PROCEEDINGS OF SCIENCE

The FCC Feasibility Study

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The Future Circular electron-positron Collider (FCC-ee) design is optimised for studying the Z, W, and Higgs bosons, and the 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 (FCC FS) to examine the detailed implementation of such a collider. This Feasibility Study will be completed by the end of 2025 and its results be presented as input to the next update of the European Strategy for Particle Physics expected in 2026/27. An important milestone is the "FCC FS mid-term review" in fall 2023. In this article we present the status of the Feasibility Study and a few design highlights.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Conference jointly organized by Universität Hamburg and the research center DESY

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1. Motivation and Context

The Future Circular Collider (FCC) Feasibility Study (FS) was launched by the CERN Council (see CERN/3566 [1] and CERN/3588 [2]), in response to the 2020 update of the European Strategy for Particle Physics (ESPP) [3]. The entire FCC governance structure (members of the Steering Committee, Collaboration Board, Scientific Advisory Committee, Coordination Group) was established by summer 2022. The FCC FS is expected to deliver a Feasibility Study Report (FSR) by the end of 2025. A "mid-term review" is scheduled for autumn 2023.

2. FCC-ee Collider Parameters

The lepton-collider beam parameters are limited by various constraints and effects [4], such as (1) beamstrahlung [5], (2) a coherent beam-beam instability in collision with a large crossing angle [6], (3) synchro-betatron resonances, (4) requirements from polarisation, and (5) impedance effects. As a result of the optimisation process under these constraints, the optics parameters and number of bunches vary not only with beam energy, but also with the number of collision points. For the mid-term review a scenario with four experiments was elaborated.

Apart from the possibly higher number of collision points, another important change with respect to the FCC-ee Conceptual Design Report (CDR) [7] is the reduced arc length, implying a lower beam current. Also refined simulations combining the effect of the full nonlinear lattice and either weak-strong or quasi-strong-strong beam-beam simulations have led to parameter adjustments.

The latest parameter sets are presented in Table 1. Two contributions to the beam lifetime are indicated separately: (1) the effect of lattice dynamic aperture and beamstrahlung plus quantum fluctuation, and (2) the unavoidable luminosity-related radiative Bhabha scattering. The total beam lifetime is the inverse of the sum of the individual inverse lifetimes.

3. Implementation

In early 2023, a lowest-risk implementation baseline was finalized, with a circumference of 90.7 km. Meetings have already been held with the 41 municipalities concerned in France and Switzerland; see Fig. 1. Environmental studies and preparations for geological investigations (drillings and seismic investigations) have been underway since February 2023.

Civil engineering has also made significant advances, resulting in a complete 3D model for the underground structures, a full set of 2D drawings, and preliminary representative designs for both the experimental and technical surface sites. Figure 2 shows example images of an FCC-ee technical surface site developed by Fermilab.

A CERN press release issued in February 2023, which had been prepared together with the Swiss and French authorities, provided information about the Feasibility Study and its organisation. This was followed, in April, by a press visit at CERN for local media representatives.

An electrical powering concept for the FCC has been defined in collaboration with the French high-voltage electricity grid operator RTE. Road accesses have been identified and documented for all eight surface sites. Four possible highway connections have been defined, which could be used for materials transport. The total length of new roads required at the departmental road level is less than 4 km.

Table 1: Preliminary key parameters of FCC-ee, as evolved from the CDR parameters, now with a shorter 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 in total. Both natural bunch lengths due to synchrotron radiation (SR) and collision values including beamstrahlung (BS) are shown. The FCC-ee has a combination of 400 MHz radiofrequency systems (at the first three energies, up to 2.1 GV) and 800 MHz (additional cavities for $t\bar{t}$ operation), with respective voltage strengths indicated. For the integrated luminosity, 185 days of operation per year, and luminosity production at 75% efficiency with respect to the ideal top-up running is assumed, as in the report [8].

Running mode	Z	W	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1270	137	26.7	4.9
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	141	20	5.0	1.25
Energy loss / turn [GeV]	0.0394	0.374	1.89	10.42
Synchrotron Radiation Power [MW]	100	100	100	100
RF Voltage 400/800 MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	3.47	3.40	1.81
Rms bunch length (+BS) [mm]	15.5	5.41	4.70	2.17
Rms horizontal emittance ε_x [nm]	0.71	2.17	0.71	1.59
Rms vertical emittance ε_y [pm]	1.9	2.2	1.4	1.6
Longitudinal damping time [turns]	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	200	240	1000
Vertical IP beta β_y^* [mm]	0.7	1.0	1.0	1.6
Hor. IP beam size σ_x^* [µm]	9	21	13	40
Vert. IP beam size σ_y^* [nm]	36	47	40	51
Beam lifetime (q+BS+lattice) [min.]	50	42	100	100
Beam lifetime (lum.) [min.]	22	16	14	12
Total beam lifetime [min.]	15	12	12	11
Int. annual luminosity / IP [ab^{-1}/yr]	17†	2.4†	0.6	0.15‡

† The integrated luminosity in the first two years is assumed to be half this value to account for the machine commissioning and beam tuning;

‡ The integrated luminosity in the first year, at a lower beam energy of about 173 GeV, is assumed to be about 65% of this value to account for the machine commissioning and beam tuning. The faster commissioning than at lower energy reflects the LEP/LEP-2 experience.

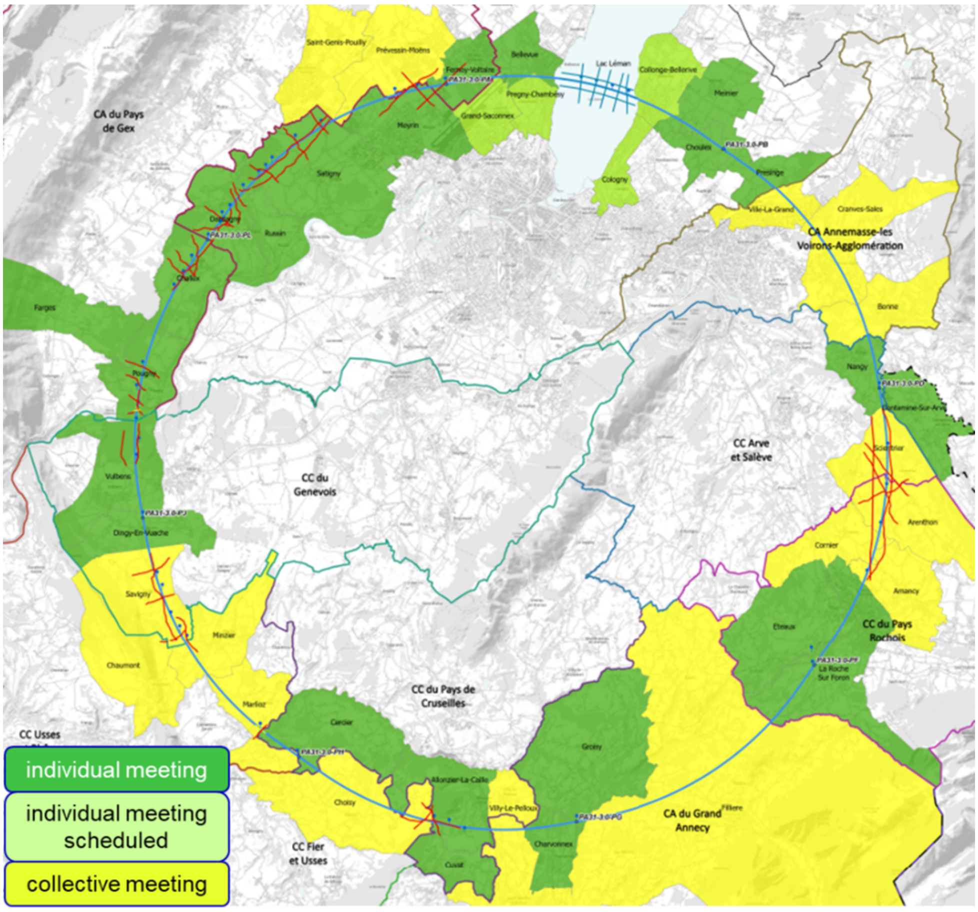

Figure 1: FCC study-team meetings with municipalities concerned in France (31) and Switzerland (10).

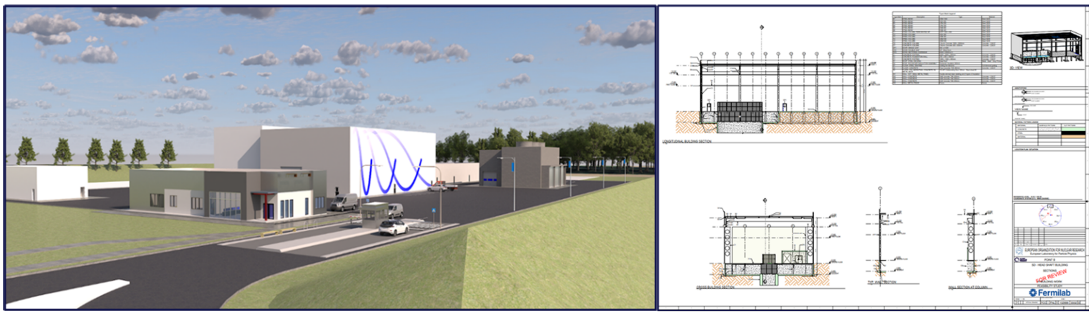

Figure 2: FCC-ee surface site developed by the Fermilab team (Courtesy FNAL).

4. HTS Magnet Option

In the framework of the Swiss CHART programme, an innovative idea is being pursued for the short straight sections in the FCC-ee arcs: PSI and CERN are jointly developing nested sextupole and quadrupole coils, made from high-temperature superconductors (HTS) and operating at about 40 K. An example design of a canted cosine theta sextupole magnet is displayed in Fig. 3. A 1-m prototype will be manufactured by 2026. This scheme promises several important benefits such as power saving, enhanced optics flexibility, and increased dipole filling factor, as is illustrated in Fig. 4.

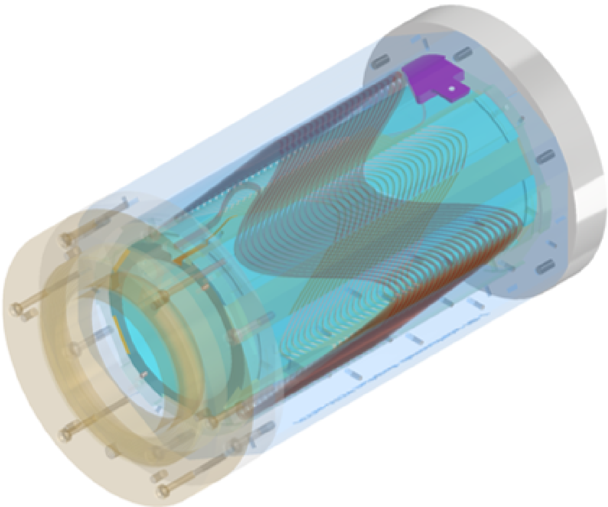

Figure 3: CAD design of HTS sextupole demonstrator based on canted cosθ coils (Courtesy M. Koratzinos).

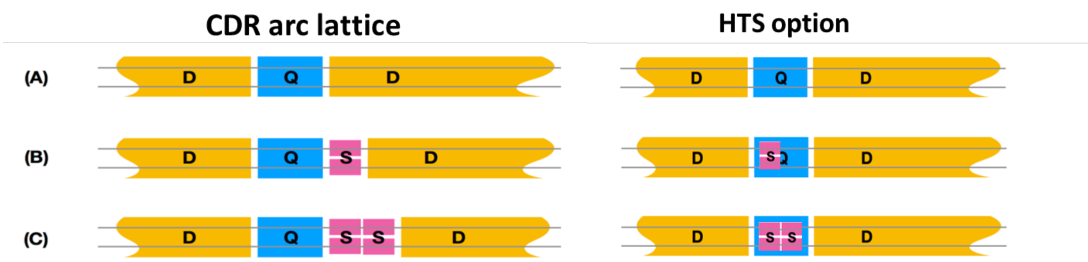

Figure 4: Three different types of short straight sections in the FCC-ee according to the 2018 CDR layout (left) and when using nested HTS quadrupole and sextupole coils (right) (Courtesy M. Koratzinos).

5. Injector Complex

A siting study for the FCC-ee pre-injector on the CERN Prévessin site has been conducted, with a preliminary layout shown in Fig. 5. There is sufficient space not only to house the 6 GeV linac and the damping ring, but also a higher-energy linac, which would accelerate electrons and positrons to an energy of 20 GeV.

6. Radiofrequency Systems

The layout of the FCC-ee superconducting radiofrequency (RF) systems has been modified. The RF systems for the collider and the booster will now be installed in the separate straight sections

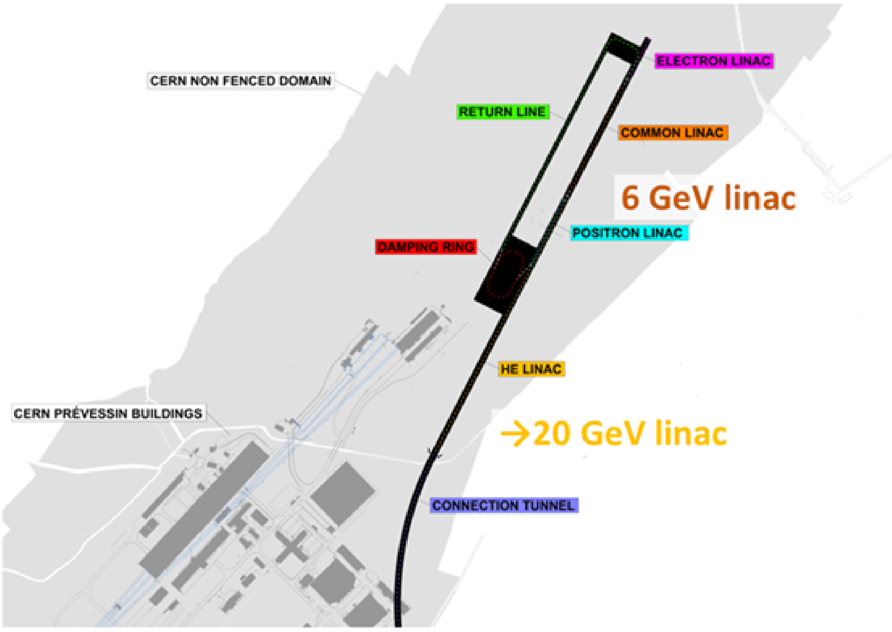

Figure 5: Basic and extended FCC-ee pre-injector complex located on the CERN Prévessin site (Courtesy T. Watson and W. Bartmann).

H (collider) and L (booster), which will also have fully separated technical infrastructure systems, such as cryogenics. The collider RF, with the highest power requirements, is now located at point H, ensuring an optimum connection to the existing 400 kV grid line and a more suitable surface site. The tunnel cross sections at the RF installations in points H and L are illustrated in Fig. 6.

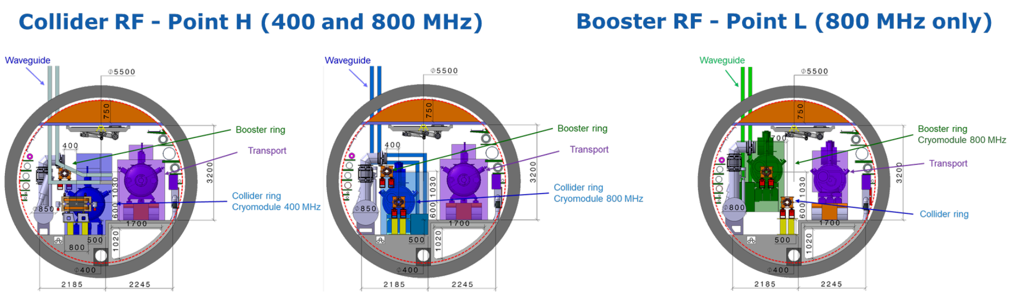

Figure 6: Tunnel cross sections in the FCC-ee RF straight sections. In each of te three images, the right-hand cryomodule, shown on a small vehicle, is being transported past an installed cryomodule, on the left, which is connected by waveguide to the RF power source in the klystron gallery (located above) and by cryogenic jumpers to to the cryogenic distribution line, on the far left (Courtesy F. Valchkova and F. Peauger).

Several alternative running sequences and RF staging scenarios are being explored. Figure 7 shows the baseline scenario, starting with 28 cryomodules containing four single-cell 400 MHz cavities, as required for operation on the Z pole (91 GeV centre-of-mass). An alternative staging scenario, in Fig. 7, begins at the Higgs-boson production peak (ZH mode of operation at 240 GeV centre-of-mass energy) with 66 cryomodules of four double-cell cavities.

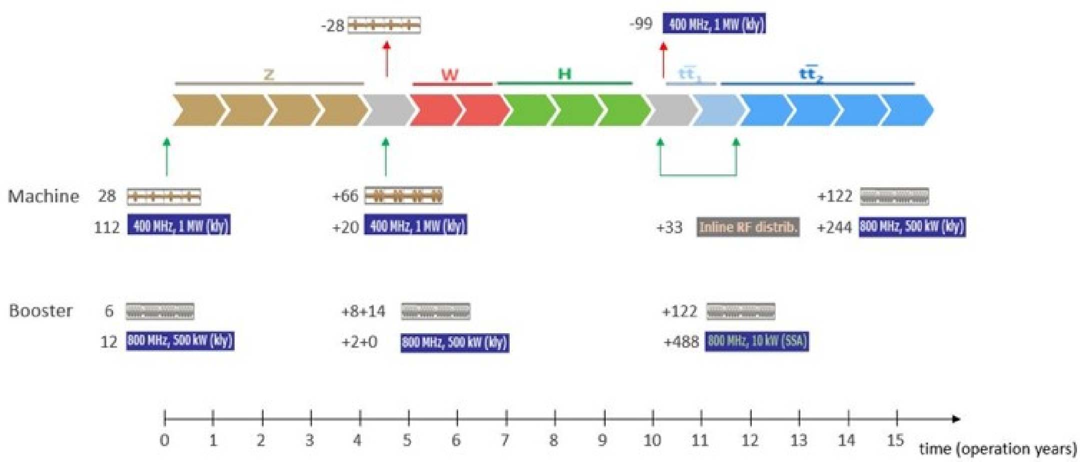

Figure 7: Baseline RF staging scenario for collider and booster ring (Courtesy O. Brunner).

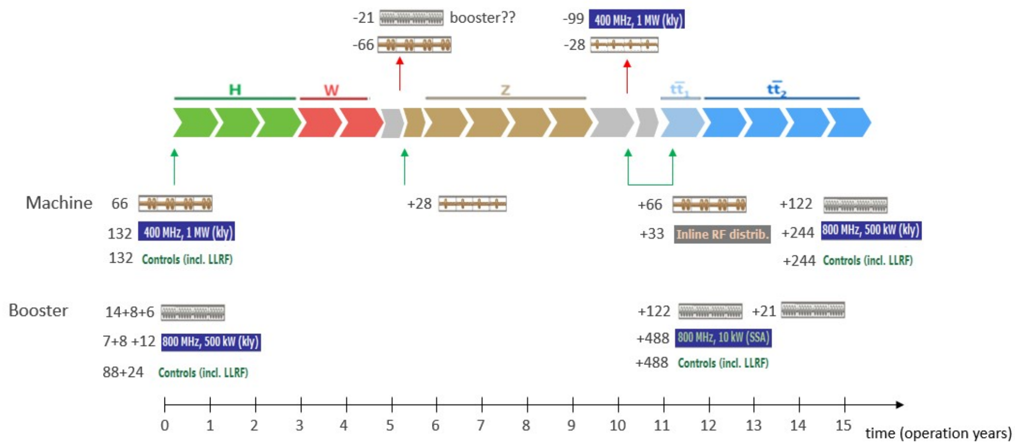

Figure 8: Alternative RF staging scenario for collider and booster ring (Courtesy O. Brunner).

7. FCC-hh Collider Parameters and Optics

The design of the hadron collider is based on the LHC experience. The key challenges are the magnet technology and the power consumption in presence of strong synchrotron radiation. To limit the latter, and also since radiation damping during the store is significant, the beam current and bunch population are relaxed compared with those of the HL-LHC.

Two parameter sets for the FCC-hh hadron collider, adapted to the new circumference and layout, are compiled in Table 2. The bunch population (close to 10^{11} protons per bunch) and the beam current (0.5 A) are kept the same as in the 2018 CDR [9]. While the CDR assumed a dipole field of 16 T, Table 2 indicates a range of possible fields, extending from 14 T based on Nb_3Sn technology to HTS or hybrid-magnet technology with a field of up to 20 T. The table illustrates how the synchrotron radiation strongly increases with higher magnetic field.

The synchrotron-radiation heat, which must be extracted from inside the cold magnets, is a major contribution to the cryogenic power. For the CDR, with 16 T Nb_3Sn magnets, the FCC-hh cryogenics required close to 250 MW of electric power. With the lower field of 14 T, this power could be significantly reduced. On the other hand, the cryogenic power might also potentially be lowered for the higher-field magnets based on HTS technology, as these could conceivably be operated at higher temperature, together with an elevated temperature of the beam-screen intercepting the synchrotron radiation.

Table 2: Key parameters of FCC-hh compared with the HL-LHC and LHC. The range of beam energies shown for FCC-hh implies different magnet technologies, as indicated. For the integrated luminosity, 160 days of operation per year, and luminosity production at 75% efficiency with respect to the ideal running is assumed, as defined in Ref. [8].

	FCC-hh		HL-LHC	LHC
	initial	nominal		
Centre-of-mass energy (TeV)	80–115		14	14
Dipole field [T]	14–20		8.33	8.33
Arc magnet technology	Nb_3Sn or HTS/hybrid		Nb-Ti	Nb-Ti
Circumference [km]	90.7		26.7	26.7
Beam current [A]	0.5		1.1	0.58
Bunch Intensity [10^{11}]	1		2.2	1.15
Bunch spacing [ns]	25		25	25
Synchr. radiation power [kW]	2040–8500		15	7
SR power / length [W/m/aperture]	13–54		0.33	0.17
Longit. emit. damping time [h]	0.77–0.26		12.9	12.9
IP beta function $\beta^*_{x,y}$ [m]	1.1	0.3	0.15 (min.)	0.55
Normalized rms emittance [µm]	2.2		2.5	3.75
Peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
Events / bunch crossing	170	1030	132	27
Stored beam energy [GJ]	6.2–8.9		0.7	0.36
Int. annual luminosity / IP [ab^{-1}/yr]	0.25	1.0	0.3	0.05

The optics of the FCC-hh hadron collider has been modified to fit to the new implementation baseline. In addition, the interaction point of the hadron collider was moved on top of the one for the lepton collider, and the footprint was further optimised to minimize the width of the tunnel, as is shown in Fig. 9.

8. FCC Collaboration

About 150 institutes and more than 30 companies from 34 countries have so far joined the FCC Collaboration. Further increased collaboration with laboratories and universities across the world is desired in all areas of the FCC Feasibility Study, in particular, on the accelerator and in the areas of particle physics, experiments and detectors. Numerous synergies have been identified with the

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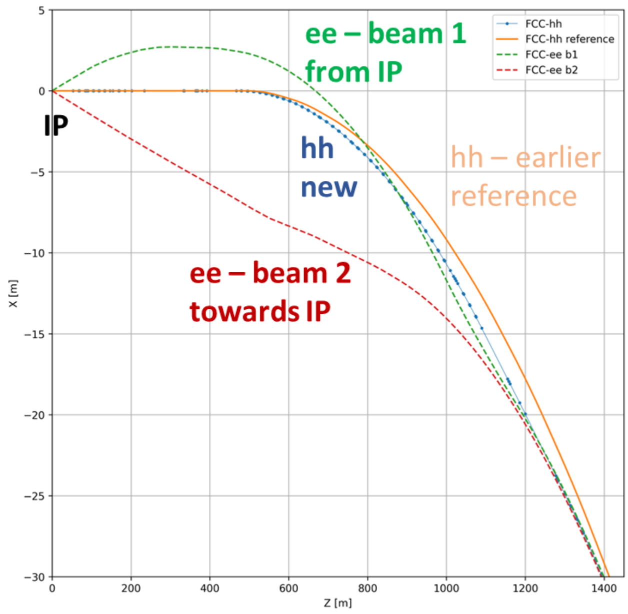

Figure 9: Three-beam footprint around an interaction point, before and after final FCC-hh interaction-region optics adjustment (Courtesy T. Risselada, M. Giovannozzi, and G. Pérez Segurana).

U.S. Electron-Ion Collider (EIC) project, whose electron storage ring parameters are quasi-identical to, or even more challenging than, those of FCC-ee.

Collaborating institutes meet at the annual FCC Week. FCC Week 2023 was held in early June. It attracted 473 expert participants, including a growing number of young scientists. London proved a highly appropriate place for many intriguing talks and discussions that significantly sharpened and cemented the case for the FCC, including talks by the CERN Director-General, Fabiola Gianotti, the CERN Council President, Eliezer Rabinovici, and the STFC Executive Chair, Mark Thomson.

9. Midterm Review and FCC-ee Timeline

The mid-term review marks the completion of the first half of the FCC Feasibility Study. The review addresses the following topics: placement and territorial aspects; technical infrastructure; accelerator design for both the FCC-ee and the FCC-hh; physics, experiments and detectors; organisation and financing; environmental impact; socio-economic impact; and a cost update.

Figure 10 presents a tentative timeline for the FCC project, FCC-ee accelerator, and detectors, till start of physics operation. Either baseline or alternative operation sequence would extend over a total of about 16 years, including, as the final stage, five years of $t\bar{t}$ operation.

Acknowledgements

We thank the FCC Collaboration for its enthusiastic development of the FCC project, and all our colleagues who are contributing to the Feasibility Study. This work was supported by the European Union's Horizon 2020 Research and Innovation programme under grant no. 951754 (FCCIS).

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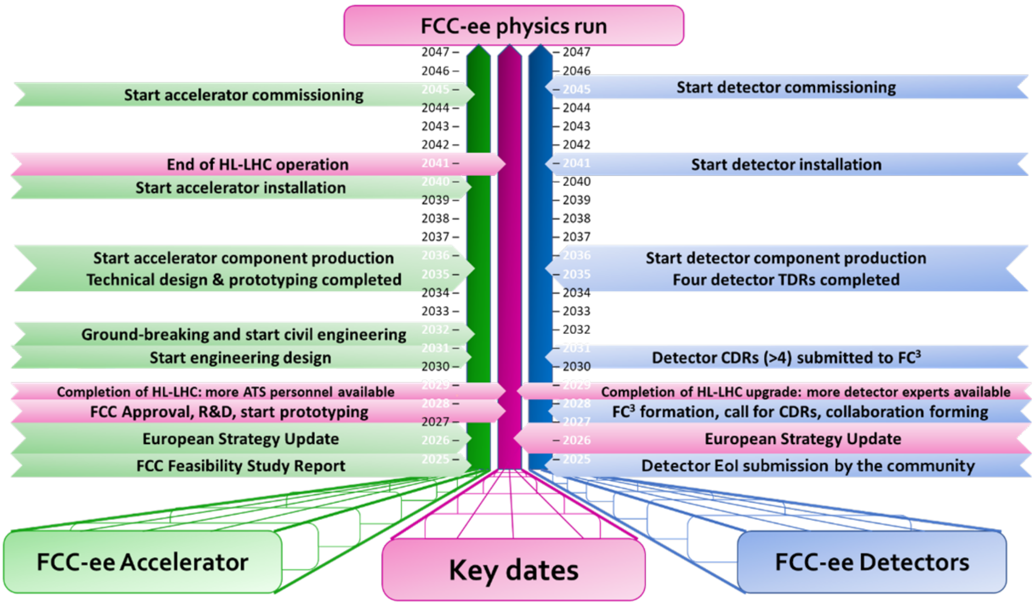

Figure 10: Tentative timeline from today to start of FCC-ee physics in the second half of the 2040s.

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