

Preliminary report of the ESG WG2a on Project Assessment

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The overall assessment of the Large-Scale Projects is based on the information made available by the proponents either in their formal submissions to the 2026 update of the European Strategy for Particle Physics (ESPP) or in their replies to our questions and, in some cases, during dedicated discussions with them. It refers therefore to the present status of the respective projects. Below we summarize briefly the preliminary key findings for the projects in alphabetical order.

CLIC

The Compact Linear Collider (CLIC) offers a relatively economic approach to realising a lepton collider at c.o.m. energies up to the TeV scale. The CLIC design has been pursued for several decades and is mature: a Conceptual Design Report (CDR) was completed in 2012, a Project Implementation Plan was released in 2018, and a further update was made in 2025; hence the scope is well defined. Proof of principle of the main accelerating technology components has been demonstrated at CTF3 and high-power X-band RF test facilities. The required next steps include a larger-scale demonstration of the two-beam acceleration technology comprising at least 10 CLIC RF modules (an accelerating length of order 25 m), as well as progress towards industrialisation of the components. An R&D plan is specified by the proponents requiring an estimated 100 MCHF and 570 FTEy for the next 8 years (not including an extended test facility), the nominal start of the construction phase. However, funding has been and still is limited, and a significant increase in resources would be required to complete an engineering design on this timescale, in particular when including an extended test facility. The performance is well predicted by start-to-end simulations developed over many years but some risks remain to be addressed via R&D. A site in the Geneva basin has been evaluated, with no known geological show-stoppers for a facility of up to c. 50 km in length (corresponding to 3 TeV c.o.m. energy); a 29.5 km tunnel has been studied in more detail, corresponding to 1.5 TeV c.o.m. energy for which only one drive beam is required. Further detailed site investigations are required in order to optimise and confirm the placement of the tunnels and surface facilities. The schedule is well understood although questions remain concerning the timescale for completing the R&D and advancing the industrialisation of the key technologies, as well as demonstrating the two-beam acceleration scheme at a larger scale. A detailed Work Breakdown Structure (WBS) forms the basis for the cost estimate and its uncertainty – the uncertainty could be reduced with further R&D. A solid assessment of the main risks has been made and the next step would be to prepare a formal risk management plan.

FCC-ee

The Future Circular electron-positron Collider (FCC-ee) design has been advanced beyond the 2019 CDR via the Feasibility Study, completed in early 2025. The project scope is well defined and the next major step would be preparation of a Technical Design Report (TDR). The remaining R&D required is well specified and funding for a pre-TDR phase has been identified in the CERN Medium Term Plan (MTP). No large-scale test facility is required. The performance is reliably predicted by simulations and experience from previous and currently-operating circular e+e- colliders. Extensive site preparation studies have been performed and further geological investigations are in progress to consolidate the tunnel placement. The schedule is credible although there are risks of delay due to both the complexities associated with realising such a large project in the Geneva region and risks inherent in a large construction project. A detailed WBS forms the basis for the cost estimate and its uncertainty, which has been extensively reviewed and found to be sound for this stage of the project preparation. A detailed risk assessment and risk management plan has been prepared and is regularly updated and reviewed. The FCC Feasibility Study has been reviewed by expert committees, the CERN Council and its subordinate bodies. Recommendations were made after the mid-term review and implemented in the final report.

FCC-hh

The hadron-hadron FCC (FCC-hh) considered as the second phase of an 'integrated project', after FCC-ee construction, has a well-defined baseline scope based on Nb₃Sn dipole magnets with a target operating field of 14 T and c.o.m. energy of 85 TeV. The development of suitable prototype magnets is a very active area of R&D but is not expected to converge towards an industrialisable design for at least 15-20 years. The alternative High Temperature Superconductor (HTS) approach is also actively pursued but currently appears to be on a roughly 10-year longer timescale, with higher risk at this stage. FCC-hh benefits from the site preparation work done for FCC-ee. The cost has been estimated and has a large uncertainty which is dominated by the uncertainty on the dipole magnet cost. The overall schedule and risks are dominated by the progress towards reaching industrialisable dipole magnets.

If FCC-hh were considered as a standalone project to be realised in a timely fashion, the risks and uncertainties associated with civil engineering would largely carry over from the assessment made for FCC-ee. The main additional risks in cost and schedule would arise from the dipole development, which would be based on the lower-risk Nb₃Sn technology. An alternative approach would be to target a slightly reduced centre-of-mass energy with ~12 T dipoles, representing a possibly lower-cost pathway.

LCF

The Linear Collider Facility (LCF) is based on the mature 1.3 GHz bulk-Nb Superconducting RF (SRF) technology, already in operation at EU-XFEL and LCLS-II. The project's WBS is complete and detailed enough to support translation into engineering designs for most systems. The specified SRF cavities' operating gradient and quality factor and their combination, not yet demonstrated in operation, is the subject of an R&D programme. Should this programme, contrary to expectations, fail to achieve its objectives, alternative solutions and their associated costs are already defined and fall within the assessed project uncertainties (for the 250 GeV c.o.m. energy scenario). Among the facility subsystems, the

polarized positron source, beam dump, and modulators suitable for tunnel installation currently have the lowest Technology Readiness Levels (TRLs). Validation studies for the Final Focus System (FFS) will require continued operation and upgrades of the ATF2 test facility at KEK. The proposed R&D programme requires 185 MCHF and 750 FTEy to conclude the optimisation of the SRF technology and to reach the level of an engineering design for all sub-systems, however its funding situation is presently unclear. Detailed start-to-end simulations support the estimated luminosity target, which is considered realistically achievable. The main uncertainty (estimated to be less than a factor of three) arises primarily from the performance of the challenging positron source, especially for the intensity and luminosity upgrade scenarios. The design choice of installing the modulators in the same tunnel as the main linac to limit the extent of civil engineering (CE) work might have implications for accessibility and hence the collider uptime. Territorial implementation studies, including more detailed geological investigations, are necessary and considered as part of a possible preparation phase. The construction schedule is considered credible, given the maturity of the SRF technology. Nonetheless, the project start depends on funding availability for the R&D and preparation phases. The presented cost estimate and associated uncertainties result from a comprehensive cost update exercise conducted for the International Linear Collider (ILC). The CE costs, reassessed for the CERN site and informed by experience from CLIC and FCC-ee, carry the largest uncertainty (Class 4). A formal risk management plan for the construction phase is not yet available, however a thorough analysis of the major risks has been conducted and mitigation strategies defined.

LEP3

The Large Electron Positron Collider 3 (LEP3) design for an electron-positron collider in the LEP/LHC tunnel is a pre-conceptual study, based primarily on extrapolations from earlier preliminary investigations and from the FCC-ee studies. As such, its scope remains only partly defined and cannot yet be translated into a complete engineering design. While CERN and the global accelerator community have extensive experience with colliding-beam facilities based on conventional storage ring technology, providing moderate confidence in the overall feasibility of LEP3, the absence of a detailed lattice design and full-scale simulations introduces significant uncertainty. This uncertainty affects the projections for the peak luminosity (by up to a factor 10), the time to reach it, and the expected power consumption. Further definition of the project scope will be essential to refine and prioritize the associated R&D programme and establish a more concrete timeline, which are currently only outlined. The resources required to complete a conceptual design study are expected to amount to 25 MCHF and 40 FTEy, while the effort needed to progress to a full engineering design can only be determined once the conceptual design is complete. At present the proposed baseline HTS nested quadrupoles/sextupoles represent the lowest TRL components and their successful demonstration will be critical for achieving the desired performance, in terms of both luminosity and power efficiency. No major test facilities are expected to be required to validate the feasibility of the project which can build upon the experience from past and operating electron-positron colliders. Reusing the LHC tunnel and situating the injectors on the Prévessin site offer the advantage of minimizing territorial implementation studies. However, these choices may also introduce schedule uncertainties, particularly related to the dismantling and disposal of LHC/HL-LHC equipment (especially components with high radiation levels such as collimators, dumps, and experimental insertion devices) as well as the current lack of a detailed WBS. In addition, dismantling the LHC and reusing its tunnel may affect future options

for reusing the LHC as an injector for the FCC-hh. A formal risk management plan for the construction phase has not yet been established, though some major risks have been identified and potential mitigation measures outlined.

LHeC

The Large Hadron electron Collider (LHeC) design has been developed over the past decade and is now at an advanced conceptual stage. However, only a high-level WBS has been produced so far, and the transition to a full engineering design is currently envisageable only for certain accelerator subsystems. The LHeC's performance critically depends on a three-pass, very-high-current Energy Recovery Linac (ERL) operating with extremely low beam losses (at the ppm level or below) and at beam power levels exceeding by at least three orders of magnitude those achieved to date. This ambitious operational regime explains the presently low TRL and the consequent need for a demonstrator facility. The PERLE demonstrator is currently under construction. The resources required for its completion amount to 46 MEUR and 328 FTEy, of which 12.5 MEUR and 77 FTEy are still unfunded. The absence of secured financing for the full programme introduces uncertainty in the R&D timeline. The current plan foresees tests at up to 40% of the nominal LHeC beam current. However, these tests will not address the impact of electron beam disruption at the Interaction Point (IP), arising from collisions with the high-brightness, high-rigidity LHC beam, on beam losses in the ERL or on the energy recovery efficiency. In the absence of energy recovery, the electron beam intensity would need to be substantially reduced, resulting in at least an order-of-magnitude decrease in luminosity compared with the proposed value of $2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, which corresponds to a 50 mA electron beam current. The novel beam-dynamics regime foreseen for such a collider may also lead to a significant performance ramp-up period. Implementation of the LHeC will require the construction of a new tunnel ($\frac{1}{3}$ of the LHC circumference) tangential to the existing LHC tunnel and sharing a common Insertion Region (IR) (currently IR2). While the territorial implementation work is expected to be modest, potential interference between CE works and HL-LHC operations could affect the overall schedule. In any case, the LHeC project timeline can only be reliably established following the successful completion of the PERLE programme. A rather detailed cost estimate was prepared in 2018 and benchmarked against comparable accelerator projects. This estimate has not yet been reviewed and has been extrapolated to 2024 values considering the European Union (EU) domestic Producer Price Index (PPI) and the EUR/CHF exchange rate evolution. At present, no formal risk management plan exists for the construction phase, although some key risks have been identified. The construction and operation of the PERLE demonstrator serve as one of the principal risk mitigation measures for the overall project. The resources needed for a complete engineering design of the LHeC can only be defined once PERLE's results are available.

MC

Among the large-scale collider proposals submitted to the ESPP2026, the Muon Collider (MC), together with the FCC-hh, promises a potentially energy-efficient path toward high-luminosity collisions at a parton centre-of-momentum energy of 10 TeV. However, the MC has not yet reached the level of maturity of the other proposals. At present, the MC initiative focuses on assessing the key technological and operational challenges of a MC in preparation for a possible conceptual design study. Consequently, only a preliminary WBS has been developed, and the project scope is not yet sufficiently well defined to support translation into

an engineering design. The technologies underpinning the MC design are in the early phases of exploration. A comprehensive R&D roadmap has been developed with the 6D-cooling demonstration facility as its cornerstone. 300 MCHF and 1800 FTEy over ten years (320 MCHF and 2700 FTEy including the experiments) represent the absolute minimum investment necessary to achieve the R&D programme. The recent Laboratory Directors Group (LDG) Accelerator R&D Roadmap review has recommended an independent evaluation of the R&D scope and the resources required. Without such an R&D effort, none of the key open questions or potential showstoppers associated with a multi-TeV muon collider can be credibly resolved. Realistic performance, schedule and cost estimates for a Muon Collider are not conceivable at this stage and before the results of the proposed R&D plan become available. Among the risks identified, the ionizing radiation generated at distance by the large neutrino flux resulting from muon decays is an issue and potential showstopper that needs to be addressed for any selected location and in particular for those close to populated areas as the CERN site.