# Future Circular Lepton Collider FCC-ee: Overview and Status

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## ABSTRACT

The worldwide High Energy Physics community widely agrees that the next collider should be a Higgs factory. Acknowledging this priority, in 2021 CERN has launched the international Future Circular Collider (FCC) Feasibility Study (FS). The FCC Integrated Project foresees, in a first stage, a high-luminosity high-energy electron-positron collider, serving as Higgs, top and electroweak factory, and, in a second stage, an energy frontier hadron collider, with a centre-of-mass energy of at least 100 TeV. In this paper, we address a few key elements of the FCC-ee accelerator design, its performance reach, and underlying technologies, as requested by the Snowmass process. The Conceptual Design Report for the FCC, published in 2019, serves as our primary reference. We also summarize a few recent changes and improvements.

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# 1 FCC Integrated Project

## 1.1 Overview

The Future Circular Collider (FCC) shall be located in the Lake Geneva basin and linked to the existing CERN facilities [1]. The FCC “integrated programme” is inspired by the successful past Large Electron Positron collider (LEP) and Large Hadron Collider (LHC) projects at CERN. It represents a comprehensive long-term programme maximising physics opportunities. A similar project is under study in China [2, 3]. In 2021, CERN has launched the FCC Feasibility Study (FS), that will address not only the technical aspects of the accelerators, but also, and in particular, the feasibility of tunnel construction and technical infrastructures, and the possible financing of the proposed future facility. The FCC FS is organized as an international collaboration with, presently, about 150 participating institutes from around the world. The FCC FS and a 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, to all which the US has made essential contributions. The US participation in CERN based accelerators and experiments during the past decades has been of great mutual benefit.

The first stage of the FCC integrated project is an $e^+e^-$ collider, called FCC-ee, which would serve as Higgs factory, electroweak and top factory at highest luminosities, and run at four different centre-of-mass energies, namely on the Z pole, at the WW threshold, at the ZH production peak, and at the $t\bar{t}$ threshold. In a second stage, the FCC-ee would be followed by a highest-energy proton collider, FCC-hh with a centre-of-mass energy of 100 TeV, that would naturally succeed the LHC at the energy frontier. This hadron collider can also accommodate ion and lepton-hadron collision options, providing for complementary physics. The lepton and hadron colliders would profit from a common civil engineering and also from sharing the technical infrastructures. In particular, the FCC would build on and reuse CERN’s existing infrastructure, e.g., the existing chain of hadron accelerators, from Linac4 over PSB, PS and SPS to the LHC, can serve as an injector complex for the FCC-hh.

The technical schedule of the FCC integrated project foresees the start of FCC tunnel construction around the year 2030 — or three years after a possible project approval —, the first $e^+e^-$ collisions at the FCC-ee in the early 2040s, and the first FCC-hh hadron collisions by 2065–70 — see Fig. 1. The FCC integrated project would allow for a seamless continuation of High Energy Physics (HEP) after the completion of the High Luminosity LHC (HL-LHC) physics programme.

A comprehensive Conceptual Design Report (CDR) for the FCC was published in 2019 [5, 6, 7], describing the physics cases, the design of the lepton and hadron colliders, and the underpinning technologies and infrastructures.

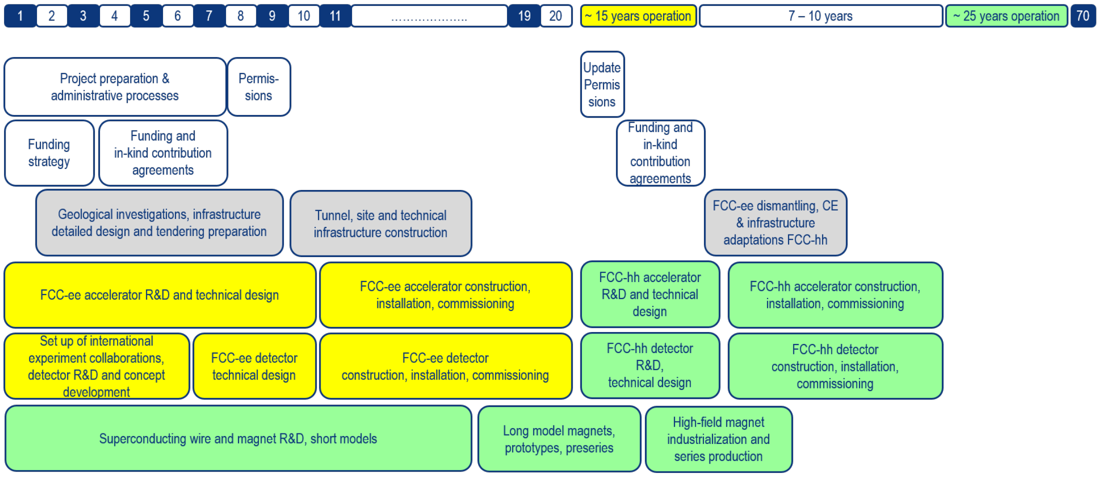

Figure 1: Technical schedule of the FCC integrated project with year 1 equal to 2021 (a similar schedule was presented in Ref. [4]).

## 1.2 Performance

The FCC-ee is designed to collide beams at four different energies, with luminosities ranging from $\sim 2 \times 10^{36}$ cm$^{-2}$s$^{-1}$ per Interaction Point (IP), or close to $10^{37}$ cm$^{-2}$s$^{-1}$ of total luminosity in case of four experiments, on the Z pole (91 GeV c.m.), to about $1.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ per IP at the $\mathrm{t\bar{t}}$ threshold. Key parameters are summarized in Table 1. Thanks to resonant depolarisation, at the two lower energies, a precision energy calibration is possible, down to 100 keV accuracy for $m_Z$ and 300 keV for $m_W$.

The electrical power consumption depends on the centre-of-mass energy. It, therefore, varies throughout the entire operation period of the project, extending from about 260 MW to 350 MW. These values can be compared 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. An estimation of the upper limit of the power drawn by the various FCC-ee systems [8] during regular luminosity production is indicated in the right-most column of Table 1. The numbers shown include 37 MW for cooling and ventilation, 36 MW for general services, 8 MW for two experiments, 4 MW for data centres, and 10 MW 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 energy consumption of only about 2.5 times the one of LEP, which consumed ∼120 MW. With additional technology advancements and optimisations during operation, the overall energy consumption is expected to remain close to 300 MW even at highest collision energies [6].

Based on the CDR parameters, the FCC-ee is the most sustainable of all the proposed Higgs and electroweak factory proposals, in that it implies the lowest energy consumption for a given value of total integrated luminosity [4], over the collision energy range from 90 to 365 GeV; see Fig. 2.

Table 1: Performance figures of FCC-ee. The ongoing Feasibility Study allows for a 4 IP collider ring with a total integrated luminosity higher by almost a factor 2. For the Z pole (or $t\bar{t}$) running the regular integrated luminosity is show in the table, while over the first two (one) years, the luminosity production is expected to be, on average, about 2 times lower.

| c.m. energy [GeV] | lum./ IP [$10^{34}$ cm$^{-2}$s$^{-1}$] | int. lum./year (2 IPs) [ab$^{-1}$/yr] | run time [yr] | power [MW] |
|---|---|---|---|---|
| 91 | 200 | 48 | 4 | 259 |
| 160 | 20 | 6 | 1–2 | 277 |
| 240 | 7.5 | 1.7 | 3 | 282 |
| 365 | 1.3 | 0.34 | 5 | 354 |

## 1.3 European Strategy Update 2020 and Feasibility Study Launch

The 2020 Update of the European Strategy for Particle Physics (ESPPU) [11] states that "*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.*" and "*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.*" Responding to this key request from the ESPPU, in the summer of 2021, the five-year Future Circular Collider Feasibility Study was launched [12, 13].

## 1.4 Collider Design Optimization

### 1.4.1 Placement and revised layout

The 2019 FCC CDR describes the baseline FCC design with a circumference of 97.75 km, 12 surface sites, and two primary collision points. In 2021, a further design optimisation has resulted in an optimised placement of much lower risk, with a circumference of about 91.2 km and only 8 surface sites, and which would be compatible with either 2 or 4 collision points. A few of the optimised FCC implementation variants currently under study are depicted in Fig. 3.

Consequently, adaptations of the CDR design and re-optimisation of the machine parameters are underway, taking into account not only the new placement, but also, for FCC-ee, the possibly larger number of interaction points, and the mitigation of complex "combined" effects, e.g. the interplay of transverse and longitudinal impedance with the beam-beam interaction. Figure 4 sketches the layout and possible straight-section functions for the

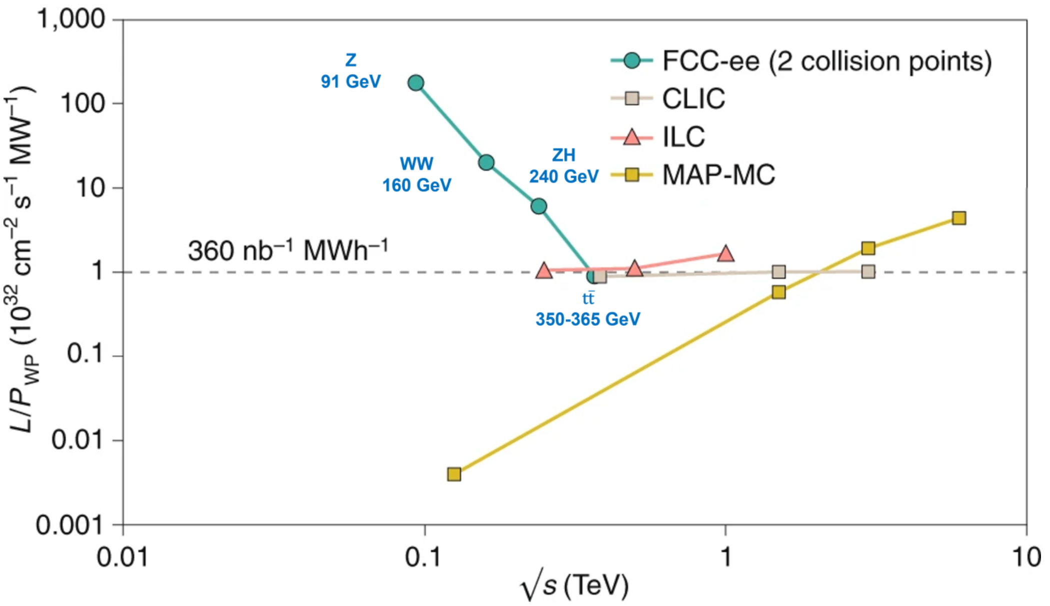

Figure 2: Luminosity $L$ per supplied electrical wall-plug power $P_{\mathrm{WP}}$ is shown as a function of centre-of-mass energy for several proposed future lepton colliders [9, 4, 10]. The FCC-ee electricity cost per Higgs boson is about 200 Euro, assuming a price of 50 Euro MWh$^{-1}$ [6, 4].

electron-positron collider. A consistent layout for the hadron collider can be found in the accompanying White Paper for FCC-hh.

### 1.4.2 Parameter update

A preliminary table with key FCC-ee parameters for the cases of either two or four IPs is shown in Table 2. In the CDR [6], the operation at the Z and W assumed a 60°/60° phase advance per arc cell. The mitigation of the combined impedance and beam-beam effects requires a larger momentum compaction factor than in the CDR [14]. This has resulted in a "long" 90° cell, of twice the cell length used for the H and $t\bar{t}$ operation [15].

The beam parameters, in particular the emittances, bunch length, lifetime, and luminosity still need to be validated in strong-strong beam-beam simulations and in weak-strong simulations including errors and optics corrections. The luminosity values per IP are slightly higher for two IPs than for four, but rather similar. Therefore, the beam lifetime due to radiative Bhabha scattering (inversely proportional to the total luminosity) is about a factor two higher, which allows a more aggressive choice for the beamstrahlung-induced lifetime.

Table 2: Preliminary key parameters of FCC-ee (K. Oide, 2021), as evolved from the CDR parameters, now with a shorter circumference of 91.2 km, and a new arc optics for Z and W running. Luminosity values are given per interaction point (IP), for scenarios with either 2 (left) or 4 IPs (right). Both the natural rms bunch lengths (b. lengths) and rms relative beam energy spreads (en. spreads) due to synchrotron radiation (SR) and their collision values including 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 $\mathrm{t\bar{t}}$ 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 $\mathrm{t\bar{t}}$ running (beam energies of 120 and 182.5 GeV).

| Running mode | Z | W | ZH | $\mathrm{t\bar{t}}$ | Z | W | ZH | $\mathrm{t\bar{t}}$ |
|---|---|---|---|---|---|---|---|---|
| Number of IPs | 2 | | | | 4 | | | |
| Beam energy (GeV) | 45.6 | 80 | 120 | 182.5 | 45.6 | 80 | 120 | 182.5 |
| Bunches/beam | 12000 | 880 | 272 | 40 | 10000 | 880 | 248 | 36 |
| Bunch population [$10^{11}$] | 2.02 | 2.91 | 1.86 | 2.37 | 2.43 | 2.91 | 2.04 | 2.64 |
| Beam current [mA] | 1280 | 135 | 26.7 | 5.0 | 1280 | 135 | 26.7 | 5.0 |
| Lum. / IP [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] | 193 | 22.0 | 7.73 | 1.31 | 182 | 19.4 | 7.26 | 1.33 |
| Energy loss / turn [GeV] | 0.039 | 0.37 | 1.87 | 10.0 | 0.039 | 0.37 | 1.87 | 10.0 |
| Synchr. Rad. Power [MW] | 100 | | | | 100 | | | |
| RF Volt. 400 MHz [GV] | 0.12 | 1.0 | 2.08 | 4.0 | 0.12 | 1.0 | 2.08 | 4.0 |
| RF Volt. 800 MHz [GV] | 0 | 0 | 0 | 7.25 | 0 | 0 | 0 | 7.25 |
| Rms b. length (SR) [mm] | 4.38 | 3.55 | 3.34 | 2.02 | 4.38 | 3.55 | 3.34 | 2.02 |
| (+BS) [mm] | 12.1 | 7.06 | 5.12 | 2.56 | 14.5 | 8.01 | 6.00 | 2.95 |
| Rms en. spread (SR) [%] | 0.039 | 0.069 | 0.103 | 0.157 | 0.039 | 0.069 | 0.103 | 0.157 |
| (+BS) [%] | 0.108 | 0.137 | 0.158 | 0.198 | 0.130 | 0.154 | 0.185 | 0.229 |
| Rms hor. emit. $\varepsilon_x$ [nm] | 0.71 | 2.17 | 0.64 | 1.49 | 0.71 | 2.17 | 0.64 | 1.49 |
| Rms vert. emit. $\varepsilon_y$ [pm] | 1.42 | 4.32 | 1.29 | 2.98 | 1.42 | 4.32 | 1.29 | 2.98 |
| Norm. hor. em. $\gamma\varepsilon_x$ [$\mu$m] | 63 | 340 | 150 | 530 | 63 | 340 | 150 | 530 |
| Norm. vert. em. $\gamma\varepsilon_y$ [$\mu$m] | 0.13 | 0.68 | 0.30 | 1.06 | 0.13 | 0.68 | 0.30 | 1.06 |
| Longit. damp. time [turns] | 1170 | 216 | 64.5 | 18.5 | 1170 | 216 | 64.5 | 18.5 |
| Hor. IP beta $\beta_x^*$ [mm] | 100 | 200 | 300 | 1000 | 100 | 200 | 300 | 1000 |
| Vert. IP beta $\beta_y^*$ [mm] | 0.8 | 1.0 | 1.0 | 1.6 | 0.8 | 1.0 | 1.0 | 1.6 |
| Beam lifetime [min.] | 35 | 32 | 9 | 16 | 19 | 18 | 6 | 9 |

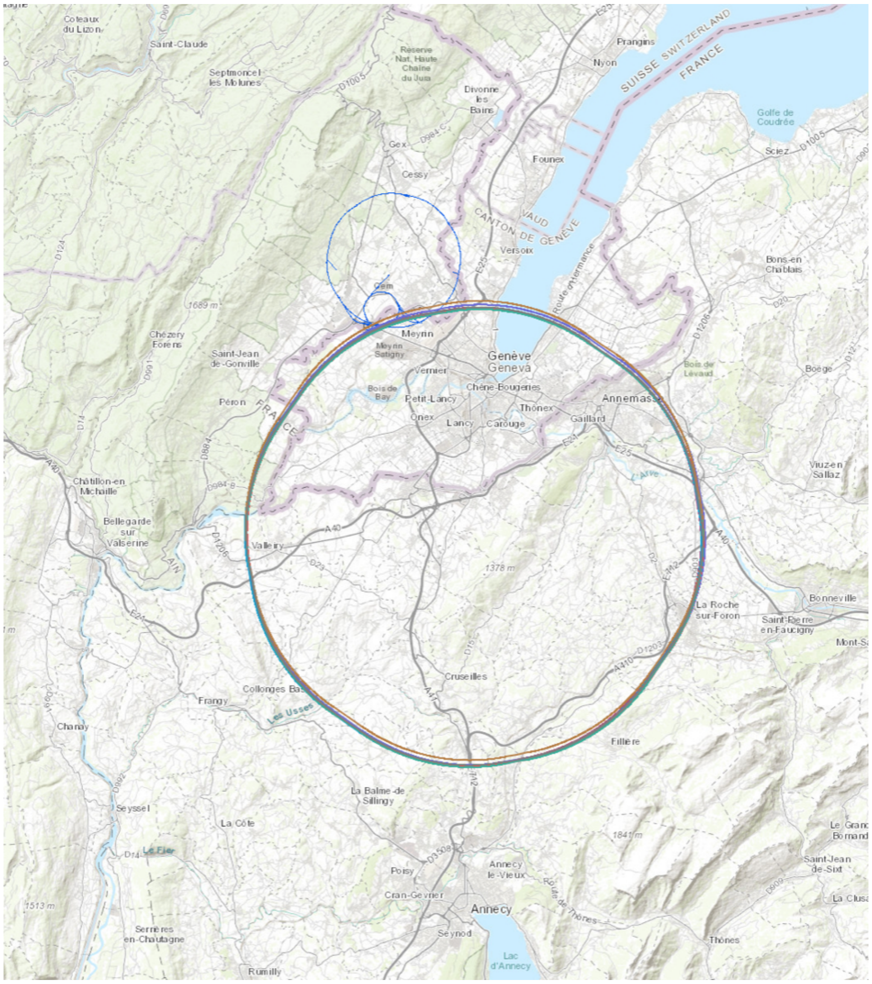

Figure 3: Some of the FCC implementation variants presently under study. The existing SPS and LHC rings are shown for reference.

### 1.4.3 Monochromatization option

In addition to the 4 baseline running modes on the Z pole, at the WW threshold, at the (Z)H production peak, and above the $t\bar{t}$ threshold, listed listed in Table 2, another optional operation mode, presently under investigation for FCC-ee, is the direct $s$-channel Higgs production, $e^+e^- \to H$, 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 [16]. Various possible techniques for monochromatization — e.g., based on nonzero IP dispersion, residual chromaticity, transversely deflecting cavities or a combination thereof — presently are under investigation. The monochromatization option, with the necessary development, control and monitoring of the monochromatization level, requires novel techniques in its own right [17].

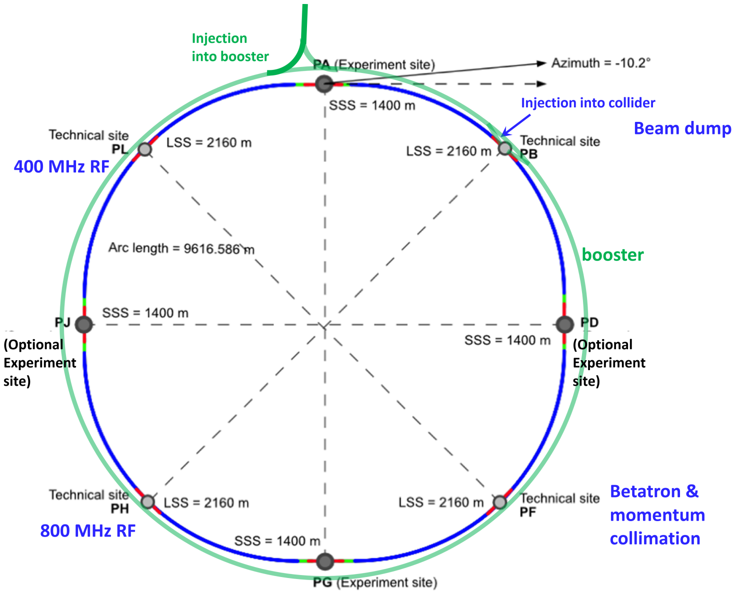

Figure 4: Schematic layout of FCC-ee and its booster with a circumference of 91.2 km and strict four-fold superperiodicity.

## 1.5 Design Challenges

The FCC-ee builds on 60 years of operating colliding beam storage rings. The design is robust and will provide high luminosity over the desired centre-of-mass energy range from 90 to 365 GeV.

Valuable lessons were learnt from the highest energy $e^+e^-$ collider so far, LEP, and from its hadronic successor, the LHC, as well as from the two B factories, PEP-II and KEKB. Importantly, the SuperKEKB collider, presently being commissioned, features many of the key elements of FCC-ee: double ring, large crossing angle, low vertical IP beta function $\beta_y^*$ (design value $\sim$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 already achieved, in both rings, the world's smallest ever $\beta_y^*$ 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 [18], in June 2021 SuperKEKB reached a world record luminosity of $3.81 \times 10^{34}$ cm$^{-2}$s$^{-1}$.

For FCC-ee, two key operational ingredients are "top-up" injection in routine operation, and "bootstrapping" injection when restarting, e.g., after a failure [19]. Alternating re-injection to top up the circulating electron and positron bunches maintains approximately constant beam current and luminosity, so that the average luminosity of FCC-ee approaches the peak luminosity. This type of operation mode was pioneered at the PEP-II, KEKB and SuperKEKB colliders. For the FCC-ee, the top-up injection needs to ensure that intensities of colliding bunches are kept equal to within a few percent, to avoid a beam-beam flip-flop effect, where one bunch would blow up and the opposite bunch shrink, resulting in an unrecoverable situation. For the same reason, when filling the machine from zero, a novel bootstrapping injection process is foreseen, with alternating injections into either of the two collider rings, avoiding large charge imbalances [19].

At the FCC-ee, highly precise energy calibration using resonant depolarisation at c.m. energies of 91 and 160 GeV, with wiggler-polarised pilot bunches, and roughly $10^5$ times higher luminosity than LEP, will allow measuring the masses of the Z and W bosons, as well as the width of the Z, with 90 times improved precision, rendering the FCC-ee an exceptional electroweak factory [20].

## 2 Technology Requirements

The main technological systems required for the FCC-ee are the 400 and 800 MHz SRF systems, the energy efficient arc magnets, the arc vacuum system, a few special magnets for the interaction region, and the positron source.

### 2.1 Technology Readiness Assessment

The technology to build a machine like FCC-ee long exists. Already in 1976 (almost half a century ago !), B. Richter stated that "An $e^+e^-$ storage ring in the range of a few hundred GeV in the centre of mass can be built with present technology" [21].

The 400/800 MHz RF systems proposed for FCC-ee are state of the art, or close to it. The 400 MHz Nb/Cu cavities are based on the technology developed for the LEP and LHC cavities [22]. A first prototype 5-cell 800 MHz bulk-Nb cavity constructed by JLAB met the design specifications [23]. R&D is necessary to reduce cost and increase reliability of the cavity production process and operation, not to reach the performance. For the klystrons the situation is similar.

Resembling modern light sources, the arc vacuum system is based on a round copper vacuum chamber featuring winglets for photon stops, and thin NEG coating. Prototypes of the energy-efficient twin-aperture arc dipoles and quadrupoles [24] have been built and measured [25]. A prototype of the SC canted-cosine-$\theta$ final focusing quadrupole has also been fabricated [26]. The positron production rate required from the positron source is comparable to those achieved at the SLC and at SuperKEKB.

### 2.2 Ongoing and Planned R&D

The FCC-ee technology R&D is focused on incremental improvements aimed mainly at further optimising efficiency, obtaining the required diagnostic precision, and on achieving the target performance in terms of beam current and luminosity. FCC-ee will strive to include new technologies if they can increase efficiency, decrease costs or reduce the environmental impact of the project. Key FCC-ee R&D items for improved energy efficiency include high-efficiency continuous wave (CW) radiofrequency (RF) power sources (klystrons and/or solid state), high-$Q$ superconducting (SC) cavities for the 400–800 MHz range, and possible applications of HTS magnets.

Aside from the various RF systems, another major component of the FCC-ee is the regular arc, covering almost 80 km. The arc cells must be cost effective, reliable and easily maintainable. Therefore, as part of the FCC R&D programme it is planned to build a complete arc half-cell mock up including girder, vacuum system with antechamber and pumps, dipole, quadrupole and sextupole magnets, beam-position monitors, cooling and alignment systems, and technical infrastructure interfaces, by the year 2025. An intriguing parallel R&D path concerns the possibility to realize the arc quadrupoles plus sextupoles using HTS. Another mock up is proposed for the interaction region, consisting, e.g., of the central beam pipe, final SC quadrupole, support structures, stabilization system, and remotely controlled flanges.

It is also envisaged to design, construct and then test with beam a novel positron source (including a superconducting solenoid as adiabatic matching device) 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.

In addition, to prepare for ultra-high precision centre-of-mass energy measurements, a focused R&D effort is covering state-of-art and beyond in terms of spin-polarisation simulations and measurements (inverse Compton scattering, beamstrahlung, etc.).

Finally, for high luminosity, high current operation of FCC-ee, advanced beam stabilization/feedback systems to suppress instabilities arising over a few turns will be developed, based on the systems developed for the B factories, but possibly augmented by a narrow band system to combat the low-frequency resistive-wall instability.

## 2.3 FCC-ee Demonstrators

With SuperKEKB an actual demonstrator machine is available. As stated, SuperKEKB features many of the same key ingredients, and its design parameters are even more challenging than those of FCC-ee. The FCC collaboration is working together with the SuperKEKB team to address, fully understand and mitigate remaining issues limiting SuperKEKB performance.

Beam studies relevant to FCC-ee — for example on optics correction, vertical emittance tuning, crab-waist collisions, or beam energy calibration — can, and will, also be conducted at INFN-LNF/DAFNE, DESY/PETRA III, and KIT/KARA [27].

The US Electron-Ion Collider (EIC) is set to start beam operation in 2030. The electron beam parameters of the EIC are similar to, and even more demanding than, those of FCC-ee. For example, the EIC foresees operation with two times higher beam current than required for the FCC-ee Z pole running. Therefore, about a decade before FCC-ee commissioning, the EIC can serve as an important test bed for a variety of FCC-ee components and concepts — collimators, radiofrequency systems, beam feedbacks, diagnostics, interaction region, operation with polarised beams, etc.

# 3 Staging Options and Upgrades

It is planned to operate the FCC-ee first on the Z pole (91 GeV c.m., 4 years), then on the W threshold (160 GeV, 2 years), on the ZH production peak (240 GeV c.m., 3 years), and, after a 1 year shutdown, at the $t\bar{t}$ threshold (365 GeV, 5 years). In general as the energy is increased and the beam current decreases, additional RF systems are installed with higher RF voltage and higher impedance. As mentioned, an additional optional running mode at 125 GeV c.m. (direct Higgs production), with monochromatization, for a couple of years.

## 3.1 Energy Upgrades

There appears to be no motivation from particle physics to increase the FCC-ee energy beyond 365 GeV c.m. For example, Ref. [28] concludes that "500 GeV is not a particularly useful energy for the lepton colliders under consideration, especially for the FCC-ee." Regardless, in principle, should there emerge a motivation to do so, the c.m. energy of FCC-ee could be raised to 400 GeV or beyond, by pushing the RF voltage or installing additional RF cavities.

### 3.1.1 100 TeV hadron collider

The main upgrade of the FCC-ee consists in its complete disassembly and replacement by a 100 TeV hadron collider, FCC-hh [7], when the high-field magnets needed for the latter are available in series production. The hadron collider would use the same tunnel infrastructure, experimental caverns, general services, cooling & ventilation systems, and surface sites as the lepton collider. It might also reuse the FCC-ee cryoplants, with upgrades and additions.

### 3.1.2 ERL option

An upgrade of $e^+e^-$ collisions to higher energies, $\sim$ 600 GeV or beyond, has been proposed through converting the FCC-ee into a few-pass ERL [29]. The general feasibility of such an upgrade, its compatibility with the FCC-ee layout, and the realistically attainable luminosity require further studies and R&D. This option is not part of the FCC Feasibility Study.

### 3.1.3 Muon collider option

Following the end of the FCC-ee physics programme, its booster ring could also be used to accelerate positrons to 45 GeV, at a high rate, in order to produce low-emittance muon beams through positron annihilation [30]. Accelerating these muons in the existing CERN complex, and colliding them in the LHC might offer a path towards a 14 TeV muon collider [31, 32]. Achieving the needed luminosity appears quite challenging, but may not be fully excluded by introducing and combining several new concepts.

### 3.2 Luminosity Upgrades

The FCC-ee luminosity already is remarkably high. Nevertheless it could be further increased in a number of ways. First, with collisions at 4 instead of 2 experiments the total luminosity can be increased by about a factor of 1.7. This option is already part of the FCC Feasibility Study. Second, enlarging the dynamic momentum acceptance through optics design improvements or more sophisticated correction schemes would allow for higher luminosity at the same beam lifetime. Third, a more powerful injector complex could sustain shorter beam lifetimes, and would, thereby, also support higher luminosity. Fourth, increasing the RF power would permit higher beam current, and again higher luminosity, but this is not a preferred path. Finally, on paper, also the ERL option promises a high luminosity at the Higgs and $\mathrm{t\bar{t}}$ energies.

### 3.3 Experimental System Upgrades

Experimental system upgrades for the up to four different detectors are presently not foreseen during the 15 years of planned physics operation.

## 4 Synergies with other concepts and/or existing facilities

Substantial synergies exist with the presently operating LHC at CERN and SuperKEKB in Japan, with the Electron-Ion Collider (EIC) in the United States, with the CEPC design in China — which is extremely similar to the FCC-ee —, and with the most modern synchrotron light sources such as ESRF-EBS in France, and next-generation low-emittance storage rings, including the APS Upgrade in the US, and PETRA IV in Germany.

### 4.1 Synergies on Machine Technologies

The FCC-ee design, optics and operation features great synergies with other past, present and future circular colliers, including LHC, SuperKEKB, and EIC, and with modern low-emittance synchrotron light sources. The SRF systems and RF power sources show additional synergies with other facilities utilizing superconducting RF, including the European XFEL, CEBAF, LCLS-II, PIP-II, etc. The injector complex equally has strong synergies with the SuperKEKB injector, but also with other warm linacs, such as the SwissFEL, FERMI, and PAL-XFEL.

### 4.2 Synergies on Detector Technologies

Various types of detectors are considered for the up to four collision points, which could be optimized for different types of physics priorities, such as "Higgs Factory" programme, "ultraprecise electroweak" programme, "heavy flavour" physics, and the search for "feebly coupled particles", respectively [33]. There are significant synergies with the developments for the existing LHC experiments and their upgrades, and with developments for the ILC and CLIC detectors.

### 4.3 Synergies on conventional facilities and green power

Numerous synergies exists and are being further developed. Noteworthy are the low-loss transport of electrical power over long distances, e.g. using HTS cables, energy efficient RF power sources, robust superconducting RF systems, energy efficient magnet systems, including HTS-based magnets, development of more efficient cryoplants, remote interventions based on robots, recovery of the spent energy, in terms of heat or electricity, and intelligent reuses of the excavated material ("mining for the future" initiative).

### 4.4 Synergies for Physics Research

An enormous synergy and complementarity exist between the FCC-ee and FCC-hh physics programmes, as detailed in Ref. [5]. Should both the ILC and the FCC-ee be constructed, the operation modes of these two $e^+e^-$ machines could be adjusted and tailored so as to maximise the overall physics output [34].

## 5 Conclusions

The circular electron-positron collider FCC-ee is a compelling, energy-efficient option for the much wanted Higgs and electroweak factory. It may also serve as a key step towards the next energy frontier machine, in the form of the subsequent FCC-hh hadron collider. The FCC Feasibility Study and a possible future FCC project offer a unique opportunity for the US to participate, similar to the LHC, but as an even more ambitious and global endeavour, to jointly develop advanced technologies with important spin offs for society, and to tackle several outstanding key questions about our universe.

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