Nuclear Instruments and Methods in Physics Research B 355 (2015) 4–10

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

High-energy physics strategies and future large-scale projects

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ARTICLE INFO

Article history:
Received 1 March 2015
Received in revised form 30 March 2015
Accepted 31 March 2015
Available online 25 April 2015

Keywords:
Colliders
High-energy physics
Storage rings
Crystal channeling
Crystal acceleration

ABSTRACT

We sketch the actual European and international strategies and possible future facilities. In the near term the High Energy Physics (HEP) community will fully exploit the physics potential of the Large Hadron Collider (LHC) through its high-luminosity upgrade (HL-LHC). Post-LHC options include a linear e^+e^- collider in Japan (ILC) or at CERN (CLIC), as well as circular lepton or hadron colliders in China (CepC/SppC) and Europe (FCC). We conclude with linear and circular acceleration approaches based on crystals, and some perspectives for the far future of accelerator-based particle physics.

1. Landscape & possibilities

The discovery of a Higgs boson at two LHC experiments in 2012 has completed the Standard Model (SM) of particle physics (concluding almost 80 years of theoretical and experimental efforts) [1]. The SM is not a full theory, since there are several outstanding questions which cannot be explained within the SM, e.g. the composition of dark matter, cause of universe's accelerated expansion [dark energy/inflation], origin of matter–antimatter asymmetry, neutrino masses, why 3 families?, lightness of Higgs boson, weakness of gravity, etc. These questions imply New Physics. Many of them can be addressed through high-energy and/or high-intensity accelerators. At present knowledge the energy scale of the new physics is unknown.

While operating at center-of-mass (c.m.) energies of 7 and 8 TeV in 2011–13, the LHC has not uncovered any evidence yet for physics beyond the standard model. Possibly new information will be provided by LHC proton–proton collisions at higher c.m. energy (13 and 14 TeV) in 2015–18.

The next quarter of a century will see the full exploitation of the Large Hadron Collider and its high-luminosity upgrade, as requested by the 2013 Update of the European Strategy for Particle Physics [2] and by the US "P5" recommendations [3].

Recognizing that circular proton–proton colliders are the main, and possibly only, experimental tool available in the coming decades for exploring particle physics in the energy range of tens of TeV, the 2013 Update of the European Strategy for Particle Physics also requests CERN to "undertake design studies for accelerator projects in a global context with emphasis on proton–proton and electron–positron high-energy frontier machines ... [which] should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide" in order to be ready "to propose an ambitious post-LHC accelerator project ... by the time of the next Strategy update" [around 2019].

In direct response to this European request, CERN has launched the Future Circular Collider (FCC) study [4,5], the purpose of which is to deliver a Conceptual Design Report and a cost review by 2018. The focus of the FCC study is a 100-TeV c.m. proton–proton collider (FCC-hh), based on 16-T Nb_3Sn magnets in a new 100-km tunnel, with a peak luminosity of $5–20 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The FCC-hh defines the infrastructure requirements. Given the enormous energy stored in the FCC-hh proton beams, machine protection and collimation pose new challenges, with crystal collimation among the options considered. The FCC study also comprises the design of a high-luminosity e^+e^- collider (FCC-ee, formerly TLEP), serving as Z, W, Higgs and top factory, with luminosities ranging from $\approx 10^{36}$ to $\approx 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ per collision point at the Z pole and *t-tbar* threshold, respectively, as a potential intermediate step. In addition, the FCC study considers a proton-lepton (FCC-he) option, with a luminosity of up to $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, reached in collisions of 60-GeV electrons with 50-TeV protons.

The future results from the LHC could also provide the physics case for a 2–3 TeV Compact Linear Collider [6]. A much smaller CERN programme would be a lepton-hadron collider based on the LHC (LHeC [7]) possibly coupled with a gamma-gamma Higgs factory (SAPPHIRE [8]). CERN is also advancing R&D on

http://dx.doi.org/10.1016/j.nimb.2015.03.090
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proton-driven plasma wake-field acceleration [9]. In parallel to these efforts, the proposed International Linear Collider [10] may proceed in Japan, or China could begin the construction of a 54-km circular Higgs factory (CepC [11]). Other large scale facilities, such as a 300-km circular collider, are proposed in the US [12]. The CERN strategy might need to be adapted in response to the worldwide developments and decisions taken elsewhere.

In the following we sketch a few aspects of possible future scenarios including possible evolutions of the CERN complex, with some emphasis on potential applications of crystals and channeling concepts.

2. LEP, LHC & HL-LHC

The Large Electron–Positron – LEP-collider at CERN has been the highest-energy e^+e^- collider in operation so far [13]. Its maximum c.m. energy was 209 GeV, and its peak synchrotron radiation power about 23 MW. LEP operation was terminated in 2000.

LHC is the present frontier accelerator, installed in the same tunnel as LEP. It should provide proton–proton collisions at the design c.m. energy of 14 TeV and a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, achieved with 1.15×10^{11} p/bunch and 2808 bunches/beam., so that each of the two colliding proton beams contains an energy of ~360 MJ .

The LHC design study began in 1983. 11 years later, 1994, the CERN Council approved the LHC project. In the year 2010 first collisions occurred at 3.5 TeV beam energy. For 2015, that is 32 years after the start of the design study, first collisions at close to the design energy are expected. Evidently, now is the time to start preparing a new collider facility for the 2030s or 2040s.

The official roadmap for the LHC and HL-LHC (from 2025 onwards) extends through the year 2035, by which time 3000 fb^{-1} of integrated luminosity should be accumulated (i.e. 100× the present [2014] value). Specifically, the HL-LHC operation will be characterized by a constant levelled luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, and by an event pile-up of about 140 (almost 10 times the LHC design value). The HL-LHC should produce about 250 fb^{-1}/year. More than 1.2 km of LHC plus technical infrastructure (e.g. cryo and powering) will be modified to render this dramatic performance increase possible. Most importantly, the HL-LHC relies on, and will promote, a technology transition from *Nb-Ti* to Nb_3Sn superconductor for hadron-collider magnets. This change of technology will allow field increases by a factor of up to two [14]. Two prototype dipole magnets have already surpassed the HL-LHC design field of 11 T [15].

3. ILC

The proposed International Linear Collider (ILC) [10] is a straight e^+e^- collider, with a total length of 30 km for a c.m. energy of 500 GeV (baseline) and 50 km at 1 TeV (energy upgrade). Its two linacs are based on SC acceleration structures at 1.3 GHz with an accelerating gradient of about 30 MV/m. A Technical Design Report for the ILC was completed in 2012. The ILC technology is being used for European XFEL now under construction at DESY. The present time line foresees a construction start in 2018 and first physics around 2027. The Japanese High Energy Physics community has expressed a strong interest in hosting the ILC [16]. The chosen candidate site is 北上市 (Kitakami) in Northern Japan. The proposal is under review by the Japanese ministry MEXT.

4. European strategy

The European Strategy for Particle Physics was updated in 2013 based on numerous inputs and discussions, including a lively symposium at Krakow the year before. As a result, the top priority of European particle physicists is the full exploitation of the LHC. The second priority is for CERN to undertake design studies for accelerator projects in a global context, with emphasis on proton–proton and electron–positron high-energy frontier machines. This strategy was formally adopted by the CERN Council at a special meeting in Brussels [2].

One response to the Strategy request is the continuation of the design of the Compact Linear Collider (CLIC) [6], which has been ongoing since the early 1980s, with several significant changes over the years. CLIC is another higher-energy linear e^+e^- collider, with a total main-linac length of ~11 km at 500 GeV c.m. and ~48 km for 3 TeV. A proposed site stretches from Geneva toward Lausanne. The accelerating gradient of CLIC, with a normal conducting warm linac, is 100 MV/m, and hence more than 3 times higher than the ILC gradient, explaining its greater compactness. Key technologies for CLIC are two-beam acceleration where an intense lower-energy drive beam is decelerated to locally generate the RF energy used for accelerating the main beam; the generation of the drive beam, and X-band RF (12 GHz). The CLIC Conceptual Design Report, with about 1400 authors and over 1200 pages, was published in 2012 [6].

5. FCC & CEPC/SPPC

5.1. FCC study

As a direct response to the aforementioned request from the European Strategy, CERN has launched the Future Circular Collider (*FCC*) Study [4,5], with the mandate to complete a Conceptual Design Report (CDR) and cost review in time for the next European Strategy Update (2018). Presently an international collaboration is being formed with the goal to design a 100 TeV *pp*-collider (*FCC-hh*) together with an 80–100 km tunnel infrastructure in the Geneva area (Fig. 1), as well as an e^+e^- collider (*FCC-ee*) as a potential intermediate step (serving as Higgs, *Z*, *W*, and top factory), and to also study a *p-e* (*FCC-he*) collider option.

Dipole magnets with a field of about 16 T would allow 100 TeV *pp* collisions in a ring of 100 km circumference. These parameters represent the study baseline.

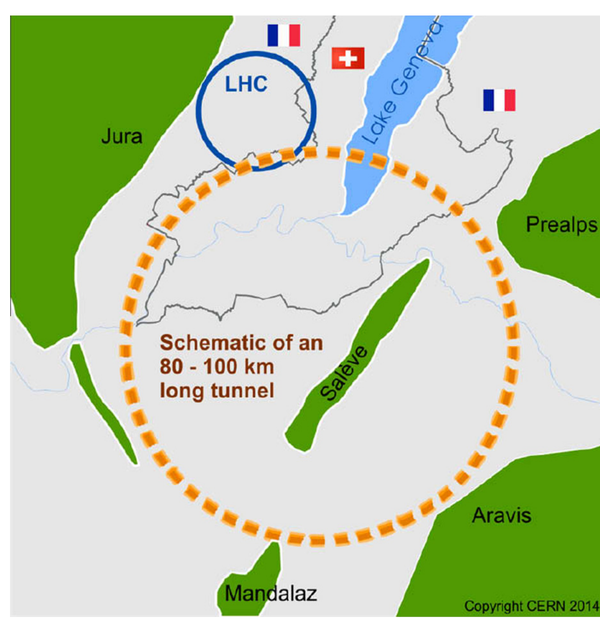

Fig. 1. Schematic of an 80–100 km FCC tunnel infrastructure in the Geneva basin.

A similar proposal of a large circular e^+e^- Higgs factory and later high-energy hadron collider is the CepC/SppC of CAS-IHEP [11]. One of the candidate sites in China is Qinhuangdao (秦皇岛), 300 km from Beijing, accessible by car (3 h) or high-speed train (1 h). This region is also known as the Chinese Toscana. Previous studies of large circular collider have been, or are, ongoing in Italy (ELOISATRON 300 km), US (SSC 87 km, VLHC/VLLC 233 km) and Japan (TRISTAN-II, 94 km).

Extrapolating the historical evolution of c.m. energies for e^+e^- colliders, hadron colliders, and lepton-hadron collider, into the future [17] shows that higher energy gains, of still an order of magnitude every 20 or 30 years, are possible for hadron colliders. For these the center-of-mass energy is given by the remarkably simple equation

$$E_{\mathrm{cm}} = 2\, ec\, B\, \rho,$$

where B denotes the magnetic field of the arc dipoles and ρ the bending radius (hence the size of the collider). The FCC studies pushes both variable parameters: the field by about a factor of two, and the circumference by a factor close to 4.

FCC key technologies include 16 T superconducting magnets, superconducting RF cavities, RF power sources, affordable and reliable cryogenics, as well as novel approaches for reliability and availability.

5.2. FCC-hh

The FCC pp collider (FCC-hh) opens three physics windows: (1) Access to new particles in the few TeV to 30 TeV mass range, beyond LHC reach; (2) immense or much-increased rates for phenomena in the sub-TeV mass range leading to increased precision w.r.t. LHC and possibly ILC; and (3) access to very rare processes in the sub-TeV mass range allowing the search for stealth phenomena, invisible at the LHC.

Table 1 summarizes the baseline beam parameters of *FCC-hh* [18] and compares them with those for the LHC and the HL-LHC. Noteworthy are the figures for the event pile up (number of events per crossing) – which, at the same luminosity of 5×10^{-34} cm^{-2} -s^{-1}, exceeds the *HL-LHC* value because of a slightly higher cross section –, the total synchrotron radiation power of close to 5 MW ($\sim$500 times the LHC value) in a cold environment, and the longitudinal damping time of about 30 min (to be compared with half a day at the LHC).

Over the last two decades Nb_3Sn high-field magnet technology has made great strides forward, thanks to ITER conductor development, US-LARP and EC co-funded R&D activities and the US DOE core development programme. The High-Luminosity upgrade of the *LHC* (*HL-LHC*), which is expected to be completed by 2025, includes a few tens of Nb_3Sn dipole and quadrupole magnets. The *HL-LHC*, thereby, prepares the technology base for the *FCC-hh*. Conceptual cost-optimized designs of *FCC* 15–20 T high field dipole magnets in block-coil geometry are illustrated in Fig. 2.

One particular challenge for the FCC-hh is machine protection, as the energy per proton beam rises from 0.4 GJ at the LHC to 8 GJ for the FCC-hh, an increase by a factor of 20. The FCC-hh beam energy corresponds to the kinetic energy of an Airbus A380 at a speed of 720 km/h. This can melt 12 tons of copper, or drill a 300-m long hole.

Directly related to this challenge is the design of the collimation system, which is most exposed to an errant beam in case of a failure. For the *FCC-hh* collimation an LHC-type solution is the baseline, but other approaches should be investigated, such as (1) hollow e^- beam as collimators, (2) *crystals to extract particles*, and (3) renewable collimators. When crystals are used, either channeling or volume reflection could be taken advantage of. In the channeling mode, a special crystal cut suppresses the dechanneling and can increase the channeling fraction from 85% to 99% [20]. In the volume reflection mode, the multiple volume reflection effect can be used to increase the deflection angle 5 times [21].

The UA9 experiment at the CERN SPS has demonstrated a strong suppression of the nuclear loss rate (including diffractive) in the aligned crystal, as is illustrated in Fig. 3. This experiment has also provided a proof of principle for crystal staging. A set of 6 crystals (each 2 mm long) mounted in series was used to reflect 400 GeV/c protons by 40 ± 2 µrad (corresponding to an effective field of 16 T), with an efficiency 0.93 ± 0.04 [22].

Another application of channeling effects and crystals is in the particle-physics detectors. Crystal-based calorimeters can exploit strong-field QED effects to enhance radiation and pair production, leading to reduced radiation length and lower calorimeter thickness, and to an improved mass resolution [23].

The FCC-hh injector complex can be based on the existing and planned (HL-LHC/LIU) injector chain. The High Energy Booster (HEB) is installed either in the LHC tunnel (e.g. a modified LHC) or in the new FCC tunnel. The injector and also the pre-injectors can feed fixed target experiments, in parallel to serving as FCC injectors. The fixed target physics could be based on crystal extraction [24].

5.3. FCC-ee

The physics requirements for the interim lepton collider, *FCC-ee*, comprise highest possible luminosity for a wide physics program ranging from the Z pole to the t production threshold, at beam energies between 45 and 175 GeV. The main physics programs are: (1) operation at 45.5 GeV beam energy for running at the Z pole as “TeraZ” factory and for high precision M_Z and Γ_Z measurements; (2) 80 GeV: W pair production threshold; (3) 120 GeV: ZH production (maximum rate of H's); (4) 175 GeV: *t-tbar* threshold. Some measurable beam polarization is expected up to $\geqslant$80 GeV, which will allow for precise beam energy calibration at the Z pole and at the W-pair threshold. Key features are the small vertical beta function at the collision point, β_y^*, of only 1 mm, and a constant value of 100 MW for the synchrotron radiation (SR) power assumed at all energies. The power dissipation then defines the maximum beam current at each energy. Eventually a margin of a few percent may be required for losses in the straight sections.

Table 2 compares the baseline parameters of *FCC-ee* [25] with those of LEP-2. For operation at the Z pole an alternative parameter set with almost ten times higher luminosity [26] is also included. The latter considers transversely smaller (lower emittance), but longer bunches (with reduced HOM losses as a welcome

Table 1
Baseline parameters of *FCC-hh* compared with *LHC* and *HL-LHC*. Numbers in curly brackets indicate parameters for 5 ns bunch spacing, those in rectangular brackets the luminosity potential.

Parameter	*LHC*	*HL-LHC*	*FCC-hh*
c.m. energy (TeV)	14		100
Dipole field (T)	8.33		16
Circumference (km)	26.7		100
Peak luminosity (10^{34} cm^{-2} s^{-1})	1	5	5 [→25]
Bunch spacing (ns)	25		25 {5}
Events/bunch crossing	27	135	170 {34}
Bunch population (10^{11})	1.15	2.2	1 {0.2}
Initial normalized transverse emittance (µm)	3.75	2.5	2.2 {0.44}
Interaction-Point (IP) beta function (m)	0.55	0.15	1.1 [→0.3]
IP beam size (µm)	16.7	7.1	6.8 {3}
Synchrotron rad. (W/m/aperture)	0.17	0.33	28
Critical energy (keV)	0.044		4.3
Total synchrotron radiation power (MW)	0.007	0.015	4.8
Longitudinal damping time (h)	12.9		0.54

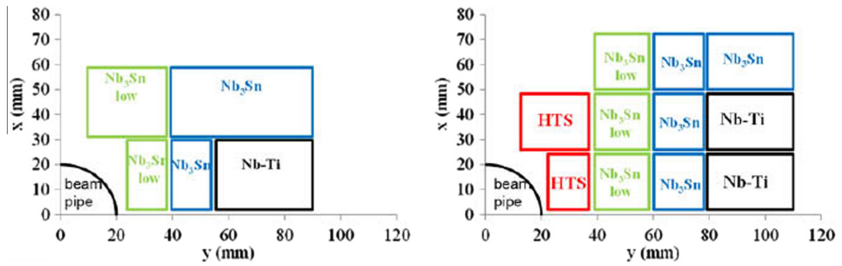

Fig. 2. Conceptual designs of 15 or 16 T (left) and 20-T dipole magnets (right) [19]. Only a quarter of one magnet is shown.

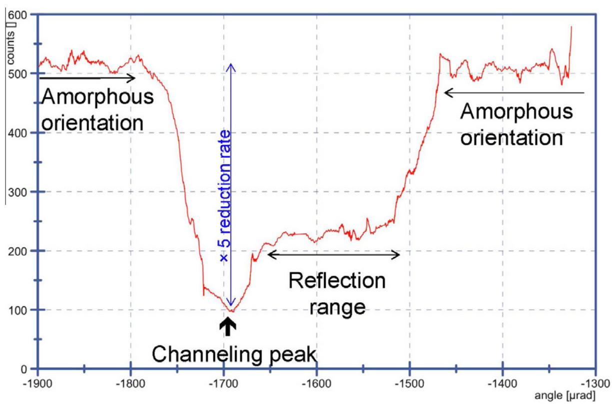

Fig. 3. Nuclear loss rate seen by a scintillator telescope downstream of the crystal as a function of crystal orientation angle, revealing the narrow channeling and (wide-acceptance) volume reflection regimes (Courtesy W. Scandale).

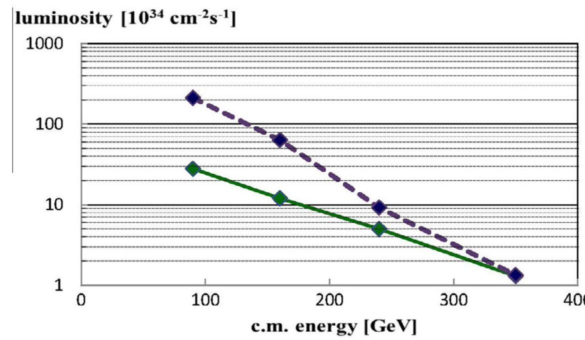

Fig. 4. FCC-ee luminosity per IP as a function of c.m. energy. Both the baseline (solid) [25] and an improved collision scheme (dashed) [26] are presented.

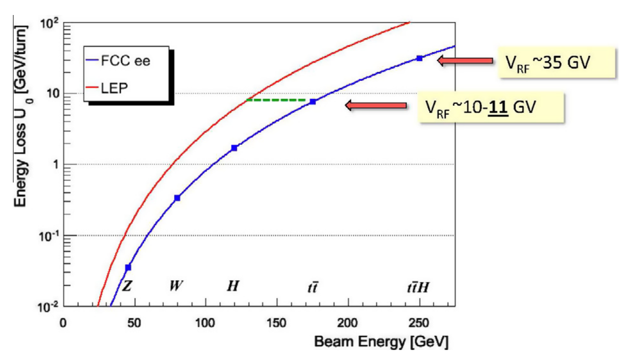

Fig. 5. Energy loss per turn as a function of beam energy for *LEP* and for *FCC-ee*, translating into a minimum RF voltage required [29].

Table 2
Baseline parameters of *FCC-ee* [25] compared with *LEP-2*. *For Z* running an alternative scenario based on crab waist collisions [26] is also indicated.

Parameter	LEP-2	FCC-ee				
		Z	*Z* (c.w.)	*W*	*H*	*t*
E_{beam} (GeV)	104	45	45	80	120	175
Circum-ference (km)	26.7	100	100	100	100	100
Current (mA)	3.0	1450	1431	152	30	6.6
$P_{SR,tot}$ (MW)	22	100	100	100	100	100
# bunches	4	16,700	29,791	4490	1360	98
N_b (10^{11})	4.2	1.8	1.0	0.7	0.46	1.4
ε_x (nm)	22	29	0.14	3.3	0.94	2
ε_y (pm)	250	60	1	1	2	2
β_x^* (m)	1.2	0.5	0.5	0.5	0.5	1.0
β_y^* (mm)	50	1	1	1	1	1
σ_y^* (nm)	3500	250	32	84	44	45
$\sigma_{z,SR}$ mm)	11.5	1.64	2.7	1.01	0.81	1.16
$\sigma_{z,tot}$ (mm) (w BS)	11.5	2.56	5.9	1.49	1.17	1.49
Hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73
Beam-b. p. ξ_y/IP	0.06	0.03	0.175	0.06	0.093	0.092
L/IP (10^{34} cm^{-2} s^{-1})	0.01	28	212	12	6	1.7
τ_{beam} (min)	434	298	39	73	29	21

side-effect) colliding at 30-mrad crossing angle together with crab-waist sextupoles. Fig. 4 presents the expected luminosity performance per interaction point (IP), assuming up to four IPs in total, as a function of center-of-mass energy.

Arc optics exists for the four operational energies and both running scenarios [27]. In all cases the horizontal design emittance is less than half the respective target value, leaving margin for the effect of errors and, possibly, high-intensity effects.

Regardless of the collision scheme, the large number of bunches at the *Z*, *W* and *H* energies requires two separate rings, and the short beam lifetime, τ_{beam}, limited by radiative Bhabha scattering at the high luminosity, calls for quasi-continuous injection (top-up) requiring an on-energy injector in the collider tunnel [28].

Fig. 5 shows the SR energy loss per turn as a function of beam energy [29]. For each collision energy this loss translates into a minimum RF voltage, determined by the overvoltage for a decent quantum lifetime and by the momentum acceptance needed with regard to beamstrahlung. At the t-tbar threshold this RF voltage amounts to about 11 GV, which is the maximum voltage considered for the *FCC-ee* design. Operation at 500 GeV c.m. would require a larger RF voltage of 35 GV.

The RF system requirements are characterized by two regimes, namely operation at high gradient for *H* and *t* with up to ~11 GV total RF voltage, and high beam loading with currents of ~1.5 A at the *Z* pole. The RF system must be distributed over the ring in order to minimize energy-related orbit excursions. At 175 GeV beam energy, the total energy loss amounts to about 4.5% per turn and optics errors driven by energy offsets may have a significant effect on the energy acceptance. The *FCC-ee* design aims at SC RF cavities with cw gradients of ~20 MV/m, and an RF frequency of 800 MHz (current baseline). The "nano-beam/crab waist" scheme

[26] favors lower frequency, e.g. 400 MHz. The conversion efficiency of wall plug to RF power is critical. R&D is needed to push this efficiency far above 50% (a value achieved at LEP-2).

The luminosity of the *FCC-ee* collider can be written as

$$L = \frac{f_{rev} n_b N_b^2}{4\pi\sigma_x\sigma_y} HF,$$

where f_{rev} denotes the revolution frequency, n_b the number of bunches per beam, N_b the bunch population, σ_x the horizontal rms IP spot size, σ_y the vertical rms IP spot size, H the luminosity reduction due to the hourglass effect, and F the additional luminosity loss factor due to a crossing angle. The product en_bNf_{rev} (with e the elementary charge) is equal to the beam current, which at constant SR power decreases as $1/E^4$. Another constraint comes from the nonlinear beam–beam interaction, the strength of which is characterized by the beam–beam parameter ξ. The vertical beam–beam parameter, roughly equal to the maximum beam–beam tune shift (per IP), is

$$\xi_y = \frac{\beta_y{}^* r_e N_b}{2\pi\gamma\sigma_y(\sigma_x+\sigma_y)} \sim \frac{\beta_y{}^* N_b}{E\sigma_y\sigma_x}$$

The beam–beam parameter is a measure of the tune spread in the beam. According to the experience at all past circular colliders the beam–beam parameter is limited to some maximum value, a fraction of an integer. Using the definition for ξ_y, introducing the limit from the SR power, and neglecting hourglass and crossing-angle effects, the luminosity scaling becomes

$$L \propto \frac{P_{SR}\xi_y}{E^3\beta_y{}^*}$$

Energy-dependent beam–beam parameter limits for 4 IPs can be scaled from LEP data and a physical model, using the inferred relation [30]

$$\xi_{y,max} \propto \frac{1}{\tau^{0.4}} \propto E^{1.2},$$

where τ refers to the radiation damping time. This scaling also is in reasonable agreement with beam–beam simulations for *FCC-ee* [26,31–33].

Including the variation of the maximum beam–beam parameter with energy, we finally obtain [29]

$$L \propto \frac{P_{SR}}{E^{1.8}\beta_y{}^*},$$

i.e. the loss in luminosity with energy is much less dramatic than a naïve look at the SR power might tend to suggest. In addition, the beam–beam limit may be raised significantly with crab-waist collision schemes [26,32,33]. The above scaling is valid as long as the strength of the interaction is dominated by the classical beam–beam interaction. At highest energies a different mechanism may constrain the beam parameters, namely beamstrahlung, i.e. the synchrotron radiation emitted during the collision in the field of the opposing bunch. The hard photon emission at the IPs can become a lifetime or performance limit for large bunch populations (N_b), small horizontal beam size (σ_x) and for short bunches (σ_z). The lifetime due to beamstrahlung depends on the bending radius ρ experienced during the collision,

$$\frac{1}{\rho} \approx \frac{N_b}{\gamma\sigma_x\sigma_z},$$

and on the relative energy acceptance η as [26,34]

$$\tau_{bs} \propto \frac{\rho^{3/2}\sqrt{\eta}}{\sigma_z\gamma^2}\exp(A\eta\rho/\gamma^2),$$

where A is a constant.

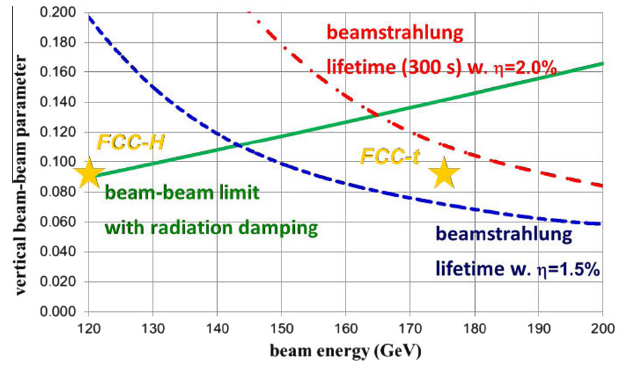

Fig. 6. Limits due to classical beam–beam effect and due to beamstrahlung, with two different values for the energy acceptance, as a function of beam energy [35].

To ensure an acceptable lifetime, the product $\rho \times \eta$ must be sufficiently large, which can be achieved by operating with flat beams (large σ_x), with long bunches, and with a large momentum acceptance of the lattice (about 1.5–2% is required; for comparison, LEP had an acceptance of less than 1%, and SuperKEKB is designed for η ~1.5%).

The transition from the beam–beam dominated regime to the beamstrahlung-dominated regime depends on the momentum acceptance, as is illustrated in Fig. 6, considering a vertical emittance of 2 pm and $\beta_y{}^*$ = 1 mm. The beamstrahlung lifetime is a steep function of the energy acceptance [26,34–36].

SuperKEKB [37] with beam commissioning to start in 2015, will demonstrate several of the *FCC-ee* key concepts, such as top-up injection at high current; an extremely low $\beta_y{}^*$ of 300 μm (*FCC-ee*: 1 mm); an extremely low beam lifetime of 5 min (*FCC-ee*: ⩾20 min); a small emittance coupling of $\varepsilon_y/\varepsilon_x \sim 0.25\%$ (comparable to *FCC-ee*); a significant off momentum acceptance of ± 1.5% (similar to the acceptance required for *FCC-ee*); a sufficiently high e^+ production rate of 2.5x10^{12}/s (*FCC-ee* needs less than 1.5×10^{12}/s for top-up operation, at all energies). SuperKEKB goes beyond the *FCC-ee* requirements for many of these parameters.

Beside the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection. The booster requires an RF system of the same size as the collider, but at low power (~MW). The top up frequency is expected to be around ~0.1 Hz, and the booster injection energy 10–20 GeV. The booster ring should bypass the particle-physics experiments. Upstream of the booster a pre-injector complex for e^+ and e^- beams of 10–20 GeV is required. The SuperKEKB injector appears to be almost suitable.

Polarized beams can be of interest for two reasons [38]: (1) they allow for an accurate energy calibration using resonant depolarization, which will be a crucial advantage for measurements of M_Z, Γ_Z, and M_W, with expected precisions of order 0.1 MeV; and (2) they are necessary for any physics programme with longitudinally polarized beams, which would, however, also require that the transverse polarization be rotated into the longitudinal plane at the IP using spin rotators, e.g. as at HERA. Electron integer spin resonances are spaced by 440 MeV.

Possible crystal applications for future e^+e^- colliders, like FCC-ee, ILC and CLIC, include (1) faster electromagnetic shower generation [23], (2) consequently smaller electromagnetic calorimeters [23], (3) generation or measurement of electron beam polarization [39], (4) enhanced positron sources [40], and (5) $e^{\pm}$ crystal collimation [41].

5.4. FCC-he

In 2012 a conceptual design report was published for the Large Electron Hadron Collider (LHeC) [7], which aims at colliding

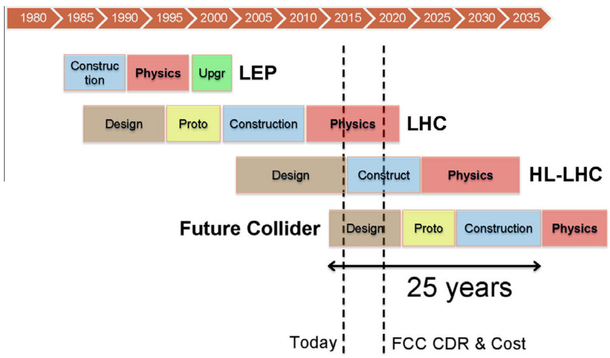

Fig. 7. Time line of high-energy physics energy-frontier projects since 1980 with an extrapolation to the Future (Circular?) Collider.

high-energy electrons (positrons) with one of the two proton beams circulating in the LHC. The two options considered for realizing the lepton branch of this collider are (1) a ring-ring collider with an additional electron ring installed in the LHC tunnel and bypasses around the LHC experiments and (2) a recirculating linac with-energy recovery in a new tunnel of about 9 km circumference, overlapping with the LHC only locally at a single interaction point. Similar two options for FCC: namely the FCC-he could be realized either (1) as a ring-ring collider or (2) as an ERL-ring collider, using the lepton beam from the LHeC ERL (if built) or a new facility.

5.5. FCC time line & collaboration status

The FCC study plan matches the time scale of high-energy frontier physics sketched in Fig. 7. After the kick-off meeting in February 2014, detailed work on the FCC-ee design has started. The wide scope of the FCC study leaves room for many interesting investigations. At present, the study emphasis is shifting toward parameter optimization and the choice between alternatives. Various technologies need dedicated design efforts, such as magnets, SRF, collimators, vacuum system, etc.

The FCC study [4,5] is presently being formalized through memoranda of understanding. More than 40 institutes from around the world, in particular from Europe, Asia and North America, have already formally joined the FCC study. In parallel, an international collaboration board with representatives from all study participants has been set up. At the preparatory collaboration-board meeting on 9–10 September 2014, Leonid "Lenny" Rivkin from PSI and EPFL (Switzerland) was unanimously elected as interim Collaboration Board Chair. The first annual *FCC* workshop will be held at Washington DC in March 2015 [42], jointly organized by CERN and the US DOE's Office of Science, and marks an important milestone of the FCC study, namely the end of the "weak interaction" phase.

6. Ultimate colliders

To go much beyond the FCC entirely new concepts will be needed.

One promising path is circular crystal colliders (CCCs), where bent crystals, with an effective field of several 100 or 1000 T, take on the role of dipole or quadrupole magnets in present-day accelerators, as is sketched in Fig. 8. Unlike conventional storage rings where particles are accelerated by raising the dipole magnetic field, in CCCs the bent crystals, defining the ring geometry, are static and the stored charged particles are accelerated instead by induction RF units [43,44]. Fig. 9 presents a possible evolution of

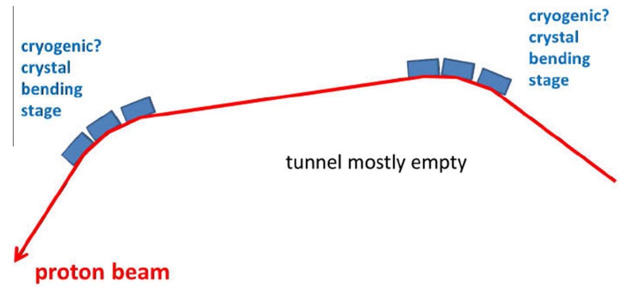

Fig. 8. Schematic of a circular crystal collider.

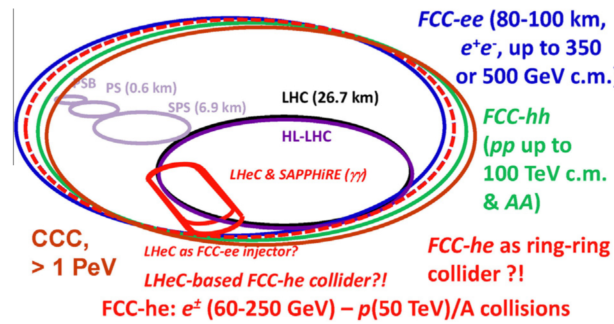

Fig. 9. Possible long-term evolution of the CERN/FCC complex with 1-PeV CCC as its final stage.

the circular CERN/FCC complex with a 1000-TeV CCC as its final stage.

Dielectric materials (quartz, diamond, garnets,...) employed for dielectric-wakefield acceleration (DWAC) would have higher breakdown limits than metal. The dielectric structures, e.g. with an aperture of several 100 nm at $\lambda = 800$ nm [45], would be driven in the THz range, at optical wavelengths or in the near-IR regime, and provide accelerating gradients of 1–3 GV/m. They could be excited by an e^- beam or by a laser (either by an external fiber laser or by an integrated semiconductor laser) [17].

Plasmas can sustain even higher gradients, of $G \approx 100$ GV/m (n_0 $[10^{18}\,\mathrm{cm}^{-3}])^{1/2}$ with a typical plasma density of $n_0 \approx 10^{17}$–10^{18} -cm^{-3}. The plasmas could also be driven by lasers or e^- beams, and in addition by p beams. The repetition rate depends on the pulse rate of the driver, which for lasers may be up to a few kHz with an accelerated charge of 50 pC per bunch [46]. "Unlimited" acceleration is predicted to be possible [47].

Even more interesting would be acceleration in crystal channels. Here, thanks to the higher density, gradients are even higher, of order $G \approx 10$ TV/m (n_0 $[10^{22}\,\mathrm{cm}^{-3}])^{1/2}$ with $n_0 \approx 10^{22}$–10^{23} cm^{-3}. The crystal accelerators would be driven by X-ray lasers (now/soon available, e.g. at SLAC LCLS, RIKEN Spring-8, European XFEL, PSI SwissFEL, ...) A maximum energy of the crystal accelerator is set by radiation emission due to betatron oscillations between crystal planes, amounting to $E_{max} \approx 300$ GeV for e^+, 10^4 TeV for muons, 10^6 TeV for p [17,48,49]. [It is unclear to the author why there is no equivalent limit for lower-density plasmas.] Operation at 10 TV/m would require a disposable crystal accelerator, while at 0.1 TV/m the crystal accelerator would be reusable. A possible laser drive could consist of side injection of X-ray pulses using long fibers. From the above limit of only 400 GeV, we conclude that $e^\pm$ beams may soon run out of steam in the high-gradient world [17]. To overcome this limit, we must change the particle type, and e.g. use muons instead of electrons to realize a linear X-ray crystal muon collider (XRCMC) [17]. Possible challenges would be the muon production rate and the neutrino

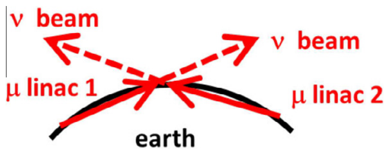

Fig. 10. Minimizing the neutrino radiation impacting the earth for a linear muon collider.

radiation. The sketch in Fig. 10 illustrates how the neutron radiation could be mitigated by colliding with a natural vertical crossing angle.

Both the circular crystal collider and the linear crystal muon collider could move the accelerator energy frontier another 3–4 orders of magnitude toward the the Greisen–Zatsepin–Kuzmin limit ("GZK limit") characterizing the highest-energy particles impacting Earth from outer space.

An ultimate limit of electromagnetic acceleration arises from the breakdown of the vacuum at the Schwinger critical field for e^+e^- pair creation [48]: $E_{cr} \approx 10^{18}$ V/m (which follows from the equation $\hbar/(m_e c)$ e $E_{cr} \sim m_e c^2$, i.e. Compton wavelength times critical field equal the rest mass of an electron–positron pair). Reaching the Planck scale of 10^{28} eV at the critical field would need a 10^{10} m long accelerator [equal to 1/10th of the distance between earth and sun]. In the 1990s this possibility of building a Planck-scale collider has been judged "*not [to be] an inconceivable task for an advanced technological society*" [48].

7. Conclusions

A bright future lies ahead for accelerator-based High-Energy Physics. The HL-LHC prepares the FCC technology. The Channeling conferences provide tools which can enhance the FCC performance and already prepare for the future machines following the FCC. Several different routes exist toward 10 TeV/100 TeV and 1 PeV collisions, e.g. a linear path: ILC → CLIC → DWAC → XRCMC, and a circular path: FCC-ee → FCC-hh → CCC. Crystals are a key ingredient for the final stages of both routes, where they are used either for bending or for acceleration. Eventually an outer-space solar-system accelerator will be needed to reach the Planck scale.

Acknowledgements

I am grateful to many colleagues, in particular V. Shiltsev, for material and stimulating discussions. This work was supported, in part, by the European Commission under the FP7 Capacities project EuCARD-2, grant agreement 312453.

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