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CHALLENGES FOR HIGHEST ENERGY CIRCULAR COLLIDERS*

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Abstract

A new tunnel of 80–100 km circumference could host a 100 TeV centre-of-mass energy-frontier proton collider (FCC-hh/VHE-LHC), with a circular lepton collider (FCC-ee/TLEP) as potential intermediate step, and a lepton-hadron collider (FCC-he) as additional option. FCC-ee, operating at four different energies for precision physics of the Z, W, and Higgs boson and the top quark, represents a significant push in terms of technology and design parameters. Pertinent R&D efforts include the RF system, top-up injection scheme, optics design for arcs and final focus, effects of beamstrahlung, beam polarization, energy calibration, and power consumption. FCC-hh faces other challenges, such as high-field magnet design, machine protection and effective handling of large synchrotron radiation power in a superconducting machine. All these issues are being addressed by a global FCC collaboration. A parallel design study in China prepares for a similar, but smaller collider, called CepC/SppC.

MOTIVATION AND SCOPE

Circular proton-proton (pp) colliders are the main, and possibly only, experimental tool available for exploring particle physics in the energy range of tens of TeV.

The bending radius ρ of a relativistic particle of charge e and momentum p is related to the magnetic field of strength B by $p = eB\rho$. Accordingly, the energy of pp collisions can be raised only by increasing either the strength of the dipole magnets or the bending radius ρ, and, thereby, the ring circumference. The Future Circular Collider (FCC) [1] design study combines both approaches in order to raise the collision energy about an order of magnitude beyond the existing Large Hadron Collider (LHC). Specifically, the FCC ring circumference of about 100 km (Fig. 1) would enable pp collisions of 50 TeV c.m. with the present 8.3-T LHC magnets, of 100 TeV with 16-T magnets (FCC-hh baseline), and of 125 TeV with 20-T magnets. The same tunnel infrastructure could accommodate a high-luminosity circular e^+e^- collider (FCC-ee), operating at 90–350 (500) GeV, as a potential intermediate step, and a high-luminosity high-energy lepton-hadron collider (FCC-he).

With a maximum centre-of-mass energy of 209 GeV, LEP2, in operation at CERN until 2001, has been the highest energy e^+e^- collider so far. The discovery, in 2012, of a Higgs-like boson at an energy reachable by a collider

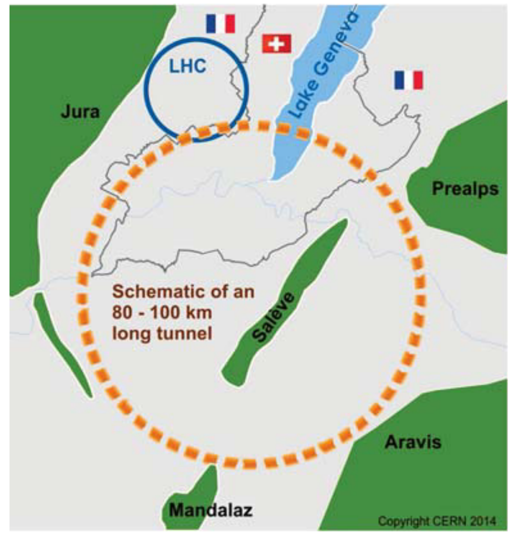

Figure 1: Schematic of a 100-km tunnel for a highest-energy circular collider in the Lake Geneva basin.

slightly more energetic than LEP2, together with the excellent performance achieved in the two B factories PEP-II and KEKB, have led to new proposals [2, 3, 4, 5, 6] for a next-generation circular e^+e^- collider. In order to serve as a Higgs factory such a collider needs to be able to operate at a least at a centre-of-mass energy of 240 GeV (for efficient $e^+e^- \to ZH$ production), i.e. 15% above the LEP2 peak energy. Reaching even higher energies, e.g. up to 350 GeV centre of mass, for $t\bar{t}$ production, or 500 GeV for ZHH and $Zt\bar{t}$ studies, might be possible for a new ring of larger circumference. CepC, a machine two times larger than LEP proposed in China [7, 8]—together with an associated 30–50 TeV proton collider, called SppC—, could provide an e^+e^- luminosity around 2×10^{34} cm^{-2}s^{-1} for Higgs production at 240 GeV. FCC-ee (formerly TLEP), a machine of 100 km circumference with 4 interaction points (IPs), aims at 2×10^{34} and 6×10^{34} cm^{-2}s^{-1} per IP at 350 and 240 GeV, respectively, as well as much higher luminosities at the Z pole and WW threshold, for high-precision measurements [9]. By tripling the number of RF cavities (at constant total RF power) its energy could be raised up to 500 GeV with a total luminosity (over 4 IPs) well above 10^{34} cm^{-2}s^{-1}.

An extended evolution of collider centre-of-mass energies from 1960 to 2050, including FCC-ee, FCC-hh, and CepC, is sketched in Fig. 2. Table 1 compares the beam parameters of the proposed future circular colliders with the LHC design and LEP2, respectively.

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Table 1: Parameters of the Proposed FCC-hh, FCC-ee/TLEP and CepC, Compared with LEP2 and the LHC Design

parameter	LHC (pp) design	FCC-hh	LEP2 achieved	FCC-ee (TLEP) Z	Z (cr. w.)	W	H	$t\bar{t}$	CepC
species	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-
$E_{\rm beam}$ [GeV]	7,000	50,000	104	45.5	45	80	120	175	120
circumf. [km]	26.7	100	26.7	100	100	100	100	100	54
current [mA]	584	500	3.0	1450	1431	152	30	6.6	16.6
no. of bunches, n_b	2808	10600	4	16700	29791	4490	1360	98	50
N_b [10^{11}]	1.15	1.0	4.2	1.8	1.0	0.7	0.46	1.4	3.7
ϵ_x [nm]	0.5	0.04	22	29	0.14	3.3	0.94	2	6.8
ϵ_y [pm]	500	41	250	60	1	7	2	2	20
β_x^* [m]	0.55	1.1	1.2	0.5	0.5	0.5	0.5	1.0	0.8
β_y^* [mm]	550	1100	50	1	1	1	1	1	1.2
σ_x^* [μm]	16.7	6.8	162	121	8	26	22	45	74
σ_y^* [μm]	16.7	6.8	3.5	0.25	0.032	0.13	0.044	0.045	0.16
θ_c [mrad]	0.285	0.074	0	0	30	0	0	0	0
$f_{\rm rf}$ [MHz]	400	400	352	800	300	800	800	800	700
$V_{\rm rf}$ [GV]	0.016	>0.020	3.5	2.5	0.54	4	5.5	11	6.87
α_c [10^{-5}]	32	11	14	18	2	2	0.5	0.5	4.15
$\delta_{\rm rms}^{\rm SR}$ [%]	—	—	0.16	0.04	0.04	0.07	0.10	0.14	0.13
$\sigma_{z,{\rm rms}}^{\rm SR}$ [mm]	—	—	11.5	1.64	1.9	1.01	0.81	1.16	2.3
$\delta_{\rm rms}^{\rm tot}$ [%]	0.003	0.004	0.16	0.06	0.12	0.09	0.14	0.19	0.16
$\sigma_{z,{\rm rms}}^{\rm tot}$ [mm]	75.5	80	11.5	2.56	6.4	1.49	1.17	1.49	2.7
F_{hg}	1.0	1.0	0.99	0.64	0.94	0.79	0.80	0.73	0.61
$\tau_{\vert\vert}$ [turns]	10^9	10^7	31	1320	1338	243	72	23	40
ξ_x/IP	0.0033	0.005	0.04	0.031	0.032	0.060	0.093	0.092	0.103
ξ_y/IP	0.0033	0.005	0.06	0.030	0.175	0.059	0.093	0.092	0.074
no. of IPs, n_{IP}	3 (4)	2 (4)	4	4	4	4	4	4	2
L/IP [10^{34}/cm^2/s]	1	5	0.01	28	219	12	6	1.7	1.8
$\tau_{\rm beam}$ [min]	2760	1146	300	287	38	72	30	23	57
$P_{\rm SR}$/beam [MW]	0.0036	2.4	11	50	50	50	50	50	50
energy / beam [MJ]	392	8400	0.03	22	22	4	1	0.4	0.3

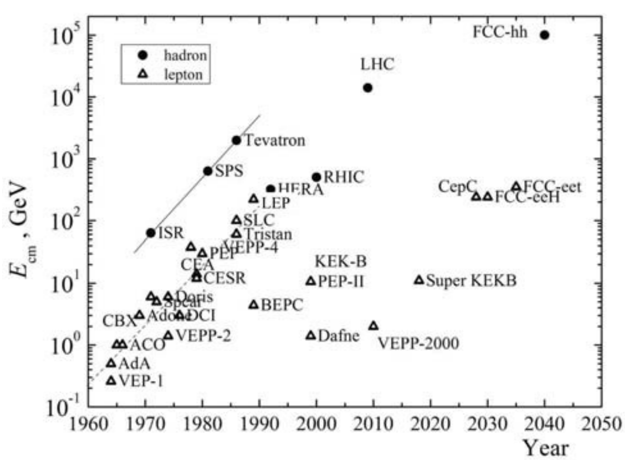

Figure 2: Collider energy vs. year [10] [V. Shiltsev].

HADRON COLLIDER

Major challenges include the development of economical high-field magnets; the arc beam pipe, which will be exposed to synchrotron-radiation (SR) levels unprecedented in a cold machine; the design of the interaction region for minimum β^*; and overall parameter optimization including constraints from the detectors.

The magnets of the present LHC are made from Nb-Ti superconductor, which supports a maximum field of about 10 T. Nb_3Sn superconductor can reach a practical magnetic field up to 16 T. The production of Nb_3Sn cables is well advanced, and the installation of a few Nb_3Sn dipole and quadrupole magnets is planned for the HL-LHC around 2023, which will represent an important milestone towards the FCC. High temperature superconductor (HTS) materials like the bismuth copper oxide BSCCO, in the form of Bi-2212, or yttrium copper oxide YBCO, in the form of Y-123, may withstand even much higher fields of up to 45 T; other materials of interest for constructing future affordable SC magnets are the conventional SC MgB_2, discovered in 2001, and iron-based SCs, discovered in 2006. The development of high-field SC magnets, especially ones based on Nb_3Sn, was pushed forward by earlier studies for a Very Large Hadron Collider (VLHC) [11] and by the ITER project. An EC-funded effort is directed at building and testing an HTS dipole insert coil for a 13-T Nb_3Sn dipole background magnet, targeting a total field of 19 T [12].

The particle-physics detector technology sets important

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limits on the total number of events per crossing (e.g. for calorimetry), as well as on the longitudinal event line density (for tracking of the primary vertices), and on the time interval between successive bunch collisions. The FCC-hh design baseline aims at a peak luminosity of 5×10^{34} cm^{-2}s^{-1}, i.e., the same value as for the LHC luminosity upgrade (HL-LHC). At 100 TeV with 25-ns bunch spacing this luminosity corresponds to a pile up of about 170 events per crossing, a beam lifetime of about 19 hours (with a total cross section $\sigma_{\rm tot} \approx 153$ mbarn), and close to 100 kW of hadronic debris at each collision point.

The possibility of shorter bunch spacings, e.g. 5 ns, is also considered as these would make better use of the strong radiation damping. Indeed, such shorter bunch spacings could yield even higher luminosities, e.g. 2×10^{35} cm^{-2}s^{-1}, and, at the same time, reduce the event pile up. Figure 3 illustrates the historical performance of hadron colliders and its projection into the future.

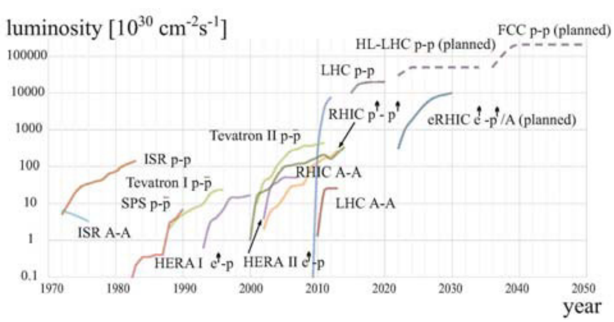

Figure 3: Past and future hadron-collider peak luminosity [Courtesy W. Fischer].

The 100-km FCC could have a mirror-symmetric polygon shape consisting of equal-length arcs and intermediate straights accommodating the particle-physics experiments, injection and extraction systems, radio-frequency (RF) cavities, collimation, etc. One extreme case is a racetrack shape with only two long straights each hosting several clustered experiments plus utilities, as for the SSC design [13]. The final layout will be determined by geological considerations and by beam dynamics.

Scaling, from the LHC, the arc longitudinal dimensions as the square root of the circumference yields an FCC-hh arc cell about 200 m long, a betatron tune around 120, and a maximum value of the arc beta functions of 350 m. Similar values are derived from considerations of beam stability, dipole fill factor, and magnet-strength limitations.

If magnetic field gradients are held constant, the length of a low-beta insertion increases roughly in proportion to the square root of beam energy [14]. For the FCC-hh the gradients are increased compared with the LHC, profiting both from smaller emittance and from advances in magnet technology. As a result the FCC IR length is about 1100 m, or only two times larger than the LHC IR. The baseline β^* value is 1.1 m. Figure 4 shows a "pushed" IR optics which achieves a significantly lower β^* of 0.3 m [15]. This could allow reducing the beam current below its baseline value of 0.5 A, while keeping the peak or integrated luminosity constant, or, else, increasing the peak luminosity by about a factor of 4 beyond the baseline. For example, with a β^* of 0.3 m, at equal average luminosity the maximum beam current would need to be only 0.20–0.25 A, instead of 0.5 A, reducing the SR power by more than a factor of two.

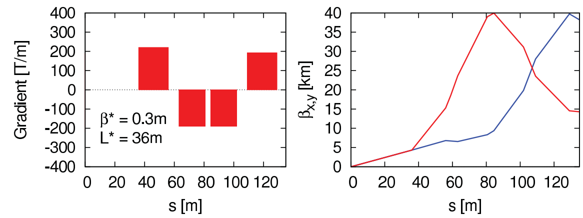

Figure 4: "Pushed" IR optics with $\beta^* = 0.3$ m and a free length l^* of 36 m ($l^* = 23$ m at the LHC) [15].

Indeed, one important novel feature of FCC-hh is the high SR power, which is close to 2.4 MW per beam (at a beam current of 0.5 A) to be contrasted with 3.6 kW at the LHC. This power translates into a baseline heat load per meter and aperture of about 30 W/m/aperture, which could be absorbed on a beam screen (BS) inside the cold magnets as for the LHC, but at a higher BS temperature than the LHC's 5–20 K, in order to minimize the total refrigerator power [16]. Raising the BS temperature improves the Carnot efficiency for heat removal, but it also increases the heat radiation from the BS onto the cold bore of the magnets. The BS temperature which maximizes the total cooling efficiency increases as a function of SR heat load. At SR levels of 10–40 W/m the optimum is found at 50–100 K [17]. On the other hand, the warmer the BS, the larger is its resulting beam impedance. The latter, together with considerations on vacuum stability (e.g. vapour pressures of CO and CO_2), favors BS temperatures at the lower end of the optimum range, i.e. between 40 and 60 K.

Cryo-pumping of hydrogen may require an operating temperature below 2–3 K for the cold magnets surrounding the beam screen [18]. With a smaller beam-pipe aperture and a larger photon desorption yield, providing sufficient pumping and avoiding pressure instabilities is likely to require a higher BS transparency than for the LHC [18].

The absorption and extraction of SR power is more efficiently achieved at room temperature, e.g. by using dedicated photon stops protruding into the beam tube at the end of each dipole magnet. Similar photon stops are routinely employed in storage-ring light sources. They were also being considered for the VLHC [19], for which a cryo-experiment demonstrated the concept. To capture all of the synchrotron radiation at the FCC-hh such photon stops would need to be spaced no further apart than $\sqrt{2\rho b}(1-\sqrt{1-f})$ (≈ 2 m) where ρ denotes the bending radius (10.4 km), b the chamber half aperture (1.3 cm), and f the fractional reduction of the chamber radius due to the photon stop ($f \approx 1/5$ for a 3-mm protrusion).

Counteracting the radiation damping, during physics runs a continuous longitudinal and transverse noise excitation needs to be applied so as to keep the bunch length

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constant (preventing both component heating and instabilities) and to avoid excessive beam-beam tune shifts [20]. The controlled slow decrease of the transverse emittance, in proportion to the intensity decay, would allow for a dynamic β^* squeeze maximizing the integrated luminosity.

The ratio of injection to full energy should not be larger than for the LHC in view of field quality, impedance, etc. This condition translates into an injection energy of at least 3.3 TeV, which could be realized with 3.6-T magnets in the LHC tunnel or 1-T magnets for a 100-km injector ring.

The transverse instability growth rates scale with the impedance and beam energy as $Z_\perp/E_{\rm beam}$. They are most critical at injection, where a 7–10 times higher beam energy than for the LHC will help. The strongest growth rate due to the arc resistive wall is expected at the lowest (or second lowest) betatron-sideband frequency $\Delta Q f_{\rm rev}$, with ΔQ denoting the fractional tune. The critical impedance at this frequency is proportional to $\sqrt{\rho(B,T)/(\Delta Q f_{\rm rev})}/b^3$. The resistivity ρ depends on the type of chamber coating, its thickness, the temperature, and the magnetic field. For the Cu-coated BS of the FCC-hh ρ is enhanced from LHC values due to the higher BS temperature (by about a factor 4–8 for RRR values of 100–200) and due to the larger magnetoresistance (at 16 T field by a factor of about 2 compared with zero field, or by a factor 1.4 compared with the 8.33-T field of the LHC) [21]. For various reasons, including magnet cost and cooling, the beam-pipe aperture b is likely to be 30% smaller than for the LHC (1.3 cm instead of 2 cm radius). The four times lower revolution frequency $f_{\rm rev}$ further increases the instability growth rate by a factor of two. The larger skin depth at this lower frequency also calls for a thicker copper coating. It needs to be examined whether the latter could withstand the forces generated during a quench of the surrounding magnet. Putting it all together, the instability growth rates expected for a Cu-coated beam screen require a bunch-by-bunch transverse feedback with a damping time of about 10 turns [22]. An alternative concept, which would greatly lower the impedance, is partially coating the beam screen with HTS (e.g., YBCO with $T_c = 85$ K) [23], a technology still to be demonstrated.

The total energy stored in the high-field magnets may exceed 100 GJ, while each of the two 50-TeV proton beams contains about 8 GJ. The systems for machine protection, beam dump, and collimation must be laid out accordingly.

LEPTON COLLIDER

Major challenges are sustaining a short beam lifetime; designing an interaction region with 1.5–2.0% momentum acceptance; achieving a vertical-to-horizontal emittance ratio of 0.1% with colliding beams; and minimizing the cost while maximizing the efficiency of the SRF system.

Due to the unavoidable radiative Bhabha scattering the typical beam lifetime at the FCC-ee is about 40 times shorter than for LEP2 as a result of the much higher luminosity. The short beam lifetime, of less than one hour, can be supported by top-up injection, a scheme which has successfully been used at the KEKB and PEP-II B factories. Top-up injection allows operating the collider at constant magnetic field and with almost constant beam current, thereby avoiding magnet cycles and thermal transients, and greatly facilitating the optics tuning of the accelerator for optimum performance. Top-up injection requires a full-energy injector, i.e. with an energy of up to 175 GeV at least, which can be installed in the same 100-km tunnel as the collider. The injector does not need to operate with the full beam current, but at most a few per cent. The best approach for passing the injector ring around the physics detectors is under investigation.

In contrast to the single ring of the CepC, the FCC-ee collider is conceived as a double ring with separate beam pipes for the two counterrotating lepton beams. This allows independently correcting the optical effects of orbit offsets in arc sextupoles due the “energy sawtooth,” i.e. the orbit variation due to synchrotron-radiation energy loss, which will be different for the two beams. It also avoids parasitic collisions and, thereby, permits operation with a large number of bunches. Finally, the double ring could simplify the absorption and shielding of synchrotron radiation [24], as well as the associated heat extraction.

The synchrotron radiation power per beam is $P_{\rm SR} = (4\pi/3)(r_e/(m_e c^2)^3)E_{\rm beam}^4 f_{\rm rev} n_b N_b/\rho$. The FCC design assumes a constant SR power per beam of 50 MW (i.e. about the same power per unit meter per beam as for LEP2), or 100 MW in total. The electrical wall-plug power is related to the emitted radiation power through the total RF-system efficiency η as $P_{\rm wall} = P_{\rm SR}/\eta$. High efficiencies are evidently desirable. With 100 MW synchrotron radiation power and $\eta \geq 50\%$, the total wall-plug power of the entire FCC-ee complex may be around 300 MW [25].

The vertical beam-beam parameter is approximately $\xi_y \approx r_e N_b \beta_y^*/(2\pi\gamma\sigma_x^*\sigma_y^*)$. Considering head-on collisions the luminosity per IP can be expressed in terms $P_{\rm SR}$ and ξ_y as

$$L = \frac{f_{\rm rev} n_b N_b^2 R_{hg}}{4\pi\sigma_x^*\sigma_y^*} = \frac{3}{8\pi}\frac{(m_e c^2)^2}{r_e^2} P_{\rm SR}\frac{\rho}{E_{\rm beam}^3}\xi_y\frac{R_{hg}}{\beta_y^*} ,$$

with $R_{hg} = \frac{1}{\sqrt{\pi}}(\beta_y^*/\sigma_z)\exp(\beta_y^*/(\sqrt{2}\sigma_z))K_0(\beta_y^{*2}/(2\sigma_x^2))$ denoting the hourglass factor. LEP2 experience [26] and dedicated simulations for FCC-ee suggest that the maximum beam-beam parameter varies with the beam energy as $\xi_{y,\max} \propto 1/\tau^{0.4} \propto E_{\rm beam}^{1.2}$ (τ: damping time). This leads to the following luminosity scaling with energy,

$$L \propto \frac{\eta P_{\rm wall}}{E^{1.8}}\frac{R_{hg}}{\beta_y^*} ,$$

highlighting the importance of β_y^* and η. Though the FCC-ee baseline β_y^* of 1 mm may appear challenging, SuperKEKB, soon to be commissioned at KEK, features a 3–4 times smaller β_y^* of about 300 μm.

Beamstrahlung, i.e. synchrotron radiation emitted during the collision in the field of the opposing beam, increases the steady-state energy spread and bunch length [27, 28]. Its high-energy tail may also limit the beam lifetime [29, 30],

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if beam particles which lose a significant fraction of their energy fall outside of the relative momentum acceptance $\delta_{\rm acc}$.

At low beam energies (running at the Z pole or at the WW threshold) beamstrahlung mainly lengthens the bunches, typically by a few tens of per cent [28] (see Table 1). The additional limit of the beam lifetime due to beamstrahlung, approximated as [29, 30]

$$\tau_{\rm bs} \approx \frac{1}{n_{IP} f_{\rm rev}} \frac{4\sqrt{\pi}}{3} \sqrt{\frac{\delta_{\rm acc}}{\alpha r_e}} \exp\left(\frac{2}{3}\frac{\delta_{\rm acc}\alpha}{r_e\gamma^2}\frac{\gamma\sigma_x\sigma_z}{\sqrt{2}r_e N_b}\right) \frac{\sqrt{2}}{\sqrt{\pi}\sigma_z\gamma^2}\left(\frac{\gamma\sigma_x\sigma_z}{\sqrt{2}r_e N_b}\right)^{3/2},$$

where α denotes the fine-structure constant, is important only at the higher operation energies of FCC-ee (from 240 GeV onward). Even here, it can be made negligibly large by lowering the bunch charge N_b at constant beam-beam tune shift (decreasing the emittance), and increasing the number of bunches in proportion. As a result of such a design optimization the FCC-ee lifetime limitation due to beamstrahlung is several 10 hours at 240 GeV (Higgs factory mode) for a momentum acceptance of $\delta_{\rm acc} = 1.5\%$. With the present parameters at 350 GeV a larger momentum acceptance of $\delta_{\rm acc} = 2.0\%$ is required to obtain a beamstrahlung lifetime of about 1 h. The possibility to achieve such a momentum acceptance is suggested by an example IR design [31]. However, if necessary, to adapt to a lower IR acceptance the emittance could further be reduced, e.g., by shortening the arc cell length.

Figure 5 compares the projected total luminosity performance of FCC-ee and CepC (sum over 4 or 2 IPs, respectively) with those for ILC [32] and CLIC [33], as a function of energy. At the Z pole the FCC-ee luminosity can be increased almost 10-fold by means of a low-emittance crab-waist scheme [30]. Strong-strong beam-beam simulations including beamstrahlung have confirmed the analytically predicted FCC-ee luminosities [28, 30, 34].

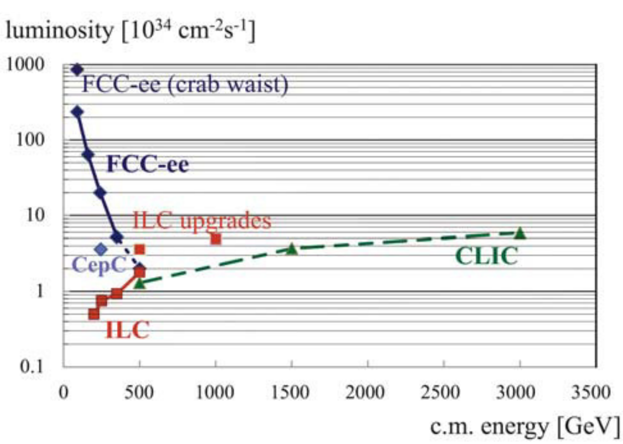

Figure 5: Projected total electron-positron luminosities vs. c.m. energy for various proposed colliders.

For operation at the $t\bar{t}$ threshold (350 GeV), FCC-ee requires a total RF voltage of 11 GV (either per beam or, more economically, shared by the two beams, implying a change in the physical configuration of the RF sections before switching to 350-GeV operation). With an RF gradient of 20 MV/m the effective RF length would be about 600 m, comparable to the corresponding length at LEP2 ($\sim$ 500 m, with a maximum gradient of 7.5 MV/m, and a total voltage of 3.5 GV). The available space would permit for a lower gradient of 15 MV/m and the correspondingly 25% longer RF sections. Currently, an RF frequency of 800 MHz is assumed; the alternative 400 MHz is also being studied.

Using state-of-the-art components, the RF efficiency η, characterizing the conversion of electrical power to beam power, is estimated to be roughly 55% for FCC-ee, or about 3 times higher than for a linear collider. This difference has primarily two reasons [25]: (1) For FCC-ee as for the past LEP2, the klystrons are operated in cw mode at saturation where their efficiency is maximum ($\sim$65%), while the working points of the pulsed klystrons at linear colliders contain margins for RF feedback. (2) For FCC-ee cw operation 100% of RF power is converted into beam power, compared with less than 50% in typical pulsed operation, e.g., of the ILC.

Extrapolating from LEP/LEP2 polarization data to FCC-ee beam energies with comparable energy spread (responsible for depolarization) suggests sufficient transverse polarization for precise energy calibration may be obtained not only at the *Z* pole, but also at the *WW* threshold [35]. Even longitudinal polarization of both beams might be achieved, with the help of spin rotators plus, conceivably, Siberian snakes, but this option requires substantial investigations as well as a strong physics motivation [35]. Another open question is the effect of a possible tunnel non-planarity (which might be desired for geological reasons) on the vertical emittance and, especially, on the polarization.

HADRON-LEPTON COLLIDER

Two options exist for realizing highest-energy lepton-hadron collisions at the FCC (FCC-he), namely colliding an FCC-hh proton (or ion) beam with one of the two FCC-ee lepton beams or with a different electron beam from a separate ERL, as for the proposed LHeC [36]. The conservatively achievable luminosity is of order 10^{34} cm^{-2}s^{-1} for electron beams of either 60 (ERL) or 80–120 GeV (FCC-ee ring) colliding with the 50-TeV protons [37].

Both for FCC-he and for FCC-hh the physics merits and accelerator requirements for providing polarized proton beams, like at RHIC, may need to be further explored.

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