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FCC: COLLIDERS AT THE ENERGY FRONTIER*

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Abstract

The international Future Circular Collider study, launched in 2014, is finalizing a multi-volume conceptual design report. The FCC develops high-energy circular collider options based on a new 100 km tunnel. Long-term goal is a 100 TeV proton-proton collider (FCC-hh). The study also includes a high-luminosity electron-positron collider (FCC-ee), and it also examines lepton-hadron scenarios (FCC-he). Civil engineering and technical infrastructure studies were carried out. Global programs advance the development of high-field superconducting magnet technology based on Nb_3Sn, the optimization of a suitable large superconducting RF system, and schemes for synchrotron radiation handling. In addition, the FCC study includes the design of the HE-LHC, housed in the LHC tunnel, and based on the same high-field magnet technology as the FCC-hh. The FCC study further includes an elaboration of the physics cases, including for heavy-ion collisions, and detector concepts, as well as staging and implementation scenarios. The FCC collaboration has grown to more than 130 institutes from 30 countries around the world. This invited talk summarizes the study achievements and the final designs.

MOTIVATION, HISTORY, AND SCOPE

The LHC design was launched in 1983, 35 years ago. The physics programme of the LHC [1] and its high-luminosity upgrade, the HL-LHC [2, 3], will extend through the 2030's. In view of these time scales, the 2013 Update of the European Strategy for Particle Physics requested preparations for a post-LHC collider at CERN [4]. European studies of highest-energy highest-luminosity large circular colliders had started already a few years earlier, in 2010–2012, for both leptons [5, 6] and hadrons [7–9], 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 [10, 11].

The centre-of-mass energy reach of a hadron collider is directly proportional to the dipole magnetic field B and to the bending radius ρ, or machine circumference. Dipole magnets with a field of 16 Tesla together with a ring circumference of about 100 km result in a centre-of-mass energy of 100 TeV, an order of magnitude above the LHC. This goal for a future circular hadron collider (FCC-hh) defines the overall infrastructure requirements for the FCC accelerator complex. The FCC study scope also includes the design of a high-luminosity e^+e^- collider (FCC-ee) operating at c.m. energies of 90–365 GeV, as a possible first step, as well as a proton-electron collision option (FCC-he) at one interaction point, where a 60-GeV electron beam from an energy recovery linac would be collided with one of the two 50-TeV proton beams circulating in the FCC-hh. The design of a higher-energy hadron collider in the LHC tunnel with a centre-of-mass energy around 27 TeV, based on FCC-hh magnet technology — the so-called High-Energy LHC (HE-LHC) — is yet another part of the FCC study. The FCC study comprises accelerator design, technology development, detector design, physics cases, conventional infrastructure, implementation scenarios and cost estimates, for all collider scenarios.

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PHYSICS AND DESIGN TARGETS

The lepton collider FCC-ee will explore the 10–100 TeV energy energy scale via couplings with precision measurements [12]. It will yield a 20–50 fold improved precision for many electroweak quantities (equivalent to a factor 5–7 in energy), such as m_Z, m_W, m_t, $\sin^2\theta_{\rm W}^{\rm eff}$, R_b, $\alpha_{\rm QED}(m_Z)$, $\alpha_s(m_Z, m_W, m_t)$, Higgs and top quark couplings. To accomplish these goals, the machine is designed for highest possible luminosities at four working points (Z, WW, ZH and $t\bar{t}$).

The FCC-hh will provide collisions at highest center of mass energy for direct production up to 20–30 TeV. There will also be huge production rates for single and multiple production of SM bosons (H, W, Z) and quarks [13]. The machine is designed for 100 TeV c.m. energy with an integrated luminosity of 20 ab^{-1} over 25 years.

The HE-LHC design aims at approximately doubling the LHC collision energy with FCC-hh 16 T magnet technology in the 26.7 km LHC tunnel. The c.m. energy of 27 TeV is obtained by scaling with the magnetic field from the LHC's 14 TeV with 8.33 T dipole field. The HE-LHC target luminosity is more than 10 ab^{-1} over 20 years. The HE-LHC machine is designed within the constraints of the existing LHC infrastructure, and it incorporates both HL-LHC and FCC technologies.

LEPTON COLLIDER FCC-ee

The design considers a value of 100 MW for the total synchrotron-radiation power emitted by both beams, which defines the total beam current at all energies. The beam parameters for the lepton collider, in particular bunch charge, horizontal emittance, bunch length and the interaction-point (IP) beta functions $\beta^*_{x,y}$, were optimized by introducing a partial crab-waist collision scheme [14, 15], and taking into account the lifetime limitation due to beamstrahlung [16], the bunch length increase due to beamstrahlung [17, 18], and also a coherent beam-beam instability, which may appear in collisions with a large crossing angle [19]. The resulting parameters at the four main operation points are summarized in Table 1. In Fig. 1 the total FCC-ee luminosity (sum of

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Table 1: Parameters of FCC-ee in different stages. The luminosity values contain at least 10% margin compared with the simulated values.

parameter	Z	W	H (ZH)	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
circumference [km]	97.8	97.8	97.8	97.8
beam current [mA]	1390	147	29	5.4
bunches / beam	16640	2000	328	48
part./bunch [10^{11}]	1.7	1.5	1.8	2.3
hor. emittance [nm]	0.3	0.8	0.6	1.5
vert. emittance [pm]	1.0	1.7	1.3	2.9
hor. IP beta [m]	0.15	0.2	0.3	1
vert. IP beta [mm]	0.8	1.0	1.0	1.6
lum. [10^{34} cm^{-2}s^{-1}]	>200	> 25	>7	>1.3

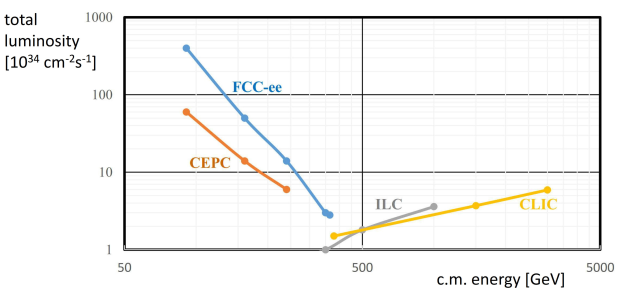

Figure 1: Total luminosity of various proposed e^+e^- colliders as a function of centre-of-mass energy.

two IPs) as a function of energy is compared with those of other proposed future e^+e^- colliders, like the International Linear Collider (ILC) [20, 21], the Compact Linear Collider [22], and the Circular (or Chinese) Electron-Positron Collider (CEPC) [23]. The figure illustrates that up to about 450 GeV, the circular lepton collider FCC-ee promises significantly more luminosity than any other machine. It will thus allow for measurements with highest possible precision of all known heavy particles, in addition to enabling direct searches of new physics through rare decays, e.g. a hunt for sterile neutrinos in the decays of the Z bosons [24].

The optics of the FCC-ee collider has been described in [25]. It follows the footprint of FCC-hh, except for the vicinity of the two IPs. Collisions at a large horizontal crossing angle of 30 mrad are realized with a (virtual) crab-waist scheme, where the strength of one of the two final-focus sextupole magnets is reduced. The optics design is flexible and supports operation at all energies, with a common lattice, except for a small rearrangement in the RF section, and a change in the arc phase advance per cell from 60 degrees (Z and W) to 90 degrees (ZH and $t\bar{t}$). The free length, l^*, between the end of the last quadrupole and the IP is 2.2 m, the detector solenoid field 2 T. The final focus is asymmetric. The critical photon energy is below 100 keV for the incoming beam emitted from 450 m upstream towards the IP [26]. A top-up injection scheme is used to maintain the stored beam current and the luminosity at the highest level during experiment runs. Transparent injection schemes have

Table 2: FCC-ee Operation Model

mode	lum./IP [nb^{-1}s^{-1}]	lum./yr [ab^{-1}/yr]	goal [ab^{-1}]	time [yr]
Z 1st 2 yrs	1000	26	150	4
Z later	2000	52		
W	2000	7	10	1
H	70	1.8	5	3
machine modification for RF installation: 1 year				
$t\bar{t}$ 1st year	8	0.2	0.2	1
$t\bar{t}$ later	14	0.36	1.5	4

been developed [27]. For the top-up injection, a booster synchrotron in the same tunnel as the collider is necessary. In the IP region the booster synchrotron follows the footprint of the hadron collider FCC-hh and, at the IP, it has a transverse offset of about 10 m from the FCC-ee collision point. “Tapering” of the magnets along the ring is employed to compensate the energy sawtooth effect.

Simulations of optics corrections and emittance tuning are encouraging: With 100 μm and 100 μrad random misalignments of arc quadrupoles and arc sextupoles, and 50 μm plus 50-μrad misalignments of the IP quadrupoles, the mean vertical emittance achieved after applying optics corrections is 0.1 pm, which is a factor ten smaller than the smallest target emittance [28]. Other simulations with errors and corrections suggest significant levels of self-polarization at the Z and W [29], which can be used for precise energy calibration using resonant depolarization. Top-up injection needs to use “bootstrapping,” in order to avoid flip-flop effects and coherent beam-beam instabilities in the presence of strong beamstrahlung [30]. NEG coating of the FCC-ee vacuum chamber is foreseen to guarantee a fast conditioning and to prevent electron-cloud formation. The impedance of the NEG coating can, however, drive the single-bunch longitudinal microwave instability [31]. Therefore, an unusually thin NEG coating of only 100 nm is preferred [31].

The FCC-ee operation model is shown in Table 2. The machine will run for four years on the Z pole. It is assumed that the average luminosity over the first two years is half the design luminosity. The integrated luminosity of FCC-ee is estimated considering 200 days per year assigned to physics collisions, and an efficiency (“Hübner factor”) of 75%. The total program duration is 14 years. The FCC-ee phase 1, covering Z, W and H measurements, lasts 8 years. Phase 1 could be followed by a one year shutdown for major RF installations, and another 5 years of $t\bar{t}$ running.

The FCC-ee will use three sets of RF cavities to cover all options for FCC-ee and its booster. At high intensity (Z running, and also for FCC-hh) 400 MHz mono-cell cavities (4 per cryomodule) with a temperature of 4.5 K will be deployed; at higher energy (W, H, t) 400 MHz four-cell cavities (4 per cryomodule), also at 4.5 K; and as $t\bar{t}$ machine “complement”, additional 800 MHz five-cell cavities (4 per cryomodule) will be operated at 2 K. The installation sequence is illustrated in Fig. 2. The installation load in

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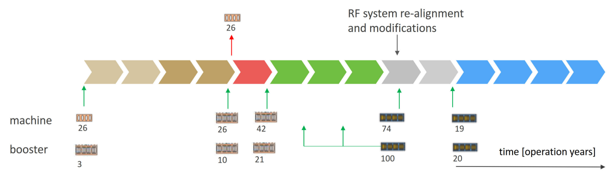

Figure 2: RF installation (and removal) sequence for the FCC-ee collider and booster, supporting the staged operation plan; the numbers indicate the number of cryomodules installed (or removed) during one shutdown.

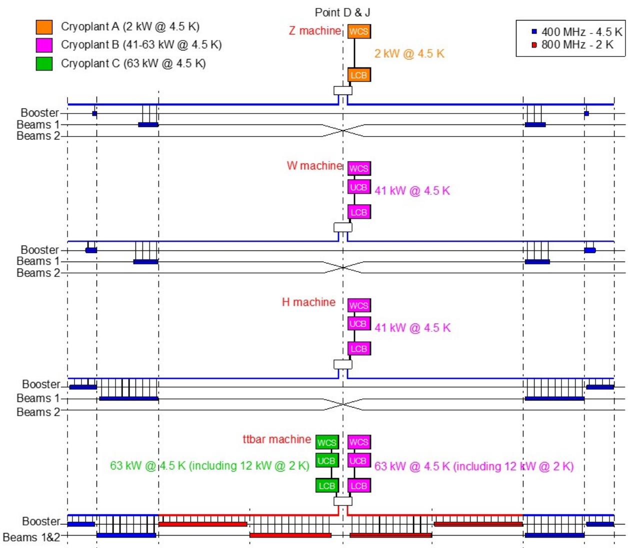

Figure 3: Cryogenic distribution and cavity layout in booster and collider rings for the four different modes of FCC-ee operation.

each shutdown is comparable to installations at LEP (about 30 cryomodules per shutdown). The RF cavities will be installed in the two long straight sections of the FCC-ee, which correspond to the collimation and beam extraction straights of the hadron collider. For Z, W and $(Z)H$ running, the RF systems are separate for the two beams. However, to obtain the highest RF voltage required for $t\bar{t}$ operation at low beam current, both beams are passed through all the cavities. Figure 3 shows the corresponding staging of the beamline layout and of the cryogenic system.

Prototype 400 and 800 MHz cavities have been fabricated. The first 5 cell cavity achieved Q values (3×10^{10}) and peak gradients (31 MV/m), higher than the FCC-ee design specification. It is shown in Fig. 4, together with a single cell cavity. In the frame of the FCC study, also novel production methods for SC cavities are being explored [32].

The FCC-ee arc magnets are based on a twin-aperture design [33], effectively reducing the electrical power consumption by a factor two. Photographs of prototype twin dipole and quadrupole arc magnets are presented in Fig. 5.

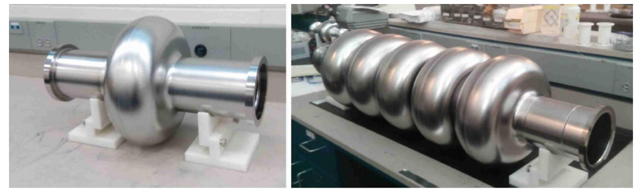

Figure 4: Prototype 1-cell and 5-cell 800 MHz cavity for FCC-ee and FCC-he, built and tested by JLAB.

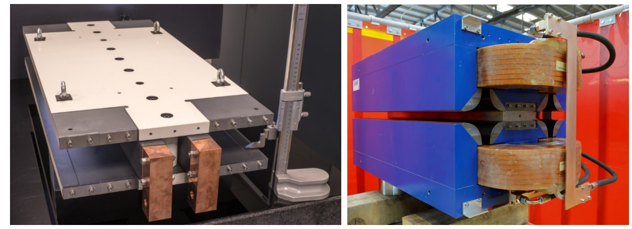

Figure 5: Photographs of prototype twin-aperture dipole (left) and quadrupole magnets (right).

HADRON COLLIDER FCC-hh

Table 3 compares the beam parameters of the FCC-hh (2 phases) and the HE-LHC with those of HL-LHC and LHC, all with 25 ns bunch spacing. Bunch population, normalized emittance, β^*, bunch length and beam current are similar to the corresponding values at the LHC or HL-LHC. However, thanks to the higher beam energy, and without leveling, the peak luminosity of FCC-hh and HE-LHC is close to 3×10^{35} cm^{-2}s^{-1}. Radiation damping times are of the order of 1 hour. The event pile up at FCC-hh and HE-LHC approaches 1000 events per bunch crossing. This value could be reduced either by luminosity leveling as for the HL-LHC (e.g. by decreasing β^* during the physics store), or by operation with shorter bunch spacing and smaller emittance. In either case, there would be a 10-20% decrease in integrated luminosity for a factor two lower peak pile up.

Figure 6 presents the FCC-hh layout. The total ring circumference is 97.8 km. Two high luminosity experiments are located at the diametrically opposed points A and G. Two other experiments in points L and B are combined with injection. The two longest straight sections accommodate betatron collimation (J) and extraction (D). Another straight (F) is used for momentum cleaning. The straight at point H houses the radiofrequency system. The layout is compatible with using either the LHC (with faster ramping) [34] or a superconducting synchrotron in the SPS tunnel [35] as injector, with injection energies of either 3.3 TeV or 1.3 TeV, respectively.

High-power beam handling is one of the challenges of the FCC-hh design. A main issue is sustaining a minimum beam lifetime of 12 minutes, corresponding to 12 MW of losses. The collimation system and individual collimators have been designed such that in the case of this worst beam lifetime there is no quench of any superconducting magnet and the maximum power deposited in any primary or secondary

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Table 3: Key parameters of FCC-hh, HE-LHC, HL-LHC and LHC, for operation with proton beams. All values, except for the injection energy, refer to collision energy. HE-LHC entries shown in parentheses refer to a larger crossing angle; LHC entries in parentheses to the HL-LHC. The bunch spacing is 25 ns for all colliders.

parameter	unit	FCC-hh		HE-LHC	(HL-)LHC
centre-of-mass energy	TeV	100		27	14
injection energy	TeV	3.3		0.45/1.3	0.45
arc dipole field	T	16		16	8.33
circumference	km	97.8		26.7	26.7
beam current	A	0.5		1.12	(1.12) 0.58
bunch population N_b	10^{11}	1.0		2.2	(2.2) 1.15
number of bunches / beam n_b	—	10600		2808	(2760) 2808
longitudinal emittance ($\sim 4\pi\sigma_z\sigma_E$)	eVs	5		4.2	2.5
norm. transv. rms emittance $\gamma\varepsilon$	µm	2.2		2.5	(2.5) 3.75
IP beta function $\beta^*_{x,y}$	m	1.1	0.3	0.25	(0.15) 0.55
initial rms IP beam size $\sigma^*_{x,y}$	µm	6.7	3.5	6.6	(8.2) 16.7
half crossing angle	µrad	37	70	(180) 133	(250) 150
peak luminosity per IP	10^{34} cm^{-2}s^{-1}	5	30	28	(5, leveled) 1
peak no. of events / crossing	—	170	1000	800	(135) 27
SR power / beam	kW	2400		100	7.3 (3.6)
transv. emittance damping time	h	1.1		3.6	25.8
initial proton burn-off time	h	17	3.4	2.5	(15) 40
luminosity per year (160 days)	fb^{-1}	$\geq$ 250	$\geq$ 1000	730	(350) 55

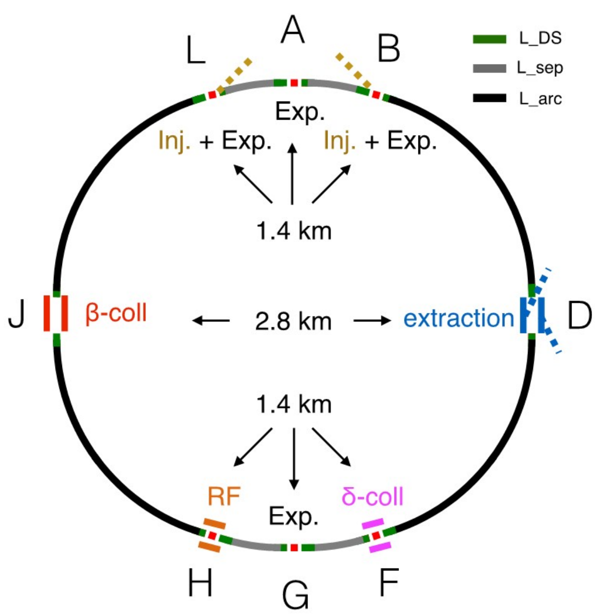

Figure 6: FCC-hh layout with 8 straights.

collimator stays below 100 kW. A shower simulation for the first secondary collimator is illustrated in Fig. 7.

The core of the hadron collider is the 16 T magnets and the underlying superconducting cable. Figure 8 shows the four different high-field magnets designs for which short model magnets will be built, and compared, in the 2018-2022 time period. The US 15 T magnet prototype under construction at FNAL and a 16 T enhanced racetrack coil being wound at CERN are illustrated in Fig. 9. The goal for the worldwide Nb_3Sn conductor effort is to raise the critical current density

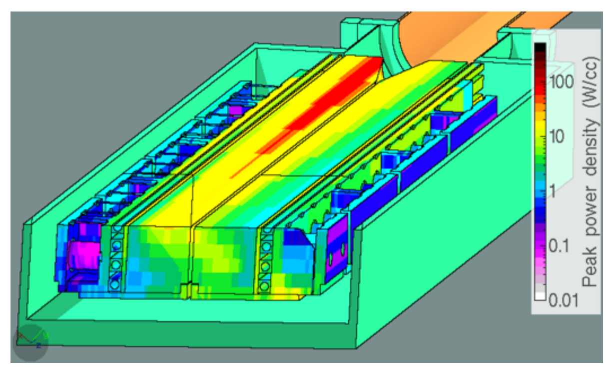

Figure 7: Shower energy deposition in first secondary collimator for a 12 minute beam lifetime.

from 1000 A/mm^2 (HL-LHC cable) to 1500 A/mm^2, which would reduce the size of the coil area by almost a factor of two and allow for greater compactness plus lower cost.

A novel feature of FCC-hh and HE-LHC is the extremely high level of synchrotron radiation, unprecedented for a hadron collider. The FCC-hh beams emit about 5 MW of synchrotron radiation power inside the cold environment of the arcs. The related heat removal can be accomplished with a dedicated beam screen. For reasons of overall energy efficiency, the FCC beam-screen temperature is chosen as 50 K, much higher than the magnets (1.9 K), and also higher than the temperature of the LHC beam-screen (5-20 K). Vacuum stability (cryo-pumping), beam impedance, and behavior under quench are other design consideration for the beam screen [38]. The latest version of the FCC beam screen is illustrated in Fig. 10.

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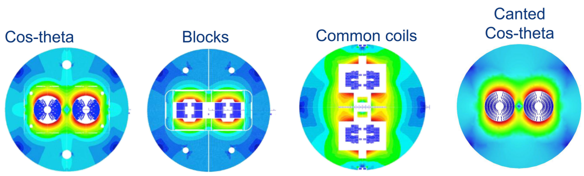

Figure 8: Four types of high-field magnets designed and prototyped in the frame of EuroCirCol [36], a special Swiss contribution, and the US Magnet Development Program [37].


Figure 9: The US 15 T magnet prototype at FNAL (left) and a 16 T enhanced racetrack coil at CERN (right).

HIGH-ENERGY LHC

The HE-LHC must be installed in the existing tunnel, with an inner diameter of only 3.8 m, compared with 5.5 m for the FCC. These space limitations result in significant constraints on the HE-LHC magnets, which must be both compact and curved, and on the HE-LHC cryogenics system, which needs to be different from, and more powerful than, the one of the LHC. The status of the HE-LHC design is discussed in a companion paper [39].

An HE-LHC optics solution with 1.3 TeV injection and 13.5 TeV top energy has been established. This solution would require a new superconducting SPS as injector. An alternative optics might eventually allow for injection at 450 (or 900) GeV with 13 TeV top energy. Related magnet design improvements are under study (e.g., active pinning centres and shimming). Challenges for the lower injection energy include physical and dynamic aperture, machine protection and collimation.

CONSTRUCTION AND SCHEDULE

Following a geological review an optimized baseline tunnel was established, with the lowest risk, the fastest and cheapest construction, and suitable locations for large-span caverns (the most challenging structures). Figure 11 shows the optimum tunnel position in the geological environment.

All surface and underground structures can be constructed within 6.5–7 years. Already 5 years after groundbreaking, the first FCC tunnel sectors would be ready for the installation of technical infrastructure.

The first physics could be expected around 2040–45, for any of the three collider scenarios considered, in the case of FCC-ee about 5 years before FCC-hh.

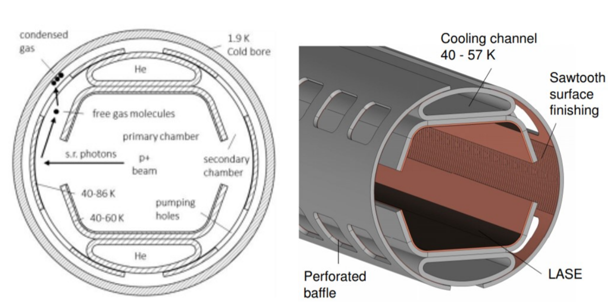

Figure 10: Optimized FCC-hh beam screen.

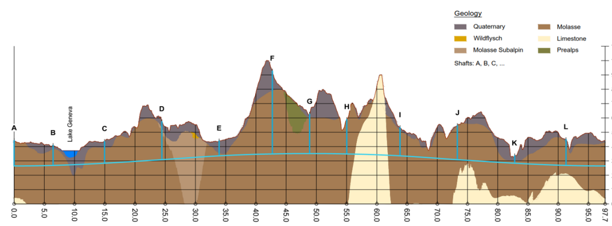
Figure 11: Optimized FCC tunnel baseline.

SUMMARY AND OUTLOOK

The FCC-ee and FCC-hh accelerator designs are ready for the conceptual design report (CDR). A worldwide R&D program is in place, on efficient high-field magnets, Nb_3Sn superconductor, and on highly efficient SC RF. The international FCC collaboration is growing steadily. By now 124 institutes and 30 companies from 32 countries are participating. The collaboration is presently focusing on the completion of the conceptual design report (CDR). The FCC-ee and FCC-hh accelerator designs are ready for the CDR. Prototyping and validation of key technical components are underway. The next phase of the FCC study, from 2019 to 2023, will focus on the implementation plan, and on the further development of key technologies, especially the high-field magnets.

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