European Strategy for Particle Physics 2020-2027

Input to the Strategy Process

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Progress in fundamental physics proceeds through a variety of actors to be considered in establishing a European Strategy in Particle Physics. Theoretical, experimental and technological capacity, initiatives in higher education and knowledge dissemination at national laboratories contribute to maintain a cultural diversity across Europe and constitute the network to rely upon, and are at the same time targets to which the Strategy guidance is directed.

This document presents status and plans of the INFN Frascati Laboratory, the largest Italian infrastructure in particle physics. Established in 1954 for the development of particle accelerators, nowadays it offers infrastructures for accelerator physics, particle detectors, interdisciplinary physics studies, and technology transfer. The laboratory hosts small-scale particle and nuclear physics experiments, including searches for low-mass dark matter candidates. Researchers' training during post-graduate and doctoral studies, outreach initiatives to support science education and to increase public awareness of science are actively pursued.

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1 Introduction

In the global vision of the network of European Research Infrastructures (RIs), national laboratories have achieved in the last decade a relevant role as centres providing facilities and specific competences which complement and support large scale projects for accelerators and experiments in particle, nuclear and astroparticle physics. This collaboration scheme has been efficiently tested in several recent scientific European endeavours, such as at the LHC, EU-XFEL, ESS, and ITER.

The grid of resources, in facilities and competences, available throughout Europe's RIs represents a formidable asset. Not only, do they contribute to innovation with a rich variety of technological know-out, potentially transferable to high-tech European industry; they also provide a wide spectrum of activities in fundamental physics. This is of particular relevance when RIs in Europe are confronted with their capabilities to access Horizon Europe funds. Open Access laboratories collaborating with European industry boost the far reaching potential of applied physics research. Moreover, ingenuity of researchers fosters the development of local small-scale experiments, which span over a very large spectrum of questions in fundamental physics, providing the multi-faceted approach which makes vivid and competitive the research communities.

The Frascati Laboratory belongs to this network and is willing to contribute to the preparation of the 2020-2027 Update of the European Strategy for Particle Physics (ESPP 2020) and to its future implementation. This document describes current activities and plans of the Laboratory, focusing on subjects of interest for the Strategy. Three are the main drivers of research at LNF: development of innovative accelerator technologies, operation and upgrades of test facilities, and local experiments for fundamental physics.

Although not addressed here, substantial human and technological LNF resources are devoted to the LHC experiments, for which a plan of contributions to the Phase II detector upgrades is being developed, and to other experiments at CERN, FNAL, JLAB, and KEK. These scientific activities are discussed in the documents prepared for ESPP 2020 by the INFN as part of the global planning of the Institute [1], and by the INFN Scientific National Committees [2] [3].

2 Accelerator Technologies

2.1 High-Gradient Accelerating Structures

The 2013 ESPP called for a "vigorous accelerator R&D program, including high-field magnets and high-gradient accelerating structures ...". This recommendation was directed to support the development of high-frequency, high-gradient RF structures, and furthermore, of Advanced Acceleration Techniques (AAT), including dielectric- and plasma-based structures. Since then, a lot of progress has been achieved in the above mentioned areas, demanding more specific statements in the next ESPP 2020 document.

Recently, LNF activity has been focused on the development of novel accelerating technologies, in collaboration with other European laboratories, with particular emphasis on high gradient conventional X-band RF structures and in plasma-based accelerators, participating in the Horizon 2020 Design Studies CompactLight [4] and EuPRAXIA [5] projects, respectively.

CompactLight aims to design for year 2020 a multi-GeV X-band Linac able to drive a FEL user facility, making use of recent developments achieved by the CLIC group at CERN [6], where the limit of X-band technology has been pushed up to gradients of ~ 120 MV/m with a breakdown rate of 3×10^{-7} pulse^{-1} m^{-1}. Future developments of higher RF frequency structures (e.g. K- or W-band) could pave the way to gradients of 500 MV/m, limited by the electrical breakdown of metal walls in the presence of high electric fields. A collaboration agreement between CERN CLIC Group and LNF for a common R&D program on X-band structures is in place since January 2018; work is in progress to realize a facility for structure tests at Frascati.

Plasma-based accelerators replace the metallic walls of conventional RF structures with a ionized gas, or plasma. This fundamental difference avoids problems with metallic or dielectric structure damage encountered in high-gradient operation. Three major milestones have been recently achieved in experiments on plasma acceleration :
- at BELLA-LBL, electron beams with energy up to 4.2 GeV have been produced from a 9 cm long capillary discharge waveguide with a laser-driven technique [7];
- at FACET-SLAC, an accelerating gradient of about 4.4 GV/m has been demonstrated with high-efficiency energy transfer from the driving bunch wake to the witness one [8], and a substantial number of positrons has been accelerated and guided over a meter-scale plasma [9];
- at AWAKE-CERN, the first electron acceleration up to 2 GeV in a plasma driven by a proton beam has been observed [10].

Wakefield accelerators must demonstrate timing, pointing, intensity, and focusing control that fulfill the demands of high-luminosity operation at future lepton colliders. Single- and multi-bunch plasma instabilities must be overcome with operation at repetition rates of tens of KHz required for high-luminosity machines. These results could qualify plasma-based accelerators as interesting candidates for HEP applications, including a e^+e^- linear collider. A fundamental milestone towards this goal is the development and the integration of high-gradient accelerating plasma modules in a short wavelength Free Electron Laser (FEL) user facility. By the end of 2019 the EuPRAXIA Collaboration will prepare a Conceptual Design Report (CDR) to build the first European RI dedicated to demonstrate the feasibility of plasma accelerators delivering high-brightness beams up to 1-5 GeV for users. In this framework, the EuPRAXIA@SPARC_LAB Collaboration has prepared a detailed CDR [11] to propose the realization of the above outlined FEL infrastructure at the Frascati Laboratory.

2.2 The EuPRAXIA@SPARC_LAB project

Some important preparatory actions are in progress to meet EuPRAXIA requirements: the design of a new building and services with size of about 150 x 30 m^2, to host the EuPRAXIA facility; the design and the necessary R&D to build a 1 GeV X-band RF Linac providing high-quality electron beam, and to install a laser in the 0.5 PW power range as possible drivers of the plasma acceleration; the design of a compact FEL source, equipped with a user beam line at 3 nm wavelength, driven by the high-gradient plasma accelerator module.

The realization of this new facility will enable synergies at LNF between fundamental physics research and high-social-impact applications, especially in the domain of Key Enabling Technologies (KET) and Smart Specialization Strategies (S3), supported by EU research funding programs. In addition, it will allow LNF to accommodate any machine configuration resulting from the forecoming completion of EuPRAXIA Design Study.

LNF is currently engaged in an intense R&D program towards the demonstration of high-quality beam production with plasma modules within an existing dedicated facility. SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Lasers and Beams) is a laboratory operating since 2005 [12], hosting a 150 MeV high-brightness electron beam injector, able to run in the velocity bunching configuration, which feeds a 12 m long undulator. Observations of FEL radiation in the self amplified, seeded and high-order-harmonic generation modes have been performed from 500 nm down to 40 nm wavelengths. A second beam line has been installed and is now hosting a narrow band THz radiation source. In parallel, a 200 TW laser is exploring laser-matter interaction, in particular with regard to laser-plasma acceleration of electrons (and protons) in the self- and external-injection modes. SPARC_LAB will be focused on plasma acceleration development in support of the EuPRAXIA project, considering both beam (PWFA) and laser (LWFA) driven plasma options. In the next 5 years SPARC_LAB will also investigate plasma lens effects, plasma driven FEL experiments and the characterization of plasma targets in various configurations, supported by dedicated numerical and theoretical studies. An intense program on advanced compact diagnostics is also underway.

Compact accelerators with plasma driven modules could become feasible not only for future high-energy linear colliders, but also for industrial and medical applications. The progress in novel accelerators will benefit from strong synergies with general advances in the laser and/or high-gradient RF structures industry, and in short-period high-field undulators. The EuPRAXIA pilot facility is a major milestone in this process. Increased support from the particle physics community could foster R&D, providing important guidance. According to the statement from the European Network for Novel Accelerators (EuroNNAc), high-gradient plasma accelerators should be recognized in the next ESPP 2020 as crucial interdisciplinary R&D for the future of HEP lepton machines.

2.3 Low Energy / High Intensity Linacs and Applied Science

Superconductive (SRF) facilities with pulsed or continuous wave beams with average currents on the order of tenths of mA are the building blocks of high-intensity, low-emittance electron beams, thought to be used in high-energy lepton colliders or in Energy Recovery Linacs. SRF technology nearly excludes the application of these techniques in "small" facilities: factories, hospitals, museums, and universities, which do not provide specific expertise in managing cryogenic plants. Nevertheless, there are several scientific applications for which the highest available average current and brillance of warm RF Linacs are needed.

The R&D goal of a future modular linear accelerator as a test facility is the study of the high-average current/low-emittance regimes and the curing of instabilities. At LNF, the experience in C-band accelerating structures, with high-order-modes dampers developed for the ELI-NP project, can be used to envisage different phases of this program. In a first stage, a variable average current (1-10 μA) is expected with a minimum emittance of 0.5 10^{-6}m rad, working at 5.712

GHz and a repetition frequency of 100 Hz. Later, an upgrade should plan operation at very high-average power, up to 100 μA.

This infrastructure would allow target testing for positron and muon sources, both for very high thermal, and thermo-mechanical stresses, dark-sector experiments with electrons and positrons, tests at very low energy for material science [13], the exploration of a compact resonant axion source by conversion in a magnetic field [14], and use as injector in a high-momentum acceptance compact lepton ring, in a further phase. The yield regime of one available positron per incident electron can be explored with dedicated experiments on positron production, capture, moderation and transport at the low energy Linac driver. High-intensity targets and high-momentum acceptance rings are at present the core of the LEMMA proposal [15] for a future muon source, to which the Laboratory is also providing support in collaboration with several other European Institutes. The corresponding studies are described in a separate INFN input document [2] to ESPP 2020.

Compact radiation sources for X- and γ-rays at high intensity may be used for several other applications (e.g. medical), starting in the X-ray domain using channelling, coherent or parametric radiation, up to the limit of 100 keV, maximizing the flux and the brilliance, attaining $10^{12} - 10^{13}\gamma/\mathrm{s}$. In this regime, the achievable performance of micro Fabry-Perot cavities coupled to the electron beams can be explored, as high flux Compton back-scattering extends the spectrum up to γ energies of 650 keV. The high power delivered would allow the set-up of a compact neutron source with an expected flux of $2\ 10^{11}$ n/s, at an initial beam power of 0.1 kW. Successive extensions could foresee the production of pharmaceutical radioisotopes and fundamental physics experiments, e.g. the neutron EDM measurement. Studies of plasma acceleration in the high-repetition frequency domain, connected with EuPRAXIA development, can be performed testing the plasma characteristics under multiple injections in a short RF period.

This field has been object of several initiatives at European level: LABSYNC (Laboratory Compact Light Sources), the ThomX source at LAL-Orsay, the Munich Compact Light Source (MuCLS), and the Hiradmat source at CERN (with protons). A more coordinated effort in the future in developing technologies for high-intensity electron Linacs would not only open new possibilities for research community, but would also boost knowledge transfer in the corresponding industrial field.

3 Experiments at LNF

3.1 Search for new mediators - The Dark Sector

The interest in dark-photon physics has been growing in recent years, due to the elegant and simple possibility that such a particle could behave as a light mediator between ordinary matter and an arbitrarily rich and almost completely secluded dark sector [16]. The muon $g-2$ anomaly, the hint of a protophobic 17 MeV boson from the radiative internal photon conversion decay of the ^{8}Be nucleus [17], and the cosmic small-scale structures formation, all point to the 10-100 MeV mass range.

The PADME experiment [18] at the LNF Beam Test Facility (BTF) profiting from the high-current electron/positron Linac of DAΦNE, is exploring this possibility thoroughly, using positive identification with the missing-mass technique.

The experiment is mainly limited by the maximum positron beam energy (~ 550 MeV), corresponding to a reach of $M_A \sim 24$ MeV and by the pile-up in the detectors, constraining the intensity to a maximum of ~ 100 particles/ns. In a first phase, 200 ns long bunch pulses would allow $\sim 2 \times 10^{13}$ positrons on target/year to be reached, accessing a range for ϵ, the coupling to the ordinary photon, down to $\sim 10^{-3}$.

The potential of the PADME experiment can be extended, both adding more physics cases and increasing the region of the explored parameter space for the different models, with different levels of complexity and investment. A direct and simple extension of the physics program is implied by the generality of the missing mass technique: any new light particle produced in the electron-positron fixed target annihilation in association with one photon ($e^+e^- \to \gamma + X$) can be very cleanly identified as a bump in the M^2_{miss} distribution or by a peak in the invariant mass of the final states. Both "visible" and "invisible" decays of an axion-like particle (ALP), mainly to $\gamma\gamma$, would produce final states that can be cleanly measured by the PADME experiment in addition to γ + missing mass: $\gamma\gamma\gamma$, $e^+\gamma\gamma$, and $e^+e^-\gamma\gamma$.

Another physics case takes advantage of the resonant behavior of the production cross-section for a dark photon when approaching the exact value of the particle mass [19], either by changing the beam energy and/or exploiting the energy loss in a thick target (the PADME target is $< 0.001X_0$). A significant improvement can be achieved by reducing the pile-up using a quasi-continuous beam, i.e. greatly extending the pulse length at the fixed maximum repetition rate (50 Hz). Longer pulses could be produced de-tuning or by-passing the SLED cavities, thus accelerating at lower energy. This option would provide intensities of tens of nC/pulse, i.e., $\sim 10^{19}$ electrons on target/year, interesting for beam-dump experiments, e.g., aimed at producing dark photons or ALPs by means of a high-intensity electron beam and absorbing the greatest possible fraction of the electromagnetic shower.

Increasing the sensitivity of the current PADME experiment would require an almost continuous positron beam structure: this could be achieved by re-using one of the DAΦNE rings as a stretcher for the Linac pulses with the resonant extraction technique. The POSEYDON proposal [20] would generate 0.2 ms-long positron pulses at ~ 500 MeV energy, extending the sensitivity by a factor $(0.2\ \text{ms}/200\ \text{ns})^{1/2} \sim 30$. Due to the small emittance ($\sim 10^{-6}$ m rad), the positron beam would be an interesting facility for radiation production studies with coherent bremsstrahlung, channeling, and parametric radiation on crystals, for beam testing and irradiation.

A significant experimental program for searching for dark-sector particles with fixed-target electron or positron interactions is currently running or planned in several laboratories in Europe: A1 and APEX at the MAMI-microtron, and the BDX dark-photon-dump experiment at the MESA new high-current machine, at Mainz; a letter of intent has been submitted for the resonant extraction of 5-20 GeV electrons from the SPS ring [21], for a variety of searches (dark photons, millicharges particles, ALPs, etc...) at CERN; a by-pass line of VEPP-3 has been designed for carrying on dark-photon searches, at Novosibirsk. A similar intense experimental interest is ongoing in the US. Therefore, a common approach in the field of fixed target dark matter searches seems to be urgently necessary, and could be catalyzed by the ESPP 2020.

3.2 Search for new mediators - Axions

Well-motivated extensions of the Standard Model of particle physics predict the existence of light particles such as axions or ALPs [22]. These may constitute the long sought dark matter, solving the strong-CP problem and explaining astrophysical anomalies. The last decade witnessed an increasing interest in this field. With the development of new experiments and dedicated laboratories, a global competition is now taking place to explore, in the next decade, the most probable region of the parameter space for QCD axions. In Europe, first generation experiments like PVLAS, CAST, ALPS and OSQAR have already set limits for axions produced in the Sun or directly in the laboratory. A second generation is now in preparation and DESY plans to host three on-site experiments: ALPSII, MADMAX and IAXO. LNF is contributing to the latter, developing new optics based on the use of polycapillary technology. Tapered capillaries with micrometric or submicrometric internal-channel diameter enable efficient X-ray transport to the detector active area, improving IAXO sensitivity.

The R&D of newly proposed experiments AXIOMA, KLASH, QUAX, and STAX, is supported by INFN. Due to the low mass and small coupling of the axion, these experiments require the development or improvement of several technologies. Most of these, such as lasers, vacuum, cryogenics, resonant cavities and strong magnets, are used at Frascati for accelerators and radiation facilities. For instance, KLASH [23] proposes to convert the former KLOE magnet into an axion detector by constructing a large cryogenic resonant cavity, QUAX [24] is investigating HTC superconductors to achieve both high magnetic fields and resonant cavities with a high-quality factor. A new class of detectors, sensitive to excitations of meV or smaller, is needed to exploit this increased axion-search sensitivity.

The recently approved SIMP project, with strong LNF involvement, proposes two solutions for single microwave photon detection: A current-biased Josephson Junction (JJ) and a Transition Edge Sensor (TES). JJ are the basic building blocks of superconducting qubits for quantum processors. Qubit-state readout is intimately connected with single-photon detection. TES are used as bolometers for the measurement of the cosmic microwave background and have proved single-photon sensitivity in the IR regime (e.g. for THz astronomy). SIMP detectors could find application in quantum metrology, quantum key distribution, cultural heritage, homeland security, medical imaging, quality control, and process monitoring.

To achieve maximum impact in the physics of axions and ALPs, a new vision of a roadmap for Weakly Interacting Slim Particles (WISPs), as already done for WIMPS in the past, must be developed, with coordinated efforts among the national laboratories and institutions involved.

4 Facilities for Research, Innovation and Knowledge Transfer

4.1 Beam Test Facility

The Beam Test Facility, currently undergoing a major upgrade to double the beam lines and experimental halls, will continue to serve a large HEP and astroparticle physics community. Test beam facilities will remain key infrastructures for research in high-energy physics detectors, and the use of the new BTF will be extended to industrial and applied physics, e.g. for electron irradiation, low energy photon and electron testing (both mostly interesting for spatial applications), as well as neutron production and detector testing.

4.2 DAΦNE as Open Infrastructure for Accelerator R&D

The conclusion of collider-mode operation by 2020, could make DAΦNE available to the accelerator community. A complex including a Linac, an accumulator, two storage rings for electrons and positrons, and a synchrotron-light laboratory with six beam lines, could be transformed in to a test facility (DAΦNE-TF) open to the international community for studies of accelerator technologies and beam physics, to perform small-scale experiments for both fundamental and applied research, to train highly qualified personnel, and as a technological test-bed for enterprises working in the field. High currents, positron beams, and short bunches represent the main assets of the DAΦNE-TF. Preserving the operation of an electron-positron facility such DAΦNE is crucial to maintain and develop the technical skills today present at LNF. A proposal has been recently submitted for approval to INFN [25].

The lines of technological research identified so far for DAΦNE-TF include studies on low secondary electron yield elements; innovative diagnostics; evaluation of 3D printed elements; high-power solid-state RF amplifiers; adjustable permanent magnets; high-power positron sources and studies of peak energy deposition density in targets; components for future SLED; emittance manipulators; interaction of beams with crystals, lasers, and plasma; and THz coherent radiation production. Most of the topics proposed are of general interest for the community of accelerator physicists, and synergies with the ongoing studies for the future colliders are clearly recognizable.

Expressions of interest have already arisen from informal discussions with groups at INFN, CERN and other foreign laboratories:
- converting the positron ring into a high-duty-cycle positron pulse stretcher [20];
- testing high-positron fluxes on thin targets, to probe new design concepts for a future muon collider (LEMMA proposal [15]);
- operating SRF cavities at high-beam currents for future machines.

A collaboration agreement between LNF and the CERN Vacuum Group, to study the behaviour of vacuum pipe surfaces with DAΦNE synchrotron lines for HE-LHC and FCC colliders, has been in place since September 2017.

The availability throughout Europe of this kind of infrastructure represents a key element for the development of a network of collaborating groups and to guarantee them high-quality access. In turn, a flexible response to the evolving needs of research is a guarantee for sustainability of RIs. Hence offering seamless access to a broad multidisciplinary community is a common goal for European particle physics community at large.

4.3 Technological Transfer

LNF is engaged in technological transfer to promote, coordinate and establish all the initiatives necessary in the field. The LATINO infrastructure (Laboratory in Advanced Technologies for INnOvation), recently funded through a grant from the local government (Regione Lazio), open to small and medium enterprises for medical and industrial applications of accelerator technologies, is an example of this effort. LATINO consists of four integrated facilities, becoming operational by mid 2020, to test accelerating sections and ultra-high-vacuum components, to characterize RF components, for magnet design and field measurements, for thermal treatments, and for mechanical integration.

The collaboration between technological facilities at European laboratories and industry has been seminal for the realization of several scientific projects, like the LHC, EU-XFEL, ESS, and ITER, which have recently projected Europe to a position of worldwide leadership. The LATINO project will increase the quality of the participation of LNF in the AMICI Horizon 2020 Design Study [26], charged to strengthen the capabilities of European companies to compete as qualified suppliers of components for accelerators, large superconductor magnets, and in the development of innovative applications in sectors such as healthcare, security, cultural heritage and space.

5 Training, Outreach and Dissemination of Knowledge

The outreach initiatives carried out at LNF are focused on bridging research and society, supporting science education in schools, informing the public about the latest discoveries, and contributing in community-building within the international particle physics environment. To this end, various activities are addressed to institutions, the scientific community, the general public, teachers and students, both inside and outside of the Laboratory.

LNF has a long-standing experience in organizing training courses for high school teachers: nearly 250 participants from all over Italy attend the courses every year. Hands-on activities in laboratories are the key ingredients of these events. Inspiring young people with the science of particle physics and of accelerators, supporting STEM career orientation, and increasing public awareness of science are the pillars of the LNF outreach programs, which involves every year more than two thousand Italian and foreign students from primary school through high schools, and a total of $\sim 10{,}000$ people on site.

Masterclass are organized in partnership with the IPPOG Masterclasses Project, together with the International Day of Women and Girls in Science, with particular care to promote gender equality in research. Efforts in engage the public include guided tours of the experimental sites and of the newly built LNF Visitor Centre, a yearly Open Day and the public lectures. The involvement of LNF is part of a coordinated effort played by European institutes in building science with and for society, according to the 3Os strategy (*Open innovation, Open science, Open to the world*) identified by the EU Commission.

6 Conclusion

National laboratories play a vital role in particle physics research and innovation, and recent years have seen a strong growth in the number of RIs that are contributing to large European research projects. They must be recognized as long-term strategic investments at all levels, deeply rooted in the particle physics community, and indispensable both for enabling and developing excellence in the European Strategy. They also have an impact on skills and education agendas, increasing the competences of researchers, and students through their outreach activities. They steadily improve the perception and understanding of science and technology in society at large. National laboratories enrich the region where they are located and as such they are important as contributors to technology transfer and to competitiveness. The health of particle physics in Europe also depends on the vitality of these laboratories in the Member States: Systematic collaborations should be reinforced or established, making optimal use of the available infrastructures and human resources. The Frascati Laboratory is willing to be active part of this process.

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