CERN-ACC-2015-112

Future Circular Collider

PUBLICATION

Outline and Status of the FCC-ee Design Study

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07 October 2015

The research leading to this document is part of the Future Circular Collider Study

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1.1 Outline and Status of the FCC-ee Design Study

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1.1.1 Motivation and Scope

The Update of the European Strategy for Particle Physics in 2013 [1] declared as its second highest priority that "…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines…". In response to this request, the global Future Circular Collider (FCC) study is designing a 100-TeV proton collider (FCC-hh) in a new ~100 km tunnel near Geneva, a high-luminosity electron-positron collider (FCC-ee) as a potential intermediate step, and a lepton-hadron option (FCC-he). The FCC study comprises accelerators, technology, infrastructure, detector, physics, concepts for worldwide data services, international governance models, and implementation scenarios. The FCC study is mandated to deliver a Conceptual Design Report and preliminary cost estimate by the time of the next European Strategy Update expected for 2019.

As of July 2015, 58 institutes from 22 countries have formally joined the FCC collaboration, which is based on a common Memorandum of Understanding (MoU) and on institute-specific addenda. All FCC member institutes are represented in the FCC Collaboration Board.

In the frame of its HORIZON 2020 programme, the European Commission is funding the design of core parts of the FCC hadron collider through the "EuroCirCol" project. EuroCirCol comprises of 14 beneficiary institutes from the EU, Switzerland and Japan, plus several US laboratories as associates.

After a successful kick-off meeting at the University of Geneva, Switzerland, in February 2014 [2], the first annual meeting at Washington DC in March 2015 [3] reviewed the progress of all FCC activities one year after the study launch.

1.1.1 Physics Requirements

The FCC-ee should achieve highest possible luminosities over a wide range of beam energies, from 35 GeV to ≈200 GeV, supporting extremely high precision tests of the standard model as well as unique searches for rare decays.

The FCC-ee physics programme [4] includes: (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 & Γ_Z measurements and allow searches for extremely rare decays (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 and LEP2 some beam polarization is expected for beam energies up to ≥80 GeV [5], which will be exploited for precise energy calibration using resonant depolarization.

The collider may be optimized for operation at 120 GeV (Higgs factory), and at 45.5 GeV (TeraZ factory) as second priority.

1.1.2 Layout and Parameters

The FCC-ee layout must be compatible with the tunnel infrastructure for the hadron collider FCC-hh. Some of its key elements are: (a) a double ring with separate beam pipes, 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, colliding at a total crossing angle of 30 mrad; (b) top-up injection based on a fast-cycling booster synchrotron housed in the same large tunnel with 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 1, for simplicity showing numbers for (only) three different operation modes. The beam current varies greatly with beam energy, ranging from a few mA, as 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 a roughly four times larger machine this results in comparable radiation power per unit length. The present numbers might translate into a total wall plug power around 300 MW. The estimated luminosity numbers scale linearly with the synchrotron-radiation power. Other important choices to be made, or to be confirmed, are the number of collisions points (2 or 4), the crossing angle (30 mrad in total), and the collision scheme (crab waist?).

Table 1: 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” [6] with varying arc cell length and small crossing angle, or a crab-waist scheme based on a larger crossing angle and constant cell length [7]).

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 x $10^{34}cm^{-2}s^{-1}$	21 - 280	5 - 11	1.5 - 2.6	0.0012
vertical IP β^* [mm]	1	1	1	50
geom. hor. emittance [nm]	0.1-30	1	2	22
energy loss/turn [GeV]	0.03	1.67	7.55	3.34
synchrotron power [MW]	100			22
RF voltage [GV]	0.2-2.5	3.6-5.5	11	3.5

Presently there is a trend to transit from the original baseline [6], in which the arc cell length is varied so as to maintain almost constant geometrical emittance at all beam energies, to the crab-waist scheme, for which the smallest possible transverse emittances are desired at all energies. On the *Z* pole, the crab-waist approach could achieve about ten times more luminosity than the baseline [7] whereas at the high energy operation points the performance of the two optics variants is about equal. Figure 1 displays the expected luminosity per IP as a function of c.m. energy, assuming crab-waist collisions at two points.

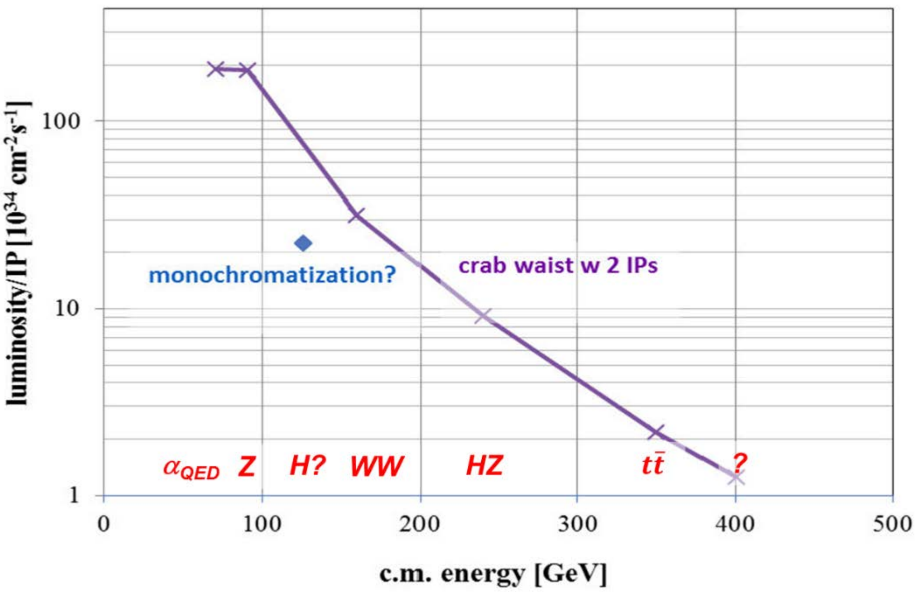

Figure 1: Projected FCC-ee luminosity per interaction point (IP) as a function of centre-of-mass energy, for a scenario with crab-waist collisions at two IPs.

1.1.3 Site Study

A tunnel optimization tool was developed in collaboration with a UK company [8]. All available information, in particular geology, from French and Swiss sources was fed into this device. A snapshot of the tool's web interface is shown in Fig. 2. Preliminary conclusions are that a tunnel of 90 – 100 km circumference fits the geological situation of the Geneva basin well, better than a tunnel of ≤80 km circumference, and that the LHC, and in particular its location, could be suitable as potential injector for the hadron collider.

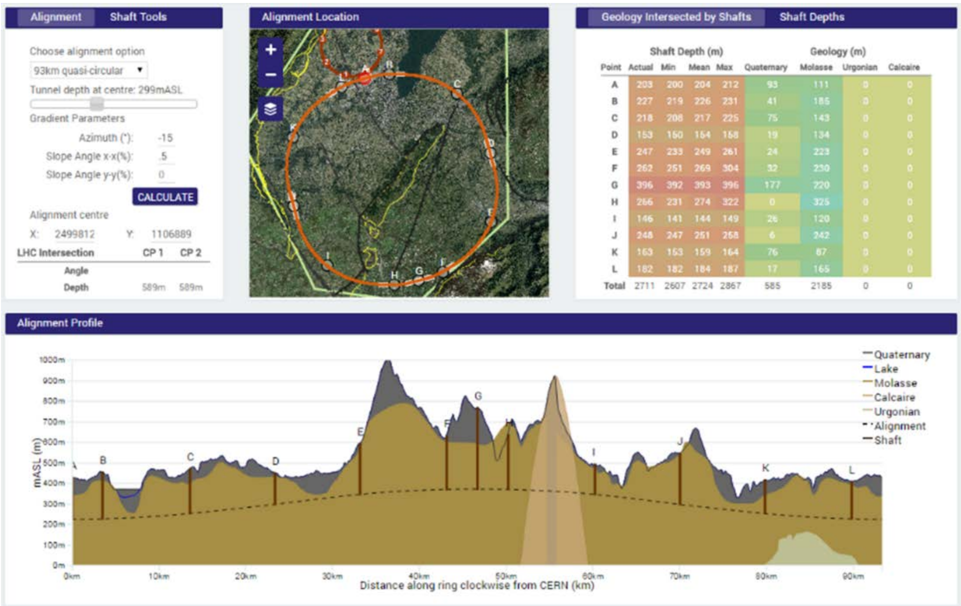

Figure 2: Web interface of the FCC tunnel optimization tool. The example is for a ring of 93 km circumference, largely located in the favorable “molasse” layer.

1.1.4 SC RF System

The superconducting RF system is the key technology of the FCC-ee [9]. The RF system requirements are characterized by two regimes – (1) high gradients for H and $t\bar{t}$ up to ≈11 GV 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 project aims at SC RF cavities with gradients of ≈20 MV/m, but lower gradients (e.g. 10-15 MV/m) are also acceptable. An RF frequency of 400 MHz has been chosen, equal to the one of the FCC-hh hadron collider.

The conversion efficiency from wall plug to RF power is an important figure for the overall power consumption of the facility. The FCC R&D target is 75% or higher. An efficiency of 65% was achieved for LEP2. Recent innovations in klystron design may allow for much higher values still [10].

Possible staging scenarios for the RF system, for the beam parameters, and for the optics have been developed [11, 12]. In particular, it is planned to share the RF systems for $t\bar{t}$ running, either by transverse displacements of the RF cavities or by means of electrostatic separators, in order to achieve the voltage required for $t\bar{t}$ running without installing more RF cavities than those required for *ZH* operation.

1.1.5 Super KEKB Test Bed

SuperKEKB [13] will be an important demonstrator for a number of key concepts of the *FCC-ee* design. Simply speaking, all elements not yet tested at LEP2, KEKB or PEP-II will be demonstrated by SuperKEK.

In various regards SuperKEKB actually goes beyond FCC-ee. For example, SuperKEKB will implement top-up injection at higher current with a shorter beam lifetime. The β_y^* of SuperKEKB will be 300 μm, to be compared with 1 or 2 mm at FCC-ee (see Fig. 3). The design beam lifetime is 5 minutes, limited by Touschek scattering, while the *FCC-ee* beam lifetime is more than 20 minutes, due to radiative Bhabha scattering (and to some extent beamstrahlung). SuperKEKB aims at a vertical-to - horizontal emittance ratio of 0.25% with colliding beams, similar to FCC-ee. The off-momentum design acceptance of SuperKEKB is ±1.5%. Such a value would also be sufficient for FCC-ee operation at the $t\bar{t}$ threshold, where beamstrahlung may have a noticeable effect on the beam lifetime [14]. The SuperKEKB-injector e^+ production rate of 2.5×10^{12}/s is even higher than required for *FCC-ee* crab-waist running on the *Z* pole ($<1.5 \times 10^{12}$/s). The SuperKEKB beam commissioning will start in early 2016.

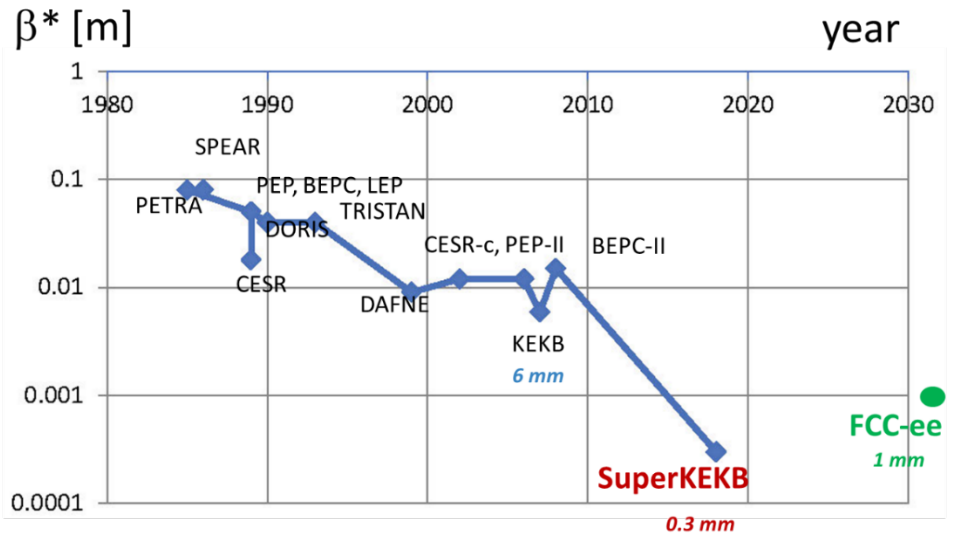

Figure 3: β_y^* evolution in circular e^+e^- colliders over 50 years, including the upcoming SuperKEKB and FCC-ee.

1.1.6 Outlook

Figure 4 illustrates that the preparation of the FCC as next circular collider is timely. Figure 5 shows the study time line towards the FCC Conceptual Design Report. FCC-ee beam-dynamics challenges and ongoing studies are discussed in a companion paper [15].

The FCC collaboration is looking forward to design convergence at its 2016 annual meeting, which will be held in Rome, Italy, from 11 to 15 April 2016 [16].

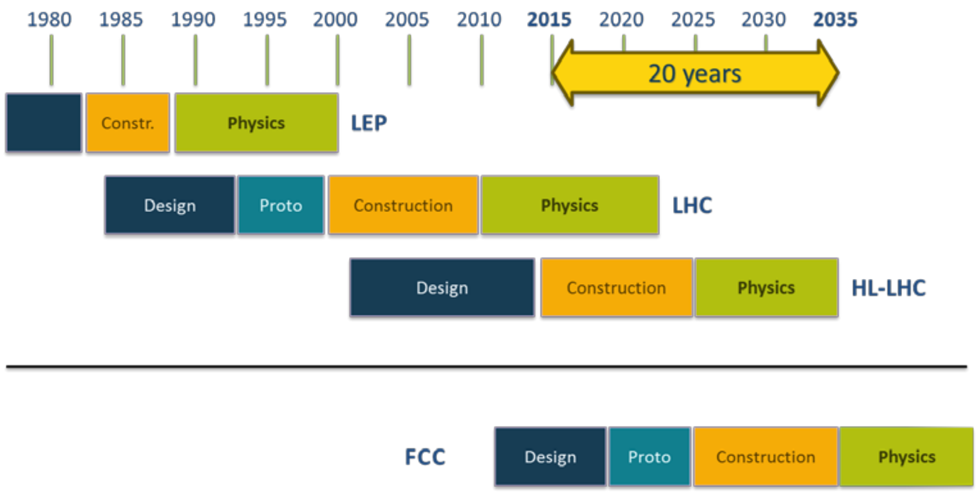

Figure 4: Time line of CERN Circular Colliders and the FCC.

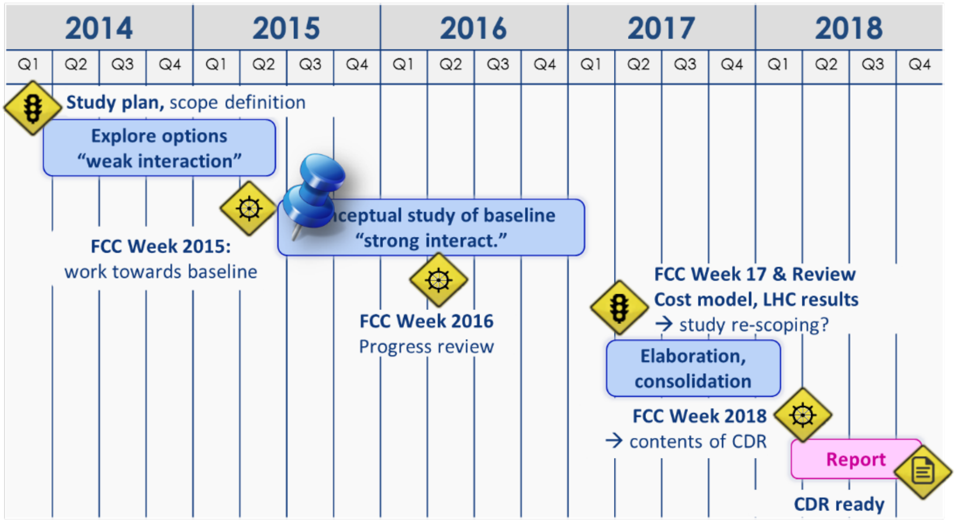

Figure 5: Study time line towards the FCC Conceptual Design Report.

1.1.7 Acknowledgements

This work is supported, in parts, by the European Commission under the Capacities 7th Framework Programme project EuCARD-2, grant agreement 312453, and the HORIZON 2020 project EuroCirCol, grant agreement 654305.

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