ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUZD1

THE ELECTRON-POSITRON FUTURE CIRCULAR COLLIDER (FCC-ee)*

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Abstract

The Future Circular electron-positron Collider (FCC-ee) is aimed at studying the Z_0 and $W^{\pm}$ bosons, the Higgs, and top quark with extremely high luminosity and good energy efficiency. Responding to a request from the 2020 Update of the European Strategy for Particle Physics, in 2021 the CERN Council has launched the FCC Feasibility Study to examine the detailed implementation of such a collider. This FCC Feasibility Study will be completed by the end of 2025 and its results be presented to the next Update of the European Strategy for Particle Physics expected in 2026/27.

INTRODUCTION

The Future Circular electron-positron Collider, FCC-ee, is a proposed new storage ring of 91 km circumference, designed to carry out a precision study of Z, W, H, and $t\bar{t}$ with an extremely high luminosity, ranging from $2{\times}10^{36}$ cm^{-2}s^{-1} per interaction point (IP), on the Z pole (91 GeV c.m.), 7×10^{34} cm^{-2}s^{-1} per IP at the ZH production peak and 1.3×10^{34} cm^{-2}s^{-1} per IP at the $t\bar{t}$. In the case of four experiments, the total luminosity on the Z pole will be close to 10^{37} cm^{-2}s^{-1}. FCC-ee will also offer unprecedented energy resolution, both on the Z pole and at the WW threshold.

The FCC-ee represents a low-risk technical solution for an electroweak and Higgs factory, which is based on 60 years of worldwide experience with e^+e^- circular colliders and particle detectors. R&D is being carried out on components for improved performance, but there is no need for "demonstration" facilities, as LEP2, VEPP-4M, PEP-II, KEKB, DAΦNE, or SuperKEKB already demonstrated many of the key ingredients in routine operation.

The FCC shall be located in the Lake Geneva basin and be linked to the existing CERN facilities. The FCC utility requirements are similar to those in actual use at CERN. The FCC "integrated programme" consists of the FCC-ee Higgs and electroweak factory as a first stage, succeeded by a 100 TeV hadron collider, FCC-hh, as the ultimate goal. This sequence of FCC-ee and FCC-hh is inspired by the successful past Large Electron Positron collider (LEP) and Large Hadron Collider (LHC) projects at CERN. A similar two-stage project is under study in China, under the name CEPC/SPPC [1].

The FCC technical schedule foresees the start of tunnel construction around the year 2030, the first e^+e^- collisions at the FCC-ee in the mid or late 2040s, and the first FCC-hh hadron collisions by 2065–70.

DESIGN OUTLINE

The FCC-ee is conceived as a double ring e^+e^- collider. It shares a common footprint with the 100 TeV hadron collider, FCC-hh, that would be the second stage of the FCC integrated programme.

The FCC-ee design features a novel asymmetric interaction-region (IR) layout and optics to limit the synchrotron radiation emitted towards the detector (a lesson from LEP [2]), and to generate the large crossing angle 30 mrad, required for the crab-waist collision scheme [3].

The latest FCC layout features a superperiodicity of four, and can accommodate either two or four experiments, in four 1.4 km long straight sections, which are alternating with 2.14 km straight sections hosting technical systems, in particular radiofrequency (RF) cavities. Each of the 8 separating arc sections has a length of 9.6 km. Figure 1 sketches the layout and possible straight-section functions for the FCC-ee.

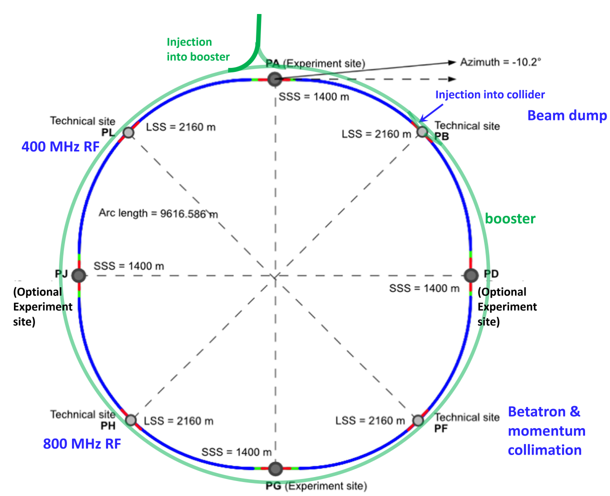

Figure 1: Schematic layout of the FCC-ee collider with a circumference of 91.1 km and four-fold superperiodicity. The full-energy booster and part of its injection transfer line are also indicated.

FCC-ee key parameters, evolved from those of the Conceptual Design Report (CDR) [4], are summarized in Table 1. Thanks to self-polarisation at the two lower energies (Z and W operation) [5], a precision energy calibration by resonant depolarisation is possible, down to 100 keV accuracy for m_Z and 300 keV for m_W [6, 7].

* Work supported by the European Union's H2020 Framework Programme under grant agreement no. 951754 (FCCIS).
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An important ingredient is the crab waist collision scheme, which was first demonstrated at DAΦNE, where it tripled the collider luminosity [8]. More recently, in 2020, at SuperKEKB the "virtual" crab waist collision, first developed for the FCC-ee [3], was successfully implemented, and is now used in routine operation [9]. SuperKEKB is also already operating with a vertical IP beta function β_y^* of 1 mm in regular operation, and, during accelerator studies, further squeezed β_y^* down to 0.8 mm, the smallest value considered for FCC-ee (see Table 1).

As shown in Table 1, the synchrotron radiation power of FCC-ee is assumed to be limited to 50 MW per beam. As the centre-of-mass energy is increased, the synchrotron radiation power is kept constant, primarily by reducing the number of bunches. Top-up injection requires a full-energy booster synchrotron in the collider tunnel.

Table 1: Preliminary key parameters of FCC-ee, now with a circumference of 91.1 km, and a new arc optics for Z and W running. Luminosity values are given per interaction point (IP), for a scenario with 4 IPs. Both the natural bunch lengths due to synchrotron radiation (SR) and their values in collision including the effect of beamstrahlung (BS) are shown. The FCC-ee considers a combination of 400 MHz radiofrequency systems (at the first three energies, up to 2×2 GV) and 800 MHz (additional cavities for $t\bar{t}$ operation), with respective voltage strengths as indicated. The beam lifetime shown represents the combined effect of the luminosity-related radiative Bhabha scattering and beamstrahlung, the latter relevant only for ZH and $t\bar{t}$ running (beam energies of 120 and 182.5 GeV).

Running mode	**Z**	**W**	**ZH**	**$t\bar{t}$**
Number of IPs		4		
Beam energy (GeV)	45.6	80	120	183
Bunches/beam	8800	1120	336	42
Beam current [mA]	1400	135	26.7	5.0
Luminosity/IP [nb^{-1} s^{-1}]	1810	173	72	12.5
Energy loss / turn [GeV]	0.04	0.37	1.87	10.0
Synchr.rad.power [MW]		100		
RF voltage 0.4GHz [GV]	0.12	1.0	2.1	2.5
RF voltage 0.8GHz [GV]	0	0	0	8.8
Bunch length σ_z w/o	4.4	3.6	3.3	2.0
and with BS [mm]	14.5	8.0	6.0	2.8
Hor. emit. $\varepsilon_{x,y}$ [nm]	0.71	2.17	0.64	1.49
Vert. emit. $\varepsilon_{x,y}$ [pm]	1.42	4.34	1.29	2.98
Long. damp. time [turns]	1170	216	64.5	18.5
Vert. IP beta β_y^* [mm]	0.8	1.0	1.0	1.6
Beam lifetime [min.]	19	20	7	10

PROJECT COST AND PROFILE

The FCC CDR of 2019 included a cost estimate for the first stage, the FCC-ee, which is reproduced in Table 2.

A draft spending profile for FCC-ee is displayed in Fig. 2. This figure assumes civil engineering construction from 2032 to 2040, installation of technical infrastructure from 2037 to 2043, construction of accelerator and experiments during the years 2032–2045, and, finally, commissioning and start of operation in the period 2045–2048.

Table 2: Construction cost estimate for FCC-ee considering a machine configurations at the Z, W, and H working points. A baseline configuration with 2 detectors is assumed. The CERN contribution to 2 experiments is included.

Cost category	**MCHF**	**%**
Civil engineering	5,400	50
Technical infrastructure	2,0009	18
Accelerator	3,300	30
Detector	200	2
total cost (2018 prices)	10,900	100

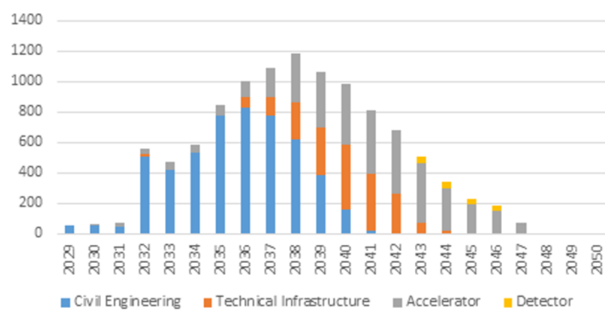

Figure 2: Example draft spending profile for FCC-ee, in units of MCHF versus the year.

FCC-ee R&D

Many of the technologies required for constructing an FCC-ee exist [10]. Ongoing FCC-ee research and development (R&D) efforts focus on further improving the overall energy efficiency, on obtaining the measurement precision required, and on achieving the target performance in terms of beam current and luminosity.

Key FCC-ee R&D items for improved energy efficiency include high-efficiency continuous wave (CW) radiofrequency (RF) power sources (klystrons, IOTs and/or solid state), high-Q superconducting (SC) cavities for the 400–800 MHz range, and possible applications of high-temperature superconductor (HTS) magnets. For ultra high precision centre-of-mass energy measurements, the R&D should also cover advanced beam measurements (inv. Compton, beamstrahlung, etc.) and spin-polarisation simulations. Finally, for high luminosity, high current operation, FCC-ee requires a next generation beam stabilization and feedback system to suppress instabilities arising over a few turns, a robust low-impedance collimation scheme, and a machine tuning system based on artificial intelligence.

SRF Cavity Developments

Since PETRA, TRISTAN and LEP-2, superconducting RF systems are the underpinning technology for modern circular

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lepton colliders. The FCC-ee baseline foresees the use of single-cell 400 MHz Nb/Cu cavities for high-current low-voltage beam operation at the Z production energy, two-cell 400 MHz Nb/Cu cavities at the W and H (ZH) energies, and a complement of five-cell bulk Nb 800 MHz cavities at 2 K for low-current high-voltage $t\bar{t}$ operation [4]. In the full-energy booster, only multi-cell 400 and 800 MHz cavities may be installed. The necessity of 400 MHz systems in the booster is under study. For the FCC-ee collider, also alternative RF scenarios, with possibly fewer changes between operating points, are being explored, such as novel 600 MHz slotted waveguide elliptical (SWELL) cavities [11].

R&D for the FCC-ee Arcs

Aside from the various RF systems, another major component of the FCC-ee is the regular arc, covering about 77 km. The arc cells must be cost effective, reliable and easily maintainable. Therefore, as part of the FCC R&D plan, an arc half-cell mock up is foreseen to be constructed by 2025. It will include girder, a vacuum system with antechamber and pumps, dipole, quadrupole and sextupole magnets, beam position monitors, cooling and alignment systems, and technical infrastructure interfaces. Similarly, for the interaction region the construction of a mock up is proposed, consisting of the central beam pipe, first SC quadrupole with its cryostat, support structures, stabilization system, and remotely controlled flanges.

Constructing some of the magnets for the FCC-ee final focus or arcs with advanced high-temperature superconductor (HTS) technology [12] could lower the energy consumption and increase operational flexibility. The focus of this HTS R&D will not be on reaching extremely high field, but on operating lower-field SC magnets at temperatures between 40 and 77 K. Nevertheless, this development could also be a first step towards higher field HTS magnets for the hadron collider FCC-hh, where operation at 40 K instead of 2 K, would dramatically reduce the electric power consumption.

Centre-of-Mass Energy Calibration

Highly precise centre-of-mass energy calibration at c.m. energies of 91 GeV (Z pole) and 160 GeV (WW threshold), a cornerstone of the precision physics programme of the FCC-ee, relies on using resonant depolarisation of wiggler-pre-polarised pilot bunches [7]. The operation with polarised pilot bunches requires constant and high precision monitoring of the residual 3-D spin-polarization of the colliding bunches, which — if nonzero — would affect the physics measurements.

FCC-ee Pre-Injector

Concerning the FCC-ee pre-injector, the CDR design foresaw a pre-booster synchrotron. At present, this choice is under scrutiny. As an alternative, and possibly new baseline, it is proposed to extend the energy of the injection linac to 10–20 GeV, for direct injection into the full-energy booster [13]. The higher-energy linac could be based on state-of-the-art S-band technology as employed for the FERMI upgrade at the ELETTRA synchrotron radiation facility. Alternatively, a C-band linac could be considered, possibly based on the SLAC C^3 technology [14].

It is also envisaged to design, construct and then test with beam a novel positron source [13, 15] plus capture linac, and measure the achievable positron yield, at the PSI SwissFEL facility, with a primary electron energy that can be varied from 0.4 to 6 GeV.

Full-Energy Booster

The injection energy for the full-energy booster is defined by the field quality of its low-field magnets. Magnet development and prototyping of booster dipole magnets, along with field measurements (presently only available for the twin collider CEPC [16]), should guide the choice of the injection energy. Maintaining beam stability at injection into the booster may require the installation of wiggler magnets for increasing the beam energy spread. An alternative optics, which may both increase the SR energy spread and avoid very low magnetic fields, is based on alternating the polarity of arc dipole magnets at injection, reminiscent of what is being planned for the Electron Storage Ring (ESR) of the US Electron Ion Collider (EIC) [17, 18], although the FCC-ee booster is fast ramping, while the ESR will operate at different constant beam energies.

Role of SuperKEKB

The SuperKEKB collider, presently being commissioned [19], features many of the key elements of FCC-ee: double ring, large crossing angle, low vertical IP beta function β_y^* (design value ~0.3 mm), short design beam lifetime of a few minutes, top-up injection, and a positron production rate of up to several 10^{12}/s. SuperKEKB has achieved, in both rings, the world's smallest ever β_y^* of 0.8 mm, which also is the lowest value considered for FCC-ee. Profiting from a new "virtual" crab-waist collision scheme, first developed for FCC-ee [3], in July 2022 SuperKEKB reached a world record luminosity of 4.71×10^{34} cm^{-2}s^{-1}. However, several issues still need to be resolved, such as a vertical emittance blow up, the transverse machine impedance and the associated single-bunch instability threshold, sudden beam losses, poor quality of the injected beam, etc.

SuperKEKB is pushing the frontiers of accelerator physics with a vertical rms beam spot size of about 300 nanometer, the lowest of any operating collider. The future goal is pushing the luminosity to 6×10^{35} cm^{-2}s^{-1}, and a beam spot size of 50 nm. SuperKEKB serves as an important testbed for FCC-ee and other future electron-positron colliders, and also as a unique facility for training the next generation of accelerator physicists, who will be commissioning these future colliders.

Collaboration with EIC

The EIC ESR [18] has almost identical beam parameters as FCC-ee, but it will operate with close to twice the maximum electron beam current, or half the bunch spacing, and it will operate at lower beam energy. These differences make

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it more challenging. About ten domains of common interest have been identified by the FCC and EIC design teams, for each of which a joined EIC-FCC working group is being set up. The EIC will start beam operation about a decade prior to FCC-ee. It would, thereby, provide another invaluable opportunity to train the next generation of accelerator physicist on an operating collider, to test hardware prototypes, beam control schemes, etc.

OPTIMIZED PLACEMENT

In 2021, the placement and layout of the FCC (common for both FCC-ee and FCC-hh) was optimized, taking into account numerous constraints and considerations, including geological conditions, depth of access shafts, vicinity of access roads, railway connections, etc., while avoiding surface sites in water protection zones, densely urbanized areas, and high mountains. The number of surfaces sites was reduced from 12 in the CDR to 8, which facilitates the placement and decreases the required surface area from 62 ha to less than 40 ha, In addition, the 8 surface sites and the new layout are arranged with a perfect 4-fold superperiodicity, which allows for either two or four collision points and experiments.

Four different FCC-ee detectors placed at the maximum number of four collision points could be optimized, respectively, for the Higgs factory programme, for ultraprecise electroweak and QCD physics, for Heavy Flavour physics, and for searching feebly coupled particles (LLPs) [20]. For the FCC-hh, two high-luminosity general-purpose experiments and two specialized experiments are foreseen [21], similar to the present LHC detectors.

By suppressing 3/4 of the resonances in the tune diagram, the superperiodicity of four will ensure the best possible beam-dynamics performance for both lepton and hadron collider. The resulting optimized placement is illustrated in Fig. 3, and the corresponding long section showing the geological situation and the depths of access shafts in Fig. 4. More than 90% of the collider tunnel are situated in the so-called “molasse” layer, which is ideally suited for tunnel boring machines. The depths of the access shafts varies from 100 m to 400 m, with most shaft depths around 200–250 m. All proposed surface sites are close to existing road infrastructures, so that in total less than 5 km of new road constructions is required for all sites together. Several sites are located in the vicinity of 400 kV electricity grid lines. Finally, the good road connection of Points PD, PF, PG, PH suggest a second operation pole around Annecy (CNRS LAPP) in the South. Detailed site investigations are planned for the period 2024–2025, with about 40 to 50 drillings and some 100 km of seismic lines.

SUSTAINABILITY

According to the conceptual design, the FCC-ee is the most sustainable of all the proposed Higgs and electroweak factory proposals, in that it implies by far the lowest energy consumption for a given value of total integrated luminosity, over the collision energy range from 90 to 365 GeV [22].

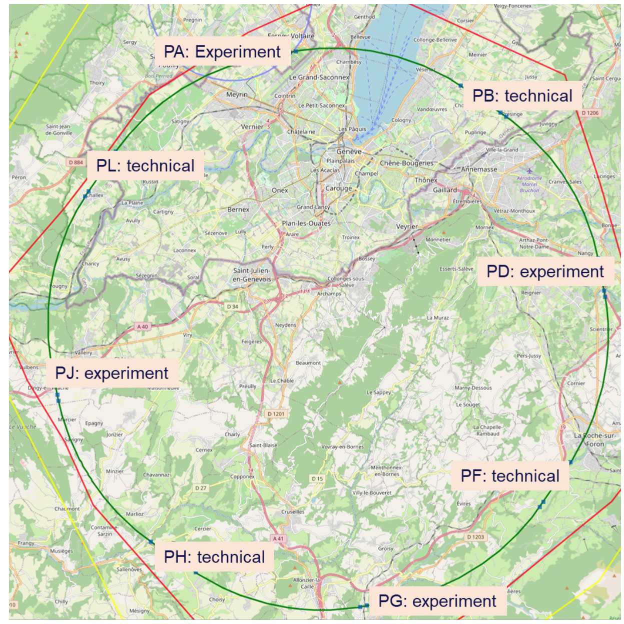

Figure 3: Optimized placement of the FCC.

The electrical power consumption depends on the centre-of-mass energy. An estimation of the upper limit of the power drawn by the various FCC-ee systems for each mode of operation was first presented in [23] and updated recently [24]. Depending on the collision energy the total facility power extends from about 238 MW at the Z to 388 MW at the $t\bar{t}$ energy. These values are comparable in order of magnitude with CERN's present power consumption of about 200 MW, when LHC is operating, or with a total CERN power consumption of up to ~240 MW at the time of the previous LEP collider. The numbers include the power required for cooling and ventilation, for general services, for two experiments, for data centres, and for the injector complex. Although the FCC-ee is three to four times larger than LEP, and achieves about 10^5 times the LEP luminosity, the design concept leads to an overall electrical peak power of only about 2.5 times the one of LEP, which alone consumed ~120 MW. Adding to FCC-ee operation also the powering required for the present CERN site running various lower-energy hadron accelerators, and for a parallel fixed target proton programme at the existing CERN SPS North Area, the total annual energy consumption is expected to range from about 1.8 TWh at the Z to 2.5 TWh at the $t\bar{t}$ [24]. Additional technology advancements and design optimisation, such as the introduction of HTS magnets in the collider rings or of permanent magnets in the damping ring, will further reduce the FCC-ee energy consumption.

The FCC-ee will be powered by a mixture of renewable and other carbon-free sources. Today, the electricity produced and consumed in France and Switzerland is already more than 90% carbon-free, an order of magnitude better than in most other countries [25]. By 2045, the electricity in France and Switzerland is expected to be 100% carbon free.

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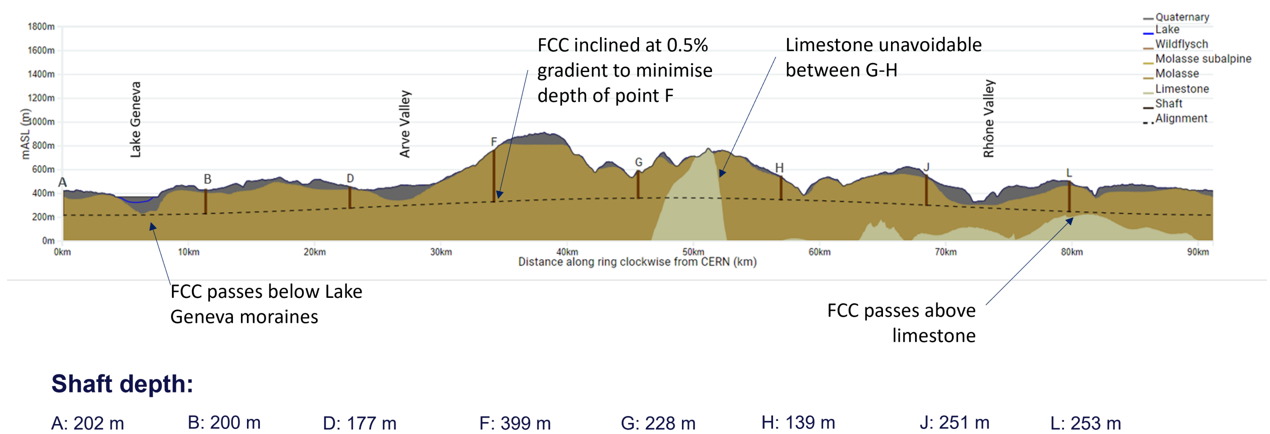

Figure 4: Long section of the optimally placed FCC.

The FCC-ee power consumption can be rapidly and easily adjusted to the power available on the European electricity grid, by varying the number of bunches in the collider.

Lastly, the optimum use of the tunnel excavation material is being studied through the international competition "Mining the Future®" [26].

FUTURE UPGRADES AND USES

The FCC-ee is not only a Higgs, but also a Z and W factory ("TeraZ"). The upgrade to $t\bar{t}$ running is foreseen, at a cost of about 1 BCHF for additional systems.

In addition to the 4 baseline running modes listed in Table 1, another optional operation mode, presently under investigation for FCC-ee, is the direct s-channel Higgs production, $e^+e^- \rightarrow H$, at a centre-of-mass energy of 125 GeV, which would allow a direct measurement of the electron Yukawa coupling. Here, a monochromatization scheme should reduce the effective collision energy spread in order for the latter to become comparable to the width of the Higgs [27].

Following the FCC-ee, the FCC integrated programme foresees as a second stage, a hadron collider, FCC-hh, which shall provide proton-proton collisions at a centre-of-mass energy of at least 100 TeV. It will also enable heavy-ion collisions at the equivalent ion energy. The FCC-hh will be installed in the tunnel which earlier houses the FCC-ee and share/re-use much of the FCC-ee technical infrastructure, including electric distribution sytems, cooling and ventilation, RF, cryogenics, experimental caverns, etc. The sequence of FCC-ee and FCC-hh would support a comprehensive long-term program maximising physics opportunities.

Numerous other possible extensions are under study, such as lepton-proton and lepton-hadron collisions (FCC-eh) [21], LHC- and FCC-based Gamma factories [28], and a Lemma-type 100 TeV muon collider, FCC-$\mu\mu$ [29, 30], which could reuse key elements of the FCC-ee and FCC-hh accelerators.

FCC FEASIBILITY STUDY

The 2013 European Strategy Update (ESU) requested a Conceptual Design of the FCC, the four-volume report of which was delivered in 2019 [4, 21, 31], describing the physics cases, the design of the lepton and hadron colliders, and the underpinning technologies and infrastructures. Following the 2020 ESU [32], an FCC Feasibility Study (FCC FS) has been launched by CERN Council in 2021 [33, 34], with a Feasibility Study Report (FSR) expected by the end of 2025. The FSR will address not only the technical design, but also numerous other key feasibility aspects, including tunnel construction, financing, and environment. The FSR will be an important input to the next European Strategy Update expected in 2026/27.

The FCC FS is organized as an international collaboration with, presently, about 150 participating institutes from around the world. The FCC FS and a possible future project will profit from CERN's decade-long experience with successful large international accelerator projects, e.g., the LHC and HL-LHC, and the associated global experiments, such as ATLAS and CMS.

OUTLOOK

A comprehensive R&D program and implementation preparation is presently being carried out in the frameworks of the FCC FS, the EU co-financed FCC Innovation Study, the Swiss CHART program, and the CERN High-Field Magnet Programme.

The first stage of FCC could be approved within a few years after the 2027 Strategy Update, if the latter is supportive. The tunnel construction could then start in the early 2030s and the FCC-ee physics program begin in the second half of the 2040s, a few years after the completion of the HL-LHC physics runs expected by 2041.

ACKNOWLEDGEMENTS

This talk was given on behalf of the global FCC Collaboration, and reports work from close to 2000 international experts. We are indebted, in particular, to I. Agapov, A. Blondel, M. Boscolo, O. Brunner, J.-P. Burnet, I. Chaikovska, P. Charitos, P. Craievich, M. Giovannozzi, A. Grudiev, J. Gutleber, K. Hanke, M. Hofer, P. Janot, J. Keintzel, M. Koratzinos, R. Losito, V. Mertens, J. Osborne, D. Shatilov, F. Sonnemann, and T. Watson for helpful discussions and material included in this article.

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