

FCC-ee FEASIBILITY STUDY PROGRESS*

Michael Benedikt, Frank Zimmermann[†], CERN, Geneva, Switzerland

Abstract

The Future Circular Collider (FCC) “integrated programme” consists of a proposed high-luminosity e⁺e⁻ collider, FCC-ee, serving as Higgs and electroweak factory, which would, in a second stage, be succeeded by a 100 TeV hadron collider, FCC-hh. FCC-ee and FCC-hh share the same 91 km tunnel and technical infrastructure. In summer 2021 a detailed FCC Feasibility Study (FCC FS), focused on siting, tunnel construction, environmental impact, financing, operational organisation, etc., was launched by the CERN Council. This FCC Feasibility Study (FCC FS) should provide the necessary input to the next European Strategy Update expected in 2026/27. In this paper we briefly review the FCC key design features, status and plans.

This paper is an updated, slightly modified version of an article submitted to the proceedings of NA-PAC’22 [1] (published under the Creative Commons Attribution 3.0 license). Sections on two planned accelerator mock-ups and on regional activities were taken from an article in the ECFA Newsletter [2].

INTRODUCTION

This paper is an updated, slightly modified version of an article submitted to the proceedings of NA-PAC’22 [1] (published under the Creative Commons Attribution 3.0 license). Sections on two planned accelerator mock-ups and on regional activities were taken from an article in the ECFA Newsletter [2].

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 $2 \times 10^{36} \text{ cm}^{-2} \text{ s}^{-1}$ per interaction point (IP), on the Z pole (91 GeV c.m.), $7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ per IP at the ZH production peak and $1.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ per IP at the t \bar{t} . In the case of four experiments, the total luminosity on the Z pole will be close to $10^{37} \text{ cm}^{-2} \text{ s}^{-1}$. 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.

* Work supported by the European Union’s H2020 Framework Programme under grant agreement no. 951754 (FCCIS).

[†] frank.zimmermann@cern.ch

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 [3].

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 [4]), and to generate the large crossing angle of 30 mrad, required for the crab-waist collision scheme [5].

The latest FCC layout features a superperiodicity of four, and can accommodate either two or four experiments, in four 1.40 km long straight sections, which are alternating with 2.03 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.

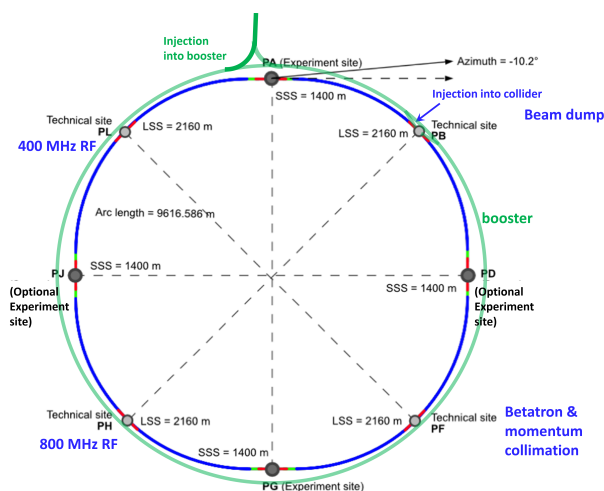


Figure 1: Schematic layout of the FCC-ee collider with a circumference of 91.1 km and four-fold superperiodicity. The full-energy booster and part of its injection transfer line are also indicated.

FCC-ee key parameters, evolved from those of the Conceptual Design Report (CDR) [6], are summarized in Table 1. Thanks to self-polarisation at the two lower energies (Z and W operation) [7], a precision energy calibration by resonant depolarisation is possible, down to 100 keV accuracy for m_Z and 300 keV for m_W [8, 9].

An important ingredient is the crab waist collision scheme, which was first demonstrated at DAΦNE, where it tripled the collider luminosity [10]. More recently, in 2020, at SuperKEKB the “virtual” crab waist collision, first developed for the FCC-ee [5], was successfully implemented, and is now used in routine operation [11]. 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). Both the natural bunch lengths due to synchrotron radiation (SR) and their values in collision including the effect of beamstrahlung (BS) are shown in Table 1. The FCC-ee considers a combination of 400 MHz radiofrequency systems (at the first three energies, up to 2.1 GV) and 800 MHz (additional cavities, with up to 9.2 GV, for $\bar{t}\bar{t}$ operation), with respective voltage strengths in each running mode as indicated. For ZH and $\bar{t}\bar{t}$ operation, the RF cavities are shared by the two beams. The beam lifetime shown represents the combined effect of the luminosity-related radiative Bhabha scattering and beamstrahlung. The assumed cross section for radiative Bhabha scattering is pessimistic, since it was computed without the beam density cutoff introduced in Ref. [12]. 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.

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

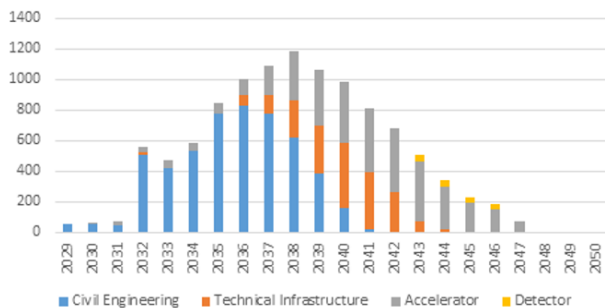


Figure 2: Example draft spending profile for FCC-ee, in units of MCHF versus the year.

Table 1: Preliminary key parameters of FCC-ee, now with a circumference of 90.7 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.

Running mode	Z	W	ZH	$\bar{t}\bar{t}$
Number of IPs	4			
Beam energy [GeV]	45.6	80	120	183
Bunches/beam	10000	880	248	40
Beam current [mA]	1280	135	26.7	5.0
Luminosity/IP [$\text{nb}^{-1} \text{s}^{-1}$]	1820	194	73	12.5
Energy loss / turn [GeV]	0.04	0.37	1.87	10.0
Synchr.rad.power [MW]	100			
RF volt. 0.4 GHz [GV]	0.12	1.0	2.1	2.1
RF volt. 0.8 GHz [GV]	0	0	0	9.2
Bunch length σ_z w/o	4.4	3.6	3.3	1.9
and with BS [mm]	15.4	8.0	6.0	2.7
Hor. emit. ϵ_x [nm]	0.71	2.16	0.64	1.49
Vert. emit. ϵ_y [pm]	1.42	4.32	1.29	2.98
Long. damp. time [turns]	1168	217	64.5	18.5
Vert. IP beta β_y^* [mm]	0.8	1.0	1.0	1.6
Hor. IP beta β_x^* [m]	0.1	0.2	0.3	1.0
Beam lifetime [min.]	8	18	6	10

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

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.

FCC-ee R&D

Many of the technologies required for constructing an FCC-ee exist [13]. 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. Work is also ongoing on an alternative collider optics with potentially much better performance.

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 superconduc-

tor (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 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 τ operation [6]. 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 [14].

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. Indeed, the arc half-cell is the most recurrent assembly of mechanical hardware in the accelerator (about 1500 similar FODO cells). Therefore, as part of the FCC R&D plan, an arc half-cell mock up is foreseen to be constructed at CERN 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. The mock-up will lead to functional prototype(s), and then further to a pre-series plus, finally, series production. Building the mock-up allows optimizing and testing fabrication, integration, installation, assembly, transport, maintenance, by working, where required, with structures of equivalent volumes, weights, and stiffness.

Similarly, for the interaction region the construction of a mock up is proposed at INFN Frascati [15]. Starting from the central interaction point vacuum chamber made from AlBeMet162, cooled by paraffin and held by a strong outer support tube, a steel transition plus bellows, the mock up could later be extended to also include the trapezoidal vacuum chamber with remote vacuum connection, a placeholder luminosity monitor, a compensation solenoid, and the first superconducting quadrupole with cryostat, more beam pipes, support structures for quadrupole and cryostat, and vibration and alignment sensors.

Constructing some of the magnets for the FCC-ee final focus or arcs with advanced high-temperature superconductor (HTS) technology [16] 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 20 K or 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 [9]. The operation with polarised pilot bunches requires constant and high precision monitoring of the residual 3-D spin-polarisation 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 [17]. 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 [18].

It is also envisaged to design, construct and then test with beam a novel positron source [17, 19] 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 [20]), 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) [21, 22], 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 [23], features many of the key elements of FCC-ee: double

Content from this work may be used under the terms of the CC-BY-4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

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 [5], in July 2022 SuperKEKB reached a world record luminosity of $4.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. 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 $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, and a beam spot size of 50 nm. SuperKEKB serves as an important test-bed 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 [22] 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 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) [24]. For the FCC-hh, two high-luminosity general-purpose experi-

ments and two specialized experiments are foreseen [25], 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 connections 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.



Figure 3: Optimized placement of the FCC.

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 [26, 27].

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 [28] and updated recently [29]. Depending on the collision energy the total facility power extends from about 238 MW at the Z to 388 MW at

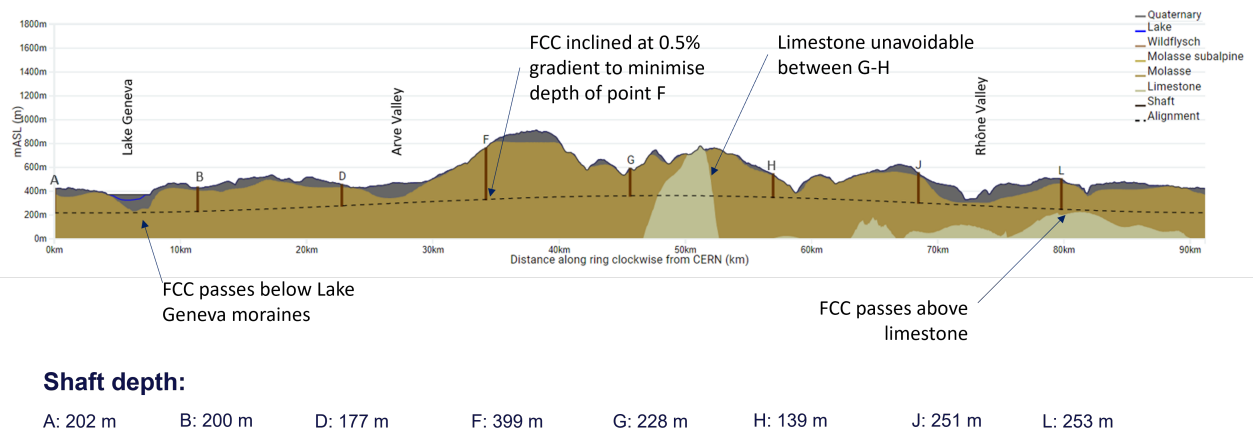


Figure 4: Long section of the optimally placed FCC.

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 $t\bar{t}$ [29]. 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 [30]. By 2045, the electricity in France and Switzerland is expected to be 100% carbon free.

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 results from the “Mining the Future[®]” competition [31] have established several credible re-use pathways for the excavation materials (molasse), which, in combination with a local re-use scheme, promise material management with a low environmental and carbon footprint.

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 [32].

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 systems, 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) [25], LHC- and FCC-based Gamma factories [33], and a Lemnate-type 100 TeV muon collider, FCC- $\mu\mu$ [34, 35], 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 [6, 25, 36], describing the physics cases, the design of the lepton and hadron colliders, and the underpinning technologies and infrastructures. Following the 2020 ESU [37], an FCC Feasibility Study (FCC

REFERENCES

- [1] F. Zimmermann, M. Benedikt, K. Oide, and T. O. Raubenheimer, “The Electron-Positron Future Circular Collider (FCC-ee),” Albuquerque, New Mexico, USA, Aug. 2022, presented at NAPAC’22, Albuquerque, New Mexico, USA, Aug. 2022, paper TUZD1.
- [2] M. Benedikt and F. Zimmermann, *FCC Feasibility Study*, 10th ECFA Newsletter, https://ecfa.web.cern.ch/sites/default/files/10th%20ECFA%20Newsletter_v6.pdf, 2022.
- [3] The CEPC Study Group, *CEPC Conceptual Design Report: Volume 1 - Accelerator*, arXiv: 1809.00285, 2018, doi:10.48550/ARXIV.1809.00285
- [4] M. Boscolo, H. Burkhardt, and M. Sullivan, “Machine detector interface studies: Layout and synchrotron radiation estimate in the future circular collider interaction region,” *Phys. Rev. Accel. Beams*, vol. 20, p. 011008, 1 2017, doi:10.1103/PhysRevAccelBeams.20.011008
- [5] K. Oide *et al.*, “Design of beam optics for the future circular collider e^+e^- collider rings,” *Phys. Rev. Accel. Beams*, vol. 19, p. 111005, 11 2016, doi:10.1103/PhysRevAccelBeams.19.111005
- [6] A. Abada *et al.*, “FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2,” *Eur. Phys. J. ST*, vol. 228, no. 2, pp. 261–623, 2019, doi:10.1140/epjst/e2019-900045-4
- [7] E. Gianfelice-Wendt, “Investigation of beam self-polarization in the future e^+e^- circular collider,” *Phys. Rev. Accel. Beams*, vol. 19, p. 101005, 10 2016, doi:10.1103/PhysRevAccelBeams.19.101005
- [8] A. Blondel and E. Gianfelice, “The challenges of beam polarization and keV-scale centre-of-mass energy calibration at the FCC-ee,” *Eur. Phys. J. Plus*, vol. 136, p. 1103, 2021, doi:10.1140/epjp/s13360-021-02038-y
- [9] A. Blondel, P. Janot, J. Wenninger, *et al.*, “Polarization and Centre-of-Mass Energy Calibration at FCC-ee,” *arXiv 1909.12245*, 2019.
- [10] M. Zobov *et al.*, “Test of “Crab-Waist” Collisions at the DAΦNE Φ Factory,” *Phys. Rev. Lett.*, vol. 104, p. 174801, 17 2010, doi:10.1103/PhysRevLett.104.174801
- [11] Y. Funakoshi *et al.*, “The SuperKEKB has Broken the World Record of the Luminosity,” Bangkok, Thailand, Jun. 2022, IPAC’22, Bangkok, Thailand, Jun. 2022, paper MO-PLXGD1.
- [12] H. Burkhardt and R. Kleiss, “Beam Lifetimes in LEP,” in *Proc. EPAC’94*, London, UK, Jun.-Jul. 1994, pp. 1353–1356.
- [13] B. Richter, “Very high-energy electron-positron colliding beams for the study of the weak interactions,” *Nucl. Instrum. Methods*, vol. 136, 47–60. 31 p, 1976, doi:10.1016/0029-554X(76)90396-7
- [14] I. Syratchev, F. Peauger, I. Karpov, and O. Brunner, “A Superconducting Slotted Waveguide Elliptical Cavity for FCC-ee,” version 1.0, 2021, doi:10.5281/zenodo.5031953
- [15] M. Boscolo, *FCC-ee IR MOCK-UP*, FCC-EIC Joint & MDI Workshop, 26 Oct. 2022 \https://indico.cern.ch/event/1186798/contributions/5074714/, 2022.
- [16] I. Agapov *et al.*, “Future Circular Lepton Collider FCC-ee: Overview and Status,” 2022, doi:10.48550/ARXIV.2203.08310
- [17] P. Craievich *et al.*, “The FCCee Pre-Injector Complex,” Bangkok, Thailand, Jun. 2022, presented at IPAC’22,

FS) has been launched by CERN Council in 2021 [38, 39], 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.

REGIONAL ACTIVITIES

Concerning progress with regional activities [2], elected representatives from the French “départements” of Haute Savoie and Ain and from the Swiss Canton of Geneva visited CERN, while information meetings and exchanges were being organised with the presidents and prefects of Ain and Haute Savoie, in preparation of the next steps. All communities concerned by the FCC trace were approached directly via information letters co-signed by the Prefect of the region Auvergne-Rhone-Apes and by the CERN Director-General (DG) for France, and by the Conseiller d’État de Genève and the CERN DG for Switzerland. Consultations with individual communities are ongoing. Technical discussions on territorial implementation, water use, excavation material reuse, etc., have started with the French department no. 74, Haute Savoie.

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, K. Oide, J. Osborne, P. Raimondi, T. Raubenheimer, D. Shatilov, F. Sonnemann, and T. Watson for helpful discussions and material included in this article.

- Bangkok, Thailand, Jun. 2022, paper WEPOPT063.
- [18] M. Bai *et al.*, *C³: A "Cool" Route to the Higgs Boson and Beyond*, arXiv: 2110.15800, 2021.
- [19] B. Humann *et al.*, "Radiation Load Studies for the FCC-ee Positron Source with a Superconducting Matching Device," Bangkok, Thailand, Jun. 2022, presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper THPOTK048.
- [20] W. Kang *et al.*, "Development of the CEPC booster prototype dipole magnets," *Int. J. Mod. Phys. A*, vol. 36, no. 22, p. 2142008, 2021, doi:10.1142/S0217751X21420082
- [21] D. Marx *et al.*, "Designing the EIC Electron Storage Ring Lattice for a Wide Energy Range," Bangkok, Thailand, Jun. 2022, presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper WEPOPT042.
- [22] F. Willeke and J. Beebe-Wang, "Electron Ion Collider Conceptual Design Report 2021," 2021, doi:10.2172/1765663
- [23] Y. Ohnishi, "Status and perspectives of the SuperKEKB project," *presented at EPS-HEP2021*, 2021.
- [24] M. Dam, "Detector R&D requirements for future circular high energy e⁺e⁻ machine, presented as ECFA Detector R&D Roadmap Input from Future Facilities," 2021, <https://indico.cern.ch/event/994685/>
- [25] A. Abada *et al.*, "FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3," *Eur. Phys. J. ST*, vol. 228, no. 4, pp. 755-1107, 2019, doi:10.1140/epjst/e2019-900087-0
- [26] M. Benedikt, A. Blondel, P. Janot, *et al.*, "Future circular colliders succeeding the LHC," *Nature Physics*, vol. 16, p. 402, 2020, doi:10.1038/s41567-020-0856-2
- [27] P. Janot and A. Blondel, "The carbon footprint of proposed e⁺e⁻ Higgs factories," *Eur. Phys. J. Plus*, vol. 137, p. 1122, 2022, doi:10.1140/epjp/s13360-022-03319-w
- [28] S. Aull *et al.*, "Electrical Power Budget for FCC-ee," in *7th IPAC*, 2016, pp. 3828-3831, doi:10.18429/JACoW-IPAC2016-THPOR024
- [29] J. P. Burnet, "Update of the power demand for fcc-ee," *FCC Week 2022, Paris, 2022*, <https://indico.cern.ch/event/1064327>
- [30] Carbon Brief web site, <https://www.carbonbrief.org/>
- [31] Mining the Future, <https://indico.cern.ch/event/1001465/>
- [32] A. Faus-Golfe, M. Valdivia Garcia, and F. Zimmermann, "The Challenge of Monochromatization Direct s-Channel Higgs Production: e⁺e⁻ → H," *Eur. Phys. J. Plus*, vol. 137, 31 2022, doi:10.1140/epjp/s13360-021-02151-y
- [33] M. W. Krasny, *The Gamma Factory proposal for CERN*, arXiv: 1511.07794, 2015, doi:10.48550/ARXIV.1511.07794
- [34] F. Zimmermann, "LHC/FCC-based muon colliders," *Journal of Physics: Conference Series*, vol. 1067, p. 022017, 2018, doi:10.1088/1742-6596/1067/2/022017
- [35] F. Zimmermann, A. Latina, A. P. Blondel, M. Antonelli, M. Boscolo, and J. P. Farmer, "Muon Collider Based on Gamma Factory, FCC-ee and Plasma Target," no. 13, p. 1691, presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper WEPOST009.
- [36] A. Abada *et al.* (The FCC Collaboration), "FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1," *European Physical Journal C*, vol. 79, 2019, doi:10.1140/epjc/s10052-019-6904-3
- [37] European Strategy Group, "2020 Update of the European Strategy for Particle Physics (Brochure)," *CERN-ESU-015*, 2020, <https://cds.cern.ch/record/2721370>
- [38] CERN Council, *Organisational structure of the FCC feasibility study. Restricted CERN Council - Two-Hundred-and-Third Session*, CERN/SPC/1155/Rev.2, 2021, <http://cds.cern.ch/record/2774006>
- [39] CERN Council, *Main deliverables and timeline of the FCC feasibility study. Restricted CERN Council - Two-Hundred-and-Third Session*, CERN/SPC/1161, 2021, <http://cds.cern.ch/record/2774007>