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Future Circular Collider

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

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. It has, therefore, taken more than 30 years to build and commission the LHC and to establish proton-proton collisions at close to design energies. In view of these time scales, the community must now 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 ranges far beyond the reach 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 increased 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 confirms 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].

2. – Hadron Collider FCC-hh

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.

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.

Table I compares key parameters of FCC-hh with those of LHC and HL-LHC. The FCC-hh design considers parameter sets for two phases of operation [3, 4]: 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 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 ($\Delta Q_{\rm tot} = 0.03$ instead of 0.01 [3, 4]; the larger value of 0.03 was already demonstrated at the LHC [5]).

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 [6]. Synthesizing the discussions from several theory workshops, an ultimate integrated luminosity goal of 10–20 ab^{-1} for the FCC-hh seems well justified [6].

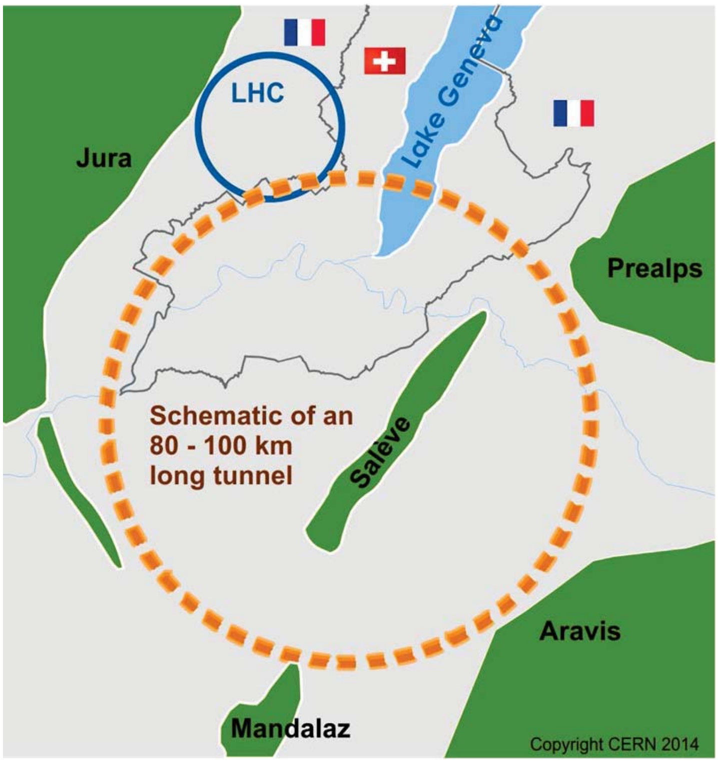

Fig. 1. – Schematic of a 100-km tunnel for a future circular collider in the Lake Geneva basin.

The key technology R&D for FCC-hh comprises the superconductor (SC) development and the high-field magnet design. A five-year magnet development programme has been launched at CERN. Parallel efforts are underway to establish complementary programmes in the United States and in Japan, in order to explore different SC-wire production lines and different magnet design approaches (e.g. cosθ coil, block coil, and canted cosθ coil).

A preliminary layout for the FCC-hh 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.

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, and that the LHC would be suitable as a potential injector [7].

Table I. – *Key parameters of LHC, HL-LHC, and FCC-hh.*

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

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, $T_{\rm BS}$, than the cold bore of the magnets, as already is the case for the LHC, where $T_{\rm BS}$ $\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 $T_{\rm BS}$, as well as the heat load on the cold bore due to thermal radiation from the BS, which becomes more significant as $T_{\rm BS}$ increases. For FCC-hh, the optimum value of $T_{\rm BS}$, which minimizes the total electrical power of the cryogenics plants, lies in the range 50–100 K, depending on the cold bore temperature [8]. In addition, the resistive-wall impedance and vacuum stability may affect the final choice of $T_{\rm BS}$. Novel BS shapes with an integrated compact antechamber can absorb most of the photons, thereby facilitating the BS cooling and stabilizing the beam vacuum [9].

A significant energy of 8 GJ is stored in each of the two FCC-hh beams, with consequences for machine protection, collimation, beam injection and transfer.

3. – Lepton Collider FCC-ee

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, with 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 $\sim$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 [10] may include: (1) $\alpha_{\rm QED}$ 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 ($\sim$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 ($\sim$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 [11], 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 (to compensate for the energy sawtooth due to synchrotron radiation), 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 of about 10 s, housed in the same large tunnel, possibly except for bypasses around the particle-physics detectors; and (c) local chromatic correction of the final-focus systems. The range of FCC-ee beam parameters is indicated in Table II, for simplicity showing numbers of (only) three different operation modes. The beam current varies greatly with beam energy, ranging from a few mA, like at LEP2, to 1.5 A, similar 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, for 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 2 (left picture) displays the expected luminosity per IP as a function of c.m. energy, assuming crab-waist collisions [13] at two interaction points. The expected luminosity performance has been confirmed by beam-beam simulations [15, 16]. Recent optics designs for the full ring, with $\beta_y^* = 2$ mm, provide an adeqate off-momentum dynamic aperture.

The right picture of Fig. 2 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 [17]. 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.

An important technological component of the FCC-ee [18] is its superconducting radiofrequency (RF) system. The RF requirements are characterized by two regimes: (1) high gradients for H and $t\bar{t}$ when operating with a few tens of bunches, and (2)

Table II. – *Key parameters for FCC-ee, at three beam energies, compared with LEP2. The parameter ranges indicated reflect a sensitivity to the number of IPs and to the choice of collision scheme ("baseline" [12]) with varying arc cell length and small crossing angle, or a crab-waist scheme based on a larger crossing angle and constant cell length [13]).*

parameter	FCC-ee			LEP2
energy / beam [GeV]	45	120	175	105
bunches / beam	13000–60000	500–1400	51–98	4
beam current [mA]	1450	30	6.6	3
luminosity / IP [10^{34} cm^{-2}s^{-1}]	21–280	5–11	1.5–2.6	0.0012
energy loss / turn [GeV]	0.03	1.67	7.55	3.34
synchrotron power [MW]	100	100	100	22
RF voltage [GV]	0.2–2.5	3.6–5.5	11	3.5

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 [19].

4. – Lepton-Hadron Option FCC-he

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 [20], 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

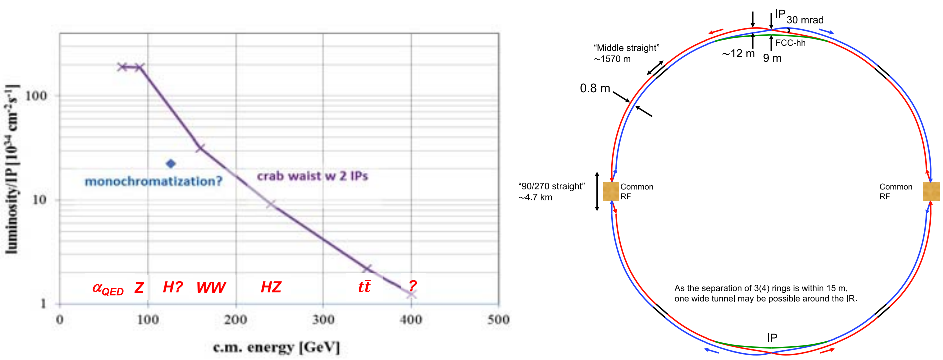

Fig. 2. – Projected FCC-ee luminosity per interaction point (IP) as a function of centre-of-mass energy, for a scenario with crab-waist collisions at two IPs (left). One possible FCC-ee optics design compatible with the FCC-hh layout [14] (right). The rf systems are located in the two long straight sections. They are common to the two beams for $t\bar{t}$ operation, which requires the maximum rf voltage, with only a few tens of bunches, while they are separate at lower beam energies with high currents and 1000's of bunches.

regimes of QCD, high parton densities, and deep inelastic scattering, the FCC-he physics programme [20] includes measurements of the Higgs self-coupling, as well as precision measurements of H-bb coupling in WW-H production.

5. – Collaboration and Time Line

Since February 2014, a total of 62 institutes from 23 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.

6. – 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. FCC-ee is an attractive intermediate step towards FCC-hh, as well as highly synergetic: It may share the infrastructure, cryogenics systems, and RF developments with FCC-hh. FCC-ee would also allow for exciting physics explorations while the FCC-hh magnets are being fabricated, and it may provide indications for new physics later to be explored at the FCC-hh. FCC-he has a fully complementary physics programme, and could be realized as an extension of the LHeC.

There is a great worldwide interest in the FCC study. A global collaboration is being formed and acquiring momentum towards the FCC goals.

* * *

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