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EuPRAXIA – A Compact, Cost-Efficient Particle and Radiation Source

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Abstract. Plasma accelerators present one of the most suitable candidates for the development of more compact particle acceleration technologies, yet they still lag behind radiofrequency (RF)-based devices when it comes to beam quality, control, stability and power efficiency. The Horizon 2020-funded project EuPRAXIA ("European Plasma Research Accelerator with eXcellence In Applications") aims to overcome the first three of these hurdles by developing a conceptual design for a first international user facility based on plasma acceleration. In this paper we report on the main features, simulation studies and potential applications of this future research infrastructure.

INTRODUCTION AND MOTIVATION

Several tens of thousands of particle accelerators are in use today with varied applications in research, industry, medicine and other fields [1]. Yet accelerator usage could be even more widespread, were it not limited by cost and size constraints, especially in funding-restricted environments, such as hospitals and universities. 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 [2], corresponding experimental techniques have been developed in particular in recent years reaching both energy records [3,4] and technological milestones, including the staging of multiple plasma accelerator structures [5], the generation of plasma-based undulator radiation [6-9] and the development of first phase-space control mechanisms [10,11].

To advance plasma accelerators towards user and application readiness, however, beam quality as well as accelerator control and stability must still be improved significantly. Some of the main challenges in this field are being faced in the areas of a) improving and controlling beam energy spread and transverse emittance, b) increasing shot-to-shot stability, c) improving machine operability and maintainability as well as d) increasing achievable repetition rates. Being affected among others by limitations in laser and diagnostics technology, these are not only physics challenges, but also to some extent engineering ones, making such work very difficult for individual research groups to succeed in. With the EuPRAXIA project, the problem is hence moved to a larger scale through international collaboration: bringing together the expertise of 41 different project partners from accelerator science, laser technology, plasma physics and photon science [12], a first demonstrator facility for the scientific use of plasma-accelerated electron beams is being developed.

THE EUPRAXIA PROJECT

Funded as a conceptual design study running from 2015 to October 2019, the EuPRAXIA 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. For this reason, laser-driven (laser wakefield acceleration, LWFA), electron beam-driven (plasma wakefield acceleration, PWFA) as well as hybrid (combining LWFA and PWFA) acceleration approaches are under consideration [13]; concurrently, both external (with the electron beam generated outside of the plasma accelerator) [14-16] and internal (with the electron beam generated inside the plasma accelerator) injection methods are also investigated [17-19]. Beyond the plasma acceleration stage itself, the EuPRAXIA study additionally focuses on researching high power laser systems (in particular pump sources at high average power and repetition rate, diagnostics, laser alignment) [20-22], ultrashort electron beam dynamics [10,23] and transport [24-27], single-shot electron diagnostics [28], synchronization and machine control [29], FEL and secondary source design [30] as well as other aspects.

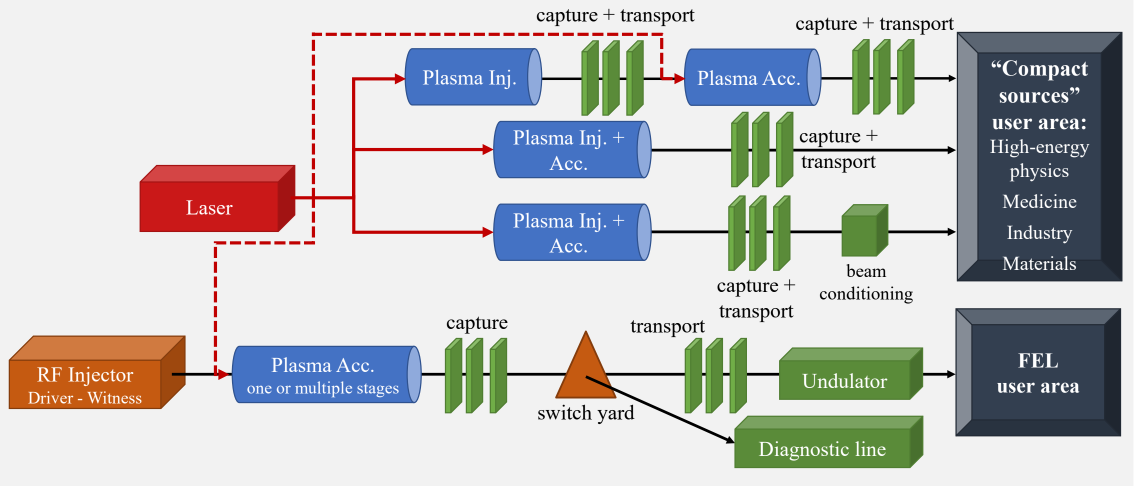

FIGURE 1: Overview over an exemplary EuPRAXIA beamline setup with its main elements and some of the design choices (such as injection and acceleration technique(s), number of beamlines and end station design) still under investigation. A final beamline layout will be presented in the EuPRAXIA Conceptual Design Report in Oct 2019.

Figure 1 outlines the main elements generally planned for the EuPRAXIA beamline layout starting from the high-power laser system and RF injector to be used for generating the driver, and driver or witness beam, respectively, depending on the final design. For the former, three laser cases with varying beam energy and duration are under design in this context, including studies on thermal management, output stability and beam transport [31]. As such, not only schemes based on an RF-injector, but also more compact, all-optical setups, generating the witness beam in a laser-plasma stage through internal injection, are investigated. The following section consists of one or multiple plasma stages bringing the electron witness beam up to 5 GeV in energy, while the transfer lines between and after the plasma targets are designed to not only capture and transport it, but also ensure good beam quality through focusing, collimation and phase-space control. Finally, depending on the application targeted in the beamline, the electron bunch can be directly transported to the user area or conditioned and employed for generating secondary particles or radiation, such as X-rays, γ-rays and positrons.

As shown in Fig. 2, one of the main features that are planned to be provided in this way is a Free-Electron Laser (FEL) in the nano- to sub-nanometer wavelength range. Just as the more compact secondary radiation and particle sources under design, the FEL will also benefit from the unique, intrinsic features of the plasma accelerators, which include ultrashort beam duration (single to tens of femtoseconds) as well as compact transverse beam size (micrometer-scale).

To include the foreseen range of sources in a compact facility layout, the design currently under investigation focuses on utilizing the small size of the plasma accelerator structures themselves: by splitting the laser system and potentially the RF injector as driver / witness generators between multiple parallel beamlines, these items dominating the layout size and cost can be shared. Yet, in turn each beamline can still be customized for specific applications through fine-tuning of the plasma stages and transport lines. This will allow a significantly reduced footprint compared to equivalent RF-based machines with first estimates for EuPRAXIA predicting an accelerator tunnel length of around 30 to 60 m (excluding laser and RF infrastructure) to generate a 5 GeV electron beam.

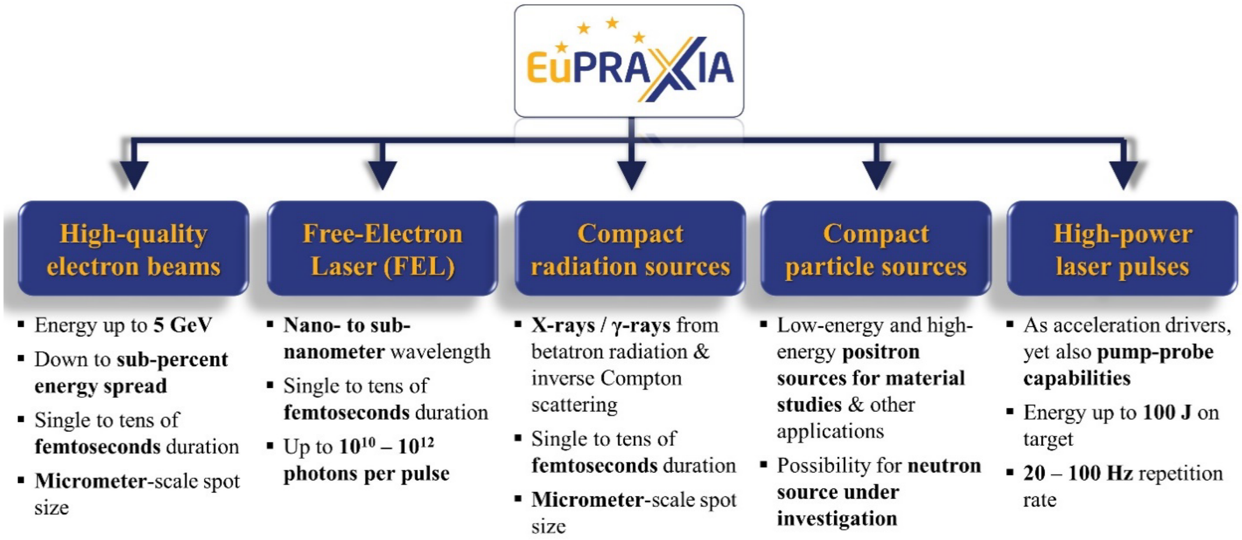

FIGURE 2: Main goals foreseen for the future EuPRAXIA facility layout and beamline properties. A more finalized and detailed description of the facility and the provided beam parameters will be available in October 2019 in the EuPRAXIA Conceptual Design Report.

SIMULATION RESULTS

Considerable effort in the current project stage is dedicated to simulation studies of possible beamline setups using various combinations of techniques for bunch generation, acceleration, beam handling and end usage. To be able to properly assess and compare these different scenarios under investigation, start-to-end simulations have been carried out by different EuPRAXIA partners. A range of different simulation codes is used in this context to study the multiple types of systems integrated within the machine, including particle-tracking codes (such as Elegant [32], TStep [33] and ASTRA [34]) for RF-based accelerator sections and beam transport, particle-in-cell (PIC) or hybrid-PIC codes (such as Architect [35], Warp [36] and HiPACE [37]) for plasma-based components, and radiation codes (such as GENESIS [38]) for some of the end applications.

An example for such a start-to-end simulation is shown for two cases in Fig. 3 where the development of the witness electron bunch parameters during acceleration up to 1 GeV is depicted. As the symbols in the top bar show, in both cases (a) and (b) the beam is generated and pre-accelerated in an RF-photoinjector and linac, before its energy is boosted in a laser-driven (a) or electron beam-driven (b) wakefield accelerator. The main section of each graph shows the evolution of the witness bunch energy, energy spread and longitudinal bunch length, all of which are shown to be well controlled, particularly also within and after the plasma stage. Hence, beam properties on the order of 2.3 % (1.1 %) relative energy spread, 2.14 µm (3.12 µm) RMS bunch length and, not shown here, 0.47 mm mrad (1.1 mm mrad) RMS normalized emittance are achieved in the LWFA (PWFA) scenario with a bunch charge of 30 pC.

This particular study has been developed by researchers from INFN (details found in [14,15,39] and references therein); further investigations are focused on acceleration up to 5 GeV energy, while also examining designs with a more compact machine size. These will be reported on in the future.

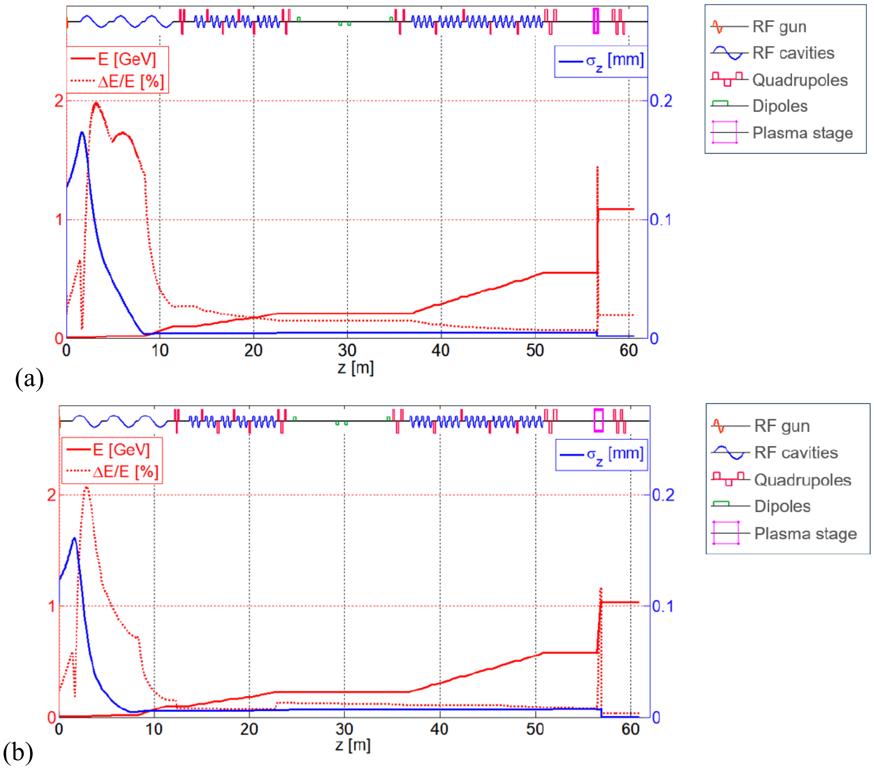

FIGURE 3: Start-to-end simulations for the witness electron bunch after acceleration using a laser-driven wakefield accelerator (Fig. (a), LWFA) and using a beam-driven wakefield accelerator (Fig. (b), PWFA). The electron bunch energy (red), relative energy spread (red dotted) and bunch length (blue) are shown in each case. Details of these simulation studies can be found in reference [39], from which these images are reproduced with permission of the authors.

USER APPLICATIONS

As Fig. 4 demonstrates, EuPRAXIA foresees a varied range of possible applications and activities. In particular two main types of users are targeted: firstly, beam users who are interested in the properties of the available radiation and particle sources, but not necessarily in the novel technology that is employed to generate them. These include major photon science user applications in fields, such as biology, chemistry, material science and others. They may benefit not only from the FEL beams (through e.g. time-resolved coherent diffraction imaging, X-ray spectroscopy), but also from the more compact radiation sources with synchrotron-radiation-like properties (e.g. for phase-contrast imaging, X-ray crystallography) as well as the compact primary and secondary particle sources (using e.g. positron annihilation spectroscopy, neutron scattering). Another important example is in high-energy physics where possibilities for detector tests, based on a tunable electron beam, are envisaged.

Secondly, co-developing users are identified who are interested in the possibilities for investigating and developing plasma accelerator concepts and applications further at EuPRAXIA in an Open Innovation approach. In this context, medical physics and material science, for example, are particularly relevant disciplines, where compact imaging and active interrogation technologies based on plasma acceleration can be investigated. Additionally, accelerator R&D, both in the context of radiofrequency-based and more compact technologies, will be another essential user application. With regard to co-development, EuPRAXIA is looking particularly also to develop relationships with industry; partnerships are already active with European laser companies, including Thales, Amplitude and Trumpf, and could be expanded to accelerator technology, accelerator applications and other fields of activity.

An important branch of work carried out within the project entails the coordination and harmonization of these two user categories through the facility design as well as the access policy. Feedback and exchange with potential future end users and co-developers, both academic and commercial, is hence particularly welcome to optimize the definition of the facility in view of applications and user needs.

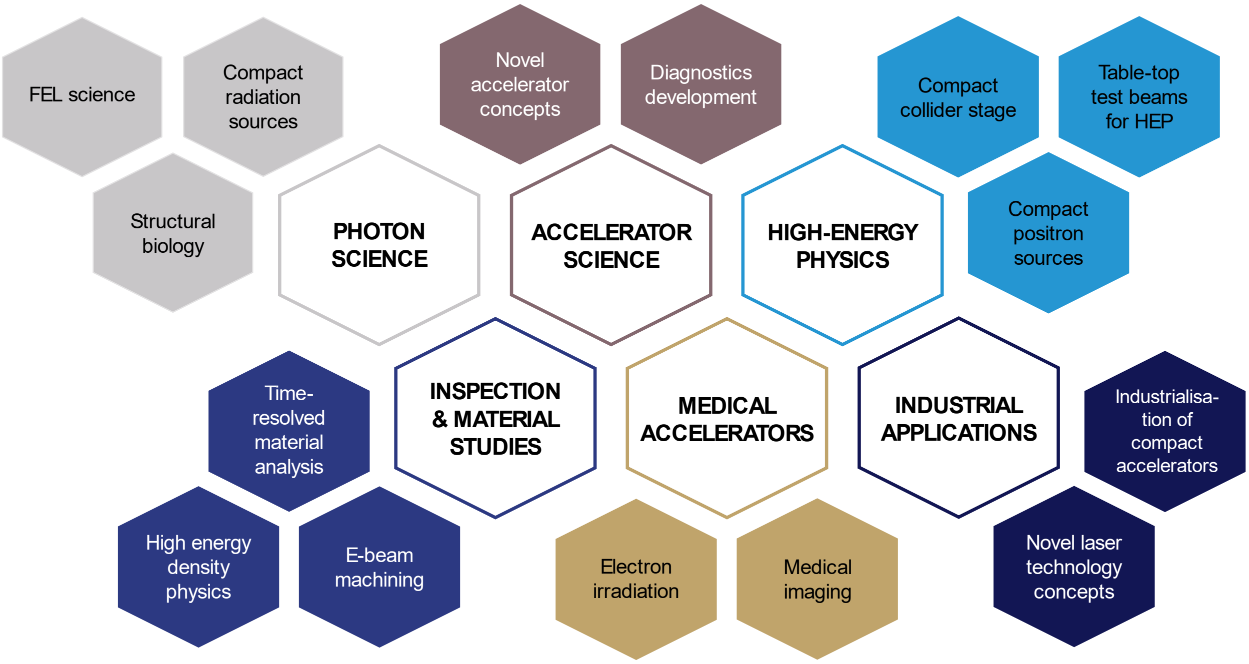

FIGURE 4. Overview over possible user applications at EuPRAXIA. This is not a comprehensive list but shows the most promising uses envisaged during the current design stage.

SUMMARY AND OUTLOOK

The EuPRAXIA Collaboration aims to develop a user facility uniquely suited for demonstrating and developing plasma accelerator technologies and their applications in photon science, medicine, life sciences, materials research, industry and other fields. During the current conceptual design phase, new technologies are being developed and combined with existing expertise and methods based on accelerator research, photon science, laser technology and plasma physics. These will be reported on in the final EuPRAXIA Conceptual Design Report published in October 2019, which will also present aspects related to the infrastructure itself, such as budget estimates, governance and legal models as well as an impact assessment. Subject to funding decisions, the current work could be succeeded by a technical design and prototyping phase before implementation as a research infrastructure is considered within the next decade.

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