of 3D-printed plastic capillaries. The data implies that the plastic material, while facilitating innovative manufacturing techniques, is subject to significant wear, affecting the plasma distribution and wakefield stability. The analysis emphasizes the necessity for robust capillary materials and manufacturing techniques. Future studies will focus on advanced 3D printing techniques using materials that can withstand high-frequency operation in plasma accelerators.

TRAINING

A structured combination of local and network-wide trainings is offered within EuPRAXIA-DN. Existing and well-proven training schemes such as international seminar series are part of this, but at the same time novel training opportunities are made available that no single partner alone could offer. In particular, hands-on training on accelerator facilities is a unique opportunity which cannot be provided within any university PhD program.

An interdisciplinary 5-day researcher skills training for the doctoral candidates in EuPRAXIA-DN and the LIV.INNO Center for Doctoral Training [12] was organized in Liverpool, UK between 13 – 17 November 2023. The training was designed for the particular needs of the researchers in these two programs, focusing on synergies, networking opportunities and possible collaboration. The school featured project-specific and general-skills parts. It included sessions on project management, presentation skills and science communication, alongside sessions that created awareness about mental health management, intellectual property and the importance of knowledge transfer for research and innovation. The participants also developed a proposal for an outreach project in small groups which competed against each other. A final year skills training, focusing on the transition to the international job market, will be provided in 2026. This will again be hosted in Liverpool and offered to both training programs.

The success of this training approach was recognized earlier in the same month: Each year the European Commission organizes a briefing day for coordinators of new networks funded within the Marie Skłodowska-Curie Actions (MSCA). The main objective of these events is to provide a briefing on the key management and procedural aspects of the project life cycle, on how to comply with the MSCA rules under Horizon Europe, and to share and discuss best practice. This year's event took place on 8/9 November in Brussels and was streamed to more than 1,000 project coordinators, managers and researchers. The EuPRAXIA-DN Coordinator was invited to talk about his experience in fostering networking and synergies, the additional opportunities for project partners and Fellows that have arisen from these collaborations, and examples of some of their highly successful initiatives.

A Media Training Week, hosted by EuPRAXIA-DN partner Carbon Digital, was hosted in Manchester's MediaCity between 20 – 24 November 2024, where the multi award-winning company worked with the EuPRAXIA-DN Fellows to help them develop the skills required to storyboard, script, film and produce their very own project outreach video by the end of an intense training week. The EuPRAXIA-DN successfully produced a film showcasing the Fellows, their research plans and the comprehensive training offered by the network. The film can now be viewed on YouTube and includes subtitles in English, Italian, Spanish, French, German, Greek, Czech, Slovak, Finnish, Hindi, Telugu, Bengali, Chinese and Vietnamese [13].

Finally, an international School on Plasma Accelerators was hosted by the network in the 'Eternal City' Rome in Italy between 22 - 26 April 2024. Lectures and topical talks were presented by research leaders from academia and industry, including 2023 Nobel Laureate Professor Anne L'Huillier. All lectures can be accessed via the school indico site [14] and this is expected to be a valuable resource for the wider community for years to come.

CONCLUSION AND OUTLOOK

All 12 EuPRAXIA-DN Fellows have been recruited and started their ambitious research projects. Examples from their initial studies were discussed in this paper, alongside an overview of the comprehensive training provided to them. The network will next organize a series or EuPRAXIA Camps, topical workshops open to the plasma accelerator community. These will be announced via the network's website and quarterly newsletter.

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