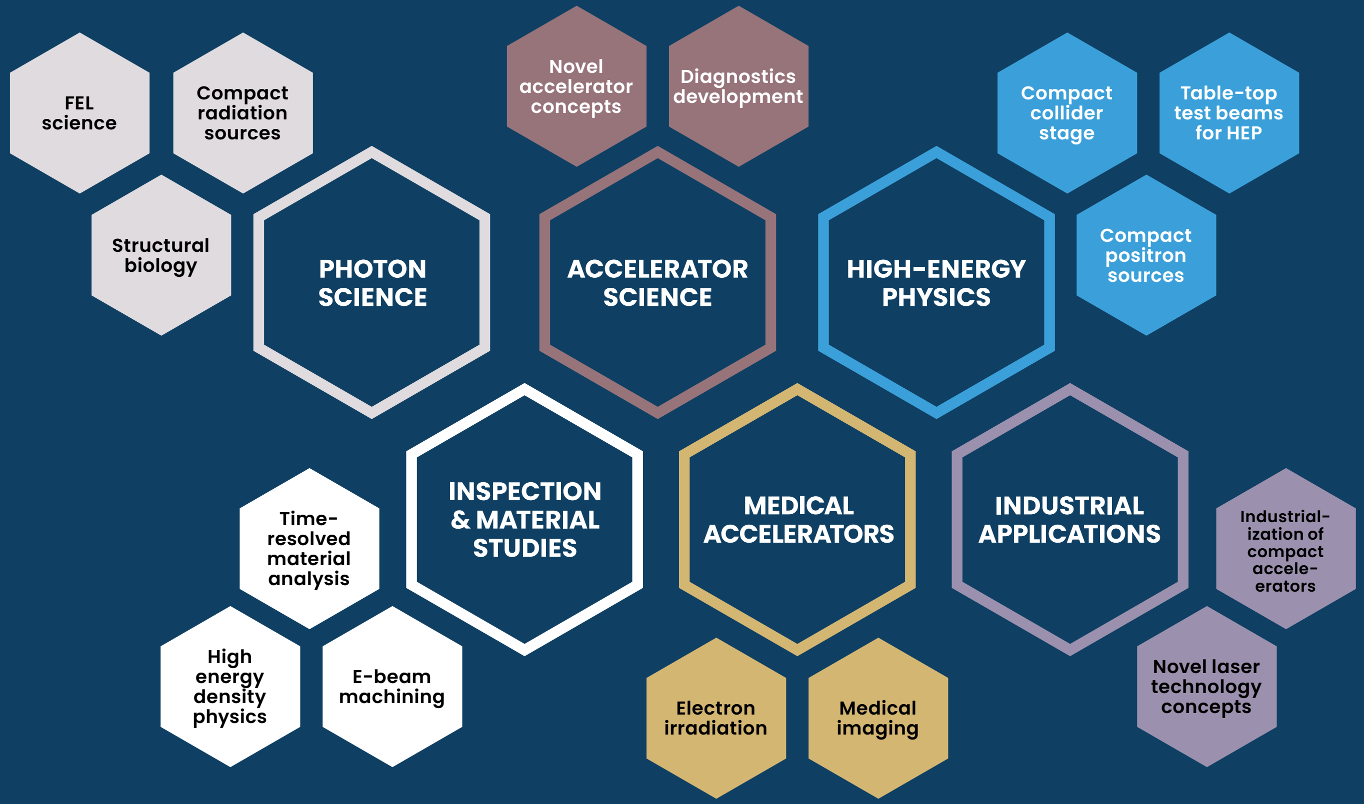
EuPRAXIA

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

CONTENTS

Background image: Plasma cell. Credit: Ricardo Torres



INTRODUCTION

EuPRAXIA is the first European project that develops a dedicated accelerator distributed research infrastructure based on novel plasma concepts and laser technology. It is ultimately expected to boost the expertise of the European scientific communities in compact accelerator technologies.

Over the last century, particle accelerators have become some of the most powerful and widely used tools in industry, healthcare, and research. Today there are more than 47,000 particle accelerators worldwide, mostly relying on highly developed technologies. However, the particle energies achievable are often limited by practical boundaries on size and cost.

A REVOLUTION IN PARTICLE ACCELERATORS

A new type of accelerator that uses plasmas instead of the usual radiofrequency (RF) cavities provides acceleration rates that are 1,000 times higher than those of conventional machines. This allows building much smaller accelerators that could be used for a wide range of applications.

TECHNICAL AND SCIENTIFIC GOALS

EuPRAXIA aims to build a highly compact plasma-based electron accelerator with beam energies of 1 to 5 GeV and a beam quality equivalent to present RF-based linacs. The machine layout will initially realize a factor three reduction in required space with respect to conventional accelerators, including all required components and infrastructure.

EuPRAXIA is the required stepping-stone to future plasma-based facilities, such as linear colliders at the energy frontier. The EuPRAXIA energy range and its performance goals will enable versatile applications in various domains, e.g. as a compact free-electron laser (FEL), compact sources for medical imaging and positron generation, test beams for particle detectors, as well as deeply penetrating x-ray and gamma ray sources for material testing.

DISTRIBUTED USER FACILITY

EuPRAXIA will be set up as a distributed Open Innovation platform with two sites providing access to experimental users. A number of centers of excellence at existing facilities in Europe will complement the pan-European implementation of this infrastructure.

CONCEPTUAL DESIGN REPORT

The EuPRAXIA Design Study project produced and published in 2019 a Conceptual Design Report (CDR) for a highly compact and cost-effective European facility with multi-GeV electron beams accelerated using plasma technology.

The CDR can be downloaded from: eupraxia-project.eu/eupraxia-conceptual-design-report

INTERNATIONAL COLLABORATION

In June 2021 EuPRAXIA was included in the European Strategy Forum on Research Infrastructures (ESFRI) roadmap for strategically important research infrastructures as a European priority.

The EuPRAXIA Preparatory Phase project is developing the organizational, legal, financial and technological aspects of EuPRAXIA, following the recommendations of ESFRI.

Together with the Preparatory Phase project, a number of initiatives support the realization of the EuPRAXIA infrastructure. These are the EuPRAXIA Doctoral Network, dedicated to training; the EuPRAXIA Advanced Photon Sources, developing a betatron radiation source as well as high power and high repetition rate laser systems; and EuPRAXIA@SPARC_LAB, dealing with the beam-driven site implementation in Frascati (Italy).

EuPRAXIA has brought together a consortium of over 50 institutions from all around the world, joining interdisciplinary excellence from particle accelerators, laser science, plasma physics, theory, and simulations.

The EuPRAXIA consortium has links with industry experts from leading European companies, which contribute directly to the project.

THE EuPRAXIA INFRASTRUCTURE – IMPLEMENTATION

The future EuPRAXIA platform is designed as a distributed research infrastructure across Europe, with two construction sites supported by a number of excellence centers and clusters.

Two EuPRAXIA sites will host the construction of the beam-driven and laser-driven plasma accelerator facilities. At these construction sites, the consortium will set up several plasma-accelerator beamlines generating high-quality electron bunches and secondary photon & particle beams, providing pilot access to academic and industrial users once target parameters have been reached.

A set of centers of excellence in plasma-based acceleration, plasma theory and simulation, and laser technology will be established. They rely heavily on already-existing large infrastructures. These facilities, perform mission-critical R&D, prototyping, testing, and construction tasks bringing in and upgrading their existing infrastructures and delivering fully tested components to the EuPRAXIA construction sites.

In addition, clusters of European institutes will collaborate jointly to address well-defined challenges and guide the overall R&D and design of the project.

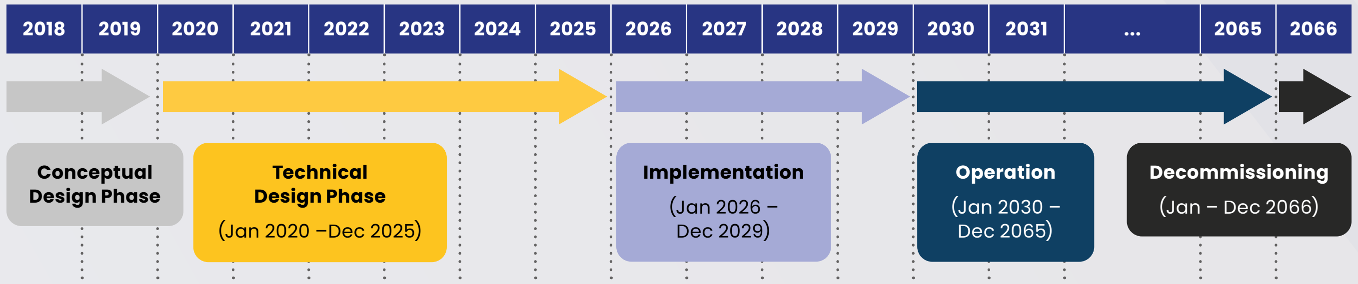
An overarching management structure will coordinate the overall technical design and prototyping. It will oversee the construction work, and it will link to industrial partners and work clusters distributed across the collaborating institutes.

This solution will ensure that the existing R&D infrastructure in Europe is fully exploited, but also avoids expensive duplication of technical and administrative structures. It minimizes the need for investment, and it provides access to a large pool of a technically educated and a young work force, which is required for building such a facility.

The combination of clusters, excellence centers, and construction sites will enable a truly European project that integrates the European R&D landscape in this research field and binds together existing facilities and investments.

Rendered aerial view of EuPRAXIA@SPARC_LAB (Italy). Credit: INFN and MYTHOS, Consorzio Stabile SCARL

PROJECT PHASES



PROJECT TIMELINE

Following the publication of the full Conceptual Design Report in October 2019, the project is undergoing a technical design phase for prototyping and R&D. Proceeding at full speed, the EuPRAXIA research infrastructure would start full operation in the next decade. Parts of EuPRAXIA could go into operation significantly earlier.

OPEN INNOVATION

EuPRAXIA will be based on an Open Innovation model where knowledge, perspectives and interests can be exchanged through direct means, such as user workshops, and indirect ones, like the shared use of beamlines and facilities. The involvement of industry as users, co-developers and suppliers will play an essential role as a more direct path for innovation and commercialization.

COSTS

Funding options for EuPRAXIA start at 68 M€ for a beam-driven and 75 M€ for a laser-driven implementation (minimal systems). The full-scale EuPRAXIA facility with two construction sites requires an investment of 320 M€ and about 1,800 full-time equivalent (FTE) person power integrated over 8 – 10 years (technical design, prototyping, and construction). The cost includes about 83 M€ that is invested in the laser technology industry. Funding will be leveraged by co-funding from the EuPRAXIA partners.

A significant pre-investment of 144 M€ has already been allocated for the beam-driven site, funded by the Italian government, the Next Generation EU recovery funds (PNRR), the Latium region, and INFN.

The EuPRAXIA Preparatory Phase project will provide a detailed cost-book and a sound financial model to ensure full sustainability for the infrastructure.

RISKS

Consistent with a high-confidence approach, the EuPRAXIA project minimizes risks by establishing scaled technology demonstrators. A risk reduction roadmap has been defined and will ensure that challenges are addressed by appropriate mitigation measures.

EuPRAXIA will form an interdisciplinary environment of Nobel-prize winning laser science, advanced RF and plasma technology, research universities, industry, and big science user labs in Europe.

The concepts, the technical designs, technical drawings of prototype devices and results achieved at the user and support facilities will be made available in the form of open innovation to the whole consortium.

Rendered image of the EuPRAXIA facility – Room 1. Credit: EuPRAXIA.

THE EuPRAXIA INFRASTRUCTURE – USER FACILITIES

As a central component to the EuPRAXIA infrastructure concept, two construction sites will host new large research facilities, exploiting beam-driven and laser-driven plasma-accelerator technology. At these construction sites, the consortium will set up several plasma-accelerator beamlines providing pilot access to academic and industrial users.

BEAM-DRIVEN PLASMA ACCELERATOR FACILITY, FRASCATI (ITALY)

The EuPRAXIA facility for beam-driven plasma acceleration is proposed to be constructed in Frascati (Italy) and is ready to proceed. The host lab is INFN-LNF, and the electron beam driver will rely on the most compact RF technology available (X-band structures). The Frascati site of EuPRAXIA will build on the investments in beam-driven plasma acceleration at SPARC_LAB. This includes a FEL user facility that combines a 1 GeV RF-based FEL option with a plasma-based advanced FEL setup at possibly higher energy. The dual approach will ensure that a new FEL user community at Frascati can be served with maximum availability and particle flux. User applications for EuPRAXIA@SPARC_LAB will focus on a 1 GeV free-electron laser with an upgrade to 2–5 GeV, an inverse Compton scattering photon source, high-energy positron beams, and test beams.

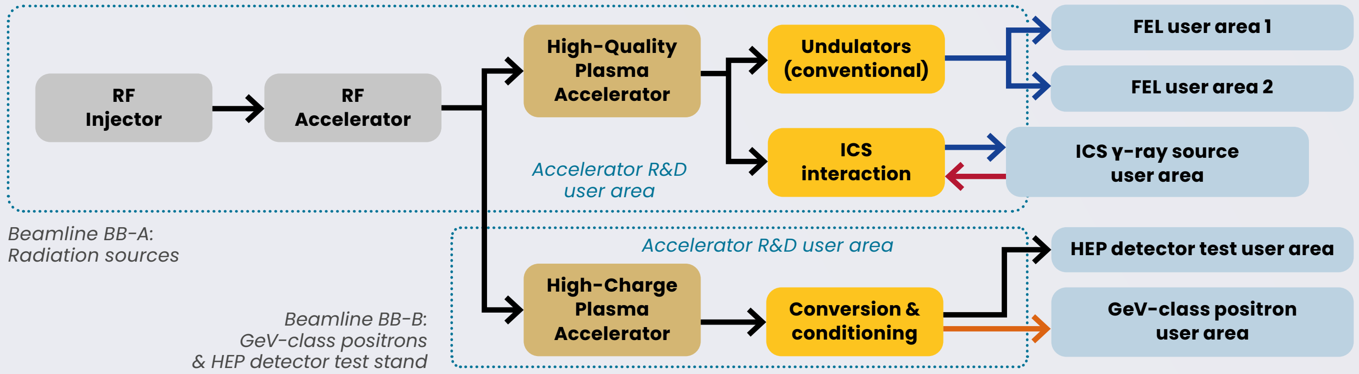
USER AREAS

User areas will be set up to exploit the inherent advantages of plasma accelerators, namely:

- Multiple parallel user lines.
- Ultra-fast electron and photon pulses with naturally short pulse lengths.
- Quasi-point–like emission of X-rays inside plasmas with the potential for ultra-sharp imaging.
- Unique pump-probe configurations with the synchronized EuPRAXIA particle and laser beams.

EuPRAXIA proposes a staged approach for the construction of sites for two complementary technical approaches in plasma acceleration. This will ensure competition in technology instead of competition among institutes.

FACILITY FOR BEAM-DRIVEN PLASMA ACCELERATORS



LASER-DRIVEN PLASMA ACCELERATOR FACILITY, (LOCATION TO BE DETERMINED)

The EuPRAXIA facility for the laser-driven plasma accelerator could be constructed at one of several options that have been identified. Laser pulses will be provided from lasers developed in collaboration with industry and scientific institutes for the EuPRAXIA needs. The laser-driven EuPRAXIA site aims at the most compact accelerator solution for future free-electron lasers, complementing the existing big science FELs at various large research centers in Europe. User applications for EuPRAXIA will focus on a compact 1–5 GeV free-electron laser, plasma-based medical imaging, a compact positron source for material science applications, and highly compact test beams.

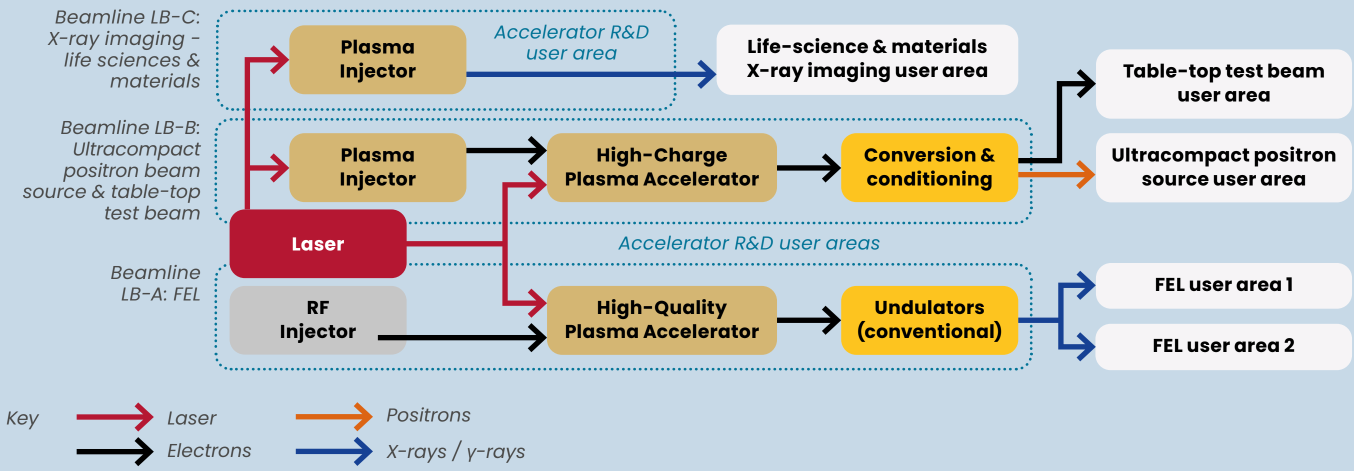
A site decision for the construction of the laser-driven plasma accelerator will be taken during the preparatory phase of the EuPRAXIA project.

The two construction sites are coordinated and governed in the common EuPRAXIA project. The project will thus prevent duplication of work and loss of resources due to internal competition.

EUPRAXIA BASELINE PARAMETERS

High-energy, ultrashort electron beams	
Energy	1 – 5 GeV
Energy spread	0.1 – 4 %
Slice energy spread	0.02 – 0.15 %
Bunch length	4 – 12 fs
Beam charge (no. of electrons)	0 – 100 pC (10^8 – $6{\times}10^8$)
Norm. transverse emittance	0.10 – 1.80 mm mrad
Norm. slice emittance	0.10 – 1.20 mm mrad
Repetition rate	20 – 100 Hz
Ultrashort Free-Electron Laser radiation pulses	
Wavelength	0.2 – 36 nm
No. of photons per pulse	10^{10} – 10^{13}
Pulse duration	2 – 20 fs
Bandwidth	0.25 – 0.5 %
Three main high-power laser systems	
Wavelength	800 nm
Energy on target	5 – 100 J
Pulse duration	20 – 60 fs
Repetition rate	20 – 100 Hz

FACILITY FOR LASER-DRIVEN PLASMA ACCELERATORS



These layouts require a floor space at least a factor 3 smaller than that needed by conventional RF accelerators. EuPRAXIA plans to reduce the facility size even further throughout its lifetime. Up to a factor of 10 reduction in size could be achieved through additional improvements and implementation of novel beam transport technologies, diagnostics and other key components.

USER APPLICATIONS AND OPPORTUNITIES

The EuPRAXIA facility offers opportunities for a variety of different applications. These include accelerator and laser science, high-energy physics, material processing and analysis, photon science as well as medicine and life sciences.

A number of flagship applications have been defined for which EuPRAXIA can offer particular benefits to users:

1. Machine performance

EuPRAXIA may provide better machine performance than other existing facilities or solutions. This would be the case for medical x-ray imaging, for example, where EuPRAXIA's compact betatron source would offer improved resolution and photon yield compared to standard x-ray sources.

2. Machine availability

EuPRAXIA may improve the availability of certain types of beams and user services, e.g. hard x-ray free-electron lasers. EuPRAXIA would not only increase the capacity for FEL experiments, but also build a roadmap towards future compact and cost-efficient FEL beamlines.

3. New features

The use of plasma accelerator technology at EuPRAXIA leads to a series of unique characteristics, such as ultrashort particle and photon pulse durations, small beam spot sizes, a small machine footprint as well as multi-species sources. These could be used for improved performance in imaging experiments and would also be relevant for testing advanced detector systems for accelerators and high-energy physics.

Beyond these well-defined flagship application fields, EuPRAXIA aims to remain open to other types of user experiments.

EuPRAXIA is targeted at three main types of users:

1. Beam users

These include major photon science user applications in fields such as biology, chemistry, material science and others. They may benefit from the FEL beams, compact sources of synchrotron-like radiation, as well as compact particle sources. Another possibility is to use tunable electron beams for high-energy physics detector tests.

2. Co-developing users

Co-developing users are those who are interested in the possibilities for investigating and further developing plasma accelerator concepts and applications. Relevant fields include medical physics and material science, as well as accelerator R&D. EuPRAXIA is looking to develop relationships with the European industry of lasers and optoelectronics, accelerator technologies, accelerator applications, and other areas of activity.

3. Trainee users

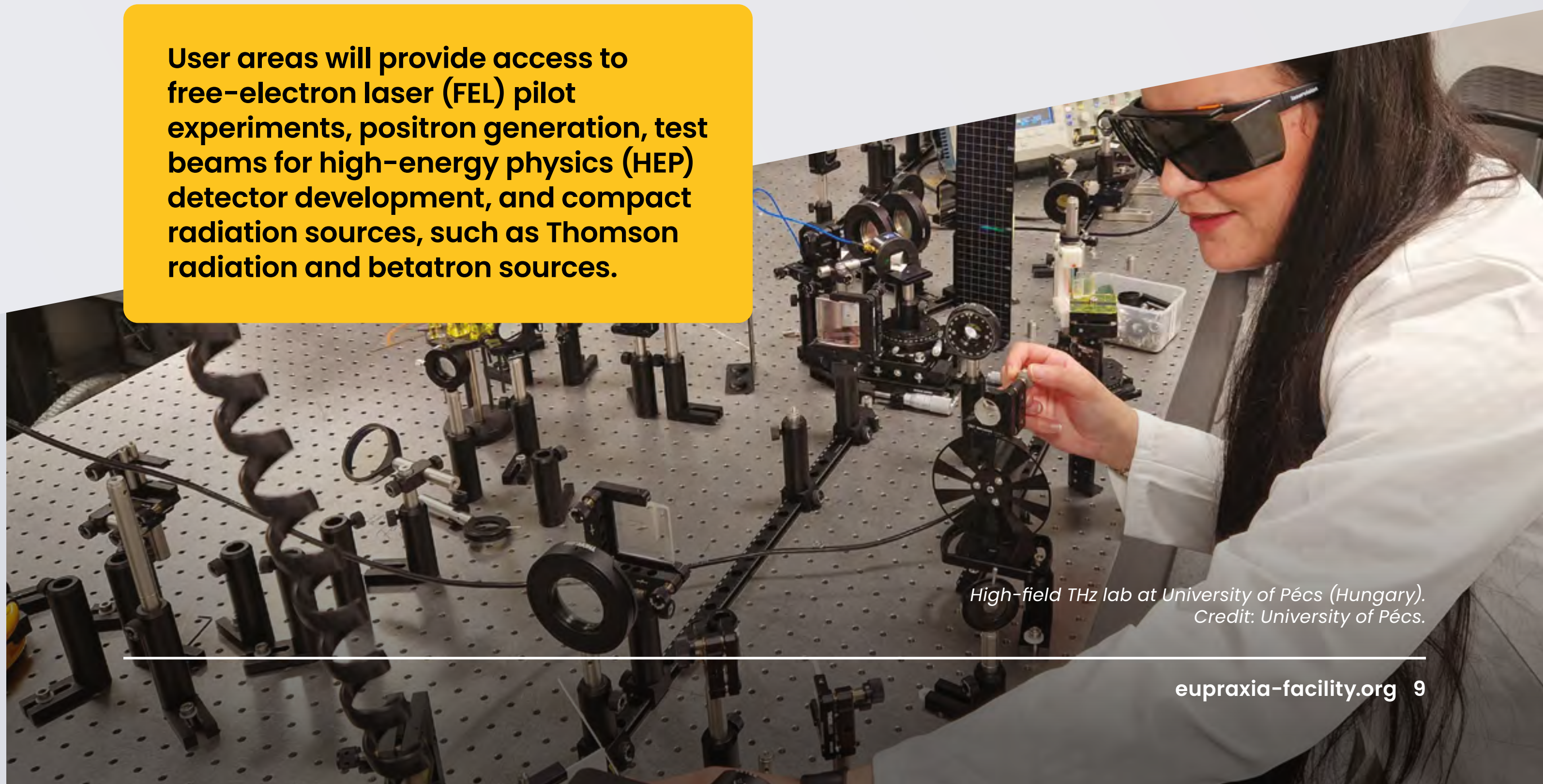
As the first user facility of its class, EuPRAXIA will serve as a platform for the training of technical staff for future plasma acceleration facilities. Therefore, EuPRAXIA foresees the use of a fraction of its beam time for trainee users, interested in gaining experience in the operation of a plasma acceleration facility.

	Beam-driven (Frascati, Italy)	**Laser-driven (location TBD)**
Phase 1	FEL beamline to 1 GeV + user area 1	FEL beamline to 1 GeV + user area 1
	GeV-class positrons beamline + positron user area	Ultra-compact positron source beamline + positron user area
Phase 2	ICS source beamline + user area	X-ray imaging beamline + user area
	HEP detector tests user area	Table-top test beams user area
	FEL user area 2	FEL user area 2
	FEL to 5 GeV	FEL to 5 GeV
Phase 3	Medical imaging beamline / user area	High-field physics beamline / user area
	Other future developments	Other future developments

The services available at each experimental site will follow a phased implementation.

EuPRAXIA				
High-quality electron beams	**Free-Electron Laser (FEL)**	**Compact radiation sources**	**Compact particle sources**	**High-power laser pulses**
• Energy up to **5 GeV** • Down to **sub-percent energy spread** • Single to tens of **femtoseconds** duration • **Micrometer**-scale spot size	• Nano- to sub-nanometer wavelength • Single to tens of **femtoseconds** duration • Up to **10^{10}–10^{12} photons per pulse**	• **X-rays / γ-rays** from betatron radiation & inverse Compton scattering • Single to tens of **femtoseconds** duration • **Micrometer**-scale spot size	• Low-energy and high-energy **positron sources for material studies** & other applications • Possibly for **neutron source under investigation**	• As acceleration drivers, yet also **pump-probe capabilities** • Energy up to **100 J** on target • **20–100Hz** repitition rate

User areas will provide access to free-electron laser (FEL) pilot experiments, positron generation, test beams for high-energy physics (HEP) detector development, and compact radiation sources, such as Thomson radiation and betatron sources.



High-field THz lab at University of Pécs (Hungary). Credit: University of Pécs.

ACCELERATOR SCIENCE

BACKGROUND

Particle accelerators have been developed and optimized over multiple decades creating a variety of machine types, components and technologies, from radiofrequency to plasma and dielectric accelerators.

Although it is a highly developed field, there are many groups worldwide that investigate and develop new concepts and methods within accelerator science.

Some of these studies, especially on a smaller scale, can be performed at local facilities. For other, especially more complex experiments, however, dedicated accelerator test facilities are required.

Currently there are a handful of test beams in operation with a variety of parameters. However, there is a lack of machines producing ultrashort electron beams, a feature that is becoming more and more useful for light-source-related and novel acceleration technologies.

> **“ ...there is a lack of machines producing ultrashort electron beams, a feature that is becoming more and more useful...”**

Beamline at Elettra (Italy).
Credit: Massimo Goina, Elettra Sincrotrone Trieste.

OPPORTUNITIES

As a test machine, EuPRAXIA will provide ultrashort beams, as well as a repetition rate on the scale of 100 Hz (with a possible upgrade to kHz in the long run). For plasma accelerators in particular, this will represent a new regime of operation, thus opening up multiple new research opportunities.

The EuPRAXIA infrastructure is designed to implement many different techniques and components into one machine, including plasma injectors with different beam energies, multiple staged plasma targets, RF injectors for external injection into a plasma as well as advanced beam transport lines and diagnostics sections. This makes it uniquely suited for accelerator science experiments, especially for topics related to novel accelerator technologies.

EuPRAXIA will be the only dedicated plasma accelerator user facility in the world. Therefore, unlike in other facilities, the generation and acceleration of electron beams does not have to be part of the experiment and the research can instead be focused on more specific challenges.

The tunability in beam parameters, the availability of various photon and particle beam types, and the overall single-femtosecond duration of these pulses is unique, and as such will allow for a multitude of varied experiments. Possible uses are:

- proof-of-principle on new plasma injection / acceleration concepts,
- prototyping or stability testing of plasma targets and components,
- beamline elements and beam transport concepts,
- development and testing of novel diagnostics,
- compact accelerator applications in high-energy physics.

PHOTON SCIENCE

BACKGROUND

Third generation synchrotron light sources rely on the radiation generated from charged particles in bending magnets or undulators. They can deliver high brilliance photon beams with partial transverse coherence to various beamlines simultaneously. These light sources are workhorses for materials research. They presently evolve towards low emittance (picometer scale) diffraction limited light sources (DLSR). The DLSR high brilliance and degree of transverse coherence has given access to serial crystallography for drug discoveries and to new techniques for material development, addressing the 21st century societal challenges of health, environment, energy, information technology and cultural heritage.

Longitudinal coherence is achieved in free electron lasers (FEL) by setting the electrons in phase. Thanks to an energy exchange between the electrons and a light wave, the electron beam produces coherent emission and light amplification. FEL-based fourth generation light sources currently offer femtosecond tunable radiation in the X -ray and vacuum ultraviolet (VUV) domains. These tunable devices open the path for deciphering unexplored areas of biology (such as protein structure and function) in a time-resolved way.

OPPORTUNITIES

The recent advent of tunable coherent X-ray FELs has opened a new era for the investigation of matter. Thanks to advances in femtosecond spectroscopy, and pump-probe techniques they enable us to:

- decrypt the structure of biomolecules and cells,
- provide novel insight into the electronic structure of atoms and molecules, and
- observe non-equilibrium nuclear motion, disordered media, and distorted crystal lattices.

X-ray FELs can also reveal the time evolution of chemical reactions. With new imaging techniques, they are exceptional tools for the investigation of the ultrafast evolution of the electronic structure in atoms and provide a deeper insight into the extreme states of matter.

Another revolution in the field could now arrive with the emergence of laser wakefield (LWFA) accelerator-based free electron lasers. These could provide compact “laboratory scale” short wavelength undulator radiation sources and, additionally, new free electron lasers available for the user community.

SPARC_LAB free electron laser at Laboratori Nazionali di Frascati (Italy).
Credit: Alexandra Welsch.

LASER SCIENCE

BACKGROUND

The implementation of a laser wakefield accelerator at the 5 GeV target energy of EuPRAXIA requires the most sophisticated and robust laser technologies available. The EuPRAXIA laser will produce bursts of infrared light with pulse durations as short as a few tens of femtoseconds and energies up to 100 joules, yielding a peak power of the order of several petawatts (1 PW = 1015 W).

State-of-the-art petawatt-level lasers can deliver up to one pulse per second (1 Hz). However, the request for sufficient average particle or photon flux for the envisioned applications of EuPRAXIA will require a rather high repetition rate for the laser systems on the order of 20 to 100 Hz. This means that the EuPRAXIA lasers will feature, beside very high peak power, an unprecedented average power. These features pose interesting challenges and at the same time will make EuPRAXIA a unique platform for testing novel concepts in the field of ultrashort and ultraintense laser science.

CHALLENGES AND OPPORTUNITIES

The design and construction of the EuPRAXIA facility will greatly benefit the research on ultrashort and ultraintense laser science.

In particular, the increase in average power of ultraintense laser systems is a crucial issue for translating laser-driven accelerator technologies to fields like medicine and material science. These developments would allow a widespread diffusion of advanced, possibly all-optical particle and secondary radiation sources. In this respect, a major research topic is the thermal management in pump and main laser amplifiers.

The project will also benefit research related to the transition to diode pumping. All novel approaches towards an ever increasing efficiency, such as direct pumping and multi-pulse extraction would come into play. EuPRAXIA could advance the transition from Titanium:Sapphire-based architectures to new laser materials.

Other aspects related to thermal management in the laser chain are expected to receive a boost from developments in EuPRAXIA. For instance, the research into novel grating materials and coatings able to withstand the high average power without introducing strong wavefront aberrations. The combined requirements on the repetition rate and the system availability (uptime) will foster new solutions for optical coatings with longer lifetime.

The high degree of complexity of the optical architecture of the laser systems coupled to their required reliability on the long term will lead to speeding up the availability of advanced technological solutions for automatic control, alignment and maintenance procedures of ultrashort laser chains, which would benefit the entire laser community.

One of the critical issues for the EuPRAXIA laser systems will be the pointing stability. Besides already consolidated measures, the search for novel, possibly active, techniques will be of interest for laser science. Another critical issue will be the active correction of wavefront distortions. EuPRAXIA will stimulate research on wavefront characterization techniques and devices as well as feedback loop algorithms suitable for high repetition rate operations.

Finally, the design, construction and further development of the EuPRAXIA lasers will offer opportunities for the development of diagnostics for measuring spectral amplitude and phase, as well as diagnostics for the characterization of pulse contrast. Solutions will be required for single-shot diagnostics, as well as fast reconstruction algorithms to provide a full shot-by-shot laser pulse characterization in high repetition rate lasers.

ILIL-PW laser system at Istituto Nazionale di Ottica (Italy). Credit: Paolo Tomassini, paolotomassini.com

HIGH-ENERGY PHYSICS

BACKGROUND

The largest operational particle collider is the Large Hadron Collider (LHC) at CERN, a 27 km ring of superconducting magnets providing proton-proton collisions with a center-of-mass energy of 13 TeV. The LHC's last most iconic result was the detection of the Higgs Boson and a determination of its mass. This represented a brilliant confirmation of the Standard Model that, however, is known to be incomplete. It does not account for important aspects of fundamental physics observed in cosmology, including dark matter, dark energy, and the excess of matter over antimatter.

To date, the extensive search for additional particles that would generalize the Standard Model has been in vain and there is a growing need in the community for the next generation of electron-positron colliders that would reach, and eventually surpass, the TeV barrier.

Conventional radio-frequency technology has intrinsic limitations on the maximum accelerating gradients that it can sustain, of the order of tens of MV/m. As an example, the proposed Compact Linear Collider (CLIC) is planning to reach 100 MV/m, implying an overall accelerating length to reach 1 TeV of 100 km.

The sheer scale and, subsequently, cost of these machines has motivated the quest for alternative accelerating technologies. Plasma-based wakefield acceleration is arguably one of the most promising, with landmark results already experimentally obtained for electrons.

Accelerating fields up to 100 GV/m have been demonstrated in a plasma. Promising results have motivated international large-scale projects to study the feasibility of building a plasma-based electron-positron collider.

CHALLENGES AND OPPORTUNITIES

While the plasma-based acceleration of electrons is rapidly progressing, positron acceleration is far more difficult, mostly due to the intrinsic and strong asymmetry of the wakefields in the plasma. In general, it is challenging to provide a positron beam with sufficient quality to be synchronised with the positron-accelerating region of a plasma wakefield and this makes experimental progress in this area slow. In particular, one would need low-emittance and short (≲ tens of fs) beams with a non-negligible charge. To date, no positron facility suitable for advanced plasma-wakefield studies is available in Europe, and the only facility existing worldwide is FACET, together with its proposed upgrade FACET-II, in the US.

The capabilities proposed in the EuPRAXIA facility design, however, could help to close this gap in the international research landscape. Whilst, FACET-II is designed to provide a higher energy beam with a lower normalized emittance than EuPRAXIA, the latter will have the capability of providing fs-scale beams at high repetition rate. The short duration of the beam is of critical importance for precision studies of wakefield acceleration for positrons and to ensure maximum energy extraction from the wakefield itself.

Moreover, the proposed positron beamline will be the only one available in Europe and thus of fundamental importance for the progress towards the design of a novel TeV-scale particle accelerator, which is the primary goal of several high-level research projects in Europe, including the European consortium ALEGRO.

CMS Detector. Credit: CERN

Image: Woman being prepared for radiation therapy.
Credit: Michael Anderson (Photographer).

MEDICAL PHYSICS

BACKGROUND

Particle accelerators have widespread use in healthcare, from the low energy (10s of MeV) linacs that are used to generate hard x-rays for radiotherapy, to the high uptime cyclotrons used in the production of short-lived radioisotopes used in both diagnosis and treatment. However, there is a need for high-precision high-energy electron accelerators in medicine too. The EuPRAXIA facility offers a number of opportunities which can be of interest to medical physics. As a relatively small scale free electron laser (FEL), EuPRAXIA will provide x-ray radiation with unprecedented quality, which can be vital in determining biological pathways and in drug discovery. EuPRAXIA can also provide advances in two applications that are considered of great interest at the moment: very-high energy electron therapy (VHEET) and phase-contrast imaging (PCI).

FEL APPLICATIONS FOR MEDICAL PHYSICS

One of the major uses of x-ray sources lies in determining the structure of biological material at the atomic scale. However, the scattering efficiency of x-rays is low and to be able to attain enough signal, large regular crystals of the material need to be grown. This limits the range of materials that can be investigated: some do not form large regular crystals, whilst others change significantly when crystallised as compared to their form in solution.

X-ray diffraction with FELs overcomes the restriction on crystal size by allowing strong diffraction from small samples due to the very large photon flux they produce. Furthermore, the short temporal duration of the source means that the diffraction takes place before the material under investigation is destroyed by the radiation. These measurements can even be extended to complex structures, such as viruses, allowing unprecedented knowledge of the working of pathogens and other complex proteins. The ultrafast nature of FELs also allows time-resolved studies of chemical reactions, so in addition to providing structures, they are also elucidating biological pathways. FELs are already revolutionising the knowledge of biochemical processes with its resultant effect on medicine and treatment.

VERY HIGH ENERGY ELECTRON THERAPY

More than half of all cancer cases are treated with some form of radiation therapy, where an intense beam of penetrating radiation is directed at the tumour to kill cancerous cells. In the vast majority of cases, this radiation is provided as high energy photons produced by bremsstrahlung of a low energy (~ 10 MeV) electron beam with a solid target. However, photons have a relatively small interaction cross section as compared to the electrons themselves. The only reason the electron beam itself is not used is that they do not have sufficient energy to reach deep-seated tumours. For these, electrons of energy in excess of 100 MeV are required, and the cost of a linac producing these energies has been considered prohibitive.

Wakefield accelerators with their reduced footprint, on the other hand, are considered an interesting source of electrons for very-high-energy electron therapy (VHEET). The laser plasma injector being developed for EuPRAXIA would produce an electron beam that is ideal to investigate this area. A prime goal of EuPRAXIA will be ensuring the reliability and robustness of the electron source which is vital for this kind of application.

PHASE CONTRAST IMAGING

As important as treatment is the development of techniques to diagnose illness. The first and most trusted tool in medical imaging is the x-ray machine, which has remained mostly unchanged since the discovery of the x-rays. With typical x-ray sources, the low resolution and low photon numbers produce grainy images which can lead to inconclusive and sometimes even incorrect diagnosis. This is especially true when imaging soft tissue, where the contrast between different types of tissue (such as healthy or cancerous) is limited.

High quality synchrotron and FEL radiation sources have been demonstrated to provide diagnostic capability comparable to invasive and time consuming biopsies. If the x-ray source has additional spatial coherence, then it can be used for phase-contrast imaging. This technique provides extra contrast in soft tissues, giving the ability to detect tumours with high confidence. The radiation sources envisioned for EuPRAXIA, both the FEL and the broadband betatron source, would be able to provide compact and versatile set-ups for medical imaging. These sources could be the forerunner of a more widespread adoption of the technology in hospitals and medical centers.

INSPECTION AND MATERIAL STUDIES

BACKGROUND

Quality assurance and innovation in manufacturing is underpinned by metrological methods. Metrology is especially important in the production of high-performance and high-value components that are made in, and are required to perform under, hostile environments. Heat and pressure treatments, new welding methods, radiation exposure, impact damage, are all examples of scenarios that can leave sub-micron defects in materials.

It is thus highly desirable for the industry to be able to assess the uniformity and quality of materials over a wide range of thicknesses, sizes, and composition, ideally while being under significant stress. Moreover, it is vital that any inspection be carried out in a non-destructive manner.

Generally speaking, non-destructive inspection can be easily performed at the surface of materials, but several difficulties are encountered when performing sub-surface volumetric inspections. Of the several techniques that have been developed, positron annihilation lifetime spectroscopy (PALS) is arguably the only one that can provide nanometer-scale resolution over a significant range of material thicknesses and detect defects and vacancies in materials down to a few parts per million.

When in a material, positrons get easily trapped at vacancy defects. In a timescale of the order of 100 ps, the trapped positron annihilates with an electron in the material, producing radiation. By studying the characteristics of the emitted radiation, one can extract a detailed map of vacancies in the material under study.

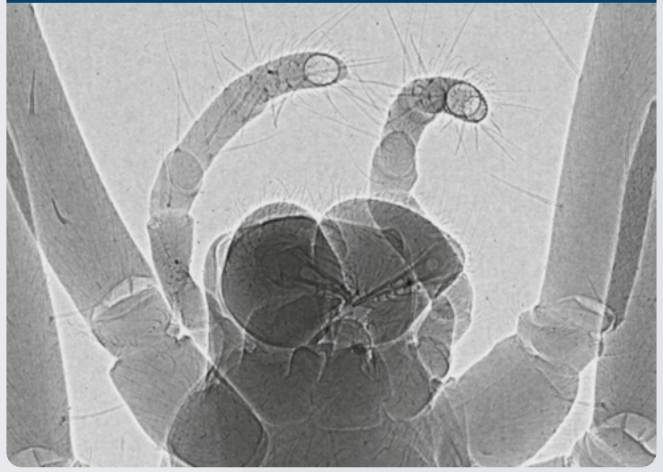
Traditionally, positron inspection of materials is carried out using $\beta+$ radioactive sources, such as 22Na. The broadband positron populations that are continuously generated from these atoms are then captured, energy-filtered, and time-gated in bursts with a duration of the order of a nanosecond. Despite the high performance of positron inspection machines, it is difficult to produce high-quality positron beams with higher energy (up to a few MeV), able to penetrate deeper into the material under study. Also, the relatively long duration of the beams, comparable to the typical timescales of annihilation in materials, limits the resolution of the system and makes data extraction rather complicated and prone to uncertainties.

OPPORTUNITIES

An alternative method to produce high-flux and short beams of positrons consists on exploiting the quantum cascade initiated by an ultra-relativistic electron beam propagating in a high-Z solid target. The positrons escaping the rear surface of the target present a duration comparable to that of the primary electron beam, a broad spectrum and divergence, and an overall number of positrons that is a significant fraction of the number of electrons in the primary beam.

In order to generate high-flux, short, and mildly-relativistic positron beams for PALS, one would require a primary electron beam with the highest possible charge, modest energy (of the order of 10s to 100 MeV), and short duration. However, higher energy electron beams, as achievable within EuPRAXIA using a multi-staged approach, are also usable for this purpose. The unavoidable spectral broadening introduced by the cascade inside the solid significantly relaxes any requirement on spectral quality of the primary electron beam, which is virtually irrelevant for the positron production. These characteristics are guaranteed by the laser-plasma based electron beams which are foreseen to be created at the EuPRAXIA infrastructure.

> **“ It is thus highly desirable for the industry to be able to assess the uniformity and quality of materials...”**



Phase-contrast x-ray image of spider.
Credit: Excillum AB, Sweden.

THE ROLE OF INDUSTRY

In order to push plasma accelerators towards user applications and commercialization, a close interaction with industry is essential.

Industry partners can help laboratories in the design of robust and reliable products. They will be able to participate actively in risk analysis studies and thus identify which activities must be carried out in the prototyping phase to move from a low technical readiness to a high technical readiness technology.

Industry partners will also be able to participate directly in prototyping projects during the EuPRAXIA technical design phase for the laser system (pump lasers, mirrors, adaptive optics, gratings), for the study of optical materials, or for electron transport and electron diagnostics, just to name a few examples.

Other topics for collaboration could include operational safety aspects or studies on the integrated logistical support necessary, depending on the mission profile and operation mode of the facility. In this way, the manufacturers will be able to commit to the delivery and installation of laser and particle beam parts in the commissioning phase thanks to an extensive collaboration in the design. They will also be able to commit more easily to maintenance procedures under operational conditions of the facility over the expected lifetime.

Additionally, companies could participate as users of the EuPRAXIA research infrastructure. Many of the features of the machines designed for EuPRAXIA have great potential for industrial applications. Industrial users could take advantage of this infrastructure as an analysis and processing tool or as a testing ground for applying plasma accelerator technology to their own facilities and processes.

Top Image: *Halo monitor setup at the Cockcroft Institute (UK).*

Bottom Image: *Front-end of ILIL-PW laser system at Istituto Nazionale di Ottica (Italy).*
Credit: Paolo Tomassini, paolotomassini.com

SOCIETAL IMPACT

There are currently more than 47,000 accelerators in operation around the world.

Large accelerators are used as colliders in particle physics, or as light sources for the study of condensed matter physics and structural biology, among other applications. Smaller particle accelerators are used in a wide variety of applications, including cancer therapy, imaging and diagnostics, manufacturing, cargo inspection, food sterilization, etc. Plasma accelerators offer a revolutionary path to more cost-effective accelerators.

MAINTAINING EUROPE'S LEADERSHIP IN PARTICLE ACCELERATION

The broad and interdisciplinary EuPRAXIA collaboration in Europe, and with international partners, will create a critical mass of expertise and capabilities in Europe. It will support and further position Europe as a world-leading competitor in accelerator innovation.

PROMOTING EUROPEAN INDUSTRY

The EuPRAXIA project will challenge and support the European and world-wide laser industry to further develop and improve their products on high-power pulsed lasers. This will strengthen the laser industry overall but in particular also enable European laser companies to stay world leading in a fair and competitive effort.

DEVELOPING HIGHLY QUALIFIED PROFESSIONALS

New generations of scientists and technicians in Europe will be exposed to innovative and highly challenging technical and intellectual problems in centrally located and well-integrated R&D facilities. The proximity to major universities and laboratories in Europe will amplify the capability of EuPRAXIA to fascinate young generations for science and technology, to foster innovative out-of-the-box thinking, to serve as a high-tech training base, and to strengthen the job base for technical work.

MAKING ACCELERATOR TECHNOLOGY ACCESSIBLE

A compact particle accelerator product as a result of the EuPRAXIA project could make accelerators available as versatile tools to new users and in new locations, e.g. laboratory spaces at university, hospitals, mobile platforms, and beyond. This would multiply access to accelerators and could create major advances in knowledge and capabilities. For instance, the availability of brilliant, time-resolved x-ray pulses for microbiological studies could multiply the number of bacteria or virus structures that can be resolved. Once the structure and dynamical behaviour of a virus has been understood, new approaches for medication can be developed and tested more quickly.

KEY TECHNOLOGIES

Plasma accelerators are a highly demanding technology with requirements close to technical feasibility limits in several areas. EuPRAXIA contributes to strengthening the technological development capacity and effectiveness of the European Research Area at the frontiers of:

- Ultrafast synchronization, electronics, and correction loops
- Compact accelerator magnets with high-field quality
- Stabilized petawatt laser technology
- Plasma cell technology
- Compact FELs
- Fast photon science detectors
- HEP detector technology

EuPRAXIA will involve the European industry and younger generations in inspiring technological challenges close to major universities and research institutions in Europe.

High-field THz lab at University of Pécs (Hungary). Credit: University of Pécs.

EuPRAXIA IN THE GLOBAL RESEARCH LANDSCAPE

EuPRAXIA brings together and represents a large fraction of the European plasma accelerator community.

EuPRAXIA has been proposed by members of the European Network for Novel Accelerators (EuroNNAc) as a European project that ensures the competitiveness of Europe in novel plasma accelerators. It builds on the expertise from several national projects in plasma acceleration, like the ATHENA project in Germany, the SPARC_LAB project in Italy, the CILEX project in France, the EPAC project in the UK and the ELI laser pillars. EuPRAXIA is connected to the LEAPS initiative through the LEAPS task on "Compact Sources" and it is fully complementary to the AWAKE plasma acceleration project, which can only be performed at CERN.

Plasma wakefield acceleration is an important research topic in various institutes across Asia and America, many of whom are already involved in EuPRAXIA as associated partners. Continuing and strengthening scientific exchanges between EuPRAXIA and the rest of the world could thus strongly advance this field of science.

Once the EuPRAXIA infrastructure is set up, it will be able to share knowledge and technologies with other facilities, providing a unique test facility for partners worldwide. At the same time, EuPRAXIA will be able to share experiences through training and knowledge exchange programs. For developing countries in particular, compact accelerator technologies could be an ideal entry point to accelerator science due to their reduced cost and size.

Prof Massimo Ferrario (INFN) presenting EuPRAXIA at the International Particle Accelerator Conference IPAC'23 in Venice (Italy). Credit: IPAC'23.

OUTREACH AND DISSEMINATION

In order to bring together the diverse scientific community involved in EuPRAXIA, to strengthen the links with relevant industries, and to connect interested users from multiple areas, the EuPRAXIA consortium carries out an extensive program of networking activities. Moreover, EuPRAXIA is strongly committed to public engagement, inspiring the younger generations with a fascination for science and technology.

COMMUNICATION AND DISSEMINATION

The EuPRAXIA outreach and liaison group based at the University of Liverpool / Cockcroft Institute works closely with the project coordinator and project partners to communicate the specific challenges and opportunities of plasma acceleration to a range of audiences.

Up to date information about EuPRAXIA Preparatory Phase can be found on the website www.eupraxia-pp.org

The newsletter *The EuPRAXIA Files* is a collection of publicly available abstracts from published papers that are relevant to the EuPRAXIA project. It is published quarterly to inform the research community of the latest advances in plasma acceleration.

Scientific outcomes and other news about the project are disseminated via scientific journals, press releases, international conferences, and dedicated LinkedIn page, as well as other social media outlets.

By communicating the specific research challenges and opportunities of plasma accelerators, EuPRAXIA has helped increase the attractiveness of the field overall.

The Surfatron game together with the mechanical version displayed at the Daresbury Open Week (UK) in July 2023. Credit: Alexandra Welsch.

PUBLIC ENGAGEMENT

The EuPRAXIA consortium endeavours to communicate its objectives and results to the public through the publication of feature articles in the media, participation in outreach events, and production of educational materials.

For instance, an interactive game called *Surfatron*, developed by the University of Liverpool, simulates the motion of a particle in a plasma wave to demonstrate the concept of wakefield acceleration. The Surfatron is available online, and a mechanical version has been built and exhibited at science fairs.

Symposium "Quantum Leap towards the Next Generation of Accelerators" at the Liverpool Arena Convention Centre (UK) in July 2018. The event gave schoolchildren the opportunity to learn about the societal benefits of plasma accelerators, and brought together scientists, industry, and policy makers involved in the development of novel accelerators. Credit: Alexandra Welsch.

EuPRAXIA PREPARATORY PHASE – MANAGEMENT AND STRUCTURE

Participants in the EuPRAXIA-PP kick-off meeting in Frascati (Italy), November 2022. Credit: EuPRAXIA.

EuPRAXIA Preparatory Phase (EuPRAXIA-PP) is a project designed to develop the organizational, legal, financial and technological aspects of the EuPRAXIA infrastructure, following the recommendations of the European Strategy Forum on Research Infrastructures (ESFRI).

The preparatory phase project EuPRAXIA-PP serves a central role in the overall implementation plan of EuPRAXIA as a truly European Research Infrastructure. This new European facility will serve users from multiple fields with cutting edge beams of particles and photons, while driving open innovation in the technology of particle accelerators. The European headquarters of EuPRAXIA has been set up at the Frascati site of INFN. Thanks to the already committed funding for the Italian pillar of EuPRAXIA, the preparatory phase project is complemented by the already started construction efforts for the first pilot user operations in 2028. The synergy and integration of the European preparatory phase project and the national Italian project ensures that this project will serve and benefit all EuPRAXIA partners and the full European Research Area (ERA).

MANAGEMENT

The overall approach of EuPRAXIA is that of a big science collaborative project. A managerial structure with clear responsibilities has been established, including milestones and deliverables. An overall planning and a resource-loaded schedule has been agreed within the project. At the same time, an open scientific approach is pursued, based on technical excellence. Several committees advise the project management and regularly evaluate the progress of the EuPRAXIA-PP project.

Project Coordinator

The project coordinator is the person responsible for supervising and coordinating the EuPRAXIA-PP work package tasks to their full completion. In this capacity, they follow up on milestones and deliverables, and monitor the use of resources.

Management Support Team

The project coordinator is supported by the management support team. They assist the management in legal and financial matters, as well as event organization and media communications.

Steering Committee

The project is directed by the steering committee. The steering committee is responsible for the coordination and management of the work packages. The committee consists of work package leaders and experts and it is chaired and organized by the project manager.

Collaboration Board

The collaboration board represents all the members of the consortium. It reviews the work progress and makes final decisions regarding modifications to the work program, the allocation of the funding, and the accession or withdrawal of partners.

The collaboration board consists of one representative of each of the project partner organizations.

WORK PACKAGES

The EuPRAXIA Preparatory Phase project structure includes 16 work packages (WP).

The organizational work packages deal with legal, financial, and other organizational matters. Detailed plans and structures for the technical implementation of the facility are worked out in the technical work packages.

COORDINATION

WP 1 Coordination & Project Management

- *Pierluigi Campana (INFN)*
- *Massimo Ferrario (INFN)*

Supervise and coordinate EupRAXIA-PP work package tasks.

ORGANIZATIONAL

WP 2 Dissemination & Public Relations

- *Carsten Welsch (INFN / University of Liverpool)*
- *Susanna Bertelli (INFN)*

Disseminate the content produced in EuPRAXIA-PP.

WP 3 Organization & Rules

- *Arnd Specka (CNRS)*
- *Andrea Ghigo (INFN)*

Develop the organizational model of EuPRAXIA.

WP 4 Financial, Legal Model & Economic Impact

- *Antonio Falone (INFN)*

Develop the financial and legal model of EuPRAXIA.

WP 5 User Strategy & Services

- *Francesco Stellato (University of Rome "Tor Vergata")*
- *Emiliano Principi (ELETTRA)*

Define a comprehensive list of services to and an access policy to users.

WP 6 Membership Extension Strategy

- *Brigitte Cros (CNRS)*
- *Andrea Mostacci (Sapienza, University of Rome)*

Outreach to European and international communities.

WP 7 E-Needs & Data Policy

- *Riccardo Fonseca (IST)*
- *Stefano Pioli (INFN)*

Define E-Needs and Data Policy.

TECHNICAL

WP 8 Theory & Simulation

- *Jorge Vieira (IST)*
- *Henri Vincenti (CEA)*

Theory and simulation of plasma accelerators and related applications.

WP 9 RF, Magnets & Beamline Components

- *Sergey Antipov (DESY)*
- *Federico Nguyen (ENEA)*

R&D of RF, magnets for focusing/correction and beamline components.

WP 10 Plasma Components & Systems

- *Kevin Cassou (CNRS)*
- *Rob Shalloo (DESY)*

Design of plasma components and related systems.

WP 11 Applications

- *Gianluca Sarri (University of Belfast)*
- *Enrica Chiadroni (Sapienza, University of Rome)*

Development of applications and delivery into user areas.

WP 12 Laser Technology & Liaison to Industry

- *Leonida Gizzi (CNR)*
- *Paul Crump (FBH)*

Technical design for the laser-driver for the 2nd site. Liaise with industry to deliver a robust laser driver.

WP 13 Diagnostics

- *Alessandro Cianchi (University of Rome "Tor Vergata")*
- *Rasmus Ischebeck (EPFL)*

Diagnostics for particle and photon beams.

WP 14 Transformative Innovation Paths

- *Bernhard Hidding (Heinrich-Heine-Universität Düsseldorf)*
- *Stefan Karsch (LMU)*

Hybrid concepts, novel plasma acceleration schemes, compact undulators, etc.

SITE-RELATED

WP 15 TDR EuPRAXIA@SPARC_LAB (beam-driven plasma)

- *Cristina Vaccarezza (INFN)*
- *Riccardo Pompili (INFN)*

Preparation of TDR for beam-driven site of EuPRAXIA.

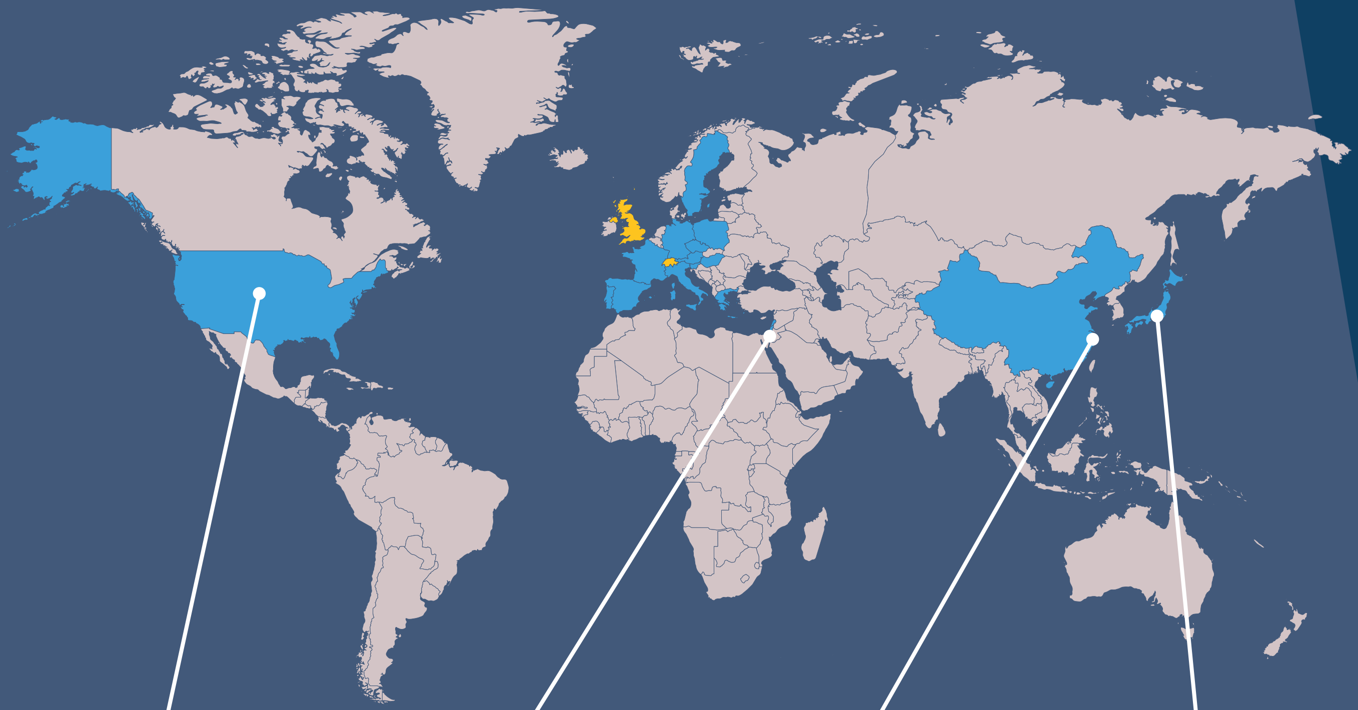
WP 16 TDR EuPRAXIA Site 2 (laser-driven plasma)

- *Alexander Molodozhentsev (ELI-ERIC)*
- *Rajeev Pattathil (STFC)*

Finalize the evaluation criteria for the laser-driven site.

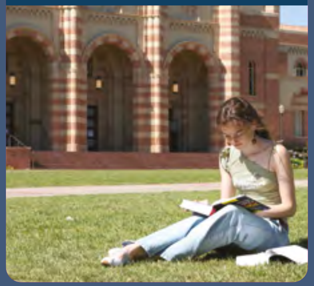
PARTICIPANTS

EuPRAXIA has brought together a consortium of over 50 institutions from all around the world, joining interdisciplinary excellence from particle accelerators, laser science, plasma physics, theory, and simulations.



USA

- University of California, Los Angeles
- Lawrence Berkeley National Laboratory



Israel

Hebrew University of Jerusalem

China

Shanghai Jiao Tong University

Japan

- Institute for Molecular Science
- Osaka University
- RIKEN SPring-8 Center
- Kansai Photon Science Institute

United Kingdom

- University of Oxford
- University of York
- University of Liverpool
- The Queen's University Belfast
- United Kingdom Research and Innovation (UKRI)
- University of Strathclyde
- University of Manchester
- Imperial College London

Germany

- DESY
- HZDR
- Helmholtz Institute Jena
- Fraunhofer Institute for Laser Technology
- Ferdinand-Braun-Institut
- Ludwig-Maximilians-Universität München
- FJZ
- KIT
- Heinrich-Heine-Universität Düsseldorf
- GSI-FAIR

Poland

- University of Warsaw
- Lodz University of Technology
- National Centre for Nuclear Research
- Military University of Technology
- Institute of Plasma Physics and Laser Microfusion

Czech Republic

ELI-ERIC

Sweden

Lund University

Austria

CIVIDEC GmbH

CERN

European Organization for Nuclear Research

Hungary

- Wigner Research Centre for Physics
- University of Pécs
- University of Szeged

Spain

- CLPU
- ALBA-CELLS

Slovenia

Instrumentation Technologies

Portugal

Instituto Superior Técnico

Greece

Institute of Accelerating Systems & Applications

France

- CNRS
- Thales LAS France
- CEA
- Synchrotron SOLEIL
- Amplitude Technologies

Italy

- **INFN (Coordinator)**
- Università degli Studi di Roma 'Tor Vergata'
- Sapienza Università di Roma
- ENEA
- CNR
- Elettra Sincrotrone Trieste

Switzerland

- Ecole Polytechnique Fédérale de Lausanne
- Swiss Federal Laboratories for Materials Science and Technology
- Paul Scherrer Institute

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

CONTACT US

Project Coordinator
Dr Pierluigi Campana, INFN
pierluigi.campana@lnf.infn.it

Deputy Coordinator
Prof Massimo Ferrario, INFN
massimo.ferrario@lnf.infn.it

EuPRAXIA Headquarter Office
Dr Antonio Falone, INFN
antonio.falone@lnf.infn.it

Claudia Pelliccione, INFN
claudia.pelliccione@lnf.infn.it

Anna Rita Ciamarra, INFN
anna.rita.ciamarra@lnf.infn.it

Communication & Outreach
Prof Carsten P. Welsch,
University of Liverpool / INFN

Dr Ricardo Torres, University of Liverpool
Alexandra Welsch, University of Liverpool
project.team@liverpool.ac.uk

TOWARDS REVOLUTIONARY APPLICATIONS AND BENEFITS FOR SOCIETY

www.eupraxia-facility.org

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