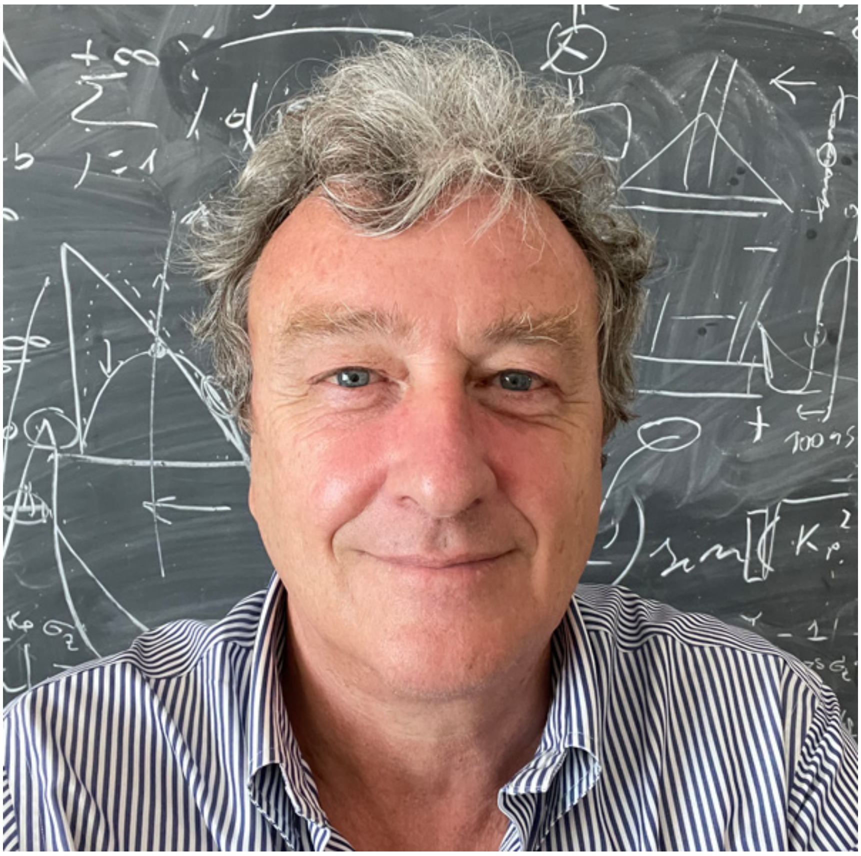
Newsletter Interview

THE FUTURE OF PARTICLE ACCELERATORS ALSO LIES IN PLASMA



Among the topics discussed during the annual International Conference on Particle Accelerators (IPAC'23), held last May in Venice Lido, the state of research on plasma accelerators certainly deserves attention: not only for the central role played by Italy, but also for the new and promising scenarios that the advent of this technology seems to shape. A future characterized by the opportunities deriving from easier access to accelerator machines and from an increasingly widespread use of these instruments in different fields. The possibility of realizing a new generation of more compact and cheaper light sources and accelerators, capable of satisfying both the needs of high-energy physics and those of the world of applied research or manufacturing sectors, is in fact the reason for the strong interest in projects that are focusing internationally on the design and development of a plasma particle acceleration technology and its applications. Initiatives like EuPraxia were hence among the themes of IPAC'23 agenda. Included already in 2021 in the European road map for research infrastructures of strategic interest, Eupraxia, which brings together more than 40 research institutes from 10 European countries, counts on the fundamental contribution from the INFN, which is engaged in the role of lead partner and has been selected to host one of the two centers dedicated to multidisciplinary activities envisaged by the project at the INFN Frascati National Laboratories (LNF). Italy's and INFN's commitment to research aimed at the development of plasma acceleration techniques has also been confirmed and relaunched with EuAPS (EuPRAXIA Advanced Photon Sources), an INFN-led project of national interest financed under the NRRP, which is proposed as a tool for the implementation and achievement of EuPRAXIA's objectives. Massimo Ferrario is the spokesperson for EuAPS and SPARC_LAB, the research facility at the Frascati National Laboratories that will serve as the headquarters for the project's activities.

During the last IPAC conference, considerable attention was given to the field of plasma acceleration. On what physical principles and phenomena is this particle acceleration technique based, what differentiates it from the systems in use today, and what disciplines are involved in its development?

The idea of using a plasma wave to accelerate charged particles is well known, and it dates back to 1979. The principle on which it is based is relatively simple: a plasma as a whole is electrically neutral, containing equal amounts of negatively charged electrons and positively charged ions. However, an externally injected pulse into the plasma, such as an intense laser beam or a particle beam, can create a perturbation in the plasma. Essentially, the beam pushes the lighter electrons away from the heavier positive ions, which in turn, remain almost stationary and form a kind of 'bubble' with an excess of positive charge, within which there is an extremely intense electric field. This perturbation propagates along the plasma like a wave on water at a speed close to that of light and can accelerate charged particles that are affected by it. The size of the accelerating bubble is very small, a few tens of microns, making it very difficult to inject a beam of electrons to be accelerated into it, but the high accelerating fields produced make the technique very cost-effective in terms of both accelerator compactness and cost reduction. I would say that this is the main feature that differentiates plasma acceleration from conventional accelerators, which, by using electromagnetic waves propagating in metallic structures, can now produce considerable accelerating fields, but with intensity lower than those obtainable in a plasma.

Much can still be done to improve the performance of plasma accelerators, particularly in terms of the stability and quality of the accelerated beam, and many interdisciplinary efforts are underway worldwide to achieve improvements in this field. Experts from plasma physics, laser physics and, of course, accelerator physics are involved, generating a virtuous circle of fertilization between different disciplinary fields that I find very stimulating. Let us remember, for example, that without the invention of the system for generating high-power short laser pulses, it would not have been possible to excite plasma waves effectively. The importance of this invention, not only for plasma acceleration, was recognized in 2018 with the award of the Nobel Prize in Physics to its inventors, Gérard Mourou and Donna Strickland.

Today, experts from the different disciplines involved in the development of plasma accelerators have strengthened a common language that facilitates an overall view in tackling the problems and that is yielding results that are clearly visible even at large general conferences such as IPAC.

What kind of benefits could the use of future plasma accelerators provide and what could their applications be?

The acceleration of electron beams using plasma is now an established achievement. Beams of up to 10 GeV have in fact already been successfully produced in 10 cm long plasma modules, confirming the main promise of this new technology: the reduction in space requirements and in the costs of construction and operation. The quality of the accelerated beams is also improving rapidly enough to make electron plasma accelerators a feasible option within the next five years for coherent synchrotron light sources such as free electron lasers (FELs). This will open a new landscape for FEL users who would have greater access to radiation sources that could be realised even in small spaces such as those available in universities or hospitals, and in some cases even in industry.

For high-energy physics, it is still premature, in my opinion, to expect an application to linear colliders in the short term. The main problem concerns the development of positron acceleration, which has not yet achieved the results obtained with electrons. The problem is partly due to some intrinsic difficulties in positron acceleration schemes that have not yet been satisfactorily resolved, and partially also to the low attention paid to this technology to date due to the lack of dedicated research programs. However, I believe that the commissioning of the first electron plasma accelerators is also a necessary step for the development of colliders.

The EuPRAXIA project is dedicated to promoting the development of plasma accelerators across Europe and INFN plays a leading role in the project. How is the project organized and how is INFN contributing to it?

The EuPRAXIA project is a dream about to become a reality. In 2014, European researchers agreed on the need for a combined and coordinated research and development effort to build a plasma accelerator facility to serve as a demonstrator. The project was to target the production of high-quality electron beams with energy up to 5 GeV, achieving significant size reduction and possible cost savings compared to radio frequency (RF) accelerators. This project was called the European Plasma Research Accelerator with eXcellence In Applications (EuPRAXIA), and, as the name suggests, was aimed primarily at applications and users. It was decided at the time that the purpose of the initiative should be to provide X-ray, photon, electron and positron pulses to users from different disciplines. The EuPRAXIA project began in 2015 with a preliminary study, funded under the European Union's (EU) Horizon 2020 program, leading to the publication of the first "Conceptual Design Report" (CDR), coordinated by Ralph Assmann (DESY), of a plasma accelerator facility in late 2019. The EuPRAXIA implementation plan envisions a distributed research infrastructure with two main sites, where "user facilities" will be built, and several centers of excellence in Europe will contribute to the research and construction of the two main sites.

A very important achievement for the entire collaboration, which now includes 51 institutes from 15 countries, was achieved in 2021 when EuPRAXIA was included in the roadmap of the Strategic Forum for European Research Infrastructures (ESFRI), which identifies research facilities of pan-European importance that correspond to the long-term needs of the European community. Italy, represented by INFN, was chosen as the lead country. INFN's role will therefore be very important, both as the entity hosting the headquarters of the entire European collaboration and because it will build one of the two planned "user facilities" in LNF. EuPRAXIA@SPARC_LAB, the name of the facility to be built in LNF, will be a plasma accelerator capable of driving a Free Electron Laser with coherent radiation emission ideal, for example, for biophysical applications.

The "Technical Design Report" of EuPRAXIA@SPARC_LAB will be published by the end of 2025. In the meantime, we are finalizing permit applications for the construction of the new building, which we expect to complete by 2027. Installation and operation of the machine will begin as soon as the facility is ready to receive it and will be started by 2028. If there are no unforeseen delays, we expect to have the first pilot users in 2029. For the realization of this infrastructure, the Italian Ministry of Universities and Research has allocated funding of 108 million euros.

Our country has also been able to recognize the strategic value of plasma accelerators, as shown by the INFN-led EuAPS project, funded by NRRP funds. What are its goals and how do they fit into the broader context of EuPRAXIA?

Indeed, we were very pleased with the result achieved in the process of selecting research infrastructure projects to be funded through the NRRP. Our project, called EuPRAXIA Advanced Photon Sources (EuAPS), led by INFN in collaboration with CNR and the University of Rome Tor Vergata, has received additional financial support of 22.3 million euros from the NRRP plan and it will address some crucial aspects for the realization of EuPRAXIA. In fact, EuAPS will include the construction in LNF of a source of incoherent X-rays emitted by plasma-accelerated electrons, known as "betatron radiation," of energy between 1 and 10 KeV, and in parallel it will see the development of high-power lasers at the INFN Southern National Laboratories and high-frequency repetition lasers at the CNR in Pisa, which are necessary for the realization of EuPRAXIA. EuAPS will in fact be the first brick of the EuPRAXIA program, to be realized within the 36-month timeframe of the NRRP call, which for us will expire at the end of 2025. This is a very challenging race against time, but one that we feel able to tackle also thanks to the great effort put forth by INFN to support all approved NRRP projects involving the institute's facilities.

SPARC_LAB, an infrastructure of INFN LNF, is an international reference laboratory for research conducted in the field of plasma acceleration. What are the lab's achievements to date and what activities will it focus on in the coming years?

SPARC_LAB has established itself in the international plasma acceleration research scenario thanks to the top-level results generated by the commitment of a group of young and brilliant researchers and the growing involvement of the Frascati Accelerator Division with its highly experienced Technical Services.

Undoubtedly the most important result recently obtained at SPARC_LAB was the first experimental demonstration of the emission of Free Electron Laser radiation at 800 nm from a plasma-accelerated electron beam. This result was published on Nature in 2022 (ed. Pompili et al., Nature, 605, 659-662 (2022)) and was recognized as a fundamental step forward toward the realization of compact radiation sources, such as EuPRAXIA. This result was achieved thanks to the experience gained since the origins of SPARC_LAB, around 2002, as a test facility for the FEL SPARX project, but especially thanks to the recent formation of a group of experts able to design the experiment both in its theoretical modeling and numerical simulation aspects and in the realization of the accelerator module itself, produced in the PLASMA_LAB laboratory in LNF. Numerous problems were faced and overcome to arrive to the results, such as those related to the design of the chamber where the interaction between beam and plasma takes place and those linked to the related pumping system to avoid gas diffusion in the accelerator.

While waiting for the realization of EuPRAXIA, SPARC_LAB will be the test facility dedicated to fine-tuning the critical components of EuPRAXIA for a few more years. One of the crucial aspects yet to be perfected will be the energy stabilization of the accelerated beams, which will require the accurate tuning of a synchronization system between the plasma wave and the accelerated beam. Certainly, a challenge for the electronics of the system, but necessary for the achievement of the final result. In parallel in the PLASMA_LAB laboratory, properly equipped for the development of the plasma modules and their characterization before installation on the accelerator, the 40 cm long modules will be developed as envisaged by the EuPRAXIA project.

Besides Frascati National Laboratories, what other INFN groups are involved in research and development work related to particle accelerators, and in what role?

The EuPRAXIA collaboration naturally extends to other INFN groups besides the LNF group. In particular, the Milan group has made and will continue to make fundamental contributions in the development of numerical simulation codes for beam-plasma interaction and FEL physics, which is indispensable both in the design phase and in the interpretation of experimental data. Recently, the Southern National Laboratories joined through the EuAPS program and will contribute to the development of power lasers for EuPRAXIA. Equally important is the collaboration with universities in the Rome area, in particular the doctoral program in 'Accelerator Physics' at Sapienza University is an avenue for recruiting young people interested in the EuPRAXIA project, as well as the Universities of Tor Vergata and Milan have been actively contributing to EuPRAXIA-related research activities for some time. A long and fruitful collaboration with ENEA in Frascati and CNR in Pisa allowed us to gain experience even in research areas in which INFN was not yet prepared, such as the development of undulators for FEL and power lasers.

EuPRAXIA and EuAPS are projects strongly tied to industries thanks to their high technological value. How do companies today contribute to INFN activities in the field of plasma acceleration, in which sectors do they operate and what benefits can the industrial world gain from this synergy?

The EuPRAXIA project has a strong link with industry. Specifically, the industry specializing in the production of High Power Lasers proved to be an important partner in finalizing the project and is currently co-developer of the high repetition laser systems planned for both EuAPS and EuPRAXIA.

The decision to use X-band accelerator structures for the conventional accelerator portion of EuPRAXIA@SPARC_LAB is also driving industry in the development of appropriate high-efficiency, high-repetition microwave sources needed to power the X-band accelerator structures. The accelerating structures themselves will be produced by specialized Italian companies.

It is our hope that the innovative dribe that the EuPRAXIA project will bring forward can have important spillovers to industry as well, succeeding, for example, in opening a new market related to the plasma accelerator modules we are designing at PLASMA_LAB. In addition, when EuPRAXIA comes into operation, industry itself will be able to benefit from the new X-ray radiation sources available at the INFN LNF and possibly use them for applications of their interest such as materials irradiation testing.