PROCEEDINGS OF SCIENCE

FCC-ee Collider Design Overview

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In response to the directives of the 2020 European Strategy for Particle Physics (ESPP), CERN, in collaboration with international partners, is exploring the feasibility of an energy-frontier, 100 TeV hadron collider, including, as an initial stage, a high-luminosity circular electron-positron collider serving as Higgs and electroweak factory.
This effort builds upon the 2019 conceptual design reports of the Future Circular Collider (FCC) study. Currently, the FCC Feasibility Study, spanning over five years, aims at providing conclusive inputs to the next update of the ESPP, with a focus on implementing these accelerators inside a 90.7 km tunnel in the Lake Geneva basin.
The ongoing study aims at validating tunnel construction, refine collider and injector designs, develop organization and funding models, and conduct R&D on critical machine components. This paper provides an overview of the study status and the latest advancements on the electron-positron collider FCC-ee.

42nd International Conference on High Energy Physics - ICHEP 2024
17-24 July 2024
Prague, Czech Republic

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PoS(ICHEP2024)830

1. FCC integrated program and Feasibility Study

The Future Circular Collider (FCC) Feasibility Study (FS), spanning from 2021 to 2025, addresses a key directive of the 2020 European Strategy for Particle Physics (ESPP). Its main goal is to explore, and prepare for, the possible construction of a next-generation energy-frontier hadron collider, FCC-hh, preceded by the FCC-ee, a high-luminosity e^+e^- collider serving as a Higgs, electroweak, and top-quark factory [1]. The FCCFS assesses the geological, technical, and environmental feasibility of a 90.7 km collider in the Lake Geneva basin. It also refines collider and injector designs, and validates sustainable operation models. The study covers several key areas:

- **Feasibility and optimization:** Geological, technical, environmental and administrative feasibility of the tunnel and surface areas, and optimisation of the placement and layout of the ring and related infrastructure; collaboration with Host States to prepare for a potential project approval and identify possible obstacles.
- **Design and R&D:** Optimisation of collider and injector chain designs, supported by R&D to develop key technologies.
- **Sustainable operational model:** Development of resource-efficient models for the colliders and experiments, considering human, financial, and environmental aspects, including energy efficiency.
- **Cost and funding:** Development of a consolidated cost estimate, funding strategies and organisational models.
- **Physics & detectors:** Consolidation of the physics case and detector concepts.

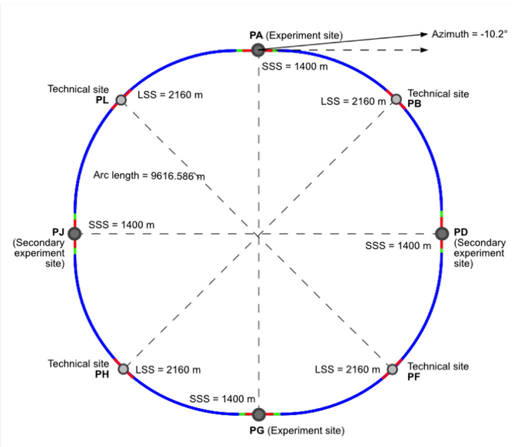

Figure 1: FCC-ee ring layout.

Operation mode	Z	$t\bar{t}$
Circumference [km]	90.659	
SR power / beam [MW]	50	
Beam energy [GeV]	45.6	182.5
Bunches/beam	11200	56
Bunch intensity [10^{11}]	2.14	1.64
Bunch length [mm]	15.5	2.33
Rms hor. emit. [nm]	0.71	1.59
Rms ver. emit. [pm]	1.90	1.60
$\beta^*_{x/y}$ [mm]	110/0.7	800/1.5
$\mathcal{L}$ / IP [10^{34}/cm^{2}s]	141	1.4

Table 1: FCC-ee, Z and $t\bar{t}$ beam parameters [2].

The integrated program is highly synergetic sharing common civil engineering and technical infrastructures between FCC-ee and FCC-hh [3], and building on CERN's existing infrastructure. The FCC integrated project will allow the development of a significant new facility at CERN, within a few years of the completion of HL-LHC. A so-called mid-term review has been completed and the final study report is expected by March 2025, as one of the inputs to the next ESPP update in summer 2026.

2. FCC Layout Overview

The layout presented in Fig. 1 is based on a double ring configuration with a circumference of 90.7 km. Top-up injection at full energy is provided by a booster ring installed in the same tunnel to maximise the luminosity. The collider features four experimental points with an asymmetric interaction region design to limit synchrotron radiation towards the particle detector, and a crab waist collision scheme with 30 mrad horizontal crossing angle. The design allows operational flexibility and its infrastructure is compatible with a subsequent hadron collider. The synchrotron radiation power is limited to 50 MW per beam across all operation modes. Table 1 shows some beam parameters for the Z-pole and top quark threshold (lowest and highest energy) operation modes.

2.1 Arc Lattice and Optics

The arc lattice and optics of FCC-ee are designed with the flexibility to support operation across multiple energy modes, ranging from Z-pole to top-quark threshold. The baseline layout employs a standard FODO optics design with a sufficiently short cell for low emittance at high energies displayed in Fig. 2, using twin aperture quadrupole magnets [4]. At lower energies (i.e., for running on the Z pole and at the WW pair threshold) the cell length is doubled to maintain an acceptable beam-beam parameter. An alternative Hybrid FODO optics design, shown in Fig. 3, provides potential advantages such as more efficient arc sextupoles and more relaxed alignment tolerances. For either optics, the energy spread created along the ring caused by synchrotron radiation, is compensated by magnet tapering. Studies are ongoing to implement potential high-temperature superconducting nested magnets comprising dipolar, quadrupolar and sextupolar components [5, 6]. These aim at reducing the power consumption while maintaining the necessary magnetic field strengths and field quality. Moreover, a half-cell mock-up, schematised in Fig. 4, is under study to examine the overall hardware integration within the diameter of the tunnel including services and support structures.

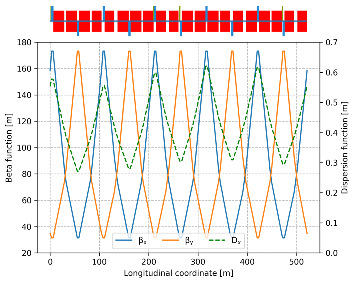

Figure 2: FODO optics design.

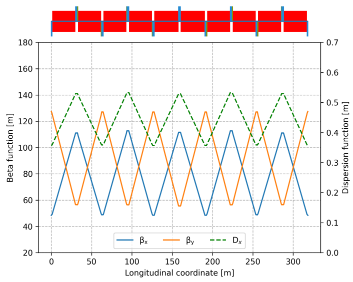

Figure 3: HFD optics design.

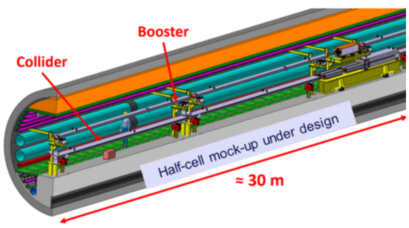

Figure 4: Arc mock-up schematic.

2.2 Interaction Region Optics Design and Machine Detector Interface

The interaction region (IR) is a critical aspect of the FCC-ee design. Two competing designs are under consideration: an asymmetric optics design [2], presented in Fig. 5, featuring virtual crab sextupoles by detuning the local vertical chromatic correction, comprises a minimum number of sextupoles. An alternative more symmetric design, illustrated in Fig. 6, features modular horizontal and vertical local chromatic correction sections and independent crab sextupoles [7]. A 2 T detector

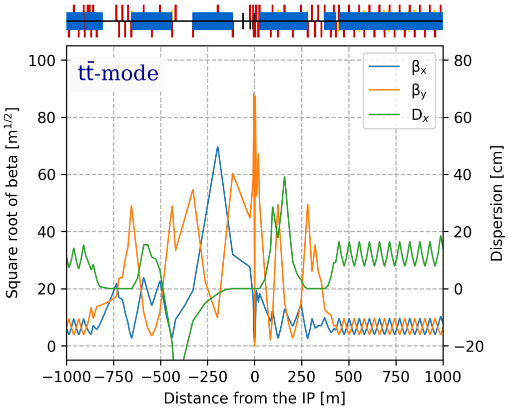

Figure 5: Hybrid IR optics.

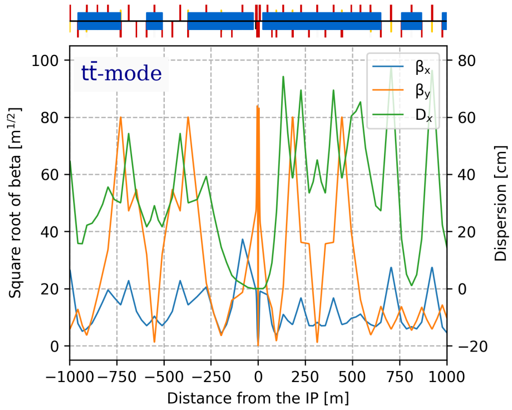

Figure 6: Modular IR optics.

solenoid is foreseen in the experiment and could be compensated locally by anti-solenoids on either side or non-locally with anti-solenoids placed about 20 m from the IP. Regarding the machine-detector interface (MDI), ongoing efforts focus on optimizing the material budget, impedance and thermal analysis. The mechanical integration [8] progressed including luminosity calorimeter, bellows, services, supports, cryostats. Multiple studies focused on various backgrounds, comprising synchrotron radiation [9], Bhabha scattering, beamstrahlung [10] and beam halo losses [11]. These background drive the design of shielding, collimation strategies, and photon beam dump. An interaction region mock-up is currently under development, and will assess various MDI design challenges. These include hardware integration, manufacturing processes, and also ensuring mechanical compatibility with the nearest detector elements.

2.3 FCC-ee Collimation

Due to the high stored beam energy in Z mode (up to 17.5 MJ), beam losses pose a serious threat to sensitive hardware in the collider such as superconducting final focus quadrupoles. Therefore, a halo collimation system has been developed to protect sensitive machine components from beam halo losses and reduce subsequent background in the experiments, conserving the detector performance. The collimation system is designed to handle three types of beam loss scenarios (horizontal halo losses, vertical halo losses, and off-energy losses) [11]. In addition to the beam halo colli-

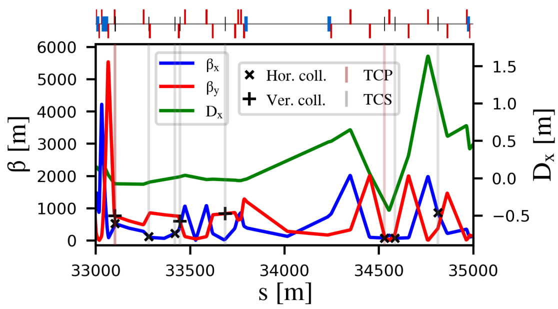

Figure 7: Collimation optics present at point F.

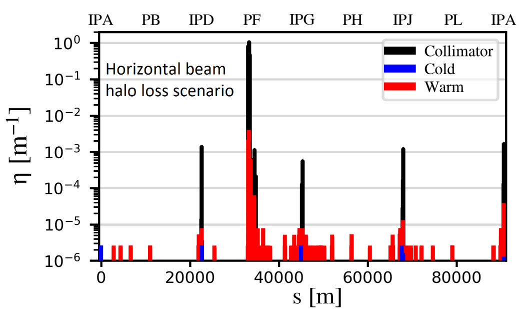

Figure 8: Efficiency η of the collimation scheme.

mation, synchrotron radiation collimators and masks have been implemented in each experimental insertion to specifically mitigate the synchrotron radiation background in the experiment.

3. FCC-ee Radio-Frequency (RF) System

The RF system of the collider foreseen at point H, is essential for compensating the energy lost due to synchrotron radiation. The baseline RF cavities installation is sequential with, initially, 1-cell 400 MHz RF cavities at 4.5 K planned for Z-pole operation, later exchanged, during a shutdown, with 2-cell 400 MHz RF cavities, re-using the same klystrons, for the W and Zh operation modes. Finally, 5-cell 800 MHz RF cavities at 2 K will be installed for $t\bar{t}$ operation mode. A recent proposal to install 2-cell RF cavities from the start simplifies the installation sequence, removing the shutdown after the Z operation, allowing flexibility during physics runs, and reducing the number of cavity types to develop. Studies are ongoing to explore this promising alternative approach.

4. Dynamic Aperture and Momentum Acceptance

The current Dynamic Aperture (DA) and Momentum Acceptance (MA) results ensure satisfactory beam lifetimes across all energies. Specifically, the lattice design achieves sufficient momentum acceptance for off-momentum injection during Z operation mode, targeting a $\pm 1\%$ momentum acceptance. At the highest energy mode, where beamstrahlung induces large energy spread, a momentum acceptance range of $[-2.8\%, 2.5\%]$ is necessary. While designs meet targets in ideal conditions, introducing realistic operational imperfections, reported in [12], significantly impacts DA and MA. Therefore, ongoing studies aim at developing mitigation and correction strategies to ensure that beam lifetimes remain sufficient for all nominal operation modes.

5. Summary and Future Timeline

The FCC Feasibility Study has made significant progress, including the successful completion of a Mid-Term Review (MTR), where a few potential accelerator performance risks were identified, as reported in [13]. The FCCFS, which will address all items raised at the MTR, is expected to be completed by March 2025, The next step forward is a pre-TDR phase (2025-2027) that will support the transition from FS to full technical design. Recent decisions by the CERN Council have allocated additional resources for FCC studies and for key R&D on superconducting radio-frequency systems, in order to accelerate the design of the future FCC-ee.

Looking ahead, the preliminary FCC-ee schedule foresees the construction to begin in the early 2030s, and the start of FCC-ee beam operation by the mid or later 2040s, providing a seamless continuation of CERN's physics program post HL-LHC. The FCC-hh operation will follow in the 2070s. This ambitious timeline relies on sustained and expanded international collaboration.

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