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Future Colliders Comparative Evaluation Working Group

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Abstract

In anticipation of the completion of the High-Luminosity Large Hadron Collider (HL-LHC) programme by the end of 2041, CERN is preparing to launch a new major facility in the mid-2040s. According to the 2020 update of the European Strategy for Particle Physics (ESPP), the highest-priority next collider is an electron–positron Higgs factory, followed in the longer term by a hadron–hadron collider at the highest achievable energy.

The CERN directorate established a Future Colliders Comparative Evaluation working group in June 2023. This group brings together project leaders and domain experts to conduct a consistent evaluation of the Future Circular Collider (FCC) and alternative scenarios based on shared assumptions and standardized criteria.

This report presents a comparative evaluation of proposed future collider projects submitted as input for the Update of the European Strategy for Particle Physics. These proposals are compared considering main performance parameters, environmental impact and sustainability, technical maturity, cost of construction and operation, required human resources, and realistic implementation timelines.

An overview of the international collider projects within a similar timeframe, notably the CEPC in China and the ILC in Japan is also presented, as well as a short review of the status and prospects of new accelerator techniques.

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Executive summary

The 2020 update of the European Strategy for Particle Physics (ESPP) identified the construction of an electron–positron Higgs factory, designed to study the Higgs boson with high precision, as the highest priority next collider. In the longer term, Europe should aim at a hadron collider at the highest achievable energy. In response to these strategic objectives, CERN has consolidated its future accelerator programme around several key initiatives:

– The Future Circular Collider (FCC) integrated programme, which has published a detailed feasibility study.
– The Compact Linear Collider (CLIC), which has progressed in the development of its radio-frequency (RF) technology, now deployed in various applications, and has published a readiness report.
– The Muon Collider (MC) study, supported by international collaborations including the International Muon Collider Collaboration (IMCC) and the EU-funded MuCol Consortium, which is investigating the potential of this novel approach.
– Participation in a wide-ranging European accelerator R&D programme, targeting technologies such as High Field Magnet (HFM), Plasma Wakefield Accelerator (PWFA) (via the Advanced Proton Driven Plasma Wakefield Acceleration Experiment—AWAKE), Superconducting radio-frequency (SRF) systems, and to a lesser extent Energy Recovery Linacs (ERLs). The accelerator R&D programme has recently undergone a mid-term international review.

In addition, the International Linear Collider (ILC) remains under discussion in Japan, although progress toward the implementation phase is limited. A proposal of a Linear Collider Facility (LCF) at CERN, building on the ILC design, has been recently developed.

CERN aims to be in a position to begin operating a new collider, by the second half of the 2040s, to follow timely after the completion of the High-Luminosity LHC (HL-LHC) programme, planned to be completed by the end of 2041. To meet this timeline, key decisions and initial resource commitments must occur between 2028 and 2030.

Given the differing levels of maturity across various proposals, this report aims to present a comparative evaluation of collider projects that could realistically be operational by 2045–2050. Projects that are unlikely to meet that timeline are discussed separately, along with advanced concepts and options to reuse the LHC tunnel. The information presented here is based on the content of the proposals submitted to the Update of the European Strategy for Particle Physics (ESPPU) 2026.

The following main criteria have been considered for the comparative evaluation of the proposals (CLIC, FCC-ee and LCF) for *first phase* e^+e^- colliders at CERN and are described in Section 2:

– main parameters and performance;
– environmental aspects;
– technical readiness;
– accelerator and experiments construction and installation: material costs;
– accelerator construction and installation: human resources;
– project timeline;
– operation: material and personnel costs.

Although the proposed e^+e^- colliders will not use existing CERN accelerators as injectors, their implementation relies heavily on CERN's expertise, institutional framework and in particular on its existing infrastructure providing access to key resources such as electrical power, cryogenics, technical workshops, water, communication and transport networks and making it a very well adapted host site.

CERN has a consolidated experience with circular colliders and has successfully operated the Large Electron Positron (collider) (LEP). Multi-ampere e^+e^- beams have been demonstrated at the Positron Electron Project II (PEP–II) and KEK B-factory (KEKB). The prospected luminosity targets for FCC-ee are challenging, particularly for the operation at the Z-pole, but they will benefit of the experience gained at DAΦNE with crab-waist operation, the ongoing performance ramp-up of SuperKEKB, which will demonstrate nearly all the required accelerator physics techniques for FCC-ee, as will the future electron ring for the Electron–Ion Collider (EIC) at Brookhaven National Laboratory (BNL). Differently from Linear Colliders (LCs), energy loss due to synchrotron radiation limits the maximum energy realistically achievable by circular colliders to the $t\bar{t}$ threshold. Circular colliders can naturally accommodate a larger number of Interaction Points (IPs) and their larger repetition rate (determined by the revolution frequency in the kHz range) allow them to provide significantly higher integrated luminosities per unit of energy consumption than LCs up to energies of 300 to 350 GeV (see Fig. ES.1). It is worth noting the significant improvement expected in the integrated luminosity per unit of electricity consumption for future circular colliders as compared to their predecessors, LEP and LEP2. In addition, FCC-ee offers the capability of varying the collision energy between 90 and 240 GeV seamlessly and at unparalleled luminosity. This flexibility is reduced after the upgrade for operation at the highest energy and operation at lower energy will be possible, albeit at lower luminosity.

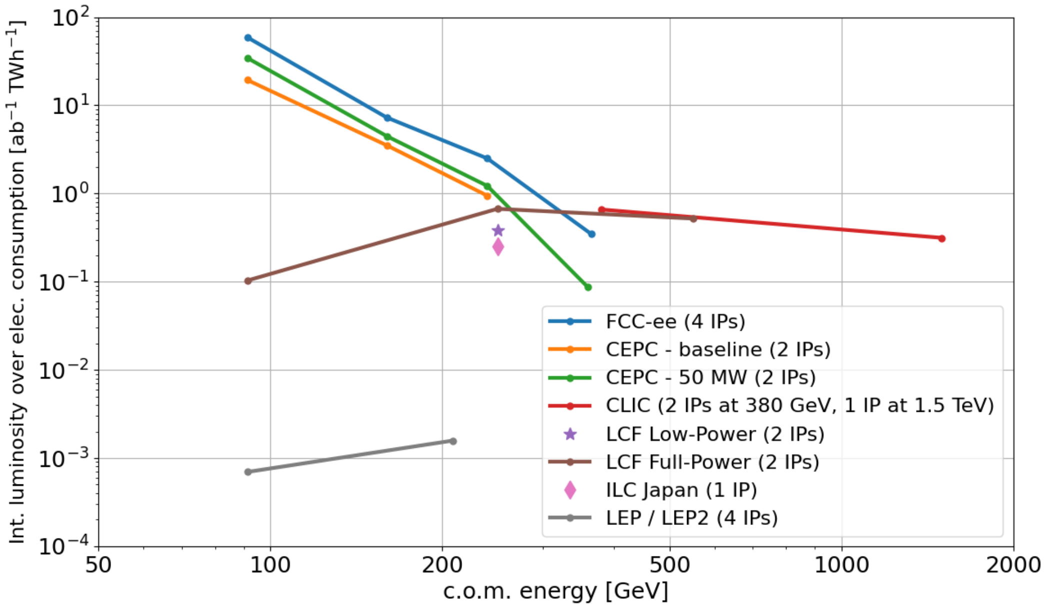

Fig. ES.1: Integrated luminosity over all experiments per year of nominal operation, per unit of electricity consumption for future electron-positron colliders (excluding off-line computing)—see Tables 3.1, 4.1 and 7.1; the performance has been rescaled to the FCC-ee operational year for CEPC and to LCF 250 Low-Power (LP) for the ILC (see Table A.1). For LCs the total luminosity (including that below 99% of the nominal c.o.m. energy) is considered. LEP and LEP2 data were respectively taken for the years 1993 and 2000 [1–3]. For the ILC, a single IP is considered but with two experiments (in "push-pull" mode, see Section 7.1). The information for LEP3 has not been added at this stage.

In their baseline design LCs can deliver polarized beams (both beams for LCF and only the electron beam for CLIC). The luminosity performance of LCs relies on high positron production rates, the capability to preserve the emittance of the beams delivered by the damping rings all through the main linac and the Beam Delivery System (BDS) and to minimize the chromatic aberrations resulting from the extremely small optics waist at the IP. This implies achieving an excellent control of the wakefields in the accelerator and of the optics at the final focus to maintain in collision beams with nanometer beam sizes at the IP in a reproducible fashion, demanding advanced feed-forward systems to minimize the effects of ground motion and temperature variations. The control of optics aberrations, the tuning algorithms and the stabilization against ground motion and temperature variation have been studied at the Accelerator Test Facility (ATF) at KEK in Japan, the Final-Focus Test Beam (FFTB) and the Facility for Advanced Accelerator Experimental Tests (FACET) at SLAC in the US, though additional R&D is required. In order to achieve high luminosity LCs must be operated in the high-beamstrahlung regime resulting in a rather broad luminosity spectrum as a function of the centre-of-mass (c.o.m.) collision energy $\sqrt{s}$. The main parameters and performance of the e^+e^-colliders proposed at CERN and based on the same operational scenario defined in Section 2.1.1 are listed in Table 3.1.

A preliminary analysis of the carbon footprint of the construction of the new collider facilities has been performed, though it is still affected by significant uncertainties given the relatively early phase of the projects and the uncertainty in the evolution of the process of decarbonisation of the energy and commodities market in the next two decades. Nevertheless the analysis has evidenced that the major contributions to Greenhouse Gas (GHG) emissions are associated with the construction of the components of the accelerators and detectors and their technical infrastructure, followed by the Civil Engineering (CE) works. The emissions associated to the generation of the electricity required for operation are lower, thanks to the low carbon intensity of the electricity generated in France, from where the electricity powering CERN facilities is purchased. The possible re-use of the CE infrastructure for future upgrades can further benefit the sustainability of the projects. The estimated annual electricity consumption of the collider, its experiments (including their local data centres) and associated injector complex (excluding the other CERN accelerators) amounts to approximately 0.8 TW h/y for CLIC and LCF LP and varies between 1.2 and 1.9 TW h/y for FCC-ee depending on the c.o.m. energy. These values should be compared with the present CERN annual electricity consumption of about 1.3 TW h/y of which approximately 0.7 TW h/y are necessary to operate the LHC collider and its experiments (injector complex excluded). HL-LHC operation will demand additional 0.1 TW h/y.

The technical readiness of CLIC, FCC-ee and LCF are comparable, though LCF benefits of the developments and industrialization effort conducted for the 1.3 GHz Superconducting radio-frequency (SRF) cavities for the DESY European X-Ray Free-Electron Laser Facility (EU-XFEL) and SLAC Linac Coherent Light Source II (LCLS–II) projects and therefore has an overall higher Technology Readiness Level (TRL) as compared to the other two proposals. Though significant progress has been made in the stabilization algorithms and in the start-to-end simulations, IP spot size control and pulse-to-pulse beam position stability remain the main challenges for LCs.

The cost estimates for the three projects (see Tables 3.7, 3.8 and 3.9) have a different level of uncertainty. FCC-ee has generally a more accurate cost estimate (at class 3 for civil engineering, accelerators and associated technical infrastructure) thanks to the higher level of detail achieved, in particular for the civil engineering and the territorial implementation as the placement scenario has been fully defined. In addition, this estimate has been extensively reviewed by CERN governing bodies. Civil engineering is the major contributor to the higher cost of FCC-ee. The cost of CLIC baseline is the lowest but any considered future upgrade requires additional CE works.

The personnel required for the construction of the projects (not including contractor personnel and the personnel required for Hardware—HW—and beam commissioning) ranges between 10 000 and 15 000 Full-Time-Equivalent-years (FTEy). The most labour-intensive activities related to the accelerator installation, as well as HW and beam commissioning, will only be able to occur towards the end and after completion of the HL-LHC programme.

Following the recommendations of the ESPPU 2020, a detailed feasibility study for the implementation of FCC in two stages has been successfully completed and a detailed timeline for the construction established. The CLIC project and, in particular the LCF project, would require a preparation phase with a corresponding investment of resources to reach a level of implementation details comparable to that of the FCC feasibility study. This phase, if successful, should be followed by an implementation preparation phase requiring Council approval and by a construction phase whose timeline should be coherent, in terms of resources, with the HL-LHC programme.

An estimate of the resources (material and personnel) required for operation of the collider accelerator complex (including technical infrastructure), and of the technical infrastructure of the experiments has been made (see Table 3.12). The resources needed for the operation of the rest of the accelerator complex (e.g. the PS and SPS complex), its technical infrastructure and the technical and scientist support for the experimental detectors and computing are excluded. The lowest requirements are for CLIC baseline option but in all cases they are comparable to those required for the operation of LHC though the expected electricity costs will be higher for FCC-ee, but for a higher integrated luminosity.

The CLIC and LCF proposals contemplate two experiments sharing the luminosity delivered by the main linac and the same experimental cavern, while four experiments (each located in a different experimental cavern) are served simultaneously in FCC-ee and therefore they could engage a larger experimental community, estimated at approximately 3500 FTEy (2/3 of which are scientists) per experiment.

After approximately 10 years of operation it is proposed to increase the energy of CLIC and LCF to 1.5 TeV and 550 GeV, respectively, essentially using the same technology. For CLIC significant CE work will be required to increase the length of the tunnel from 12.1 to 29.6 km and additional higher-gradient accelerating modules will have to be installed. The length of the Beam Delivery System (BDS) also needs to be increased and new magnets installed. No additional CE work will be necessary for the LCF energy upgrade as the length of the collider tunnel has been defined for the c.o.m. energy of 550 GeV assuming nominal parameters for the SRF cryomodules. The bulk of the upgrade work will consist in installation of additional cryomodules. The expected cost breakdown of the proposed upgrades for the LCs is presented in Tables 4.2 and 4.3.

In the FCC "integrated programme" the e^+e^-collider would be replaced by a proton-proton collider (FCC-hh) after approximately 15 years of operation. FCC-hh will be installed in the same tunnel of FCC-ee, sharing much of its CE and Technical Infrastructure (TI), and it would operate at a c.o.m. energy of at least 85 TeV, extending the physics discovery potential by an order of magnitude in the 10 TeV parton center-of-momentum (pCM) energy range. The FCC-hh baseline assumes 14 T magnets which are close to the state of the art of Nb_3Sn technology. R&D towards HTS magnets is pursued and could enable higher collision energies.

As a second phase after FCC-ee, FCC-hh could start operation in the mid of the 2070s. On a technically-limited timescale, FCC-hh, as a stand-alone project with 14 T Nb_3Sn dipoles, could start operation in the mid of the 2050s. The availability of resources will drive the real schedule. The cost breakdown of the construction of FCC-hh as a second phase after FCC-ee is shown in Table 5.3.

The Muon Collider (MC) has also the ambition to approach the 10 TeV pCM. Two conceptual scenarios with a maximum c.o.m. energy of 7.6 TeV have been developed for CERN. The MC injectors would be installed in SPS and LHC tunnels. One or two additional tunnels would need to be built for the installation of the collider serving two IPs. While progress is being made, the MC has not yet reached a maturity level that gives sufficient confidence in its feasibility. Significant investments in a staged R&D programme requiring conspicuous demonstration facilities are necessary to reach that level. Namely, a demonstration of 6D cooling is a necessary condition to assess the feasibility and performance of a MC. The technical design of the demonstrator and its construction demand an amount of resources significantly exceeding the present level of R&D resources. A detailed timeline cannot be defined at present but only sketched with some decision points. Given the uncertainty on the feasibility, the construction and installation costs (see Fig. 6.2) are only indicative.

The possibility to reuse the LHC tunnel to host an e^+e^-collider was proposed for the first time in 2012 and recently revived in preparation of the ESPPU 2026. This proposal envisions a collider operating between 91.2 and 230 GeV with two IPs. The main parameters, listed in Table 8.1 (column

LEP3 - 2025), are based on scaling from earlier conceptual designs and assume the use of FCC-ee SRF systems. The collider would require a booster installed in the same tunnel to provide top-up injection and operate at a maximum intensity corresponding to a synchrotron radiation power loss of 50 MW per beam as for FCC-ee. A detailed design of the lattice, magnet system specifications as well as integration of the collider and booster and the associated accelerator and technical systems in the LHC tunnel (whose diameter is limited to 3.8 m in the arcs and 4.4 m in the Long Straight Section—LSS) will need to be produced. Extensive studies would be necessary to bring the level of maturity of this proposal to a level at least comparable to that of the other e^+e^-collider projects above considered. The electricity consumption prospected by the proponents is comparable to that of FCC-ee at the lowest energy and we can expect that the resources required to operate LEP3 will be similar to those necessary for the LHC operation, though with a prospected lower performance by an order of magnitude as compared to FCC-ee in terms of integrated luminosity per year of nominal operation. As a result, the reduced initial CApital EXpenditure (CAPEX) might be, at least partly, offset by higher operation costs in order to achieve similar integrated luminosities as FCC-ee over the full programme. In addition it will not be possible to run LEP3 at the $t\bar{t}$ threshold.

Among the initiatives considering the re-use of the LHC, the Large Hadron-electron Collider (LHeC) would collide a 50 GeV electron beam, accelerated by a new 3-turn high-current ERL, with a proton or ion beam from HL-LHC producing collisions at a c.o.m. energy of 1.18 TeV in the LHC IP2, where the ALICE experiment is located. The ERL would require the construction of a new tunnel with a length corresponding to 1/3 the circumference of the LHC. The main parameters of this machine are listed in Table 8.3. The annual electricity consumption of the LHeC would be approximately 1.1 TW h/y (excluding the electricity consumption of the LHC injectors complex). High-current multi-turn energy recovery still needs to be demonstrated for beam powers exceeding 1 MW (well below the nominal LHeC beam power of 2.5 GW). The approval of LHeC could only occur after such a demonstration is successful. The completion of the construction of LHeC can only be realistically envisaged after the end of the HL-LHC programme. The resources required for its operation would be comparable to those necessary for the present operation of LHC and its injectors implying a delay of at least a decade in the construction of a next-generation flagship collider.

The parameters of the High-Energy Large Hadron Collider (HE-LHC), a hadron collider in the LHC tunnel, using High Field Magnet (HFM) magnets studied as part of the FCC Conceptual Design Study (CDS), are also recalled in Table 8.2. Such a collider would be limited to a maximum c.o.m. energy of 34 TeV, well below the goal of a 10 TeV parton center-of-momentum (pCM), even if equipped with 20 T magnets, and it could start operation only at the beginning of the 2070s.

A short review of the status and prospects of new accelerator techniques is presented in Section 9. Although significant progress has been made towards the acceleration of higher quality electron beams, several technological and accelerator/plasma physics challenges remain. The level of maturity of the wakefield-based accelerators does not allow to consider them as realistic alternatives to the above proposals, at least on the timescale considered.

An overview of the collider projects proposed for other regions is also available in Section 7.

1 Introduction and context

The 2020 update of the European Strategy for Particle Physics (ESPPU 2020) has identified the priorities for the field in Europe, within the global context [4]:

- *An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least* 100 TeV *and*

with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

- *Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

Given these recommendations, CERN consolidated its future accelerator programme in 2020 to address the priorities of the ESPPU 2020 outlined above by establishing or extending the following initiatives:

- **Future Circular Collider (FCC) feasibility study**: the principal aim was the delivery of a feasibility study report by the end of March 2025. A successful mid-term review took place during Q4 2023, and the final report was recently delivered on time.
- **Compact Linear Collider (CLIC)**: following extensive R&D, the key X-band radio-frequency (RF) technology has been deployed world-wide in a number of projects as well as for societal applications. Studies continued with the aim of delivering a Project Readiness Report which has been submitted to the ESPPU 2026.
- **Muon Collider (MC)**: an International Muon Collider Study was launched with a dedicated funding line. An international collaboration has been set-up. It includes the MuCol Consortium established under a grant agreement within the Horizon Europe Framework Programme (HORIZON) and a strong US component.
- **Accelerator Research and Development (R&D)**: An European Accelerator R&D roadmap has been outlined [5] and its execution is underway and looking to secure the requisite technology for the next generation of machines. At CERN it is realized through four main lines:
  - High Field Magnet (HFM) R&D: both Low Temperature Superconductor (LTS) and High Temperature Superconductor (HTS) magnet development;
  - RF technology R&D: both Normal Conducting (NC) X-band and Superconducting radio frequency (SRF);
  - Proton-driven Plasma Wakefield Accelerator (PWFA) with the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) study;
  - CERN Linear Electron Accelerator for Research (CLEAR).

There is limited progress in Japan moving to a pre-lab phase for the International Linear Collider (ILC). A targeted R&D phase is ongoing and a proposal for an International Linear Collider (ILC) implementation at CERN has been submitted to the ESPPU 2026 under the appellation Linear Collider Facility (LCF).

The High-Luminosity LHC (HL-LHC) baseline schedule foresees operation until the end 2041. CERN is positioning itself to be able to start operating an e^+e^-Higgs factory in the second half of the forties. This implies down-selection, a decision, and an initial commitment of resources in 2028, with subsequent project preparation and execution in the following decade.

In the global context it is important to note that:

- in its report, the US 2023 Particle Physics Project Prioritization Panel (P5) has endorsed *an off-shore Higgs factory, located in either Europe or Japan, to advance studies of the Higgs boson following the HL-LHC while maintaining a healthy on-shore particle physics program*, adding that *The US should actively engage in design studies to establish the technical feasibility and cost envelope of Higgs factory designs. We recommend that a targeted collider panel review the options after feasibility studies converge. At that point, it is recommended that the US commit funds commensurate with its involvement in the LHC and HL-LHC*. The panel recommended *dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a* 10 TeV *parton center-of-momentum (pCM) collider to search for direct evidence and quantum imprints of new physics at unprecedented energies.* and recommended a *targeted collider R&D to establish the feasibility of a* 10 TeV *pCM muon collider. A key milestone on this path is to design a muon collider demonstrator facility* [6].
- In China, the Circular Electron Positron Collider (CEPC) community continues a robust R&D programme and development of site options and has published a Conceptual Design Report (CDR) at the end of 2023 [7].
- In Japan, despite the reluctance to move into the pre-lab phase, the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) is actively supporting continued ILC R&D.

The maturity of the above-mentioned proposals differs and as input to the incoming ESPPU a comparative evaluation is presented.

First phase future collider proposals that could become operational at CERN at the latest in 2045–2050 are compared. Other equivalent options proposed elsewhere in the world in the same time frame are also presented. Proposals that are presently not anticipated to match realistically the above time frame (including possible major upgrades or developments) are discussed separately.

The latest version of the proposals for re-use of the LHC tunnel have been summarized as reference for completeness. A short summary of some advanced collider concepts, for which extensive studies (e.g. a CDR) do not exist, has also been provided.

1.1 General considerations about a next flagship project at CERN

CERN's current accelerator complex, centred on the LHC, supports a diverse and world leading scientific programme spanning high-energy proton–proton collisions, heavy-ion physics, and a broad array of fixed-target experiments. These include studies of antimatter, nuclear physics with radioactive ions and neutrons, and a variety of precision measurements enabled by unique facilities such as ISOLDE, n_TOF, AD–ELENA, and the East and North Areas.

Looking ahead, the High-Luminosity LHC (HL-LHC) upgrade will be installed during Long Shutdown 3 (LS3, 2026–2030). By the end of HL-LHC operation in 2041, the total proton-proton integrated luminosity delivered to ATLAS and CMS at or above 13 TeV since the beginning of the LHC is expected to reach 3 ab^{-1}. LS3 will also see significant investment in consolidating the broader accelerator complex, ensuring its continued effectiveness in the following decades.

The financial and personnel demands of HL-LHC operations mean that the commissioning of any major new facility at CERN cannot realistically begin before the end of HL-LHC exploitation. Moreover, a transitional period will be required to redeploy resources, complete installation and commissioning activities, and ramp up new infrastructures. Thus, a future collider at CERN cannot realistically start operation before the mid-2040s, regardless of the precise nature of the project and its technical readiness.

The approval within the current strategic period of a large-scale post-LHC collider project aiming for operation in the mid-2040s would significantly constrain CERN's ability to pursue other long-term options. It is therefore critical to balance ambition with realism in assessing near- and long-term pathways.

The FCC integrated programme foresees a sequential implementation of FCC-ee followed by FCC-hh, with operation potentially spanning from the mid 2040s to the end of the century. Should circumstances evolve, a stand-alone FCC-hh collider with operation starting at the end of the 2050s remains a technically viable and potentially competitive option.

The FCC feasibility study has included detailed territorial implementation studies and established structured, multi-level engagement with the Host State authorities and local communities. These developments represent a substantial investment in building a sustainable, long-term foundation for the project. In this context, parallel developments for alternative options in the local region should not undermine this process. Any siting analysis for such alternatives should be limited to conceptual studies making use of existing information, as Host State authorities and local services and communities would not be able to support implementation studies for two big infrastructures.

While the Muon Collider represents an exciting long-term possibility with excellent physics potential, it remains at an early stage of development. The required R&D is substantial and includes demonstration of key feasibility elements such as 6D cooling. Given its technical immaturity and high resource demands, it cannot be considered as a realistic option for implementation in the strategic timeframe discussed here. The Muon Collider should therefore be pursued through a sustained, staged R&D effort, independent of the decision on the next major collider.

Alternative solutions, such as LEP3 or LHeC, would entail major infrastructure investments and operating costs and therefore delay the implementation of a next-generation collider by at least one to two decades. For this reason, they cannot be considered as “bridges”, but rather as alternative options to other proposed colliders.

A linear collider facility at CERN would preclude the construction of FCC-hh due to infrastructure and other constraints in the local, highly-populated region.

2 Criteria and metrics for the comparison

The following main criteria have been considered for the comparative evaluation, in particular for the projects at CERN, when available:

– Main parameters and performance
– Environmental aspects
– Technical readiness
– Accelerator and experiments construction and installation: material costs
– Accelerator construction and installation: human resources
– Project timeline
– Operation: material and personnel costs.

Consideration has been given also to the following subjects:

– Upgrade potential
– Size of the experimental community that could be served
– Accelerator technology production capabilities and potential buy-in from European institutes.

2.1 Main parameters and performance

A short description of the colliders and of the associated injector chain with their main components and technologies is given. Re-use of existing infrastructure/accelerators with the required upgrades vs. construction of new ones is addressed. Peak luminosity as well as yearly integrated nominal performance (as well as expected integrated electricity consumption) are presented based on reference yearly operational schedules (see Section 2.1.1). When different values are assumed by the proponents, corresponding tables are also presented separately in the relevant Appendix.

In order to achieve high luminosity linear colliders must be operated in the high-beamstrahlung regime resulting in a rather broad luminosity spectrum as a function of the c.o.m. collision energy $\sqrt{s}$. For these machines both the instantaneous luminosity above 99% of $\sqrt{s}$ and the total instantaneous luminosity integrated over the full energy spectrum are presented.

The estimates for the electricity consumption include the following infrastructure:

- collider;
- injectors;
- transfer lines;
- experiments (which normally represent a small fraction of the overall consumption—a few percent) and their local data centres;
- general services and controls;
- off-line data-analysis centres;

unless specified differently.

Considerations on the complexity of the accelerator proposal and on its impact on performance ramp-up are also made.

2.1.1 Operational year

The breakdown of the operational phases for the e^+e^- colliders and the hadron colliders and their duration have been defined in Ref. [8] based on past experience. An extrapolation for the muon colliders is also proposed here, though with a larger uncertainty due to the maturity of the related study. The fraction of electricity consumption (expressed as a percentage of the consumption for nominal operation with beam) required for each operational phase, is also given. These values are used to estimate the yearly electricity consumption.

e^+e^- *colliders*

The main parameters for circular and linear e^+e^- colliders are presented in Table A.1 and Fig. A.1. The annual scheduled physics time amounts to 185 days, with an efficiency for data taking of 75%. Operation occurs at constant luminosity for both the circular (top-up injection) and linear e^+e^- colliders, with no turn-around time between physics fills (the beams in the circular colliders are injected from the injectors at collision energy and no time is lost for acceleration in the collider).

Hadron colliders

The main parameters are presented in Table A.2 and Fig. A.2. It is assumed that 160 days of high-luminosity physics operation are scheduled, based on LHC experience. A longer Year End Technical Stop (YETS), the required powering tests of the SC circuits following it, the necessary recovery time after technical stops and the need of special physics runs at lower luminosity (e.g. for luminosity calibration) explain the shorter scheduled physics time as compared to e^+e^- colliders. The machine is assumed to be available for 70% of the scheduled high-luminosity physics time and to deliver luminosity for experiment data taking (also called “stable beam” phase) for 35% of the scheduled high-luminosity physics time.

Muon colliders

The main parameters are presented in Table A.2 and Fig. A.3. The breakdown of the operational phases for the MC is assumed to be similar to that of the hadron colliders because of the large superconducting magnetic system. No special physics runs are contemplated. Machine availability is assumed to be 70% as for the hadron colliders. Operation at constant luminosity (top-up mode) is tentatively assumed with no turn-around time between physics fills as the collider is operated at constant energy.

2.2 Environmental aspects

Accelerators and detectors construction and operation (including on-line and off-line computing), as any other human activity, make use of natural resources and impact the environment.

Life Cycle Assessment (LCA) (see Glossary p. 68) is a structured, comprehensive and internationally standardised (ISO 14040/44) method to quantify some of the potential environmental impacts such as emissions and resources consumed. Existing methodologies identify several impact categories which, apart from Greenhouse Gas (GHG) emissions, are not widely reported and are subject to large uncertainties [9]. For that reason the reporting will be limited to GHG emissions expressed in g CO_2 eq. (or multiples).

Host states legislation requires a precise set of parameters to be presented in the environmental impact study and limits to be respected. It is important to underline that here we provide a simplified set of indicators to evaluate the GHG emissions in construction and operation, rather than a list of parameters ready to be submitted to the authorities. The numbers also will have different level of uncertainty due to the different level of maturity of the various studies. Those numbers have therefore to be considered mostly for the purpose of understanding the main drivers of the environmental impact, and eventually whether there is any margin to reduce such impact.

2.2.1 GHG emissions associated with construction and operation

Where available, the following contributions have been considered:

- "Cradle to gate with options" (LCA modules A1 to A5—i.e. raw material supply, transport, manufacture, transport to work site, construction process on the work site), as defined in EN 15804) for CE works. The contribution of the modules A1 to A5 represents more than 80% of the overall GHG emissions [9, 10]. Strategies to reduce carbon footprints—such as using alternative cements, enhancing material efficiency, and adopting green energy—are being proposed, broader advancements in cement production and concrete construction are also underway, but are not yet consolidated. The suitability of the materials, their availability in the required quantities and the associated cost are not fully assessed. Therefore, both the GHG emissions associated to the utilization of presently used materials, based on Portland (CEMI) cement, as well as those considering low-carbon content concrete are presented. This approach is consistent with the roadmap established by the European Cement Association (CEMBUREAU) [11]. CEMBUREAU, the leading representative of the cement industry in Europe, aims to reduce the embodied carbon associated with cement production and usage. To achieve this, CEMBUREAU has established a net zero roadmap, targeting carbon neutrality for the European cement industry by 2050. This roadmap aims for a 37% reduction in GHG emissions by 2030 and a 78% reduction by 2040, ultimately reaching carbon neutrality by 2050.
- Module A1 to A3 (i.e. raw material supply, transport, manufacture) for the main components of the accelerators, their technical infrastructure and the detectors.
- The GHG emissions due to the generation of the electricity required for the operation of the accelerators (main collider and injectors), experiments (including local data centres), the worldwide computing grid and their general infrastructure and services (see below).

Although the above list is not exhaustive, it provides an indicative assessment of the relative impact of construction and operation of the accelerators.

The presented estimates are inherently affected by uncertainties related to the carbon factors used in the LCA.

Carbon intensity of electricity generation

The evolution of the carbon intensity of electricity generation (expressed in g CO_2 eq. per kW h) predicted by Réseau de Transport d'Électricité (RTE), the French transmission system operator for electricity, has been assumed for projects at CERN for the period spanning 2030 to 2050. Table 2.1 lists the projected ranges for the life cycle emissions encompassing both: a) direct emissions related to the combustion of oil, gas and coal and b) upstream emissions related to the extraction and transport of fuels as well as the construction and end-of-life of production and network infrastructure [12]. In its analysis, RTE accounts for the CO_2 eq. emissions from cross-border electricity trading, ensuring that imported electricity emissions are proportionally included in France's total electricity generation mix and exported emissions excluded accordingly. The reported values are therefore based purely on the electricity consumption data.

Table 2.1: Life cycle carbon intensity [g CO_2 eq. per kW h] of electricity consumption. Each lower (upper) value is the average of the minimum (maximum) carbon intensity values for six possible scenarios for the evolution of the French electricity system [12]. The reference years for RTE are 2019 and 2050. A linear interpolation was applied to estimate the values in the intermediate years.

Country | Year	2030	2035	2040	2045	2050
France	39–41	32–34	25–29	19–23	14–18

2.2.2 Consumption of land

Data concerning the surface of land required or affected by the construction work are presented.

2.2.3 Other considerations

Optimization measures proposed by the various projects to reduce the carbon footprint during construction and operation, reduce electricity consumption and reuse energy, to make responsible use of natural resources and to limit the environmental impact are briefly discussed.

2.3 Technical readiness and R&D requirements

Similarly to what has been done by the Snowmass'21 Implementation Task Force [13], the aspects related to the technical readiness of the collider proposals are discussed. These include:

- Technology Readiness Level (TRL) of the accelerator component/subsystems representing the highest technical risk (see Table A.3 in Appendix A.2).
- Improvement factor to be achieved between the state of the art and the requirements for the most representative and difficult parameter of the considered component/subsystem. This could also be the required unit cost reduction factor assumed in the estimate of the overall cost, or the electricity consumption reduction assumed in the estimate of the overall electricity consumption, or the required increase in the Mean Time Between Failures (MTBF) to realistically achieve the prospected accelerator complex availability.
- Effort (personnel and material) required to develop and/or validate the technology underlying the above components/subsystems before (series) production can start, considering the scale of the validation (single component to full-scale).
- Technically-limited timescale necessary to bring the component or subsystem to be ready for (series) production.

2.4 Construction and installation costs

Unless explicitly indicated, the cost estimates for the construction and installation of accelerators and detectors quoted by the proponents of the projects in 2024 prices are provided. They include the cost of the technical components, materials, contracts, services, civil construction and conventional systems and associated implicit labour such as that provided by a company to produce components, unless otherwise explicitly stated.

The cost estimate includes:

- construction costs, i.e. from project approval to commissioning;
- tooling dedicated for production of components;
- reception tests and pre-conditioning of components;
- commissioning of technical systems (without beam);
- costs related to land, roads, electricity and water connections as well as for administrative processes;
- implicit labour (external companies, Field Support Units—FSU);
- total detector costs;

while it does not include:

- explicit labour provided by the host institution and the collaborating laboratories, this is provided separately and expressed in Full-Time-Equivalent-years (FTEy);
- contingency;
- any potential future inflation;
- the costs prior to project approval (construction and R&D);
- off-line computing;
- spares, maintenance;
- beam commissioning;

unless explicitly stated.

For the projects considered for implementation at CERN, taxes and customs as well as general laboratory infrastructure and services (these being already available) are not included.

We follow the classification of the Association for the Advancement of Cost Engineering International (AACE®) [14] to assign cost uncertainty classes based on their level of definition (or maturity) assessed from the information available (see Table A.4 in Appendix A.3).

When costs have not been provided in 2024 prices, the expected relative cost increase considering inflation and in particular the volatility of many commodity prices due to the economic disruptions in the COVID years 2020–2021, has been quoted. This has been derived considering the evolution of the domestic (industrial) Producer Price Index (PPI) of the region from where most of the components are going to be built (see Appendix A.4).

Cost estimates are also provided in Swiss Franc (CHF) using the exchange rates listed in Table A.5 in Appendix A.5.

Considering that all the projects discussed will likely become an international endeavour, at least partially, Purchasing Power Parity (PPP) conversion rates [15] allow to establish a more realistic value of international (e.g. in-kind) contributions than currency-exchange rates. The exchange rates corrected for the PPP used in this report are listed in Table A.6 in Appendix A.6.

The cost breakdown according to the following main domains for the baseline design has been provided, when available:

- Main tunnel accelerators
- (pre-)Injectors & transfer lines
- Civil Engineering (CE)
- Technical Infrastructure (TI)
- Experiments.

When available the cost of additional upgrades and options are also presented.

2.5 Accelerator construction and installation: human resources

An estimate of the personnel (explicit labour) required for the construction and installation of the accelerators and their technical infrastructure, as well as the technical infrastructure of the experiments, is presented. It does not include contractor personnel and the personnel required in the R&D phase of the project, nor the personnel required for Hardware (HW) and beam commissioning. The estimations of the personnel needs by the various projects presented in this document are compared with those obtained by a formula correlating explicit labour in FTEy to the project CApital EXpenditure (CAPEX) (excluding CE [16]) developed by the Snowmass'21 Implementation Task Force (ITF) [13]:

$$Explicit\ labour\ [\text{FTEy}] = 15.7 \times (CAPEX\ [\text{2010 MCHF}])^{0.75} \tag{1}$$

where $CAPEX$ is expressed in 2010 MCHF.

2.6 Project timeline

The expected project timeline is presented and commented with the main phases and milestones expected for projects of such extent:

- Exploratory studies to assess the most critical feasibility issues and define the R&D programme (this could include the development of critical components and/or systems, or demonstration facilities required to assess the feasibility, in particular if the concept relies on equipment, systems or performance well beyond the state of the art).
- Approval of the R&D programme.
- Technical design, construction and validation of the components, systems, and demonstration facilities.
- Conceptual Design Report (CDR) providing a conceptual description of the main components of the accelerators and their infrastructure, resulting from the exploratory study and R&D results above. The CDR should allow to produce a first cost estimate (at least Class 5—see Table A.4).
- Definition of the placement scenario for the collider complex and its infrastructure after assessment of their territorial compatibility: i.e., respecting the territorial requirements and constraints as well as leveraging territorial assets and developing meaningful synergies such as a co-development activities with the relevant regional stakeholders. This implies a broad spectrum of environmental aspects and considerations including: limiting the consumption of land, developing a credible plan for the management of the excavated materials, limiting the consumption of resources such as electricity and water, keeping technical infrastructures as compact as possible, placing the underground structures away from geologically uncertain locations, optimizing access to electricity lines, water supply and treatment, sewage networks and existing major roads and railway lines, avoiding unfavourable topographic and elevation conditions, and some proximity to spoil dumps. An initial review of the implementation scenario with the relevant regional and local stakeholders is included in this phase.
- Preliminary implementation. This includes: reserving all land plots potentially affected by the project for the period of more detailed investigations, geological investigations and studies of:

territorial constraints and mitigation/compensation measures, road access, railway access, agricultural studies, forest studies, analysis of the environmental initial state, sustainable energy supply concept. The identification of the legal and regulatory conditions under which the project has to be developed, authorized and implemented (e.g. plan approval process and environmental evaluation process) will be required during this phase.

- Feasibility Report. It includes the comprehensive conceptual design of the collider, the injectors, the experiments, all technical infrastructures that are required to construct and operate them as well as all directly related civil works, the results of the geological investigations, the results of the preliminary territorial implementation studies with the host region/states, and an estimate of the cost (at least Class 4—see Table A.4) and of the personnel required.
- First version of a Technical Design Report (TDR) (or pre–TDR) outlining the detailed technical specifications and design considerations.
- Project approval by the relevant governing body or bodies (e.g. Council for the CERN projects).
- Environmental evaluation and project authorization processes. Depending on the project's host country, different project authorisation processes will apply. In Europe, large-scale development projects are typically subject to a unique authorisation that is obtained as a result of an "environmental evaluation" process.
- Main technologies R&D completion. This refers to the R&D phase on the critical technologies affecting the main parameters of the accelerators and technical infrastructure and/or having an impact on civil engineering, procurement of components requiring large-scale production, acceptance tests and validation or production with long lead times.
- Final version of the TDR including: functional requirements of the project (performance criteria, safety requirements, regulatory compliance, and any other constraints or expectations), component or module specifications and interfaces; material and equipment specifications, quantities, and sourcing information; testing and validation plan; safety and regulatory compliance. The TDR can be delivered only after completion of the R&D phase on the critical technologies of the project and it should allow to assess the cost of the project with an uncertainty corresponding to Class 3 to 2, or better (see Table A.4).
- Installation. It includes the installation of technical infrastructure inside the shafts and in the tunnels as well as the installation of the accelerator components and of the detectors.
- Hardware and beam commissioning of the injectors and collider.

2.7 Collider complex operation: resource requirements

The operation costs will be considered only for options proposed for CERN.

The resources required for operation (material and personnel) of the collider accelerator complex (including technical infrastructure), and of the technical infrastructure of the experiments are included. The resources needed for the operation of the rest of the accelerator complex and its technical infrastructure (e.g. the PS and SPS complex) and the technical and scientist support for the experimental detectors and computing are excluded.

For the annual material costs the following items should be considered [17]:

- Maintenance and replacement costs estimated with the following methodology:
  - 3% of powering systems (e.g. klystrons, RF and magnet power converters) or other "consumable" CAPEX, considering the limited lifetime of these parts;
  - 1% of remaining accelerator HW (e.g. RF cavities/structures, magnets, vacuum chambers) or other "fixed installation" CAPEX, for replacements;
  - 5% of technical infrastructure (e.g. cooling, ventilation, electronics and electrical infrastructures, access and safety systems, cryogenics, computer and network infrastructure, control

systems, robotics, lifts and transport system) CAPEX. It includes the cost of contractors. As an example, the typical ratio between the maintenance cost and the capital cost of Cooling and Ventilation (CV) equipment for industries operating for more than 7000 h/year (CERN CV installations operate between 7000 and 8000 h/year) is 7% but lower (3%) for the LHC [18]. The yearly maintenance costs for the LHC cryogenics represent approximately 3% of the corresponding initial CAPEX [19]. These include the cost of helium procurement to compensate for the small but inevitable losses and of liquid nitrogen procurement.

– Electricity cost, assuming a price of 80 EUR/MW h.This value is subject to a large uncertainty given the rapidly evolving energy market and the long timespan considered here.

The personnel (in FTE) required for the operation of the collider complex and its experiments' technical infrastructure is estimated considering the present personnel required for operating the LHC by type of equipment. On average the personnel cost matches the material maintenance and replacement costs. The average cost of a staff FTE at CERN is assumed to be 210 kCHF/y.

These estimates might be pessimistic and represent an upper limit considering the expected impact of modern controls, Artificial Intelligence (AI) and robotics by the time of the operation of the future colliders.

3 Future collider options at CERN for operation starting in 2045–2050

3.1 Main parameters and performance

CLIC

The Compact Linear Collider (CLIC) is a linear e^+e^- collider with a proposed initial configuration operating at a c.o.m. energy of 380 GeV, with a potential upgrade to 1.5 TeV [20]. CLIC uses a novel two-beam acceleration technique, with Normal Conducting (NC) 12 GHz accelerating structures operating in the range of 72 MV m^{-1} to 100 MV m^{-1}. A schematic layout of the CLIC collider is shown in Fig. 3.1.

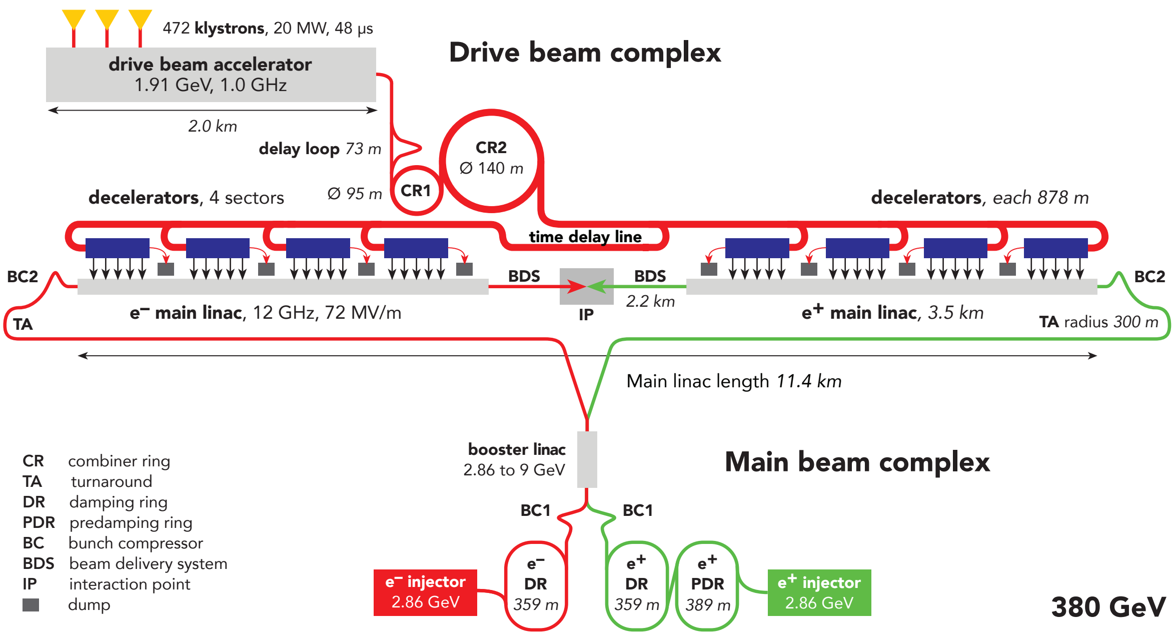

Fig. 3.1: Conceptual layout of the CLIC collider (380 GeV).

The electron beam is produced in a conventional RF injector, which allows polarisation. The beam emittance is then reduced in a damping ring. To create the positron beam, an electron beam is accelerated to 2.86 GeV and sent into a conventional tungsten target generating photons that produce e^+e^- pairs. The positrons are captured and accelerated to 2.86 GeV and their beam emittance is reduced, first in a pre-damping ring and then in a damping ring. The Ring-to-Main Linac system (RTML) accelerates both beams to 9 GeV, compresses their bunch length, and delivers the beams to the main linacs. The main linacs accelerate the beams to the collision energy of 190 GeV. The BDS removes transverse tails and off-energy particles with collimators, and compresses the beam to the small size required at the IP. After collision, the beams are transported by the post-collision lines to their respective beam dumps.

The RF power for each main linac is provided by a high-current, low-energy (1.91 GeV) drive beam that runs parallel to the colliding beam through a sequence of Power Extraction and Transfer Structures (PETS). The drive beam generates RF power in the PETS and is decelerated; the resulting RF power is then transferred to the accelerating structures using a waveguide network. The drive beam is generated in a central complex that delivers trains with bunches spaced by 2.5 cm (i.e. with a repetition frequency of 12 GHz). This concept reduces the cost compared to powering the structures directly by klystrons, especially for the upgrades to higher energies. The drive-beam and main-beam injectors are located in the CERN Prévessin site.

Ten years of operation are assumed for CLIC in its first, 380 GeV stage [20]). A luminosity ramp-up is foreseen during the first three years, providing successively 10%, 30% and 60% of the design luminosity. The CLIC total programme corresponds to eight years of operation at nominal luminosity. An optional initial stage at 250 GeV is considered. Upgrades at 550 and 1500 GeV are contemplated but require an extension of the tunnel to approximately 15 and 29 km, respectively. Upgrade to even higher energies would require a second drive beam and longer tunnels that might traverse areas with unfavourable geological characteristics.

The main CLIC parameters are listed in Table 3.1 [20]. The repetition frequency of the Main Linac (ML) has been doubled to 100 Hz as compared to the baseline presented in Ref. [17]. In the updated proposal [20] the CLIC ML distributes the beam pulses between two BDS bringing the beams in collisions at two IPs where two experiments running in parallel share the luminosity.

Operating the fully installed 380 GeV CLIC accelerator complex at lower energy E results in lower luminosity, expected to scale roughly as E^3 [17], though detailed performance studies have not been performed for operation at the Z-pole with a 380 GeV configuration [17]). An installation of just the linac needed for operating at lower energies and an appropriately adapted beam delivery system, would result in higher luminosities though this can only be implemented at the very beginning of the first stage, or during the transition to the second stage. In both cases additional set-up time would be required. At the Z-pole, 7.5 and 135 fb^{-1} can be achieved per year with an unmodified and a modified collider, respectively.

FCC-ee

The Future Circular Collider integrated programme begins with a luminosity-frontier e^+e^- machine (FCC-ee) spanning c.o.m. energies from below the Z pole, over the WW pair threshold and ZH production peak, to beyond the top-pair production threshold, later evolving to an energy-frontier hadron collider (FCC-hh), as described in Ref. [21]. The presently proposed schedule of the FCC programme foresees 14 years of FCC-ee physics operation and 25 years of FCC-hh operation, interleaved with a shutdown of 10 years to dismantle the lepton collider and install the hadron collider in the FCC tunnel.

FCC-ee is a double-ring collider—a schematic view is shown in Fig. 3.2. Its main parameters are listed in Table 3.1. The two beams collide in four interaction points. The synchrotron radiation power is restricted to 50 MW per beam. A full energy booster with an injection energy of 20 GeV, located in the same tunnel (5.5 m diameter) as the collider, is used to steadily top up the beam currents in the two colliding rings. A High-Energy (HE) linac accelerates the electron and positron beams, extracted from a damping ring at 2.86 GeV, to 20 GeV for injection into the full-energy booster ring.

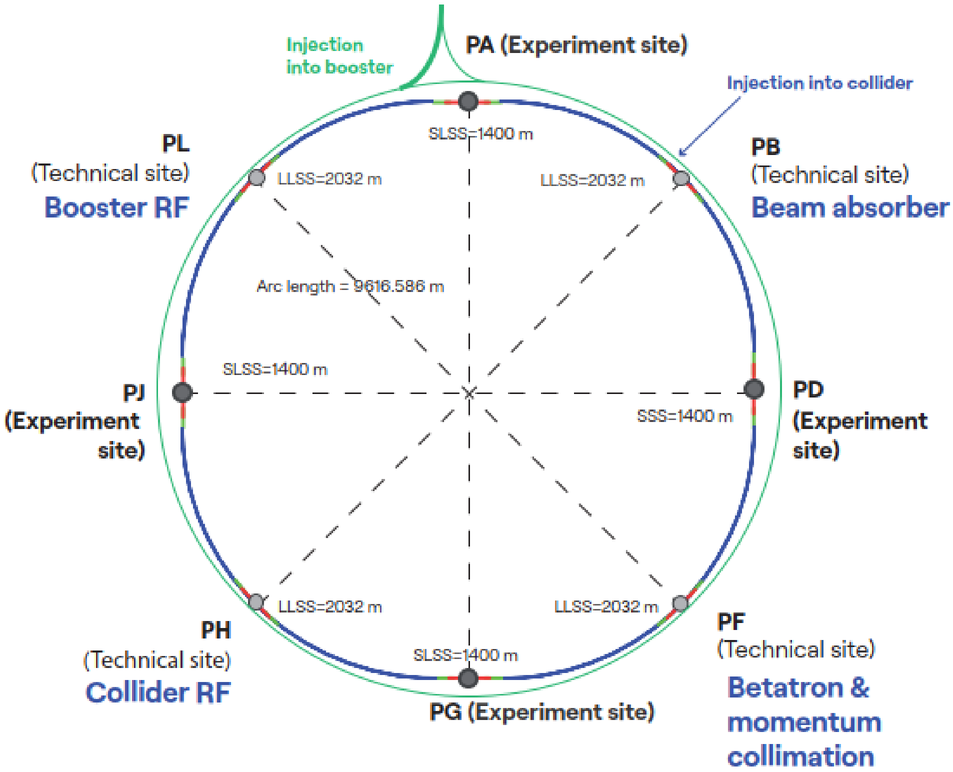

Fig. 3.2: Schematic diagram of the FCC-ee collider.

From the end of the HE Linac, the electron and positron beams are transferred via new tunnels of 5.5 km total length from surface at CERN Prévessin site directly down to the collider tunnel around FCC Point A (PA). Over the first 4 km both lepton beams can share the same tunnel. Thereafter, the two beams will be split and injected symmetrically around PA at the two ends of the experimental LSS, respectively.

The injector complex footprint extends over about 1.2 km in length. The linacs and damping ring will be installed about 6 m below ground level, using cut and cover techniques. Klystron and service buildings will be located on the surface, and connected to the linac tunnels via ducts for waveguides and cables.

The RF installation in collider and booster is identical for the Z, WW and ZH modes of operation, which is made possible by reverse phase operation at the Z pole. Additional RF cavities will have to be installed for $t\bar{t}$ operation. In the collider, during the Z and WW modes, each of the two beams uses half of the installed RF system, whereas for the ZH and $t\bar{t}$ modes with much fewer bunches, both beams go through the full RF system. The switch from beam crossing, in the middle of the RF LSS for Z and WW operation to beam combination and separation at the start and end of this straight for ZH running is achieved by a combination of magnets and electrostatic separators [21]. The collision energy can be flexibly changed between these three modes of operation, e.g., year by year, or even faster. The klystron galleries are separated from the main tunnel, allowing for installation activities during machine operation.

In total, 14 years of physics operation are foreseen for FCC-ee. Following 1.5 years of beam commissioning, a first operation block contains a four-year run on the Z pole (the first two years of which being at half the design luminosity), a two-year run at the WW energy, and a three-year run for ZH Higgs production. As mentioned above, the order of the runs in this first block of operation can be modified and even multiple switches between runs can be envisaged. Once the first block completed, one year of shutdown will be required for the additional RF installation, for the second operation block, namely a five-year run around the $t\bar{t}$ threshold.

Linear Collider Facility (LCF)

An additional proposal [22] for a e^+e^- Linear Collider Facility (LCF) to be built at CERN has been submitted as input for the update of the ESPP 2026. The design of the accelerators is identical to that of the ILC (see Section 7.1), and it is based on bulk-Niobium SRF cavities operated at 1.3 GHz with an accelerating gradient of 31.5 MV m^{-1}. The conceptual layout is shown in Fig. 3.3.

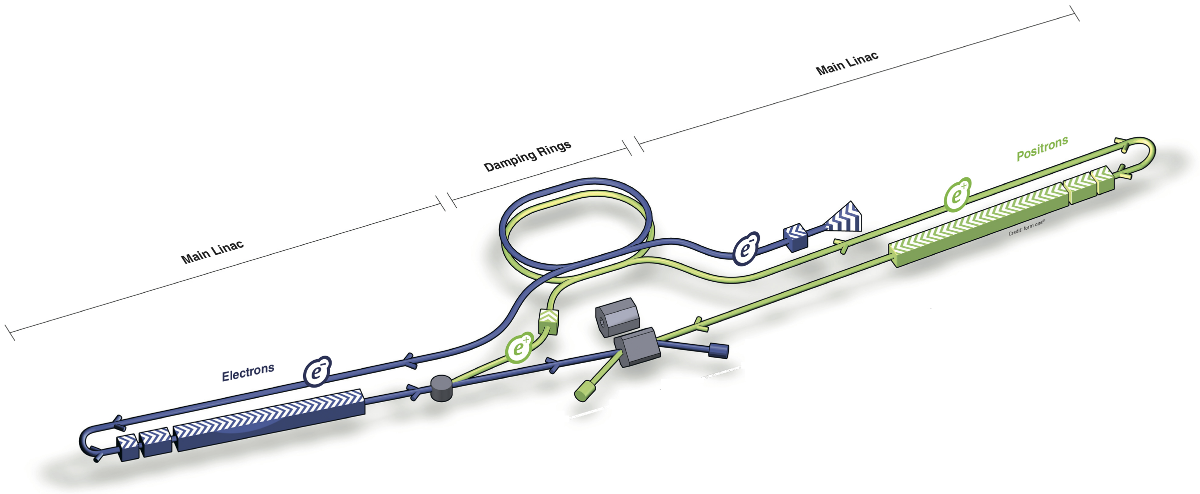

Fig. 3.3: Conceptual layout of the LCF/ILC collider.

The baseline scenario considers a c.o.m. energy of 250 GeV with the linear collider installed in a tunnel 33.5 km long (to be compared with 20.5 km of the ILC) offering the possibility to increase the c.o.m. energy to 550 GeV or higher at later stages and providing operational margin for the baseline c.o.m. energy by installing some additional cryomodules, if needed. Most of the tunnel would have a circular cross-section of 5.6 m diameter. In the baseline configuration—Low-Power (LP) version—the LC would operate with a repetition rate of 10 Hz (double as compared to that of the ILC) with the same number of bunches per pulse (1312) serving two experiments installed in two separated IPs located in the same cavern and sharing the pulses delivered by the collider alternatively. The operation at 10 Hz has implied the increase of the nominal Q_0 of the cavities installed in the cryomodules from 1×10^{10} (ILC specification) to 2×10^{10} at the same nominal gradient of 31.5 MV m^{-1}.

A luminosity ramp-up is foreseen during the first three years, providing successively 10%, 30% and 60% of the design luminosity. An upgrade to higher intensity (doubling the number of bunches per pulse) is also contemplated after five years of operation—Full-Power (FP) version—and it would require a Long Shutdown (LS) of one year. The first year after the intensity upgrade would be dedicated to a run at the Z-pole. The main parameters of the baseline proposals (LP and FP) are listed in Table 3.1.

The tunnel maximum size has been reduced significantly as compared to the ILC design (see Section 7.1). There is no more a shielding wall separating the main linac and the RF power sources, similarly to the European X-Ray Free-Electron Laser Facility (EU-XFEL) tunnel implementation. This has consequences for RF testing, preventing access to the RF power sources when the RF cavities are powered. Radiation to electronics might also become an issue in the absence of sufficient shielding.

Figure ES.1 shows the integrated luminosity over electricity consumption for the various e^+e^- colliders proposed and their upgrades and compares them to LEP and LEP2 performance.

Table 3.1: Main parameters for CLIC, FCC-ee and LCF. The instantaneous and integrated luminosity in-between parentheses includes also the contribution from energies below 99% of the c.o.m. energy $\sqrt{s}$.

	CLIC	FCC-ee				LCF		
						LP	FP	
Circumference/length collider tunnel [km]	12.1	90.7				33.5		
Number of experiments (IPs)	2	4				2		
Synchrotron radiation power per beam [MW]	—	50				—		
c.o.m. energy [GeV]	380	91.2	160	240	365	250	91.2	250
Longitudinal polarisation (e^- / e^+) [%]	±80 / 0	0 / 0[a]				±80 / ±30		
Number of years of operation (total)	10	4	2	3	5	5	1	3
Nominal years of operation (equivalent)[b]	8	3	2	3	4.5	3	1	3
Instantaneous luminosity per IP above 0.99 $\sqrt{s}$ (total) [10^{34} cm^{-2} s^{-1}]	1.3 (2.2)	140	20	7.5	1.4	1 (1.35)	0.28 (0.28)	2 (2.7)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs per year of nominal operation [ab^{-1}/y]	0.32 (0.54)	69	9.6	3.6	0.67	0.24 (0.32)	0.067 (0.067)	0.48 (0.65)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs over the operational phase [ab^{-1}]	2.56 (4.4)	205	19.2	10.8	3.1	0.72 (0.97)	0.067 (0.067)	1.44 (1.94)
Peak power consumption [MW]	166	251	276	297	381	143	123	182
Electricity consumption per year of nominal operation [TW h/y][c]	0.82	1.2	1.3	1.4	1.9	0.8	0.7	1.0

[a] Vertical polarisation of at least a few percent for ~200 non-colliding pilot bunches, enabling precise quasi-continuous measurement of the beam energy. No longitudinal polarisation in the baseline. Residual longitudinal polarisation of colliding bunches should be controlled at the 10^{-5} level.
[b] This row lists the equivalent number of years of operation at nominal instantaneous luminosity, hence taking into account the luminosity ramp-up.
[c] Computed from the peak power consumption and the assumptions on the operational year (see Table A.1).

3.2 Environmental aspects

3.2.1 GHG emissions associated with construction and operation

CLIC

The CLIC and ILC projects have commissioned two LCA [9,10]. These assessments (A1 to A5 modules—see Glossary p. 68) provide an estimate of GHG emissions expected for CLIC construction including:

- civil engineering for underground and surface infrastructures for the whole CLIC accelerator complex, particularly for the ML tunnel featuring a 5.6 m internal diameter;
- main hardware components for the whole accelerator complex;
- technical infrastructure for the whole accelerator complex;
- detectors.

The results of the analysis are summarized in Table 3.2. Possible reduction opportunities have been identified, particularly for the CE of the injector linacs. The analysis has revealed that support structures constitute a significant part of the carbon footprint of the accelerator HW and of the detectors and an appropriate choice of the material and design could lead to an appreciable reduction.

FCC-ee

An LCA for the civil engineering works for the whole FCC-ee complex has been commissioned [23]. The LCA for the accelerator systems and TI components having the largest impact is under way. The GHG emissions for FCC-ee are presented in Table 3.2 and therefore represent a lower bound.

Potential further reductions of the carbon footprint of civil construction have been outlined and might result from a refined design, use of materials with higher performance and reduced carbon footprint and requiring less steel, local production of construction materials, use of recycled materials and optimisation of the construction process permit. These could further reduce the corresponding minimum value by 5% for the surface sites and by 16% for the underground construction works but the implications (e.g. on cost, schedule, etc.) have not been assessed. The estimate of the GHG emissions for the four detectors is based on the LCA for the CLIC detectors provided in Ref. [10], as we expect similar detector concepts for all e^+e^- collider proposals.

Extensive work is ongoing to improve the efficiency of the RF sources with the R&D on high-efficiency klystrons that could further increase their efficiency from the presently assumed value of 80% to 90%.

LCF

The values of the expected GHG emissions associated with the project construction (CE, accelerator HW, TI, detectors) are based on the study conducted for the ILC machine with a c.o.m. energy of 250 GeV, see Refs. [9, 10], and adapted to account for the design differences, in particular a second BDS, a third damping ring for FP operation, and longer tunnel. No estimate of GHG emissions associated with the construction of the surface buildings is available. For LCF, these comprise mainly a detector assembly hall at the IP location and supply buildings for electricity, cooling and cryogenic plants at the access shaft locations. All injectors and pre-accelerators are located underground in tunnels that are included in the GHG emission estimate.

Table 3.2: GHG emissions of the CLIC [10], FCC-ee [23]and LCF construction. The range of values for the CE works considers the advancements in cement production and concrete constructions as discussed in Section 2.2.1. In a similar fashion, the range for the GHG emissions associated with the construction of accelerators, technical infrastructure and detectors provide an indication of the possible reduction achievable by optimisation of the design, choice of the materials and of the construction methods as provided in Ref. [10]. The range of values for carbon intensity of electricity generation is taken from Table 2.1. The expected electricity consumption of off-line computing is also included. It has been assumed that the electricity consumption per experiment is the same for all the e^+e^- collider proposals. The estimate is based on the expected requirements for FCC-ee [24] and the energy consumption for the off-line computing for LHC [25] and on the expected HW performance evolution. A range of values is provided to account for different levels of development of the off-line reconstruction algorithms [26]. The present CERN GHG annual emissions amount to approximately 360 kt CO_2 eq./y [27].

	CLIC (2 IPs)	FCC-ee (4 IPs)				LCF (2 IPs)		
						250 LP	250 FP	
c.o.m. energy [GeV]	380	91.2	160	240	365	250	91.2	250
Civil engineering (A1–A5)								
Underground [kt CO_2 eq.]	143–286	480–1000				190–380[a]		
Surface sites [kt CO_2 eq.]	59–118	50–184				N/A		
Total GHG emissions from CE [kt CO_2 eq.]	202–404	530–1184				>190–380		
Operation period with CE infrastructure [years]	20[b]	39[b]				20[b]		
Accelerators, technical infrastructure, detectors								
Accelerators (A1–A3) [kt CO_2 eq.]	105–140	N/A[c]				169–225	+18–+24[d]	
Technical infrastructure (A1–A3) [kt CO_2 eq.]	14–19	N/A[c]				35–46[e]		
Detectors (A1–A3) [kt CO_2 eq.]	71–94	142–186[f]				71–94[g]		
Total GHG emissions for accelerator, TI and detector HW [kt CO_2 eq.]	190–253	N/A				>275–365	>293–389	
Number of years of physics operation	10	4	2	3	5	5	1	3
Electricity consumption								
Carbon intensity of electricity generation [g CO_2 eq. per kW h]	14–18							
Accelerators and detectors [TW h/y]	0.82	1.2	1.3	1.4	1.9	0.8	0.7	1.0
Off-line computing [TW h/y]	0.07–0.14	0.14–0.28				0.07–0.14		
GHG emissions/year of physics operation [kt CO_2 eq./y]	12–17	18–26	20–29	22–31	29–40	13–17	10–14	15–20

[a] Based on a rescaling of the CE carbon footprint of CLIC.
[b] Include the expected physics operation of FCC-hh for 25 years, of CLIC–1.5 TeV for 10 years and of LCF–550 GeV for 10 years.
[c] The LCA for the systems having the largest impact is under way.
[d] GHG emissions for the injectors' upgrade to run at FP.
[e] Based on the estimate for Main Linac services, scaled up to cover injectors and BDS.
[f] We assume that FCC-ee will use detectors very similar to the LC ones, so we scale here the emissions on the base of four detectors for FCC-ee.
[g] A1 estimate provided [10] for the main materials in LCF detectors, not including supports, experimental infrastructure or services.

3.2.2 Consumption of land

CLIC

The tunnel of the baseline 380 GeV collider includes four access shafts, two of which are serving the IP and are located in land attributed to CERN close to the Prévessin site, and two are located at the extremities of the tunnel. An energy upgrade to 1.5 TeV would require the construction of additional four shafts. The orientation and depth of the tunnel are adapted to the maximum operating energy of 1.5 TeV. The exact location of the shafts needs detailed studies in the next phase of the project. The main parameters defining the consumption of land are summarized in Table 3.3.

FCC-ee

Compared to an initial scenario of 97.75 km length and twelve surface sites considered in the 2019 Conceptual Design Report [28], the reference scenario is now a 90.65 km long circular collider with eight surface sites. The space requirements for the surface sites have also been gradually reduced. Except for the damping ring (located in land attributed to CERN), the injector is entirely located inside the fenced area of the CERN Prévessin site, thus not consuming any additional land. One experiment site (PA) leverages synergies with the existing LHC Point 8 site in Ferney-Voltaire.

With eight surface sites, FCC-ee requires approximately 0.5 km^2 of land, down from 1.1 km^2 in the initial scenario. In total, about 0.26 km^2 of this land would be constructed. About 0.08 km^2 involve areas with ecological value. The indicated values include all the space necessary for a subsequent FCC-hh phase and include all the buffer zones required for landscape integration. All sites are located close to roads and highways. A total of about 3 km of new road construction are required. The main parameters defining the consumption of land are summarized in Table 3.3.

LCF

The 33.5 km long tunnel includes three access shafts, for accelerator and detectors, at the IP. These are located in land attributed to CERN close to Prévessin site. Along the tunnel there are four access points on each side. As for CLIC the exact location of the shafts needs detailed studies in the next phase of the project. For LCF it is possible to move the IP infrastructure inside the CERN fence if this is advantageous, as there are no conflicts with a drive beam. The main parameters defining the consumption of land are summarized in Table 3.3.

Table 3.3: Area of land consumed by the CLIC, FCC and LCF projects, i.e. lying outside the fenced CERN site. The fraction of the area that lies outside the land attributed to CERN is indicated in parentheses (the rest lies outside the CERN fence but still within CERN-attributed land).

	CLIC 380 GeV	FCC-ee	LCF
Number of new access shafts	4	12	11
Number of new surface sites	3	8	9
Area of land permanently consumed (fraction outside CERN-attributed land) [km^2]	0.37 (14%)	0.5 (100%)	0.34 (62%)
Area of surface constructions (fraction outside CERN-attributed land) [km^2]	0.118 (5%)	0.26 (100%)	0.073 (55%)

3.2.3 Other measures to reduce the environmental impact during construction and operation

Currently, approximately 90% of CERN's direct GHG emissions come from its experiments. These use a wide range of gas mixtures for particle detection and detector cooling, including fluorinated gases (F-gases) which have a high Global Warming Potential (GWP) and therefore account for about 78% of CERN direct emissions [27]. Design of detectors with improved gas tightness and R&D towards detector gases with lower GWP is pursued [29] within the Detector R&D (DRD) Collaborations to reduce significantly and/or possibly eliminate this contribution.

CLIC

Means of reducing the GHG emission and cost associated with the electricity required to operate the complex by optimizing the machine schedule have been considered and the possibility of reusing the waste heat has been explored [30]. A more comprehensive approach, as followed by FCC, would be part of future environmental studies.

FCC-ee

The FCC project takes a comprehensive approach to reduce its environmental impact across construction, operation, and long-term sustainability. Key strategies outlined in Ref. [31] include, among others:

- reuse of excavated materials in construction, agriculture, and ecological restoration;
- waste heat recovery;
- gas management in detectors;
- ecosystem and biodiversity protection with site-specific plans to minimize disruption to local wildlife and ecosystems;
- water conservation to maintain the operational demands within the current CERN levels.

Following an analysis of the demand potential for low-grade heat in the vicinity of the surface sites [32, 33], FCC will integrate the recovery and supply of heat. The concept has been successfully demonstrated with an installation in Ferney-Voltaire (France) in relation to the LHC Point 8. The supply of heat allows reducing the consumption of electricity and water of the cooling system because of the lower demand for operating the evaporation towers.

Depending on the mode of operation, between 300 and 424 GW h of heat can be supplied per year on a perimeter of 5 km with a minimum of 60 GW h during shutdown periods. Supplying these amounts of heat directly results in a reduction of 24% to 30% of the expected water intake per year, which varies from 1.5 to 2.8 million m^3 according to the mode of operation, and of the power consumption of the cooling circuits.

3.3 Technical readiness and R&D requirements

CLIC

The recent review of the LDG accelerator R&D programme has analysed, among others, the status of the R&D of the main RF components of the large accelerator projects [34, 35]. The CLIC design relies on the achievement of gradients >72 MV m^{-1} over a large number of X-band high-gradient structures. This gradient has been exceeded, but on a limited number of structures. Demonstration of reproducibility of performance over larger samples and with acceptable conditioning times as well as industrialization of the production are key goals for the next phase of the project.

The drive-beam linac is the main post contributing to the overall CLIC electricity consumption. An efficiency of 82% for the L-band klystrons powering it is targeted; 70% has been reached with industrial prototypes, but prototyping of new cost-effective designs for higher efficiency is needed [35, 36].

LCs require larger rates of positron production as compared to circular colliders where the beams are stored and only losses need to be compensated for. CLIC average positron intensity is a factor 16 higher than that required for FCC-ee, which exceeds by a factor two the maximum intensity achieved so far at SLC. Demonstration of such performance for CLIC is for the time being at component level (TRL 5) [13].

CLIC performance relies on the capability to preserve the emittance of the beams delivered by the damping rings all through the main linac and the BDS and to minimize the chromatic aberrations resulting from the extremely small optics waist at the IP. This implies achieving an excellent control of the wakefields in the accelerator and of the optics at the final focus to maintain in collision nanometric vertical beam sizes (a factor 4 smaller than for LCF and at least 20 than for FCC-ee) at the IP in a reproducible fashion demanding complex feed-forward systems to minimize the effects of ground motion and temperature variations. Though quite some experience has been gained at the Final-Focus Test Beam (FFTB) and Facility for Advanced Accelerator Experimental Tests (FACET) at the Stanford Linear Accelerator Center (SLAC) and at the Accelerator Test Facility (ATF) at KEK, the demonstration of wakefield minimization in long accelerating sections and beam spot size control and stability at the IP under realistic conditions remain major challenges that require further validation with beam tests for the CLIC proposal. These challenges and the TRL levels of the associated technologies are discussed in Ref. [13].

The five most critical/high-risk systems/components for which R&D effort is still required before reaching a sufficient level of confidence for construction are listed in Table 3.4 in order of increasing TRL.

Table 3.4: Technical readiness and R&D requirements for CLIC. The colour code corresponds to the code used in Ref. [35].

Component/Sub-system	TRL	Main parameter to be improved	Improvement factor	R&D effort Personnel [FTEy]	Material [MCHF]	Timescale [years]
High-efficiency klystrons for drive-beam linac	4	Efficiency	1.2	6	3	4
X-band high-gradient structures	5	Industry yield / gradient	Verification	36	12	6
Positron source	5	e^+ rate	33	8	3	6
IP spot size/stability	5	BDS	1.3	18	4	6
Emittance preservation	6	ML	1.3	6	2	4

The R&D items described above are part of a larger six year preparation phase programme, which also covers site specific studies and further design and parameter optimisation, described in Ref. [20]. The klystron efficiency has a softer impact than the others. The performance improvements that can be expected within the R&D programme described cover improvements in damping emittances and emittance preservation methodology, as well as a potential shortening of the beam-delivery system. These improvements are currently foreseen to increase the robustness of the design, but can also, combined with technical studies, potentially reduce costs and power consumption of the collider in the 3–10% range.

FCC-ee

The power consumption estimated for FCC-ee relies on the availability of HE klystrons with efficiencies of 85% in the range of frequency from 400 to 800 MHz. Significant progress has been made in this technology, also boosted by the need of replacing the LHC klystrons, indicating a TRL 4 [34–36]. Further improvement in efficiency could be obtained with multi-beam Tristrons (not considered in the baseline for the time being) though these have a lower TRL (2 to 3) [35]. The analysis presented in Refs. [34, 35] indicates a TRL 4 for both the 800 MHz RF cryomodules operated at 2 K and the 400 MHz RF cryomodule operated at 4.5 K. The positron source performance is very close to the SLC positron source one and significantly less demanding than those of the CLIC and LCF sources. The FCC-ee vacuum system performance relies on distributed Non-Evaporable Getter (NEG) pumping with fast conditioning of localised synchrotron radiation absorbers. The R&D of several critical technologies to fulfil FCC-ee requirements and/or to reduce costs is in full swing for the pre-TDR phase. The main challenge is to minimise costs by making these technologies scalable, industrially viable, and capable of operating with low maintenance and operational costs. The five most critical/high risk systems/components for which R&D effort is still required before reaching a sufficient level of confidence for construction are listed in Table 3.5 in order of increasing TRL.

Table 3.5: Technical readiness and R&D requirements for FCC-ee. The colour code corresponds to the code used in Ref. [35].

Component/Sub-system	TRL	Main parameter to be improved	Improvement factor	R&D effort Personnel [FTEy]	R&D effort Material [MCHF]	R&D effort Timescale [years]
RF power sources	4	Efficiency	1.3	~10	~6	5–6
800 MHz RF cavities[a]	4	Q_0	6	~10	6	5–6
400 MHz RF cavities[b]	4	Gradient	2	~12	6	5–6
Vacuum system	6	Cost & industrialisation	2 (on cost)	10	10	5–6
Positron source	6	e^+ rate	2	20	2	4

[a] Bulk-Nb 800 MHz RF cavities operated at 22.5 MV m^{-1} with $Q_0 = 3.5 \cdot 10^{10}$ [21].
[b] Nb-coated copper 400 MHz RF cavities operated at 11.8 MV m^{-1} with $Q_0 = 2.7 \cdot 10^{9}$ [21].

LCF

As compared to ILC the 1.3 GHz cavities are assumed to reach $Q_0 \geq 2 \times 10^{10}$ in the cryomodules, twice the value considered for ILC, in order to double the operational repetition rate. Given the large number of items of this type, this must be re-assessed after industrial level studies for the proposed new surface treatments are available [13, 37]. The LCF baseline design foresees a 6% margin of additional cryomodules in the 250 GeV configuration, and would reach 240 GeV c.o.m. energy with an average gradient of 28.5 MV m^{-1} in the main linac. Furthermore, the associated risk can be alleviated by installing larger number of modules than the minimum required based on the experience during production, or by an increase of the cryogenic cooling. This is possible thanks to the length of the tunnel designed for a c.o.m. energy of 550 GeV.

As mentioned earlier, linear colliders have demanding positron rates, in particular the LCF FP requires a factor around 90 higher production rate as compared to that achieved at the SLC.

Emittance preservation and IP spot/size stability remain critical aspects also for LCF, though to a lesser extent as compared to CLIC, due to the larger aperture of the L-band RF cavities. BDSs for two experiments were extensively studied in the past but need to be improved and adapted to the machine layout at CERN. Beam sharing between two experiments provides additional reproducibility/stability challenges for the beam position at the IP. The LCF requirements have been partially demonstrated at the ATF at KEK.

The main dumps and their entry windows are a critical item as they need to be able to absorb 17 MW beam power. Their design, based on the 2 MW SLAC water dump, needs to be validated.

An efficiency of 80% is assumed for the klystrons powering the main linac RF cavities, based on the same two-stage design as considered for CLIC and FCC-ee. Present devices have an efficiency of about 65%. The TRL for the required power sources has been assessed to be 4 [34,36]. Failure to achieve the target efficiency will imply more powerful modulators and cooling systems and therefore higher costs and larger power consumption though these are considered to remain in the percent range.

Table 3.6 summarizes the most critical elements above described.

3.4 Construction and installation costs

CLIC

The capital cost for construction of CLIC is summarised in section 3.7. This cost includes construction of the entire new infrastructure and all equipment for operation up to 380 GeV. Collider includes main linac and decelerators in the main tunnel as well as Beam Delivery System (BDS), final focus and post collision lines and dumps. The cost of the experiments includes the full cost of the detector and the required infrastructure.

Table 3.6: Technical readiness and R&D requirements for LCF. The colour code corresponds to the code used in Ref. [35].

Component/Sub-system	TRL	Main parameter to be improved	Improvement factor	R&D effort Personnel [FTEy]	R&D effort Material [MCHF]	R&D effort Timescale [years]
RF power sources	4	Efficiency	1.25	10	3	3
Positron source	5	Target cooling Pulsed solenoid peak field	N/A	15	5	3
Main dump	5	Maximum power	8	4	2	5
IP spot size/stability	6	Vertical beam size at nominal bunch population	10%	18	4	6
1.3 GHz RF cavities/cryomodules	7	Q_0	2	30	10	3

Table 3.7: Cost summary table in 2024 MCHF for the CLIC accelerator operating up to a maximum c.o.m. energy of 380 GeV—with two experiments [20]. Cost classes are defined in Table A.4. The total cost of the experiments is listed here—it is expected that CERN contribution to the detector construction plus host laboratory responsibility is 146 MCHF. Costs related to land, roads, electricity and water connections as well as for administrative processes and underground rights-of-way are not included, though these are expected to represent only a minor contribution to the total cost (at the percent level).

Domain	CLIC – 380 GeV Cost [MCHF]	CLIC – 380 GeV Cost class
Collider	2471	3–4
Main beam production and transfer lines	1046	3–4
Drive beam production and transfer lines	1060	3–4
Civil engineering	1403[a]	4
Technical infrastructures	1361	3–4
Experiments	795	4
TOTAL	**8136**	

[a] The cost for spoil removal (estimated at 100 MCHF) is included here.

FCC-ee

The main cost items for the construction of FCC-ee are listed in Table 3.8. This cost includes construction of the entire new infrastructure and all equipment for operation up to 240 GeV. Operation at higher energies will require later installation of additional RF cavities and associated cryogenic cooling infrastructure with a corresponding total cost of 1260 MCHF. The cost estimate has not varied significantly as compared to that presented in the 2024 mid-term report. The latter was the subject of an extensive external review whose conclusions and recommendations have been reviewed by the CERN Finance committee and Council.

Table 3.8: Cost summary table in 2024 MCHF for the FCC-ee accelerator operating up to a maximum c.o.m. energy of 240 GeV—with four experiments [21]. Cost classes are defined in Table A.4. The total cost of the experiments is listed here—it is expected that CERN contribution to the detector construction plus host laboratory responsibility is 292 MCHF.

Domain	FCC-ee – 240 GeV Cost [MCHF]	FCC-ee – 240 GeV Cost class
Booster and collider	4140	3
Pre-injectors and transfer lines	590	3
Civil engineering	6160	3
Technical infrastructures	2840	3
Experiments	1590	4
TOTAL	**15320**	

LCF

The LCF cost estimates are based on the ILC TDR [38], updated in 2017 [39] and in 2024 by the International Development Team (IDT) [40–42] and on a new evaluation of the construction costs for the CERN site from 2025 [43]. The updated 2024 cost estimate was reviewed by an international expert panel in December 2024 [40]. The total cost for the baseline 250 GeV LCF LP configuration amounts to 9287 MCHF in 2024 prices, as presented in Table 3.9, The additional cost of the upgrade to FP is 770 MCHF.

Table 3.9: Cost summary table in 2024 MCHF for the LCF accelerator operating up to a maximum c.o.m. energy of 250 GeV—with two experiments [37]. Cost classes are defined in Table A.4. Land acquisition and site activation (external roads, water supplies, power lines) are not costed, though these items are expected to represent a minor contribution to the total cost (at the percent level). The total cost of the experiments is listed here—it is expected that CERN contribution to the detector construction plus host laboratory responsibility is 146 MCHF.

Domain	LCF LP – 250 GeV	
	Cost [MCHF]	Cost class
Collider	3864	3
Injectors and transfer lines	1181	3
Civil Engineering	2338[a]	4
Technical infrastructures	1109	4
Experiments	795	4
TOTAL	**9287**	

[a] The cost for spoil removal (estimated at 200 MCHF) is included here.

3.5 Accelerator construction and installation: human resources

CLIC

According to Eq. (1), approximately 10 500 FTEy of explicit labour would be required for the construction of CLIC and its technical infrastructure.

FCC-ee

An integrated total of approximately 15 000 FTEy is required for the accelerator construction and installation. This estimate was obtained through various approaches that converge on a similar result:

- an overall fit based on scaling from comparable accelerator infrastructures;
- scaling by individual equipment type;
- a bottom-up approach.

According to Eq. (1), approximately 13 100 FTEy would be required for the construction of the accelerators and their technical infrastructure (the latter including that of the experiments).

LCF

The personnel required for the construction of the 250 GeV baseline LP configuration is estimated in Ref. [39] and it amounts to 10 120 FTEy, to be compared with 10 900 FTEy estimated according to Eq. (1).

3.6 Project timeline

FCC-ee

Preparatory placement studies for the FCC are well advanced. The further timeline is mainly determined by the preparation of the civil engineering (subsurface investigations, civil engineering design and tendering, and the project authorisation processes with the host states, planned to advance in parallel), and, afterwards, by the civil construction and the subsequent installation of technical infrastructure and accelerator components. Key dates are summarized in Table 3.10, including work already accomplished.

Table 3.10: Timeline for design, construction, and operation of FCC-ee.

Milestone	FCC-ee
Conceptual Design Study	2014–2018
Definition of the placement scenario	2022
Preliminary implementation with the Host states	2024–2025
Feasibility Report ready	2025
Earliest Project Approval[a]	2028
Environmental evaluation & project authorisation processes	2026–2031
Main technologies R&D completion[b]	2031
Technical Design Report ready[c]	2032
Civil engineering	2033–2041
TI installation	2039–2043
Accelerator installation	2041–2045
HW commissioning	2042–mid 2046
Beam commissioning – collider	mid 2046–2047
Physics operation start	2048

[a] This is the approval by the Council and it must follow the process of the Update of the European Strategy for Particle Physics—assumed to take at least two years once the feasibility report is delivered.
[b] Based on the information in Table 3.5.
[c] The TDR can be delivered only once the environmental evaluation, project authorization processes and main technologies R&D is completed.

CLIC

A timeline for the implementation of the CLIC project has been outlined in Ref. [20]. This is summarized in Table 3.11 where the main phases are sketched, including those already achieved. The timeline suggests initial preparatory phase studies to finalise the collider design and optimise its placement, in parallel with technical studies. It is followed by a extended preparatory phase for implementation studies with the host states, environmental studies and industrialization. The technically-limited seven year construction timeline assumes [20]:

- three years for the civil engineering works (drive beam, injectors, collider, surface infrastructures);
- four years for the installation of the drive beam, injector and collider HW;
- one year of HW commissioning of the collider followed by one year of beam commissioning of the collider.

Some of these activities overlap in time as they affect different areas (e.g. injectors and collider).

While the initial phase requires limited resources and can be implemented as a potential outcome of the strategy update, specific decisions processes are needed for entering in an extended preparatory phase and construction. This is indicated in Table 3.11 by starting these phases at T_0 and T_1, and indicating their length with respect to these starting times. To accommodate the fact the transition between the phases might require some time, and also to avoid the clear conflict between operating HL-LHC and beam commissioning of a new collider, the construction phase is increased in the table to take ten years before beam commissioning, instead of the technically-limited seven years.

LCF

The implementation studies for CLIC and LCF have been done in common over the last two years. The timeline for LCF is very similar and organised in the same phased structure: Preparation phases 1 and 2 are followed by construction, as for CLIC in Table 3.11.

Table 3.11: Timeline of essential development and construction steps of the CLIC and LCF projects. T_0 is determined by a process in 2028–29 to validate the progress and promise of the project for a further development towards implementation. T_1 following Preparation Phase 2 will be determined by the processes needed, by the CERN Council and with host-states, for project approval and to start construction. The construction phase is extended as explained in the text with respect to the technically-limited schedules to allow a transfer time into construction, and to avoid the resource conflict between HL-LHC operation and initiating beam commissioning for a next collider. While many aspects can initially be studied together for the two options, it will be necessary to prioritize one of the two LC options for detailed implementation studies during Phase 1.

Milestone	CLIC	LCF
Conceptual/Reference Design Report	2004–2012	2002–2007
Site-independent TDR for ILC 500 GeV		2007–2013
Project Implementation Plan, Readiness Report	2013–2025	
ILC 250 GeV reports and Prelab planning		2013–2025
Project Preparation Phase 1	2026–2028	
Definition of the placement scenario Design optimisation and finalization Main technologies R&D conclusions Technical Design Report—two IPs at CERN		
Project Preparation Phase 2	T_0–(T_0+5)	
Site investigation and preparation Implementation studies with the host states Environmental evaluation & project authorisation processes Industrialisation of key components Engineering design completion		
Construction phase (from ground breaking)	T_1–(T_1+10)	
Civil engineering Construction of components Installation and hardware commissioning		
Beam commissioning and physics operation start	T_1+11	

The LCF RF technology is industrially more mature and requires less development resources than for CLIC. The construction, installation and commissioning timeline is mostly based on the ILC one [38]:

- four years for the civil engineering works (drive beam, injectors, collider, surface infrastructures);
- four years for the installation of the TI and of the accelerator HW;
- one year of HW commissioning of the collider followed by one year of beam commissioning of the collider.

This schedule has some overlapping activities as work affects different areas. The experience from construction and installation of existing SRF linacs has been folded into this schedule providing important guidelines for resources needed and schedules to use. Nevertheless, as for CLIC, to accommodate the fact the transition between the phases might require some time, and also to avoid the clear conflict between operating HL-LHC and beam commissioning of a new collider, the construction phase is increased in Table 3.11 from eight to ten years before commissioning is started.

3.7 Collider complex operation: resources requirements

Table 3.12 summarizes the resources required for the operation of the CLIC, FCC-ee and LCF colliders:

- annual maintenance and replacement material costs estimated according to the methodology defined in Section 2.7 by individually categorising each item of equipment according to its nature;

– annual electricity cost range according to the operation energy (or beam power for LCF) based on the annual electricity consumption in Table 3.1;
– personnel required for the operation of the collider complex and its experiments' technical infrastructure.

Table 3.12: Annual resource requirements for the operation of the accelerator complex of the proposed e^+e^- colliders at CERN.

	CLIC 380 GeV	FCC-ee 91.2–365 GeV	LCF 250 GeV LP–FP
Maintenance and replacement material cost [MCHF/y]	137	200[a]	170[b]
Electricity cost [MCHF/y]	63	92–146	61–77
Personnel for operation of the future collider accelerator complex [FTE/y]	650	950	800

[a] Average of the costs for the different energy configurations.
[b] Average of the costs for the LP and FP configurations.

4 Future collider options at CERN for operation beyond 2050: e^+e^- colliders

4.1 Main parameters and performance

CLIC 1.5 TeV

After ten years of operation with the baseline configuration it is proposed to upgrade the collider to provide collisions to a c.o.m. energy of 1.5 TeV. This is within the maximum achievable energy with a single drive-beam accelerator whose energy will have to be increased from 1.91 GeV to 2.4 GeV. The number of colliding bunches per pulse will be reduced from 352 to 312 and their population will be reduced from 5.2×10^9 to 3.7×10^9 to permit the acceleration to higher gradients. The repetition rate will be reduced from 100 to 50 Hz to keep the power below 300 MW. Only one IP will be served. The upgrade to higher energies requires an increase of the length of the tunnel and of the main linacs, connecting new tunnels to existing tunnels, moving the existing modules providing accelerating gradients of 72 MV m^{-1} at the extremities of the new tunnels and adding new, higher-gradient (100 MV m^{-1}) modules. The length of the BDS needs to be increased and new magnets installed. The main-beam production complex needs only minor modifications while the drive-beam complex needs to be extended to increase the drive-beam energy. The overall length of the collider tunnel will be 29.6 km. New detectors are currently not considered, but upgrades and improvements will be important. The main parameters after the upgrade are listed in Table 4.1.

An alternative upgrade to 550 GeV, maintaining the repetition rate at 100 Hz and two IPs, is also considered. A possible implementation would be to start with a longer tunnel by 5 km from the beginning adding about 25% to the initial cost of the CE of the baseline 380 GeV machine. CLIC at 550 GeV provides $\sim$45% higher luminosity than the 380 GeV collider, at $\sim$30% higher cost and power [20].

LCF 550 GeV

The upgrade in energy from 250 to 550 GeV is proposed to take place after ten years of operation at 250 GeV and it would require a LS of two years assuming that the upgrade from LP to FP has already taken place in the previous phase. It does not require any additional CE as the length of the collider tunnel has been defined based on the requirements for a c.o.m. energy of 550 GeV assuming nominal parameters for the SRF cryomodules. The bulk of the upgrade will consist in the installation of additional cryomodules. Technology improvements could reduce the number of modules needed. As for CLIC new detectors are not required, but upgrades and improvements will be important. The main parameters after the upgrade are listed in Table 4.1.

Table 4.1: Main parameters for CLIC and LCF after upgrade. The instantaneous and integrated luminosity in-between parentheses includes also the contribution from energies below 99% of the c.o.m. energy $\sqrt{s}$.

	CLIC	LCF FP
Length collider tunnel [km]	29.6	33.5
Number of experiments (IPs)	1	2
c.o.m. energy [GeV]	1500	550
Longitudinal polarisation (e^- / e^+) [%]	±80 / 0	±80 / ±60
Number of years of operation (total)	10	10
Nominal years of operation (equivalent)[a]	9[b]	9[b]
Instantaneous luminosity per IP above 0.99 $\sqrt{s}$ (total) [10^{34} cm^{-2} s^{-1}]	1.4 (3.7)[c]	2.25 (3.85)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs per year of nominal operation [ab^{-1}/y]	0.17 (0.44)[c]	0.54 (0.92)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs over the full programme [ab^{-1}]	1.51 (3.96)[c]	4.85 (8.32)
Peak power consumption [MW]	287	322
Electricity consumption per year of nominal operation [TW h/y][d]	1.4	1.8

[a] This row lists the equivalent number of years of operation at nominal instantaneous luminosity, hence taking into account the luminosity ramp-up.
[b] A luminosity ramp-up is assumed with a luminosity corresponding to 25% and 75% over the first two years, respectively.
[c] The improvement in luminosity obtained recently for CLIC 380 GeV, has not been included for CLIC at 1.5 TeV, because the start-to-end studies have not yet been been completed at that energy.
[d] Computed from the peak power consumption and the assumptions on the operational year (see Table A.1).

4.2 Environmental aspects

In the following we identify the main origins of the additional GHG emissions but no detailed estimate is available to provide quantitative values. The corresponding contributions have even larger uncertainties than those provided for the baseline configuration also considering that low carbon technologies might have further progressed by the time of the construction (expected to take place at the earliest at the end of the 50s) and low- or zero- carbon electricity might be available. Considerations on the consumption of land are also added.

CLIC 1.5 TeV

The additional GHG emissions associated to the energy upgrade are related to:

- the CE work required to the extension of the tunnel, the construction of four additional shafts outside of the CERN fence, the associated surface buildings, and the construction of two additional underground turn-around loops to transport the drive beam;
- the construction, transport and installation of the accelerator HW and the associated technical infrastructure;
- generation of the electricity required for the operation of the collider.

The construction of the four additional shafts and corresponding surface sites will require to consume additional land outside of the CERN fence.

LCF 550 GeV

The additional GHG emissions associated to the energy upgrade are related to:

- the construction, transport and installation of the accelerator HW and the associated technical infrastructure;
- generation of the electricity required for the operation of the collider.

No additional CE or land consumption are necessary.

4.3 Technical readiness and R&D requirements

CLIC 1.5 TeV *and LCF* 550 GeV

Both upgrades build on the technologies developed for the baseline configuration though pushing further the requirements on gradients and on stabilization due to the reduced beam size at the IP. The necessary technologies are expected to be mature by the time of the upgrades also considering the experience gained in the first low-energy phase of operation of the colliders.

4.4 Construction and installation costs

CLIC 1.5 TeV

The cost of the upgrade of CLIC from 380 GeV to 1.5 TeV is expected to amount to 7116 MCHF. The breakdown in the main items is presented in Table 4.2. The CE costs for the tunnel extension will also need to consider costs related to land, roads, electricity and water connections as well as for administrative processes and underground rights-of-way, as for the initial stage. The cost uncertainty for the upgrade is similar to that for the construction of the baseline version as both versions share the same technology.

Table 4.2: Cost summary table in 2024 MCHF for the upgrade of the CLIC accelerator from 380 GeV to 1.5 TeV with one IP [20]. Cost classes are defined in Table A.4. The cost of possible detector upgrades is not included.

Domain	CLIC – 1.5 TeV	
	Cost [MCHF]	Cost class
Collider	4684	3–4
Main beam production and transfer lines	23	3–4
Drive beam production and transfer lines	302	3–4
Civil engineering	703	4
Technical infrastructures	1404	3–4
Experiments	N/A	
TOTAL	**7116**	

LCF 550 GeV

The cost of the upgrade of LCF from 250 GeV to 550 GeV is expected to amount to 5464 MCHF. The breakdown in the main items is presented in Table 4.3. Here it is assumed that the upgrade from LP to FP has taken place during the previous phase. The cost uncertainty for the upgrade is similar to that for the construction of the baseline version as both versions share the same technology.

Table 4.3: Cost summary table in 2024 MCHF for the upgrade of the LCF FP collider from 250 to 550 GeV—with two IPs [37]. Cost classes are defined in Table A.4. The cost of possible detector upgrades is not included.

Domain	LCF FP – 550 GeV	
	Cost [MCHF]	Cost class
Collider	4204	3
Injectors and transfer lines	86	3
Civil Engineering	0	
Technical infrastructures	1174	4
Experiments	N/A	
TOTAL	**5464**	

4.5 Project timeline

CLIC 1.5 TeV

The construction and installation of the upgrade extend over a period of 4.5 years and the decision about the next higher energy stage would need to be taken after 4–5 years of data taking in the baseline configuration. Most of the construction and installation work can be carried out in parallel with the data-taking at 380 GeV. According to the proponents a LS of two years is needed to make the connection between the existing machine and its extensions, to reconfigure the modules, and to modify the BDS. This timescale is ambitious and needs to be reevaluated based on experience from the initial stage.

LCF 550 GeV

Differently from CLIC preparation work in the tunnel for the upgrade will be more limited as the additional SRF cryomodules will be installed in the same tunnel of the 250 GeV machine, but no CE is required. According to the proponents, the activities will take place during a LS of two years. As for CLIC this timeline will need further reevaluation based on the initial stage experience.

5 Future collider options at CERN for operation beyond 2050: FCC-hh

5.1 Main parameters and performance

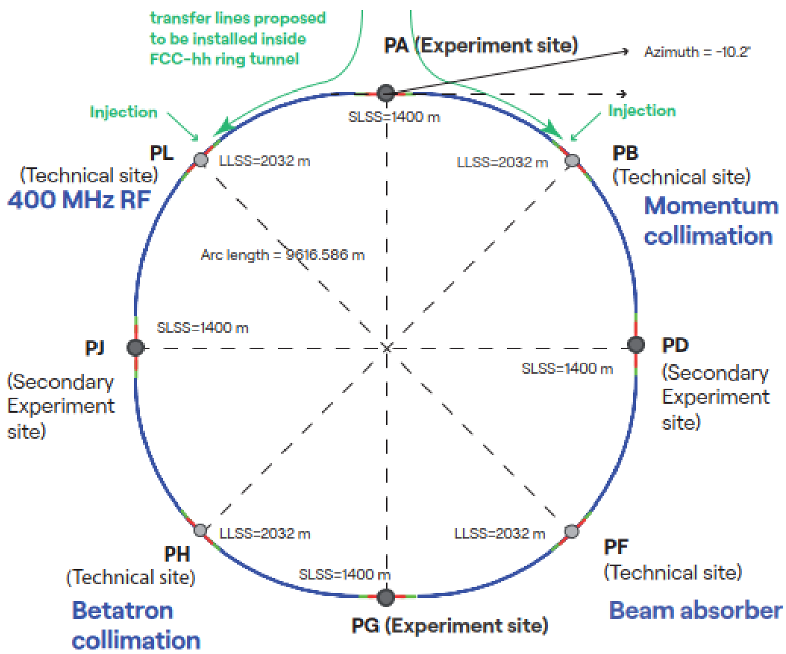

Fig. 5.1: Schematic diagram of the FCC-hh collider.

FCC-hh will be installed in the same tunnel of FCC-ee and the current baseline c.o.m. energy is approximately 85 TeV. The present design allows four collision points and experiments. Two multi-purpose detectors are operated at high-luminosity and the other two specialised detectors are operated at lower luminosity. In addition to colliding protons with protons, also proton-ion and ion-ion collisions are envisaged. A schematic diagram of FCC-hh is shown in Fig. 5.1. FCC-hh shares much of the CE and TI of FCC-ee [21].The FCC-hh baseline [28] assumes 14 T magnets whose performance is closer to the state of the art of Nb_3Sn technology and are a relatively lower-risk and potentially fast-tracked option [21]. R&D towards HTS magnets is pursued and could enable higher collision energies.

The main parameters for FCC-hh are compiled in Table 5.1. The table illustrates how the synchrotron radiation strongly increases with higher magnetic field. The synchrotron-radiation heat, which must be extracted from inside the cold magnets, is a major contribution to the thermal load on the cryogenic system. To limit the latter and also because the radiation damping during the store is significant, the beam current and the bunch population are relaxed compared to those of the HL-LHC. The synchrotron radiation power has been significantly reduced by reducing the magnetic field from 16 to 14 T as compared to the CDR [44].

Table 5.1: Parameters of FCC-hh compared with the nominal HL-LHC and LHC designs. The plan to operate the Nb_3Sn magnets at 4.5 K, being studied, would further reduce the annual electricity consumption to 1.8 TW h/y.

	FCC-hh	HL-LHC	LHC
c.o.m. energy [TeV]	84.6	14	
Circumference [km]	90.7	26.7	
Arc dipole field [T]	14	8.33	
Beam current [A]	0.5	1.1	0.58
Synchrotron radiation power per beam [kW]	1200	7.5	3.5
Peak luminosity per IP [$10^{34}\,cm^{-2}\,s^{-1}$]	30	5 (levelling)	1
Peak number of events per bunch crossing	1000	132	27
Integrated luminosity per IP per year of nominal operation [ab^{-1}/y]	0.9	0.25	0.05
Electricity consumption per year of nominal operation [TW h/y][a]	2.0[b]	0.8	0.7

[a] The power consumption of the injectors is not included.
[b] Computed from the peak power consumption and the assumptions on the operational year (see Table A.2).

Three options for an FCC-hh injector exist. All options can deliver the main beam parameters required, such as intensity, emittance, and bunch spacing. The main difference is the implied FCC-hh injection energy. An attractive option for a high-energy injector is a new 4 T machine in the LHC tunnel. Another possibility, with intermediate beam energy, is a 2 T superferric machine. If a collider injection energy of 1.3 TeV is acceptable, a SC ring in the SPS tunnel (Superconducting Super Proton Synchrotron—scSPS) becomes attractive.

5.2 Environmental aspects

Efforts are ongoing to minimize the power consumption of the collider. The introduction of an *eco-mode* for the cryogenic system during shutdown periods reduces the power consumption during non-operational periods. In addition the possibility of operating the Nb_3Sn magnets at 4.5 K is being investigated and it would reduce the annual electricity consumption to 1.8 TW h/y.

Most of the CE and land consumption for FCC-ee have been conceived considering the needs for FCC-hh. The only additional underground structures that will have to be built for FCC-hh [21] are:

- two beam dump tunnels (approximately 2 km long in total) and caverns with corresponding junction tunnels;
- two transfer line tunnels with a total length varying between 2.5 and 5.7 km, depending on the selected option for the injector.

Additional surface CE will be required for FCC-hh as compared to FCC-eefor the assembly halls of at least the two largest FCC-hh experiments and to provide additional space for additional cryogenics and cooling plants. Space reservations will already be made during the FCC-ee design phase.

5.3 Technical readiness and R&D requirements

The key challenges for the construction of FCC-hh are the HFM technology and power consumption in the presence of strong synchrotron radiation. The technologies needed for delivery that are still under development, and the target performance parameters of each development are summarised in Table 5.2.

Table 5.2: Technical readiness and R&D requirements for FCC-hh. The material and personnel estimates refer to CERN contribution, the contributions from collaborations is not included.

Component/Sub-system	TRL	Main parameter to be improved	Improvement factor	R&D effort Personnel [FTEy]	Material [MCHF]	Timescale [years]
Nb_3Sn conductor[a]	7	Cost & industrialisation (more manufacturers)	3	10	30	7
Nb_3Sn magnet short model	6	Max. field[b]	20%	100	20	5
Nb_3Sn scaling to 5 m	5	Length	3	100	40	10
Nb_3Sn scaling to 15 m	4	Length	3	100	100	15
HTS magnet short model 20 T	3	Field[c] and all accelerator magnets' features	5–10	100	50	10
HTS long magnet 20 T	1	Length	15	100	150	25

[a] This includes only contracts to lower the price and to have more manufacturers, not the conductor cost for the model and prototype that is included in the next lines.
[b] Target of 15 T, for operation at 14 T.
[c] 2 to 4 T already achieved, but not with all requirements.

According to the reviewers of the European Accelerator R&D platform [35], the maturity gap between LTS and HTS implies that the decision on FCC-hh magnet technology cannot be taken before 2035 and HTS magnets do not appear compatible with a "fast track" FCC-hh.

HTS can generate magnetic fields in excess of 20 T, well above the levels allowed by Nb_3Sn and can operate at temperatures of the order of 20 K with corresponding energy savings in the cryogenic systems. HTS technology has been proven for solenoids operating above 20 T in steady state, but no high-field dipoles with the requirements needed for accelerators have been built and tested successfully so far. In particular, the field quality across the whole operational range and with ramping times compatible with FCC-hh operation as well as the protection aspects have not been mastered, yet. The HFM programme aims to demonstrate Nb_3Sn magnet technology for large-scale deployment pushing it to its limits in terms of maximum field and production scale and to demonstrate the suitability of HTS for accelerator magnets providing a proof-of-principle of HTS magnet technology beyond the reach of Nb_3Sn [45].

Among HTS, ReBCO superconductor does not need reaction after winding, allowing a simplified process of magnet manufacturing with respect to Nb_3Sn, but it is available only in tapes and the architecture of a ReBCO accelerator magnet cable is one of the main technological challenges. BSCCO is available in round strands, but the manufacturing process involves a reaction of the coil at temperature higher than Nb_3Sn (>800 °C), and in high-pressure oxygen [45]. IBS offer promise for larger cost reduction than ReBCO and BSCCO, although their technological readiness currently lags behind both of them [45].

5.4 Construction and installation costs

The capital cost for FCC-hh construction, as a second stage of the integrated FCC programme, is summarized in Table 5.3. The total construction cost amounts to 19080 MCHF and it is dominated by cost of the the collider magnets, amounting to approximately 10000 MCHF .

The main additional CE structures required for FCC-hh as second stage are the beam dump tunnels and the transfer-line tunnels. Most of the electrical, cooling and ventilation installations are reused. The cryogenics infrastructure for the main magnet cooling, therefore, drives the capital cost. The cost of the FCC-hh injector and transfer lines is included but not that required by the possible upgrade of the pre-injectors. The final cost will depend on which injector option is chosen. At the time of the FCC CDR [44], the combined cost estimate for modifying the existing LHC and for the new transfer lines was 615 MCHF. The cost of the four FCC-hh experiments can be estimated only at a later stage, once more detailed designs of the detectors exist.

Table 5.3: Cost summary table in 2024 MCHF for the construction of FCC-hh. Cost classes are defined in Table A.4.

Domain	FCC-hh	
	Cost [MCHF]	Cost class
FCC-ee dismantling	200	4
Collider	13400	4
Injectors and transfer lines	1000	4
Civil Engineering	520	4
Technical infrastructures	3960	4
Experiments	N/A	
TOTAL	**19080**	

5.5 Project timeline

The timelines of FCC-hh as a second phase of the FCC integrated programme or as a stand-alone project are summarised in Tables 5.4 and 5.5, respectively.

Table 5.4: FCC-hh timeline as a second phase after FCC-ee.

Milestone	FCC-hh
Conceptual Design Study	2014–2018
Definition of the placement scenario	2022
Feasibility Report ready	2025
Main technologies R&D completion	2054
Technical Design Report ready	2054
Latest Project Approval	2054
Environmental evaluation & project authorisation processes	2054–2058
Industrialization & magnet production	2054–2069
Civil engineering – collider	2060[a]–2068
FCC-ee dismantling	2063–2064
TI installation – collider	2065–2069
Accelerator installation – collider	2068–2072
HW commissioning – collider	2071–2073
Beam commissioning – collider	2073
Physics operation start	2074

[a] The starting date corresponds to the start of the surface CE works.

Table 5.5: Fastest possible FCC-hh timeline as a stand-alone project.

Milestone	FCC-hh
Conceptual Design Study	2014–2018
Definition of the placement scenario	2022
Feasibility Report ready	2025
Latest Project Approval	2033
Environmental evaluation & project authorisation processes	2026–2035
Main technologies R&D completion	2037[a]
Technical Design Report ready	2037
Industrialization & magnet production	2038–2053
Civil engineering – collider	2037–2046
TI installation – collider	2043–2050
Accelerator installation – collider	2046–2052
HW commissioning – collider	2049–2053
Beam commissioning – collider	2054
Physics operation start	2055

[a] Assuming an accelerated R&D programme as compared to that outlined in Table 5.2.

6 Future collider options at CERN for operation beyond 2050: Muon Collider

6.1 Main parameters and performance

The muon collider is an innovative concept to reach multi-TeV lepton collisions. The associated design and the technologies are less mature than for some other approaches and require a significant R&D to reach a maturity level to make informed decisions.

The baseline muon collider design is a green-field, 10 TeV c.o.m. collider [46,47] based on a concept which was developed by the US Muon Accelerator Programme (MAP) until 2017 [48]. The design is now being progressed by the International Muon Collider Collaboration (IMCC) [49]. A schematic layout of the collider is shown in Fig. 6.1 and contains the following key areas:

1. The proton driver (blue box in the diagram) produces a short, high-intensity proton pulse (e.g. a 2 MW beam at 5 GeV, with a repetition rate of 5 Hz [47]).

2. This pulse hits the target (indigo) and produces pions. The decay channel guides the pions and forms a beam with the resulting muons via a buncher and phase rotator system.

3. Several cooling stages (purple) reduce the longitudinal and transverse emittance of the beam using a sequence of absorbers and RF cavities in a high magnetic field.

4. A system of a linac and two recirculating linacs accelerate (light red) the beams to 63 GeV, followed by a sequence of high-energy accelerator rings (Rapid-Cycling Synchrotron—RCS) which reach 1.5 TeV or 5 TeV.

5. Finally the beams are injected at full energy into the collider ring (red). Here, they will circulate and collide within the detectors until they decay. The muon collider ring has to provide sufficient luminosity, leading to a challenging design with β^* and RMS bunch length of a few mm, while the RMS momentum spread remains large at around 10^{-3} [47].

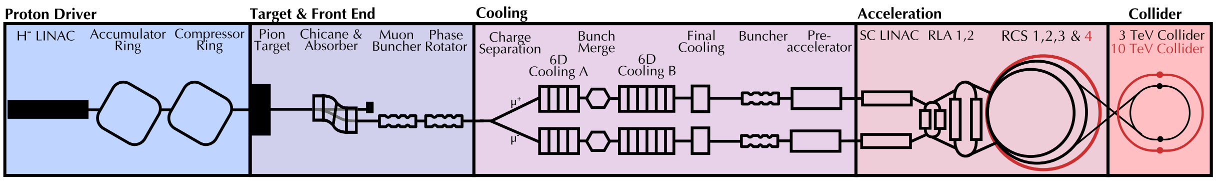

Fig. 6.1: Conceptual layout of the 3 TeV (black line) and 10 TeV (red line) MC complex [50].

An implementation at CERN is under consideration and could reuse the existing SPS and LHC tunnels to accelerate the muon beam. This design could reach a c.o.m. collision energy of up to 7.6 TeV and a practical initial energy stage could reach up to 3.2 TeV, depending on the layout. The significant reduction of CE and associated environmental impact might justify the reduction in physics scope with respect to the 10 TeV machine, though the feasibility of integrating the RCSs in the SPS and LHC tunnels has not been demonstrated.

Example parameters for a CERN implementation are given in Table 6.1, assuming in a first option that a single new collider ring tunnel is constructed and used for both energy stages, which is consistent with the use of 11 T Nb_3Sn magnets at full energy. This scenario assumes magnets whose performance is state of the art but development towards industrialization is required. It also allows to implement a 3.2 TeV collider using very mature NbTi technology. A second scenario is also shown, in which two independent collider rings at CERN are used with Nb_3Sn dipoles for the 3.2 TeV and HTS for the 7.6 TeV stage. The luminosities would then increase to $2 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ and $10.1 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$, respectively. Both scenarios are shown in Table 6.1, and the high-level parameters of the corresponding RCS in Table 6.2.

Table 6.1: Tentative high-level parameters for an implementation at CERN using the SPS and LHC tunnels [50,51]. The first scenario uses a common collider ring tunnel for both energy stages. The second uses an optimised collider ring tunnel for each collision energy. Luminosity is assumed to ramp up over the first three years as 5%, 25%, 70%, respectively. In the table the number of years operation is chosen so to achieve an integrated luminosity of at least 1 ab^{-1} (10 ab^{-1}) at 3.2 TeV (resp. 7.6 TeV).

	Common tunnel		Separate tunnels	
Circumference/length collider tunnel [km]	11	11	4.8	8.7
Number of experiments (IPs)	2	2	2	2
Injected beam power per beam [MW]	2.8	5.5	2.8	5.5
c.o.m. energy [TeV]	3.2	7.6	3.2	7.6
Arc dipole peak field [T]	4.8	11	11	14
Longitudinal polarisation (μ^- / μ^+) [%]	N/A			
Number of years of operation (total)	8	9	5	7
Nominal years of operation (equivalent)[a]	6	7	3	5
Instantaneous luminosity per IP [10^{34} cm^{-2} s^{-1}]	0.9	7.9	2.0	10.1
Integrated luminosity over all IPs per year of nominal operation [ab^{-1}/y]	0.18	1.58	0.4	2.02
Integrated luminosity over all IPs over the full programme [ab^{-1}]	1.1	11.1	1.2	10.1
Peak power consumption [MW]	117	182	117[b]	182[b]
Electricity consumption per year of nominal operation [TW h/y][c]	0.8	1.2	0.8	1.2

[a] This row lists the equivalent number of years of operation at nominal instantaneous luminosity, hence taking into account the luminosity ramp-up.

[b] The power has been estimated for the common tunnel scenario and would be minimally smaller in the separate tunnel scenario, due the shorter static losses of the magnets in the collider tunnel.

[c] Computed from the peak power consumption and the assumptions on the operational year (see Table A.2).

Table 6.2: High-level parameters for the Rapid-Cycling Synchrotrons (RCSs) of the MC for the CERN implementation [47].

	RCS1 in SPS	RCS2 in LHC	RCS3 in LHC
Circumference [km]	6.912	26.659	
Beam injection energy [TeV]	0.063	0.35	1.6
Beam extraction energy [TeV]	0.35	1.6	3.8

6.2 Environmental aspects

The power consumption has been estimated for the two energy stages at CERN at respectively 113 and 172 MW [51]. The use of NbTi dipoles for the 3.2 TeV collider stage and of HTS dipoles for the 7.6 TeV is assumed. The main contributions come from the cryogenics for the SC magnets and the RF systems all along the collider, the RF power to drive the cavities, and the power to drive the fast-ramping magnets. Additional heat load induced by muon beam decay to the RF cryostats in the RCS was not included into the power budget mentioned above. Mitigation for this load is considered and requires detailed study. In the very worst case the full load would have to be removed at 1.9 K and would require a maximum electric power of the order of 12 MW for the 3.2 TeV stage and up to 29 MW for the 7.6 TeV case. At this stage, as a first estimate, one third of the maximum has been included in the numbers given in Table 6.1, leading to respectively 117 and 182 MW for the first and second stage. The electricity consumption is then obtained using the operation times and the fraction of the peak power needed for each operational phase from Table A.2.

Regarding the impact on land and on GHG emissions, at CERN the muon collider can potentially benefit from existing infrastructure. An initial CE exploration at CERN indicates that the surface installations of the accelerator facility could be built fully on land attributed to CERN provided that the RCSs can be integrated in the SPS and LHC tunnels. Under this assumption, the GHG impact from the CE of the underground structures was estimated at 150 kt CO_2 eq. [51], using the evaluation per km of tunnel obtained for CLIC (6.38 kt CO_2 eq. per km—A1–A3 components [9]), for a similar tunnel diameter, and additional scaling factors of 1.3 to account for access shafts and additional galleries, and 1.25 for the A4–A5 components.

Muon decays occurring in the LSS of the collider produce neutrinos that will exit the earth's surface far from the accelerator facility. Two of these areas located on the Jura mountains will have to be fenced and these could host neutrino detectors on the surface where the neutrino beam emerges. The other exit points are located in the Mediterranean Sea. The neutrinos arising from the rest of the facility must be diluted so that there is negligible radiation outside the CERN site. A system of movers are required in collider arcs to displace the magnets vertically to achieve this. Tentative studies indicate that it is possible to comply with the RP regulations. Further optimisation and expansion of the studies to the full complex are required.

Table 6.3: Estimated area of land consumed by the MC project, i.e., lying outside the fenced CERN site. All surface sites are on CERN-attributed land with the exception of the two sites where the neutrino beam emerges in the Jura, potentially hosting two experiments. These two sites have not been estimated at this moment.

	MC
Number of new access shafts	2
Number of new surface sites	4[a]
Area of land permanently consumed (fraction outside CERN-attributed land) [km^2]	0.2151 (0%)
Area of surface constructions (fraction outside CERN-attributed land) [km^2]	0.1035 (0%)

[a] Including two surface sites where the neutrinos emerge in the Jura.

6.3 Technical readiness and R&D requirements

The development of the MC technologies faces several significant challenges that must be overcome in order to reach a level of maturity comparable to that of other colliders proposed for operation after 2050.

Following the European Accelerator R&D Roadmap, the MC development has focused on the most critical parts of the complex that provide specific design challenges or require beyond start-of-the-art technologies. At the time of writing, start-to-end simulations of the muon collider have not been completed and a tool capable of modelling the entire complex is not yet available. This will be essential to consolidate performance predictions, optimize key parameters, perform sensitivity analyses and refine background and radiation estimates. A number of the MC technologies are at a readiness level of 3 or lower [35] and require an extensive experimental development programme. The resources needed are estimated to be around 300 MCHF and 1800 FTE-years for the accelerator and 20 MCHF and 900 FTEy for the detector. The technically-limited timeline for the implementation of the R&D programme is 10 years [47].

Key milestones include construction and testing of essential magnets and demonstrating cooling technology, both of which drive the schedule. A detailed description of the R&D requirements is provided in Ref. [47]. Selected elements and key deliverables for the accelerator design are listed in Table 6.4; in general, one can distinguish the following R&D (see also Ref. [35]):

- **Magnet technology developments:** HTS solenoids for muon production and cooling, large-aperture collider ring dipoles and fast-ramping magnet systems.
- **RF technologies:** klystrons, cavities working in high magnetic field and with high beam loading and test infrastructure.
- **Muon cooling technology and demonstration programme:** technologies for muon cooling and

their integration into the 6D cooling, the final cooling system and the demonstrator. Performance verification and development of key components like HTS solenoids and RF systems.
- **Design and technologies:** further study of key design challenges, including collider modeling lattice optimization, advanced simulations, site impact studies including neutrino flux, proton complex and technical developments as target, RF and MDI.
- **Detector R&D priorities:** simulation, technology and software to enhance physics output while reducing beam-induced backgrounds.

Table 6.4: Selected key deliverables of the proposed R&D programme of the MC.

Technologies	Deliverables	Key parameters and goals
Magnets		
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K
Fast-ramping magnet system	Prototype magnet string and power converter	30 mm x 100 mm, 1.8 T, 3.3 T s^{-1}
Radio frequency		
RF test stands	Assess cavity breakdown rate in magnetic field	20–32 MV m^{-1}, 704 MHz–3 GHz cavities in 7–10 T
Muon Cooling		
5-cell module	Build and test first 5-cell cooling module	
Design & Other Technologies		
Neutrino flux mover system	Prototype components and tests as needed	Range to reach O (±1 mrad)

The Muon Cooling Technology Demonstration programme, aiming at validating with beam the ionization cooling technology in a typical section of the cooling channel, is a necessary condition for the assessment of the feasibility of the MC and of its performance.

As pointed out in Section 6.2 neutrino flux assessment and mitigation remains a critical issue, particularly with regard to its impact on potential host sites. A thorough evaluation of neutrino flux at different energy levels and site locations is needed [35].

6.4 Construction and installation costs

At this stage of the study an estimate of the construction and installation costs is subject to significant uncertainties and only a cost range can be specified. The construction and installation costs of the MC at CERN is dominated by the magnets (in particular, solenoids) which account for 37 to 45% of the total costs depending on the energy (3.2 or 7.6 TeV). Then comes the RF, at 26 to 30% of the total. CE and general infrastructures exhibit a limited cost (between 15 and 17% of the total), provided that the feasibility of installing the RCSs in the SPS and LHC is demonstrated.

The estimated capital cost range is provided for the CERN scenario and compared to a green-field realization in Fig. 6.2. The cost of the detectors is not included.

6.5 Project timeline

To guide the definition of the R&D programme, an ambitious technically-limited timeline has been explored and it is shown in Table 6.5. This scenario assumes a firm commitment to implementing a muon collider in Europe as soon as possible after the HL-LHC and the reuse of existing CERN infrastructure to minimize CE costs and limits the collider's center-of-mass energy to approximately 3 TeV.

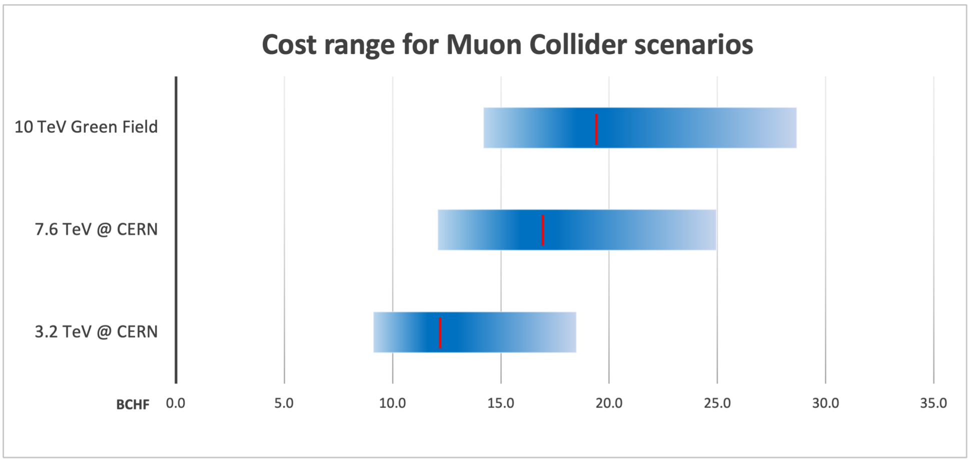

Fig. 6.2: Cost range for a MC implementation at CERN using existing infrastructure and for a site-independent implementation. The cost of the two experiments is not included in the estimate.

Table 6.5: MC timeline.

Milestone	Muon Collider
Construction of RF test stands	2025–2028
Production of test cavities	2026–2039
Operation of test stands	2027–2040
Demonstration Phase	T_0–(T_0+7)
Demonstrator technical design	
Construction of initial demonstrator	
Construction of muon cooling module (five cells)	
Definition of the placement scenario for the collider	
Project Preparation Phase	T_1–(T_1+5)
Final demonstrator	
Implementation studies with the Host states	
Environmental evaluation & project authorisation processes	
Main technologies R&D completion	
Industrialisation of key components	
Engineering Design completion	
Construction phase (from ground breaking)	T_2–(T_2+9)
Civil engineering	
TI installation	
Component construction	
Accelerator HW installation	
HW commissioning	
Beam commissioning	
Physics operation start	T_2+10

The initial phase of the project focuses on advancing the design and the required technologies to a level that allows the feasibility of a muon collider to be demonstrated with confidence. Key expected deliverables of this phase are listed in Table 6.4. Part of the R&D programme (in particular, on the RF test stands and cavities) has already started. At present, R&D progress is limited by available resources, both in Europe and particularly in the US, where organisational structures are still being established. It is therefore important to increase the design effort in order to complete a start-to-end design of the collider and to launch the R&D for technologies that have the strongest impact on the timeline, this could be launched following the outcome of the ESPPU.

The construction of the Initial Cooling Demonstrator demands significant resources and will require a specific decision (at time T_0 in Table 6.5) after a revision of the Roadmap by the IMCC planned for 2028, following the results of the ESPPU and the subsequent mid-term review panel recommended by the P5 report. Once the muon cooling technology has been successfully demonstrated, the Project Preparation Phase can be launched (T_1). Upon successful completion, the ground breaking and construction can start (T_2).

7 Future collider proposals outside CERN

In this Section we give an overview of two collider projects proposed for other regions:

- the Circular Electron Positron Collider (CEPC) in China;
- the International Linear Collider (ILC) in Japan;

both are green-field projects, therefore requiring each the construction of a laboratory campus in support of the research and technical activities at the accelerator complex and the experiments.

The following aspects are discussed:

- Main parameters and performance
- Technical readiness
- Accelerator and experiments construction and installation: material costs
- Accelerator construction and installation: human resources
- Project timeline.

7.1 Main parameters and performance

CEPC

The Circular Electron Positron Collider (CEPC) features a 100 km collider with two IPs. Its injector chain includes a 30 GeV 1.8 km-long linac, a 1.1 GeV positron damping ring and a Booster synchrotron accelerating the electron and positron beams from 30 GeV to the beam collision energy. The CEPC baseline design involves three operating modes (ZH, Z, and WW, in chronological order) with a synchrotron radiation power of 30 MW per beam for the ZH and WW operating modes, and 10 MW per beam for the Z-mode. Possible upgrades include [7]:

- increase of the power to 30 MW per beam for the Z-mode of operation;
- increase of the power to 50 MW per beam for the ZH, Z and WW modes of operation;
- increase the c.o.m. colision energy to 360 GeV for $t\bar{t}$ operation at 30 MW and 50 MW per beam.

The transfer lines connecting the pre-injectors with the booster in the main collider tunnel are approximately 2 km long [7]. A SC proton-proton collider, the Super Proton Proton Collider (SPPC), designed to operate at a c.o.m. energy of 125 TeV with 20 T SC dipoles, could be installed at a later stage in the same tunnel. This could operate simultaneously with the CEPC collider and booster [7], though the integration of the three accelerators and their services in the same tunnel (including the cryogenics for SPPC) appears to be challenging given the size of the tunnel.

The main parameters of CEPC as provided in Ref. [7] are listed in Table B.1: the integrated luminosity has been estimated assuming data taking over 150 days (corresponding to a 60% machine availability over a scheduled operation period of 250 days) [7] while 139 days have been assumed, in general, in Table A.1. No luminosity ramp-up has been assumed [7], differently from what has been done for FCC-ee and CLIC in Table 3.1. The yearly electricity consumption has been determined assuming 5000 h (full-power equivalent) per year [52].

The main CEPC parameters, re-scaled for the operational scenario defined in Table A.1, are listed in Table 7.1. On-axis injection is considered for the ZH mode of operation; this will require switching off the high-voltage of the detectors during this process [7], with a corresponding reduction of the fraction of time for data-taking when the machine is available (assumed to be 100% in Table A.1). Finally, the power consumption does not include the contribution of the Science Campus and of the off-line computing.

Table 7.1: High-level parameters of the ILC 250 in Japan [40] and of CEPC for different options [7, 52] (baseline parameters for CEPC are in **bold**), re-scaled respectively to the LCF 250 LP and FCC-ee operational year (see Table A.1). For the ILC we follow an operational scenario adapted from [53], with 10 years of operation including three years of ramp-up at one third the luminosity, and no luminosity upgrade (not costed in Ref. [40]). The integrated luminosity over the full programme is also adapted from [53], following such a scenario. The instantaneous and integrated luminosity in-between parentheses includes also the contribution from energies below 99% of the c.o.m. energy $\sqrt{s}$.

	CEPC				ILC 250
Circumference/length collider tunnel [km]	99.955				20.5
Number of experiments (IPs)	2				2 (1)[a]
c.o.m. energy [GeV]	**91**	**160**	**240**	360	250
Longitudinal polarisation (e^- / e^+)	0 / 0[b]				0.8 / 0.3
Number of years of operation (total)	**2**	**1**	**10**	5	10
Nominal years of operation (equivalent)[c]	**2**	**1**	**10**	5	8
Synchrotron radiation power per beam [MW]	**10** / 30 / 50	**30** / 50	**30** / 50	30 / 50	–
Instantaneous luminosity per IP above 0.99 $\sqrt{s}$ (total) [10^{34} cm^{-2} s^{-1}]	**38** / 115 / 192	**16** / 26.7	**5** / 8.3	0.5 / 0.8	1 (1.35)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs per year of nominal operation [ab^{-1}/y]	**9.1** / 27.6 / 46.1	**3.8** / 6.4	**1.2** / 2.0	0.12 / 0.19	0.12 (0.16)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs over the full programme [ab^{-1}]	**18.3** / 55.2 / 92.2	**3.8** / 6.4	**12.0** / 19.9	0.60 / 0.96	1 (1.3)
Peak power consumption [MW]	**100**[d] / 203 / 287	**225** / 299	**262** / 339	358 / 432	111
Electricity consumption per year of nominal operation [TW h/y][e]	**0.47** / 0.95 / 1.3	**1.1** / 1.4	**1.3** / 1.6	1.8 / 2.2	0.64

[a] Two experiments at a single IP ("push-pull" mode).
[b] No longitudinal polarisation is considered in the baseline, but such a possibility is being explored, especially at the Z energy.
[c] This row lists the equivalent number of years of operation at nominal instantaneous luminosity, hence taking into account the luminosity ramp-up.
[d] Extrapolated from [7].
[e] Computed from the peak power consumption and the assumptions on the operational year (see Table A.1).

ILC

The International Linear Collider (ILC) [38] is a linear electron-positron collider relying on Superconducting radio-frequency (SRF) cavities, foreseen to operate at c.o.m. energies from 250 GeV up to 1 TeV, thanks to possible tunnel extensions and upgrades. The ILC would be initially operated as a Higgs factory (250 GeV c.o.m.) for 10 years [53]. The main accelerator fits into a 20.5 km-long tunnel [53] (9.5 m-wide [53] and 5.5 m-high [54]), and consists of two arms: one of 9.65 km containing the positron main linac and the low emittance transfer line—Ring-to-Main Linac system (RTML), and one of 10.85 km including the electron main linac, the 1.1 km undulator section for the polarised positron source, and the RTML. A conceptual layout of the ILC is shown in Fig. 3.3.

The RF powering equipment is separated by a shielding wall of 1.5 m thickness from the main linac, and access to it is possible when beam operation is stopped but the RF cavities are powered, as the shielding protects the personnel from the X-rays generated in the RF cavities. Access during beam operation would have required a wall thickness of 3.5 m which has been abandoned for cost considerations [53].

The electron and positron sources produce both 5 GeV polarised beams (1312 bunches with 554 ns bunch spacing), which are injected into the damping rings sharing the same 3.2 km-long tunnel, before being extracted towards the main tunnel. Operation at the Z pole (91.2 GeV c.o.m. energy) is also envisaged, using the same linac and cavities with a reduced klystron power [53], albeit with a more complex cycle, as the positrons production requires 125 GeV electrons from the main linac—the latter would then have to alternate between 45.6 GeV and 125 GeV. The interaction point features two detectors operating on movable platforms, in a "push-pull" scheme (exchange is possible in less than 24 hours) [53]. The machine may also use beam dumps as fixed-target experiments, specially the main dumps, tune-up dumps, and the photon dump from the positron source undulator [53]. The baseline features polarization of both the electron and positron beams [53].

Main summary parameters are given in Table B.1, while in Table 7.1 the integrated luminosity and electricity consumption are re-scaled to the LCF 250 LP operational year (see Table A.1), in particular 139 days of data taking per year, as opposed to 170–180 days foreseen in the ILC operational scenario [53].

On top of the baseline scenario, several options are also envisaged and (at least partly) costed: the increase of the centre-of-mass energy from 250 to 500 GeV, the use of an electron-driven positron source instead of the undulator-driven one (as a backup plan), and/or the addition of a second interaction point.

7.2 Technical readiness and R&D requirements

CEPC

The main technical requirements of CEPC are similar to those of FCC-ee and the overall technology readiness level is comparable (see Table 3.5).

The collider RF system is based on bulk-Nb SRF 650 MHz 2-cell cavities operated at 2 K. The cavity has been designed to meet the following specifications: a vertical acceptance test with $Q_0 > 5 \times 10^{10}$ at 30 MV m^{-1}, a horizontal acceptance test with $Q_0 > 4 \times 10^{10}$ at 28 MV m^{-1}, and a normal operation gradient of 28 MV m^{-1} with $Q_0 > 3 \times 10^{10}$ when integrated in the cryomodule. $Q_0 \approx 7 \times 10^9$ at $\approx$ 28 MV m^{-1} has been achieved in a vertical test of individual cavities, so far [7].

The power consumption of CEPC is mostly driven by the power consumption of the RF system. The estimated values of the overall electricity consumption are based on the assumption that the RF klystrons can reach an efficiency of 80%. An efficiency of 78.5% has been reached in the laboratory at 800 kW in CW mode [52].

While the technical readiness for a number of items is similar to that reached at CERN for similar FCC-ee components, the deadline for the completion of the R&D phase by 2027 (see Table 7.4) is ambitious.

ILC

Several items have to be developed within the four years foreseen for the pre-lab phase of the ILC, and are already the subject of intense R&D by the ILC Technology Network (ITN), in particular the SRF cavities, the electron and positron sources, and the nano beam technology. One of the main challenges regards the $\sim$ 8000 RF cavities, which are 10 times more numerous than the European X-Ray Free-Electron Laser Facility (EU-XFEL) ones, with 30% more gradient (31.5 MV m^{-1}) and a Q_0 above 10^{10}. Other critical R&D topics are the undulator-based positron source and in particular its rotating photon target, and the damping rings and final focus, aiming at 7.7 nm vertical beam size at the IP. The technological challenges and corresponding TRL are essentially the same as those of the LCF, which can be found in Table 3.6.

Regarding civil engineering and tunneling, the Kitakami site in the Tohoku region, offers good geological conditions (good quality granite and no active seismic faults). Geological survey and seismic measurements were performed; the impact of a large earthquakes (e.g. the 2011 one—magnitude 9) was checked and will not be an issue for operation. Up to 50 km of tunnel can be dug, covering ILC energy upgrades—operation may also continue while excavating a longer tunnel for an energy upgrade [53].

7.3 Construction and installation costs

CEPC

A cost estimate (in CNY—2023 prices) of the CEPC project has been presented in Refs. [7, 52]. The cost includes installation and commissioning of the accelerator hardware and technical infrastructure with a provision of 3% of the corresponding material cost for each of these activities. The cost summary table (in CNY, CHF and after correction for the PPP as discussed in Section 2.4) is presented in Table 7.2.

Compensation for resettlement and land acquisition as well as territorial developments, such as the connection to site-specific existing networks (e.g. utility power lines, raw-water adduction, roads) are not included [7, 55]. The laboratory campus has not been costed.

Material price averages over the 2018–2022 period have been considered in Ref. [7] and therefore they do not fully account for the inflation to 2023 prices; the average 2023 Chinese PPI has increased by 3.4% as compared to its average value in the period 2018–2022.

The cost estimate includes gamma-ray beam lines, accelerator physics studies and project management in addition to the items indicated in Section 2.4. A contingency of 8% of the overall cost of the project is assumed in Ref. [7], lower than the present level of uncertainty of the cost estimate indicated above.

ILC

First cost estimates were given in the 2013 TDR [38] for the ILC 500 collider with a very detailed breakdown, using a bottom-up approach. These were then re-evaluated in 2017, when the baseline c.o.m. energy became 250 GeV, and more recently in 2024, the latter version having been submitted to the ESPPU [40]. Around 75% of the cost were hence re-evaluated in 2024, in particular the accelerator components (SRF technology), the utilities and conventional facilities, and the civil engineering. The costs for preparatory work such as engineering design, land acquisition, local infrastructure's access to the site (roads, electricity, and water) were not included, as well as the experiments. All costs, except civil engineering, were expressed in 2024 USD (also called ILCU, defined by 1 ILCU = 1 USD in 2024), thanks to PPP conversion rates (using specific values for either machinery & equipment, or material [40], which are different from the values of Table A.6). The civil engineering costs were instead expressed in JPY—this part of the cost update was performed following the strict guidelines of the Japanese Government and the national tunnel costing standards as for other major Japanese projects. The costs were reviewed by an international committee [40].

The baseline costs of ILC 250 are shown in Table 7.3, converted to CHF using the PPP from Table A.6. No cost classes are available, but the uncertainty was evaluated at 30%, broadly corresponding to cost class 3.

Three options were evaluated in addition in Ref. [40]:

- c.o.m. energy increase from 250 to 500 GeV, costed at 3.9–4.2 BUSD for hardware (accelerator components plus conventional facilities) and 55 BJPY for civil engineering, for a total (after PPP conversion) of 4.6 BCHF equivalent,
- electron-driven positron source (backup plan if the undulator-based positron source is not available in time), costed at 0.2 BUSD for hardware and 12.5 BJPY for CE, for a total of 320 MCHF equivalent,
- an additional interaction point, for 0.5 BUSD (480 MCHF equivalent), including a second BDS and interaction point, but excluding CE work and the new beam splitting systems needed at both BDS upstream ends.

Table 7.2: Cost summary table for the CEPC project for the baseline scenario with two experiments and its possible upgrades to high beam power and energy. The first three columns are derived from the data presented in Ref. [7]. The following six columns are derived applying the currency exchange rate, and that rate corrected for the PPP as described in Section 2.4. The sub-total represents the sum of the cost items considered for the other projects described in this document. The cost of installation and commissioning has been included in each of the corresponding cost items to have a similar categorisation as for the other projects. Inflation between 2023 and the 2018–2022 period (average PPI has increased by approximately 3.4%) has not been included.

	10 MW Z 30 MW W ZH **baseline**	30 MW Z W ZH	50 MW Z W ZH $t\bar{t}$	10 MW Z 30 MW W ZH **baseline**	30 MW Z W ZH	50 MW Z W ZH $t\bar{t}$	10 MW Z 30 MW W ZH **baseline**	30 MW Z W ZH	50 MW Z W ZH $t\bar{t}$
	[100 MCNY—2023]			[MCHF—2023]			PPP [MCHF—2023]		
Booster and collider	151	164	212	1856	2015	2601	4016	4360	5626
Pre-injectors and transfer lines	21	21	21	263	263	263	570	570	570
Civil engineering[a]	71	71	71	872	872	872	1885	1885	1885
Technical infrastructure[b]	46	48	65	570	583	802	1234	1262	1735
Experiments[c]	40	40	40	491	491	491	1062	1062	1062
Sub-total	**330**	**344**	**410**	**4053**	**4225**	**5029**	**8768**	**9139**	**10879**
Gamma ray beam lines	3	3	3	37	37	37	80	80	80
Accelerator physics	1	1	1	10	10	10	21	21	21
Project management	3	3	3	37	37	37	80	80	80
Contingency	27	28	33	331	345	409	716	746	885
Total	**364**	**379**	**450**	**4467**	**4653**	**5521**	**9664**	**10066**	**11944**

[a] Including transport and logistics.
[b] Excluding transport and logistics.
[c] Total cost of two experiments.

Table 7.3: Cost summary table for ILC 250 in Japan [40, 56], in various currencies and 2024 prices. The last but one column (in MCHF) is derived applying the currency exchange rate (Table A.5), while the last column includes the PPP (Table A.6).

	Uncertainty	Cost			
		[MUSD] (or [MILCU])	[BJPY]	[MCHF]	PPP [MCHF]
SRF	30%	3690		3250	3560
Other accelerator components	30%	1710		1510	1650
Civil engineering	30%		196	1150	2000
Technical Infrastructure	30%	1380		1220	1330
Experiments	N/A				
Total	**30%**			**7120**	**8550**

7.4 Accelerator construction and installation: human resources

CEPC

According to Ref. [52], the human resources necessary for the accelerator construction and installation amount to about 15 000 FTEy over a period of seven years. According to Eq. (1), approximately 11 000 FTEy would be required. A project the size of CEPC, if conducted in a short timespan as proposed, might exceed the skilled personnel resources available in national institutes.

ILC

After a first, detailed estimate in the 2013 TDR, the labor force needed for the construction of the ILC was re-evaluated in 2017, following the decrease in energy to 250 GeV. A simple scaling by 75% of the TDR value was then used, obtaining 10 120 FTEy [53, 57], over a period of nine years. This number has not been updated since then. Applying Eq. (1) would give instead 11 300 FTEy.

7.5 Project timeline

The timelines for the construction of the colliders and the associated technical infrastructure are presented in this Section. These do not include the effort necessary for the construction of the full laboratory infrastructure in a green field, that might absorb a significant amount of resources and require considerable time.

CEPC

The major milestones for the CEPC project [7, 52] are listed in Table 7.4. A final selection of the site has not been made. The selection should be followed by the definition of the placement scenario and the preliminary implementation with the Host region and by an Environmental Impact Assessment (EIA). Civil engineering is expected to take less than five years. The schedule is aggressive but considered to be feasible [58], though with a significant uncertainty, pending more detailed geological investigations that will have to follow the site selection.

As mentioned in Section 7.2, the timescale for the completion of the R&D phase is ambitious, as well as the overall construction and installation schedule. The scale of the requirements on production, transport means as well as storage and logistics are significantly larger as compared to previous projects such as BEPCII, CSNS and HEPS.

ILC

The technically-limited timeline for the ILC project is presented in Table 7.4. After project approval, the preparation should last four years (ILC pre-lab construction and R&D) [40, 53]. Then, construction is assumed to last nine years, followed by one year of commissioning—this schedule has remained unchanged since the 2013 TDR [38].

For a possible energy upgrade, assuming that all cryomodules would be already available before shutting down the machine, a one-year shutdown is foreseen [53].

Table 7.4: Timeline for the CEPC [7, 52] and ILC projects [38, 40].

Milestone	CEPC	ILC
Conceptual Design Study	2018	2007[a]
Definition of the placement scenario	N/A	N/A
Preliminary implementation with the Host region	N/A	N/A
Feasibility Report ready	N/A[b]	2022[c]
Earliest Project Approval	2025	T_0
Environmental evaluation & project authorisation processes	N/A	N/A
Main technologies R&D completion	2027	T_0+4
Technical Design Report ready[d]	2027	T_0+4
Civil engineering	2028–2032[e]	T_0+4–T_0+9
Installation	2033–2035[f]	T_0+9–T_0+13
HW and beam commissioning	2036–2037	T_0+13

[a] Reference Design Report (RDR) [59].
[b] The CEPC TDR [7] does not correspond to a full Feasibility Report as defined in Section 2.6. Neither the final, nor the preliminary implementations with the host regions are discussed.
[c] The ILC feasibility study can be considered done since 2022; it is documented in several reports: the 2013 TDR [38] for ILC 500, the 2022 report to Snowmass [53] for the changes related to ILC 250, and the 2020 "Tohoku ILC Civil Engineering Plan" for the geological survey and CE planning [54]. The latter was reviewed by a committee within the Japan Society of Civil Engineers.
[d] For CEPC and ILC this is called Engineering Design Report (EDR).
[e] Assuming the drilling and blasting method for the tunnel construction. The CE could be completed one year earlier if the TBM method is used [7].
[f] The timeline for the installation of the detectors in the corresponding experimental caverns is not presented in Ref. [7]. According to Ref. [52] this might occur one or two years after the completion of the installation of the accelerator.

Regarding the detectors, it has been noted [53] that the originally envisioned timeline for the approval of the first set of experiments to proceed towards TDR, contemplated at least six to seven years from the launch of the calls for Expression of Interest (EoI). So time might be very limited for the standard process of EoI, Letter of Interest (LoI), and the actual proposal for experiments at the ILC.

8 Options reusing the LHC tunnel

8.1 LEP3

Motivated by first hints of a Higgs boson at the LHC, a circular e^+e^- Higgs factory in the LHC tunnel with a maximum c.o.m. energy of 240 GeV, LEP3, was first proposed in 2011 [60], together with a new machine at twice the circumference, DLEP [60]. A few months later also a circular Higgs factory of three times the circumference, TLEP, was considered [61, 62], which eventually became the FCC-ee [28].

For the ESPPU 2013, a proposal for LEP3 was submitted [63–65] (see Table 8.1) but it did not receive significant support [66, 67]. A 1.3 GHz SRF system was initially considered but later discarded given the anticipated beam currents. Therefore, already in 2012, an SRF frequency of 700 MHz was considered [68].

Further studies were performed in 2017 [69, 70] considering an 800 MHz SRF system, four IPs and a maximum c.o.m. energy of 240 GeV. The lattice considered has a rather aggressive design with half the cell length of the FCC-ee ZH mode. This implies a reduction of the magnet filling factor (unless nested magnets are used) and therefore of the main dipole bending radius as compared to that of LEP (see Table 8.1), and also higher gradient quadrupoles and sextupoles than for FCC-ee.

More recently an additional proposal has been made [71] to reuse the LEP tunnel to host an

e^+e^-collider providing collision at c.o.m. energies ranging from 91.2 to 230 GeV in two IPs. All the LEP3 studies envisage top-up injection from a cycling high-energy booster to the collider, similarly to what is proposed for FCC-ee. The high-energy booster, located in the same tunnel of the collider, would regularly accelerate the beams delivered from a pre-injector chain to the collision energy. The machine parameters are listed in Table 8.1 together with those of LEP2 and those of the earlier proposals and studies. The main dipole bending radius has been increased with respect to the value mentioned in Refs. [69, 70] implying likely a further increase of the gradient of the quadrupoles and sextupoles to maintain a compact cell length. Optics and beam dynamics simulation still need to be performed [71] to support the performance estimate. Scaling from the parameters listed in Refs. [69, 70], considering only two IPs and the lower maximum c.o.m. energy (230 GeV) indicate a possible luminosity of 1.5×10^{34} cm^{-2} s^{-1} (the lowest value of the range considered in Ref. [71] and lower than the value of 1.8×10^{34} cm^{-2} s^{-1} used to estimate the integrated luminosities) at 230 GeV and a higher energy loss per turn by about 8% as compared to Ref. [71].

The 2025 proposal [71] is based on two separate 800 MHz SRF systems for the collider and the booster. Each of them would be distributed over two LHC LSS. The high currents required for the operation at the Z-pole will likely demand the installation of two high-power 400 MHz SRF systems (one per beam and in separate LSS) for the collider for the operation at that energy, in order to compensate for the synchrotron radiation power loss of 50 MW. The 400 MHz SRF system will have to be dismantled and replaced by the 800 MHz SRF system to operate at the maximum energy therefore it will not be realistically possible to interleave low and high energy runs during the operational lifetime of the collider.

The integration of the collider and booster rings in the RF LSS might be challenging and requires a detailed integration study to assess the need of civil engineering work, not contemplated in the proposal, in those areas.

Table 8.1: Tentative parameters of a LEP3 Higgs factory as proposed in 2011 [63–65], studied in 2017 [69, 70] and proposed in 2025 [71] and compared with the corresponding parameters achieved by LEP2 and those expected for FCC-ee [1, 3, 65].

Parameter	LEP2	LEP3 - 2012	LEP3 - 2017		LEP3 - 2025		FCC-ee	
c.o.m. energy [GeV]	209	240	91.2	240	91.2	230	91.2	240
Number of IPs	4	4	4		2		4	
Main dipole bending radius [m]	3096	2600	2755		2958		10021	
Beam current [mA]	4	7.2	346	7.2	371	9	1292	26.8
Peak luminosity per IP [10^{34} cm^{-2} s^{-1}]	0.01	1.1	52	1.1	44	1.8	144	7.5
Int. luminosity per year over all IPs [ab^{-1}/y][a]	$9 \cdot 10^{-4}$	0.53	25	0.53	10.6	0.43	69	3.6
Energy loss per turn U_0 [GeV]	3.5	7	0.144	6.92	0.13	5.4	0.039	1.86
RF frequency [MHz]	352	1300	800		800		400	
Total RF Voltage [GV]	3.65	12	0.2	8	0.18	6	0.085	2.09
Critical photon energy in the arc [MeV]	1.1	1.7	0.08	1.4	0.07	1.14	0.021	0.38
Synchrotron radiation power per beam [MW]	11.5	50	50		50		50	
Peak power consumption [MW]	N/A	N/A	N/A	N/A	N/A	250	251	297
Electricity consumption per year [TW h/y][a]	0.57	N/A	N/A	N/A	N/A	1.22	1.21	1.43

[a] Computed from the peak power consumption and the assumptions on the operational year of FCC-ee (see Table A.1), except for LEP2.

The LEP3 electrical power consumption quoted by the proponents amounts to about 250 MW at top energy, comparable to that of the FCC-ee, but providing a lower luminosity and at lower maximum energy.

The cost of the project has been estimated extrapolating from the cost of the main systems for FCC-ee and it amounts to 3850 MCHF, including the total cost of two new experiments (795 MCHF), assuming the same cost per experiment considered for the other e^+e^-collider proposals. CERN contribution to the detector construction plus host laboratory responsibility is 146 MCHF. The cost estimate assumes that no CE work will be required in the RF LSS. This hypothesis would need to be validated by integration studies including the RF system, the booster and the collider in the relevant sections. The requirements in terms of integration and cost of a possible distributed HTS magnet system that might be required to limit the power consumption to the value above-mentioned (but whose feasibility has not been demonstrated) have not been detailed either.

LEP3 could be installed only after the end of the HL-LHC programme and after the removal of the LHC machine, implying that LEP3 physics could begin at the earliest in the second half of the 2040s. The operation of LEP3 will likely require a similar amount of resources (material and personnel) to that required for LHC/HL-LHC.

In conclusion, several technical aspects of this collider necessitate detailed design studies, and the performance goals need to be verified before this project, as proposed, can be considered as feasible.

8.2 HE-LHC

In 2010 an inter-departmental CERN working group explored the possibility of a High-Energy Large Hadron Collider (HE-LHC) in the existing 27 km tunnel, based on assumed 20 T magnets with a c.o.m. energy of 33 TeV [72]. This early HE-LHC effort was terminated at a 2010 EuCARD workshop [73], where—in view of the HE-LHC technical difficulties combined with the limited time available for preparing a post-LHC machine, the unfavourable cost scaling laws when pushing dipole magnetic fields to 20 T or beyond, and the much higher collision energy required by physics (an argument further reinforced by the LHC results obtained since then)—a future hadron collider of larger circumference, >80 km, was proposed, for the first time, as a much preferred option compared to the HE-LHC.

The HE-LHC proposal was nevertheless submitted as input to the 2012/13 ESPPU [74] and, in response to the generic recommendations from the 2013 strategy update [66], also the HE-LHC design effort was revived as part of the FCC Conceptual Design Study [75], as input to the ESPPU 2020, but this option was not recommended.

In the CDR version, the HE-LHC dipole magnetic field was reduced to 16 T, the same as for the (then) FCC-hh, and a collision energy around 27 TeV targeted [75] further reducing the c.o.m. energy to 24 TeV. Recent studies indicate that 14 T should be the maximum operational field realistically to be assumed for large series of Nb_3Sn accelerator magnets. This HE-LHC would require a new superconducting SPS (scSPS) as injector.

The HE-LHC must be installed in the existing LHC tunnel, with an inner diameter of only 3.8 m, compared with 5.5 m for the FCC. These space limitations result in significant constraints on the HE-LHC machine layout, on the magnets which must be compact and curved, and on the HE-LHC cryogenics system, which needs to be more powerful than the one of the LHC. The HE-LHC high-field magnets, vacuum system, cryogenics, and tunnel integration all appear more challenging than those of the FCC-hh. The cost of HE-LHC reported in Ref. [75] was 7200 MCHF (excluding the cost of the experiments).

A recent study considered various alternative magnet technologies and dipole fields [76]. The tentative beam parameters and projected performance figures for HE-LHC are listed in Table 8.2. The synchrotron radiation power increases by roughly one to two orders of magnitude with respect to the (HL-)LHC. Assuming a new scSPS as injector, the total electrical power consumption is expected to stay below 200 MW (for 16 T magnets) [75].

The physics perspectives for the HE-LHC were discussed in Ref. [77] as input to the 2020 ESPPU process. The 2020 ESPPU [67] called for a future hadron collider with collision energies in excess of 100 TeV, as could be obtained by the FCC-hh.

The installation of the HE-LHC can only take place after the removal of the LHC components at the end of the HL-LHC programme. This, together with the time required for the development of high-field magnets discussed in Section 5.3, would likely imply an earliest potential start date for HE-LHC at the beginning of the 2070s for the highest c.o.m. of 34 TeV.

In conclusion, based on the current physics landscape emerging from the LHC and other results,

Table 8.2: Main parameters of HE-LHC options, based on different magnet technologies and dipole fields, compared with HL-LHC (nominal) and LHC (achieved), for operation with proton beams [76]. All values, except for the injection energy itself, refer to the collision energy. The ring circumference and the straight section length are the same of the LHC tunnel. The scheduled physics time and accelerator availability correspond to those assumed in Ref. [8].

Parameter	HE-LHC		(HL-)LHC
Centre-of-mass energy [TeV]	27	34	(14) 13.6
Injection energy [TeV]	0.8	1.0	0.45
Peak arc dipole field [T]	16	20	(8.33) 8.1
Instantaneous luminosity (levelled) / IP [10^{34} cm^{-2} s^{-1}]	16	16	(5) 2.2
Stored energy / beam [GJ]	1.3	1.7	(0.7) 0.41
Synchrotron radiation power / beam [kW]	100	251	(7.3) 4.4
No. of high-luminosity IPs	2		2
Scheduled physics time per year [days]	160		160
Accelerator availability [%]	75		(80) 79
Integrated luminosity per year of nominal operation per IP [fb^{-1}/y]	500	520	(250) 123

the HE-LHC offers a very limited physics reach.

8.3 LHeC

A CDR for the Large Hadron-electron Collider (LHeC) was published in 2012 [78] and updated in 2020 [79]. Exploiting energy recovery technology, LHeC collides an intense electron beam provided by a new 3-turn high-current Energy Recovery Linac (ERL) with a proton or ion beam from the High-Luminosity LHC (HL-LHC). The accelerator and interaction region are designed for concurrent electron-hadron and hadron-hadron operation and LHeC could operate either in parasitic or dedicated mode.

The ERL accelerator is located in a new tunnel tangential to the LHC ring, tentatively in IP2 where a dedicated experiment would be installed. The length of the ERL is a fraction of the LHC circumference as required for the electron and proton matching of bunch patterns. The electron accelerator may be built independently, to a considerable extent, of the status of operation of the LHC.

The baseline parameters of LHeC have evolved since the publication of the 2020 updated CDR [79]. The ERL circumference considered in Ref. [80] is 1/3 of the LHC circumference as compared to 1/5 considered in the CDR [79]. The main baseline parameters for electron-proton operation are summarized in Table 8.3.

After a first year of operation at reduced luminosity LHeC would reach nominal luminosity and operate for five more years (with a LS of one year after the first three years of operation) aiming to a total integrated luminosity of approximately 1 ab^{-1}. Electron-lead ion operation is also considered in Ref. [80]. The design parameters have been selected to limit the power consumption to less than 100 MW (except for the dedicated mode of operation with an ERL circumference corresponding to 1/5 of the LHC).

The expected maximum power consumption of LHeC with the associated experiment is 220 MW, when operated in dedicated mode, i.e. approximately 75 MW more than the nominal LHC. A yearly electricity consumption of approximately 1.1 TW h/y is expected; this value does not include the electricity consumption of the LHC injector complex.

Implementation of LHeC would require the construction of a new tunnel situated at a depth of approximately 100 m and intersecting the LHC tunnel in IP2.

The cost of LHeC (with an ERL circumference 1/3 of the LHC circumference) was estimated in 2018 to 1600 MCHF (CE representing approximately 24% of the overall cost), therefore we can expect

Table 8.3: Main parameters of LHeC. It is assumed that the ERL does not contribute to significant additional downtime for the machine. The dedicated mode of operation could only take place at the end of the HL-LHC programme. The scheduled physics time and accelerator availability correspond to those assumed in Ref. [8].

	CDR 2020 [79]			ESPPU 2026 [80]	
Parameter	Initial	Design	Dedicated	Initial	Nominal
ERL circumference [km]	5.332 (1/5 of LHC circumference)			8.886 (1/3 of LHC circumference	
c.o.m. energy [TeV]	1.18			1.18	
Electron beam energy [GeV]	50			50	
Average electron beam current [mA]	15	25	50	20	50
Initial luminosity [10^{34} cm^{-2} s^{-1}]	0.5	1.2	2.3	0.9	2.3
Integrated luminosity per year of nominal operation [fb^{-1}/y]	20	50	180	70	180

a 2024 cost of about 2000 MCHF [80][1]. The cost of the experiment should be added and it has been estimated to 360 MCHF (2024 value) excluding the cost of the magnet, beam pipe, Data Acquisition (DAQ), trigger, mechanical structure and infrastructure. We can therefore estimate an overall cost of approximately 2400 MCHF of which about 2100 MCHF borne by CERN.

In order to achieve high-power efficiency, the LHeC ERL design is based on bulk Nb 5-cell 800 MHz SRF cavities operated in CW mode with an accelerating gradient of 22 MV m^{-1} and $Q_0 > 3 \times 10^{10}$ at 2 K. The above requirements coincide with those for the FCC-ee booster and collider RF 800 MHz cavities and they have been achieved in vertical tests conducted at Jefferson Lab in 2018 [81].

The highest energy achieved by an ERL so far is 1 GeV at the Continuous Electron Beam Accelerator Facility (CEBAF), while the Jefferson Lab (JLab) Free Electron Laser (FEL) has reached the highest current of all SRF ERL with 10 mA. Larger currents have been achieved in the normal-conducting, lower-frequency ERL facility at Budker Institute of Nuclear Physics (BINP) [5]. High-current multi-turn energy recovery (i.e. with beam power significantly exceeding the installed RF power) still needs to be demonstrated for beam powers exceeding 1 MW (well below the nominal LHeC beam power of 2.5 GW). 4-turn acceleration to 150 MeV and energy recovery[2] has been demonstrated recently at the Cornell BNL ERL Test Accelerator (CBETA) but at significantly lower current (1 nA) than the design one (40 mA), limited by beam losses, particularly in the last recovery loop, and radiation protection constraints [5, 83, 84]. CBETA used a novel and challenging Fixed-Field Alternating-Gradient (FFAG) transport based on permanent magnets for the arcs; the choice of this technology has imposed a stringent limit on losses and therefore on current to prevent damage to the permanent magnets.

An international collaboration has been established to build a 3-turn 250 MeV ERL—the Powerful Energy Recovery Linac for Experiments (PERLE)—at IJCLab Orsay [85] aiming to deliver a beam current of 20 mA at top energy in bunches of 500 nC charge at 40 MHz as for LHeC, for a design electron beam power of 5 MW. Acceleration and energy recovery will take place in one cryomodule equipped with 5-cell 800 MHz SRF cavities with the same specifications as those required for LHeC.

The PERLE facility is supposed to study and address coherent beam instabilities, incoherent effects and to demonstrate the stable operation of the SRF system with the sixfold current (120 mA) due to the simultaneous acceleration and deceleration of bunches at three different beam energies [5]. A CDR [86] has been written in 2018 and a TDR is in preparation. An ambitious schedule aiming demonstration of the design performance for a 250 MeV ERL at the beginning of the 2030s [80, 85] is put forward. An intermediate stage with a single-turn operation (89 MeV) is contemplated. Future plans include the possibility of reaching 10 MW and a final energy of 500 MeV by the installation of an

[1]This is consistent with an estimate of about 1900 MCHF obtained by considering that the European Union (EU) domestic PPI has increased from 90 to 127 in the period 2018–2024 while the EUR/CHF exchange rate has decreased from 1.15 to 0.95.

[2]Energy recovery efficiency for single-turn acceleration and recovery has been measured to be 99.4%, when taking into account beam losses, and approximately 100% for the cavity single particle energy recovery [82].

additional cryomodule.

A 3-turn ERL configuration had been adopted also for the FCC-eh, albeit maintaining the original 60 GeV energy as default. For FCC-eh the preferred position was interaction point L, for geological reasons mainly [79], though this straight section is now planned to host the main RF system of the collider and the injection system of the anti-clockwise beam, but the LHeC HW could still be used in a different location.

High-Order Mode (HOM) damping and HOM losses management, emittance preservation of the high-brightness electron beam in the recirculating arcs, beam diagnostics, synchrotron radiation handling at high energy, represent the main technical challenges for the LHeC project, with a TRL of 4 for the most critical aspects (see Appendix A.2) [13,35]. Operation in recirculation mode (no energy recovery) would still be possible, though at significantly lower current (likely by an order of magnitude), and therefore at a correspondingly lower luminosity, with a power consumption smaller than 250 MW.

The time to first physics was estimated to be 13 to 18 years (assuming a technically-limited schedule) in Ref. [13], limiting significantly (if not completely) the temporal overlap of LHeC with the HL-LHC programme expected to be completed by the end of 2041. In addition, IP2 is presently allocated to ALICE, the LHC experiment dedicated to the study of heavy ion collisions. ALICE has been upgraded in LS2 to operate at higher luminosity during Run 3 and 4 and, following the recommendations of the 2020 ESPPU, it is proposing an experimental programme until the end of the HL-LHC era. Operation of LHeC after the completion of the HL-LHC programme, after a two year-long shutdown for the completion of the CE and of the installation, is presently contemplated [80]. This implies the validation of the main concepts and in particular the successful operation of PERLE by the beginning of the 2030s. An alternative scenario [87], considering a staged construction of LHeC with a first phase completed by the end of LS4 and allowing collisions of 20 GeV electrons from a single-pass ERL during Run 5, appears not to be realistic for the above-mentioned reasons and it would require an adaptation of the ALICE3 detector.

The personnel required for the construction of the LHeC accelerator and its infrastructure is expected to be comparable to that required for HL-LHC, a project of similar size, and it would amount to 2500 FTEy, over seven years [80], to be compared with 3400 FTEy according to Eq. (1).

9 New acceleration techniques

Wakefield Accelerator (WFA) hold the promise for a path towards more compact, and hence potentially more sustainable, high-energy colliders than those relying on conventional technology. Their distinctive feature is a high peak gradient that can reach one to several orders of magnitude larger values than conventional RF acceleration schemes. The potential of these new techniques is well illustrated by the 52 GeV/m energy gradient obtained with an electron-driven plasma WFA in the Facility for Advanced Accelerator Experimental Tests (FACET) [88], or more recently the 30.7 GeV/m energy gradient achieved at BErkeley Lab Laser Accelerator (BELLA) in a laser-driven WFA [89], in both cases with energy gain more than 9 GeV.

In such systems, the wakefields provide the acceleration and are driven by either a pulsed laser, or by particle bunches—typically made of electrons, although protons can also be used, for example in the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) [90]. Wakefields must be sustained either using a plasma, in a Plasma Wakefield Accelerator (PWFA) or Laser Wakefield Accelerator (LWFA), or thanks to a dielectric-based structure surrounding the beam, in a Structure Wakefield Accelerator (SWFA) [13] or Dielectric Laser Accelerator (DLA). In the case of SWFA, the two beams (drive beam and accelerated beam) may either be traveling in the same structure in a Collinear Wakefield Accelerator (CWA), or in two different structures in a Two-Beam Accelerator (TBA) [91].

Both plasma- and dielectric-based schemes can sustain very large electric fields, thus overcoming the breakdown voltage in conventional RF structures. SWFA exhibit typically smaller gradients (few hundreds of MV/m) compared to plasma-based accelerators (in the GV/m range). In principle, compact e^+e^-colliders could be built using such advanced acceleration schemes, and several options were considered in the Snowmass process [13] (see also update in Ref. [92]).

Such technologies exhibit a disrupting potential, and steady progress has been made in the past decade. For instance, the Laser–plasma driven undulator beamline (LUX) in DESY, was able to run stable for 24 hours [93]. A milestone was also reached when Free Electron Laser (FEL) amplification was achieved with a LWFA in China [94] and in Europe [95], as well as with a PWFA at the Sources for Plasma Accelerators and Radiation Compton with Laser And Beam (SPARC_LAB) facility [96, 97]. Nevertheless, to date no user facility based on wakefield acceleration, aiming at high-energy physics, has been built yet. A FEL, PWFA project is close to completion, the European Plasma Research Accelerator with eXcellence in Applications (EuPRAXIA) [98] (EuPRAXIA@SPARC_LAB [99], to be operated as of 2029), but its beam parameters (in particular, beam energy of 1–5 GeV, less than $0.2 \cdot 10^9$ e^- per bunch, and no more than 100–400 Hz repetition rate [100]), remain far from those required by a Higgs factory, and no staging of plasmas is foreseen, nor any positron acceleration.

For LWFA as proposed in Ref. [101], and for PWFA such as the electron-driven Plasma Wakefield Acceleration Linear Collider (PWFA-LC) [102] or the proton-driven Advanced Linear collider for Very high Energy (ALiVE) [103], positron acceleration in the plasma remains an outstanding challenge [104]: contrary to electrons, positrons usually experience strong defocusing, as a consequence of the charge asymmetry of the plasma [105]. Structure-based accelerators such as SWFA and DLA avoid this problem, but suffer from other limitations such as beam break up caused by the strong wakefields generated in the dielectric structure, leading to the need for very small charges per bunch, and hence requiring very high repetition rates (or very small bunch spacing) to maintain an acceptable luminosity. In general, structure-based acceleration is currently not considered the preferred option for WFA technology [5], and hence R&D is less active in this field than for plasma-based WFA. $\gamma\gamma$ colliders may also circumvent the positron acceleration problem, since they use only electrons [104].

In general, the critical challenges common to most wakefield-based accelerators, are related to large-scale staging (with all subsequent issues such as synchronisation, phasing and alignment [106]), BDS with a final focus aiming at beam sizes of tens of nm, emittance preservation along the chain, the relatively small bunch intensity that could be accelerated so far, the very large repetition rates needed to achieve the luminosities required by high-energy physics, and the energy efficiency of the whole process. More details can be found in the International Committee for Future Accelerators (ICFA) Beam Dynamics Newsletter dedicated to beam dynamics challenges in advanced accelerator concepts [107], and in the Laboratory Directors Group (LDG) Accelerator R&D Roadmap [5]. In addition to these, for the specific case of LWFA, laser technology needs to reach tens of kW of average power with tens of kHz repetition rate, while current state of the art is still below 1 kW average, at the 100 Hz level [35]. Coherent combination of high-efficiency, high-repetition rate fiber lasers, to replace the traditional but less efficient Titanium:Sapphire technology, might address this issue in the future [108]. Finally, regarding the more recent concept of proton-driven PWFA as in ALiVE or AWAKE, the challenge of staging is replaced by that of realizing a single plasma of hundreds of meters with a plasma density gradient [103]. For such accelerators, the achievable repetition rate is also limited by the high-energy proton complex needed to generate the driver, but rapid cycling synchrotrons or Fixed-Field Alternating-Gradient (FFAG) are being proposed to solve this issue [109].

Regarding the wall plug efficiency, three factors [110] are mainly driving it: the efficiency of the driver generation, that of the drive to wake process, and finally the part of the energy transferred from the wake to the accelerated beam. The last of these requires a trade-off between accelerating gradient (low accelerated bunch charge) and efficiency (high accelerated charge). In addition, the drive-to-wake efficiency may be limited by stability [111].

We summarise in Table 9.1 two examples of wakefield-based collider studies, giving their main parameters and R&D challenges: the Hybrid Asymmetric Linear Higgs Factory (HALHF), and a recent concept proposed by the ALiVE collaboration for proton-driven PWFA. Other designs proposed earlier for the Snowmass report, or in the aforementioned ICFA newsletter, were not selected here as they are much less developped: the DLA in Ref. [112] and the SWFA Argonne Flexible Linear Collider (AFLC) [91] concepts were still very preliminary, the LWFA presented in Ref. [101] and in the Snowmass report, still lacks a clear design, while the PWFA-LC study [102, 113] has not been updated since 2014. Current design studies focus on Higgs factories based on PWFA such as HALHF and ALiVE, while 10 TeV e^+e^-collider options including PWFA, LWFA, and SWFA components are considered in Ref. [114].

For the selected studies, even with the (optimistic) assumption that all the challenges are overcome, the peak luminosity achievable remains a significant factor below what is accessible in major Higgs factory projects (especially circular ones). The wall plug efficiency foreseen lies in the range 3–12%, comparable to that of linear colliders such as CLIC, LCF and ILC.

The proton-driven PWFA proposed by ALiVE misses a conceptual design for the proton driver, and faces the outstanding challenge of the positron acceleration. On the other hand, HALHF circumvents the latter issue thanks to an innovative, asymmetric design in which only the electrons are accelerated to a high energy (375 GeV) by a PWFA, while the positrons are accelerated to a lower energy (41.7 GeV) using an RF accelerator based on Cool Copper Collider (C^3) technology [115], which is still in its R&D phase, for a c.o.m. energy of 250 GeV—note that higher energy options are also envisaged, requiring longer facility length. The size of such a machine would be very competitive, and the critical issue of emittance preservation in the PWFA e^- linac, is slightly relaxed thanks to the asymmetry. Nevertheless, many PWFA issues remain to be solved for the electron linac; quoting from Ref. [116]: "[...] there must be progress toward the use of multiple stages, self-correction mechanisms, higher accelerated charge (by a factor ~ 10), higher repetition rate (by a factor ~ 1000), plasma-cell design required to cope with large power dissipation (by a factor ~ 1000) and reduction of beam jitter to an acceptable level (by a factor $\sim 10-100$)". On some of the challenges mentioned above, recent progress were reached, for instance regarding emittance preservation in a single plasma [117], or the issue of plasma heating and its related recovery time, which could limit the collision rate to the tens of MHz range when using Argon ions [118] (to achieve a 16 ns bunch spacing, as foreseen in HALHF [119], the use of lighter ions may be required [120]). Asymmetric collisions also require R&D on the detector side. A 15 years-roadmap for the R&D needed to validate the technology required by HALHF, was submitted recently to the ESPPU [121]; the total resources foreseen amount to 213 MCHF and 341 FTEy.

For any multistage wakefield accelerator, and in particular for all the multi-TeV alternatives presented in Ref. [13], heavy R&D (and hence the corresponding resources) is needed, and a multi-GeV demonstrator required as a first step, before any realistic design could be presented—hence in all these cases a TDR remains decades away, and no costing is available. Nevertheless, it should be mentioned that so far, no definitive showstopper has been found, and the field is very active, as can be seen from the submissions for the ESPPU 2026 [109, 114, 122, 123] and the number of WFA projects around the world (see e.g. the list in Ref. [124]). The LC Vision is also contemplating the possible use of WFA for future upgrades of linear colliders [125].

It is finally worth noting that in plasma-based accelerators a number of effects may pose fundamental limits. In the "blow-out" or nonlinear regime, where the acceleration gradient is the largest, the strong focusing in the plasma induces energy loss from betatron radiation [110], as well as challenges related to the matching of adjacent plasmas [126] (the matching issue does not apply to a proton-driven PWFA, which uses a single plasma). In general, in WFA the beam spot size at the interaction point, hence the luminosity, may also be limited by chromatic aberrations [92], or the Oide effect from betatron radiation related to the strong focusing [127]. Besides, because of the high energies and ultra short bunches, the beamstrahlung parameter gets well above one, contrary to conventional linear colliders [92], leading to e.g. energy spread and background in the detectors.

In summary, in recent years there were many advances towards the possible use of WFA for the acceleration of higher quality electron beams and the field is very active to try to address the encountered issues through R&D. Nevertheless, the lack of maturity of the technology currently prevents wakefield-based accelerators to be considered as alternatives to the main projects presented in the above sections, at least in the timescale considered.

Table 9.1: Main parameters for potential wakefield-based e^+e^- colliders. A single IP is assumed in all cases.

<table>
<tr><td>Name</td><td colspan="2">HALHF (250 GeV)</td><td>ALiVE</td></tr>
<tr><td>Main reference</td><td colspan="2">[122]</td><td>[109]</td></tr>
<tr><td>Main principle</td><td>375 GeV e^-
e^- driven PWFA</td><td>41.7 GeV e^+
C^3 RF system [115]</td><td>p^+ driven
PWFA</td></tr>
<tr><td>c.o.m. energy [TeV]</td><td colspan="2">0.25</td><td>0.25</td></tr>
<tr><td>Full facility length [km]</td><td colspan="2">4.9</td><td>$\sim$5.5 [128][a]</td></tr>
<tr><td>Length per linac [km]</td><td>1.1</td><td>1.1</td><td>0.24 [128]</td></tr>
<tr><td>Instantaneous luminosity above 0.99 $\sqrt{s}$ [10^{34} cm^{-2} s^{-1}]</td><td colspan="2">0.76</td><td>0.25 [128]</td></tr>
<tr><td>Integrated luminosity above 0.99 $\sqrt{s}$ per year [ab^{-1}/y][b]</td><td colspan="2">0.09</td><td>0.03</td></tr>
<tr><td>Wall plug power [MW]</td><td colspan="2">106</td><td>$\sim$200 [128]</td></tr>
<tr><td>Acceleration gradient [GV/m]</td><td>1</td><td>0.04</td><td>0.5 [128]</td></tr>
<tr><td>Particles per bunch</td><td>10^{10}</td><td>$3 \cdot 10^{10}$</td><td>$2 \cdot 10^{10}$</td></tr>
<tr><td>Bunches per train</td><td colspan="2">160</td><td>1</td></tr>
<tr><td>Bunch spacing in train</td><td colspan="2">16 ns</td><td>-</td></tr>
<tr><td>Train repetition rate</td><td colspan="2">100 Hz</td><td>7.2 kHz</td></tr>
<tr><td>Emittance $\varepsilon_x/\varepsilon_y$ [µm]</td><td>90 / 0.32</td><td>10 / 0.035</td><td>0.1 / 0.1 (e^-)
0.4 / 0.4 (e^+)</td></tr>
<tr><td>Size σ_x/σ_y at IP [nm]</td><td colspan="2">636 / 6.6</td><td>73 / 13 (e^-)
146 /26 (e^+)</td></tr>
<tr><td>RMS bunch length [µm]</td><td>40 (150 at IP)</td><td>150</td><td>105 (e^-)
75 (e^+)</td></tr>
<tr><td>RMS energy spread at IP</td><td colspan="2">0.0015</td><td>0.001</td></tr>
<tr><td>Single beam power [MW]</td><td>9.6</td><td>3.2</td><td>2.9</td></tr>
<tr><td>Beam vs wall power ratio</td><td colspan="2">0.12</td><td>0.03</td></tr>
<tr><td>R&D challenges</td><td colspan="2">- For the PWFA: staging, short bunch separation (plasma recovery issue), self-correction mechanisms, progress needed by orders of magnitude for key parameters: accelerated charge, repetition rate, acceptable power dissipation in plasma cell, beam jitter, alignment; emittance preservation

- BDS (both sides)
- e^+ source</td><td>- e^+ acceleration
- Development of long plasma cell, energy efficiency
- Proton driver complex: design of four FFAG up to 500 GeV, short bunches (0.7 mm), tailored emittance profile, high repetition rate (14.4 kHz), novel superconducting magnets and cavities, dump system for $\sim$30 MW beams
- Demonstrator
- BDS, control of energy spread</td></tr>
<tr><td>Timescale (technically-limited)</td><td colspan="2">15 years R&D
Construction in 15 years</td><td>N/A</td></tr>
</table>

[a] The proton complex is not included, and may be as large as 6.9 km long [109].
[b] Computed from the instantaneous luminosity above 0.99 $\sqrt{s}$, assuming 139 days of data taking per year (see Table A.1).

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Appendices

A Criteria and metrics for the comparison

A.1 Operational year

e^+e^- colliders

The operational parameters (number of days of operation in each phase, and corresponding fraction of the peak power needed) are presented in Table A.1 and Fig. A.1.

Table A.1: Breakdown of the operational phases [8,17,21] and of the corresponding fractional electricity consumption [17,21], for the linear and circular e^+e^- colliders. For CLIC the baseline and energy upgrade are considered, and for LCF [22] the baseline and upgrade options are given—Low-Power (LP) at 250 GeV and Full-Power (FP) at 250 GeV and 550 GeV.

Operational phase	Number of days	Fraction of the peak power consumption [%]								
		circular				CLIC		LCF		
		Z	W	ZH	$t\bar{t}$	380 GeV	1.5 TeV	250 LP	250 FP	550 FP
Annual shutdown	120	12	12	11	11	6	5	28	18	25
Commissioning	30	58	60	60	62	55	55	77	72	72
Technical stops	10	27	28	27	28	55	55	54	45	44
Machine development	20	39	45	50	61	55	55	77	72	72
Downtime (faults)	46	30	36	42	55	55	55	54	45	44
Data taking	**139**	100								

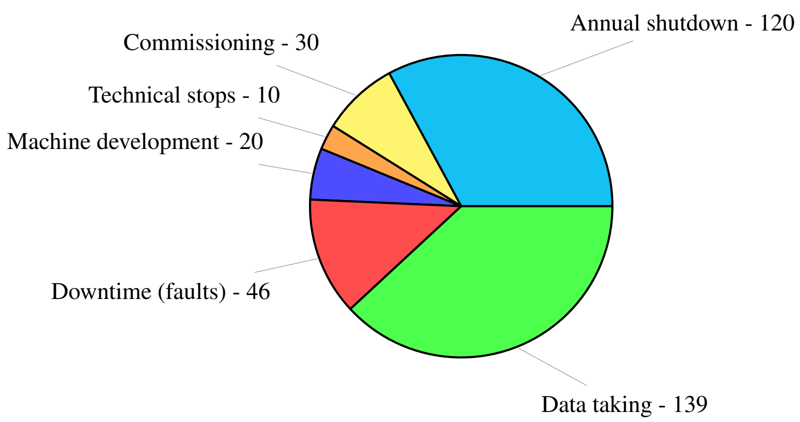

Fig. A.1: Breakdown of the operational phases for e^+e^- colliders (see Table A.1).

Hadron colliders

The operational parameters are presented in Table A.2 and Fig. A.2.

Muon colliders

The main parameters for the MC are presented in Table A.2 and Fig. A.3.

A.2 Technology readiness level

The definition of the TRL is provided in Table A.3.

Table A.2: Breakdown of the operational phase and the corresponding fractional power consumption for hadron colliders [8] and the Muon Collider [51]. For comparison, the breakdown of the operational phases during LHC Run 2 can be found in Refs. [129, 130].

Operational phase	Number of days		Fraction of the peak power consumption [%]		
	FCC-hh	MC	FCC-hh	MC	
				3.2 TeV	7.6 TeV
Annual shutdown	125	125	34	50	38
Commissioning	40	40	91	100	100
Technical stops	10 +5 (recovery)	10 +5 (recovery)	34	62	61
Machine development	20	20	91	100	100
Special runs	5	–	91	–	–
Downtime (faults)	48	49	34	72	71
Turnaround	56	–	91	–	–
Data taking	**56**	**116**	100	100	100

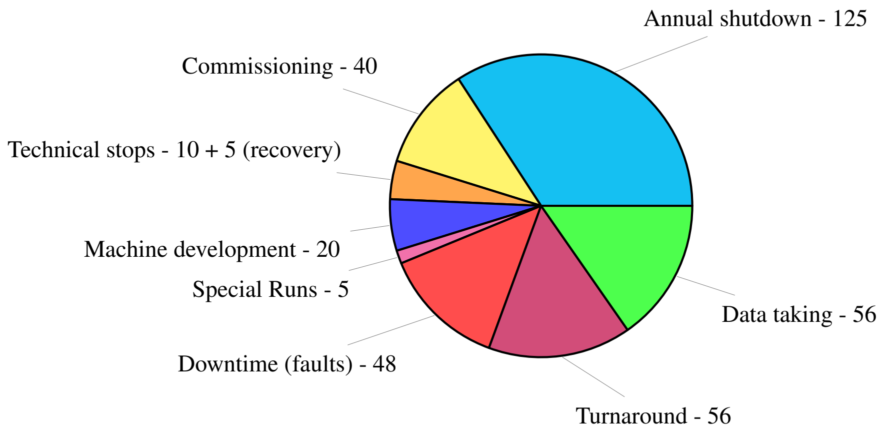

Fig. A.2: Breakdown of the operational year for hadron colliders (see Table A.2).

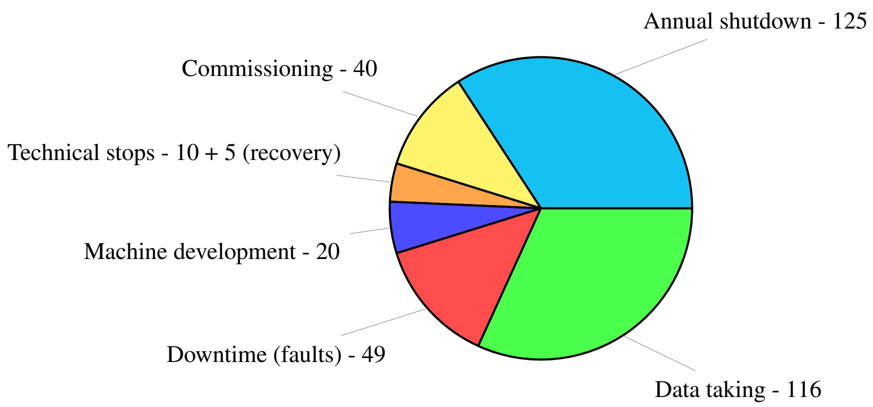

Fig. A.3: Breakdown of the operational year for the MC (see Table A.2).

A.3 Cost classes

The definition of the cost classes used in the report is presented in Table A.4.

Table A.3: Definition of the Technology Readiness Level (TRL) [35]. The same *traffic light* colour coding is used as in Ref. [35].

Level	Short description
1	Basic principles observed and reported.
2	Technology concept formulated.
3	Experimental critical proof of concept.
4	Technology validated in laboratory environment.
5	Technology (component or breadboard) validation in relevant environment (industrially relevant environment in case of key enabling technologies).
6	Technology (system/sub-system) demonstration in a relevant environment (industrially relevant environment in case of key enabling technologies).
7	System prototype demonstration in an operational environment.
8	Actual system completed and qualified through test and demonstration.
9	Actual system proven in an operational environment.

Table A.4: Cost estimate classification matrix used in the report. Source: AACE® [14].

Cost class	Level of definition	Typical estimating technique	Typical purpose of estimate	Expected accuracy ranges, low (L) and high (H)
Class 5	0/2%	Capacity factored, stochastic, most parametric models, judgement or analogy	Concept screening	L: -20/-50%; H: +30/+100%
Class 4	1/15%	Equipment factored, more parametric models	Study or feasibility	L: -15/-30%; H: +20/+50%
Class 3	10/40%	Semi-detailed unit costs with assembly level line items. Combination of various techniques (detailed, unit-cost, or activity-based; parametric; specific analogy; expert opinion; trend analysis).	Preliminary, budget authorization	L: -10/-20%; H: +10/+30%
Class 2	30/70%	Detailed unit costs. Combination of various techniques (detailed, unit-cost, or activity-based; expert opinion; learning curve).	Control or bid/tender	L: -5/-15%; H: +5/+20%
Class 1	50/100%	Deterministic, most definitive cost estimation.	Check estimate or bid/tender	L: -3/-10%; H: +3/+15%

A.4 Producer price index (PPI)

The data concerning the PPI have been obtained from the following sources:

- China (National Bureau of Statistics of China): https://tradingeconomics.com/china/producer-prices;
- European Union (EUROSTAT): https://tradingeconomics.com/european-union/producer-prices;
- Japan (Bank of Japan): https://tradingeconomics.com/japan/producer-prices.

A.5 Exchange rates

Table A.5: Currency exchange rates used in the report.

Chinese Yuan Renminbi (CNY) to CHF	Euro (EUR) to CHF	Japanese Yen (JPY) to CHF	US Dollar (USD) to CHF
0.123	0.959	0.00587	0.881

A.6 Purchasing power parity (PPP)

Table A.6: Currency exchange rates corrected for the PPP used in the report (2023 data—Source: Organisation for Economic Co-operation and Development (OECD) [131]).

Chinese Yuan Renminbi (CNY) to CHF	Euro (EUR) to CHF	Japanese Yen (JPY) to CHF	US Dollar (USD) to CHF
0.266	1.546	0.0102	0.966

B Additional tables

B.1 Published parameters of CEPC and ILC

In Table B.1 we provide the high-level parameters originally given for CEPC and the ILC, i.e. without applying any rescaling as done for Table 7.1.

Table B.1: High-level parameters of the ILC [40], and of CEPC for different options [7, 52] (baseline parameters for CEPC are in **bold**). For the ILC we follow an operational scenario adapted from Ref. [53], with 10 years of operation including three years of ramp-up at one third the luminosity, and no luminosity upgrade (not costed in Ref. [40]). The integrated luminosity over the full programme is also adapted from Ref. [53], following such a scenario. The instantaneous and integrated luminosity in-between parentheses includes also the contribution from energies below 99% of the c.o.m. energy $\sqrt{s}$.

	CEPC				ILC 250
Length collider tunnel [km]	99.955				20.5
Number of experiments (IPs)	2				2 (1)[a]
c.o.m. energy [GeV]	**91**	**160**	**240**	360	250
Longitudinal polarisation (e^- / e^+)	0 / 0[b]				0.8 / 0.3
Number of years of operation (total)	**2**	**1**	**10**	5	10
Nominal years of operation (equivalent)[c]	**2**	**1**	**10**	5	8
Synchrotron radiation power per beam [MW]	**10** / 30 / 50	**30** / 50	**30** / 50	30 / 50	–
Instantaneous luminosity per IP above 0.99 $\sqrt{s}$ (total) of nominal c.o.m. energy [$10^{34}\,cm^{-2}\,s^{-1}$]	**38** / 115 / 192	**16** / 26.7	**5** / 8.3	0.5 / 0.8	1 (1.35)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs per year of nominal operation [ab^{-1}/y]	**10** / 30 / 50	**4.2** / 6.9	**1.3** / 2.2	0.13 / 0.2	0.15 (0.2)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs over the full programme [ab^{-1}]	**20** / 60 / 100	**4.2** / 6.9	**13** / 21.6	0.65 / 1	1.2 (1.6)
Peak power consumption [MW]	**100**[d] / **203** / 287	**225** / 299	**262** / 339	358 / 432	111
Electricity consumption per year of nominal operation [TW h/y]	**0.5** / 1.0 / 1.4	**1.1** / 1.5	**1.3** / 1.7	1.8 / 2.2	0.73

[a] Two experiments at a single IP ("push-pull" mode).
[b] No longitudinal polarisation is considered in the baseline, but such a possibility is being explored, especially at the Z energy.
[c] This row lists the equivalent number of years of operation at nominal instantaneous luminosity, hence taking into account the luminosity ramp-up.
[d] Extrapolated from Ref. [7].

List of acronyms

HL-LHC High-Luminosity LHC ... 1, 3–7, 28, 29, 34, 40, 50–53
HOM High-Order Mode ... 53
HORIZON Horizon Europe Framework Programme ... 6
HTS High Temperature Superconductor ... 4, 6, 33, 35, 37–40, 50
HW Hardware ... 3, 13, 14, 19–21, 28, 29, 31, 36, 41, 48, 53

IBS Iron Based Superconductor ... 35
ICFA International Committee for Future Accelerators ... 54, 55
IDT International Development Team ... 27
IJCLab Laboratoire de Physique des 2 Infinis Irène Joliot-Curie ... 52
ILC International Linear Collider ... v, 1, 2, 6, 7, 18–20, 25, 27, 29, 42–45, 47, 48, 55, 61, 62, 65
ILCU ILC unit ... 45, 47
IMCC International Muon Collider Collaboration ... 1, 37, 41
IP Interaction Point ... 2–5, 16, 18–26, 29–32, 34, 38, 42–44, 48, 49, 51, 53, 56, 62
ISO International Organization for Standardization ... 10
ISOLDE Isotope Separator On Line DEvice ... 7
ITF Implementation Task Force ... 13
ITN ILC Technology Network ... 44

JLab Jefferson Lab ... 52
JPY Japanese Yen ... 45, 47, 61

KEK High Energy Accelerator Research Organization in Japan ... 3, 24, 25
KEKB KEK B-factory ... 2

LC Linear Collider ... 2–4, 18, 21, 23, 29, 55
LCA Life Cycle Assessment ... 10, 11, 19–21, 68
LCF Linear Collider Facility ... 1–4, 6, 18–22, 24–33, 43, 44, 55, 58
LCLS–II Linac Coherent Light Source II ... 3
LDG Laboratory Directors Group ... 23, 54, 57
LEP Large Electron Positron (collider) ... 2, 18, 48
LEP2 Large Electron Positron (collider) 2 ... 2, 18, 49
LEP3 Large Electron Positron (collider) 3 ... v, 2, 5, 8, 48–50
LHC Large Hadron Collider ... v, 1, 3–5, 7, 9, 15, 21–24, 34, 35, 37, 38, 40, 48–53, 59
LHeC Large Hadron-electron Collider ... v, 5, 8, 51–53
LoI Letter of Interest ... 48
LP Low-Power ... 2, 3, 18, 19, 21, 27, 30, 32, 43, 44, 58
LS Long Shutdown ... 7, 18, 30, 33, 51, 53
LSS Long Straight Section ... 5, 17, 39, 49
LTS Low Temperature Superconductor ... 6, 35
LUX Laser–plasma driven undulator beamline ... 54

Glossary

(industrial) Producer Price Index The (industrial) Producer Price Index (PPI), also called output price index, is a business-cycle indicator showing the development of transaction prices for the monthly industrial output of economic activities. [132]. 12

Environmental Impact Assessment The process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made [133]. 47

Global Warming Potential (GWP) is a term used to describe the relative potency, molecule for molecule, of a GHG, taking account of how long it remains active in the atmosphere. The global-warming potentials currently used are those calculated over 100 years. Carbon dioxide is taken as the gas of reference and given a 100-year GWP of 1 [134]. 22

Life Cycle Assessment Life Cycle Assessment (LCA) is a process of evaluating the effects that a product has on the environment over the entire period of its life thereby increasing resource-use efficiency and decreasing liabilities. It takes into account a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste. LCA is commonly referred to as a "cradle-to-grave" analysis [135, 136]. LCA modules A1 to A5 ("cradle-to-gate" analysis) include the raw material extraction to construction activities on site (including energy consumption). B1–B8 modules are related to the use of the product over the entire life cycle of the project, with the end-of-life stage (C1–C4 modules) for the deconstruction and demolition of the construction project including the impacts of transport to waste processing sites and the disposal of said waste. D module covers the net benefits and loads arising from the reuse of products or the recycling or recovery of energy from waste materials resulting from the construction stage, the use stage and the end-of-life stage [9]. 10

Purchasing Power Parity Purchasing power parities (PPPs) are the rates of currency conversion that try to equalise the purchasing power of different currencies, by eliminating the differences in price levels between countries. The basket of goods and services priced is a sample of all those that are part of final expenditures: final consumption of households and government, fixed capital formation, and net exports. This indicator is measured in terms of national currency per US dollar [15]. 12

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