14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOZD2

EuPRAXIA AND ITS ITALIAN CONSTRUCTION SITE*

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Abstract

The EuPRAXIA@SPARC_LAB facility is the beam driven pillar of the EuPRAXIA project which is expected to provide by the end of 2028 the first European Research Infrastructure dedicated to demonstrating usability of plasma accelerators delivering high brightness beams up to 1-5 GeV for users. Among the possible EuPRAXIA@SPARC_LAB applications the realization of a short wavelength Free Electron Laser (FEL) able to provide radiation in the "water window" of the e.m. spectrum for bio-physical investigations is one of its main goals. Another interesting X-ray radiation source based on betatron radiation will be implemented by the end of 2025 in the framework of the PNRR initiatives. In this paper we report about the recent progress in the context of the EuPRAXIA collaboration including the new perspectives offered by the Italian Next Generation Eu program (PNRR).

INTRODUCTION

Particle beams are used to investigate nature's fundamental forces, create known and unknown particles, and generate novel states of matter. Photon science also depends on electron beams, which can radiate powerful synchrotron light pulses including soft and hard X-rays. This physics success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics and demanding always higher beam energies.

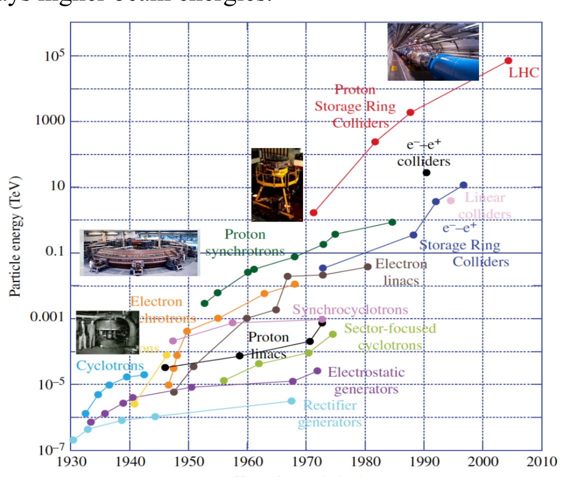

Figure 1: The Livingston Plot. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy. Image adapted from the 2001 Snowmass Accelerator R&D Report.

The Livingston plot, shown in Figure 1, illustrates how the progress in achieving the energy frontier has been enabled by the history of invention in accelerator science and technology. One can clearly see that over several decades, there has been an exponential growth in the maximum attained energy. But the exponential growth in maximum achieved energy was made possible by the development of different accelerator technologies (for example Electrostatics, Cyclotrons, Linacs, Synchrotrons, Colliders). As often occurs in any technological field, new accelerating technologies often replaced each other once the previous technology had reached its full potential and saturates its evolution curve [1]. In more recent decades, represented by the LHC collider, the exponential energy growth has started slowing down again. This suggests that existing acceleration technologies have reached their maximum potential and further advancements would require the development of new accelerator concepts, possibly based on more compact and cost-effective methods. Promising emerging techniques, such as laser-driven and beam-driven plasma acceleration, have the potential to reestablish the exponential trend in the energy growth depicted by the Livingston plot.

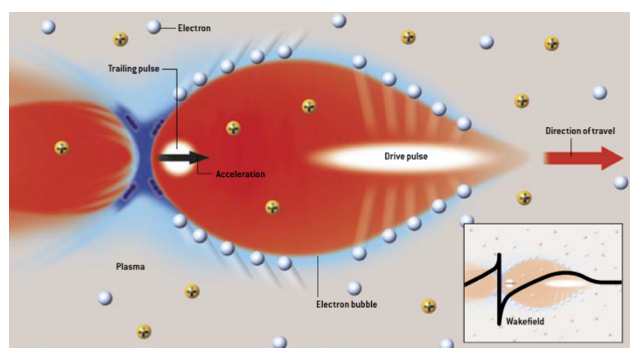

Figure 2: Conceptual drawing of the plasma wakefield accelerator [2].

Plasma wakefield accelerator relies on a coherent charge density oscillation in a plasma to provide the accelerating force. The plasma oscillation is driven by an externally injected short pulse, which can be either a laser (LWFA [3]) or an electron beam (PWFA [4]), which blows outward the electrons in an ionized gas (plasma), leaving behind a region of positive charge, as shown in Figure 2. Along the axis where the beam propagates, the electric field causes a trailing pulse of electrons injected near the rear of the bubble to feel a very strong forward acceleration. Gradient up to 100 GV/m have been observed in several experiments [5]. Difficulties in the plasma scheme arise from the small scales involved (sub-mm transverse diameter), required micrometer tolerances and stability which may cause beam quality degradation with respect to

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conventional accelerators. But in recent time the plasma generated beam quality has advanced sufficiently to reach the requirements for driving a Free Electron Laser (FEL). There have been several reports of pilot free-electron lasing in plasma-based accelerators: one relying on LWFA by a team in China [6] and one relying on PWFA by the EuPRAXIA team in Frascati [7,8], Italy. Another experiment run by a French and German team has also recently confirmed seeding of the FEL process in a LWFA plasma accelerator [9].

THE EuPRAXIA ESFRI PROJECT

In 2014, researchers in Europe agreed that a combined, coordinated R&D effort should be set up to realize a larger plasma-based accelerator facility that serves as a demonstrator. The project should aim to produce high-quality 5 GeV electron beams via innovative laser- and electron-driven plasma wakefield acceleration, achieving a significant reduction in size and possible savings in cost over state-of-the-art RF accelerators. This project was named European Plasma Research Accelerator with eXcellence In Applications (EuPRAXIA) and it was agreed that it should deliver pulses of X rays, photons, electrons and positrons to users from several disciplines. EuPRAXIA's beams will mainly serve the fields of structural biology, chemistry, material science, medical imaging, particle-physics detectors and archaeology. It is not a dedicated particle-physics facility but will be an important stepping stone towards any plasma-based particle physics collider like for example the HALHF proposal [19]. The EuPRAXIA project started in 2015 with a design study, which was funded under the European Union (EU) Horizon 2020 program and culminated at the end of 2019 with the publication of the worldwide first conceptual design report for a plasma accelerator facility [10]. The targets set out in 2014 could all be achieved in the EuPRAXIA conceptual design. In particular, it was shown that sufficiently competitive performances could be reached and that an initial reduction in facility size by a factor of two-to-three is indeed achievable for a 5 GeV plasma-based FEL facility. The EuPRAXIA conceptual design report was submitted to peer review and published in 2020.

The EuPRAXIA implementation plan proposes a distributed research infrastructure with two construction and user sites and several centers of excellence. The presently foreseen centers, in Czech Republic, France, Germany, Hungary, Portugal and the UK, will support R&D, prototyping and the construction of machine components for the two user sites. This distributed concept will ensure international competitiveness and leverage existing investments in Europe in an optimal way. Having received official government support from Italy, Portugal, Czech Republic, Hungary and UK the consortium applied in 2020 to the European Strategy Forum on Research Infrastructures (ESFRI). The proposed facility for a free-electron laser was then included in the 2021 European Strategy Forum on Research infrastructures (ESFRI) roadmap, which identifies those research facilities of pan-European importance that correspond to the long-term needs of European research communities, with Italy thorough INFN as leading country. EuPRAXIA will integrate work in the accelerator, plasma and laser research communities, in association with European industry, thus bringing plasma accelerators to the users and the market. The EuPRAXIA consortium includes 51 institutes from 15 countries [11].

THE ITALIAN CONSTRUCTION SITE

In its first implementation phase, the EuPRAXIA consortium will construct a beam driven plasma accelerator user facility at Laboratori Nazionali di Frascati (INFN-LNF), named EuPRAXIA@SPARC_LAB, funded by the Italian Minister of Research through INFN with 108 M€. It will set up a compact and innovative FEL with first user operation foreseen in 2028 [12]. A second EuPRAXIA construction site in Europe for a laser driven user facility will be decided in 2024.

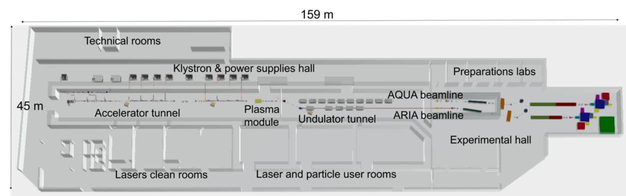

Figure 3: EuPRAXIA@SPARC LAB layout

Figure 3 depicts the overall layout of the EuPRAXIA@SPARC LAB that will be hosted inside a new building (159 m X 45 m) whose construction will start in 2024 [13].

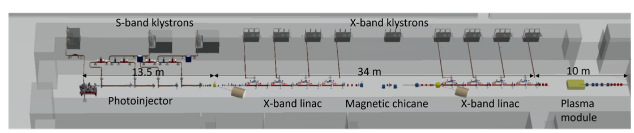

Figure 4: EuPRAXIA@SPARC LAB accelerator layout

In figure 4 the accelerator area is shown with more details. From left to right one can see a 55 m long tunnel hosting a high brightness S-band RF photoinjector equipped with a hybrid compressor scheme based on both velocity bunching and magnetic chicane. The energy boost from 120 MeV up to a maximum 1 GeV will be provided by a chain of high gradient X-band RF cavities. The RF accelerator is designed to operate at 100 Hz repetition rate, that is the state-of-the-art klystrons performance, an upgrade will be possible once the new Klystrons able to reach up 400 Hz repetition rate with 25 MW output power will be available.

At the linac exit a 5 m long plasma accelerator section will be installed, which includes the plasma module (0.4 m long) and the required matching and diagnostics sections. In the downstream tunnel a 40 m long undulator hall is shown, where the undulator chain will be installed. Further downstream after a 12 m long photon diagnostic section the users hall is shown. Additional radiation sources as Betatron and Compton sources are foreseen in the other shown beam lines. The upper room is dedicated to Klystrons and Modulators. In the lower room will be installed

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the existing 300 TW FLAME laser eventually upgraded up to 500 TW. The plasma accelerator module will be driven in this layout by the electron bunch driver (PWFA scheme). A staged configuration of both PWFA and LWFA schemes will be also possible in order to boost the final beam energy beyond 5 GeV. In addition FLAME is supposed to drive plasma targets in the parallel room in order to drive electron and secondary particle sources that will be available to users in the downstream 30 m long user area.

The X-band accelerating technology adopted for the 1 GeV RF drive linac is a very convenient option because it allows to reduce the overall drive linac length, taking profit of the high gradient operation of the X-band accelerating structures (up 60 MV/m in our design) [14]. In addition it will allow implementing at LNF the state of the art high gradient RF technology. This technology has already shown its usefulness for medical and industrial applications but it is also another possible technological option for compact radiation sources and for the future Linear Collider.

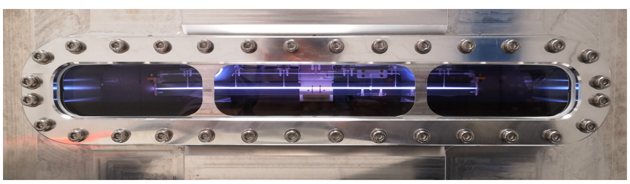

Figure 5: Discharge in a 40 cm capillary.

One of the most innovative device of the project is the plasma accelerating module, see Figure 5. It consists in a 40 cm long, 1 mm diameter capillary pipe in which the plasma is produced by a high voltage discharge in hydrogen. Our PIC simulations show that a 200 pC bunch can drive the acceleration of the subsequent 30 pC bunch to more than 1 GeV and with good electron parameters (reported in tab 1 in the PWFA columns) in a about 40 cm long plasma column. The repetition rate of the PWFA section is limited by the time required to remove the spent gas from the chamber and restore high vacuum. We have currently achieved a repetition rate of 1 Hz, with 100 Hz appearing to be feasible in the near future. In our longer-term plan, we intend to improve this repetition rate to be matched with that of the upgraded linac up to 400 Hz. After the plasma section, quadrupoles or active plasma lenses in a focusing-defocusing configuration will be inserted with small apertures in the focal position of the FEL driving bunch to remove the spent PWFA driver bunch in subsequent stages. The electron beam will be injected into the two FEL beamlines via a small chicane and matching quadrupoles. Reference working points are reported in table 1, while we are now studying the parameter stability and the jitters of the working point.

Two FEL beamlines with different undulator configurations are foreseen in the project, as shown in Figure 6. The upper one is called AQUA and will operate in the water window in SASE configuration, the lower one, called ARIA, will operate in the VUV range in seeding configuration [15].

The photon wavelengths of the AQUA beamline will reach the so-called ”water window” in the wavelength range between carbon (4.40 nm) and oxygen (2.33 nm) K-absorption edges. Since biological samples are mainly composed of light atoms (mostly carbon) and find their native environment in aqueous solutions, the absorption contrast between the carbon atoms of the biological samples and the oxygen of the water surrounding them is the highest in the water window. As a result, measurements of unstained cells, viruses, and organelles in their hydrated, native state have become possible. Aside from photon spectroscopy and imaging experiments, the AQUA beamline will also allow for resonant inelastic X-ray scattering, electron spectroscopies, and photofragmentation measurements.

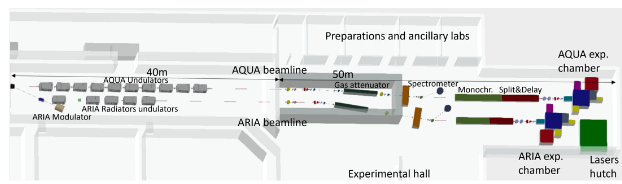

Figure 6. EuPRAXIA@SPARC LAB FEL beamlines, AQUA and ARIA layout.

In order to reach the water window, a GeV electron beam (either from PWFA or from the X-band RF linac at full power) is sent to ten Apple-X undulators with a period of 18 mm. Those undulators will produce SASE FEL light, with typical parameters reported in table 1. The undulator can also change the beam polarization, for example, from linear to circular which allows the photoelectron circular dichroism (PECD) to study chirality effects in molecules.

The FEL light is then fully characterized before being delivered to the experiments via the photon beamline. The beamline transmission is about 34%, due to primarily the Ni-coated mirror reflectivity (in the order of 80% per mirror at 2◦ grazing angle). There is the possibility to insert in the beamline a split-and-delay system to have two geometrically separated beams in the picoseconds range, with an additional loss of about 60% of the beam due to mirror reflectivity. Another system needed by some experiments that can be inserted on the beam is a grating monochromator. A grating monochromator is another system required by some experiments that can be inserted on the beam.

Due to the short temporal length of the beam, a compensating grating configuration will be used to avoid chirping the beam, but with a beam transmission of about 3% due to grating diffraction efficiency and mirror reflectivity, in addition to beamline losses and the amount of spectrum cut by the monochromator.

The stability issues in the monochromator caused by the SASE process and PWFA acceleration will be investigated further. A gas intensity monitor removable scintillating screens, an online grating spectrometer, and beam position monitors will be among the beam diagnostics. Based on gas ionization streaking, dedicated instrumentation for full

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temporal characterization and polarization measurements will be investigated. The beam will be focused at the end by K-B mirrors inside the experimental chamber, which will be outfitted with the necessary instrumentation and sample delivery.

Table 1: Expected Electron and Photon beam parameters

	AQUA		ARIA	
Electron beam	**PWA**	**RF**	**PWA**	**RF**
Charge [pC]	30	200	30	200
Peak Current [kA]	1.8	1.8	1.8	0.8
Energy [MeV]	1.2	1.0	1.2	1.0
Slice Norm. emittance [μm]	0.6	0.5	0.8	1.5
Slice energy spread [%]	0.022	0.05	0.022	0.02
Photon beam	**PWA**	**RF**	**PWA**	**RF**
Pulse Energy [μJ]	10	10	200	200
Wavelength tunability [nm]	4-10	4-10	50-180	50-180
Bandwidth [%]	0.3	0.3	3	0.05
Pulse length [fs]	15	60	15	100

The second FEL beamline we are planning is called ARIA, and it will operate at a lower wavelength energy in the VUV range (around 50-180 nm), is easier to realize, has a larger input parameter acceptance, and requires fewer undulators to operate (thus having a lower economic impact on the project); for those reasons it can begin operations sooner than the AQUA beamline and it can also be used for machine commissioning. The seeded VUV ARIA FEL line exploits the standard High-Gain Harmonic Generation (HGHG) configuration with one Apple-II modulator undulator and four radiator undulators. A commercial OPG-OPA Ti:Sapphire laser system will generate the seed pulse, with a tunability in the range of 600-800 nm (for the fundamental) and 320-400 nm (for the second harmonic), an energy per pulse of more than 20 μJ in all the spectral range, and a time duration of about 200 fs. Typical parameters are reported in the Table 1. The simulated number of photons in both cases will be almost the same.

The ARIA photon beamline will be conceptually similar to the AQUA beamline, but due to the different energy ranges of the photons with different coatings and materials of the beam instrumentation, such as mirrors, filters, and gratings. We expect higher overall transmission than the one in the AQUA beamline due to the higher reflectivity of the C-coated optics in the VUV range, the optics are now under study. Removable split-and-delay and monochromator systems will be available in the beamline.

The ARIA beamline can support a wide range of experiments in atomic, molecular, and cluster physics, as well as solid, liquid, and gas phase materials. The ARIA energy range allows us to probe new electronic transitions well within the 7-20 eV range for classes of cluster materials such as nano-carbons and potential gap dielectrics such as metal oxides using the ultra-fast pump-probe configuration. Photoemission spectroscopy, photo-electron circular dichroism, photo-fragmentation of molecules, and time of flight are examples of experimental techniques we intend to construct that provide powerful tools for investigating excited states such as excitons, polarons, and spin-charge-orbital ordering. Using this experimental techniques, various materials and compositions can be studied with potential applications in hybrid organic–inorganic hetero-junctions of organic solar cells as well as in modulation-doped semiconductor heterostructures of metal–semiconductor interfaces and spintronics devices such as spin valves or diluted magnetic semiconductors, among others.

Beside the design effort the ongoing EuPRAXIA@SPARC_LAB R&D activities at LNF are based on two dedicated facilities: SPARC_LAB [16] and TEX [14].

SPARC_LAB is an inter-disciplinary laboratory devoted to R&D activities in the field of advanced accelerators and lasers technologies in operation since 2005 which is now one of the test and training facilities in the EuPRAXIA project. Since 2015 a plasma chamber has been installed thus allowing several experiments oriented to plasma acceleration of high-quality electron bunches. Important investigations have been done at this facility culminating recently in the first demonstration of a Free Electron Laser driven by a plasma accelerated electron beam [7,8]. This experiment has shown the characteristic SASE and Seeded FEL exponential growth at 800 nm.

In 2021 started the commissioning of the TEX (Test stand for X-band). This facility has been founded in the framework of the LATINO (Laboratory in Advanced Technologies for INnOvation) project. The current facility layout includes an high power X-band (11.994 GHz) RF source, realized in collaboration with CERN, which will be used for validation and development of the X-band RF high gradient technology. The RF source is based on a CPI VKX8311 Klystron and a solid state ScandiNova k400 modulator to generate a maximum RF output power of 50 MW at 50 Hz, that will be mainly used for accelerating structure conditioning and waveguide components testing.

THE BETATRON RADIATION SOURCE

As stated in the CDR, EuPRAXIA will include the development, together with laser industry, of a new generation of high peak power lasers, into the regime of 20 - 100 Hz repetition rate for 100 Joule class lasers and pulse durations of 50 femtoseconds and will deliver betatron X rays to users from the medical area. The EuPRAXIA Advanced Photon Sources (EuAPS) project, led by INFN in collaboration with CNR and University of Roma "Tor Vergata",

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will address precisely the previous topics [17]. EuAPS foresees the construction of a laser-driven "betatron" X Ray user facility at the LNF SPARC_LAB laboratory and the development of high power (up to 1 PW at LNS) and high repetition rate (up to 100 Hz at CNR Pisa) drive lasers for EuPRAXIA.

EuAPS has received a financial support of 22.3 M€ from the PNRR plan, ("Piano Nazionale Ripresa e Resilienza," which is the Italian for "National Recovery and Resilience Plan.").

The Laser-driven "betatron" [18] X-Ray facility has inherent advantages in resolution due to the small (point like) emission volume in plasma. Preliminary simulations show that with a plasma density of 5 10^{17} cm^{-3} in a 3 cm long capillary an accelerating gradient of 50 GeV/m, an output energy of 1.5 GeV for an electron beam charge of 500 pC can be achieved. A total number of 2 10^{9} photons with a critical energy above 1 keV is then expected (tunable, thorough electron energy), with more than 10^{5} photons in the 0.1% of the bandwidth. Moreover, operation at 1-10Hz will increase the average number of the photons with respect to the state of the art. Advanced photon diagnostics will be developed at CNR-ISM Potenza and Montelibretti (RM) to fully characterize x-ray betatron radiation, while University of Tor Vergata will provide the compact user end station. The expected betatron radiation spectrum at EuAPS overlaps the designed radiation wavelength of the FEL beam lines of EuPRAXIA facility, thus facilitating the final integration of the EuAPS components into the EuPRAXIA project. A dedicated user interaction chamber with related sample's manipulation and diagnostics tools will be designed and installed downstream of the plasma module.

EuAPS includes the development of the required drive Lasers, targeting a 50% increase in energy efficiency and complying with the green deal goals. The work towards High Power (up to 1 PW) and High Repetition Rate (up to 100 Hz) is spear-headed by the INFN-LNS-Catania and CNR-Pisa laboratories, offering a platform for advanced laser-based industrial developments. At CNR-Pisa the consortium will establish user access to the next generation of kW scale high repetition rate laser operation. At INFN-LNS-Catania the focus will be placed on high charge secondary particle production with high power lasers and ion-plasma interaction for astrophysical investigations.

CONCLUSION

We presented in this paper the progress of our planned FEL facility EuPRAXIA@SPARC LAB in the framework of the European EuPRAXIA Project. The technical design report will be published by the end of 2025. Meanwhile, we are moving forward with the civil permits for the building's realization; we plan to begin construction in 2024 and complete it by 2027. The machine's installation and operation will begin as soon as the structure is ready to receive it and it will be commissioned by 2028. If no unforeseen delays happen, we anticipate having pilot users in 2029.

ACKNOWLEDGEMENTS

Greatly appreciate contributions from: F. Villa, C. Vaccarezza, E. Chiadroni, D. Alesini, R. Pompili, A. Biagioni, A. Cianchi, L. Giannessi, A. Gallo, F. Stellato, U. Rotundo, A. Falone, A. Ghigo and the entire EUPRAXIA@SPARC_LAB team.

We also thank the EuPRAXIA-ESFRI and EuPRAXIA-PP consortia, especially the Preparatory Phase WP leaders, for useful discussions, input and support.

We acknowledge the funding support for the Frascati facility in EuPRAXIA provided from INFN programs, the Lazio region and the national Italian government, including the support through the PNRR funding program.

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773.

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