INTRODUCTION OF THE EuPRAXIA PROJECT*

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EuPRAXIA is an acronym meaning "European Plasma Research Accelerator with Excellence in Applications" which almost completely explains the goals and purposes of the project. EuPRAXIA aims at planning and constructing two state-of-the-art accelerator facilities based on current plasma accelerator technologies. Plasma-based accelerators make it possible to radically reduce the facility size and overall costs compared to current radio-frequency (RF) accelerators. The two planned facilities — the first is beam-driven and the second is laser-driven — are envisioned to provide electron beams in the energy range of 1–5 GeV, and with beam parameters and quality comparable to the existing RF machines. In the following, we give a short overview of the status of the project in February 2025. Finally, we give a short overview of the possible Hungarian contributions to the EuPRAXIA project.

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1. Introduction

Depending on the literature, there are approximately 30 [1] to 35 thousand [2] smaller or larger particle accelerators operating worldwide. Most of them are electron accelerators run by the industry for material testing. Smaller particle accelerators are used in a wide variety of applications, including ion implanters for the manufacturing of semiconductors, particle

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therapy for oncological purposes, radioisotope production for medical diagnostics, and accelerator mass spectrometers for measurements of rare isotopes such as radiocarbon.

One of the biggest challenges in accelerator science today is to make particle accelerators much cheaper and more compact, as this would significantly reduce the cost of oncological therapy. The most promising idea is the plasma acceleration concept which has already been proven at the level of proof-of-principle. The first idea is the laser electron accelerator worked out by Tajima and Dawson in 1977. Intense electromagnetic pulses can create a wake of plasma oscillations through the action of the non-linear ponderomotive force. Electrons trapped in the wake field can be accelerated to high energy [3]. The second (also very promising) similar concept is the particle-driven plasma accelerator where charged particles (in most cases protons) create the plasma wave which accelerates electrons [4]. In the next section. we give the up-to-date and relevant information about the EuPRAXIA project, and we present the possible Hungarian contributions.

2. The EuPRAXIA project

The EuPRAXIA plasma accelerator project will provide major benefits for society by pioneering a new generation of compact, cost-effective particle accelerators. By using advanced plasma technology, EuPRAXIA will make high-performance accelerators more accessible for applications in medicine, such as cancer therapy and medical imaging, as well as in industry, materials science, and security screening. Its innovative approach will also reduce energy consumption and infrastructure needs compared to traditional accelerators, supporting Europe's goals for sustainability and technological leadership. Moreover, EuPRAXIA will drive scientific innovation, create high-skilled jobs, and strengthen international collaboration in cutting-edge research. The idea that plasma-based accelerators should be planned and built in Europe was first formulated in the early 2010s. As a first active step, the "Horizon 2020 EuPRAXIA" design study was published in 2017 by 55 research institutes mostly European [5].

In the framework of Horizon 2020 which is the Framework Programmes for Research and Technological Development the Conceptual Design Report (CDR) [6] of EuPRAXIA project was completely worked out by a consortium of 74 scientific institutes.

Updated technical details of the present status (February 2025) can be found in the «Technical Status Report on Plasma Components and Systems» by Biagioni *et al.* [7]. The reader can find various extra documents and science popularizer information on the EuRPAXIA official side as well [8].

In the following, we present the most relevant technical information, collected mainly from these documents.

2.1. The beam-driven facility

The accelerating structure in plasma is generated by the creation of charge separation. In the beam-driven case, the plasma electrons are displaced by the Coulomb force. It can be shown that the typical operating plasma density lies in the range of 10^{14} cm^{-3} to 10^{16} cm^{-3}. With a 1D non-relativistic simplified wave-breaking model, it can be easily derived that, in general, beam-driven accelerators operate with accelerating fields in the range of 1 GVm^{-1} to 10 GVm^{-1}.

Both EuPRAXIA accelerators are mainly planned to drive Free Electron Lasers (FEL). This first (EuPRAXIA beam-driven FEL) facility will be based at INFN-LNF in Frascati and driven by the EuPRAXIA SPARCLAB RF accelerator [7]. It comprises two instruments, the photoinjector, which generates a high-brightness electrons, and an X-band linac, which accelerates that electron beam to high energy. The accelerator can be operated in single- or multi-bunch mode up to 400 Hz, delivering electrons with energies up to 0.5 GeV. A beam-driven plasma accelerating stage attached to the linac will boost the beam energy up to 1 GeV. An active plasma lens is planned for beam capture after the accelerating stage. The physical parameters of the plasma systems and additional components relevant to the beam-driven FEL facility in Frascati are listed in Table 1.

Table 1. EuPRAXIA SPARC_LAB parameters extracted from Biagioni technical status report 2024 [7].

Device	Parameter	Value	Unit
Plasma accelerator stage	Energy gain	0.5	GeV
	Length	> 50	cm
	Density	10^{15}–10^{17}	cm^{-3}
	Repetition rate	10–100	Hz
Active plasma lens	Strength	1–5	kT
	Length	2–4	cm
	Density	1–10×10^{17}	cm^{-3}
	Repetition rate	10–100	Hz

2.2. The laser-driven facility

The charge separation is now done by the ponderomotive force which pushes electrons away from the area of high laser intensity. Due to this different physical mechanism, the typical plasma density lies several orders of magnitude higher compared to the beam-driven case which is now between

10^{17} cm^{-3} and 10^{19} cm^{-3}. In general, laser-driven accelerators operate with accelerating fields in the range of 30 GVm^{-1} to 300 GVm^{-1}, which is more than an order of magnitude larger than the beam-driven setup.

The location of the second facility is to be decided in the first half of 2025. As such, various configurations are considered to achieve 1–5 GeV beams [6]. There are three different institutes from different locations, each proposing different planned configurations The first configuration consists of a low-energy laser-plasma injector (LPI-LE) generating 150–500 MeV high-brightness electron beams, which would then be injected in a laser-driven plasma accelerating stage (LPAS) to reach a few GeV final energy.

The second layout considers a PW-class laser driver to drive a high-energy laser-plasma injector (LPI-HE) in a single stage to reach 1–5 GeV beam.

The third possible combination is the hybrid configuration, where LPI generates a bright beam driving a beam-driven accelerator in a second plasma stage. Like for the beam-driven site, active plasma lenses are of significant interest for the capture section or coupling the beam in the LPAS stage. General parameters for plasma systems and components for a laser-driven FEL facility at this site are summarized in Table 2. Assmann *et al.* [6] in the Technical Design Report (TDR) analyzed various configurations of plasma accelerator linacs for FEL (see Table 8.1 and Fig. 8.3 there [6]).

Table 2. EuPRAXIA laser-driven general parameters from CDR [6] and references therein.

Scheme	Parameter	Value	Unit
LPI-LE	Energy gain	0.25–0.5	GeV
	Density	10^{18}–10^{19}	cm^{-3}
	Length	1–10	mm
	Repetition rate	10–100	Hz
Active plasma lens	Strength	1–5	kT
	Density	$1–10 \times 10^{17}$	cm^{-3}
	Length	2–4	cm
	Repetition rate	10–20	Hz
LPI-HE/LPAS	Energy gain	1–5	GeV
	Density	10^{17}–10^{18}	cm^{-3}
	Length	10–20	cm
	Repetition rate	10–100	Hz

3. The Hungarian contributions

Three Hungarian organizations have established an informal center of excellence contributing to the EuPRAXIA project. These will come from the HUN-REN Wigner Research Centre for Physics (RCP), Budapest, the University of Pécs at Pécs, and the University of Szeged at Szeged.

3.1. HUN-REN Wigner RCP

The HUN-REN Wigner RCP and its legal predecessor have a half-century-long tradition and experience in plasma physics. In the last decade the HUN-REN Wigner RCP contributed in some plasma diagnostics methods to help the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) at CERN [9]. This experiment is the world's first proof-of-principle experiment, which investigates wakefield plasma acceleration using a proton bunch as a driver. The plasma wake field is produced in laser-ionized rubidium gas [10].

Our facility in the HUN-REN Wigner RCP focuses on research in high-intensity laser physics, materials science, and fusion energy. We employ advanced technologies to develop experimental arrangements and encourage collaborative partnerships to achieve significant progress in fundamental physics such as laser-driven particle acceleration or fusion reactions. Our primary mission is to enhance efficiency and advance through innovative target and detector systems. A key focus area is the development of compact, high-efficiency laser-plasma accelerators capable of producing high-energy electron and ion beams. This research leads to deeper investigations of relativistic plasma dynamics, and optimization of energy transfer through advanced target designs, paving the way for transformative applications in science and industry, too. The laboratory can also be used for educational purposes.

Central to this work is a 10 Hz repetition rate Ti:sapphire chirped-pulse amplification (CPA) laser system (Coherent Hidra-25) producing 40 fs pulse duration with a maximum pulse energy of 30 mJ at 800 nm central wavelength. Pulse duration and shape can be measured by frequency-resolved optical gating (FROG). The peak intensity at the focal point reaches 10^{17}–10^{18} W/cm^2. The moderate pre-pulse contrast of $10^6 : 1$ can be measured using the ultra-high contrast third-order autocorrelator (UltraFast Innovations Tundra), ensuring precise control over pulse properties.

Our laboratory operates six pieces of high-vacuum systems including target and detector chambers designed for the studies of laser–matter and laser–plasma interactions. We have a dedicated beam path and vacuum system to study the enhancement of the temporal contrast using a nonlinear Fourier filtering technique [11] based on the ionization of a noble gas jet injected into vacuum. Tuning of laser contrast is an essential requirement in the investigation of laser–atom interaction. Other dedicated gas or liquid injection system can be used for high-harmonic generation (HHG) detected by a microchannel plate (MCP) or X-ray CCD (Andor). We have gas or liquid injection systems, where the spatial and temporal density distribution can be investigated through Rayleigh laser scattering and interferometric diagnostics.

We explore the local near-field enhancement using plasmonic nanostructures. We investigate the effect of metal nanoparticles doping into the foil of polymer to achieve higher-energy absorption and more energetic particles [12]. We utilize sophisticated diagnostic tools for characterizing high-energy ions generated during laser–plasma interactions. The alpha particle yield from proton–boron nuclear reactions is investigated with a Thomson parabola spectrometer coupled to a 3 inch MCP detector which is a fundamental technique that reveals detailed information about mass/charge ratio, ion energy, and species. For the investigation of particle flux, spatial distribution, identification of ion species, and energy, the CR-39 nuclear track detectors are employed. Additional diagnostics such as semiconductor and scintillation detectors can measure the temporal distribution of ions and X-ray/gamma radiations coming from the interactions. We have femtosecond Laser-Induced Breakdown Spectroscopy (LIBS) setup with a high-resolution ICCD Echelle spectrometer for detailed measurements and a quadrupole Mass Spectrometer (MS) coupled to the target chamber for material analysis after a laser shot.

On the theoretical side, electron acceleration in underdense plasmas was modeled and calculated with a classical effective theory [13, 14].

Collaboration is a key aspect of our research efforts. We maintain a strong partnerships with different institutions, including HUN-REN Institute for Nuclear Research, High-field Terahertz Research Group (University of Pécs), and ELI-ALPS.

3.2. University of Pécs

The University of Pécs (UP) hosts one of the EuPRAXIA-Doctoral Network (DN) [15] projects in the Work Package 4 of applications. Thanks to its expertise in the field of lasers and terahertz (THz) generation [16], UP investigates the design of an intense multi-cycle THz source [17] and a dielectric THz-driven accelerator (DTA). The UP was one of the first to design a proton accelerator using prisms in the THz range [18]. The THz-driven acceleration and manipulation offers several advantages over typical RF cavities [19] thanks to their shorter wavelength. Therefore, high-intensity, multi-cycle THz sources are needed for the lucrative operation of THz-driven particle accelerators. On the other side, dielectric laser-driven accelerators (DLAs) are capable of acceleration gradients up to 10 GV m^{-1}, and they are a potential candidate for reducing the cost and size of current accelerators [20]. However, DLAs work with optical lasers, which have some rigid restrictions on the bunch size and charge, fabrication tolerances, and timing jitters. These limitations can be avoided by operating the dielectric accelerator in the THz range. Consequently, the inclusion of multi-cycle THz pulses and THz-driven dielectric microstructures also falls within the goals of the EuPRAXIA project.

Several methods exist for generating multi-cycle THz pulses, but optical rectification in non-linear crystals is one of the best candidates as a compact source [21]. Optical-to-THz conversion efficiencies (a key figure of merit of terahertz generation) can be increased by using a cooled-down periodically-poled lithium niobate (PPLN) wafer stack and convenient optical systems to manipulate the pump pulse conveniently. Numerical simulations carried out at UP [22] show a significant improvement in the conversion efficiency in such setups. A promising setup to increase the THz output is implementing a chirped-and-delayed [23] pumping system. Chirp-and-delay consists of superposing two chirped Gaussian pulses delayed at a fixed time Δt. This pulse sequence can mitigate the red-shifting in the cascaded-down conversion of the optical pulse during the THz generation if $f_{\mathrm{THz}} = \Delta t b/\pi$, where b is the linear chirp rate of the pulses. According to simulations, the conversion efficiency is increased by 65% for an 8 mm long PPLN wafer stack, 750 fs, 100 GW cm^{-2} Ti:Sapphire laser pump in the chirped-and-delayed setup. At the UP, a tabletop intense multi-cycle terahertz source is analyzed through experiments and simulations. Several technical details are considered in the design of the source before experimental testing.

On the other hand, an innovative accelerating structure, including a DTA, is being examined through finite-difference time-domain and particle-in-cell simulations. The structure is optimized to maximize the energy gain of relativistic electrons. The dielectric microstructure chosen is a dual-pillar grating structure, but it is also predicted to work with other geometries. Important acceleration quantities, such as the acceleration gradient, bunch charge, and energy gain are calculated from simulations. When employing terahertz peak fields of the order of 1 GV m^{-1}, an acceleration gradient of approximately 600 MeV m^{-1} can be achieved according to simulations, surpassing current RF cavities.

3.3. University of Szeged

The University of Szeged (USZ) is one of the most prestigious educational, scientific, research and development, and innovation establishments in Hungary. Various international rankings place it among the top 100 universities in Europe. USZ contributes to the EuPRAXIA project in two fields. One of the tasks is related to the design and development of the driving ultrashort pulse laser system, while the second aims at biomedical applications of the produced electron (and other particle) beam.

The TeWaTi research group, the first Hungarian high-intensity, ultrashort laser pulse laboratory in Hungary, operates at the Department of Optics and Quantum Electronics. It has been working on various aspects of the research and development of ultrashort laser systems and applications since 1998, including development of laser diagnostics, novel ways of short-pulse amplification, ultrafast time-resolved measurements, and femtosecond material processing. Following the most recent upgrade, the laser system operates at a 100 Hz repetition rate and delivers laser pulses with 60 mJ energy and < 26 fs duration on the target [24]. The two main current applications are the development of *(i)* a pilot system of laser-based X-ray CT equipment for industrial imaging [24], and *(ii)* high-repetition target systems for laser-ion acceleration [25] and neutron production [26].

Research on the biological effects of laser-generated charged particles on living tissues and animals began at the Department of Oncology over a decade ago. Initially, we developed appropriate methods that include novel endpoints and model systems for the quantitative assessment of radiation-induced biological effects at morphological, histopathological, functional, and molecular levels in both normal and tumor tissues [27, 28]. During the same time, we successfully established reference irradiation protocols and defined dose-effect curves. Our group introduced a novel *in vivo* zebrafish embryo system that proved to be a highly effective vertebrate model for evaluating laser-driven ionizing radiation sources, characterized by pulsed operation, ultrahigh dose rates per shot, and an adjustable beam size. A key focus of our research has been determining the relative biological effectiveness (RBE) of various particle beams along the dose depth curve and investigating the potential of the FLASH effect of the ultrahigh dose rate for normal tissue sparing [27, 29].

4. Summary

In this work, we presented the current status of the EuPRAXIA project which plans and builds two plasma-based particle accelerators. The planned facilities will produce electron beams in the energy range of 1–5 GeV. The beam-driven plasma accelerator will be built in Frascati. The location of the laser-driven plasma accelerator had not yet been decided as of February 2025. (Now, at the beginning of November 2025, when we submit the final version of the manuscript, according to the final decision, the equipment will be built in Eli Beamlines Prague.) In the second part of our study, we outlined the planned Hungarian contributions to the EuPRAXIA project from the HUN-REN Wigner RCP, the University of Pécs, and the University of Szeged.

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