

THE EUROPEAN RESEARCH ROADMAP ON CONCEPTS AND TECHNOLOGIES FOR ACCELERATORS

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Abstract

The European accelerator R&D Roadmap for the European Strategy for Particle Physics Update (ESPPU) outlines the path towards future large-scale particle physics facilities, involving five R&D panels. Two of them cover technologies: a program for High Field Magnet (HFM) developments, and one on RF systems including RF sources and variants of s.c. and n.c. structures. The other three 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. This presentation will motivate the different research topics, describe the progress made in implementing these, the successes achieved and the priority activities proposed, which will form the basis of the future R&D programme.

INTRODUCTION

The 2020 update of the European Strategy for Particle Physics (ESPP) called for the creation of a roadmap for accelerator R&D across five key R&D themes over the next five–ten years. These topics include two technology panels: high-field magnets and advanced radiofrequency (RF) structures and systems. Three panels cover advanced concepts for colliders, namely plasma acceleration, bright muon beams and colliders, and energy-recovery linear accelerators (linacs). The Roadmap was prepared under the guidance of the LDG, and an implementation plan for the period 2022–2026 was approved by the Council in March 2022. A comprehensive description of the original roadmap plans is published in [1].

In addition, the LDG inaugurated a sixth coordination panel in 2024, charged with assessing the environmental sustainability of particle colliders.

The accelerator R&D activities are primarily aimed at developing a future collider facility for particle physics research. Many synergies exist to create benefit also for other accelerator applications like intensity frontier facilities, light- or neutron sources.

This report describes the R&D activities of the accelerator roadmap in a concise way, including references to more detailed publications by the individual panels. A recent review paper on the accelerator roadmap is found under [2].

LDG R&D COORDINATION PANELS

High-Field Magnets

The High-Field Magnet (HFM) Programme is a directed R&D programme, focused mostly on the FCC-hh accelerator. The baseline envisages a 14 T operational field based on Nb₃Sn dipoles at 1.9 K, corresponding to a centre-of-mass energy of 85–90 TeV. The roadmap for Nb₃Sn foresees the down-selection 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. Five types of designs are today being developed, with first tests in 2026–2027, by four national laboratories: CEA, CIEMAT, INFN and PSI, as well as CERN.

High-temperature superconductors (HTS) open up the possibility of reaching operational fields at or above 14 T at higher operational temperatures. With HTS magnets it is still a challenge to demonstrate accelerator requirements, which include a field reproducibility of 10 ppm from injection to collision energy (an energy increase by a factor of 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 high-energy physics (HEP) can benefit from the potential benefits of HTS technology. The achievements and status of the HFM panel's work are described in detail in a submission to the ESPP [3].

High-Gradient RF Structures and Systems

The RF Coordination Panel (RFCP) is evaluating future collider needs in RF performance, focused on several R&D themes. These include: bulk Nb resonators to increase the cavity quality factor (Q_o) and accelerating field (E_{acc}) to reduce power consumption and accelerator length; SRF thin films, similarly to increase E_{acc} and Q_o, 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; high-gradient normal-conducting structures, to reliably demonstrate high E_{acc} to reduce length and capital cost and to improve energy efficiency and overall performance; high-efficiency amplifiers to improve the electrical power transfer effectiveness, significantly reducing energy consumption; and low-level RF (LLRF) controls, highly intelligent architectures to stabilise and provide resilient RF control. All of this is anticipated to provide an escalated level of sustainability in terms of increased performance, increased efficiency and reduced capital and operating costs. The achievements and status of the panel's work are described in a submission to the ESPP [4].

Plasma Acceleration

Plasma acceleration offers an innovative pathway to overcome the size and cost limitations of conventional RF accelerators. Particles can be accelerated to high energies over millimetre to metre scales. In this context, the Hybrid Asymmetric Linear Higgs Factory (HALHF) concept was proposed in 2023. It integrates a beam-driven plasma accelerator for electrons with an RF linac for positrons, positioning it for a next-generation Higgs factory. A report on HALHF was submitted to the ESPP [5]. In parallel, AWAKE [6] has successfully demonstrated the proof-of-principle for proton-driven plasma wakefield acceleration (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. Other key facilities include FLASH Forward at DESY, SPARC LAB at LNF, FACET at SLAC and CLARA at Oxford University. Significant milestones have been achieved in beam quality and stability. EuPRAXIA (European Plasma Research Accelerator with Excellence in Applications) [7] is the first European project to design a compact plasma accelerator-based free-electron laser. It is envisaged that EuPRAXIA and the UK Science and Technology Facilities Council (STFC)’s Extreme Photonics Applications Centre (EPAC) will have significant impact beyond high-energy physics, including applications in biomedical imaging, defence and security, and industrial processes.

Bright Muon Beams and Colliders

The Muon Beam Panel’s long-term aim is to build a muon collider of around 10 TeV, with an initial stage targeted for completion around 2050. The International Muon Collider Collaboration (IMCC) consists of 58 full-member institutes. Significant advancements have been made in several key areas, including accumulator and compressor rings as part of the proton driver systems, while a graphite target conceptual design has been completed and the latest cooling complex achieves twofold smaller emittances in longitudinal and transverse planes than in previous studies. In the development of the Rapid Cycling Synchrotrons (RCSs), the first lattice designs have been completed. A conceptual design has also been developed for a high-efficiency, fast-ramping magnet and power converter system. The 10-TeV collider ring lattice has been designed to achieve the required beta-functions, though further improvements in energy acceptance are needed. Realistic performance expectations for dipoles, solenoids and quadrupoles across different magnet technologies have been established, with the next critical step being the experimental verification of these magnet designs with prototypes and models. The status of and plans for the muon collider study have been submitted to the ESPP [8, 9].

Energy-Recovery Linac (ERL)

The energy-recovery linac (ERL) technique is being further developed to address the significant power requirements of future particle physics colliders while maintaining high physics performance. Instead of recirculating the

particle beam itself, the ERL concept recovers the beam power of the spent beam for acceleration of the next beam, thereby avoiding the losses from synchrotron radiation in a ring. The LHeC high-intensity electron ring is one proposed application of the concept [10]. The objective of the ERL R&D Roadmap is to demonstrate during this decade the ability of the high-power ERL technique to unlock a portfolio of impactful applications in particle physics. PERLE at IJCLab is an ERL R&D facility being installed by an international collaboration with the objective of demonstrating the performance of high-power multi-turn ERLs during this decade. 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. Pending additional budgets, the facility could thereafter be extended to a multi-turn ERL. A report on PERLE, a demonstrator facility for a future collider, has been submitted to the ESPP [11].

Panel for Sustainable Colliders

The panel was mandated by the LDG to draw up a framework with guidelines and key parameters for assessing the sustainability of future particle physics projects. The working group, established in 2024, has prepared a report that targets future accelerators – although much of the work will be of relevance for other current or future research infrastructures. The panel’s work addresses several topics, ranging from socioeconomic impact to the life-cycle assessment (LCA) methodology, and from impact categories to mitigation and compensation measures.

Collider projects should perform LCAs at each project stage to understand the most critical elements in the design, provide input for technological choices reducing environmental impact and fulfil requirements for project submission. Coordinated efforts to obtain a common database and shared results on the materials and components of future accelerators are strategic for establishing a framework for project accountability. A list of parameters has been developed, which are relevant for greenhouse gas emissions, to be reported for the construction and operation of future accelerators. An energy management system (EnMS), as defined by ISO 50001, is expected to be implemented, with the development of a policy for the efficient use of energy. Finally, sustainability assessment involves the evaluation of mitigation and compensation measures such as the use of greener materials and procedures for civil engineering works, responsible procurement and electricity, the implementation of systems for heat recovery and supply, investment in R&D for green accelerator technologies and nature-based interventions. The panel published a comprehensive report [12].

OUTLOOK

The European Strategy for Particle Physics 2026 recommended the electron positron collider FCC-ee as the next large infrastructure. The development of several technologies and concepts for particle colliders was highlighted,

including high-field magnets, s.c. RF technology and energy efficient RF sources. The demonstration of high-current multi-turn energy recovery in linacs constitutes an important step towards power-efficient lepton accelerators. Furthermore it was recommended to develop advanced concepts like high gradient plasma acceleration and technologies underpinning bright muon beams at appropriate level.

In line with these recommendations the priorities for the LDG accelerator roadmap will be updated during 2026. Technologies for FCC will receive high priority. One area of focus is R&D into superconducting technologies, including s.c. RF with higher performance and lower cryogenic losses, and high-field magnets, including those using high-temperature superconductors. Research into advanced concepts such as ERL, plasma acceleration and the development of a muon collider will continue as well.

A new mandate for the coordination panel on sustainable colliders was worked out by an LDG subcommittee. Key elements of the mandate include fostering networking and coordination between CERN and the LDG laboratories in this area and developing a set of best practices to improve the sustainability of research infrastructures' accelerators with ranked priorities.

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