Future Circular Colliders

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In response to a request from the 2013 Update of the European Strategy for Particle Physics, the global Future Circular Collider (FCC) study is preparing the foundation for a next-generation large-scale accelerator infrastructure in the heart of Europe.

The FCC study focuses on the design of a 100-TeV hadron collider (FCC-hh), to be accommodated in a new ∼100 km tunnel near Geneva. It also includes the design of a high-luminosity electron-positron collider (FCC-ee), which could be installed in the same tunnel as a potential intermediate step, and a lepton-hadron collider option (FCC-he). The scope of the FCC study comprises accelerators, technology, infrastructure, detectors, physics, concepts for worldwide data services, international governance models, and implementation scenarios.

Among the FCC core technologies figure 16-T dipole magnets, based on Nb_3Sn superconductor, for the FCC-hh hadron collider, and a highly efficient superconducting radiofrequency system for the FCC-ee lepton collider.

The international FCC study, hosted at CERN, is mandated to deliver a Conceptual Design Report together with a preliminary cost estimate by the time of the next European Strategy Update expected for 2019.

Following the FCC concept—or, more precisely, the preceding "TLEP/VHE-LHC" studies in Europe —IHEP Beijing has initiated the design study for an e^+e^- Higgs factory in China (CEPC), which is to be succeeded by a high-energy hadron collider (SPPC). At present a tunnel circumference of 54 km and a hadron collider c.m. energy of about 70 TeV are being considered.

This article reports the motivation and the present status of the FCC study, design challenges, R&D subjects, as well as the emerging global collaboration.

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1. Motivation

The LHC and its high-luminosity upgrade, the HL-LHC, have an exciting physics programme, which extends through the mid 2030's, i.e. covering the next 20 years.

The original LHC design study was launched in 1983. In other words, it has taken more than 30 years to design, build and commission the LHC and to establish proton-proton collisions at close to design energies. In view of these time scales, it is urgent for the community to start preparing the next accelerator for the post-LHC period, as has clearly been recognized by the 2013 Update of the European Strategy for Particle Physics [1].

A large circular hadron collider seems to be the only approach to reach energy levels far beyond the range of the LHC, during the coming decades, so as to provide access to new particles with masses up to tens of TeV, through direct production, as well as to deliver much increased rates for phenomena in the sub-TeV mass range, with the corresponding greatly improved precision.

The strong physics case for a future higher-energy hadron collider is reflected in an ICFA statement and in the US P5 recommendations from 2014. The latter confirm that "a very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window [10–20 years] ..." [2].

European studies in this context started in 2010–2013, for both lepton [3, 4] and hadron colliders [5, 6, 7], under the names LEP3/TLEP and VHE-LHC, respectively. In early 2014 these efforts were combined and expanded as global Future Circular Collider (FCC) study [8].

Meanwhile, on the other side of the world, also in 2014, the Chinese High Energy Physics Association concluded that a "Circular e^+e^- Circular Higgs Factory (CEPC) plus Super pp Collider (SPPC) is the first choice for China's future high energy physics accelerator" [9].
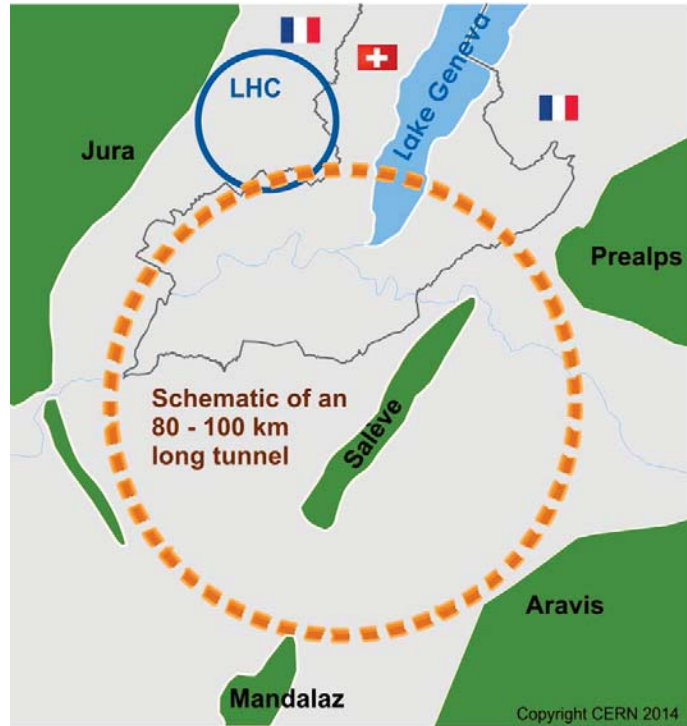
2. Hadron Collider

The long-term goal of the FCC study is a 100-TeV hadron collider (FCC-hh), which determines the infrastructure needs of the new facility. The energy reach of a high-energy hadron collider is simply proportional to the dipole magnetic field and to the bending radius: $E \propto B \times \rho$. Assuming a dipole field of 16 T, expected to be achievable with Nb_3Sn technology, the ring circumference must be about 100 km in order to reach the target value 100 TeV for the centre-of-mass energy.

The development of the FCC-hh can profit from the design studies for previously considered large hadron colliders, such as the ill-fated Superconducting Super Collider (SSC) in Texas [10], and a Very Large Hadron Collider (VLHC) in Illinois [11].

Figure 1 presents a schematic of the FCC tunnel. Prior to FCC-hh installation, this new tunnel could host a high-luminosity circular e^+e^- collider (FCC-ee). Concurrent operation of hadron and lepton colliders is not foreseen, however. In addition, the FCC study considers aspects of pe collisions, as could be realized, e.g., by colliding the electron beam from an energy recovery linac (ERL) with one of the two FCC-hh hadron beams.

The focus of the Chinese project, proceeding in parallel, is on a circular e^+e^- Higgs factory (CEPC), whose tunnel could later host a hadron collider (SPPC) operating concurrently, and also

Figure 1: Schematic of a 100 km tunnel for a Future Circular Collider in the Lake Geneva basin.

Figure 2: Schematic of 50 or 100 km tunnel for a Chinese electron-positron Collider (CEPC) and Super proton-proton Collider in Qinhuangdao [12].

allow for ring-ring hadron-lepton collisions [12]. One of the preferred sites of CEPC is Qinhuang-dao (see Fig. 2). The CEPC tunnel circumference has preliminarily been chosen to be 54 km [13], i.e. substantially smaller than the FCC's. For this reason, the SPPC necessitates a higher dipole field of about 20 T in order to reach *pp* collision energies above 70 TeV in the centre of mass. Such a field cannot be realized with Nb_3Sn coils. Instead the SPPC magnets need to be based on high-temperature superconductor.

Table 1 compares key parameters of FCC-hh and SPPC with those of LHC and HL-LHC. The

Table 1: Key parameters of LHC, HL-LHC, FCC-hh, and SPPC.

parameter	FCC-hh	SPPC	HL-LHC	LHC (*pp*)
c.m. energy [TeV]	100	71.2	14	14
ring circumference [km]	100	54.4	26.7	26.7
arc dipole field [T]	16	20	8.33	8.33
number of IPs	2+2	2	2+2	2+2
initial bunch intensity [10^{11}]	1.0	2.0	2.2	1.15
beam current [A]	0.5	1.0	1.11	0.58
peak luminosity/IP [10^{34} cm^{-1}s^{-1}]	5–29	12	5 (levelled)	1
stored energy per beam [GJ]	8.4	6.6	0.7	$\approx$0.4
arc synchrotron radiation [W/m/aperture]	28.4	$\sim$ 50	0.33	0.17
bunch spacing [ns]	25 or 5	25	25	25
IP beta function $\beta_{x,y}^{*}$ [m]	1.1–0.3	0.75	0.15	0.55
initial normalized rms emittance [μm]	2.2	4.1	2.5	3.75

FCC-hh design considers parameter sets for two phases of operation [14, 15]: Phase 1 (baseline) aims at a peak luminosity of 5×10^{34} cm^{-2}s^{-1}, and should deliver about 250 fb^{-1} per year on average. In Phase 2 (ultimate) the peak luminosity is increased by almost a factor of six, to 2.9×10^{35} cm^{-2}s^{-1}, and the integrated luminosity by a factor of four to 1000 fb^{-1} per year. The daily luminosity evolution for these two phases is illustrated in Fig. 3.
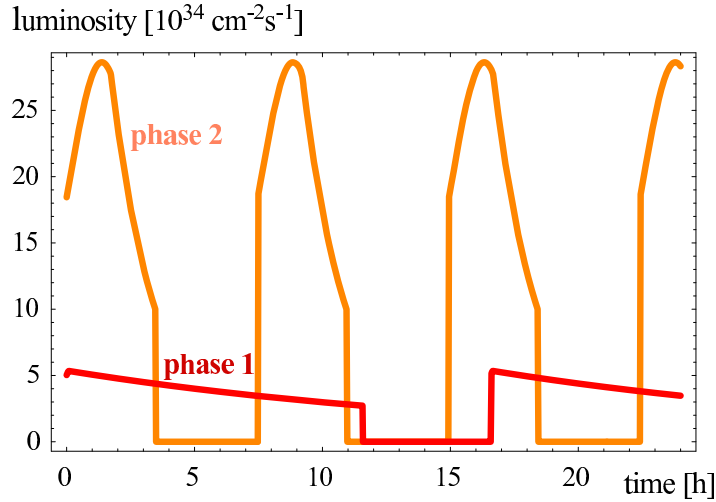
Figure 3: Instantaneous luminosity as a function of time during 24 hours for FCC-hh phases 1 and 2 [15].

The transition from FCC-hh Phase 1 to Phase 2 is realized without any increase in the beam current, primarily by reducing β^{*} from 1.1 to 0.3 m, and by accepting a three times larger beam-beam tune shift ($\Delta Q_{\text{tot}} = 0.03$ instead of 0.01 [14, 15]; the larger value of 0.03 has been demonstrated at the LHC [16]).

The key physics goals of the FCC-hh are the complete exploration of the Higgs boson and a

significant extension, via direct and indirect probes, of the search for physics phenomena beyond the Standard Model [17]. Synthesizing the discussions from several theory workshops, an ultimate integrated luminosity goal of 10–20 ab^{-1} for the FCC-hh seems well justified [17]. This goal can be accomplished over 25 years of operation with the two planned FCC-hh phases.

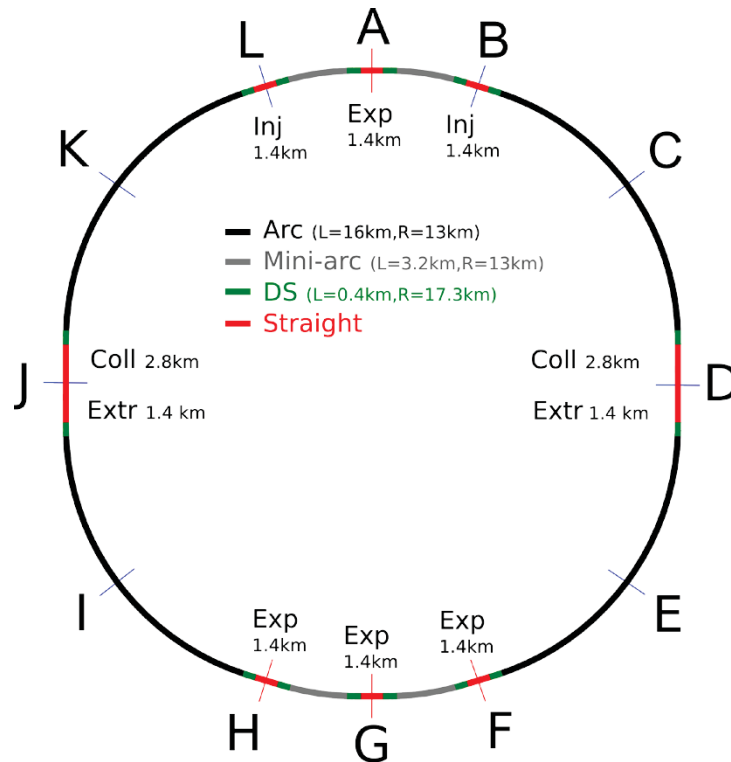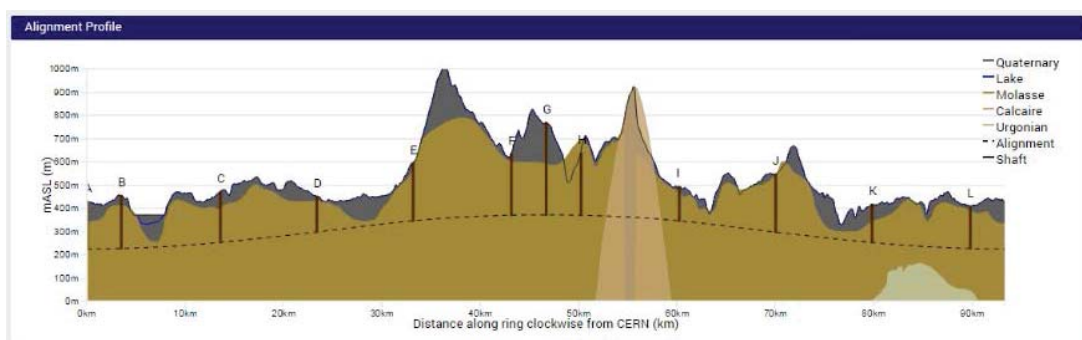**Figure 4:** Preliminary layout of FCC-hh [18].

Figure 5: Example placement of a tunnel with 93 km circumference in the Geneva region, together with geological layers and access shafts; this is a snapshot from a tunnel optimization tool developed in the frame of the FCC study [19].

A preliminary layout for the FCC-hh is shown in Fig. 4. It features two 4.2 km long straight sections for collimation and beam extraction, as well as six shorter 1.4 km long straight sections, four of which may accommodate experiments (two high-luminosity and two special-purpose detectors), while the two others serve for injection.
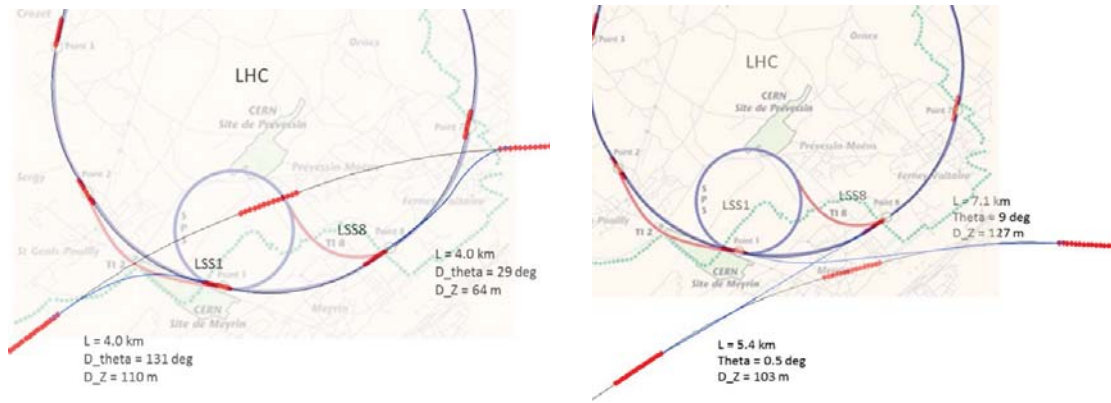
Figure 6: Possible configurations of FCC-hh with LHC used as "High Energy Booster" (HEB) injector [22].

An explorative study of the geology in the Lake-Geneva basin has concluded that a tunnel circumference of 90–100 km would fit the geological situation well (Fig. 5), and that the LHC would be suitable as a potential injector [19]. Using the LHC as "High Energy Booster" for injecting into the FCC-hh also looks feasible from the technical point of view [20, 21]. Two possible configurations of FCC-hh and its LHC injector are illustrated in Fig. 6. For CEPC/SPPC, site investigations are underway in various Chinese provinces, including Qinhuangdao [23].
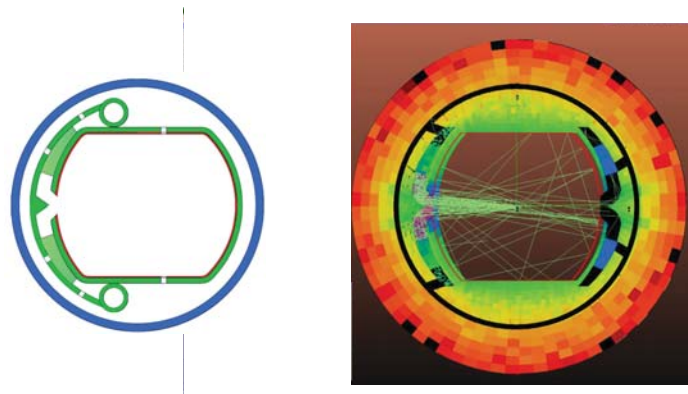
Figure 7: Novel beam-screen design with integrated "folded" antechamber behind a wedge, absorbing most of the synchrotron radiation; asymmetric shape (left) and and alternative symmetric layout together with photon ray tracing (right) [25, 26].

The 50 TeV proton beams of the FCC-hh emit substantial amounts of synchrotron radiation (SR), at the level of 30 W/m/aperture. This SR may be intercepted by a beam screen (BS) held at a higher temperature, T_{BS}, than the cold bore of the magnets, as already is the case for the LHC, where $T_{BS} \approx$ 5–20 K. Contributions to the heat load to be removed by the cryogenic systems include the direct heating of the BS, the cooling of which becomes more efficient at higher T_{BS}, as well as the heat load on the cold bore due to thermal radiation from the BS, which becomes more significant as T_{BS} increases. For FCC-hh, the optimum value of T_{BS}, which minimizes the total electrical power of the cryogenics plants, lies in the range 50–100 K, depending on the cold bore temperature [24]. In addition, the resistive-wall impedance and vacuum stability may affect the final choice of T_{BS}. Novel BS shapes with an integrated compact antechamber, illustrated in

Fig. 7 (left), can absorb most of the photons, thereby facilitating the BS cooling and stabilizing the beam vacuum [25]. A more symmetric version of this BS shape (right picture) completely avoids the pumping slots on the inner part, and, thereby, further lowers the beam impedance [26, 27].

In each of the two FCC-hh beams a significant energy of 8 GJ is stored—about 20 times higher than for the LHC, and equivalent to the kinetic energy of an Airbus A380. This has important consequences for machine protection, collimation, beam injection and transfer. The beam transfer for injection is a particularly critical (and unavoidable) process. The number of bunches which can be transferred together will be limited by the associated protection constraints. It increases for a lower injection energy. At top energy a single impacting bunch can destroy a conventional collimator. One of the possible mitigation schemes is the use of indestructible collimators, e.g. hollow-electron lenses [28].

3. Lepton Collider

With a circumference of about 27 km, LEP, in operation at CERN from 1989 to 2000, reached a maximum c.m. energy of 209 GeV, at a peak SR power around 23 MW. The FCC-ee parameters related to energy range and synchrotron radiation represent rather moderate extrapolations from those of LEP2, while the FCC-ee parameters related to luminosity performance resemble those of the more recent B factories (KEKB, and PEP-II). Importantly, SuperKEKB, soon to be commissioned, will demonstrate many of the FCC-ee high-luminosity ingredients.

FCC-ee collisions over a wide range of beam energies, from 35 GeV to ∼200 GeV, will support extremely high precision tests of the standard model as well as unique searches for rare decays. The FCC-ee physics programme [29] may include: (1) α_{QED} studies (with energies as low as 35 GeV) to measure the running coupling constant close to the Z pole; (2) operation on the Z pole (45.5 GeV), where FCC-ee would serve as a "TeraZ" factory for high precision M_Z and Γ_Z measurements and allow searches for extremely rare decays (also enabling the hunt for sterile right-handed neutrinos); (3) running at the H pole (63 GeV) for H production in the s channel, with mono-chromatization, e.g. to map the width of the Higgs; (4) operation at the W pair production threshold (∼80 GeV) for high precision M_W measurements; (5) operation in ZH production mode (maximum rate of H's) at 120 GeV; (6) operation at and above the $t\bar{t}$ threshold (∼175 GeV); and (7) operation at energies above 175 GeV per beam, should a physics case for the latter be made. Scaling from LEP, at FCC-ee some beam polarization is expected for beam energies up to about 80 GeV [30], permitting a precise energy calibration.

Some of the key elements of the FCC-ee are: (a) a double ring with separate beam pipes and magnetic systems, magnet-strength tapering (see below), and independent optics control for the counter-circulating electron and positron beams, which intersect each other at two interaction points (IPs) under a total crossing angle of 30 mrad; (b) top-up injection based on a booster synchrotron with a cycle period of about 10 s, housed in the same large tunnel, possibly except for bypasses around the particle-physics detectors; and (c) an at least partially local chromatic correction of the final-focus systems.

The range of FCC-ee beam parameters is indicated in Table 2, for simplicity showing numbers of (only) three different operation modes, together with those of CEPC and LEP2. The beam current varies greatly with beam energy, ranging from a few mA, like at LEP2, to 1.5 A, similar

Table 2: Key parameters for FCC-ee, at three beam energies, and for CEPC, compared with those achieved at LEP2. The FCC-ee parameter refer to a crab-waist scheme with constant, energy-independent arc-cell length [31]).

| parameter	FCC-ee			CEPC	LEP2
energy / beam [GeV]	45	120	175	120	105
bunches / beam	60000	1400	98	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity / IP [10^{34} cm^{-2}s^{-1}]	200	9	2	2	0.0012
energy loss / turn [GeV]	0.03	1.67	7.55	3.11	3.34
synchrotron power [MW]	100	100	100	104	22
RF voltage [GV]	0.2	3.6	11	6.9	3.5

to the B factories. As a design choice, the total synchrotron radiation power has been limited to 100 MW, about 4 times the synchrotron-radiation power of LEP2, on all FCC-ee operation points. For a roughly four times larger machine this results in comparable radiation power per unit length. The estimated luminosity numbers scale linearly with the synchrotron-radiation power. Figure 8 displays the expected luminosity per IP as a function of c.m. energy, assuming crab-waist collisions [31] at two interaction points. The anticipated luminosity performance has been confirmed by beam-beam simulations [36, 37]. Recent optics designs for the full ring, with $\beta_y^* = 2$ mm, provide an adequate off-momentum dynamic aperture.
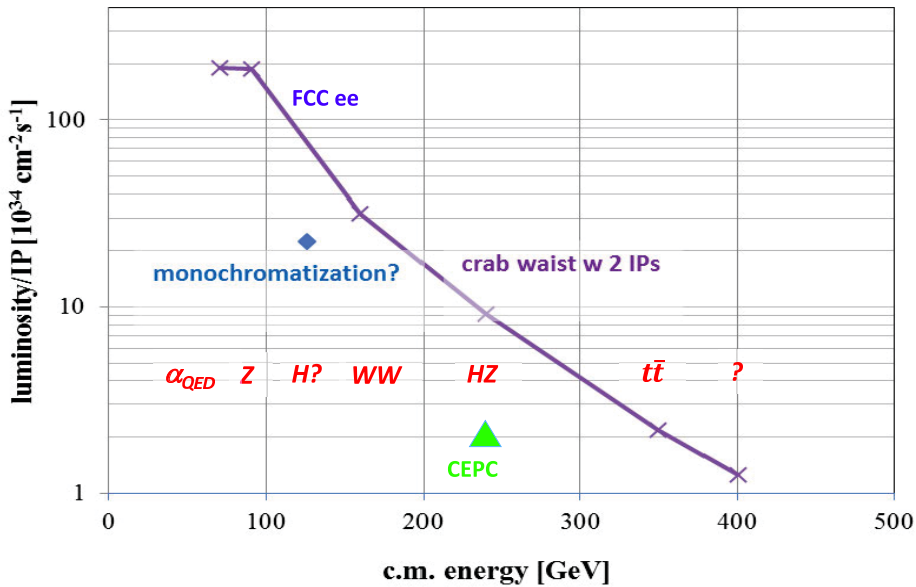
Figure 8: Projected FCC-ee and CEPC luminosity per interaction point (IP) as a function of centre-of-mass energy. cepc

Two optics versions for the final-focus system are illustrated in Fig. 9. Both systems feature a local chromatic correction in the vertical plane, and provide for a crab-waist collision scheme.
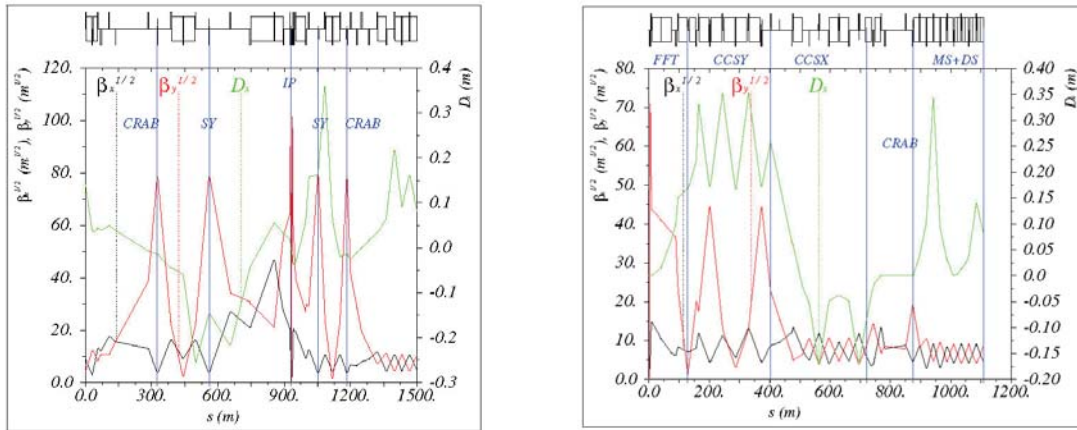
Figure 9: Two alternative optics for the FCC-ee final-focus system, plotted with $\beta_x^* = 1$ m and $\beta_y^* = 2$ mm: asymmetric layout with two sextupoles per side of IP and low photon energies on the incoming side (K. Oide) [34] and symmetric with five sextupoles per side and smaller peak separation, but more energetic photons (A. Bogomyagkov) [35].

The system shown on the left uses a total of two sextupoles only, the second of which cancels the geometric aberrations of the first, and, at reduced strength, also creates a "virtual" crab waist. In this version the horizontal chromaticity of the final focus is corrected by adjusting the strengths of numerous sextupole pairs in the arcs. The system is asymmetric, in that the incoming side includes only weak bending magnets with a critical photon energy below 100 keV on the last 500 m before the collision point, while the outgoing side has stronger dipoles. By contrast, the system on the right is perfectly symmetric, with critical photon energies up to 400 keV. It comprises five sextupoles, two each for vertical and horizontal chromatic correction, and an additional sextupole generating the crab waist. The larger photon energies on the incoming side are a concern as, through neutron production, they may affect the particle-physics detector. On the other hand, an advantage of the symmetric system is that the maximum distance between the two beam lines is reduced, by roughly a factor of two compared with the asymmetric design.

To support the high target luminosity with its associated short beam lifetime, top-up injection is an essential ingredient of the FCC-ee. Promising options to realize this top up include conventional off-momentum injection and multipole-kicker injection [32, 33].

Figure 10 presents one possible FCC-ee collider layout compatible with the geometry of the hadron collider FCC-hh, which features two collision points at opposite positions of the ring. The incoming beam line is bent less than the outgoing beam line in order to minimize the synchrotron radiation emitted in the direction of the experimental detector [38]. This leads to a rather large separation of the inner and outer beam lines on each side of each interaction point (IP). The inner tunnel, corresponding to the hadron collider, as sketched in the figure, might accommodate the detector-bypass for the FCC-ee booster ring. The outer and inner beam lines of the FCC-ee collider cross in the long straight sections half way between the two experiments. In these two long straight sections, the rf systems are located. For $t\bar{t}$ operation, which requires the maximum rf voltage, with only a few tens of bunches, the rf systems are common to the two beams, while at lower beam energies, with high currents and 1000's of bunches, they are separate. For FCC-ee
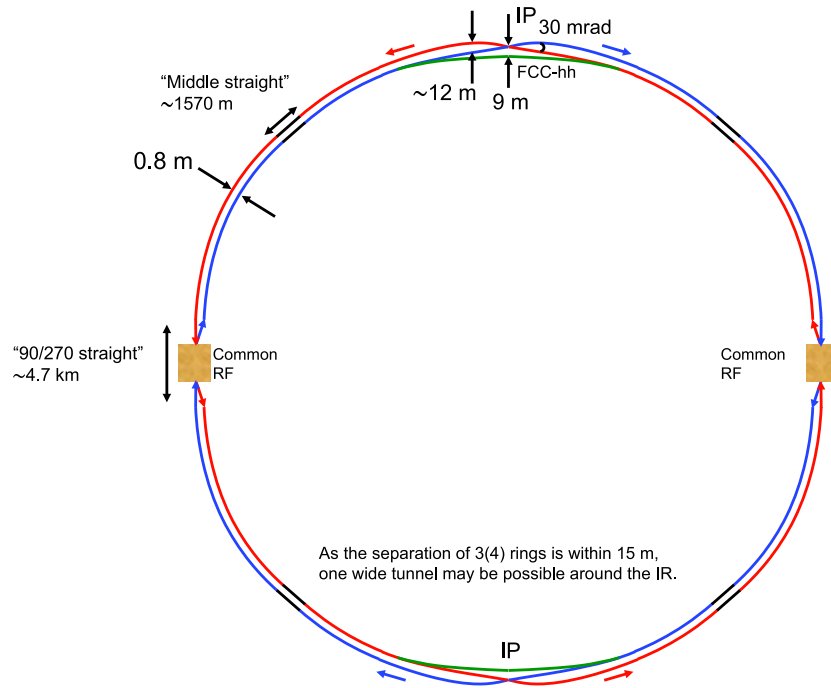
Figure 10: Layout for one possible FCC-ee optics design compatible with the FCC-hh geometry [34].

in $t\bar{t}$ operation the energy variation around the ring is significant. The resulting energy sawtooth induced by synchrotron radiation will be compensated by adjusting the strength of the magnets to the local beam energy. Such a tapering of the dipole and quadrupole magnets can be accomplished through separate powering per half arc, or, more locally, by means of parallel shunts in the magnet-circuits. In the common rf section this type of tapering is not possible, and, here, a simultaneous (symmetric) optics matching for the two beams is performed, similar to the procedure applied for energy recovery linacs [34].
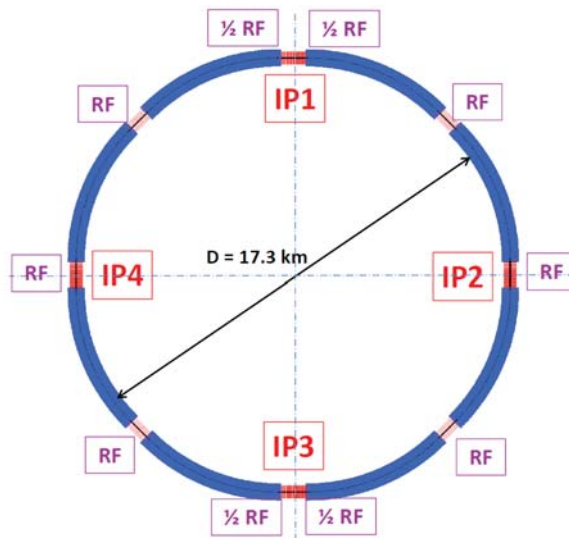
Figure 11: CEPC layout [12].

The layout of CEPC is illustrated in Fig. 11. Electrons and positrons are sharing the same beam pipe, preventing the tapering of the magnets, and, as a result, the rf system is distributed over all 8 straight sections.

4. Lepton-Hadron Option

An FCC-he lepton-hadron collider may consist of a high-current low-emittance electron beam, provided by an energy-recovery linac (ERL), which collides with the hadron beam circulating in one of the two FCC-hh rings, similar to the proposed LHeC [39], where ERL electrons scatter off an LHC hadron beam. Indeed, the same ERL could first be employed for the LHeC and later for the FCC-he. In addition to exploring new regimes of QCD, high parton densities, and deep inelastic scattering, the FCC-he physics programme [39] includes measurements of the Higgs self-coupling, as well as precision measurements of *H-bb* coupling in *WW-H* production.

Differently from the FCC, the CEPC and SPPC rings are supposed to be installed together in the same tunnel, and could, therefore, be operated concurrently. This coexistence allows for high-luminosity electron-proton ring-ring collisions [12].

5. Key Technologies

The key technology R&D for FCC-hh comprises the superconductor (SC) development and the high-field magnet design. The conductor development aims at a 50% higher critical current density than achieved for the HL-LHC (see Fig. 12). As for the magnets themselves, a five-year development programme has been launched at CERN [41, 42] (Fig. 13).
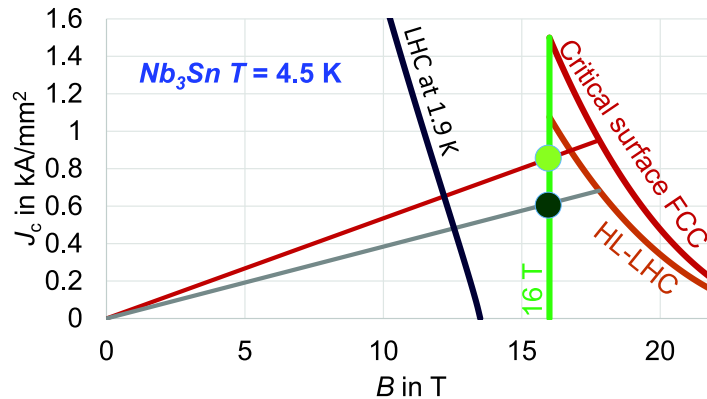
Figure 12: Critical current density versus magnetic field for the HL-LHC Nb_3Sn conductor at 4.5 K (lower red curve), and the FCC-hh target performance (upper red curve) together with the associated 16 T operating points at 10% margin (the black and green circle, respectively) [41, 42]. For completeness, the criticial current of the present LHC Nb-Ti superconductor at 1.9 K is also displayed (the black curve).

Parallel efforts are underway to establish complementary programmes in the United States, Japan, and other countries, in order to explore different SC-wire production lines and different coil layouts (e.g. $\cos\theta$ coil [43], block coil [44], and canted $\cos\theta$ coil [45]). Already in September 2015 a small Nb_3Sn racetrack model at CERN exceeded a field of 16 T at the coil [46]. While the FCC-hh design relies on Nb_3Sn technology, the SPPC's 20 T accelerator dipole magnets must include a
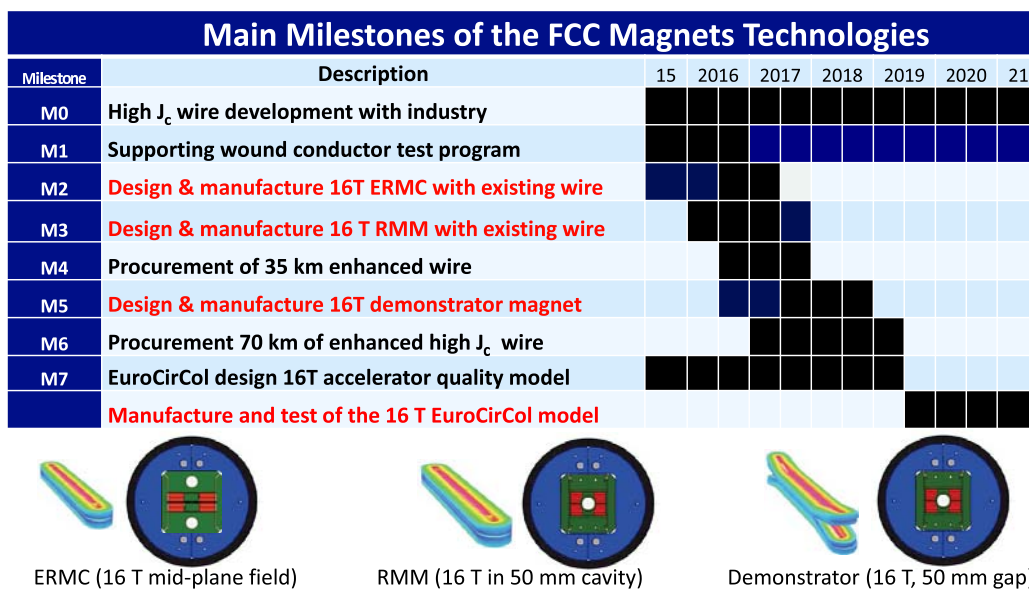
Main Milestones of the FCC Magnets Technologies									
Milestone	Description	15	2016	2017	2018	2019	2020	21
M0	High J_c wire development with industry	■	■	■	■	■	■	■	■
M1	Supporting wound conductor test program	■	■	■					
M2	Design & manufacture 16T ERMC with existing wire	■	■	■					
M3	Design & manufacture 16 T RMM with existing wire		■	■					
M4	Procurement of 35 km enhanced wire		■	■					
M5	Design & manufacture 16T demonstrator magnet		■	■	■				
M6	Procurement 70 km of enhanced high J_c wire			■	■	■			
M7	EuroCirCol design 16T accelerator quality model	■	■	■	■				
	Manufacture and test of the 16 T EuroCirCol model					■	■	■	

ERMC (16 T mid-plane field)   RMM (16 T in 50 mm cavity)   Demonstrator (16 T, 50 mm gap)

Figure 13: Time line of FCC magnet technology program [41, 42].

significant portion of high-temperature superconductor, for which both Bi-2212 or YBCO are being considered [12]. The coil shape also differs in that the SPPC magnets are made from racetrack coils.

An important technological component of the lepton colliders FCC-ee and CEPC is their superconducting radiofrequency (RF) system. The CEPC will operate at moderate beam current and moderate RF voltage, for which a state-of-the-art system appears suitable [12]. By contrast, the RF requirements for FCC-ee [40] are determined by the following two regimes: (1) high gradients for H and $t\bar{t}$ when operating with a few tens of bunches, and (2) high beam loading with currents of about 1.5 A at the Z pole. The FCC R&D aims at a conversion efficiency from wall-plug power to beam power (roughly equal to the SR power) of 70% or higher, e.g. by means of innovative klystron design [47].

6. Collaboration and Time Line

Since February 2014, a total of 63 institutes from 24 countries and four continents have joined the FCC collaboration. The FCC study aims at delivering a conceptual design report and cost estimates for all collider options by the end of 2018. In early 2015 the FCC study was recognized by the European Commission through the funding of the FCC technical design study (EuroCirCol) via the programme of HORIZON2020. The multipurpose laboratory KEK in Japan and sixteen beneficiaries from the European Research Area committed to perform the core of the FCC-hh collider ring design and the 16 T magnet R&D. The four key themes addressed are the arc design (led by CEA Saclay), the interaction-region design (John Adams Institute), the cryo-beam-vacuum system (ALBA-CELLS), and the high-field magnet design (CERN). Four major U.S. laboratories (BNL, NHMFL, FNAL, LNBNL) are associated with EuroCirCol.

7. Conclusions

Preparation for the post-LHC period is now urgently needed. The FCC study heralds a bright long-term future of accelerator-based high energy physics.

A circular hadron collider appears to be the only path available in this century towards direct discoveries at energies of 10's of TeV. FCC-hh profits from, and extends, the new Nb_3Sn technology of the HL-LHC. In addition, it promotes numerous other technological innovations. SPPC requires a novel accelerator-magnet technology based on high-temperature superconductor.

FCC-ee is an attractive intermediate step towards FCC-hh, just as CEPC is towards SPPC. The lepton and hadron collider projects are also highly synergetic: FCC-ee (or CEPC) may share the infrastructure, cryogenics systems, and RF developments with FCC-hh (respectively, SPPC). FCC-ee (CEPC) would also allow for an exciting physics programme during the fabrication of the FCC-hh (SPPC) magnets, and it may provide indications for new physics later to be explored at the FCC-hh (SPPC). FCC-he supports fully complementary physics studies, and could be realized as an extension of the LHeC, while CEPC/SPPC electron-proton collisions can be realized by intersecting these two rings, which will be operating concurrently.

There is a great worldwide interest in the FCC and CEPC/SPPC studies. A global collaboration is being formed and acquiring momentum towards the FCC goals [48]. An internationalization of CEPC/SPPC is also being pursued.

Acknowledgements

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