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THE FUTURE CIRCULAR COLLIDER STUDY*

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Abstract

At the end of 2018, a large worldwide collaboration, with contributors from more than 350 institutes completed the conceptual design of the Future Circular Collider (FCC), a ~100 km accelerator infrastructure linked to the existing CERN complex, that would open up the way to the post-LHC era in particle physics. We present an overview of the two main accelerator options considered in the design study, namely the lepton collider (FCC-ee), serving as highest-luminosity Higgs and electroweak factory, and the 100-TeV energy-frontier hadron collider (FCC-hh), along with the ongoing technological R&D efforts and the planned next steps. A recently approved EU co-funded project, the FCC Innovation Study (FCCIS), will refine the design of the lepton collider and prepare the actual implementation of the FCC, in collaboration with European and global partners, and with the local authorities.

INTRODUCTION

The FCC Conceptual Design Report (CDR) [1–4] was released at the end of 2018. The results of the conceptual design study naturally gave rise to an integrated FCC programme [5–7], which was proposed as input to the European Strategy Process: Inspired by the successful past LEP-LHC sequence at CERN, this integrated programme features in its first stage the lepton collider FCC-ee — namely a Higgs and electroweak factory, which will produce Z, W and H bosons, and top quarks at considerable rates: At its design luminosity, FCC-ee will repeat the the entire LEP Z physics programme in about 1 minute. The second stage will be the FCC-hh proton collider (~100 TeV c.m. energy) as the natural continuation of the LHC at the energy frontier, with additional ion and lepton-hadron collision options. The integrated FCC programme represents a comprehensive cost-effective approach, aimed at maximizing the physics opportunities. FCC-ee and hh will offer complementary physics, while profiting from common civil engineering and technical infrastructures. They will both build on, and reuse, CERN's existing infrastructure. In addition, the FCC integrated project, with its technical schedule, allows for a seamless continuation of High Energy Physics (HEP) after the High Luminosity LHC (HL-LHC) programme, expected to end in the second half of the 2030's.

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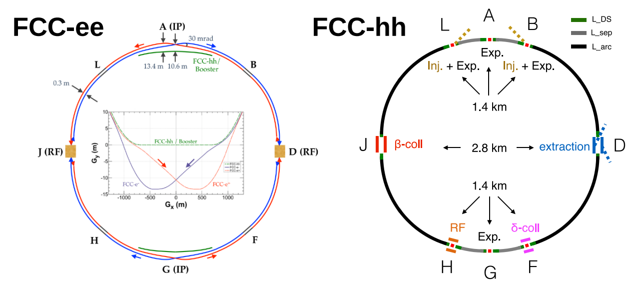

Figure 1: Layouts of FCC-ee and FCC-hh successively housed in the same tunnel [2, 3, 6].

FCC-ee

FCC-ee is conceived as a double-ring e^+e^- collider whose 97.75 km baseline circumference follows the footprint of FCC-hh, except around the Interaction Points (IPs) at locations A and G — see Fig. 1. The FCC Interaction Region (IR) features an asymmetric layout and optics in order to limit synchrotron radiation (SR) emitted towards the detector [8]. The critical photon energy is kept below 100 keV over the last 450 m from the IP, which is one of the lessons learnt from the LEP collider [9]. The present baseline envisions 2 IPs. Alternative layouts with 3 or 4 IPs are under study. The electron and positron bunches are collided under a large horizontal crossing angle of 30 mrad with a so-called crab-waist optics [10, 11]. The IR optics accommodates only one sextupole pair per final focus side, used for a local correction of the vertical chromaticity, with a cancellation of geometric aberrations. Reducing the strength of the outer sextupoles creates the crab waist [8]. This low number of strong sextupoles ensures a minimum amount of nonlinearity and a correspondingly large dynamic aperture. The FCC-ee synchrotron radiation power is limited to 50 MW per beam at all beam energies. The magnet strengths in the arcs are tapered so as to match the local beam energy. A common radiofrequency (RF) system is used for the $t\bar{t}$ running, where the maximum RF gradient is required, but the number of bunches is quite low, so that parasitic collisions in the RF straights can be avoided.

Key parameters of FCC-ee are compiled in Table 1. Figure 2 illustrates that the FCC-ee offers an attractive luminosity level over its entire centre-of-mass energy range from 90 to 365 GeV. From about 2 TeV onward a hypothetical muon collider (MAP-MC) is expected to yield the best performance. Between about 400 GeV and 1 or 2 TeV the linear colliders ILC and CLIC, respectively, appear optimally suited.

The FCC-ee design is based on proven techniques from past and present colliders, not pushing any key parameter (beam lifetime, β_y^*, e^+ production rate, SR photon energy)

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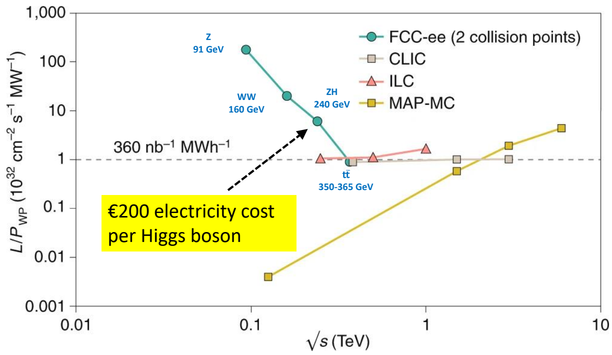

Figure 2: Luminosity L per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders [7, 12]. Also indicated is the FCC-ee electricity cost per Higgs boson, assuming a price of 50 Euro MWh^{-1} [2, 7].

Table 1: Key Parameters of FCC-ee

parameter		Z	WW	ZH	$t\bar{t}$
c.m. energy	[GeV]	91	160	240	365
beam current	[mA]	1390	147	29	5.4
no. bunches/beam		16640	2000	393	48
bunch intensity	[10^{11}]	1.7	1.5	1.5	2.3
longit. damping	[turns]	1281	235	70	20
hor. IP beta	[m]	0.15	0.2	0.3	1
vert. IP beta	[mm]	0.8	1	1	1.6
hor. emittance	[nm]	0.3	0.8	0.6	1.5
vert. emittance	[pm]	1.0	1.7	1.3	2.9
lum./IP	[10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55
beam lifetime	[min.]	68	49	12	12

beyond what has already been achieved. The B-factories KEKB and PEP-II, along with DAΦNE, have demonstrated the merit of double-ring lepton colliders, and the possibility of operating with high beam currents, of up to a few Ampere. KEKB, PEP-II, BEPC-II and SuperKEKB have successfully used top-up injection, greatly increasing the daily integrated luminosity. SuperKEKB has already achieved the low β_y^* of 1 mm [13], as required for FCC-ee; it is ultimately aiming for values of about 0.3 mm. Both DAΦNE and SuperKEKB have improved their specific luminosity and beam-beam performance by operating with the crab-waist collision scheme. LEP has explored operation at high beam energy, with about the same SR power per unit length and very similar critical photon energies as planned for FCC-ee. LEP and VEPP-4M have pioneered precision energy calibration based on resonant depolarisation [14, 15]. The KEKB and SuperKEKB e$^+$ sources provide a positron production rate similar to the one needed for FCC-ee top up injection, which is less than the world record achieved at the SLC. HERA, LEP, and RHIC have established various techniques of spin gymnastics and for optimising the degree of self-polarisation, which are relevant for the FCC-ee energy calibration at the Z and WW energies. In particular, SuperKEKB, presently under commissioning, is demonstrating FCC-ee key concepts. Its design beam lifetime is 3–6 times shorter than the smallest lifetime expected at FCC-ee.

Nevertheless, the FCC-ee design must also address a few new challenges. The FCC-ee IR will potentially experience significant heat loads from radiative Bhabha scattering (kW level), beamstrahlung (possibly MW level, intercepted about 50 m downstream of the IP), resistive wall heating (kW), higher order mode (HOM) excitation — which is addressed by an optimised chamber design and a dedicated HOM absorber close to the crotch [16] — and SR from the final quadrupoles. The IR magnet system is quite complex. In addition to the 2 T detector solenoid and final focusing quadrupole Q1, it features a compensation solenoid in front of Q1, and a shielding solenoid surrounding Q1 [17]. To maximise the detector acceptance a novel thin-wall cryostat has been proposed [18].

For a ~100 km long collider the resistive wall becomes a dominant source of impedance. If the vacuum chamber is coated with a standard 1 µm thick NEG film, this impedance can drive the longitudinal microwave instability [19]. Therefore, for the FCC-ee, a novel ultrathin NEG coating, of about 100 nm thickness, has been developed and qualified with respect to pumping properties, secondary emission yield, activation behaviour, and impedance [20].

In collision, the FCC-ee bunch profiles are strongly affected by beamstrahlung. Suitable high-throughput single-shot diagnostics is being developed at KIT's KARA facility, where longitudinal bunch profiles are already recorded with an electro-optical spectral decoding setup [21–23].

LEP saw no polarisation for beam energies above 65 GeV. The much larger bending radius of FCC-ee reduces the beam energy spread, and, thereby, the spin tune spread. This should allow for reaching several tens of per cent polarisation, not only on the Z pole, but also at the WW threshold [24], enabling a precise energy calibration at the 10^{-6} level in both these modes of operation [25]. The precise knowledge of the collision energy is an important component of the physics program for the electroweak factory.

While R&D efforts also pursue cost-effective, low-power, low-field magnets for the FCC-ee collider arcs [26], the thrust of FCC-ee technology R&D is on the superconducting RF (SRF) system, especially advanced cavities, RF power sources, and cryomodules. Here the R&D aims at improving performance and efficiency, and at reducing cost. Example FCC-ee SRF developments include improved Nb/Cu coating/sputtering (e.g. electron cyclotron resonance fibre growth, high-power impulse magnetron sputtering) new cavity fabrication techniques (e.g. electro-hydraulic forming [27], improved polishing, seamless production, ...), coating of A15 superconductors (e.g. Nb_3Sn), cryo-module design optimisation, bulk Nb cavity R&D in collaboration with FNAL, JLAB, and Cornell (also KEK and IHEP are active in this domain), MW-class fundamental power couplers for 400 MHz, and novel high-efficiency klystrons exploiting new bunching methods.

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FCC-hh

The FCC-hh seeks an order of magnitude performance increase in both energy and luminosity, with 100 TeV c.m. collision energy (versus 14 TeV for LHC), and 20 ab^{-1} accumulated per experiment collected over 25 years of operation, to be compared with 3 ab^{-1} for the (HL-)LHC. The transition from LHC to FCC-hh amounts to a similar performance increase as the step from the Tevatron to LHC. Table 2 compares the main parameters for two phases of FCC-hh with those of HL-LHC and LHC. Beam and optics parameters of FCC-hh appear to be less demanding than those for the HL-LHC. The key technology to realize the FCC-hh is high-field magnets, that is developing and fabricating a few thousand dipole magnets with a field of 16 T in a reliable and economical way. Recently substantial progress has been made in Nb_3Sn magnet development at both FNAL (demonstrator magnet MDPCT1 reached 14.1 T at 4.5 K [28]) and CERN (eRMC achieved a field of 16.5 T at the conductor [29]). Alternative options under study include magnets based on high-temperature superconductor.

Table 2: Parameters of FCC-hh Compared with (HL-)LHC

parameter		FCC-hh		HL-LHC	LHC
c.m. energy	[TeV]	100		14	14
dipole field	[T]	16		8.33	8.33
beam current	[A]	0.5		1.1	0.58
no. bunches/beam		10400		2760	2808
bunch intensity	[10^{11}]	1.0		2.2	1.15
SR power/ring	[kW]	2400		7.3	4.6
longit. damping	[hr]	0.54		12.9	12.9
IP beta	[m]	1.1	0.3	0.15	0.55
norm. emittance	[μm]	2.2		2.5	3.75
lum./IP	[10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/crossing	[100]	1.7	10	1.3	0.3
energy/beam	[GJ]	8.4		0.7	0.38

Other challenging FCC-hh parameters pertain to the synchrotron radiation (SR) power, the number of physics events per bunch crossing, and the energy stored in the beam. At FCC-hh, almost 5 MW of SR power is emitted inside the cold arc magnets. To efficiently remove this heat it is intercepted by a beam screen (BS) at an elevated temperature of about 50 K (to be compared with 4.5–20 K for the LHC). This beam screen is mounted inside the 1.9 K cold bore of the magnets. The beam screen should also provide sufficient pumping capacity, present a low impedance to the beam, suppress photo-electrons and prevent electron cloud. An optimized "double" beamscreen design for FCC-hh was developed in the framework of the EuroCirCol project [30], and illuminated with synchrotron radiation at the KIT KARA facility, whose electron-beam SR power spectrum closely resembles the one of the FCC-hh proton beam [31]. Results in a warm setup have confirme the chosen approach [32]. Recently installed liquid nitrogen lines also allow experiments at cryogenic temperature. The tests at KARA demonstrate a drastic reduction of molecular photo-desorption yield for the FCC-hh BS geometry as compared with flat Cu chamber (factor 15), and when irradiating at cold (factor 100 except H_2) [33].

FCC IMPLEMENTATION

The present baseline position for the 97.75 km long tunnel was established by choosing the least risky, fastest and cheapest construction, and feasible positions for large span caverns (which are the most challenging structures). More than 75% of this tunnel lies in France, including 8 or 9 out of a total of 12 access points; the other 3 or 4 access points are located in Switzerland. The next step of the site investigation entails a review of these site locations and of the machine layout. Figure 3 illustrates the tunnel integration for FCC-ee and FCC-hh in the arcs, where the inner tunnel diameter is 5.5 m, to be compared with 3.8 m for the LEP/LHC tunnel.

The technical schedule of the FCC integrated project is shown in Fig. 4. At present, the R&D for the FCC-ee (in yellow) focuses on an optimized engineering design, energy efficiency, and maintainability. The R&D for FCC-hh (in green) concentrates on conductor development and high-field magnet technology. With a start in 2020 the entire programme would conclude by 2090, after another ~20 years of LHC, 15 years of FCC-ee and 25 years of FCC-hh operation. The only period without physics is the ten years, ~2055–64, needed to dismantle the FCC-ee and install the FCC-hh.

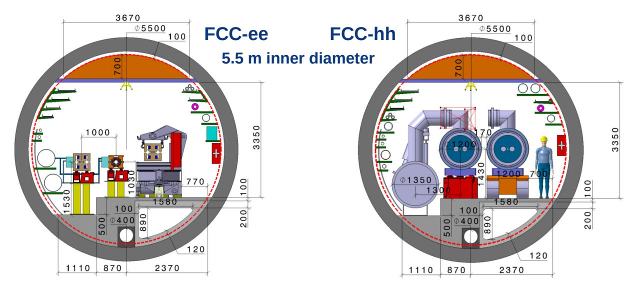

Figure 3: FCC tunnel integration in the arcs [2, 3, 6].

FCC COLLABORATION

The FCC study proceeds as a collaborative, world-wide effort. One example is the participation of the Karlsruhe Institute of Technology (KIT), which is contributing to both FCC-ee and FCC-hh.

At present, the FCC collaboration includes 139 institutes and 30 companies hailing from 34 countries, plus support from the European Commission through various projects like EuroCirCol, EasiTrain and the FCCIS. Further increasing the international collaboration is a prerequisite for success: Links with science, research & development and high-tech industry are essential for preparing the FCC implementation.

EuroCirCol was a European Union Horizon 2020 program with 3 MEuro co-funding, that was completed in December 2019. It included 15 European beneficiaries and KEK plus, as associated partners, the US laboratories FNAL, BNL,

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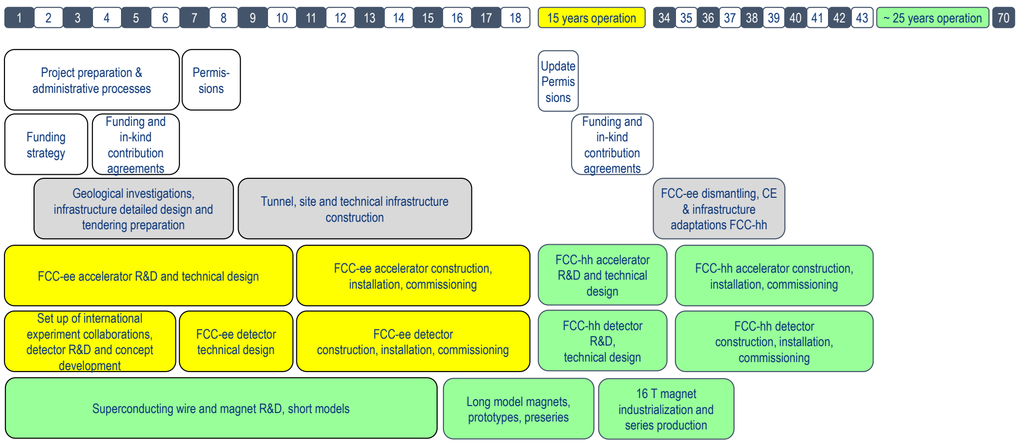

Figure 4: Technical schedule of FCC integrated project [7,12]. Top row shows the years from start of project implementation.

LBNL, and NHFML. The EuroCirCol scope covered the key work packages for the FCC-hh collider: Optics design for arcs and IR; design of the cryogenic beam vacuum system including beam tests at KARA; the 16 T dipole design with a construction folder for demonstrator magnets. The FCCIS was recently accepted for funding by the European Commission with the highest achievable score. Its beneficiaries are displayed in Fig. 5. Also included as important partners are the local authorities in Switzerland (État de Genève) and France (D.R.R.T.), the US D.O.E., BINP in Russia and Oxford University in the UK. FCCIS covers the FCC-ee design optimisation, preparation of construction planning and environmental evaluation, management of excavation materials, user community building, public engagement, and socio-economic impact studies.

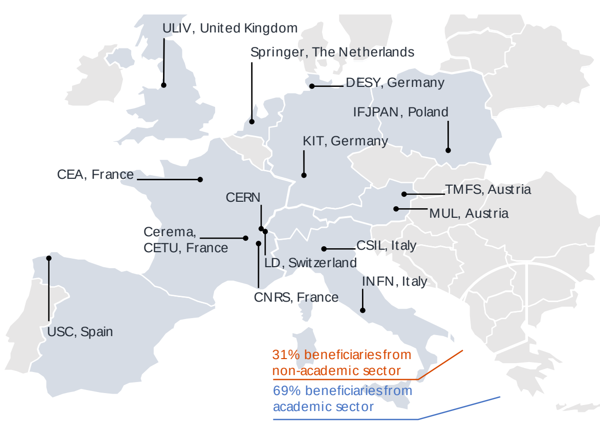

Figure 5: Beneficiaries of the FCCIS (J. Gutleber).

Preparatory work with the host states is progressing. Administrative processes for the project preparatory phase were developed; a first review of the tunnel placement was performed. Requirements for urban, environmental, and economic impact, land acquisition and construction-permit processes are being defined. A common optimisation of the collider tunnel and surface site infrastructure is underway.

SUMMARY AND OUTLOOK

FCC-ee is a compelling Higgs and electro-weak factory at c.m. energies from 90 to 365 GeV. The FCC-ee key concepts, ingredients, and parameters were already demonstrated, or exceeded, at various past and present machines. The main technologies for FCC-ee exist today; a strong R&D program with industry is being set up for optimising energy efficiency maintainability, machine availability, and construction cost.

FCC-hh is the highest-energy collider conceivable in the 21st century. Its design is based on lessons from the LHC. The required high-field 16 T magnets are not yet at hand. A rigorous conductor and magnet R&D program aims at rendering these magnets available around 2050/55.

The FCC-ee/FCC-hh integrated programme represents a coherent long-term strategy, with a sharing of tunnel, technical infrastructure (electricity, cooling and ventilation, etc.), perhaps reuse of detector modules, along with complementary physics, and exploitation of existing CERN facilities.

The first phase of the FCC study delivered baseline machine designs with a performance matching the physics requirements. The integrated FCC programme was submitted to the European Strategy Update 2019/20. The next step will develop a concrete implementation scenario in collaboration with the host-state authorities, accompanied by machine optimisation, physics studies and technology R&D. This step is supported by the EC H2020 Design Study FCCIS.

The long-term goal is to provide a world-leading HEP infrastructure for the 21st century, which will push the particle-physics precision and energy frontiers far beyond the present state-of-the-art.

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