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**VIETATO
L'ACCESSO**

HIGHLIGHTS

ONE YEAR OF RESEARCH AT LNF

2025



Scientific Direction

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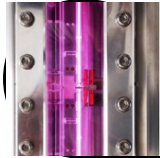
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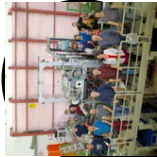
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Some LNF achievements during 2025



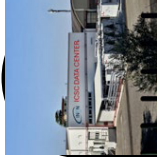
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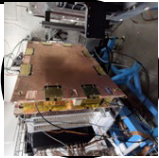
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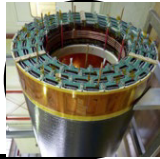
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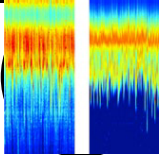
New Infrastructures



P DME



Gaseous Detectors



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FOREWORD

The main activity carried out at the Frascati National Laboratory in 2025 has been the preparation of the Technical Design Report (TDR) for our flagship project, **EuPRAXIA@SPARC_LAB**. This document — more than six hundred pages long — details all the technical aspects of a facility designed to establish a pioneering research infrastructure that employs **Plasma Wake-Field Acceleration (PWFA)** to drive a high-brightness **Free-Electron Laser (FEL)** in the soft X-ray regime.

This ambitious endeavor aims to provide both a cutting-edge scientific facility for users and a technological demonstrator capable of validating the integration of high gradient plasma acceleration with X-band RF technology in a compact FEL light source. Its successful implementation will lay the foundations for future compact and more sustainable accelerator-based facilities.

The development of the TDR involved nearly the entire Accelerator and Technical Divisions of the laboratory, and underwent rigorous scrutiny by an international review committee composed of leading experts from CERN, the PSI Swiss laboratory, the STFC UKRI agency, and Stockholm University. The document, approved in early

February 2026, marks the starting point of the project's implementation phase. This phase began with the launch of the tender for the construction of the building that will host the facility. First beams are expected to be delivered in 2031. The ramp-up of activities for **EuPRAXIA@SPARC_LAB** runs in parallel with the completion of the **DAΦNE** physics program, whose final experiment, **SIDDHARTA-2**, has achieved the world's first direct measurement of kaonic deuterium — a major milestone in the spectroscopy of exotic atoms. The exceptional performance of a new generation of Silicon Drift Detectors, optimized for X-ray transitions in kaonic atoms, combined with the unique characteristics of the low-energy kaons produced at **DAΦNE**, enabled the **SIDDHARTA-2** collaboration to conduct the most complete and precise survey of kaonic atoms to date. This dataset will stand as a significant legacy of LNF, contributing to our understanding of strong interactions at low energies.

In 2025, the **DAΦNE** complex operated only through its LINAC, which provided beam time both for the **PADME** experiment and for external users of the Beam Test Facility (BTF). **PADME**, a positron on target experiment installed in Hall 1 of the BTF, has recently emerged as an ideal setup for studying the so-called “**X17 anomaly**”. Following pilot data taking campaign in 2022, whose intriguing results have been recently published, the collaboration carried



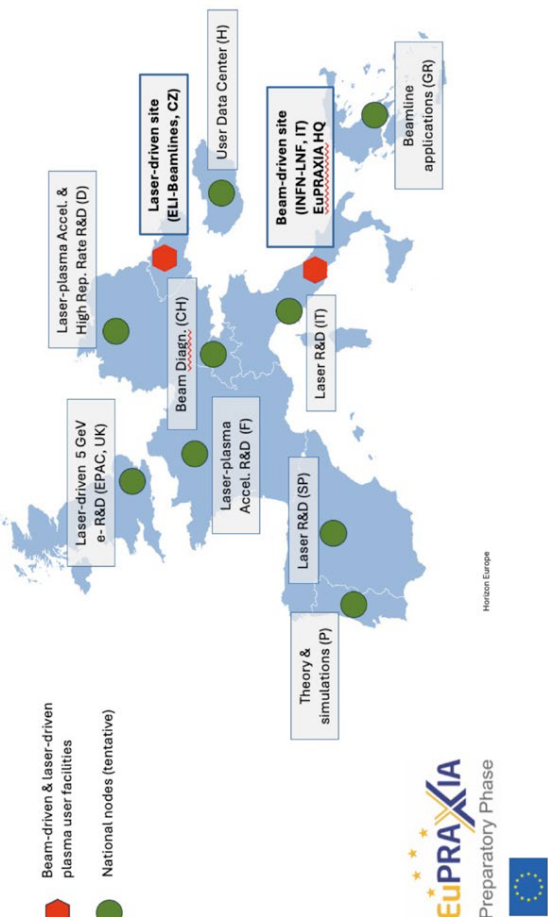
Paola Gianotti / LNF Director

out in 2025 a dedicated run with the aim of providing a definitive clarification of the phenomenon. Research activities related to the **DAΦNE** complex also include work on **Synchrotron Radiation (SR)**. This research field is a powerful tool for material science and a wide range of applied studies and is expected to expand further with the increasing exploitation of light sources available at **SPARC_LAB** through the **SABINA** and **EuAPS** beamlines, and in the coming years through the two FEL beamlines, **ARIA** and **AQUA**, planned for **EuPRAXIA@SPARC_LAB**. To take stock of the ongoing work and future prospects in this area, a dedicated workshop was held at LNF on December 4, 2025. The event was conceived not only to highlight the laboratory's SR legacy, but also to underline its growing strategic importance. Rather than offering a purely historical perspective, the workshop placed emphasis on the role that photon beamlines exploitation will play in shaping the laboratory's future development.

EUPR XI PROJECT: BRINGING PLASMA ACCELERATORS TO USER FACILITY



EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) is one of the most ambitious European initiatives in advanced accelerator technology. Included in the ESFRI (European Strategy Forum on Research Infrastructures) Roadmap, the project aims to develop a new generation of compact particle accelerators based on plasma acceleration and to apply them to photon science, high-energy physics and interdisciplinary research. Within this framework, the EuPRAXIA@SPARC_LAB facility, currently under development at LNF, represents the Italian pillar of the EuPRAXIA distributed infrastructure, see Fig. 1, and the first user facility designed to exploit beam-driven plasma wakefield acceleration (PWFA). The year 2025 marked a major milestone for the project with the completion of the Technical Design Report (TDR) of EuPRAXIA@SPARC_LAB^[1]. The document consolidates several years of research and development carried out at LNF and by the international collaboration.



Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange). Credit: . Martinez de la Ossa/DESY, from CERN Courier, April 2023.

It defines the full design of the accelerator, the plasma acceleration stage, the Free-Electron Laser (FEL) beamline, and the supporting infrastructure required to operate the facility as a scientific user laboratory. With the publication of the TDR in early 2026, the project has reached the level of technical maturity required to move toward implementation.

The EuPRAXIA@SPARC_LAB facility is conceived as a compact soft-X-ray light source capable of delivering

high-brightness electron beams with an energy of 1 GeV. These beams will drive the AQUA free-electron laser, producing radiation in the so-called “water window” spectral region between approximately 3 and 5 nanometers. This wavelength range is particularly important for imaging biological samples in aqueous environments and for studying ultrafast chemical and physical processes. The combination of femtosecond pulse duration and high photon flux will enable experiments that are currently possible only at a limited number of large international facilities.

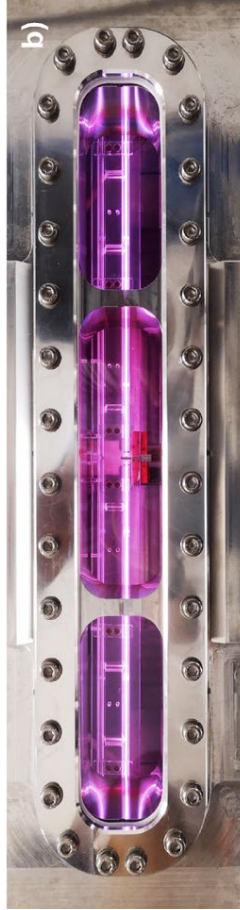
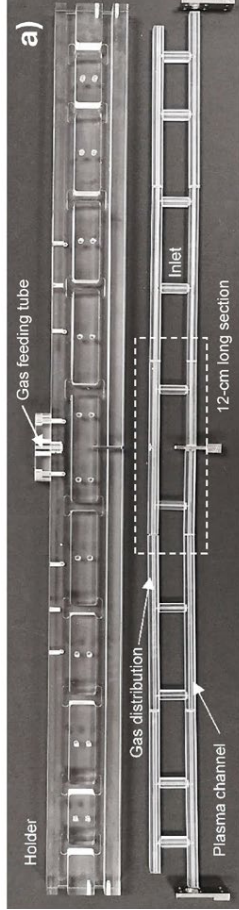


Figure 2: 60 cm-long gas-filled discharge capillary.
a) Single components before the capillary assembly.
b) Plasma discharge generated after the assembly.

A key innovation of the project is the integration of plasma acceleration within a conventional radio-frequency accelerator. In the baseline configuration, the electron beam is first accelerated using high-gradient X-band RF technology and then further boosted in energy within a short plasma module only about sixty centimeters long, see Fig. 2. Inside this plasma channel, accelerating gradients of the order of one gigavolt per meter can be achieved, allowing the beam energy to be doubled in a very compact distance. This approach combines the reliability of RF accelerators with the exceptional gradients achievable in plasma, paving the way for more compact and cost-effective accelerator facilities.

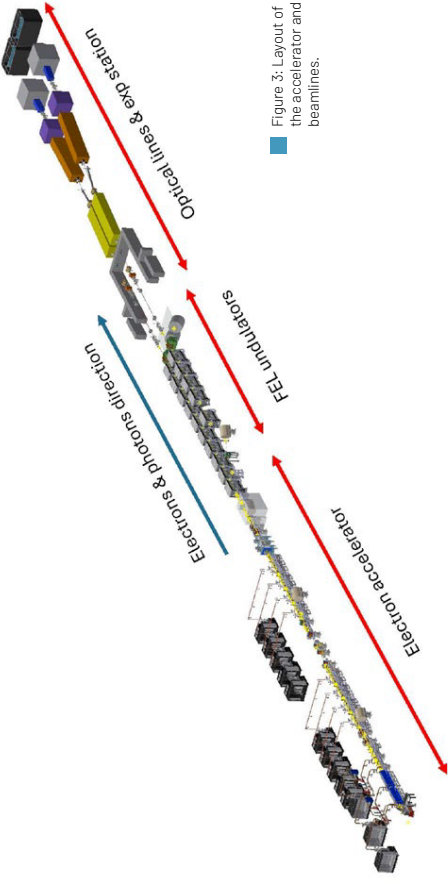


Figure 3: Layout of the accelerator and beamlines.

The accelerator architecture integrates several advanced subsystems developed at LNF and within European collaborations, see Fig. 3. A high-brightness RF photo-injector produces the electron bunches that are subsequently accelerated in a high-gradient X-band linac. Downstream of the linac, the plasma module provides the energy boosting stage, while a dedicated beam transport system matches the beam into the undulator line where the FEL radiation is generated. The photon beam is then delivered to experimental stations equipped for spectroscopy, coherent imaging and ultrafast pump-probe studies.

Alongside the accelerator design, significant progress has been achieved in the development of key enabling technologies. High-gradient X-band accelerating structures have been tested at the TEX test facility at LNF, demonstrating performance compatible with the requirements of the project. In parallel, dedicated experiments in the PLASMA LAB have advanced the development of the plasma source, addressing crucial aspects such as discharge stability, density control and long-term reliability of the plasma channel. These activities are essential to ensure that plasma acceleration can operate with the stability required for a user facility.

EuPRAXIA@SPARC_LAB also plays a central role within the broader European EuPRAXIA initiative. During 2025, the EuPRAXIA Preparatory Phase continued to develop the governance and implementation strategy of the future

distributed infrastructure. A key milestone was the selection of ELI-ERIC (Prague) as the second implementation pillar of EuPRAXIA, dedicated to laser-driven plasma acceleration. Together with the Italian beam-driven pillar at LNF, these facilities will form the core of a European infrastructure aimed at advancing plasma accelerator technologies and their scientific applications.

Looking ahead, the completion of the Technical Design Report marks the transition from design to realization. The next steps will focus on the construction of the new accelerator building at LNF, as discussed later in this issue, further validation of X-band RF systems, and continued development of the plasma acceleration stage.

Once operational, EuPRAXIA@SPARC_LAB will demonstrate for the first time that plasma wakefield acceleration can be integrated into a reliable scientific user facility. Beyond its immediate scientific impact, the project will contribute to establishing Europe as a global leader in advanced accelerator technologies and to shaping the future generation of compact accelerator-based research infrastructures.

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P DME HUNTS THE MYSTERIOUS X17P RTICLE

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hile the Standard Model of particle physics (SM) is known to describe successfully and with great precision the phenomenology of ordinary matter, it is also known to be incomplete. In particular, new physics is required to address open problems such as the nature of dark matter, the origin of neutrino masses and matter-antimatter asymmetry.

The hunt for physics beyond the SM is therefore at the very core of present day theoretical and experimental efforts of particle physicists. On the one hand, theorists explore new ideas and models that encompass and extend the SM, supersymmetry or string theory for instance; on the other, experimentalists look for possible measurements that cannot be explained by it.

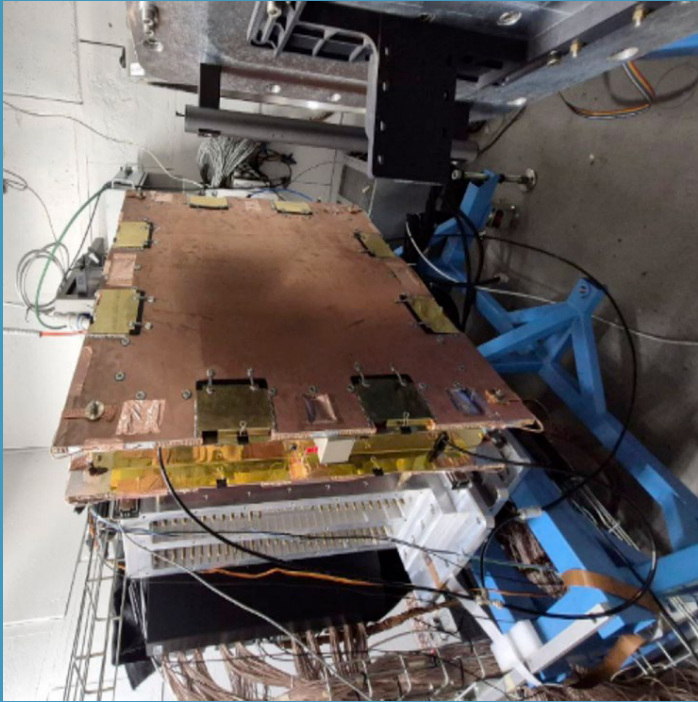
Among the latter, in recent years a series of experiments performed at the ATOMKI Laboratory in Debrecen, Hungary, have repeatedly reported deviations in the observed angular spectrum of the electron-positron pairs emitted in rare decays of excited Beryllium, Carbon and Helium nuclei ^[1]. All these observations point to the possible existence of a new neutral particle of mass around 17 MeV/c², thus christened X17, carrier of a fifth force not envisaged by the SM.

It has been immediately realized that, since the X17 can decay into an electron-positron pair, it can therefore be produced by electron-positron collisions. Moreover, if the energy of the collision is tuned to be equal to the X17 mass, the probability for its production is strongly enhanced. This is the principle of the "resonant production", a well-established technique in particle physics; and this is in fact the principle that the PADME experiment at LNF has exploited to perform a search of the X17, whose results have been recently published in [2].

PADME is a positron-on-target experiment installed in Hall1 of the BTF facility of the LNF, whose original purpose is the search of another exotic particle, called "dark photon".

To the essential, it consists of an active target made of diamond which provides the almost at rest electrons onto which a positron beam impinges, and a finely segmented electromagnetic calorimeter (ECal), which catches the products of the collisions and measures their energy and flight directions. Other detectors (TimePix, PbG) provide information on the beam parameters and on the background signals which might spoil the quality of the measurement. A schematic layout of the detector is shown

Left: a picture of the new P DME tracking detector.



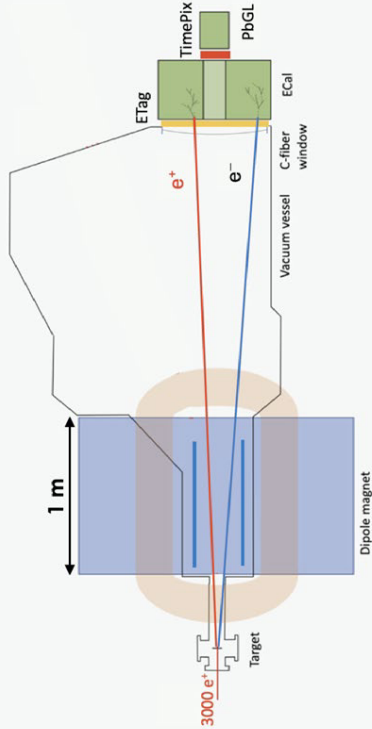
in Figure 1. A primary beam of positrons with a repetition rate of 49 Hz and custom energy and intensity selections is provided by the DAΦNE LINAC and Beam Test Facility 1 (BTF-1) complexes [3].

In the fall of 2022, the Collaboration has dedicated the data taking (RUN III) to the above-mentioned resonant search. For the purpose the BTF team has tuned the energy of the positron beam to about 40 different energy values, corresponding to values of the center-of-mass energy of

number of observed two-body events (a “resonant peak”) with respect to SM expectations.

The result of two years of careful data analysis performed by the PADME team is shown in Fig. 2. The Collaboration has been able to reach a relative uncertainty uncorrelated between the various energy points below the percent, a quite remarkable result indeed. Very interestingly, an excess of data for a center-of-mass energy of 16.9 MeV is seen. This corresponds exactly to the preferred mass value for

Figure 1: Top-view layout of the P DME detector in the Run III configuration.



the positron-atomic electron pair ranging between 16.5 and 17.5 MeV. When a positron of the beam interacts with an electron of the target it can produce a final state consisting of two particles, either two photons ($\gamma\gamma$) or an electron-positron (e^+e^-) pair. This final state is what PADME is looking for. Standard Model processes can be responsible for this signature, at a rate that is almost independent of the energy of the beam. If, however, the X17 exists, for the center-of-mass energy corresponding to its mass one should observe a substantial increase in the

the events of interest by a factor of 2. Secondly, a tracking detector has been installed with the aim of discriminating between e^+e^- and $\gamma\gamma$ final states (see Fig. 3); this tracker uses the so-called micromegas detector design, a technology mastered for decades by the LNF ATLAS group. Thirdly, about twice the data were acquired per energy point with respect to Run III, to reduce the statistical uncertainty.

The analysis of the data has already started. The experience with RUN III tells that a lot of attention has to be paid to

several details, to prevent errors and to minimize all possible instrumental uncertainties. Therefore, the first preliminary results are not expected before the end of the year 2026.

In the meanwhile, other experiments are being programmed and performed all over the world, to try to catch signals of the mysterious X17. An exciting time is ahead of us: if the existence of the X17 will be proven, a completely new world will be opened in front of us, a world to be discovered in the years to come.

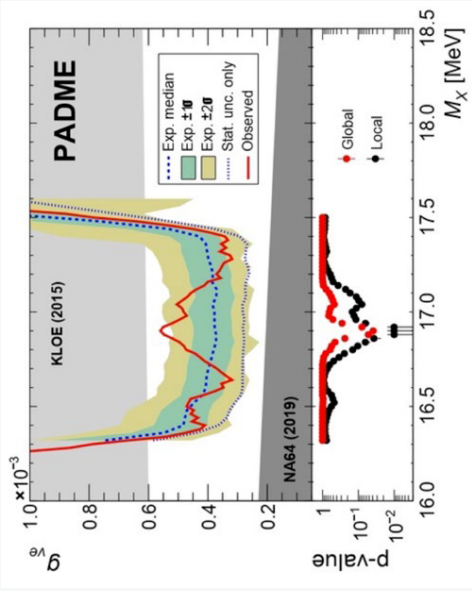


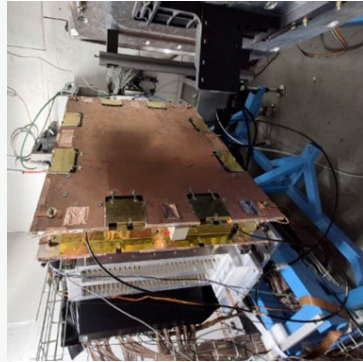
Figure 2: Exclusion upper limits as a function of the supposed particles mass (M_X) at 90% CL.

The solid red line is the observed limit curve, and the green and yellow bands are the 1 and 2 local envelopes around the median expected curve (dashed blue line) for the background-only hypothesis.

The gray filled areas are the excluded regions at 90% CL from the KLOE and N 64 experiments, respectively. The bottom panel shows the probability values corresponding to the observed upper limits.

Black and red dots denote local and global probabilities, respectively.

Figure 3: picture of the new P DME tracking detector.



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Kaonic Deuterium Beyond: Breakthroughs in Exotic Tom Spectroscopy at DΦNE



More than four decades ago, Richard Henry Dalitz pointed out that “the most important experiment to be carried out in low-energy K-meson physics is the definitive determination of the energy-level shifts in K⁺p and K⁺d atoms, due to their direct connection to the physics of the antikaon-nucleon ($\bar{K}N$) interaction.” SIDDHARTHA-2 has now performed the first direct measurement of kaonic deuterium at DΦNE, achieving a major milestone in exotic atom spectroscopy. Beyond kaonic deuterium, the experiment has carried out several unique precision measurements of kaonic atoms, setting a new standard in the field.

Kaonic atoms are systems in which a negatively charged kaon replaces an electron. They provide a unique tool to investigate the strong interaction between antikaons and nucleons/nuclei at threshold energies. The measurement of the energy shifts and widths of the lowest-lying atomic levels, induced by the strong interaction, gives direct access to the antikaon-nucleon scattering lengths. These are fundamental quantities for studying the strong interaction in the non-perturbative regime with strangeness, with implications ranging from particle and nuclear physics to astrophysics^[1].

Despite its fundamental importance, the measurement of kaonic deuterium remained on the wish list for decades due to enormous experimental challenges. The production of low-energy kaon beams and the detection of the very low-yield X-ray transitions to the ground state required a combination of breakthroughs in collider performance and

X-ray detector technologies.

The SIDDHARTHA-2 collaboration (Fig. 1) developed a new generation of high-performance spectroscopic Silicon Drift Detectors (SDDs) specifically optimized for this measurement. Combined with the excellent performance of the DAΦNE collider at LNF in delivering low-energy kaons^[2], about 1 fb⁻¹ of data were collected between 2023 and 2024, enabling for the first time a statistically significant observation. The kaonic deuterium spectrum, obtained after applying dedicated trigger and veto systems^[3], for Run 1 (May-July 2023) is shown in Fig. 2. It exhibits a shift of various hundreds of eV and a broadening of the $K\alpha$ transition with respect to the pure QED expectation, directly caused by the strong kaon-nucleus interaction.

The refined analysis, currently under publication, allows the extraction of the strong-interaction-induced shift and width of the 1s ground state, providing stringent constraints on theoretical models of low-energy QCD in the strangeness sector. In particular, it will help to disentangle and potentially resolve the long-standing discrepancies among different theoretical predictions^[1], significantly improving our understanding of the antikaon-neutron interaction.

Beyond kaonic deuterium, the SIDDHARTHA-2 collaboration has performed a series of unique measurements of various light kaonic atoms^[4]. Among these, particularly remarkable are the high-precision (some of them also first) measurements of kaonic helium, fluorine,

Figure 1: Photo of the SIDDHARTHA-2 apparatus and part of the collaboration.

boron, and neon, the latter shown in Fig. 3. Unlike the deuterium case, these kaonic atoms also provide access to tests of Quantum Electrodynamics (QED) in a previously unexplored regime. QED, the quantum theory describing electromagnetic interactions, is one of the most successful and precisely tested theories in physics. Even small deviations from its predictions could signal physics beyond the Standard Model. By measuring transitions in kaonic neon and fluorine we probe QED in the strong-field regime (Fig. 3 for kaonic neon), characterized by electric fields exceeding the Schwinger limit, above which spontaneous electron-positron pair production from the vacuum is expected^[4]. This result represents the first experimental test of this previously unexplored regime in strange systems and

opens new perspectives for future investigations. In conclusion, the SIDDHARTA-2 collaboration, together with the DAΦNE collider staff, carried out the most extensive campaign of kaonic atom studies in the modern era, including the first direct measurement of kaonic deuterium. These results pave the way for future systematic precision studies of kaonic atoms, for a deeper understanding of the kaon-nucleon/nuclei interaction, and potential insights into physics beyond the Standard Model. Moreover, they provide strong motivation for next-generation initiatives such as EXKALIBUR, a proposal aimed at fully exploiting kaon-beam facilities, such as DAΦNE and J-PARC, to further advance the field of kaonic atoms physics^[5].

Figure 2: Kaonic deuterium energy spectrum for Run 1 measured by the SIDDHARTA-2 experiment. The $K\alpha(2p \rightarrow 1s)$, $K\beta(3d \rightarrow 1s)$, and $K\gamma$ complex ($n \rightarrow 1s$) transitions are highlighted in blue, together with other kaonic atom transitions originating from kaon interactions with the walls of the deuterium target cell.

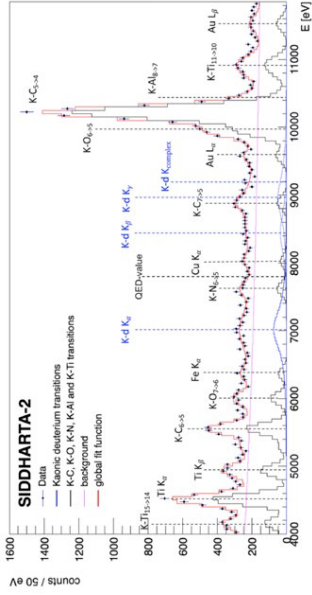
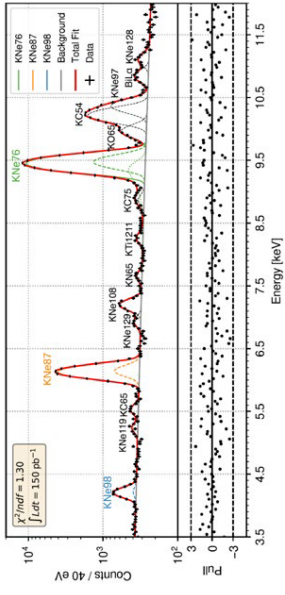


Figure 3: Kaonic neon energy spectrum, from^[4].



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FROM WIRE CHAMBERS TO MICRO-PATTERNED Gaseous DETECTORS: THREE DECADES OF INNOVATION TALKS

F

or more than half a century, gaseous particle detectors have been a key technology in experimental particle physics. Their low material budget, scalability to large sensitive areas, moderate cost, and excellent spatial and timing performance make them well suited for tracking and triggering systems in high-energy and nuclear physics experiments.

A breakthrough occurred in 1968 with the invention of the Multi-Wire Proportional Chamber (MWPC) by Charpak^[1] (Fig.1) which enabled the detection of charged particles over large areas. However, with the advent of high-luminosity colliders it became clear that traditional wire-based detectors would face limitations in environments with very high particle fluxes, as the millimetric spacing between anode wires leads to relatively long ion-collection times and limits the achievable rate capability.

A decisive step forward came in 1988 with the Micro-Strip Gas Chamber (MSGC) proposed by Oed^[2]. By replacing wires with photolithographically produced metallic strips, amplification structures could be reduced to micrometric dimensions, significantly improving rate capability.

This development marked the birth of the Micro-Pattern Gaseous Detector (MPGD) family. During the 1990s two technologies became particularly successful implementations of this concept: MICROMEGAS^[3] and the Gas Electron Multiplier (GEM)^[4]. In MPGDs the amplification structures are defined through micro-fabrication techniques derived from the printed circuit board (PCB) industry, rather than mechanically tensioned wires. Today many of these structures are produced by the Micro-Pattern Technology MPT-Workshop at CERN, which plays a key role in the worldwide development of MPGD technologies.

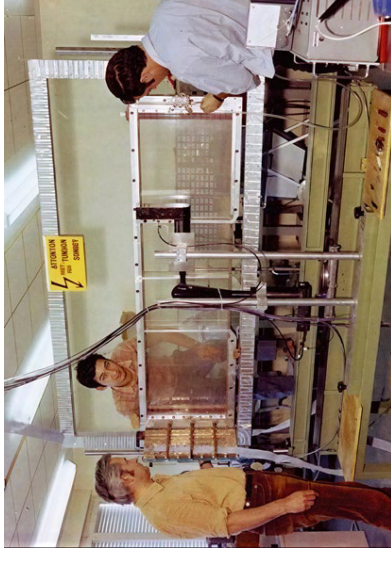


Figure 1: The Multi-Wire Proportional Chamber (MWPC) concept introduced by G. Charpak in 1968.

Gaseous detectors have been developed at LNF since the early years of experimental particle physics. A notable example is the invention of the Plastic Streamer Tubes (PST) by Iarocci and collaborators in the late 1970s^[5], widely used in several experiments at the LEP collider as active elements of hadron calorimeters and muon detection systems. Another major achievement was the construction of the KLOE drift chamber (Fig. 2) in the 1990s^[6], one of the largest drift chambers ever built. This detector, about 4 m

in diameter and 3.5 m long, was constructed using carbon-fiber composite materials and contains approximately 12,500 thin (20 μm diameter) tungsten sense wires and 40,000 thick (100 μm diameter) aluminum field wires.

In this framework, the LNF Detector Development Group (DDG-LNF) has played a central role in the research and construction of gaseous detectors. Around 2000 the group moved into the field of MPGD through R&D activities on GEM detectors for the LHCb experiment at CERN.

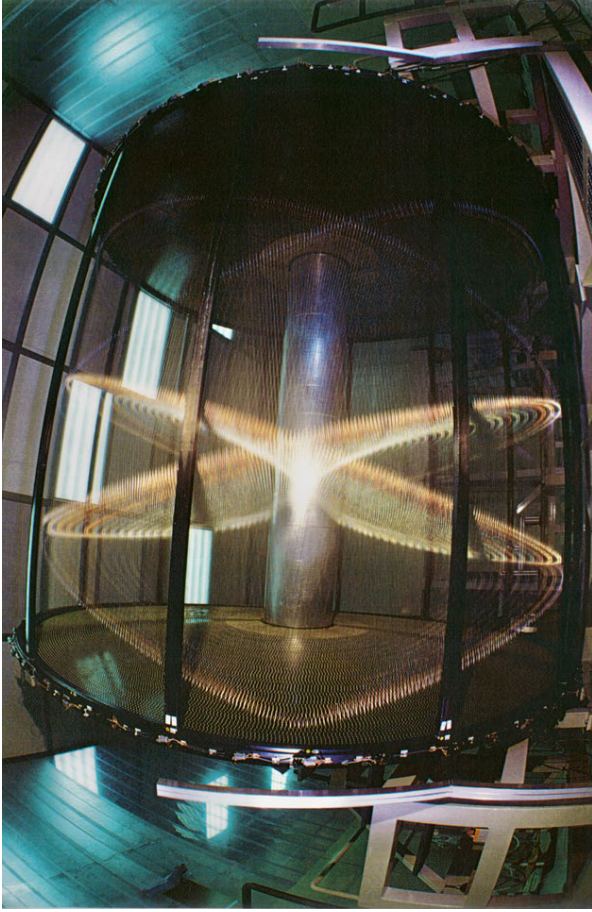


Figure 2: The KLOE drift chamber built at the Frascati National Laboratories in the 1990s.

This work later evolved into the Cylindrical-GEM technology, successfully implemented as the inner tracker of the KLOE-2 experiment, representing the first Cylindrical-GEM detector ever realized (Fig. 3).

Based on this experience, the DDG-LNF initiated the development of new detector architectures aimed at simplifying construction while preserving the excellent performance typical of GEM. In this context, a new MPGD architecture was introduced at LNF in 2014 as a natural evolution of GEM-based detectors: the micro-Resistive WELL (μ -RWELL).

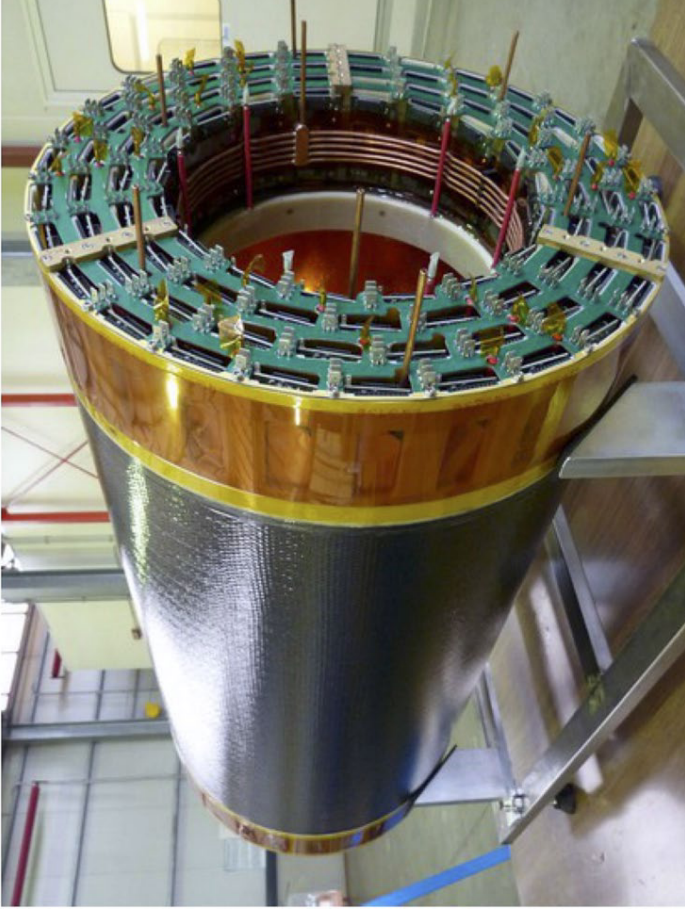


Figure 3: Cylindrical GEM Inner Tracker (CGEM-IT) of the KLOE-2 experiment: the first cylindrical implementation of the GEM technology.

The μ -RWELL^[7] is a compact resistive MPGD architecture designed to combine high performance, operational stability, and simplicity of construction. The detector (Fig. 4) consists of a cathode electrode and a multilayer structure referred to as the μ -RWELL PCB. This hybrid structure includes a 50 μm thick Kapton foil patterned with microscopic WELL-shaped holes and coated with copper on the top side, which acts as the amplification stage. Below this layer a thin Diamond-Like Carbon (DLC) resistive film, typically with surface resistivity in the range 50–100 $\text{M}\Omega/\square$, is deposited through magnetron sputtering and coupled to a standard readout PCB segmented into pads, strips or pixels connected

to the front-end electronics.

The resistive layer suppresses electrical discharges during avalanche multiplication, enabling stable operation even at very high particle rates. Over the past decade the μ -RWELL technology has been extensively studied and optimized. Typical performance include gas gain up to $\sim 2 \times 10^4$, spatial resolution better than 100 μm , time resolution of about 5 ns, stable operation at particle rates exceeding several MHz/cm^2 . Unlike GEM detectors, which typically require multiple amplification stages to control discharge probability, the μ -RWELL can operate safely with a single amplification stage thanks to the resistive layer.

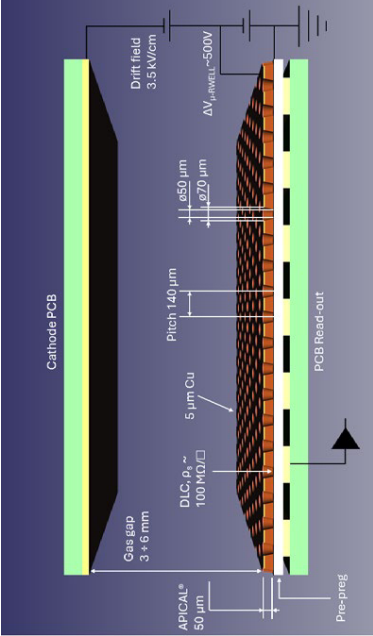


Figure 4: Sketch of the μ -RWELL detector showing the amplification stage, the resistive DLC layer and the readout PCB.

The resulting detector is extremely compact, requires minimal assembly operations, and is fully compatible with standard PCB manufacturing processes, making the technology intrinsically scalable and suitable for industrial production. The μ -RWELL technology is currently being considered for several applications in particle physics, including upgrades of the LHCb muon system, tracking detectors for the EPIC and CLAS12 experiments at BNL and Jefferson Laboratory, respectively, and possible use in future collider experiments such as FCC-ee, where detector surfaces of several thousand square meters may be required.

The development of resistive MPGD technologies has also stimulated collaborations with the PCB industry. Contacts with the Italian company ELTOS S.p.A. aim at exploring the industrial engineering and large-scale production of μ -RWELL detectors.



Figure 5: The MSPC prototype developed by DDG-LNF as a possible evolution of MPGD layouts for large area HEP applications.



Figure 6: The Magnetron sputtering machine of the CERN-INFN collaboration used for the DLC deposition on Kapton foil.



Figure 7: Technicians of the SSR-LNF during the wiring of the frames of the new beam-monitor chambers for the CERN beam test facilities (left). Completed wired frame of the chambers (right).

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Frascati National Laboratories and Synchrotron Radiation: Past, Present and Future

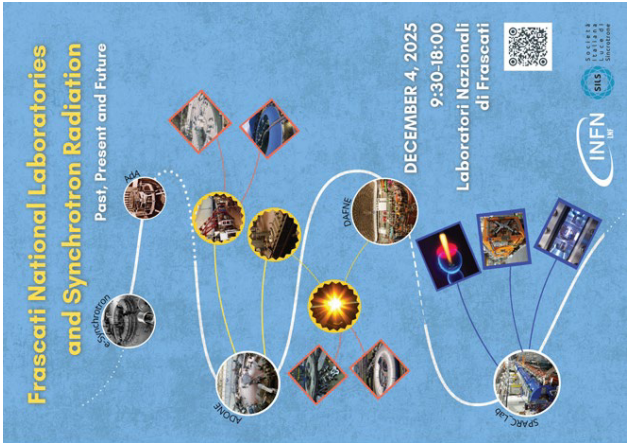


Figure 1: Poster of the workshop "Frascati National Laboratories and Synchrotron Radiation", held at LNF on December 4, 2025.

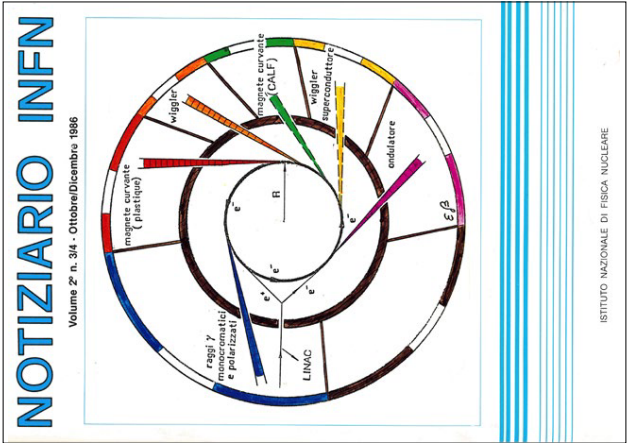


Figure 2: Cover of an INFN report dedicated to the ongoing synchrotron radiation activities at the ADONE electron storage ring in 1986.

S

ince its discovery in 1947, synchrotron radiation (SR) has evolved into a powerful tool for material science and a wide range of scientific disciplines, driven by both the detailed understanding of its properties and the development of dedicated storage rings. Early scientific applications started using synchrotrons, but significant achievements were obtained with the advent of storage rings, later enhanced by the introduction of insertion devices, such as wigglers and undulators, in their straight sections. More recently, free electron lasers (FELs) have further expanded the capabilities of SR-based techniques. Continuous improvements in SR sources, including low-emittance or ultimate storage rings and FELs, have led to a significant increase in the beam brightness. This progress has enabled the development of advanced spectroscopic methods and experimental techniques that were previously unattainable.

Within this global context, the LNF has a long-standing tradition in the use of SR. This activity began in the 1960s with the 1 GeV e-synchrotron and continued with the electron storage rings of the ADONE (operational until 1993) and DAΦNE colliders. In the near future, SR-based research at LNF will further expand with the exploitation of the light produced by the EuPRAXIA@SPARC_LAB free-electron laser (FEL). To emphasize this legacy and its future perspectives, a workshop has been organized on December 4, 2025 (Fig.1), by the DAΦNE-Light group.

Rather than being a purely historical overview, the event aimed to position synchrotron radiation as an important component of the laboratory's future development. The participation of more than 130 attendees, including a considerable number of young researchers, confirmed both the vitality of the field and the relevance of this perspective. The meeting was supported by the INFN-LNF laboratory and sponsored by the Italian Synchrotron Radiation Society (SILS).

Given the importance of LNF for the city of Frascati, the Mayor was invited and delivered her greetings, expressing appreciation to both the organizers and the participants, following the introductory remarks given by the LNF Director.

The successful organization of the workshop^[1] relied on a coordinated effort covering scientific, logistical, and archival aspects, highlighting the importance of preserving and valorizing institutional memory alongside scientific progress. Reconstructing this legacy required a dedicated effort to reconnect with a dispersed scientific community spanning more than six decades. This included contacting former researchers, collecting historical material, conducting interviews, and exploring archival sources such as INFN (Fig. 2) and LNF reports and photographic records. This process itself reflects the continuity of SR activities at Frascati.

The workshop also served as an opportunity to recognize the individuals who shaped this history. Among them, Emilio Burattini, commemorated for his pivotal role, embodies



Figure 3: Emilio Burattini showing X-ray mammography images obtained using the SR beam to journalist Federico Fazzuoli during a RAI UNO television program in 1982.

activities of the laboratory within the broader European and international context. Settimo Mobilio and Enrico Bernieri then illustrated the development of the PULS and PWA facilities, demonstrating how the ADONE electron storage ring was successfully transformed also into a national synchrotron radiation infrastructure serving a wide user community. Recalling some important activities related to Frascati and ADONE, the development of programs for X-ray absorption data analysis, underlying also the role of LNF scientists like Calogero Natoli and Maurizio Benfatto, was presented by Adriano Filippini while Antonio Bianconi gave a talk on the importance of research activities in the biology and life science fields.

The evolution towards more modern synchrotron radiation facilities was addressed by Gianfelice Cinque and Mariangela Cestelli Guidi, who presented the origins and current status of the DAΦNE-Light facility, emphasizing its multidisciplinary applications and its operation alongside the collider activities. Finally, Riccardo Pompili, Stefano Lupi, Federica Stocchi, and Francesco Stellato discussed the activities at SPARC_LAB and outlined the next generation of radiation sources under development at LNF, including novel THz^[10], betatron^[11], and future FEL-based infrastructures^[9].

The long-standing experience in synchrotron radiation at Frascati emerged clearly across these contributions. Giorgio Margaritondo highlighted that the first synchrotron radiation spectra in Europe were recorded at Frascati using the photon beam from the electron synchrotron, an achievement later documented by Pierre Jaegle^[4] and made possible through the collaboration with Yvette Cauchois and her group in Paris with researchers from the Istituto Superiore di Sanità in Rome^[3,4].

This pioneering phase was followed by the realization of AdA (Anello di Accumulazione - the Italian for storage ring), the first electron-positron collider, conceived by Bruno Touschek. Beyond its importance for particle physics, AdA represents a conceptual precursor of modern storage-ring light sources, with the first observation

the continuity of SR development at Frascati, from the electron synchrotron to ADONE and DAΦNE-Light (Fig. 3). More broadly, the event highlighted a community of scientists whose contributions were reference points in the evolution of radiation-based research.

This legacy was further symbolically represented in the workshop materials, such as the metallic key-chains reproducing a storage-ring scheme originally designed by Burattini, linking past developments with present identity.

Through talks and posters dedicated to past and present SR activities, the workshop provided an opportunity to recall and acknowledge many key figures in the field, including Adolfo Savoia, Mario Capozzi, Andrea La Monaca, Gilberto Vlaic, Armando Reale, Raffaele Rinzivillo, and others who made significant contributions.

The scientific program^[2] was designed to explicitly bridge historical milestones with current activities and future developments, highlighting the relevance of synchrotron radiation at Frascati. Contributions spanned from the early pioneering phase of synchrotron radiation in Europe^[3,4], where Frascati played a foundational role, to the development of national user facilities such as PULS^[5] and PWA^[6], and up to the present and future perspectives represented by the DAΦNE-Light facility^[7], the SPARC_LAB^[8] and the EuPRAXIA@SPARC_LAB^[9] infrastructures.

Following the introductory remarks by Roberto Cimino, based in part on material prepared by Antonella Balerna, Giorgio Margaritondo (Fig. 4) opened the scientific session with a lecture on “The birth of synchrotron radiation and the key role of Frascati”, placing the early



Figure 4: Giorgio Margaritondo giving his talk on “The birth of synchrotron radiation and the key role of Frascati” during the workshop.

of synchrotron radiation from a storage ring achieved at Frascati. This approach was further developed with ADONE, whose electron storage ring, after the end of the collider operations, was dedicated also to synchrotron radiation activities, enabling the establishment of the PULS and PWA facilities. These infrastructures supported a large user community between 1978 and 1993, and their scientific output continues to be cited today.

The continuity of SR activities was then ensured by the DAΦNE electron storage ring (0.51 GeV), where the DAΦNE-Light facility operated in parallel with collider activities, primarily in parasitic mode but also in dedicated configurations. Looking ahead, the shutdown of DAΦNE in July 2024 marks not an interruption but a transition towards a new generation of radiation sources. Current efforts are focused on the realization of a THz beamline SABINA^[10] and a betatron radiation source EuAPS^[11] at SPARC_LAB, while the approved Technical Design Report of EuPRAXIA@SPARC_LAB anticipates the

development of FEL-based facilities that will further expand the scientific capabilities of LNF.

In this perspective, synchrotron radiation at Frascati should not be seen as a legacy activity, but rather as an evolving platform that integrates accelerator physics, advanced instrumentation, and multidisciplinary applications, from materials science to cultural heritage and life sciences.

The strong engagement observed during the workshop, particularly among early-career researchers, reflects the ongoing relevance of this field. At the same time, the event provided a unique opportunity for different generations of scientists to reconnect, reinforcing a shared identity and highlighting the strategic importance of light-based techniques also for the future of LNF.

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NEW RESULTSON PL SM W KEFIELD CCELER TION TSP RC_L B

Plasma wakefield acceleration (PWFA) is a technique in which a relativistic electron bunch - the driver - traverses a plasma and displaces plasma electrons, creating a large-amplitude longitudinal electric field (wakefield) in its wake. A trailing witness bunch, correctly timed, is then accelerated by this field. Gradients exceeding GeV/m are achievable, orders of magnitude beyond conventional RF technology. Two recent experimental studies at SPARC_LAB have advanced the state of the art in two complementary directions: the use of laser-generated plasma filaments as a novel plasma source, and the resonant excitation of wakefields using trains of electron bunches.

Beam-Driven cceleration in a Laser-Plasma Filament

Conventional PWFA experiments rely on plasmas generated by high-current electrical discharge through a gas-filled capillary. While effective, discharge-based plasmas suffer from stochastic ignition, substantial energy deposition (~100 mJ per shot for a 3 cm capillary), and are limited to repetition rates of ~100 Hz. The new approach reported in [1] exploits laser filamentation: a femtosecond laser pulse propagating through low-pressure nitrogen gas undergoes self-focusing via the Kerr effect. The result is an extended,

self-guided plasma channel — the filament — without the need for external confinement structures. This technique has been tested at SPARC_LAB, by focusing a 10 mJ, 350 fs pulse from a Ti:Sapphire laser into a 3-cm-long, 2-mm-diameter dielectric capillary filled with nitrogen at a density of 10^{16} cm⁻³. As a result, a filament is created with length ~45 mm, with an rms transverse size of ~70 μm and an on-axis plasma electron density of $\sim 8 \times 10^{14}$ cm⁻³, in excellent agreement with numerical simulations.

To test the beam-driven acceleration in the plasma filament an experiment has been conducted, as shown in Fig. 1. Two electron bunches - a high-charge driver and a low-charge witness - are accelerated to 97 MeV in the RF linac, then co-focused into the capillary by permanent-magnet quadrupoles. Energy spectra measured with a magnetic spectrometer show that, with the laser on, the witness bunch gains $\Delta E^* \approx 8$ MeV, reaching a final energy of 104.5 ± 0.4 MeV. Over the 3 cm plasma length, this corresponds to an average accelerating gradient of ~266 MeV/m. The witness charge and relative energy spread are both preserved.

A key advantage of the filament scheme is its reproducibility. Because the same laser system generates both the electron bunches (via a frequency-doubled beamline) and the plasma filament, the timing between the plasma and the

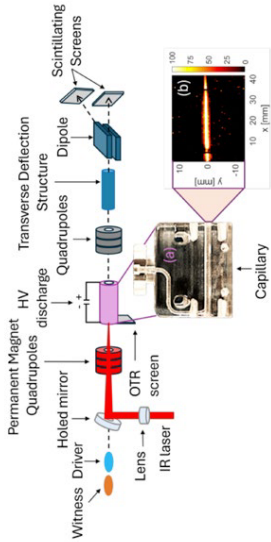


Figure 1. Experimental layout of the SP RC_L B PWF campaign. The IR laser pulse is injected co-axially into the capillary via a lensed mirror, generating the plasma filament ~100 ps before the electron bunches arrive. The inset (b) shows a side-imaging snapshot of the glowing filament.

beam is intrinsically jitter-free. Over 100 consecutive shots, the witness bunch is successfully accelerated in 95% of events with an rms energy jitter below 0.5%. By contrast, a discharge-based plasma source operated under identical beam conditions achieved acceleration in only 75% of events, with an energy jitter of ~1.3% - a factor of three worse (see Fig. 2).

As additional bonus, the energy deposition of the filament laser is only ~2.5 mJ per shot, corresponding to a thermal wall load below 1 mJ/cm² - two orders of magnitude

below damage thresholds. This, combined with the use of a commercially available GW-class laser (rather than a TW-class system required for alternative methods), makes the filament approach compatible with operation at tens of kHz repetition rates.

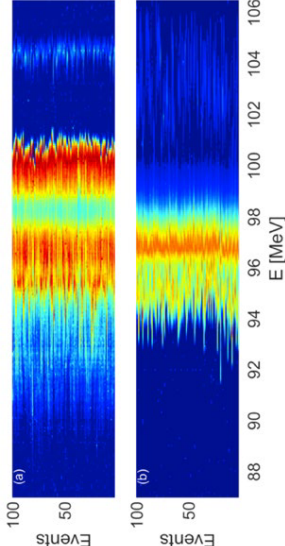
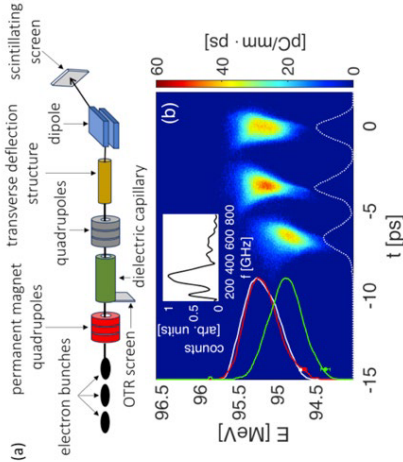


Figure 2. Waterfall plots of 100 consecutive events: (a) filament-based PWF — the witness peak is narrow and consistent across shots; (b) discharge-based PWF — wider, less stable witness distribution. The filament configuration achieves a threefold reduction in energy jitter.

Resonant Excitation of Wakefields with Bunch Trains

The second study [2] investigates how a train of multiple electron bunches, rather than a single driver, can be used to resonantly build up the wakefield amplitude. When successive bunches are separated by an integer multiple of the plasma electron period, each new bunch arrives in the decelerating phase of the wakefields driven by the preceding ones. In this condition, the wakefields add up coherently, and their amplitude grows along the train. This technique is particularly valuable because it allows the use of lower-charge bunches that are easier to handle in a linac, while still achieving large accelerating fields.

The experiment (see Fig. 3) used a train of three bunches accelerated to 95 MeV, separated by ~ 3.3 ps, chosen to match the plasma electron frequency at the target density of $1.3 \times 10^{15} \text{ cm}^{-3}$. As a result, the measured maximum energy loss increases progressively along the train: $\Delta E_{1,2,3} = (0.3, 0.7, 0.9) \pm 0.1$ MeV. The third bunch loses nearly three times the energy it would lose without the preceding drivers, demonstrating that the wakefields driven by each bunch accumulate coherently.



Conclusions and Outlook

Together, these two studies represent significant advances toward practical, high-performance plasma wakefield accelerators. The laser-filament approach demonstrates that plasma stages can be created with high reproducibility, minimal energy deposition, and intrinsic synchronization with the electron beam - removing a major bottleneck for high-repetition-rate operation. The resonant bunch-train technique opens a route to higher energy-transfer efficiency.

Both results are directly relevant to the EuPRAXIA@SPARC_LAB project, which targets a 60-cm plasma stage operating at $\sim 10^{15} \text{ cm}^{-3}$ for driving a free-electron laser at few nanometers wavelengths. The filament plasma generation scheme, scaled with a longer capillary, could provide the required plasma length with dramatically lower wall loading than discharge-based sources. Meanwhile, ramped bunch trains could push the witness energy into the multi-GeV range needed for hard X-ray FEL operation, using the same linac infrastructure already in place at Frascati.

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MAJOR WORKS UNDERWAY AT LNF



On the threshold of its 70th anniversary, which will be celebrated next year, the laboratory is undergoing a major transformation with the construction of new and modern experimental infrastructures. Among these, the most important is undoubtedly the EuPRAXIA@SPARC_LAB facility and the dedicated building complex, which will be constructed on the south side of the laboratory. At the same time, on the northern border, within a recently acquired complex of pre-existing industrial buildings, a new data center dedicated to HPC machines is being completed. This will constitute an important component of the national computing infrastructure, centered in Bologna, dedicated to research and its industrial applications. New research infrastructures require modernization of the service networks, also with a view to greater efficiency and environmental sustainability. In this regard, an important initiative has been the construction of a photovoltaic park that takes advantage of the significant roof space of the laboratory buildings.

EuPR XI @SP RC-Lab building
The EuPRAXIA@SPARC_LAB project requires the construction of new buildings to house the accelerator infrastructure and its beamlines. The new complex will be set in the south-east part of LNF site, partially below a little hill, sitting near the current facilities and offices of the laboratory. The design and authorization phases are now over, and the tender to assign the construction contract is just starting the award process. Construction work is expected to begin at the end of this year.

An architectural rendering of the complex (top view) is shown in Fig.1: it will include a main building to house the accelerator and its services, a secondary building to house a fire-prevention tank, and a large car park with 55 slots for users.



Figure 1: rchitectural rendering (top view) of the EuPR XI @SP RC-L B facilities.

The main building will occupy an area of approximately 5,600 m² and a volume, including open spaces and technical rooms, of almost 50,000 m³. It will consist of two floors above ground with main vehicular and pedestrian accesses from the north-west facade (Fig. 1 bottom) while on south-east facade (Fig. 1 top) only one floor above ground will provide a secondary accesses reserved for maintenance. At

its maximum extension above ground, the building will be approximately 140 m long and 45 m wide, with a narrowing to 36 m towards the north-west; it will end on the ground floor with a rectangular appendix measuring 21 m by 13 m completely underground. A further architectural rendering is shown in Fig. 2, providing a 3D view of the complex, as it will appear from north-west.

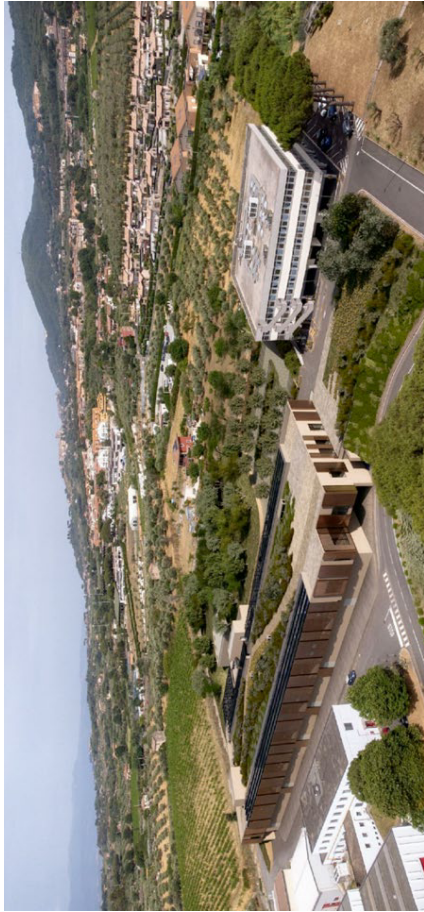
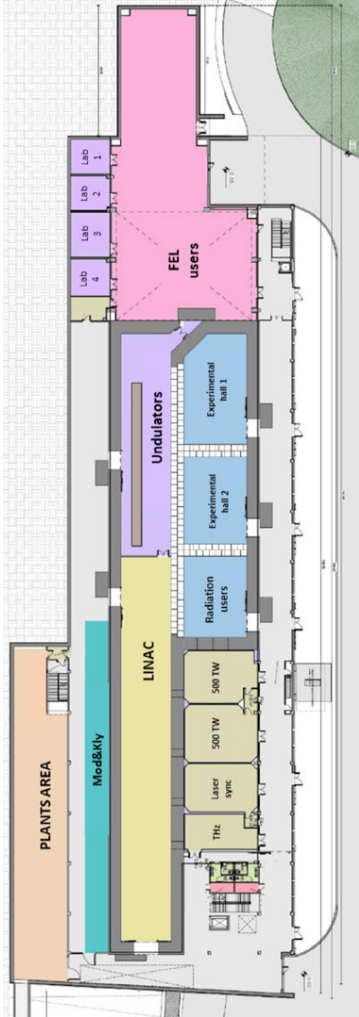


Figure 2: rchitectural rendering (3D view) of the EuPR XI @SP RC-L B facilities, from north-west. On the right, the building housing the INFN central administration (C) is also visible.

On the ground floor (see Fig. 3), the main building will house the linac, the FEL, experimental halls and support laboratories. On the first floor (see Fig. 4) there will be a control room, the racks room, a meeting room, offices and service spaces, which include two Air Handling Unit (AHU) areas.

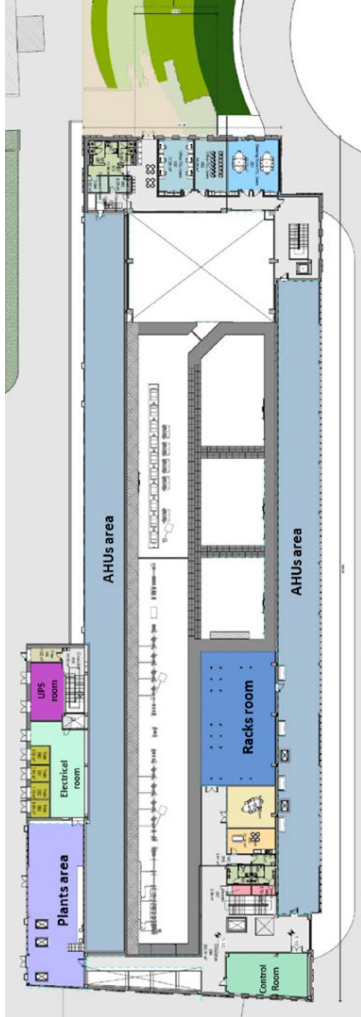
Figure 3: EuPR XI @SP RC-L B main building functional layout - ground floor.



Finally, the secondary building will be a parallelepiped buried on three sides, with a rectangular base of approximately 19 m by 16 m, housing the tanks that will contain the water reserve and the water-fire tank.

The preparatory work for the EuPRAXIA@SPARC_LAB project foresaw the design and implementation of the civil infrastructures for the facility, including the main building layout, utilities, power distribution, HVAC (Heating

Figure 4: EuPR XI @SP RC-L B main building functional layout - first floor.



Ventilation & Air Conditioning) systems, and ancillary infrastructures. Requirements for accelerator operations, radiation protection, and sustainability were met in accordance with the environmental criteria mandated by Italian law.

The final design, delivered at the end of 2022, obtained the formal authorization on May the 30th, 2023, with archaeological and landscape superintendence assent, as well as planning and building permission. The executive

design was completed in January 2025, and it was verified by a certification body accredited in accordance with the UNI CEI EN ISO IEC 17020 standard. The executive design was completed at the end of July 2025 and then validated by the responsible of the tendering process. Finally, in December 2025 the tender for the construction of the new complex was published, with deadline for the bids at the end of March 2026. The construction phase is expected to start at the end of 2026.

Figure 5: The main building of the LNF ICSC Data Center, with the external cooling plant.

The ICSC data center

The LNF "Space Economy" Data Center (DC) is one of the building blocks of the ICSC (Italian Research Center on High-Performance Computing, Big Data and Quantum Computing), a consortium which was funded by the Italian PNRR (National Recovery and Resilience Plan). This new LNF infrastructure, currently being finalised, is designed to host an HPC/HTC farm devoted to scientific computing up to a power consumption of 1.2 MW. Thanks to its flexible configuration, which makes use of both conventional air-cooled servers in high density racks and Direct Liquid Cooling (DLC) devices, the data center is well equipped for future technology applications. The building, hosting the new DC, is part of a new estate at the north border of the laboratory, which has been acquired for this purpose by LNF in 2022 (see Fig. 5).

The DC design incorporates redundancy criteria that reflect both the high availability of the high-voltage power supply and the intended operation of the DC as a farm able to endure occasional (<1 per year) scheduled interruptions. Unexpected interruptions will be managed coordinating gentle-shut-down procedures and UPS (Uninterruptible Power Supply). A dedicated redundant MV substation and distribution system has been built, and an emergency gen set will assure power for critical loads, allowing users to interact with the DC, even during outages.

Up to 36 high density racks can be installed in the implemented hot-aisle configuration, with thermal conditions compliant with 2021 guidelines for data processing environments^[1].

The DC air cooling system is based on the so-called hot-

center successfully supplying about 1 GWh of thermal energy per year for the winter heating of 11 buildings throughout the district heating network at LNF. The new DC will extend and enhance this solution that is now also recommended by the best practice guidelines from EU on data center energy efficiency^[2]. The tender for the executive design and construction of the infrastructure was issued in March 2024, and the contract awarded in February 2025. The construction started at the end of April 2025 under the supervision of the TD personnel, and the hall is now ready for the commissioning of the cooling system, and for hosting the new IT equipment (see Fig. 8).

Figure 6: Data Center rendered model, showing a section of the hall with false floor and rack layout.

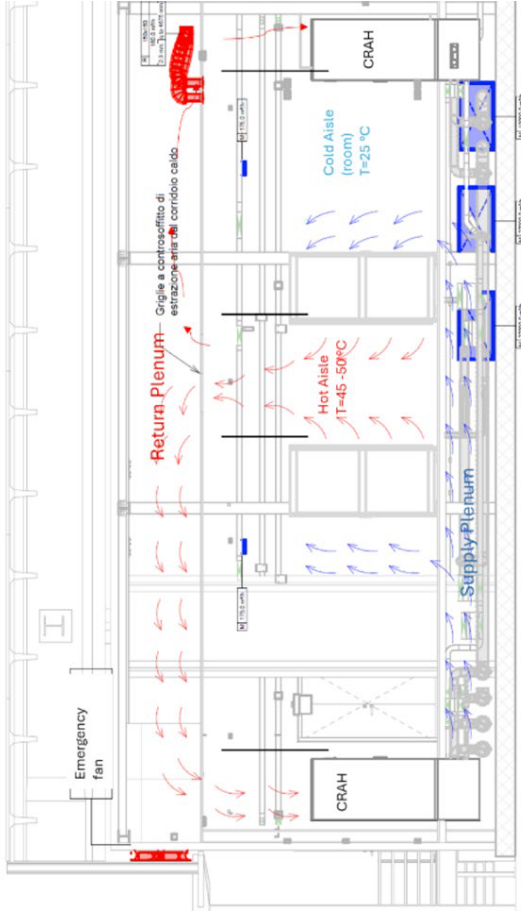


Figure 7: scheme illustrating the principle of the hot aisle rack layout.

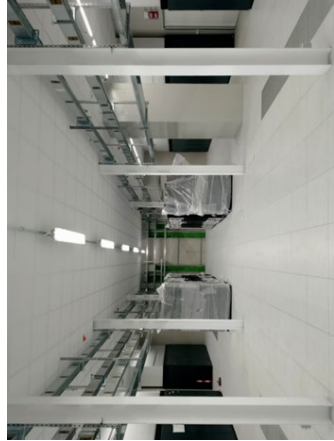


Figure 8: The hall of the new LNF Data Center ready to host IT equipment.

LNF Photovoltaic Park

The idea of a photovoltaic park at LNF dates back to 2017, when a private company submitted a public-private partnership proposal to exploit LNF roofing to house photovoltaic (PV) modules. After further refinement of the proposal by the LNF TD personnel, a tender for concession for private public partnership was issued in July 2022, and a contract was signed in July 2024. The installation of 2380 PV modules, of 465 W each, over the roof of 15 buildings has been successfully completed in July 2025 (Fig. 9 and 10), for a total peak power of the photovoltaic plant of 1.1 MW. Once the authorisation process will be finalised and the photovoltaic plant will enter in operation, within



Figure 9: South view of building 2 with PV modules installed.

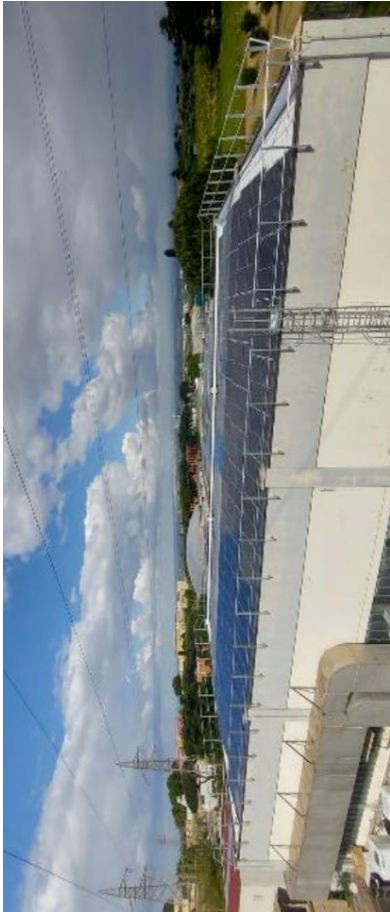


Figure 10: South view of building 7 with PV modules installed.

2026, it will be able to produce 1.3 GWh/y of green power (16% of LNF base load) and will avoid emissions for about 300 tons of CO₂.

This intervention also allowed the renewal of the roofs for 18 LNF buildings. “Cool roof” sheath water proofing and insulation upgrade are going to provide better thermal performances and comfort for about 50% of the LNF buildings.

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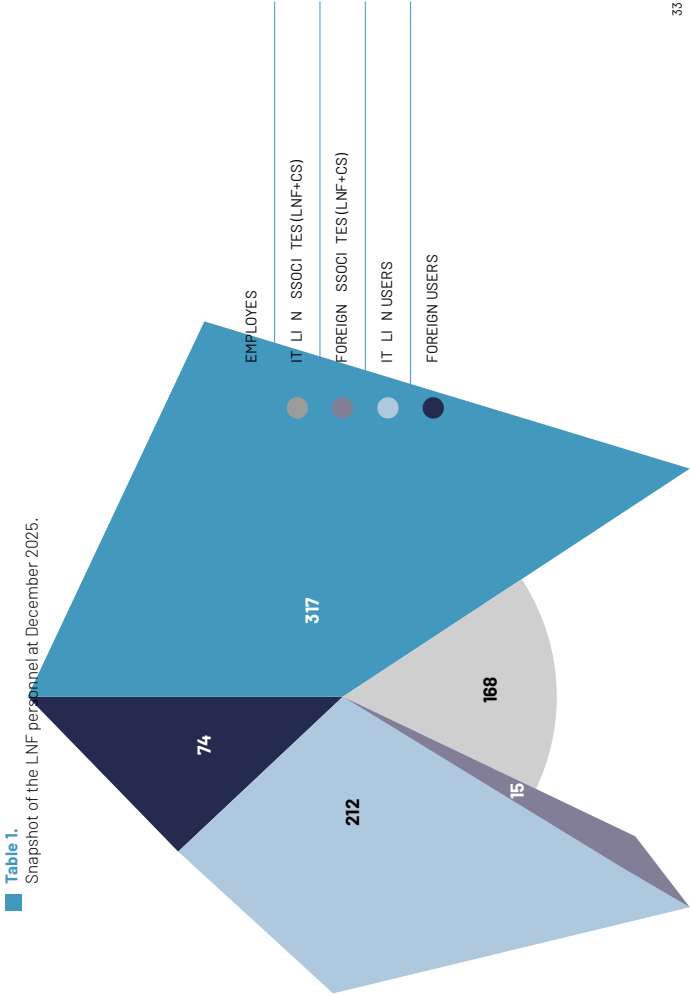
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LNF IN NUMBERS

The LNF personnel, at the end of 2025, consists of 317 units, including 34 with a fixed term contract, plus 183 associate members. Among these, there are university and PhD students, young post-Docs and employees of the LNF personnel among the different profiles.

	ST FF	TEMP.	TOT.
RESE RCHER	65	0	65
ENGINEER	75	20	95
DMINISTR TIVE	44	3	47
TECHNICI N	99	11	110
TOT.	283	34	317

Table 1. Snapshot of the LNF personnel at December 2025.



HIGHLIGHTS

ONE YEAR OF RESEARCH AT LNF

2025



Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati