STATUS OF THE FUTURE CIRCULAR COLLIDER STUDY*

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Abstract

Following the 2013 update of the European Strategy for Particle Physics, the international Future Circular Collider (FCC) Study has been launched by CERN as host institute. Its main purpose and long-term goal is to design an energy-frontier hadron collider (FCC-hh) with a centre-of-mass energy of about 100 TeV in a new 80–100 km tunnel. The FCC study also includes the design of a 90–350 GeV high-luminosity lepton collider (FCC-ee) installed in the same tunnel, serving as Higgs, top and Z factory, as a potential intermediate step, as well as an electron-proton collider option (FCC-he). The physics cases for such machines are being assessed and concepts for experiments will be developed by the end of 2018, in time for the next update of the European Strategy for Particle Physics.

This overview summarizes the status of machine designs and parameters, and it discusses the essential technical components being developed in the frame of the FCC study. Key elements are superconducting accelerator-dipole magnets with a field of 16 T for the hadron collider and high-power, high-efficiency RF systems for the lepton collider. In addition, the unprecedented beam power presents particular challenges for the hadron collider. First conclusions from geological investigations and implementation studies are available. We report the status of the FCC collaboration and outline the further planning.

INTRODUCTION

The Large Hadron Collider (LHC) presently in operation at CERN, and its high-luminosity upgrade, the HL-LHC, have an exciting physics program, which extends through the mid 2030's, i.e., covering the next 20 years. From the initial proposal in 1983, it has taken more than 30 years to design, build and fully commission the LHC. In view of such time scales, it is urgent for the community to start preparing the next accelerator for the post-LHC period.

European studies for a large post-LHC physics-frontier machine began in 2010–2013, for both lepton and hadron colliders (at the time called LEP3/TLEP and VHE-LHC, respectively). In response to the 2013 Update of the European Strategy for Particle Physics [1]. in early 2014 these efforts were combined and expanded as global Future Circular Collider (FCC) study [2, 3], hosted by CERN.

FCC STUDY SCOPE & TIME LINE

A large circular hadron collider seems to be the only approach to reach, during the coming decades, energy levels far beyond the range of the LHC. The long-term goal and focus of the FCC study [3], therefore, 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 center-of-mass energy.

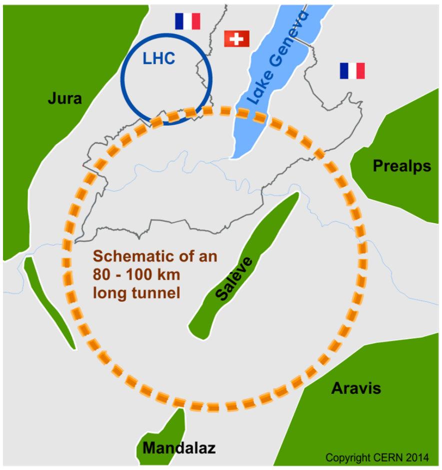

Figure 1: Schematic of a 100 km tunnel for a Future Circular Collider in the Lake Geneva basin.

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 with one of the two FCC-hh hadron beams. The FCC study also includes the design of a High-Energy LHC (HE-LHC) realized by installing 16 T magnets developed for FCC-hh in the existing 27 km LHC tunnel, so as to approximately double the energy of the LHC.

The FCC study has launched international R&D efforts on key enabling technologies through dedicated collaborative programmes, e.g. on high-field magnets, advanced cryogenics, superconducting radiofrequency systems (e.g. thin film coating) and highly efficient radiofrequency power sources. The FCC R&D includes the design of a 100 km tunnel infrastructure in the Geneva area, linked to the existing CERN accelerator complex, as requested by the European Strategy. The FCC study further explores the particle-physics opportunities and discovery potentials for the hadron, lepton and lepton-hadron colliders. The results of these physics studies drive the collider performance targets (e.g. luminosity, energy, lepton polarization). In addition, the FCC study is developing experiment concepts for the three types of colliders, addresses machine detector interface, and defines further R&D needs for detector technologies. Last not least,

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the FCC study aims at establishing an overall cost model for the various collider scenarios — including infrastructure and injectors —, at formulating global realization concepts, and at forging early partnerships with key industries.

Figure 2 shows the FCC time line in relation to previoun collider projects at CERN.

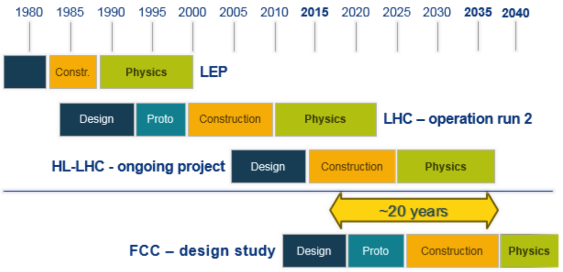

Figure 2: Time line of CERN circular colliders with the Future Circular Collider (FCC) as the next step.

MACHINE DESIGNS

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. 3). From the technical point of view, the LHC would be suitable as a potential injector [4], with an injection energy around 3.3 TeV [5–7]. Two possible configurations of the FCC-hh and its LHC injector are illustrated in Fig. 4. A 100 km tunnel version intersecting the LHC is now being studied in greater detail. Injecting into the FCC-hh from a new fast-cycling superconducting machine located in the SPS tunnel would also be permitted by the chosen configuration. In this case the injection energy would be about 1.5 TeV.

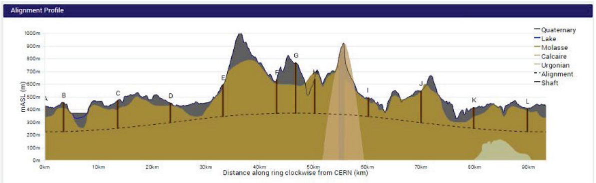

Figure 3: Example placement of a tunnel with a 93 km circumference in the Geneva region, together with geological layers and access shafts; obtained from a tunnel optimization tool developed in the frame of the FCC study [4].

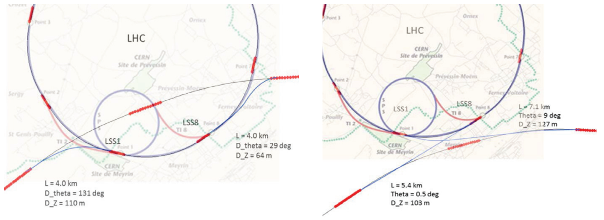

Figure 4: Two configurations of FCC-hh and LHC [7].

Common layouts and consistent optics footprints for the hadron and lepton colliders have been established. Figure 5 shows two main interaction points located at positions ‘A’ and ‘G’, for both machines.

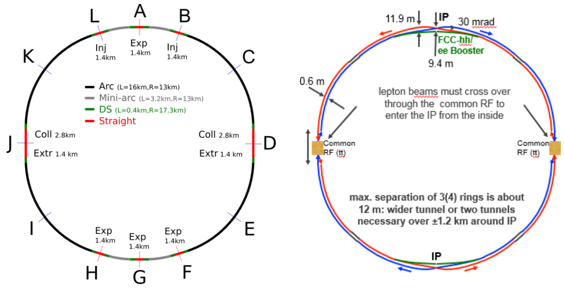

Figure 5: Layouts of hadron (left) and lepton collider (right). The optics of FCC-ee [8] was designed so as to exactly agree with the footprint of the hadron collider [9], except for the intreaction regions, where the collision points are offset by about 9 m, and only the lepton injector (top-up booster) follows the path of the protons.

Table 1 compares key parameters of FCC-hh and HE-LHC with those of LHC and HL-LHC. The FCC-hh design considers parameter sets for two phases of operation [11, 12]: 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. 6.

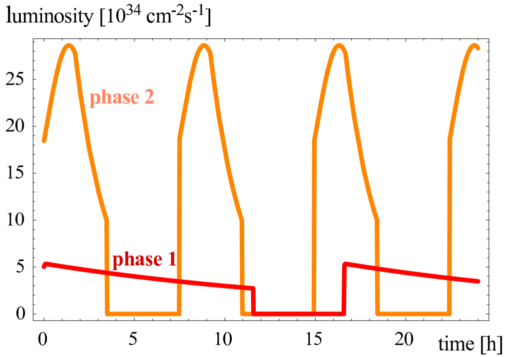

Figure 6: Instantaneous luminosity as a function of time during 24 hours for FCC-hh phases 1 and 2 [12].

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 [11, 12]; the larger value of 0.03 has been demonstrated at the LHC [13]).

The total integrated luminosity of FCC-hh over 25 years operation is estimated as about 20 ab^{-1} per experiment, which matches the particle-physics goals [14]. The FCC-hh physics programme covers standard-model processes, Higgs physics and electroweak symmetry breaking studies, phenomena beyond the standard model, physics with heavy ions, and physics opportunities at the FCC-hh injectors [14].

A full ring optics design is available for the FCC-hh, comprising arcs, intereaction regions, injection region combined with radiofrequency section, momentum collimation, betatron collimation, and extraction. Example optics segments are displayed in Fig. 7.

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

parameter	FCC-hh phase 1	FCC-hh phase 2	HE-LHC	HL-LHC	LHC (*pp*)
c.m. energy [TeV]	100	100	25	14	14
ring circumference [km]	100	100	26.7	26.7	26.7
arc dipole field [T]	16	16	16	8.33	8.33
initial bunch intensity [10^{11}]	1.0	1.0 (0.2)	2.5	2.2	1.15
beam current [A]	0.5	0.5	1.27	1.11	0.58
peak luminosity/IP [10^{34} cm^{-1}s^{-1}]	5	30	34	5 (lev.)	1
events / crossing	170	1020 (204)	1070	135	27
stored energy per beam [GJ]	8.4	8.4	1.4	0.7	0.36
arc synchrotron radiation [W/m/ap.]	28.4	28.4	4.1	0.35	0.18
bunch spacing [ns]	25	25 (5)	25	25	25
IP beta function $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	0.15	0.55
initial normalized rms emittance [μm]	2.2	2.2 (0.45)	2.5	2.5	3.75
transv. emittance damping time [h]	1.1	1.1	4.5	25.8	25.8

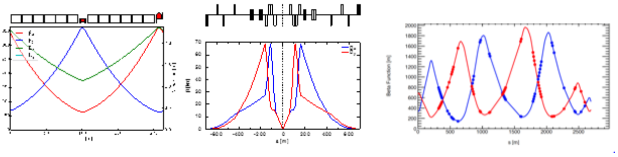

Figure 7: Optics for the FCC-hh arcs (left), interaction region (center) and betatron collimation (right) [9].

In Table 2 key parameters for the electron-positron collider FCC-ee [10] are compared with those of LEP2. The FCC-ee design exploits the lessons and recipes from past and present colliders (synchrotron radiation, high beam current, crab waist, ultralow β^*_y, polarization. etc.), as is sketched in Fig. 8. The present optics design of FCC-ee achieves the required performance for all four target energies [8]. The interaction-region optics and geometry are asymmetric (Fig. 9), to limit the amount and energy of synchrotron-radiation photons emitted towards the physics detector. Sufficient dynamic aperture and a ±2% off-momentum acceptance are obtained at all working points.

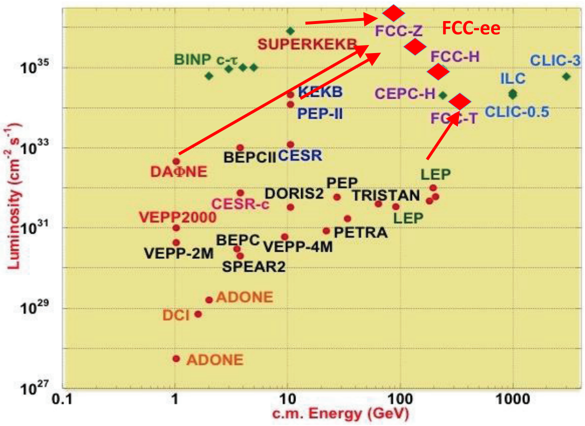

Figure 8: Luminosity as a function of c.m. energy for past, present and future e^+e^- colliders (M. Biagini).

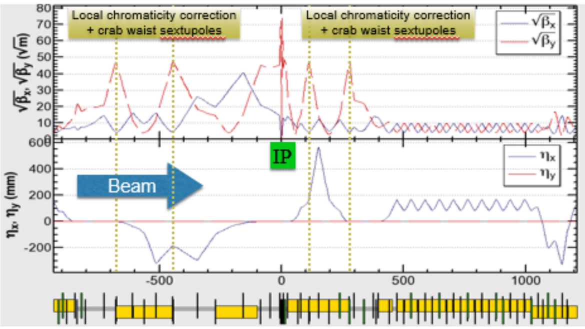

Figure 9: Asymmetric final-focus optics for the FCC-ee interaction region [8].

TECHNOLOGIES

At the FCC-hh an unprecedentedly large synchrotron radiation power of about 2.3 MW per beam is emitted in the cold arcs. To efficiently absorb this synchrotron radiation, a new beam screen, inserted inside the cold bore of the magnets, is proposed [16, 17]. As is shown in Fig. 10, it features two slits with an integrated wedge such that most primary photons are deflected upward and downward behind the beam screen, where pumping holes are placed. Very few photoelectrons are generated inside the beam screen proper. First FCC-hh beam screen prototypes have been fabricated. Their cryogenic and vacuum behaviour will be tested at the synchrotron light source ANKA at KIT Karlsruhe, in the presence of synchrotron radiation resembling the conditions expected in the FCC-hh arcs. At the FCC-hh, the beam screen temperature will be raised, from 5–20 K at the LHC to 40–60 K. The higher temperature improves the Carnot efficiency and, thereby, facilitates the removal of the synchrotron radiation heat load. The effect of beam-screen temperature on total refrigerator power is illustrated in Fig. 11.

The key technology R&D for the FCC-hh comprises superconductor (SC) development and high-field magnet design. Nb_3Sn is one of the major cost & performance factors for FCC-hh and requires highest attention. The main development goals until 2020 are: (1) an increase of the critical current density J_c (at 16 T, 4.2 K) to above 1500 A/mm^2

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Table 2: Key parameters for the FCC-ee, at three beam energies, compared with those achieved at LEP2. The FCC-ee parameters refer to a crab-waist scheme [15], with constant, energy-independent arc-cell length.

parameter	FCC-ee					LEP2
circumference	100					26.7
energy / beam [GeV]	45.6		80	120	175	105
bunches / beam	30180	91500	5260	770	78	4
beam current [mA]	1450		152	30	6.6	3
luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	207	90	19	5.1	1.3	0.0012
energy loss / turn [GeV]	0.03		0.3	1.67	7.55	3.34
total synchrotron radiation power [MW]	100		100	100	100	22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	3.5
rms horizontal emittance ε_x [nm]	0.2	0.1	0.26	0.6	1.3	22
rms vertical emittance ε_y [pm]	1	1	1	1	2.5	250
horizontal IP beta function β_x^* [m]	0.5	1	1	1	1	1.2
vertical IP beta function β_y^* [mm]	1	2	2	2	2	50
rms bunch length (SR) σ_z [mm]	1.2	1.6	2.0	2.0	2.1	12
full crossing angle θ_c [mrad]	30	30	30	30	30	0
longitudinal damping time [turns]	1320		243	72	23	31
beam lifetime from radiative Bhabha scattering [min.]	94	185	90	67	57	434

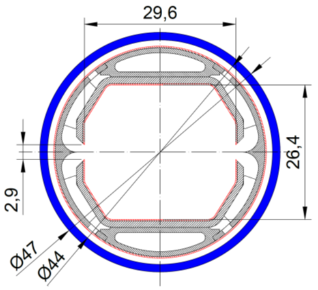

Figure 10: FCC-hh beam-screen design with integrated “folded” antechamber [16, 17].

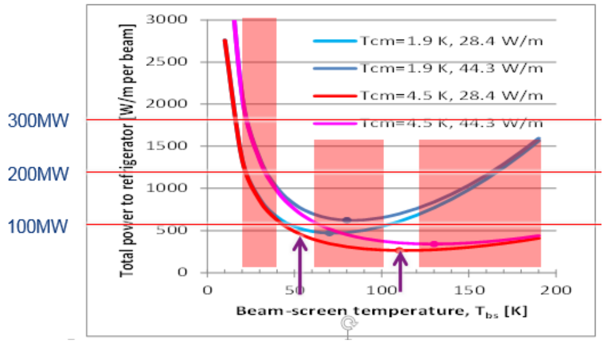

Figure 11: Total cryogenics power in units of Watt per meter per beam as a function of beam-screen temperature, for two different temperatures of the magnet cold bore and two different synchrotron-radiation power loads [18]. Regions excluded by vacuum considerations are shaded in red.

i.e. a 50% rise with respect to the HL-LHC wire [19, 20] (see Fig. 12), (2) a reference wire diameter of 1 mm, and (3) preparing the ground for large scale production and cost reduction.

To accompish these goals, various international collaborations have been set up. The FCC Nb_3Sn conductor program has started with the procurement of state-of-the-art conductor for prototyping from European (Bruker) and US industry (OST). FCC conductor development is planned, or already underway, in Japan, Russia, Korea, and Europe.

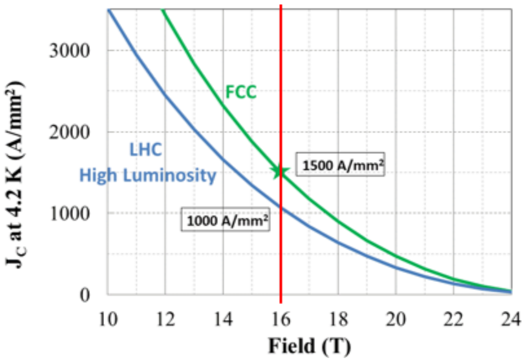

Figure 12: Critical current versus magnetic field for the HL-LHC Nb_3Sn conductor at 4.5 K, and the FCC-hh target curve together with the planned operating point [19, 20].

A new US DOE magnet development program [21] directs joint activities of US industry (OST) and US laboratories. A project ‘EuroCirCol’, supported in the frame of the EU’s HORIZON2020 programme, contributes to core elements of the FCC-hh hadron collider (optics, cryo-vacuum system, and 16 T dipole design including a construction folder for demonstrator magnets). Four different design approaches for 16 T dipole magnets are shown in Fig. 13. In Europe three of these designs are pursued by EuroCirCol, the fourth one by PSI/Switzerland. A down-selection of options by mid 2017 will allow for detailed design work. This will be followed by model production (2018–2022) and prototype production (2023–2025). A parallel US magnet program advances the cosine theta and canted cosine theta designs.

The radiofrequency (RF) system for the lepton collider must cover a large range of operation parameters, ranging

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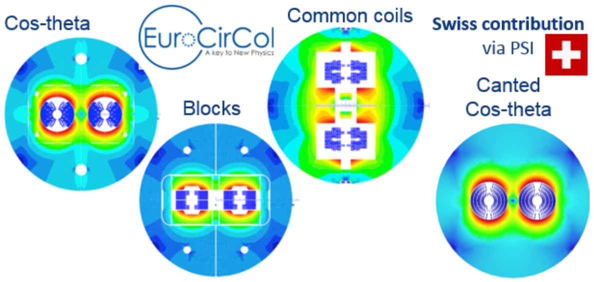

Figure 13: Four different design concepts for 16 T magnets.

from Ampere beam currents to high accelerating gradients. The RF voltages and beam currents span more than two orders of magnitude. No well-adapted single RF system solution is available to satisfy all the requirements. Instead, two separate sytems are being considered [22, 23], as is illustrated in Fig. 14. For both FCC-ee Z operation (45.6 GeV/beam with RF gradients of a few MeV/m) and the hadron collider FCC-hh, 400 MHz single-cell cavities are preferred. For these cavities, the baseline choice is Nb/Cu at 4.5 K. This development also has ample synergies with HL-LHC and HE-LHC. The associated R&D must address the power coupling for up to 1 MW/cell, and HOM power handling (damper, cryomodule). For the higher-energy operation modes of FCC-ee (ZH, $t\bar{t}$ and WW), 400 or 800 MHz multi-cell cavities would be suitable. Two possible options for these cavities are either 400 MHz of Nb/Cu at 4.5 K, or an 800 MHz bulk Nb system at 2 K. The pertinent R&D focuses on high Q_0 cavities, coating, and, in the long term, on Nb_3Sn-like components.

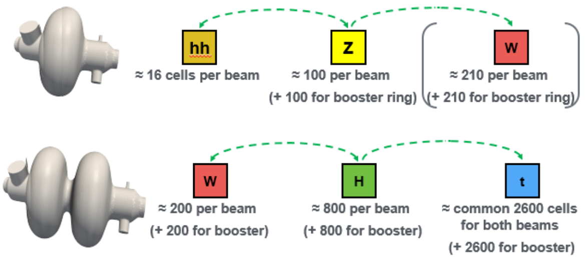

Figure 14: Single- and multi-cell SC cavities for different FCC collider branches [22, 23].

ORGANISATION & COLLABORATION

Since February 2014, a total of 88 institutes from 28 countries and four continents have joined the FCC collaboration, including BINP Novosibirsk, JINR Dubna, MEPHi Moscow, and NUST MISiS Moscow. The latest status can be found on the FCC web site [3]. One major FCC conference — the "FCC Week" — is being organized every year. The next one will be held in Berlin, Germany, from 29 May to 2 June 2017 [24].

SUMMARY

The FCC study is advancing well towards the delivery of a Conceptual Design Report for end of 2018. Consolidated parameter sets exist for both hadron (FCC-hh) and lepton machines (FCC-ee). These are supported by complete baseline optics designs, assessment of beam dynamics, and estimated performance compatible with the physics requirements. A first round of geology, civil engineering and infrastructure studies have been completed. Superconductivity is the key enabling technology for FCC. The Nb_3Sn program towards 16 T model magnets is of prime importance for the FCC-hh and the development of high-efficiency superconducting radiofrquency systems is critical for FCC-ee. International collaboration is essential to advance on all the challenging subjects, and the community is warmly invited to join the FCC efforts.

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