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Future Circular Collider

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Status and Challenges of the Future Circular Collider Study

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STATUS AND CHALLENGES 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, to design an energy frontier hadron collider (FCC-hh) in a new 80-100 km tunnel with a centre-of-mass energy of about 100 TeV, an order of magnitude above the LHC's, as a long-term goal. The FCC study also includes the design of a 90-350 GeV high-luminosity lepton collider (FCC-ee) fitting 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 will be assessed, concepts for experiments be worked out, and complete accelerator designs be developed in time for the next update of the European Strategy for Particle Physics by the end of 2018.
Beside superconductor improvements and high-field magnet prototyping, the FCC R&D program includes the advancement of SRF cavities based on thin film coating, the development of highly efficient RF power sources, the beam dump technology required for disposing a beam with a stored energy of almost 10 GJ, radiation shielding concepts, performance models, a reliability analysis, and a global implementation strategy.
As of January 2016, 70 institutes from around the world have joined the FCC collaboration. Part of the global study is co-funded by the European Commission under a HORIZON 2020 grant (“EuroCirCol”), which addresses the core aspects of the hadron collider design.

KEYWORDS
Storage Ring, Collider, High-Field Magnets, Superconducting Radiofrequency System, Collimation

1. MOTIVATION

The LHC and its high-luminosity upgrade, the HL-LHC, have an exciting physics program, which extends through the mid 2030's, as is illustrated in Fig. 1.

The design of the LHC was launched in 1983. It has taken more than 30 years to develop, 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 era, as has clearly been recognized by the 2013 Update of the European Strategy for Particle Physics [1].

Another, even larger 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 obtain much increased rates for phenomena in the sub-TeV mass range, with the corresponding greatly improved precision.

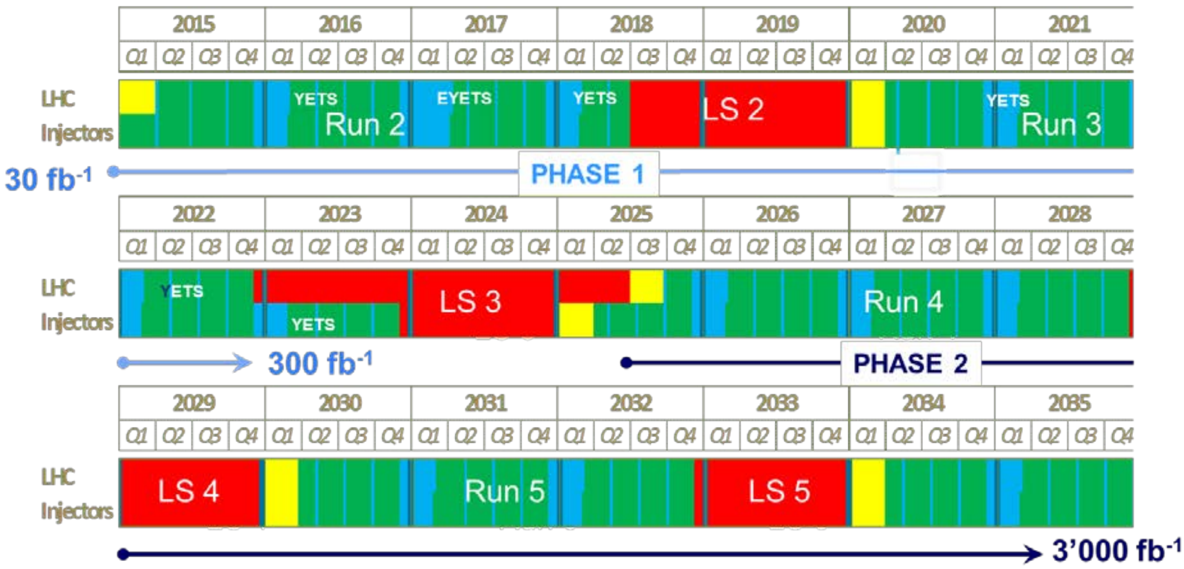

Figure 1. LHC roadmap - schedule through 2035.

The strong physics case for a future higher-energy hadron collider is reflected 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 [3-7] and hadron colliders [8-10], 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 [11]. 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" [12]

2. HADRON COLLIDER

The long-term goal of the FCC study is a 100-TeV hadron collider (FCC-hh). This goal 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: $E \propto B\rho$. 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 results of earlier design studies for previously considered large hadron colliders, such as the ill-fated Superconducting Super Collider (SSC) in Texas [13], and a Very Large Hadron Collider (VLHC) in Illinois [14]. Importantly, the HL-LHC – to be implemented during the LHC's Long Shutdown 4 (LS4) around 2025 – will contain a number of novel Nb_3Sn quadrupole and dipole magnets, along with several other innovative technologies (compact SC crab cavities, electron lenses, etc.). The HL-LHC will, thereby, be an important stepping stone towards the FCC.

Figure 2 presents a schematic of the FCC tunnel. As mentioned above, 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.

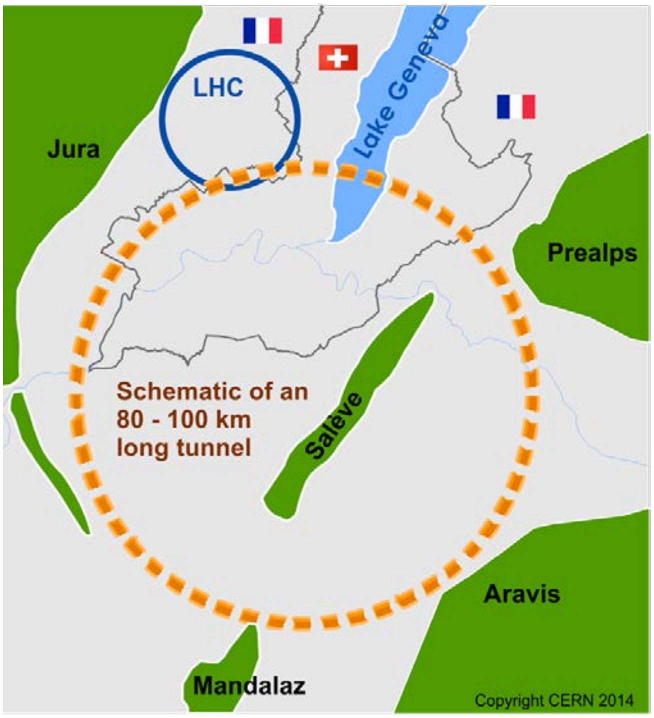

Figure 2. Schematic of a 100 km tunnel for a Future Circular Collider in the Lake Geneva basin.

The focus of the Chinese project is on a circular e^+e^- Higgs factory (CEPC), whose tunnel could later host a hadron collider (SPPC) operating concurrently, and also allow for ring-ring hadron-lepton collisions [15]. The CEPC tunnel circumference of 54 km [16] is substantially smaller than the FCC's. For this reason, the SPPC necessitates a dipole field of about 20 T to reach pp collision energies above 70 TeV in the centre of mass, and its magnets must be based on high-temperature superconductor.

Table I compares key parameters of FCC-hh and SPPC with those of LHC and HL-LHC. The FCC-hh design considers parameter sets for two phases of operation [17,18]. Phase 1 (baseline) aims at a peak luminosity of $5x10^{34}$ $cm^{-2}s^{-1}$, and should deliver about 250 fb^{-1} per year on average. In Phase 2 (ultimate), thanks to a reduced β* and a higher beam-beam tune shift, the peak luminosity increases by almost a factor of six, to $2.9x10^{35}$ $cm^{-2}s^{-1}$, 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.

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

Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
no. of interaction points	2 main & 2 others		2	2 main & 2 others	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	29	12	1	5
events/bunch crossing	170	990 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchrotron radiation [W/m/aperture]	30		58	0.2	0.35

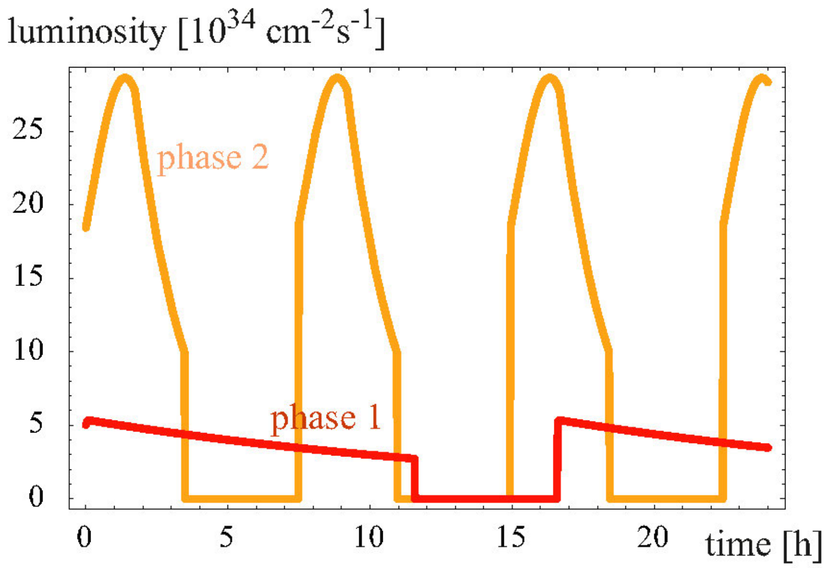

Figure 3. Instantaneous luminosity versus time during 24 hours for FCC-hh phases 1 and 2 [18].

For the FCC-hh proton beams the transverse emittance damping time due to synchrotron radiation is about 1 hour. The strong damping effect needs to be counteracted by controlled noise excitation, lest the beam-beam tune shift (or the event pile up) become unacceptably high, in particular for phase 1.

Similar to the LHC, the FCC-hh can also be operated as a heavy ion collider [19]. Synchrotron radiation damping, scaling as Z^5/m_A^4 (with Z the atomic number and m_A the atomic mass), for lead ions is about twice as fast as for protons. In addition, *Pb* nuclei are accompanied by intense fluxes of high energy quasi-real photons, resulting in powerful secondary beams, extreme luminosity burn-off, and complicated collimator interaction. Stronger intra-beam scattering ultimately limits the minimum acceptable emittance of the FCC-hh heavy-ion beams.

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 in e^+e^- collisions, at a peak total synchrotron-radiation (SR) power around 23 MW. The FCC-ee energy range and synchrotron radiation represent rather moderate extrapolations from those of LEP2, while the targeted FCC-ee luminosity performance resembles more those of the recent B factories (KEKB, and PEP-II). Importantly, SuperKEKB, soon to be commissioned, will demonstrate the feasibility of many of the FCC-ee high-luminosity ingredients.

FCC-ee collisions over a wide range of beam energies, from 35 GeV to ~200 GeV per beam, will support precision tests of the standard model as well as unique searches for rare decays. The FCC-ee physics program [20] includes: (1) operation on the Z pole (45.5 GeV/beam), 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); (2) operation at the W pair production threshold (~80 GeV/beam) for precise M_W measurements; (3) operation in ZH production mode (maximum rate of H's) at 120 GeV/beam; and (4) operation at and above the $t\bar{t}$ threshold (~175 GeV/beam). Scaling from LEP, some beam polarization is expected up to about 80 GeV/beam [21], permitting a precise energy calibration on the Z pole and at the WW threshold.

Some of the key elements of the FCC-ee accelerator are: (a) a double ring with separate beam pipes and magnetic systems for electrons and positrons, 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) strength tapering of the separated magnet systems (following the local beam energy) allowing the radiofrequency (RF) systems to be concentrated in only one or two straight sections; (c) top-up injection based on a full-energy booster synchrotron with a cycle period of about 10 s, housed in the same large tunnel; and (d) a (partial) local chromatic correction of the final-focus systems. For CEPC, electrons and positrons are sharing the same beam pipe, preventing the tapering of the magnets. As a result, the CEPC RF system is distributed over 8 straight sections.

The range of FCC-ee beam parameters is indicated in Table II, for simplicity showing numbers of (only) three different operation modes, together with those of CEPC and actual numbers from LEP2. The FCC-ee 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 is 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 yields a comparable radiation power per unit length.

Table II. Key parameters for FCC-ee, at three beam energies, and for CEPC, compared with those achieved at LEP2. The FCC-ee parameters refer to a crab-waist scheme with constant, energy-independent arc-cell length [22].

Parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	45	120	175	120	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	68	5	1.3	2.0	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5

4. R&D TOPICS

The 100-TeV hadron collider (FCC-hh) calls for key technology R&D on superconductor (SC) development and high-field magnet design. The FCC conductor development aims at a 50% higher critical current density than achieved for the HL-LHC. For the 16 T magnets themselves, a five-year development program has been launched at CERN [23,24]. Parallel efforts are underway to establish complementary programs 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 [25], block coil [26], and canted $\cos\theta$ coil [27]). Already in September 2015 a small Nb_3Sn racetrack model at CERN exceeded a field of 16 T at the coil [28]. While the FCC-hh design relies on Nb_3S technology, the SPPC's 20 T accelerator dipole magnets must include a significant portion of high-temperature superconductor, for which both Bi-2212 and YBCO are being considered [15]. The coil shape also differs in that the SPPC magnets are made from racetrack coils, an option not being considered for the FCC-hh.

An important technological component of the two lepton colliders, FCC-ee and CEPC, is their superconducting RF system. The CEPC will operate at moderate beam current and moderate RF voltage, for which a state-of-the-art system appears suitable [15]. By contrast, the RF requirements for FCC-ee [29] 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.

For the FCC, cost is of paramount importance. To minimize the cost of construction and operation, new fabrication modes of key components will be explored (e.g., additive manufacturing of the vacuum chamber), as will be new materials (e.g. for collimators or beam screen), better cryogenics (more efficient cryogen mixtures), and automated maintenance concepts.

The 50 TeV proton beams of the FCC-hh will emit significant amounts of synchrotron radiation (SR), at the level of 30 W/m/aperture, inside the cold arcs. This SR can be intercepted by a beam screen (BS) held at a higher temperature, T_{BS}, than the cold bore of the magnets. Such a concept is already applied for the LHC, where T_{BS}~5-20 K. Specific heat loads to be removed by the cryogenic systems include the direct SR heating of the BS, the cooling of which becomes more efficient at higher T_{BS}, and the heat load on the cold bore due to thermal radiation from the BS, which becomes more significant as T_{BS} increases. The overall dependence on temperature, therefore, is non-monotonic. For FCC-hh, an optimum value of T_{BS}, i.e. the value which minimizes the total electrical power of the cryogenics plants, lies in the range 50-100 K, depending, e.g., on the cold bore temperature [30]. 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 are proposed for the FCC-hh [31], which absorb most of the photons. These designs facilitate the BS cooling and help stabilize the beam vacuum.

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 at full speed. This has important consequences for machine protection, collimation, beam disposal, beam injection and transfer.

Especially at top energy, even small amounts of continuous beam loss are important, in view of experimental background, quenches, activation, and single-event upsets. Already a single impacting bunch can destroy a conventional collimator, e.g. as the result of a fast kicker failure. One of the possible mitigation schemes is the use of indestructible collimators, e.g. hollow-electron lenses [32].

Another critical procedure for FCC-hh is the safe disposal of the high-energy beam, without destroying the beam dump absorber itself. A 1.5 km long dump line (resulting in β~4 km) implies an rms beam size of about 400 μm at the entrance of the beam dump. Limiting the peak temperature of a graphite dump absorber to ~1500°C requires a minimum transverse separation of ~1.8 mm between successive bunches, which can be provided by a dilution kicker system in the extraction line. The absolute kicker strengths need to be significantly higher than for the LHC, since the beam energy is higher and since the beam has to be swept over a much longer path across the dump block [33]. In consequence, the development of advanced pulsed kicker systems and the exploration of superconducting thin septa figure prominently on the FCC R&D list.

The beam transfer during injection into the collider is yet another, particularly critical (and unavoidable) process. The number of bunches which can be transferred together may be severely limited by the associated protection constraints. The number of bunches which may be transferred on a single injection shot increases for lower injection energy.

Comprehensive Reliability, Availability, Maintenance and Safety (RAMS) studies for the FCC [34] aim at understanding and reproducing the current CERN injector and LHC availability with a model, to identify promising knobs which significantly impact delivered integrated luminosity, and to estimate costs associated with these enhancement measures.

For the particle-physics experiments, a baseline geometry has been defined, together with a detailed engineering design of detector twin solenoids and double dipole SC magnet systems. The present tracker layout is based on HL-LHC (“phase II”) technology, HCAL granularity studies have been performed. Benchmark physics channels for detector performance studies have been determined. An FCC detector software framework has been set up, supporting studies for all three types of collisions.

5. COLLABORATION STATUS & TIME LINE

Since February 2014, a total of 70 institutes from 26 countries and four continents have joined the FCC collaboration, including from North America the US Department of Energy and 8 US universities. The latest status can be found on the FCC web site [35]. One major annual FCC conference is being organized every year. The FCC study aims at delivering a conceptual design report and cost estimates for all collider options, along with associated detector concepts and physics cases, 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. 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, LBNL) are associated with EuroCirCol; another one (TJNAF) is contributing to the FCC SRF development.

6. CONCLUSIONS

Circular colliders are a powerful option for future accelerator-based High Energy Physics. The worldwide community now needs to urgently prepare a solid design for 2018, exploiting all available synergies and profiting from rising activities around the globe.

High-energy circular colliders present challenging R&D requirements for beam handling, SC magnets, SRF, and several other technically areas, all of which are addressed by the FCC study. The FCC R&D results will benefit may other ongoing or future projects, and will have a direct impact on society.

We are looking forward to intensifying collaborations with international partners, especially in the United States, and in particular with the nuclear science community.

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