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EuPRAXIA Advanced Photon Sources

PNRR_EuAPS Project

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Abstract

The EuPRAXIA Advanced Photon Sources (EuAPS) project**,** led by INFN in collaboration with CNR and University of Roma "Tor Vergata", foresees the construction of a laser-driven "betatron" X Ray user facility at the LNF SPARC_LAB laboratory. EuAPS also includes 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, Mission 4 "Education and Research", Action 3.1.1 "Creation of new research infrastructures strengthening of existing ones and their networking for Scientific Excellence under Horizon Europe" and has received the highest score among the submitted projects of the ESFRI area "Physical Sciences and Engineering".

The EuAPS project starting date has been fixed on December 1st, 2022 and will last 30 months (with a possible extension of additional 6 months).

In this paper we report the introductory part of the submitted proposal.

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1 Introduction

Advanced Photon Sources are key components for the successful operation of the EuPRAXIA ESFRI facility [1]. They act, for example, as drivers for plasma waves in ultra-high-gradient accelerators or as plasma-based sources of ultra-short pulses of high intensity x-rays. The proposed EuPRAXIA Advanced Photon Sources (EuAPS) project bundles several frontier science aspects in this domain, to be pursued in Italian research centers and universities. This project will enable the creation of new advanced photon test facilities in Italy that operate at internationally competitive levels and will support users from medical applications or other domains. The proposal includes a Laser-driven "betatron" [2] X-Ray facility to be tested and put in operation at the SPARC_LAB test facility [3]. This proven concept, part of the EuPRAXIA science goals, has inherent advantages in resolution due to the small (point like) emission volume in plasma. Advanced photon diagnostics will be developed at CNR-ISM Potenza and Rome to fully characterize x-ray betatron radiation, while University of Tor Vergata will provide the compact user end station. 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. The work in EuAPS will play a crucial role in complementing the EuPRAXIA construction project at Frascati [4].

Figure 1: Geographical distribution of the participant institutes INFN (Frascati, Catania, Milano), CNR (Pisa, Montelibretti (RM), Potenza), University of Roma "Tor Vergata (Roma).

EuAPS resulted to be one of the national interest projects selected within the framework of PNRR ("Piano Nazionale Ripresa e Resilienza," which is the Italian for "National Recovery and Resilience Plan."), which sees INFN committed as the leader through its Frascati National Laboratories, in collaboration with CNR and University of Roma "Tor Vergata". EuAPS has received a financial support of 22.3 M€ from the PNRR plan, Mission 4 "Education and Research", Action 3.1.1 "Creation of new research infrastructures strengthening of existing

ones and their networking for Scientific Excellence under Horizon Europe" and has received the highest score among the submitted projects of the ESFRI area "Physical Sciences and Engineering".
The EuAPS project will last for 30 (+6) months and the starting date has been fixed on December 1rst, 2022. The kick-off meeting [5] took place on February 28th, 2023, at the INFN headquarter in Roma.

2 Context analysis and state of the art

The European Plasma Research Accelerator with eXcellence In Applications (EuPRAXIA) will implement a new kind of accelerator infrastructure, considerably reducing the size of particle accelerators and creating a new market. EuPRAXIA will serve users in ultra-fast science with X rays for high-resolution medical imaging, with deeply penetrating positron annihilation spectroscopy for materials and with Europe's most southern Free-Electron Laser (FEL).
The EuPRAXIA concept, as described in detail in its published Conceptual Design Report [1], is a distributed, compact, and innovative accelerator facility based on plasma technology.
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. The European Strategy Forum on Research infrastructures (ESFRI) has successfully assessed maturity and readiness of the EuPRAXIA project and placed it on the ESFRI Roadmap 2021, with Italy thorough INFN as leading country. In its first implementation phase, the EuPRAXIA consortium will construct a beam driven plasma accelerator at Laboratori Nazionali di Frascati (INFN-LNF) funded by Italy through INFN. It will set up a compact and innovative FEL with first user operation foreseen in 2028. A second EuPRAXIA construction site in Europe for a laser driven FEL will be decided in 2023, see Figure 2.

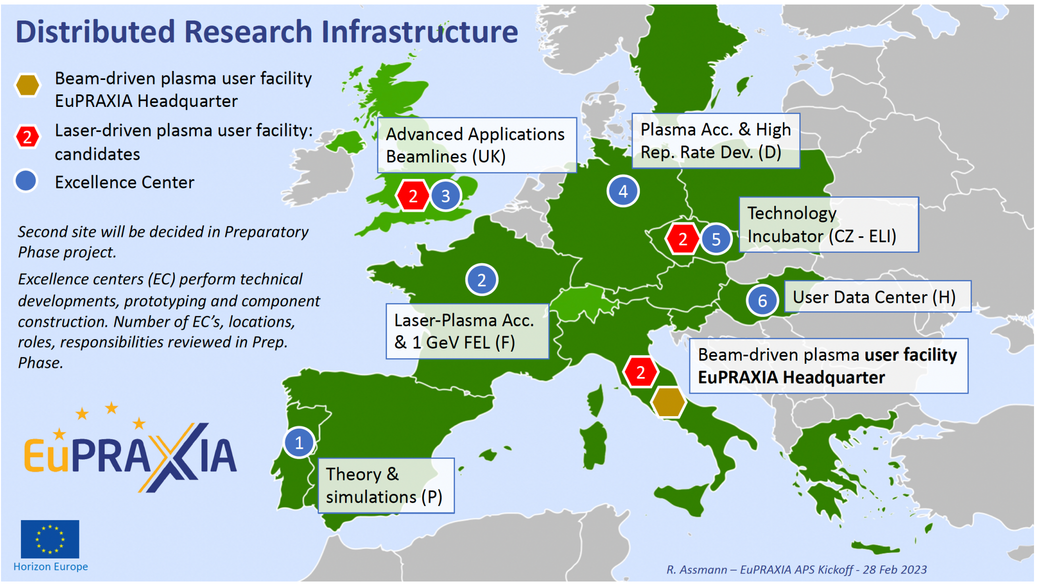

Figure 2: The consortia supporting the EuPRAXIA distributed research infrastructure (green countries) and the location of the two User Facility with additional proposed supporting Excellence Centers.

The proposed EuPRAXIA Advanced Photon Sources "EuAPS" project complements the overall EuPRAXIA project and the ongoing work at INFN-LNF with an Italian-wide project on the required Advanced Photon Sources and related additional innovations and applications. Advanced Photon Sources act here as drivers for plasma waves in ultra-high-gradient accelerators or as plasma-based sources of ultra-short pulses of high intensity x-rays. The proposed work will enable the production of unique ultra-short particle and photon beams with applications in ultra-fast science, amongst others highly accurate medical imaging, material characterization and medical treatment.

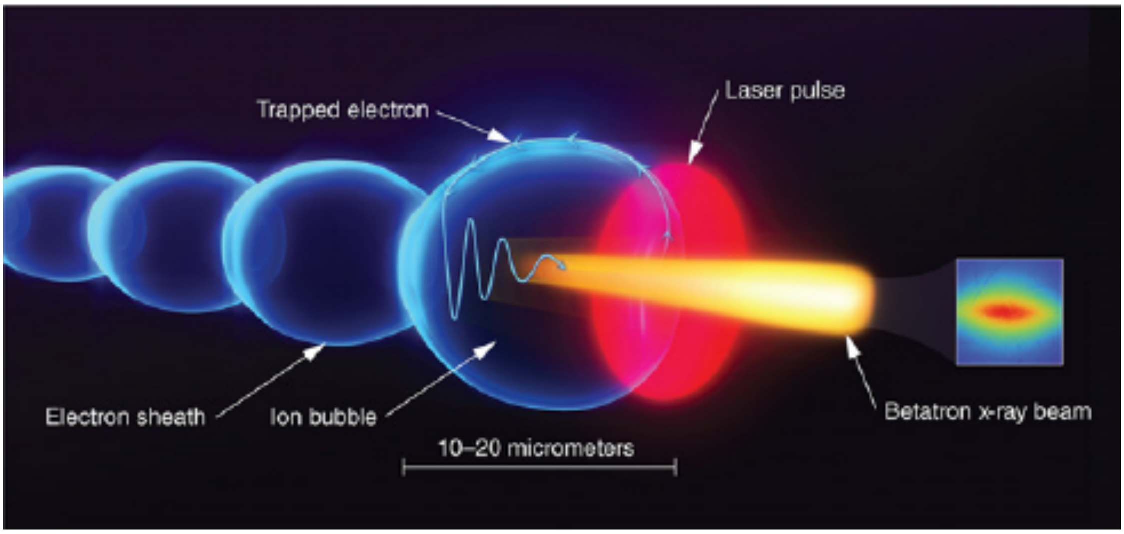

Figure 3: Principle of betatron X-ray emission from a LWFA. Electrons trapped at the back of the wakefield are subject to transverse and longitudinal electrical forces; subsequentlythey are accelerated and wiggled to produce broadband, synchrotron-like radiation in keV energy range [6].

EuAPS will set up a laser-driven “betatron” X Ray facility at the existing SPARC_LAB test facility. Betatron sources are spatially coherent and can fill the large performance gap between synchrotron and X-ray tube-based sources [6]. This already proven concept, illustrated in Figure 3, part of the EuPRAXIA science goals, has inherent advantages in resolution due to the small (point like) emission volume in plasma. The potential of a bright µm-sized source of hard x-rays based on the betatron oscillations of laser wakefield accelerated electrons has been demonstrated in 2015 in the Rutherford Appleton Laboratory (UK) [7]. Micro-computed tomography of a human femoral trabecular bone sample, allowing full 3D reconstruction to a resolution below 50 µm has been possible with electron beam at energies of about 800 MeV and charge > 100 pC. This beam was generated in a 1.2 cm long gas cell with plasma density $n_e = 3x10^{18}$ cm^{-3}. Each photon pulse contained about 10^9 photons above 1 keV. This remarkable result has been limited by the very low repetition rate of the driving laser, only 1 pulse/minute, thus considerably reducing the average photon flux. Advancement in Laser technology today allows to use a higher peak power system (up to 1 PW at 10 Hz) thus increasing the extracted electron energy [8, 9]. In addition, progress in controlling the electron injection process allows to increase the bunch charge. This will result in an enhancement of the number of photons per pulse. Alternatively, the repetition rate can be increased (up to 100 Hz with 300 TW) thus providing in both cases users with higher average photon flux. EuAPS includes the development of the required drive lasers. 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-INO-Pisa laboratories, offering a platform for advanced ultrafast laser-based industrial developments.

Advanced photon diagnostics tools will be developed at CNR-ISM-Potenza and Rome to characterize the intensity, beam divergence, size and stability as well as the spectral distribution and pulse duration of the x-ray betatron radiation. University of Tor Vergata will provide the compact and integrated user end station.

3 Pre-project scenario

The EuAPS project will rely on well-established facilities able to host the proposed developments.

An inter-disciplinary laboratory devoted to R&D activities in the field of advanced accelerators and lasers technologies is in operation since 2005 at INFN-LNF: the SPARC_LAB facility [3], see Figure 4, which is now one of the test and training facilities in the EuPRAXIA project.

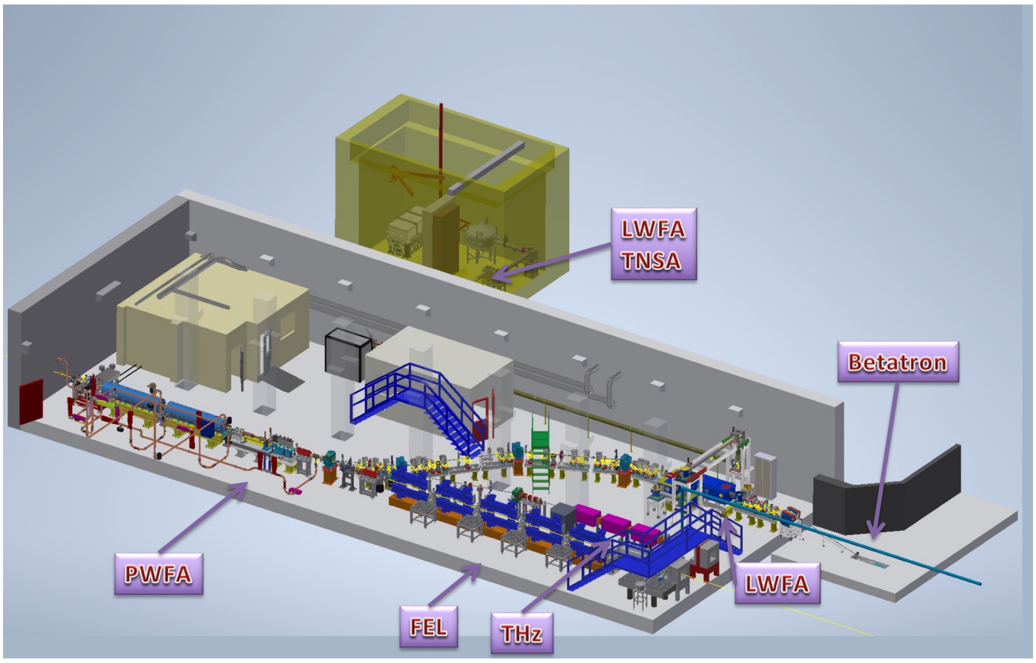

Figure 4: Layout of the SPARC_LAB facility.

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. This experiment has shown the characteristic SASE and Seeded FEL exponential growth at 800 nm and it has been published in the Nature journal [10,11]. The external injection beamline for the Laser driven acceleration experiments is under commissioning and preparatory experiments have been performed.

The Laboratori Nazionali del Sud (LNS) of INFN is a well-established European ion beam research infrastructure covering nuclear physics, material analysis, medical physics, development and test of detectors for dosimetry, radiobiology, environmental and cultural heritage applications. At the LNS two particle accelerators, a Superconducting Cyclotron and a Tandem, provide ion beams from Hydrogen to Lead with energies up to tens of MeV per nucleon. The research team of INFN-LNS has outstanding experience in the realization of clinical transport beamlines for proton beams, including proton and light ion irradiation beamlines for multidisciplinary applications [12].

Two Nd: Yag lasers operating at 1064 nm fundamental wavelength, a pulse width of 6-9 ns, 0.9 J maximum pulse energy, and 10 Hz are installed and available at LNS. The research team has a wide experience in the acceleration, transport, and diagnostic of radiation produced in the interaction of high-power lasers with matter.

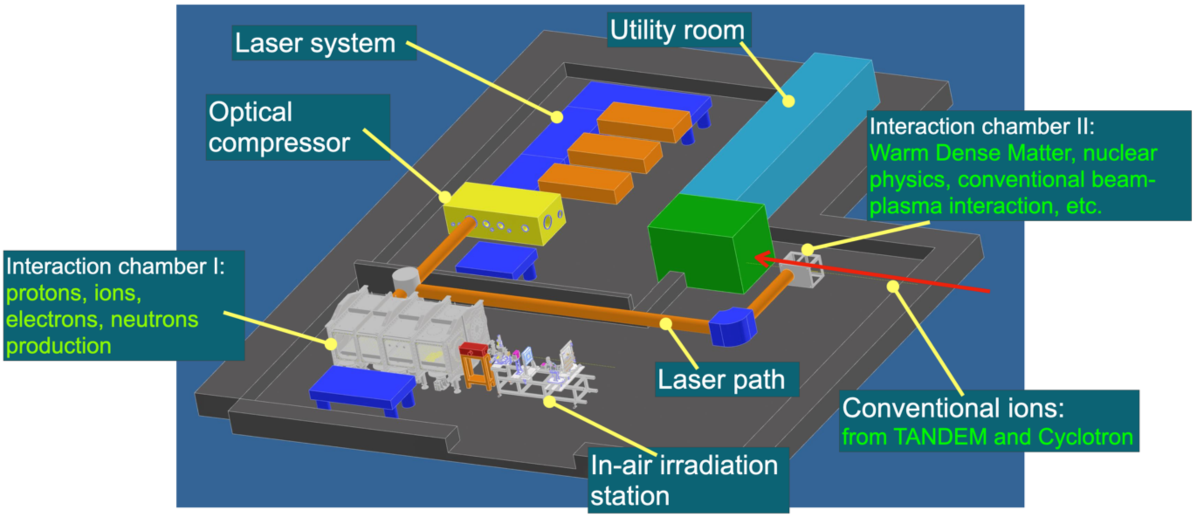

Figure 5: I-LUCE (INFN Laser indUCEd radiation production) at LNS

At CNR-INO-Pisa, the Intense Laser Irradiation Laboratory currently operates a laser with ultrashort (<25fs duration pulses) pulses. Two beamlines are available (220TW, with pulse energy >5J, and 15TW, with pulse energy >450mJ, respectively), each equipped with its own vacuum chambers and shielded target areas [13].

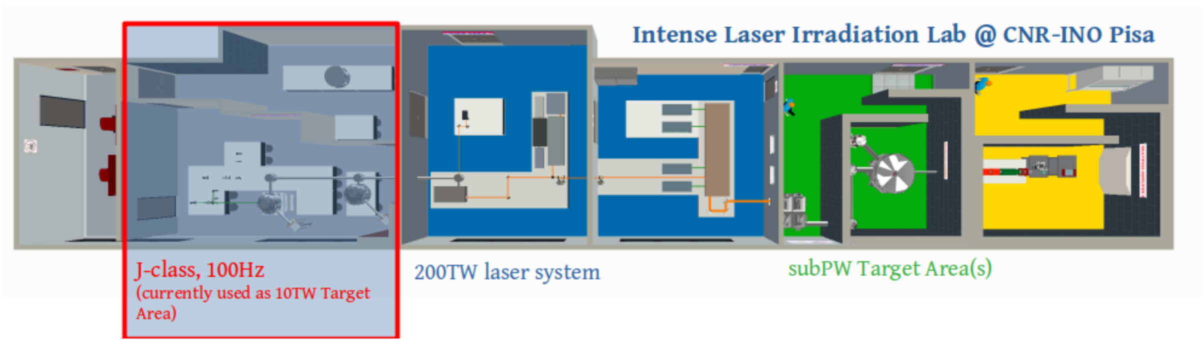

Figure 6: Intense Laser Irradiation Lab at CNR-INO in Pisa

Over the past few years, a system has been employed to carry out laser-plasma based particle acceleration experiments, as well as advanced detectors and/or materials studies using the laser photon beam [14,15]. Ultrashort and high-power laser systems are currently limited to a typical 10Hz repetition rate thus limiting the ultimate average particle/photon flux in novel concept sources such as EuPRAXIA. CNR-INO-Pisa is currently engaged, together with industrial partners, to make ultrashort, high power laser systems available at a higher repetition rate. The laser infrastructure proposed here, hosting a laser system with Joule-level energy and 100Hz rep-rate, will be crucial in providing, together with industrial partners, laser beam amplification, transport and manipulation schemes with the required energy and repetition rate for the EuPRAXIA infrastructure.

4 Most important changes and impact on the reference domain for a new RI

The EuAPS project will provide SPARC_LAB with a new user beamline fully equipped with a user end station for betaron X ray imaging. It will extend user capabilities for INFN-LNF, building on long-lasting developments through the existing facilities DAFNE-Light source, Beam Test Facility (BTF) and X_Lab. At INFN-LNS a new high charge secondary particle production line will be set up, exploiting the innovation from high-density plasmas and high-power lasers. At CNR-Pisa user access to the next generation of sub-kW scale, high repetition rate, ultrashort laser beams will be established. The key figures of such a laser are expected to match the ones currently envisioned for the EuPRAXIA laser front-end. EuAPS will leverage Italian capabilities at existing facilities and will advance some of EuPRAXIA`s main challenges in an Italian and European context.

5 Proposed actions, their implementation, and possible critical issues

The main actions required to achieve a full implementation of the EuAPS proposal are distributed in the 3 main laboratories.

At LNF the Betatron Radiation Source will be installed. The dedicated Plasma Target, the fs-Synchronization system and the Photon Diagnostics system will be developed, procured, installed and commissioned. Improvements of the laser transport system and electron beam injection and extraction regions will be implemented to optimize the photon flux. 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 and 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. 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.

At LNS a High-Power Laser Beamline will be dedicated to the development of a new high-power (> 300 TW) laser system at the frontier of technological innovation. The system will deliver pulses up to PW with an energy of at least 30 J, pulse duration <30 fs and repetition rate up to 10 Hz. Dedicated transport, selection and diagnostics systems for the charged particles (electrons, protons and ions) will be realized to optimize and to deliver the produced particle pulses for different applications (i.e. biological, fusions reactions in plasma, cultural heritage, astrophysics, etc.).

At CNR-INO-Pisa the High Repetition Rate Laser Beamline will implement a state-of-the-art high repetition rate, ultrashort and high-power laser system. A laser with <25fs duration, >1J pulse energy and 100Hz repetition rate will be installed, complemented by a dedicated end user station. The system, based on TiSa gain modules with diode-pumped Nd pumps, is expected to match the figures currently foreseen for the EuPRAXIA laser front-end. Thus, EuAPS will develop a crucial component for the next generation of high average power laser systems at ~10J pulse energy. The work includes high power amplifier stages, high damage threshold optical components and fast manipulation devices for longitudinal and transverse laser functions.

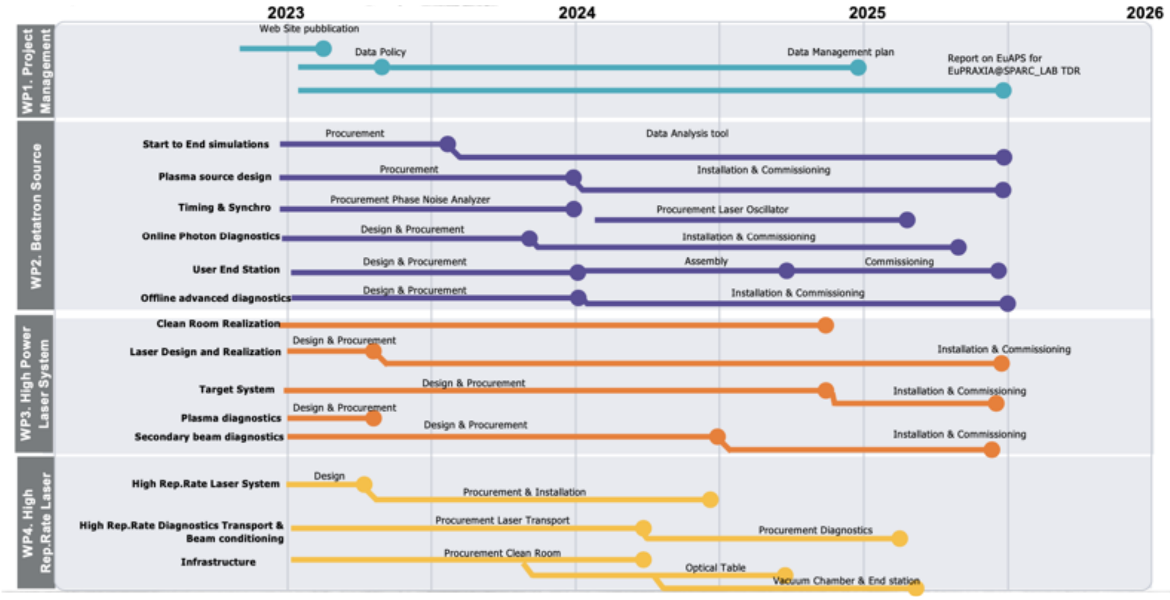

Figure 7: EuAPS timeline.

The EuAPS goals are firmly connected to the preparatory phase of the EuPRAXIA ESFRI project, making sure that the goal and accomplishment of the EuAPS proposal are aligned with the general goal of the EuPRAXIA facility, see Figure 7. The innovative EuAPS project relies on recently proven concepts and a realistic extrapolation of technology together with industry. Critical risks are therefore expected in the administrative project setup, mainly timely hiring of qualified personnel and procurement of high-tech components on schedule and on budget. A risk mitigation strategy will be put in place from the project start, for example by working closely with industry from day 1, by using multiple supply chains and by expert help from the EuPRAXIA institutes.

6 Post-project scenario and description of the upgraded research infrastructure

The EuAPS project will enable the creation of new advanced photon facilities in the three main laboratories, as preliminary bricks of the EuPRAXIA project. According to the EuPRAXIA Consortium Agreement, already signed by all the proponent institutes, the future sustainability of the EuAPS infrastructure is guaranteed. The EuPRAXIA Distributed Research Infrastructure has received official government support from Italy, Czech Republic, Portugal, Hungary and UK. Financial support of 118 M€ has been already committed, mainly from Italy as lead country. The work in EuAPS plays a crucial role in complementing the EuPRAXIA construction project at Frascati, further developing and strengthening the EuPRAXIA technology, its use case and user basis in Italy and beyond. It will contribute to further developing the required expertise to run such an innovative facility, including training a new generation of young scientists that eventually run the EuPRAXIA facility in the next decades. To this end a fruitful collaboration with the PhD programs of the Universities of Roma, Pisa and Catania is already in place, in particular with the dedicated "Accelerator Physics" PhD program of the University of Roma "La Sapienza". The compactness of the betatron radiation source will allow future installations in hospitals close to patients or in dedicated small laboratories close to delicate material samples. The EuAPS innovation will then be exploited not only in the EuPRAXIA facilities but also in hospitals, museums, universities and companies.

7 Expected results and their impact

The EuAPS project will develop innovative EuPRAXIA advanced photon sources that will enhance existing research infrastructures to be used by Italian industry and universities. It will build on and enhance Italian leadership and excellence established in the science, technology and innovation in ultra-compact plasma accelerators. This outstanding excellence is proven by the recent ESFRI approval of the Italian-led EuPRAXIA project. EuAPS will strengthen this excellence and will exploit the innovation potential within an Italian network of institutes. New user capabilities will be delivered, reaching out to users from additional domains like health. EuAPS will therefore not only strengthen proven excellence but also diversify to new application domains. The IP model will follow the EU policies as implemented in the EuPRAXIA consortium agreement, signed in December 2020 for its preparatory phase. The work will generally aim at an open innovation approach, as defined in the EuPRAXIA CDR report. However, some IP will be protected if brought into the work or developed with industrial companies. Standard EU policies will be followed. The proposed new research tools and facilities in Catania, Potenza, Pisa, Roma and Frascati will be used by local, national and international communities for their cutting-edge research. Industry will profit both as suppliers or as carriers of innovation spin-offs. An important outcome of the EuAPS project will be a contribution to the EuPRAXIA Technical Design Report (TDR), illustrating full alignment and synergy with the ESFRI goals. All the participant institutes have a considerable experience in running advanced technology systems and to participate to regional, national and EU call for external funds (e.g. EUROFEL (FP6), IRUVX (FP7), EuPRAXIA and XLS (H2020)). EuAPS will allow additional fund-raising opportunities in the framework of accelerators and light sources programs. The use of highly compact and energy efficient new technologies will open a long-term path towards minimizing energy consumption and CO_2 footprints.

8 Objectives and ambition

The main objectives and ambitions of the EuAPS project are the development of world-leading compact photon sources to drive plasma accelerators and the setup of ultra-compact, high performing X ray and particle sources for multiple users from health to materials. Those EuAPS objectives and ambitions are reflected in the Work Package (WP) structure, see Figure 8. In addition to the management and dissemination WP we foresee 3 Technical WP each based at one of the 3 main involved laboratories. The collaboration between the technical WP`s is crucial for the success of the project: concepts, various technical components, strategic goals and the EuPRAXIA context are shared. For example, the Laser development at INFN-LNS-Catania and CNR -INO-Pisa in WP4 will provide the laser technology required for the Laser Driven Betatron Radiation source located at INFN-LNF.

The EuAPS project is organized in 4 Work Packages (WP) in order to properly monitor the evolution of each activity and to guarantee the expected final results. To this end we have identified the following WP structure:

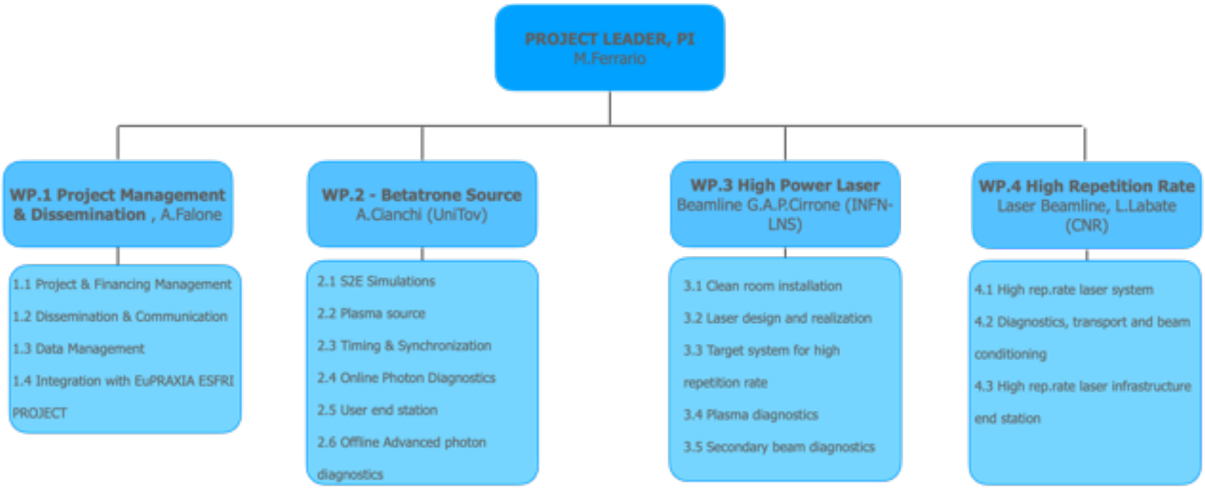

Figure 8: EuAPS organization structure showing the 4 Work Packages and the related main deliverables.

WP1 – "Management and Dissemination". The implementation of the EuAPS project will be monitored by a dedicated "Management and Dissemination" structure. The leadership will implement project management methodologies to ensure that the project execution is performed in due time and within budget, accomplishing the technical and scientific goals of the project. The Management team will also be responsible to identify and implement the appropriate dissemination and communication strategies towards a set of stakeholders. It will ensure a comprehensive data management plan to secure the operability for at least the next 10 years and the coherence with FAIR principles and the EuPRAXIA ESFRI policies.

WP2- "Betatron radiation Source" will deliver a new Plasma based Laser driven X-rays source at INFN-LNF.

The implementation of this WP includes numerical simulations and optimization of the plasma target, design and realization of the plasma source, commissioning of the timing and synchronization system, photon diagnostics design and implementation, user end station design and test. The expected outcome is a bright and stable X rays source based on betatron radiation for interdisciplinary applications.

The plasma source task will ensure the design and construction of its main components: the plasma capillary, the discharge system, the vacuum pumping and gas systems and the plasma diagnostics. The existing laser facility at SPARC_LAB will be upgraded. Betatron radiation is emitted from the fast oscillations that electrons execute in a high gradient plasma wave during their fast acceleration. To this end two schemes will be investigated, internal and external injection of electron bunches in the plasma. In both cases a high power laser pulse (10^{19} W/cm^2) is needed, as well as transport and focalization optics, longitudinal compression stages, a laser extraction system and vacuum pumping. The required laser system and laser handling components will be developed in WP3 and WP4. This interaction is fundamental to the proper upgrade of the existing SPARC_LAB laser facility.

Another fundamental goal of WP2 is to develop a system to keep electron beams and laser pulses synchronized at the level of few tens of femtosecond. This requires a replacement of the existing RF modulator and of the FLAME laser oscillator. The ambition of this activity includes reaching the performance required for the optimal operation of the EuPRAXIA FEL, thus establishing additional synergy.

Short pulses of X rays will be emitted from this source. A proper beamline with the diagnostics for photons and electrons will be developed to measure longitudinal and transverse properties of the beams. The end station will be built to allocate the experiments with the needed instrumentation.

WP3- "High Power Laser Beamline". The main aim of this WP will be the design and installation of an high-power (> 300TW and up to 1 PW) laser beamline dedicated to the production of electrons and high charge secondary particle and to the production and high-density plasmas. This will constitute an open Users facility, called I-LUCE (INFN Laser indUCEd radiation production) where different laser-driven radiation will be available for future Users.

This WP will permit the realization, installation, and use of the laser system with highest pulse peak power in Italy. Thanks to the use of the latest available technology, the system will be able to amplify light up to 1 PW peak power, with a very short pulse duration and with a repetition rate up to 10 Hz. This will open the possibility to initiate and to study innovative physics regimes to produce high-intensity, high-energy radiation with exceptional spatial-temporal characteristics. The realization of such a system will allow acquiring new competencies in the field of plasma physics, high-intensity optic, laser-driven particle acceleration and laser system realization for the benefit also of WP2.

The construction of this laser system at INFN-LNS will have a significant impact both in terms of science and applications. With such a system, INFN-LNS will bring together its scientific, engineering, and medical missions for the benefit of industry and society. First, the system will open up unprecedented new possibilities in particle physics, nuclear physics, high energy beam science, nonlinear field theory and ultrahigh-pressure physics. Besides its fundamental physics mission, a paramount objective of the new system will be to provide ultra-short pulses of energetic particles (0. 1 to 10 GeV) and photons (up to a few MeV), both produced with compact laser plasma accelerators.

Furthermore, the system will have a considerable impact on several fields of materials sciences, medicine, and environment protection. In materials science it will help to clarify the mechanisms leading to defect creation and aging of materials in nuclear reactors. Since the optical, X-ray and particle beams provided by the laser will be synchronized at the tens of fs level, they will enable pump-probe investigations in a very broad range of energies for photons (eV–MeV) and particle beams (eV–GeV) with very high accuracy. Finally, there is a concurrent presence of intense (up to micro-A) and energetic (up to 100 MeV) ion beams at the INFN-LNS laboratories produced by a conventional accelerator. Together with the new laser system this will give the possibility to perform new experiments and studies based on plasma-ion interactions that are so far only possible in two other facilities in the world.

The INFN-LNS laser area of the I-LUCE facility, where the laser system will be installed and where the interaction chambers for the radiation production and for the plasma studies will be installed is shown in Figure 6 above.

WP4- "High Repetition Rate Laser Beamline" will develop and construct at CNR-INO-Pisa a laser system based on TiSa gain modules with diode-pumped Nd pumps, matching the requirements currently foreseen for the EuPRAXIA laser front-end. It is noted that the use of the diode-pump technology will significantly improve energy efficiency, aiming at a 50% increase of efficiency and ensuring that green deal goals are met. The work of WP4 will enable and spearhead the upgrade of the laser system at INFN-LNF.

The new laser system is expected to achieve parameters as needed for the 100 Hz option of the front-end laser system of the EuPRAXIA laser (ultrashort, 100 Hz repetition rate, J-class laser system with pulse duration <25fs and pulse energy >1J). It will thus prepare the development of further amplification stages for the final EuPRAXIA laser system. In addition, the commissioning of adaptive mirrors able to withstand high average power, with fast correction capability will be another important contribution to the EuPRAXIA ESFRI project. The CNR-INO-Pisa facility will be equipped with a user end station, that includes a vacuum chamber for testing high power, ultrashort laser optics.

9 Project framework and main expected impact

In the long term, the EuPRAXIA ESFRI project and the herewith proposed EuAPS project aim to establish the scientific and technological foundations upon which a new market, and therefore, a new industry for non-RF-based accelerators could emerge, characterized by a much shorter length and possibly a cost representing only a fraction of what RF-based accelerators cost. The economic advantages of more compact accelerators are seen as a factor to make accelerator-based machines affordable to a much wider customer base. EuAPS will form a strong Italian community around this goal, connecting to authorities, universities, industrial companies, and spin-off opportunities in various Italian regions beyond Lazio. Local industry acts as supplier, innovation partner and carrier for high-tech spin-offs. Currently around 45,000 accelerators are in use world-wide as size and cost of implementation and operation are prohibitive for many use cases. New use cases include compact X-ray machines that are easily positioned for inspection of bridges, cargo or security. Additionally, time-resolved medical imaging with high spatial resolution could be used for fast online monitoring in high-precision surgery on human organs. Compact FELs in basements of universities could provide students with fascinating tools for studying bacteria and viruses. In other words, EuPRAXIA is ultimately expected to boost the expertise of the European scientific communities in compact accelerator technologies and to advance the expertise of European companies involved in the development of key components for novel accelerator technologies to deliver expected beam parameters. Thus, it can create the conditions for the emergence of an European industrial leadership in compact accelerator solutions. Because novel accelerator technologies are expected to result in smaller and more economical accelerators, EuPRAXIA can facilitate the creation of a brand-new market for accelerators, a market estimated to be two orders of magnitude larger than the current market.

The target groups, identified within the EuPRAXIA ESFRI project and also all relevant for EuAPS, are:

1) FEL users. With two FEL beamlines and compact X-ray sources, EuPRAXIA will address the demand for increased access to FEL facilities in Europe. It will raise the capacity for user experiments and directly support scientific progress in e.g. medicine, chemistry and material science.

2) Medical and material engineering user communities (including industry). The EuPRAXIA RI offers unique features in time resolution, pump-probe capabilities, spatial resolution for X-ray imaging and penetration depth for material analysis. EuAPS with the development of betatron X ray based medical imaging is placing an emphasis in this aspect. Combined with the EuPRAXIA and EuAPS focus on co-development and industrial engagement, this will target the need for a strengthened base in high-tech innovation. EuPRAXIA and EuAPS provide a platform for development and testing of new technologies.
3) Particle accelerator community (including industry). Particle accelerators rely on mature technology that is encountering practical limitations. The application reach and benefits of accelerators will be dramatically increased if their size and cost are reduced. This RI leverages innovative concepts and technologies for demonstrating a reduction in facility size for accelerator-based machines. EuPRAXIA be a new kind of RI and a transformative step to a new generation of compact accelerator facilities. It will be the first RI worldwide to realize an accelerator facility based on novel concepts that so far have only been used in experimental tests. EuAPS develops the required laser drivers for the Italian context of this project.
4) Education and training users. As part of its vision of accelerator innovation, EuPRAXIA and EuAPS provide unique opportunities for education and training in innovative technologies in the ERA and beyond. In the long term, the capabilities to use brilliant, time-resolved X-ray pulses in every university e.g. could multiply the number of virus structures to be resolved. Young scientists could have early access to powerful research, new ideas and directions could be tested quickly. Experience shows that such wider access and education in pioneering tools will strongly accelerate knowledge gain and innovation.

The progress towards ultra-compact and more cost-effective accelerators and applications, which is in EuPRAXIA's core mission, will lower the entry barrier for accelerator-assisted research, allowing access to research groups and countries typically not making use of particle accelerators. EuAPS extends its impact into the local regions of Italy.

EuPRAXIA and EuAPS are expected to contribute to several of the grand societal challenges:

1) Health, demographic change and well-being: through advancing medical imaging and through providing ca-pabilities for science studies on viruses like SARS-CoV-2, on multi-resistant bacteria and on drug develop-ment. Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the Bioeconomy: through advanced and mobile X-ray (nano-pollution of plants) and sterilization techniques. Climate action, environment, resource efficiency and raw materials: through advanced material imaging tech-niques, such as for example compact, deeply penetrating positron annihilation spectroscopy for nm-scale fatigue investigations.
2) Europe in a changing world - inclusive, innovative, and reflective societies: through securing high-tech expertise and a job base, attracting and training young generations in transformative and ground-breaking technology developments, building on and defending world-leading laser expertise in Europe. Secure societies protecting freedom and security of Europe and its citizens: through mobile X-ray techniques with superior resolution via the point-like emission of X-rays (small emission length in plasma undulators).

3) Socio-economic impact. A socio-economic impact study for EuPRAXIA has been performed as part of the ESFRI application. The estimated ratio of costs to benefits shows an 81 M€ economic net present value with a socio-economic internal rate of return of 9.2%. The operation and further development of the EuPRAXIA facility requires trained specialized technicians, engineers, and scientists. They need to master complex technologies, be open to new ideas, embrace innovation and operate in interaction with international colleagues and guests. We estimate that inside EuPRAXIA per year about 20 technicians will be trained in addition to about 30 master theses for engineers. Many of these might work some years at EuPRAXIA and then proceed to a career in the local or regional industry, transferring the knowledge on new technologies. Some trained personnel might develop their own ideas and found spin-off companies. Experience shows that about 10 patents could result per year from an innovative infrastructure like EuPRAXIA. Until 2032, we estimate 200 PhD students (FTEs) involved, with 33 degrees per year produced.
4) Scientific output. The new technologies on compact accelerators and the scientific results on bacteria, viruses, materials and other subjects of study will be reported in, on average, about 500-600 journal articles per year. Scientific results will be reported in outreach talks to the local and regional communities, especially connecting to schools and universities. Enthusiasm about science and technology will be fostered in the population. Ultimately, the goal of EuPRAXIA is to establish the scientific and technological foundations on which a new market – and therefore, a new industry – for non-RF-based accelerators could emerge. These new accelerators, because of their reduced cost and size, could thus widen the access of accelerator-based machines to a broader audience and could lead to the production of new goods and services.

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