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Future Circular Collider: Integrated Programme and Feasibility Study

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The Future Circular Collider (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. This programme well matches the highest priority future requests issued by the 2020 Update of the European Strategy for Particle Physics. In 2021, with the support of the CERN Council, a five-year FCC Feasibility Study was launched. In this article, we present the FCC integrated project and the preparations for the FCC Feasibility Study.

Keywords: hadron collider, lepton collider, future circular collider, European strategy for particle physics, Higgs factory, electroweak factory, top-quark factory, TeraZ factory

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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 [4]. 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 [25, 32].

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 during the early 2040s, and the first FCC-hh hadron collisions by 2065–70 — see **Figure 1**. In this way, 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 [26–28], describing the physics cases, the design of the lepton and hadron colliders, and the underpinning technologies and infrastructures. According to this design, the FCC-ee is the most sustainable of all the proposed Higgs and electroweak factory proposals, in that it implies the lowest energy

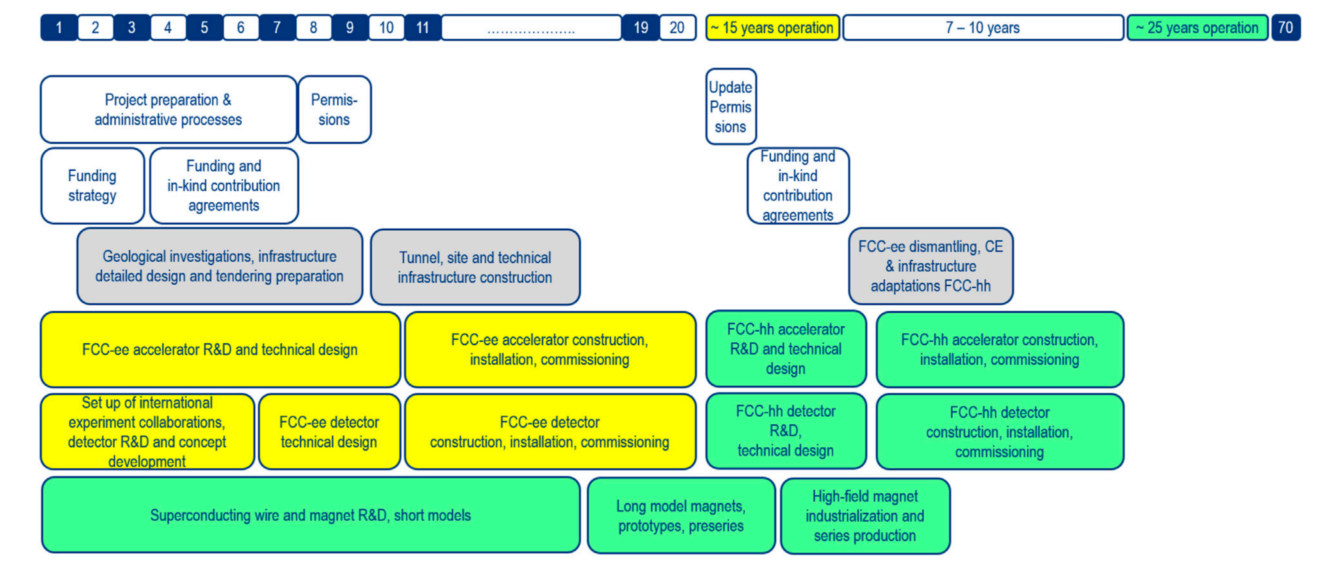

FIGURE 1 | Technical schedule of the FCC integrated project with year 1 equal to 2021 (a similar schedule was presented in Ref. [3]).

consumption for a given value of total integrated luminosity [3], over the collision energy range from 90 to 365 GeV.

1.2 FCC-ee R&D

FCC-ee research and development (R&D) focuses on further improving the overall efficiency, on obtaining the measurement precision required, and on achieving the target performance in terms of beam current and luminosity.

Key FCC-ee R&D items for improved energy efficiency include high-efficiency continuous wave (CW) radiofequency (RF) power sources (klystrons and/or solid state), high-Q SC cavities for the 400–800 MHz range, and possible applications of high-temperature superconductor (HTS) magnets. For ultra high precision centre-of-mass energy measurements, the R&D should cover state-of-art and beyond in terms of spin-polarisation simulations and measurements (inv. Compton, beamstrahlung, etc.). Finally, for high luminosity, high current operation, FCC-ee requires a next generation beam stabilization/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.

1.2.1 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, four-cell 400 MHz Nb/Cu cavities at the W and H (ZH) energies, and a complement of five-cell bulk Nb 800 MHz cavities at 2 K for low-current high-voltage $t\bar{t}$ operation [26]. In the full-energy booster, only multi-cell 400 and 800 MHz cavities will be installed. 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 [24].

1.2.2 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 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.

Constructing some of the magnets for the FCC-ee final focus or arcs with advanced high-temperature superconductor (HTS) technology could lower 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.

1.2.3 Beam Diagnostics

As experience at previous and present colliders has taught us, adequate beam diagnostics is essential for reaching or exceeding design performance. For this reason, the FCC-ee R&D programme foresees the prototyping of key beam diagnostics, like bunch-by-bunch longitudinal charge-density monitors, ultra-low emittance measurements, beam-loss and beamstrahlung monitors, real time monitoring of the collision offsets, a polarimeter for each beam able to measure the 3D polarization vector as well as the beam energy, and fast luminometers.

1.2.4 Polarimetry and 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

[5]. The operation with polarised pilot bunches requires constant and high precision monitoring of the residual 3-D spin-polarization of the colliding bunches, which—if nonzero—would affect the physics measurements.

1.2.5 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. The S-band linac could be based on state-of-the-art technology as employed for the FERMI upgrade at the ELETTRA synchrotron radiation facility.

It is also envisaged to design, construct and then test with beam a novel positron source 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.

1.2.6 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, should guide the choice of the injection energy.

1.2.7 Lessons from SuperKEKB and Beam Studies

The SuperKEKB collider, presently being commissioned [19], features many of the key elements of FCC-ee: double ring, large crossing angle, low vertical IP beta function β_y^* (design value ~0.3 mm), short design beam lifetime of a few minutes, top-up injection, and a positron production rate of up to several 10^{12}/s. SuperKEKB has achieved, in both rings, the world's smallest ever β_y^* of 0.8 mm, which also is the lowest value considered for FCC-ee. Profiting from a new "virtual" crab-waist collision scheme, first developed for FCC-ee [21], in December 2021 SuperKEKB reached a world record luminosity of $3.81 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. However, many issues still need to be addressed, such as a vertical emittance blow up due to an unexplained mechanism, the transverse machine impedance, and single-bunch instability threshold, sudden beam losses without any accompanying beam oscillation, insufficient quality of the injected beam, etc.

In view of the SuperKEKB experience, studies of vertical emittance tuning is another important R&D frontier for FCC-ee. This includes simulating realistic beam measurements, constructing optics tuning knobs, especially for the final focus, and developing beam-based alignment procedures for the entire ring. Software development is an important component of this activity. Effects of beam-beam collisions and monitor resolution limits need to be considered, as should be the impact of machine errors and tuning on the dynamic aperture and on the achievable polarisation levels.

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 [14].

1.3 High-Field Magnet R&D

The primary technology of the future circular hadron collider, FCC-hh, is the high-field magnets, Both high-field dipoles and quadrupoles [27] are required, or, possibly, combined-function magnets [12].

For constructing the accelerator magnets of the present LHC, the Tevatron, RHIC, and HERA, wires based on Nb-Ti superconductor were used. However, Nb-Ti magnets are limited to maximum fields of about 8 T, as being operated for the LHC. The HL-LHC will, for the first time in a collider, deploy some tens of dipole and quadrupole magnets with a peak field of 11–12 T, based on a new high-field magnet technology using a Nb_3Sn superconductor. The Nb_3Sn superconductor holds the promise to approximately double the magnetic field, from ~8 T at the LHC, to 16 T for the FCC-hh.

Recently, several important milestones were accomplished in the development of high-field Nb_3Sn magnets. At CERN, a block coil magnet, FRESCA2, with a 100 mm bore, achieved a world-record field of 14.6 T at 1.9 K [29]. In the US, a Nb_3Sn cosine-theta accelerator dipole short-model demonstrator with 60 mm aperture [33], reached a similar field, of 14.5 T at 1.9 K [34].

Forces acting on the magnet coils greatly increase with the strength of the magnetic field, while, at the same time, most higher-field conductors, such as the brittle Nb_3Sn, tend to be more sensitive to pressure. Therefore, force management becomes a key element in the design of future high-field magnets.

Beside the development of optimized magnet design concepts, such as "canted cosine-theta" dipoles [7], higher field can be facilitated by a higher-quality conductor. A Nb_3Sn wire development programme was set up for the FCC [2]. For Nb–Ta–Zr alloys, it could be demonstrated that an internal oxidation of Zr leads to the refinement of Nb_3Sn grains and, thereby, to an increase of the critical current density [6]. The phase evolution of Nb_3Sn wire during heat treatment is equally under study, as part of the FCC conductor development programme in collaboration with TVEL, JASTEC, and KEK [13]. Advanced Nb_3Sn wires with Artificial Pinning Centers (APCs) produced by two different teams reached the target critical current density for FCC, of 1500 A/mm^2 at 16 T [1, 30], which is 50% higher than for the HL-LHC wires. The APCs allow for better performance; they decrease magnetization heat during field ramps, improve the magnet field quality at injection, and reduce the probability of flux jumps [31].

In addition to Nb_3Sn wire, also high-temperature superconductors (HTS) are of interest, since they might allow for higher fields, operation at higher temperature, and, ultimately, perhaps even lower cost. In this context, the FCC conductor programme has been exploring the potential of REBCO coated conductors (CCs). In particular, the critical surfaces for the current density, $J_c(T, B, \theta)$, of coated conductors from six different manufacturers: American Superconductor Co. (US), Bruker HTS GmbH (Germany), Fujikura Ltd. (Japan), SuNAM Co. Ltd. (Korea), SuperOx ZAO (Russia) and SuperPower Inc. (US) have been studied [22].

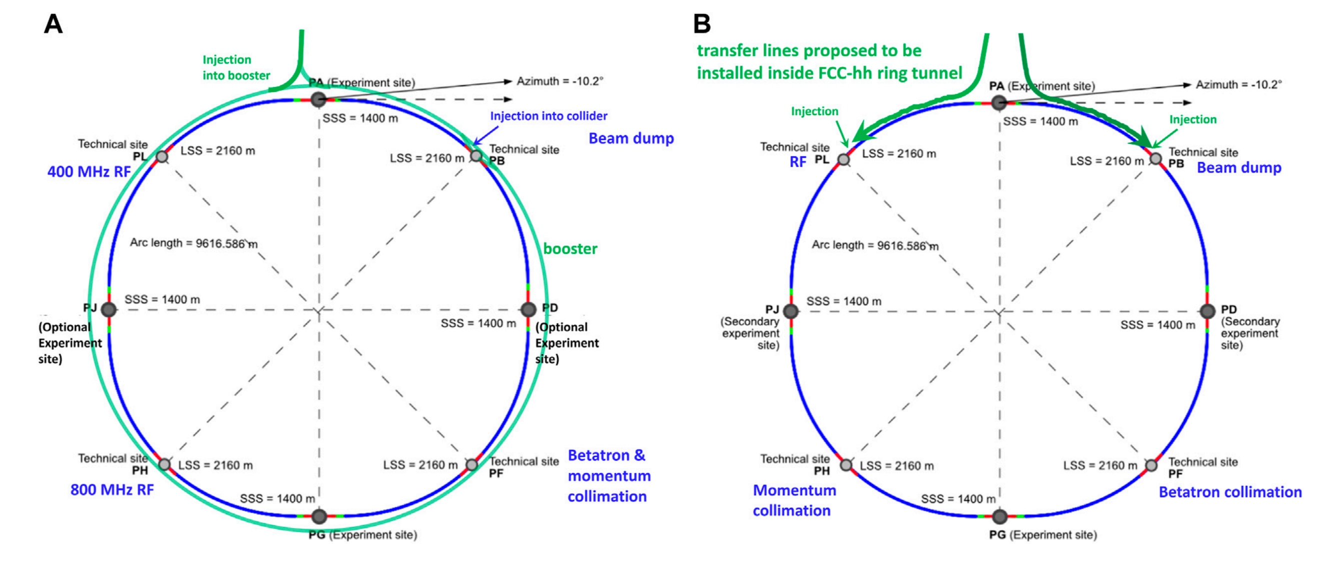

FIGURE 2 | Schematic layout of FCC-ee and its booster **(A)** and of FCC-hh **(B)** with a circumference of 91.2 km and strict four-fold superperiodicity.

Outside the accelerator field, HTS magnet technology could play an important role for fusion research. A number of companies are developing HTS magnets in view of fusion applications. One of these companies is Commonwealth Fusion Systems who in partnership with MIT's Plasma Science and Fusion center are designing SPARC, a compact net fusion energy device [18]. Their magnets are based on second generation ReBCO (Rare-earth barium copper oxide) conductors. Recently they successfully demonstrated a coil with 20 T field [17]. An interesting view on HTS prospects is presented in a Snowmass 2020 Letter of Interest [16], according to which the actual material and process costs of HTS tapes are a small fraction of their current commercial value and that there is a historical link between manufactured volume and price [15].

2 FCC FEASIBILITY STUDY

2.1 European Strategy Update 2020 and Feasibility Study Launch

The 2020 Update of the European Strategy for Particle Physics (ESPPU) [10] 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 [8, 9].

2.2 Collider Design Optimisation

2.2.1 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 91.2 km and only 8 surface sites, and which would be compatible with either 2 or 4 collision points. 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 2** sketches the layouts and possible straight-section functions for both electron-positron and hadron collider.

2.2.2 Parameter Update

Preliminary FCC-ee parameters for the cases of either two or four IPs are shown in **Table 1**, updated parameters for FCC-hh in **Table 2**. In the FCC-ee CDR [26], 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 [23]. This has resulted in a "long" 90° cell, of twice the cell length used for the H and $t\bar{t}$ operation [20]. 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

TABLE 1 | Preliminary key parameters of FCC-ee [20], 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 bunch lengths 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 $t\bar{t}$ operation), with respective voltage strengths as indicated. The beam lifetime shown represents the combined effect of the luminosity-related radiative Bhabha scattering and beamstrahlung, the latter relevant only for ZH and $t\bar{t}$ running (beam energies of 120 and 182.5 GeV).

Running mode	Z	W	ZH	$t\bar{t}$	Z	W	ZH	$t\bar{t}$
Number of IPs	2				4			
Beam energy (GeV)	45.6	80	120	182.5	45.6	80	120	182.5
Bunches/beam	11600	1120	380	44	8800	1120	336	42
Beam current [mA]	1400	135	26.7	5.0	1400	135	26.7	5.0
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	181	19.5	7.5	1.31	181	17.3	7.2	1.25
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 Voltage 400/800 MHz [GV]	0.12/0	1.0/0	2.48/0	4./7.67	0.12/0	1.0/0	2.48/0	4./7.67
Rms bunch length (SR) [mm]	4.35	3.55	2.50	1.67	4.32	3.55	2.50	1.67
Rms bunch length (+BS) [mm]	11.4	7.02	3.75	2.16	15.2	7.02	4.45	2.54
Rms hor. emittance $\varepsilon_{x,y}$ [nm]	0.71	2.17	0.64	1.49	0.71	2.17	0.64	1.49
Rms vert. emittance $\varepsilon_{x,y}$ [pm]	1.42	4.34	1.29	2.98	1.42	4.34	1.29	2.98
Longit. damping time [turns]	1170	216	64.5	18.5	1170	216	64.5	18.5
Vertical IP beta β_y' [mm]	0.8	1.0	1.0	1.6	0.8	1.0	1.0	1.6
Beam lifetime (BS + lum.) [min.]	38	36	10	12	19	20	7	10

TABLE 2 | Key parameters of FCC-hh compared with the HL-LHC and LHC.

	FCC-hh		HL-LHC	LHC
Centre-of-mass energy (TeV)	100		14	14
Dipole field [T]	16–17		8.33	8.33
Circumference [km]	91.2		26.7	26.7
Beam current [A]	0.5		1.1	0.58
Bunch Intensity [10^{11}]	1	1	2.2	1.15
Bunch spacing [ns]	25	25	25	25
Synchr. radiation power [kW]	5400		15	7
SR power/length [W/m/aperture]	32.1		0.33	0.17
Longit. emit. damping time [h]	0.45		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	1000	132	27
Stored energy beam [GJ]	7.8		0.7	0.36

luminosity values per IP are slightly higher for two IPs than for four. 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 in $t\bar{t}$ operation.

2.2.3 Monochromatisation

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 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. 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 [11].

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

MB is the FCC Study Leader, FZ his deputy. They have jointly managed the FCC conceptional design study, since 2014, and are also coordinating the new Feasibility Study. Together, they have defined the structure and contents of this article, and wrote the text.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.