PROCEEDINGS OF SCIENCE

Accelerator Research

B. Auchmann,[a] **G. Bisoffi,**[b] **J. D'Hondt,**[c] **W. Leemans,**[d] **P. McIntosh,**[e] **R. Pattathil,**[e] **D. Schulte,**[f] **Mike Seidel,**[a,g,*] **S. Stapnes,**[f] **A. Stocchi**[h] **and E. Todesco**[f]

[a] *PSI, Switzerland*
[b] *INFN Legnaro, Italy*
[c] *Nikhef, Netherlands*
[d] *DESY, Germany*
[e] *STFC, United Kingdom*
[f] *CERN*
[g] *EPF Lausanne, Switzerland*
[h] *IJCLab, France*

E-mail: mike.seidel@psi.ch

Following a recommendation of the 2020 update of the European Strategy for Particle Physics Update (ESPPU) to intensify the accelerator R&D, the European Accelerator R&D Roadmap with five topical research panels was implemented in 2022. Two of the panels, high field magnets, and high gradient RF structures and systems are technology oriented and their R&D efforts will support several collider concepts. Three panels are developing advanced concepts for a future energy frontier collider facility. These concepts involve specific advancements over classical circular or linear collider concepts, but are associated with higher technical complexity. These include high gradient plasma and laser accelerators, bright muon beams and muon colliders and energy recovery linac (ERL).

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

*Speaker

 ISSN 1824-8039 . Published by SISSA Medialab.

PoS(EPS-HEP2025)032

1. Introduction

The Large Hadron Collider LHC, which was developed and is operated by CERN, represents today the state of the art regarding particle colliders. The concept is based on synchrotrons that accelerate and store the two counter-rotating proton beams. Superconducting magnets based on NbTi technology are used to reach the high energy of 6.8 TeV per beam. Achieving the best possible performance when operating the collider poses a complex optimisation problem for the beam dynamics and technical parameters. Through the continued effort of a large team of experts the luminosity was raised by a significant factor since 2011. The improvements were possible by increasing the beam brightness delivered from the injector chain, and by reducing the beam size at the interaction points (reduction of β^*). So far, more than 400 fb^{-1} of integrated luminosity has been delivered, and the HL-LHC upgrade project aims at a significant increase to 3000 fb^{-1} by 2042. Despite the relatively straightforward ring collider concept of the LHC, the long-term improvement plans and associated efforts demonstrate the complexity of the operation of large colliders. Among many remarkable achievements from a technical perspective, the reliable operation of more than a thousand superconducting magnets is particularly notable.

For future generations of particle colliders various schemes ranging from ring- and linear colliders to advanced concepts are proposed. The European accelerator roadmap [1] covers both, technological R&D but also conceptual developments for future collider facilities. The panels for high field magnets and RF systems address R&D on key technologies that are essential for several collider concepts. The advanced concept of high gradient and plasma acceleration provides a path to reach high particle energies in a compact installation, thus associated with a moderate environmental footprint. The bright muon beams and colliders panel is developing concepts for a muon collider, which will ultimately enable lepton collisions at the 10 TeV scale by exploiting the advantage of muons' higher mass compared to that of electrons. The advantages of both ring and linear colliders will be combined in energy-recovery linacs. Rather than particles, the beam power is recirculated to avoid excessive losses in the form of synchrotron radiation.

2. High-Field Magnets

The High-Field Magnet (HFM) Programme is a directed R&D programme, focused mostly on the FCC-hh accelerator. The baseline foresees 14 T operational field based on Nb_3Sn dipoles at 1.9 K, corresponding to an energy in the c.o.m. of 85-90 TeV. It should be noted that the 1-m-long models of these dipoles should systematically aim at 15.0-15.5 T to prove an adequate margin for scaling in length and operation in an accelerator environment. The road map for Nb_3Sn foresees the downselection of designs by 2028, a short model programme in 2028-2032, and the scaling to 5 m and then to 15-m-long magnets in 2041. Industrialization and 8 years of production brings the commissioning date to 2055. This date could be advanced by 5-10 years by introducing more parallelization and earlier involvement of the industry.

Four options to the above baseline are being studied for low-temperature superconducting magnets in the HFM Programme. They promise enhanced cost efficiency and sustainability in operation. Higher-performance Nb_3Sn wires, if they are not more costly in production, can help reduce the total amount of conductor needed. Also in the context of conductors, the HFM Programme

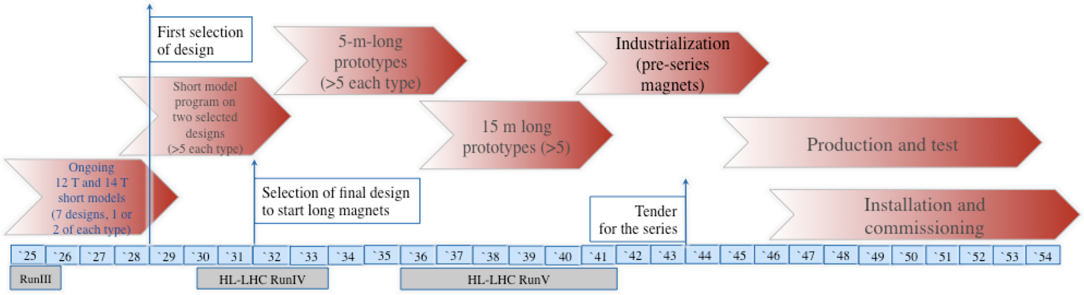

Figure 1: Timeline for the Nb_3Sn high-field magnet development for FCC-hh.

strives to qualify more suppliers for high-performance wires. A 4.5 K operational temperature would help reduce the power consumption of the cryogenic system. HL-LHC Nb_3Sn magnets have systematically shown stable performance at 4.5 K on the test bench. A lower-field and lower-cost option at 12 T field is being investigated, which could provide 73 TeV c.o.m. energy. The option could reduce the amount of conductor by 30%. Lastly, a hybrid Nb_3Sn/Nb-Ti option at 1.9 K could provide substantial cost savings on the conductor for both, the 14 T baseline and the 12 T option.

Five types of designs are today being developed, with first tests in 2026-27, by four national laboratories: CEA, CIEMAT, INFN, and PSI, as well as CERN. Recently, a technology demonstrator built at CERN, based on block coils and a closed cavity, has reached stable operation at 15.75 T flattop, thus proving that an adequate margin is present for operating at 14 T. New ground has been broken for the stress managed structures, following the path indicated by the Magnet Development Program in the US, and a common coil sub-scale model reached 5 T in PSI. A novel protection system (ESC) has also been successfully tested for the first time on a small-scale coil at CERN: this could allow for more efficient magnets with higher current densities.

High Temperature Superconductors (HTS) open the possibility of reaching operational fields at or above 14 T at higher operational temperatures. The technology has been proven for solenoids and the field has gained in momentum by the results in toroidal field coils for fusion with REBCO tape. However, there is no proof of concept based on REBCO to date that demonstrates accelerator requirements, which include a field reproducibility of 10 ppm from injection to collision energy (an energy increase by a factor 15-20). Quench protection, hysteresis losses, and mechanical issues are also posing significant challenges. Vigorous R&D is therefore needed over the coming years to demonstrate how HEP can benefit from the potential benefits of HTS technology.

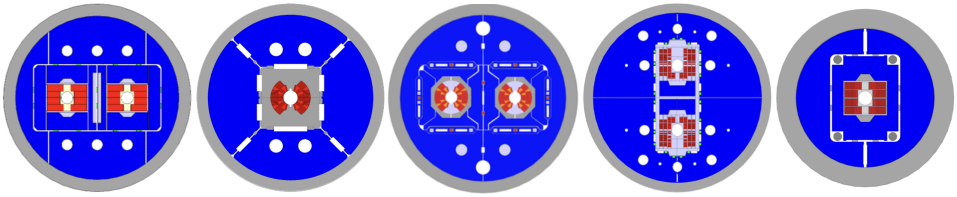

Figure 2: Conceptual design of 14 T and 12 T magnets, developed (from left to right) at CERN, INFN/CERN, PSI, and CEA.

3. High-Gradient RF Structures and Systems

The RF Coordination Panel (RFCP) [2] is evaluating future collider needs in RF performance, focused on several R&D themes. This includes on bulk Nb to increase the cavity quality factor (Qo) and accelerating field (Eacc) to reduce power consumption and accelerator length; SRF thin films, to similarly increase Eacc and Qo, but using higher critical temperature thin films to operate at temperatures > 4 K; high power couplers to efficiently transmit 100s kW into SRF cavities through thin, cooled ceramic windows with minimal power loss; on high-gradient normal-conducting structures, to reliably demonstrate high Eacc to reduce length, capital cost and to improve energy efficiency and overall performance; on high-efficiency amplifiers to improve the electrical power transfer effectiveness, significantly reducing energy consumption; and on low-level RF (LLRF) controls, highly intelligent, fully automated and standardized architectures to stabilise and provide resilient RF control. All of which is anticipated to provide an escalated level of sustainability in terms of increased performance, increased efficiency, and reduced capital and operating costs. The following key achievements have been established by a wide variety of projects and/or R&D community RF activities during this implementation phase: a) for ILC [3] a > 30 MV/m prototype cryomodule, with cavities at Qo >1E10 at 1.3 GHz [4]; b) for LCLS-II a >20 MV/m production cryomodule, with cavities at Qo >3 E10 at 1.3 GHz [5]; c) for SHINE a > 30 MV/m prototype cryomodule, with cavities at Qo > 3E10 at 1.3 GHz [6]; and d) for FCC/PERLE a 22 MV/m prototype cavity with Qo = 3E10 and at 800 MHz (CERN, JLAb, IJCLab) [7]. Improved preparation of copper substrate cavities and the identification of refined high-Tc SRF thin film deposition processes have been demonstrated [8]. First verification of a Ferro-Electric Fast Reactive Tuner (FE-FRT) application at CERN, has shown a reduction of 10 in the RF power needed [9] to maintain Eacc for an SRF cavity. For Normal Conducting RF, 100 MV/m has been achieved for X-band structures [10], at an acceptable break-down rate, with improved cell manufacture benefits being realised. The KlyC design optimisation tool [11] was developed collaboratively by CERN and ULAN. A number of high-efficiency klystrons were also developed i.e. 400 MHz, CW, 350 kW at 70% (prototype) [12], 12 GHz, 50 MW at 65% (design) [13], 650 MHz, CW, 800 kW at 78% (prototype) [14], with klystron industries actively engaged. Commercial availability of digital LLRF systems (uTCA, ATCA, VME and White Rabbit etc.) have increased in industry, providing system-ready solutions for further refined application development. Several ongoing development priorities need to establish appropriate levels of technology readiness for the various HEP facility RF specifications, which include achieving appropriate mitigation of field emission degradation, both at the SRF cavity manufacture and cryomodule integration stage. The global scarcity of bulk-Nb material providers and SRF cavity manufacturers is a serious future constraint, requiring suitable resolution. For SRF thin films, establishing seamless substrate cavity manufacture is a priority, along with having increased access and throughput for SRF cavity test infrastructures, to validate expected iterative performance improvements. The distinct lack of availability for A15 material deposition targets from industry significantly restricts progress. Increased staffing levels are required to achieve performance targets using thin films, as currently these are sub-optimal. Improving the thermal power transfer capability for high purity alumina ceramics, for high power RF coupler transfer to both NC and SRF cavities remains important, with expertise lacking in TiN coating of ceramics being a critical risk.

Having suitable RF/Cryo test stand capability for HTS NC cavity and Muon Collider RF/Solenoid validation [16] is a priority to address for both the Muon Collider (MC) and C3 [17]. With strong industry engagement the innovative Tristron tube-amplifier at 400 MHz [16], with > 90% efficiency predicted, is a development priority for the FCC [19]. For the MC, a more optimum 1 GHz technology solution is needed. Improving efficiency further by reducing the klystron focussing power remains a longer-term aspiration. GaN/SiC amplifiers are required to reach 1 MW pulsed power. The positron linac RF demands for the HALHF [20] accelerator, have high gradient acceleration and high power/efficiency amplifier requirements at S-band frequencies. Widely applied standardisation is needed for LLRF control systems, with long-term support from industry and wider collaboration between different labs. MicroTCA to further spread out as a standard for applicable system integration is required.

Significant progress is evident in various RF areas within specific environments, leading to the development of higher energy (or more compact) accelerators. These innovations not only reduce electrical power consumption but also enhance operational stability, significantly boosting overall scientific productivity. To therefore drive global progress in these critical RF fields, forging stronger collaboration at the European institutional level is imperative.

In the next ESPP Update period, we must channel even more targeted resources to meet the ambitious goals and tight schedules of the proposed future colliders.

4. High-Gradient Plasma and Laser Accelerators

Plasma acceleration offers an innovative pathway to overcome the size and cost limitations of conventional RF accelerators. By utilizing the high electric fields created in plasma waves, particles can be accelerated to high energies over millimeter to meter scales. When an intense laser pulse (LWFA) or a high-energy particle beam (PWFA) travels through the plasma, it excites plasma oscillations, creating a wakefield. This wakefield can trap and accelerate charged particles to extremely high energies. This breakthrough technology opens new opportunities for scientific discovery and technological innovation, including on a longer time scale a plasma-driven lepton linear collider.

In this context, the Hybrid, Asymmetric Linear Higgs Factory (HALHF) concept was proposed in 2023, and its collaboration is currently advancing toward a pre-conceptual design report. The HALHF concept integrates a beam-driven plasma accelerator for electrons with an RF linac for positrons, positioning it as a compelling approach for a next-generation Higgs factory. In parallel, AWAKE has successfully demonstrated the proof-of-principle for proton-driven PWFA, with Run 2 set to focus on controlling electron beam quality and developing scalable plasma sources—both of which are critical for HALHF's future viability. Another plasma-based collider concept that has emerged last year is ALIVE (A Linear accelerator for Very high Energies) which relies on electron and positron acceleration in single stage enabled by energetic and short proton-driven plasma wakefields.

While the collider concepts mature with benchmarking simulations, prototyping and testing concepts, the work in the area will concentrate on applications of plasma accelerators in the near-term, including plasma-based FEL's and Radiation sources for Medical and National Security applications. In the medium term, plasma-based sources could be useful for Particle Physics and

High Energy Physics Applications, including fixed target experiments and injectors for synchrotrons or colliders. In this context, the EuPRAXIA project (European Plasma Research Accelerator with eXcellence In Applications) envisaging plasma-based FEL facilities (both beam and laser-driven) by 2031 and having a laser-Driven 6 GeV Plasma Wakefield Injector for PETRA IV in order to decrease the spatial footprint and power requirements are significant. These projects would showcase the maturity of plasma accelerators as a baseline technology for future facilities.

Significant progress has been achieved across multiple R&D areas in this field. Key PWFA facilities like FLASH_Forward at DESY, SPARC_LAB at LNF, FACET at SLAC, and AWAKE at CERN have achieved significant milestones in beam quality and stability. Notably, on the experimental front, FLASH_Forward has successfully demonstrated emittance and energy spread preservation, SPARC_LAB has observed exponential gain in a plasma-driven FEL experiment, and promising plasma source developments have emerged from CLARA, Oxford University, and SPARC_LAB. The AWAKE experiment at CERN has recently demonstrated proton-driven wakefield acceleration over 10-meter plasma cells, achieving stable acceleration with gradients around 200 MV/m and energy gains approaching 2 GeV. In the LWFA domain, plasma acceleration experiments have demonstrated electron beams with energies near 10 GeV over just a few centimeters of acceleration length, achieving acceleration gradients on the order of 100 GV/m — nearly three orders of magnitude higher than conventional accelerators. Multi-GeV electron beams with energy spreads below 1% and emittance below 1 mm·mrad have been reported and recent works in DESY have demonstrated energy compression below 0.7% for LWFA electrons. Computational advancements have also been made in plasma acceleration simulations, including adaptive grid methods, spin tracking, and GPU-enabled PIC codes. There is significant progress on the development of high repetition rate laser-drivers as well; stable 10 J, 100 Hz pump lasers have been demonstrated at STFC's Central Laser Facility and this technology is being used to develop short-pulse plasma accelerator drivers.

EuPRAXIA is the first European project to design a compact plasma accelerator-based FEL. With the focus on delivering high-brightness electron beams and advancing key technologies like plasma sources, high-repetition rate laser drivers, and beam diagnostics, the EuPRAXIA collaboration will play a crucial role in demonstrating high quality acceleration and validating the feasibility of plasma accelerators for future collider projects. Plasma accelerator facilities such as EuPRAXIA and the Extreme Photonics Applications Centre (EPAC) in STFC, UK are envisioned to have significant impact beyond high-energy physics, including applications in bio-medical imaging, defense & security, and industrial processes. Plasma-driven accelerators promise more compact and cost-effective systems for producing high-quality X-rays and gamma rays, with potential use in next-generation free-electron lasers (FELs) and synchrotron radiation facilities.

Despite remarkable progress, many challenges remain with key demonstrations pending: Achieving low-emittance and high-brightness beams due to plasma instabilities; Controlling the emittance and energy distribution of accelerated particles requires precise tuning of beam and plasma interactions, including damping of plasma instabilities, accelerating positron beams due to specific difficulties in the generation of a proper accelerating and focusing fields in the plasma; scalability towards HEP-relevant energies via staging of multiple GeV-scale plasma accelerators. Several interconnected factors remain to be addressed: maintaining uniform plasma density over long distances, developing stable and high-repetition-rate laser systems, and ensuring consistent

beam focusing and alignment. Advanced plasma channeling techniques, such as capillary discharge waveguides and preformed plasma channels, offer promising solutions by guiding laser pulses and particle beams over extended distances with minimal diffraction. Furthermore, modular staging of multiple plasma cells is being explored to incrementally boost particle energies, though maintaining phase coherence and minimizing energy spread across stages requires sophisticated synchronization and diagnostics. A dedicated staging test is certainly required, possibly in some existing or future facilities like EuPRAXIA.

5. Bright Muon Beams and Muon Colliders

The Muon Beam Panel is advancing the development of the muon collider concept within the framework of the International Muon Collider Collaboration (IMCC). The long-term goal is to build a muon collider around 10 TeV, with an initial stage targeted for completion around 2050. The timeline for the initial stage appears technically feasible, provided sufficient resources can be made available for the R&D and demonstration programme.

The IMCC consists of 61 full-member institutes, alongside several collaborating institutions, and receives co-funding from the European Union. Following the strong recommendation of the Particle Physics Projects Prioritization Panel in late 2023, U.S. institutes have begun ramping up muon collider R&D, with notable contributions to a second detector design and the broader muon collider R&D efforts.

Significant advancements have been made in several key areas of muon collider design. Initial designs for the accumulator and compressor rings have been developed as part of the proton driver systems. A graphite target conceptual design has been completed for muon production. The latest cooling complex achieves emittances in both longitudinal and transverse planes that are twice as good as in previous studies.

In the development of the Rapid Cycling Synchrotrons (RCSs), first lattice designs have been completed, and studies suggest that ILC-type cavities can be used for beam acceleration. A conceptual design has also been developed for a high-efficiency, fast-ramping magnet and power converter system. Meanwhile, the 10 TeV collider ring lattice has been designed to achieve the required beta-functions, though further improvements in energy acceptance are needed.

Detailed detector studies that include also the beam-induced background indicate that the important physics measurements can be performed. Further improvements of the machine detector interface, the detector and the reconstruction methods are ongoing and are expected to remove the residual background impact on the physics.

A systematic method has been established to determine realistic performance expectations for dipoles, solenoids, and quadrupoles across different magnet technologies. This has led to slight refinements in the collider design, with the next critical step being the experimental verification of these magnet designs with prototypes and models.

An initial evaluation suggests that a muon collider could be implemented at CERN. The SPS and LHC tunnels could be repurposed to house the RCS stages, while muon production and cooling facilities could be located at the Prévessin site. A 10 km tunnel would need to be constructed for the collider ring, positioned to mitigate neutrino flux from the straight sections housing the experiments.

All required surface infrastructure could be built on CERN land, with the two experimental sites near CERN.

A bottom-up estimate of the cost scale has been performed, and is based on conceptual designs for muon collider specific components and for other components on scaling from different projects. Also the power consumption has been estimated.

The IMCC has provided comprehensive reports summarizing the status of its studies and outlining a detailed 10-year R&D plan to the European Strategy for Particle Physics update process [15, 16].

The R&D programme demonstrates muon cooling technology through component development, integrated tests, and a dedicated demonstrator facility (with schedule shown in figure 3). It includes construction and testing of superconducting magnets, particularly HTS solenoids, with strong links to societal applications and industrial developments, and model dipoles for the collider ring. A complete start-to-end collider model with refined lattice design, beam physics simulations, and availability studies will guide component choices and luminosity predictions. Target robustness will be verified experimentally. Conceptual and experimental work on superconducting and normal-conducting RF cavities, including tests in high magnetic fields, will optimise design, supported by high-power, high-efficiency klystron development. Demonstration of fast-ramping magnets and power converters for RCS is foreseen. Site and environmental studies will ensure minimal impact, while global optimisation of cost, power, and risk will guide the facility design.

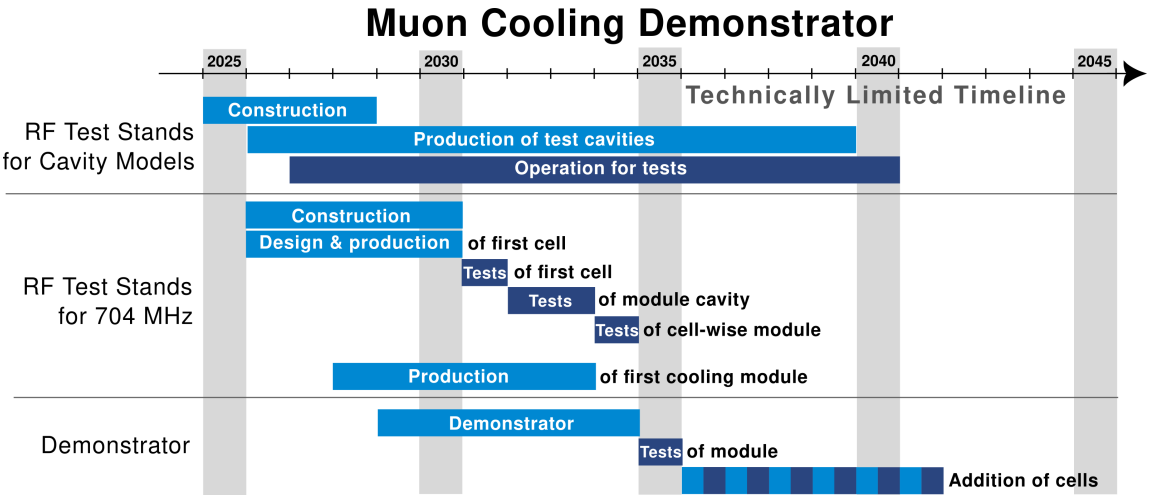

Figure 3: Technically limited timeline for the Muon Cooling Demonstrator programme, including the prerequisite RF R&D.

6. Energy-Recovery Linacs

The Energy Recovery Linac (ERL) technique is being further developed to address the large power requirements of future particle physics colliders, while maintaining their excellent physics performance and aiming to improve the luminosity per unit of grid power [21]. During the past decades, low-power ERLs have been built that are inherently energy-efficient because the RF power transferred to the kinetic energy of the particles during the acceleration phase is recovered during

a deceleration phase when the unused part of particle beam transfers its power back into the RF field. As such, the recovered power is ready to be used for the acceleration of a next particle beam. While not all the power can be recovered, the overall efficiency of the process has been proven to be extremely high. In addition, because the path of the particle beam from the accelerator's injector to the experiment is short, an excellent brightness of the beam develops enhancing the luminosity of a collider. The objective of the ERL R&D Road Map is to demonstrate during this decade the ability of the high-power ERL technique to unlock a portfolio of impactful applications in particle physics. We report on the two main research facilities, central to the development of the high-current SRF-based ERLs:

PERLE at IJCLab is an ERL R&D facility being installed by an international collaboration with the objective to demonstrate the performance of high-power multi-turn ERL during this decade [22]. Since 2024, the electron source is being installed, with commissioning planned for the end of 2025. Meanwhile, the full injector line and the LINAC cryomodule will be installed in the coming years to start the commissioning of a 1-turn ERL facility in 2029 [25], [26] Pending additional budgets, the facility can thereafter be extended to a multi-turn ERL. The timeline for PERLE is shown in Figure 4.

Already in the 1-turn operation mode, PERLE could also become a Test Facility for Future Accelerator and System aimed at improving their energy efficiency and in particular for validating and testing the 800-MHz cryomodules for FCC.

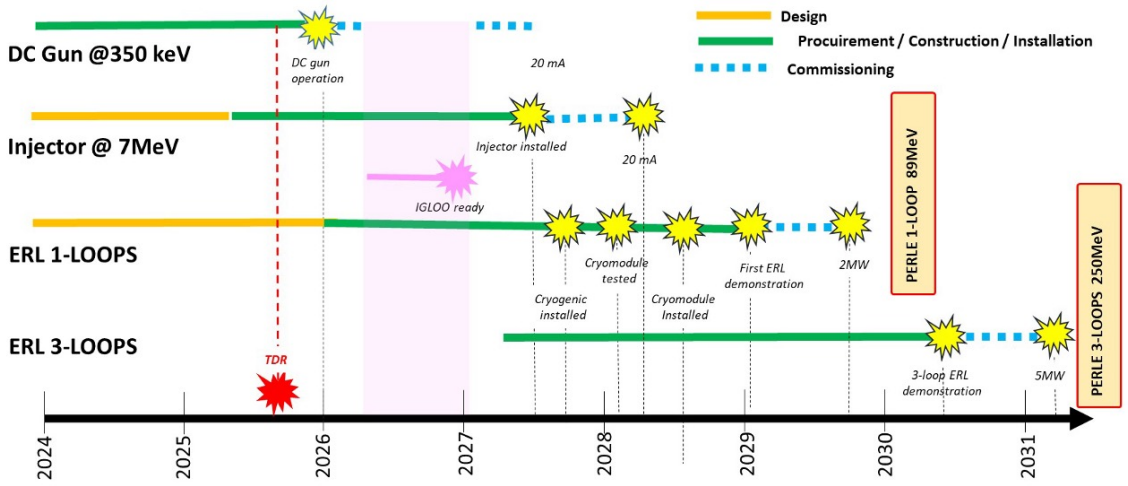

Figure 4: Technically timelines for the PERLE research programme.

bERLinPro at HZB is configured as a high-intensity one-turn ERL demonstrator for high average beam currents up to 100 mA. The superconducting RF photoinjector is installed and is being commissioned now. Pending additional budgets for the LINAC cryomodule, the facility could thereafter be ready to demonstrate the performance of the ERL concept with high-current beams.

The main building block of a modern SRF accelerator is the cryomodule, where grid power is transferred to the kinetic energy of the particles in the beam when traversing the RF fields in the cavities embedded in the cryomodule. Grid power is used for the cryogenic cooling of the

superconducting cavities and for the generation of the RF power required to generate the oscillating field in the cavities. The Horizon Europe supported iSAS project is dedicated to develop, prototype and test energy-saving technologies for SRF accelerators that have the largest leverage to minimize the intrinsic energy consumption [23]. The focus is on energy-saving technologies from the RF power, from the cryogenics and from energy recovery sides.

Based on the ERL technology, a full conceptual design for the LHeC (and FCC-eh) [24] has been made for a three-turn, energy-recovery racetrack structure to enable TeV-energy electron-proton collisions at unprecedented luminosity enabling a competitive and complementary Higgs, EW/top, QCD and BSM physics programme based on CERN's intense hadron beams (HL-LHC and FCC-hh). The timeline to demonstrate the ERL technology with PERLE, as a prototype of the LHeC, matches with the LHeC technical implementation timeline to become operational immediately after the HL-LHC programme. Embedding the ERL technology in the design of future ERL e^+e^- colliders has the potential to significantly enhance their physics potential.

7. Conclusion and Outlook

The accelerator roadmap comprises five R&D panels. Two of them cover technologies: a program for High Field Magnet (HFM) developments for a future hadron collider, and one on RF systems including RF sources, superconducting and normal conducting accelerator structures. Achieving the 10 TeV parton collision center of mass scale is a visionary goal for the future development of particle physics research. A proton-proton collider with $O(100)$ TeV CM presents the most straightforward path to this energy scale today. The high field magnet program with parallel routes of high temperature- and low temperature superconductors presents a very important investment to achieve performance, cost efficiency, energy efficiency and the overall feasibility of a future hadron collider. The second core ingredient for any particle collider are RF systems. Also in this area developments are needed to achieve high performance and energy efficiency, which ultimately contributes to acceptable overall grid power consumption of an accelerator based research infrastructure. The other three R&D programs are covering advanced concepts: plasma wakefield acceleration, muon colliders and energy recovery linacs. These concepts have potential advantages over the classical collider concepts, but they are associated with a need for significant R&D as well as with increased complexity. Launched in 2022 the first phase of the roadmap will conclude in 2026. The Accelerator Road Map R&D Programme will be refreshed and aligned with European particle physics strategic decisions from 2026 onwards. A first step is a roadmap workshop, planned for February 2026.

References

[1] European Strategy for Particle Physics - Accelerator R&D Roadmap, N. Mounet (ed.), CERN Yellow Reports: Monographs, CERN-2022-001, Geneva, 2022. https://doi.org/10.23731/CYRM-2022-001

[2] Report to LDG and CERN Council by the RF Coordination Panel, https://ldg-rfcp.com/downloads/CERN-Council-Report-THE%20COMMON%20DOCUMENT-1.0.pdf

[3] Specification, Design, Production and Test Schedule of Cryomodule for SRF 5-year Plan (MEXT-ATD) at KEK by Global Collaboration for ILC Technology Network, Y.Yamamoto, SRF25, Tokyo, Oct 2025, to be published.

[4] Stable Beam Operation at 33 MV/m in STF-2 Cryomodules at KEK, Y.Yamamoto et al, SRF21, East Lansing, USA, Sept 2021, pp. 382 – 386.

[5] LCLS-II-HE verification cryomodule high gradient performance and quench behavior, S. Posen et al, arXiv:2110.14580, Oct 2021.

[6] Ultra-high quality factor and ultra-high accelerating gradient achievements in a 1.3 GHz continuous wave cryomodule, J. Chen et al, NUCL SCI TECH 36, 25 (2025), Jan 2025.

[7] Towards the first high-Q treatments for the FCC 800 MHz 5-cell elliptical cavities, K. McGee, IPAC24, Taipei, Jun 2024, WEPS25.

[8] Test of thin-film samples, O. Kugeler et al, IFAST D9.6, DOI 10.5281/zenodo.14905672, Feb 2025.

[9] Ferroelectric Fast Reactive Tuner (FE-FRT) to Combat Microphonics', N. Shipman et al, IPAC21, Virtual, May 2021, pp. 1305 – 1310.

[10] The Compact Linear e+e- Collider (CLIC), arXiv:2503.24168 [physics.acc-ph], Mar 2025.

[11] KlyC. The 1D/1.5D large signal computer code for the Klystron simulations. User Manual. Version 6. (included CGUN for the 2D electron beam optics simulation), C.Jinchi et al, CERN-ACC-2022-0008 ; CLIC-Note-1177, May 2022.

[12] Klystron Prototype Completed and Validated, N. Catalan-Lasheras, IFAST D11.2, DOI 10.5281/zenodo.15322728, Apr 2024.

[13] CERN and Canon Demonstrate Efficient Klystron, CERN Courier, Sept 2022.

[14] Design and High-Power Test of 800-kW UHF Klystron for CEPC, O. Zhao et al, DOI: 10.1088/1674-1056/ac6b26, 2022.

[15] The Muon Collider: Input to the European Strategy for Particle Physics 2025: https://indico.cern.ch/event/1439855/contributions/6461618/

[16] The Muon Collider, arXiv:2504.21417 [physics.acc-ph], Apr 2025.

[17] E. Nanni et al, 2023 JINST 18 P09040, Sept 2023.

[18] Powering Into the Future, I. Syratchev et al, CERN Courier, May 2025.

[19] Future Circular Collider Conceptual Design Report – Vol 2, CERN-ACC-2018-0057, Dec 2018.

[20] Updated Baseline Design for HALHF: the Hybrid, Asymmetric, Linear Higgs Factory, C. Lindstrom et al arXiv:2505.21654 [physics.acc-ph], May 2025.

[21] The Development of Energy-Recovery Linacs, arXiv:2207.02095v2, Sept 2022.

[22] PERLE: Powerful energy recovery linac for experiments (CDR), J.Phys.G 45 (2018) 6, 065003.

[23] Website iSAS project: isas.ijclab.in2p3.fr

[24] The Large Hadron–Electron Collider at the HL-LHC, J.Phys.G 48 (2021) 11, 110501.

[25] Kaabi W., Stocchi A., PERLE: A novel facility for ERL development and applications in multi-turn configuration and high-power regime, Acta Phys. Pol. B Proc. Suppl. 16 (2023).

[26] Bogacz S.A., André K.D.J., Brüning O., Holzer B.J., Hounsell B.R., Klein M., Militsyn B.L., Williams P.H., Segurana G. Pérez, Bailey I., Apsimon R., Setiniyaz S., Abukeshek R., Barbagallo C., Abdillah M. Ben, Bruni C., Duchesne P., Duthil P., Fomin A., Guyot C., Kaabi W., Michaud J., Olry G., Perrot L., Reynet D., Roux R., Stocchi A., Wurth S., Abualrob H., Baylac M., Bouly F., Jacquot B., Beam dynamics driven design of powerful energy recovery linac for experiments, Phys. Rev. Accel. Beams 27 (2024) 031603.