HIGGS FACTORY CONCEPTS*

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Abstract

Designs for future high-energy circular electron-positron colliders are based on both established and novel concepts. An appropriate design will enable these facilities to serve not only as “Higgs factories”, but also as Z, W and top factories, and, in addition, to become a possible first step to a higher-energy hadron collider.

PAST AND FUTURE

Figure 1 illustrates the successful history of circular e^+e^- colliders. Since 1970 the luminosity has constantly increased, on average by more than an order of magnitude per decade. SuperKEKB, presently being commissioned, will mark the next major step in the vertical direction. Future contenders are the e^+e^- collider of the CERN-hosted Future Circular Collider (FCC) study [1, 2], called FCC-ee, and the Circular Electron Positron Collider [3, 4], known as CEPC, studied by a collaboration based at IHEP Beijing.

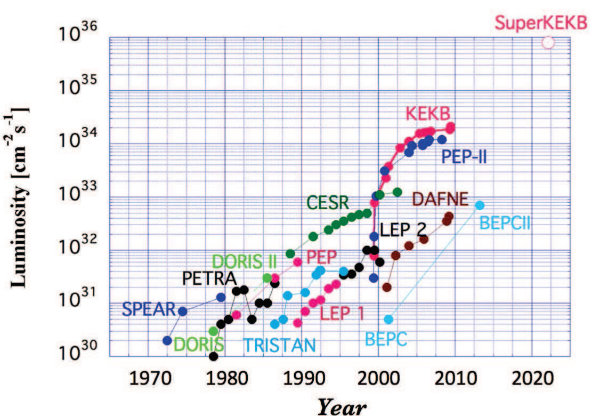

Figure 1: Luminosity trends of circular e^+e^- colliders (Courtesy Y. Funakoshi).

HIGGS FACTORY PHYSICS

In order to support extremely high precision tests of the standard model along with unique searches for rare decays, the proposed “Higgs factories” should operate over a wide range of high beam energies, from about 35 GeV to above ∼175 GeV, For comparison, the maximum beam energy reached at LEP2 was 104.5 GeV. The FCC-ee physics programme [5] may include: (1) $\alpha_{\rm QED}$ 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/beam), where FCC-ee would serve as a “Tera-Z” factory for high precision M_Z and Γ_Z measurements and allow searches for extremely rare decays (also enabling the hunt for sterile right-handed neutrinos); (3) running at the H pole (63 GeV/beam) for H production in the s channel, with mono-chromatization, e.g. to map the width of the Higgs and measure the electron Yukawa coupling; (4) operation at the W pair production threshold (∼80 GeV/beam) for high precision M_W measurements; (5) operation in the ZH production mode (maximum rate of H’s) at 120 GeV; (6) operation at and above the $t\bar{t}$ threshold (∼175 GeV/beam); and (7) operation at energies above 175 GeV per beam, should a physics case for the latter be made. Scaling from LEP, at FCC-ee some beam polarization is expected for beam energies up to about 80 GeV [6], permitting an extremely precise energy calibration for the Z and W modes of operation.

The Higgs factories FCC-ee and CEPC would also each be a possible first step towards a future highest energy hadron collider, called FCC-hh and SPPC, respectively.

LESSONS LEARNT

A key design approach consists in exploiting the lessons and recipes from past and present colliders. The demonstrated successful ingredients can be combined so as to optimize the performance and to achieve extremely high luminosity at high energy. This approach is sketched schematically in Fig. 2.

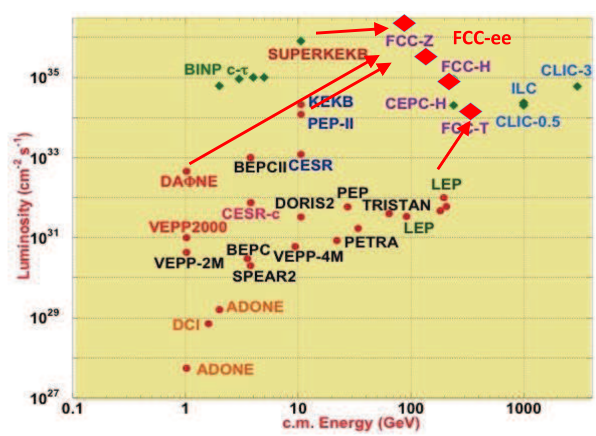

Figure 2: Luminosity as a function of c.m. energy for past, present and future e^+e^- colliders. The proposed FCC-ee and CEPC exploit lessons and recipes from precedent colliders.

At LEP and LEP-2 the operation at high beam energy (up to 104.5 GeV/beam) was demonstrated as well as the handling of synchrotron radiatoin with critical photon energies at the 1 MeV level. The two B-factories at SLAC and KEK, PEP-II and KEKB, demonstrated the operation with high beam currents of up to a few Ampere, and smooth operation with top-up injection. At DAΦNE the first implenentation of crab-waist collisions [7, 8] led to a dramatic luminosity

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increase. SuperKEKB, now being commissioned, will prepare the path for operation at extremely low β_y^* (~ 0.3 mm). It also includes a positron source which would be quite adequate for all operation modes of the proposed Higgs factories. Self-polarized lepton beams were established at HERA and LEP, by means of harmonic spin matching. Operational experience and impressive availability levels (e.g. of the cryogenics systems) from the LHC will also help guide the design of the future machines.

PARAMETERS AND CONSTRAINTS

The beam current is limited by the total synchrotron radiation power per beam $P_{\rm SR}$,

$$P_{\rm SR} = n_b N_b \frac{c C_\gamma E^4}{\rho C} , \qquad (1)$$

where n_b denotes the number of bunches per beam, N_b the bunch population, c the speed of light, E the beam energy, ρ the bending radius in the arc dipoles, C the ring circumference, and $C_\gamma = (4\pi/3) r_e/(m_e c^2)^3 \approx 8.846 \times 10^{-5}$ m/GeV^3, with m_e the electron rest mass and r_e the classical electron radius. All designs assume that other beam power losses, such as those due to higher-order modes or electron cloud, are small compared with the synchrotron radiation power.

Both FCC-ee and CEPC consider two interaction points (IPs) as baseline. The preliminary CEPC design [3] foresees head-on collisions. The FCC-ee design is based on a crossing angle with a crab-waist collision scheme [9].

For collisions with a horizontal full crossing angle θ_c the Piwinski angle is defined as

$$\phi_{\rm piw} \equiv \frac{\sigma_z \theta_c}{2\sigma_x^*} , \qquad (2)$$

where σ_z signifies the rms bunch length (in collision), and σ_x^* the horizontal rms beam size at the collision point. Crab-waist collisions increase the luminosity if $\phi_{\rm piw} \gg 1$.

The classical strength of the beam-beam interaction is characterized by the two beam-beam parameters [10]

$$\xi_x = \frac{r_e N_b}{2\pi\gamma} \frac{\beta_x^*}{\sigma_x^{*2}(1+\phi_{\rm piw}^2)} \qquad (3)$$

$$\xi_y = \frac{r_e N_b}{2\pi\gamma} \frac{\beta_y^*}{\sigma_y^* \sigma_x^* \sqrt{1+\phi_{\rm piw}^2}} \qquad (4)$$

where $\gamma = E/(m_e c^2)$ is the relativistic Lorentz factor, and $\beta_{x(y)}^*$ the horizontal (vertical) beta function at the IP. With a large Piwinski angle the vertical beam-beam parameter — a measure of the beam-beam induced tune shift — is much larger than the horizontal one. We may, therefore, expect that beam-beam effects will first be encountered in the vertical plane.

The luminosity per IP is [11]

$$L = \frac{c}{C} \frac{n_b N_b^2}{4\pi \sigma_y^* \sigma_x^* \sqrt{1+\phi_{\rm piw}^2}} R_{\rm hg} . \qquad (5)$$

The luminosity reduction factor due to the hourglass effect, $R_{\rm hg}$, is important if the rms longitudinal extent of the beam overlap,

$$L_{\rm int} \approx \frac{\sigma_z}{\sqrt{2}} \frac{1}{\sqrt{1+\phi_{\rm piw}^2}}, \qquad (6)$$

becomes comparable to the vertical IP beta function (β_y^*). It can be approximated as [12]

$$R_{\rm hg} \approx \sqrt{\frac{2}{\pi}} \sqrt{a} e^a K_0(a) , \qquad (7)$$

where

$$a \equiv \frac{{\beta_y^*}^2 (1+\phi_{\rm piw}^2)}{2\sigma_z^2} . \qquad (8)$$

For example, for $a = 1, 2$ and 5 the luminosity loss due to the hourglasss effect amounts to 9%, 5% and 2%, respectively. In the following we assume $R_{\rm hg} \approx 1$.

Using (1) and (4) we can rewrite the luminosity (5) as

$$L = C_{\rm lum} \frac{P_{\rm SR} \rho \xi_y}{\beta_y^* E^3} , \qquad (9)$$

where we have introduced a new constant

$$C_{\rm lum} \equiv \frac{3 (m_e c^2)^2}{8\pi r_e^2} \approx 4 \times 10^{15}\ ({\rm TeV})^2/({\rm m}^2) . \qquad (10)$$

In (9) we recognize a decrease of the luminosity with the inverse cubic power of energy, which well matches the energy dependence of the FCC-ee baseline luminosity in Fig. 3. At constant synchrotron radiation power $P_{\rm SR}$ and fixed vertical tune shift ξ_y, the luminosity increases linearly with the bending radius ρ and with the inverse of β_y^*. The luminosity scaling with energy would change if the collider became limited by beamstrahlung instead of by the beam-beam tune shift.

Key parameters for FCC-ee [13] and CEPC [3] are compiled in Table 1.

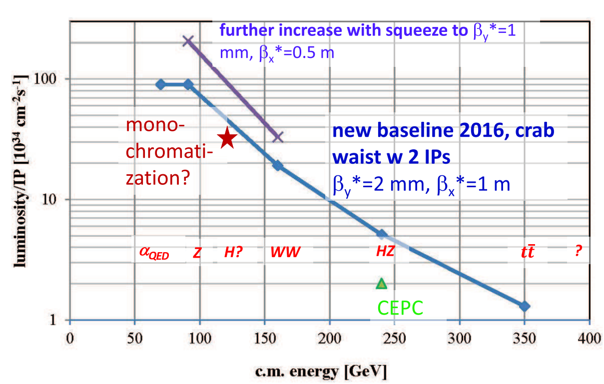

Figure 3: Projected FCC-ee and CEPC luminosity per interaction point (IP) as a function of c.m. energy.

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Table 1: Key parameters for the FCC-ee, at three beam energies, and for the CEPC, compared with those achieved at LEP2. The FCC-ee parameters refer to a crab-waist scheme [9], with constant, energy-independent arc-cell length.

parameter	FCC-ee					CEPC	LEP2
circumference	100					54.4	26.7
energy / beam [GeV]	45.6		80	120	175	120	105
bunches / beam	30180	91500	5260	770	78	50	4
beam current [mA]	1450		152	30	6.6	16.6	3
luminosity / IP [10^{34} cm^{-2}s^{-1}]	207	90	19	5.1	1.3	2	0.0012
energy loss / turn [GeV]	0.03		0.3	1.67	7.55	3.11	3.34
total synchrotron radiation power $2P_{SR}$ [MW]	100		100	100	100	103	22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	6.9	3.5
rms horizontal emittance ϵ_x [nm]	0.2	0.1	0.26	0.6	1.3	6	22
rms vertical emittance ϵ_y [pm]	1	1	1	1	2.5	18	250
horizontal IP beta function β_x^* [m]	0.5	1	1	1	1	0.8	1.2
vertical IP beta function β_y^* [mm]	1	2	2	2	2	1.2	50
horizontal IP beam size σ_x^* [μm]	10	9.5	16	25	36	70	182
vertical IP beam size σ_y^* [nm]	32	45	45	49	70	150	3200
rms bunch length (SR) σ_z [mm]	1.2	1.6	2.0	2.0	2.1	2.1	12
rms bunch length (SR+BS) σ_z [mm]	6.7	3.8	3.1	2.4	2.5	2.6	12
horizontal beam-beam parameter ξ_x	0.025	0.05	0.07	0.08	0.08	0.118	0.040
vertical beam-beam parameter ξ_y	0.16	0.13	0.16	0.14	0.12	90.083	0.060
full crossing angle θ_c [mrad]	30	30	30	30	30	0	0
Piwinski angle ϕ_{piw}	10	6	2.9	1.4	1.0	0	0
interaction region length L_{int} [mm]	0.47	0.44	0.71	0.99	1.25	1.84	8.5
longitudinal damping time [turns]	1320		243	72	23	39	31
beam lifetime from rad. Bhabha scattering [min]	94	185	90	67	57	61	434

TOP-UP INJECTION

Top-up injection is an essential ingredient of future Higgs factories [14]. It is needed to support the rather short beam lifetime of around 1 hour due to radiative Bhabha scattering in collision (see Table 1), to achieve peak performance and and to maximize the integrated luminosity. Using top-up, the collider will operate with constant magnet settings, at stable beam currents, and at a steady temperature. This will also provide optimum conditions for optics fine-tuning.

Top-up injection was successfully employed at both PEP-II and KEKB. For FCC-ee and CEPC, tue to the large energy loss per turn, especially at the highest energy, the booster ring providing the injected beam must have a circumference similar to the collider ring itself, and should, for cost reasons, be housed in the same tunnel. The long-standing question of how the booster can bypass the detector has been solved by an asymmetric IR optics of the collider [15]. In this case the top-up booster follows the footprint of the hadron collider, while the e^+e^- collision point is displaced horizontally by, e.g., 9.5 m, larger than, or equal to, the projected half size of the lepton detector. Various options for the actual injection process, including longitudinal injection and multipole-kicker injection, are under study [16].

Intensity rates required from the FCC-ee injector complex are highest at lowest energy (Z pole). The peak rate required for top-up injection is of order 1–2×10^{12} positrons per second, which can be delivered already, e.g., by the SuperKEKB injector complex.

TRANSVERSE EMITTANCE

The horizontal emittance is determined by the optics and by the beam energy. It can be written as [17]

$$\epsilon_x = C_q \gamma^s l_b^3 F / \rho^3 \quad (11)$$

where l_b denotes the length of the bending magnet(s) in a half cell, ρ the bending radius, $C_q = 55/(32\sqrt{3})\hbar c/(m_e c^2) \approx 4 \times 10^{13}$ m for electrons, and F is a form factor depending on the type of arc optics ($F \approx 3$ for a standard FODO lattice with 90 degree phase advance per cell).

The emittance increases with the square of the beam energy, and decreases with the third power of the bending radius. The cell length (dipole length l_b) can be adjusted to obtain the desired emittance. Due to the large bending radius and the shorter cell length (50 m for FCC-ee versus 79 m for LEP) the horizontal emittance of the FCC-ee is much smaller than the emittance at LEP2, at all energies including the $t\bar{t}$ threshold. The vertical emittance is determined by residual errors, in particular spurious vertical dispersion and betatron coupling, which add to the unavoidable small contribution from local vertical design dispersion caused by the horizontal crossing angle together with the detector and compensation solenoid fields around the IP. An emittance

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ratio ϵ_y/ϵ_x at the level of 1% is being aimed at. This is much higher than routinely achieved at many storage-ring light sources, but may still be a challenge in the presence of low-beta insertions and with colliding beams.

Figure 4 shows that the target emittance values in the emittance plane are compatible with those of modern light sources and linear-collider damping rings. Figure 5 indicates that given the size of these rings the targeted horizontal emittance — albeit small — should easily be achieved.

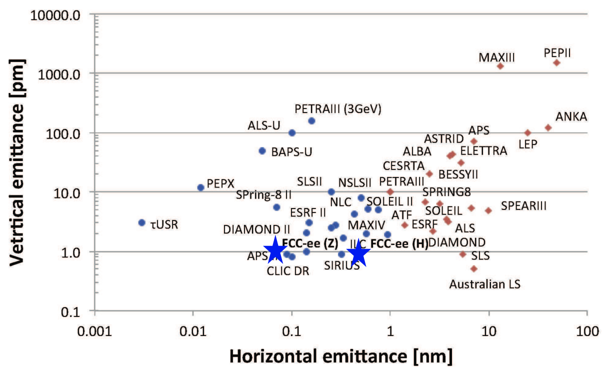

Figure 4: Vertical vs. horizontal emittance for present and future electron storage rings (Courtesy Y. Papaphilippou).

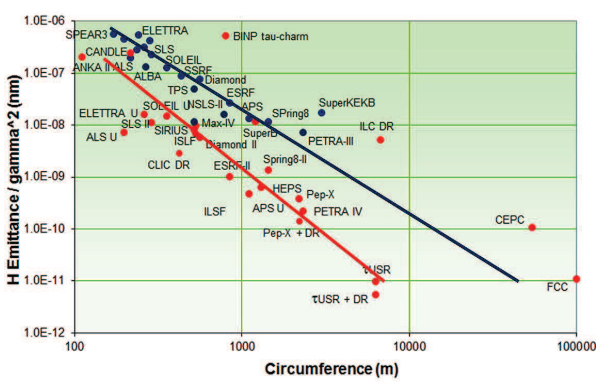

Figure 5: Emittance normalized to beam energy vs. circumference for storage rings in operation (blue dots) and under construction or being planned (red dots). The ongoing generational change is indicated by the transition from the blue line to the red line (Courtesy R. Bartolini).

BEAMSTRAHLUNG

For the first time in a storage-ring collider, beamstrahlung will have a significant impact on the beam parameters and the performance. The term beamstrahlung refers to the synchrotron radiation emitted in the field of the oppositing beam during the collision. This can become a limitation on beam lifetime or collider performance for large bunch populations (N_b), small horizontal beam size (σ_x^*) and short bunches (σ_z).

At the highest energy ($t\bar{t}$ running) the hard tail of the beamstrahlung spectrum may limit the beam lifetime due to the fact that electrons or positrons can emit photons of so high an energy that the emitting particles fall outside the momentum acceptance of the storage ring, The beamstrahlung-limited beam lifetime scales as [9, 18]

$$\tau_{\rm bs} \propto \frac{\rho_{\rm coll}\sqrt{\eta}}{\gamma^2\sigma_z}\exp(A\eta\rho/\gamma^2)\,, \quad (12)$$

where A designates a constant, η the relative momentum acceptance, and the effective bending radius during the collision is

$$\frac{1}{\rho_{\rm coll}} \approx \frac{N_b r_e}{\gamma\sigma_x^*\sigma_z}\,. \quad (13)$$

For an acceptable lifetime in the $t\bar{t}$ mode of operation the product $\rho_{\rm coll}\eta$ must be sufficiently large. This can be achieved by operating with flat beams ($\sigma_x^* \gg \sigma_y^*$), relatively long bunches, and by designing an optics with large momentum acceptance (typically one is aiming at $\eta \geq 1.5\%$ — a value of 2% has already beem demonstrated in simulations without any errors [15]).

At lower energy another effect of beamstrahlung is important. Namely the aditional photon emission at the IP increases the equilibrium energy spread and bunch length of the colliding beams. Analytical formulae for this blow up are available [19, 20]. That this indeed is a large effect at low energy can be seen by comparing the value of σ_z from synchrotron radiation alone (SR) with the bunch length expected from the combined effect of synchrotron radiation and beamstrahlung (SR+BS) in Table 1.

NOVEL CONCEPTS

Several novel concepts are either necessary or can further boost the performance. These include an asymmetric IR optics, with low critical photon energies over the last 500 m on the incoming side of the IP, a "virtual crab-waist" scheme, realized by reducing the strength of one of two final-focus sextupoles, and a footprint which matches the footprint of a future hadron collider and allows for the top-up booster injector to bypass the detector. All of these are included in the FCC-ee optics design [15].

FCC-ee consists of two rings with separate beam pipes, which only intersect at the collision points, while the CEPC design is based on a single, common beam pipe. The double ring layout allows for a new efficient measure against the energy sawtooth: "tapering" the strength of all dipoles, quadrupoles, and sextupoles according to the local beam energy. In this way the beam stays nominally centered in all elements, which minimizes the magnitude of beta beating and wake field effects created by orbit offsets from the center of the arc sextupoles or the center of the arc beam pipe, respectively. The RF systems are concentrated in two long straight sections.

CEPC considers a single beam pipe in an attempt to reduce the costs for the arc magnet and vacuum systems. Electron and positron orbits are separated using a pretzel scheme based on electrostatic separators as utilized at CESR, and explored at LEP-1 with fewer bunches. Superimposed on this separation is the energy sawtooth (an inward drift of the

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orbit between accelerating sections due to the beam energy loss by synchrotron radiation), which will be different for the two beams. Resulting orbit offsets can lead to significant beta beating [21], which would need to be controlled by sextupoles, independently for the two beams. Off-center beams also excite additional resistive-wall wake fields, which could lead to a unwanted "head-tail" tilts and increase the effective IP beam size [22]. Furthermore, octupole magnets would be required to adjust the chromaticity of either beam, as was the case at the Fermilab Tevatron due to the separation helix. The common beam pipe and its side effects limit the number of bunches which can be stored and significantly reduces the luminosity attaimable at the Z pole. One possible mitigation measure is a partial double-ring scheme [23], illustrated in Fig. 6. Partial separation around the two interaction points allows for operation with a bunch train of a certain length (one per beam), which increases the potential luminosity at the Z. However, the transient beam loading of the radio-frequency (RF) cavities could be unacceptably large with a single bunch train. For this reason the simple scheme of Fig. 6 has been extended, to 8 partial separations and 16 RF sections, which enables operation with 4-on-4 bunch trains and, thereby, reduces the magnitude of the transient beam loading to an acceptable value, at the expense of a greater complexity in the layout.

At the highest beam energy, the maximum accelerating voltage is needed. At this energy there are only few bunches in the ring, so that parasitic collisions and impedance effects are less of a concern. For the FCC-ee, sharing the RF system in the two long straights at the $t\bar{t}$ energy saves a factor two in the total number of RF cavities to be installed. The beams are only sharing the two RF straights, but remain in separate beam pipes over the rest of the ring. The sharing of the RF sections can be accomplished with an identical symmetric optics for the two beams [15], and while avoiding any emission of synchrotron radiation on the incoming side of the RF section.

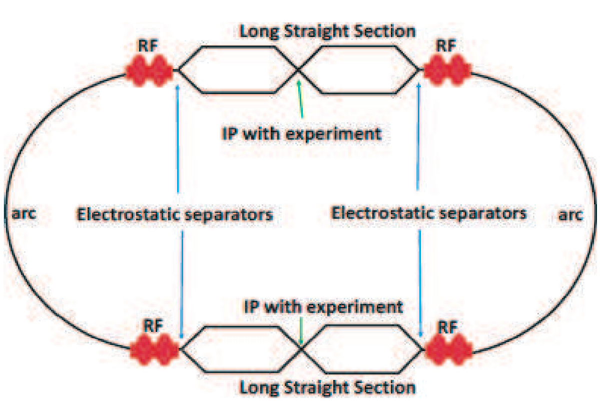

Figure 6: Single ring with partial separation around two IPs (Courtesy M. Koratzinos).

IP BETA FUNCTION

As is evident from (9) a smaller value of β_y^* leads ot higher luminosity. Figure 7 shows the historical evolution of β_y^* in e^+e^- colliders. For a long time the minimum β_y^* values were stuck around 1 cm, which was comparable to the bunch length in most of the associated machines. The present β_y^* record in a storage ring, of about 6 mm, is held by the former KEKB. SuperKEKB, presently under commissioning, has a much smaller design value, around 0.3 mm, and will enter a new regime for ring colliders. Therefore, SuperKEKB will pave the way towards the 1–2 mm values of β_y^* targeted for the future Higgs factories.

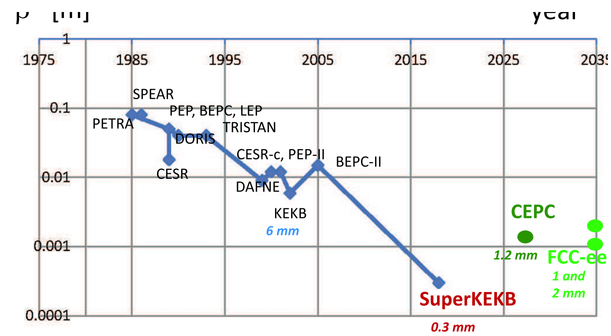

Figure 7: Evolution of β_y^* in e^+e^- colliders over 40 years.

ENERGY EFFICIENCY

The power loss P_{SR} must be constantly sustained by the radiofrequency (RF) system. The associated wall-plug power $P_{\mathrm{wall,SR}}$ is equal to P_{SR} divided by the overall efficiency of the RF system, η_{RF}, or

$$P_{\mathrm{wall,SR}} = P_{\mathrm{SR}}/\eta_{\mathrm{RF}} \ . \qquad (14)$$

The various designs are targeting RF efficiencies well above 50%, by use of superconducting cavities at medium gradients (7–10 MV/m), and advanced RF sources, such as highly-efficient "BAC" klystrons [24] or advanced inductive output tubes (IOTs).

In the $t\bar{t}$ mode of operation also the power consumption of the arc magnets becomes significant, scaling with the square of the beam energy. To keep this power as low as possible, for the FCC-ee double-ring arcs novel twin-aperture dipoles, with common Al conductor, and even twin-aperture quadrupoles, with common copper coils, are proposed [25].

Profiting from such innovation, the estimated total power consumption of FCC-ee may stay below 370 MW for the $t\bar{t}$ running, close to 300 MW for the Higgs production mode, and well below 300 MW for the Z and W modes of operation [26].

Considering 200 days of running with 160 days of physics per year the above power levels translate into an annual consumption of about 1400 GWh, which is comparable to the yearly electrical power consumption of the present CERN LHC complex.

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MONOCHROMATIZATION

Another possible mode of operation, not yet in any baseline, is monochromatization. Monochromatization could enable an interesting option presently under study for the FCC-ee collider, namely the possibility of direct Higgs production in the s channel, $e^+e^- \rightarrow H$, at a beam energy of 62.5 GeV. This could result in an acceptable Higgs event rate, exactly on the Higgs resonance, and also provide the energy precision required to measure the width of the Higgs particle and the electron Yukawa coupling.

A monochromatized collision can be realized most easily in the case of head-on collisions (i.e. zero crossing angle or nonzero crossing angle with crab cavities), by introducing IP dispersion of opposite sign for the two beams, so that particles with an excess energy ($E + \Delta E$) collide on average with particles of lower energy ($E - \Delta E$) and the spread in the center of mass energy W is reduced by the monochromatization factor λ,

$$\left(\frac{\sigma_W}{W}\right)_{\text{m.c.}} = \frac{\sigma_\delta}{\sqrt{2}}\frac{1}{\lambda} \; . \qquad (15)$$

For a horizontal IP dispersion $D_x^* \neq 0$, λ is given by

$$\lambda = \sqrt{\frac{D_x^{*\,2}\sigma_\delta^2}{\epsilon_x \beta_x^*} + 1} \; . \qquad (16)$$

In view of the resonance width of the standard model Higgs of 4.2 MeV and the significantly larger natural rms energy spread of the electron and positron beams at 62.5 GeV of about $\sigma_\delta \approx 6 \times 10^{-4}$ (or $\sigma_\delta E \sim 37$ MeV), the monochromatization factor should be at least 5, which would result in $\sigma_W \leq 10$ MeV.

Simply adding dispersion would not only reduce the effective energy spread, but it would also increase the horizontal beam size and, thereby, lower the luminosity by a factor λ too.

To do better, we need to re-optimize all beam parameters, taking into account both the classical beam-beam limit and the effect of beamstrahlung. In the presence of nonzero IP dispersion, the beamstrahlung will also lead to a blow up of the transverse emittance. The relevant equations were derived in [20] and a partial parameter optimization for monochromatization was reported in [27]. A further refined optimization, varying additional parameters, indicates that for $\lambda \approx 5$ a luminosity of about 4×10^{35} cm^{-2}s^{-1} [28,29] can be attained. Taking into account the standard-model cross section of 1.64 fb for Higgs production in the s-channel, this monochromatizatton scenario is already of interest for particle physics [30].

SUMMARY

Designing the next generation of circular e^+e^- colliders is a fabulous experience.

The presently proposed designs profit from combining advanced concepts and from the expertise accumulated over the last decades, e.g. concerning optics, collision scheme, high beam currents, polarization, and top-up injection.

Additional novel ideas help optimize the performance and overcome any obstacles encountered. Such new concepts include the virtual crab waist, the asymmetric final focus, the magnet-strength tapering, twin-aperture arc magnets, highly-efficient klystrons, partial double ring, etc.

The next high-energy e^+e^- collider might be the crucial step towards a future 100-TeV hadron collider. It will provide — most importantly — the tunnel, a large part of the infrastructure, the time needed for high-field magnet production, plus additional physics motivation and energy targets for the subsequent hadron machine.

Potentially measuring the Higgs self coupling and Higgs top coupling better than any other proposed facility, this hadron collider may finally become the "ultimate Higgs factory".

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