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Status and Perspectives of e^+e^- Factories

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A review of the state of the art of presently working e^+e^- colliders, from low to medium center-of-mass energy, with a very brief summary of their performances is presented. A review of proposed e^+e^- colliders, both circular and linear, under study in Europe and Asia is also presented with highlights on the technical challenges and most recent developments in their design.

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1. Introduction

The quest for high precision measurements in rare e^+e^- decay modes requires dedicated colliders with very high peak luminosity and high operation reliability, in order to collect the huge amount of data needed. PEP-II [1] and KEKB [2] colliders were in operation (until 2008 and 2010) at SLAC (USA) and KEK (Japan) for the study of the B mesons decays, while at lower energy BEPCII at IHEP (China) [3] at the τ/charm energy, DAΦNE at LNF (Italy) [4] and VEPP2000 at BINP (Russia) [5] at the Φ resonance are still collecting data. A "super" B-Factory, SuperKEKB in Japan [6], is in the commissioning phase. At much higher energy larger and more ambitious projects, circular and linear, are being proposed at CERN (FCC-ee [7], CLIC [8]), China (CEPC) [9] and Japan (ILC) [10].

To show the trend of the peak luminosity with center-of-mass (c.m.) energy, in Fig. 1 is reported the achieved or design peak luminosity for past, present and future e^+e^- colliders, both circular and linear. It is clear that to improve the performances by orders of magnitude requires these state-of-the-art colliders to solve several design and technology issues, and push R&D on special topics, as for example the energy saving.

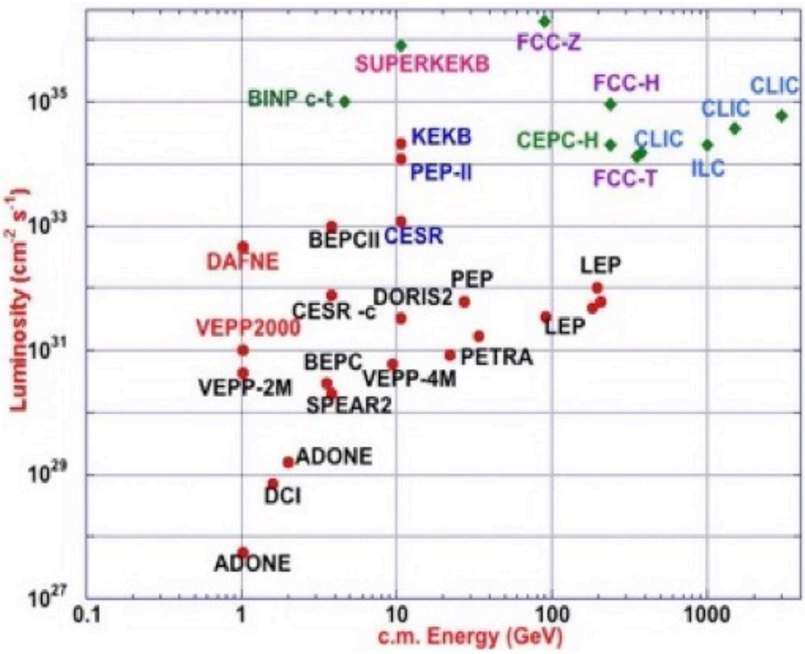

Fig. 1: Peak luminosity as a function of the c.m. energy in world lepton colliders: past [black, blue], present (2017) [red, magenta], and future lepton colliders [light blue, purple, green top-left].

2. Lessons learnt from past experience

From the experience gained from the first lepton colliders built in the '60 to the high performances B-Factories in the '90, it is possible to draw some lessons on what can actually be achieved and maybe improved with further R&D in the years to come. The list below summarizes some of them and their "costs" in terms of design and technology:

a) high beam currents are achievable: at the cost of controlling the trapped High Order Modes (HOMs) in the beam pipe with a careful impedance budget design and of mitigating the e-cloud instability in the positron ring;

b) the *crab waist sextupoles* collision scheme developed at INFN-Frascati [x] works: since the scheme demands to meet the sextupoles requirements in terms of position, strength and betatron phase advance, and to minimize non-linearities in between them, this poses challenges on the dynamic aperture optimization;

c) a continuous (top-up) injection is needed in order to keep peak luminosity constant: with on-energy injection (no ramping) and high repetition rate a reliable injection complex is needed;

d) the e-cloud instability in the e^+ ring has to be mitigated: beam pipe needs low Secondary Electron Yield (SEY) material, achieved also with coating and/or laser treatment, and special techniques to get rid of the cloud such as solenoidal windings around the beam pipe, clearing electrodes, grooves, NEG coating, etc…;

e) bunch-by-bunch feedbacks are needed and work well: upgrades to low-noise, sophisticated digital units are under study;

f) backgrounds increase proportionally to the luminosity and beam currents: a careful design of the Interaction Region (IR) is mandatory, including shielding, masks, collimation;

g) low beam emittance for high luminosity need to be tuned: alignment errors are to be minimized, low emittance tuning fast procedures, both off-line and online, are needed for correction of closed orbit, β-beating, spurious dispersion and x-y coupling;

h) high luminosity requires a control of the beams position at the Interaction Point (IP): a fast IP feedback is needed;

i) nano-beam sizes are achievable: precise alignment and mechanical vibrations controls of the IP quadrupoles are mandatory.

Table I below summarize the best results achieved by the lepton Factories.

Table I: Lepton Factories performances.

Factories		Design Luminosity	Achieved Luminosity
KEKB	B-Factory KEK, Japan	1 x 10^{34}	2.1 x 10^{34}
PEP-II	B-Factory SLAC, USA	3 x 10^{33}	1.2 x 10^{34}
DAΦNE Phase 1	Φ-Factory Frascati, Italy	1 x 10^{32}	1.6 x 10^{32}
DAΦNE Upgrade	Φ-Factory Frascati, Italy	5 x 10^{32}	4.5 x 10^{32}(*) 2.2 x 10^{32}
BEPCII	τ/charm Factory Beijing, China	1 x 10^{33}	1 x 10^{33}

(*) without detector solenoid

3. Present colliders

At present several low-energy lepton colliders are operating in Italy (DAΦNE), Russia (VEPP2000, VEPP-4M) and China (BEPC-II), and a medium-energy one (SuperKEKB) has started its commissioning phase in 2016 in Japan.

The DAΦNE Φ-Factory at INFN-Frascati (Italy) is operating since the late '90 at a c.m. energy of 1.02 GeV. It holds the world record for the higher electron stored current (2.5 A) in single beam. The record peak luminosity of 4.5×10^{32} cm^{-2} s^{-1} was reached in 2009 by exploiting the LPA and CW collision scheme (see below). In its 20 years of operation several original ideas and R&D were developed, which were also applied to other colliders:

a) "*Large Piwinski Angle*" (LPA) and "*Crab Waist*" (CW) sextupoles collision scheme, developed by P. Raimondi [12,13] which allowed for a boost in peak luminosity and mitigation of synchro-betatron resonances (see in Fig. 2 the jump in luminosity in 2009 due to the implementation of the scheme, with a detector without solenoidal field). This scheme has been adopted by SuperKEKB (just the LPA part) and the future circular collider designs (FCC-ee, CEPC);
b) very low impedance beam pipe design, with special bellows and cavity designs [14];
c) e-cloud clearing electrodes in the positron ring, which were able to increase the instability threshold [15];
d) new design "cavity" kicker for the transverse feedback, with high broad-band shunt impedance and all HOM damped, also worldwide implemented at KEKB, BESSY-II, PLS, HLS, TLS, ELETTRA/SLS, BEPC-II, KEK Photon Factory, Duke storage ring, PEP-II, CESR, SuperKEKB, DELTA, ELSA, ALS, Diamond, ESRF, LNLS-UVX, PETRA-III, MAX-IV [16];
e) modified wigglers, with shifted poles, to compensate for the high order magnetic field multipoles [17];
f) fast kickers R&D for the ILC design [18];
g) upgraded low noise bunch-by-bunch digital feedbacks [19];
h) test on the use of wires in the IR for mitigation of the beam-beam (BB) from parasitic crossings [20].

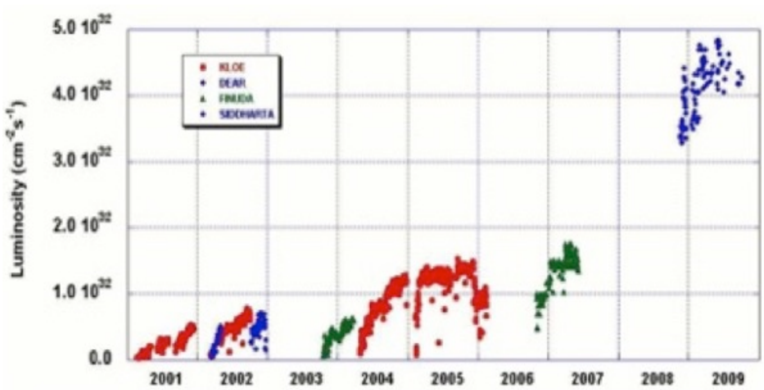

Fig. 2: DAΦNE luminosity evolution before (2001-2007) and after the implementation of the LPA and CW collision scheme for the experiment Siddharta.

The VEPP2000 Φ-Factory at BINP, Novosibirsk (Russia) is exploiting a different scheme with two round colliding beams and just one bunch. The idea is that the x-y symmetry of both BB force and IP-to-IP transfer matrix introduces partial integrability of motion and results in a luminosity increase. An accurate orbit and lattice correction yielded a peak luminosity of about 3×10^{31} cm^{-2} s^{-1} at 500MeV/beam. The achieved peak luminosity is about a factor of 3 lower than the design, limited by BB effects, while the average luminosity was limited by the lack of positrons in whole energy range of 160–1000 MeV. The injection chain was significantly upgraded in 2013-2016 to be able to operate in the full energy range. Fig. 3 below shows the achieved luminosity as a function of the beam energy, as measured by the detector CMD-3.

At BINP there is also a project for the upgrade of VEPP-4M, an old collider with low luminosity (4×10^{31} cm^{-2} s^{-1} @ 5 GeV) but advanced accelerator technologies (resonant depolarization, unique e^+e^- tagging system, etc.), allowing for performing a number of interesting experiments like particles mass measurement, two-photon physics, etc...

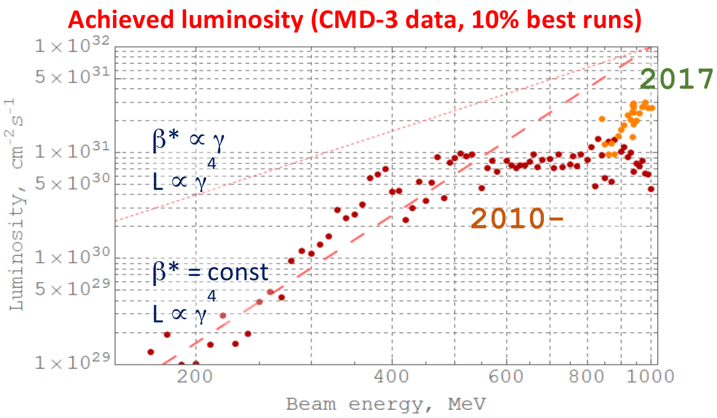

Fig. 3: VEPP2000 achieved luminosity as a function of the beam energy.

BEPC-II is at present the only τ/charm Factory, operating at IHEP, Beijing (China). It is the upgrade of the BEPC collider and has been built with the possibility of a dedicated synchrotron light source (SR) operation mode too. The collider can operate between 2 and 4.6 GeV center-of-mass energy, with focus on the 1.89 GeV/beam. The design luminosity of 10^{33} cm^{-2} s^{-1} was reached in April 2016, after few years of optimization and hardware improvements, the highest luminosity yet achieved for such an accelerator in this energy region. See Fig. 4 for the evolution of luminosity and beam currents at BEPCII.

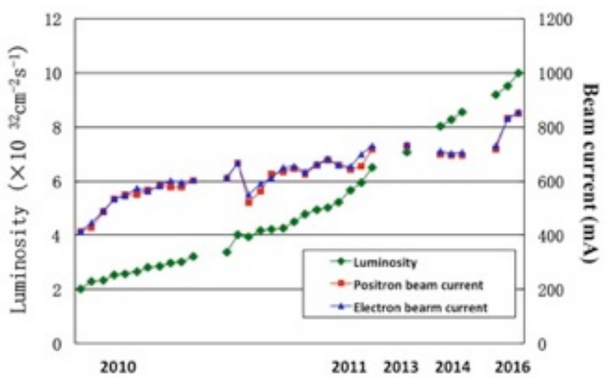

Fig. 4: Evolution of luminosity and beam currents for BEPCII.

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After the success of the PEP-II and KEKB asymmetric B-Factories, which reached unprecedented luminosities and beam currents, a “super B-Factory” was studied for several years. The *SuperB*-Factory project in Italy [21], aiming at a peak luminosity of 10^{36} cm^{-2} s^{-1} at 10.58 GeV c.m. energy, incorporated the LPA and CW collision scheme, already tested at DAΦNE, and the nano-beams concept. Unfortunately, the project was cancelled, but its design principles have been integrated into the upgrade of KEKB to a SuperKEKB collider, whose construction started in 2011. A boost in performances, with respect to KEKB, with a design luminosity of $8x10^{35}$ cm^{-2} s^{-1} at 10.58 GeV, is expected by the implementation of the LPA collision scheme (without the crab waist sextupoles for the time being), a major upgrade of the technical systems, the installation of an in-house built high charge/low emittance RF photo-injector for the electrons, a Damping Ring for the positrons, and a sophisticated Final Focus (FF) layout, aiming at suppressing high order non-linearities and cancel the coupling due to the detector solenoidal field. In Table II is a comparison of KEKB and SuperKEKB parameters.

Table II: Comparison of KEKB and SuperKEKB parameters

	KEKB Achieved		SuperKEKB Nano-beam		Factor
	LER	HER	LER	HER	
I_{beam} [A}	1.6	1.2	3.6	2.6	> 2
β_y* [mm]	5.9	5.9	0.27	0.30	< 20
ξ_y	0.09	0.12	0.088	0.081	~ 1
L [cm^{-2} s^{-1}]	2.1 x 10^{34}		8 x 10^{35}		> 40

SuperKEKB started Phase I operation [6], without the BelleII detector, the Final Focus quadrupoles, and beams crossing, in February 2016 for 5 months, facing and solving quite a few problems. Phase II, when BelleII will be installed without the vertex detector, with a detuned lattice and a goal luminosity of 10^{34} cm^{-2} s^{-1}, is due to start in February 2018. Phase III, with the vertex detector and the low-β lattice, aiming at the design luminosity, is foreseen for Fall 2018. A plot of beam currents, beam lifetimes and vacuum pipe pressure during Phase I is shown in Fig. 5 below.

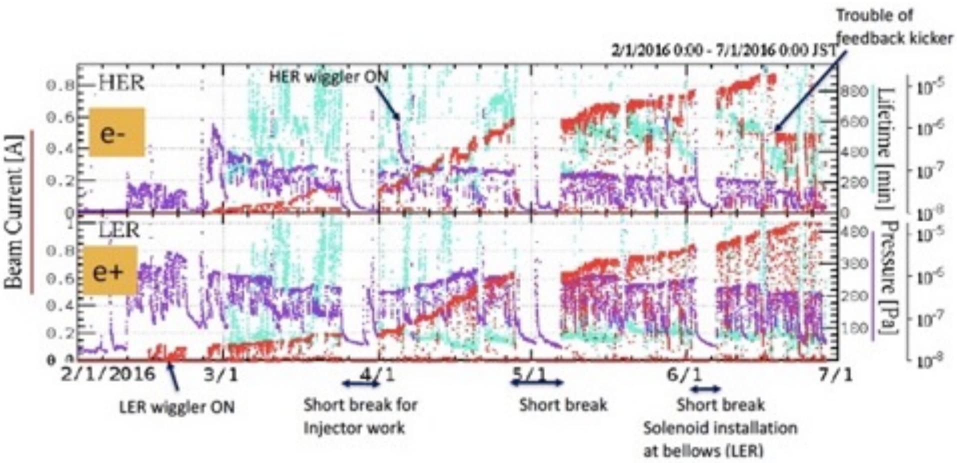

Fig. 5: Phase I evolution of beam currents, beam lifetimes and vacuum pipe pressure at SuperKEKB.

4. Future lepton colliders

The discovery of the Higgs boson at LHC has triggered the quest for New Physics and the need for precision measurements of rare decays on a large energy range. Two different approaches have been taken accelerator-wise: the linear colliders, ILC and CLIC, whose appeal is the high and extendable energy, and the circular colliders, FCC-ee and CEPC, which cannot compete with the linear ones in terms of the high energy attainable, but can reach higher luminosities. Recently these designs have changed to cope with the need to limit the power and the strong demand for costs reduction. Staging options are envisaged for the linear colliders, ILC baseline energy being now 250 GeV c.m. and CLIC Phase 1 being rescaled to 380 GeV, with an option to be fully klystron based. The circular colliders have also changed their initial design to meet the expected performances, CEPC being now a 2 rings, 100 km, collider FCC-ee-like, and FCC-ee planning on a 6 GeV linac injector, CEPC-like. Remarkably, the costs of all these projects is now very similar.

In the following the latest studies on this four projects will be summarized.

4.1 Linear colliders

The design of a high energy linear collider started years ago and a very detailed study lead to the proposal of an International Linear Collider with Super Conducting accelerating cavities, similar to those developed for the TESLA accelerator at DESY (Germany) [22]. A present ILC foresees a staging option to start with 250 GeV c.m. energy [10], with a luminosity of 0.8×10^{34} $cm^{-2}\ s^{-1}$, a value just scaled down from the 1 TeV design. A proper 250 GeV lattice design should still be done. Luminosity can be doubled by doubling the number of bunches (from 1312 to 2625), but lowering the horizontal beam emittance seems the only way to boost the luminosity at low energy. Another factor of 2 could come from 10 Hz collisions, only viable at 250 GeV since for lower energy the positron yield is too low and above the power will be too large.

A 10-15% reduction on costs could come from improved Linac technology, such as higher gradient (from 31 to 35 MV/m), higher Q values (from 10^{10} to 2×10^{10}), and Nitrogen infusion at 120C of SC cavity surface as developed at FNAL.

The positron source present design with undulators is not suitable at low energy, a conventional, electron-driven source maybe be considered, even though not polarized, however the 10 Hz operation in this case would not be possible.

There is still a debate if a 500 GeV or a 250 GeV tunnel should be built.

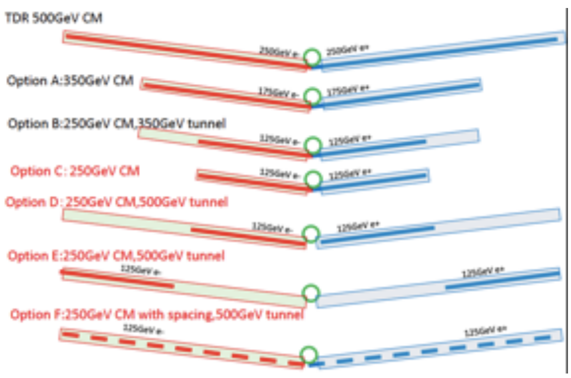

Fig. 6: ILC staging options under consideration.

The Compact Linear Collider (CLIC) [8] project at CERN has a different design, with a two-beam acceleration scheme and X-band accelerating cavities. Recently a staged approach with three main c.m. energy stages at 380 GeV, 1.5 TeV and 3 TeV for a full CLIC program spanning 22 years has been considered. The accelerating gradient needed for these stages are ranging from 72 to 100 MV/m, for design peak luminosities of 1.5×10^{34} cm^{-2} s^{-1} at 380 GeV, 3.7×10^{34} cm^{-2} s^{-1} at 1.5 TeV and 5.9×10^{34} cm^{-2} s^{-1} at 3 TeV.

The new CLIC layout at 380 GeV c.m. energy (for Higgs and Top running) aims at optimizing costs and power consumption (see Fig.7). For this an alternative to the original design, based on "beam driven" acceleration, is being studied, in which the main Linac power is produced using X-band klystrons. The other two stages will depend on LHC findings. At present the CLIC design study supports the efforts to develop high-efficiency klystrons and to consolidate high-gradient structure test results.

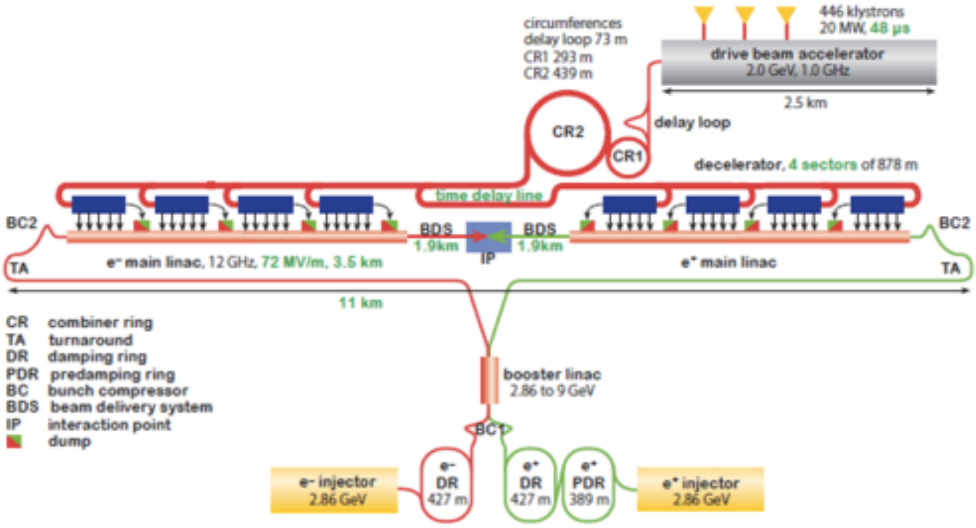

Fig. 7: CLIC 380 GeV option layout.

4.2 Circular colliders

Two circular colliders are being studied to deliver data on a large energy range: the FCC-ee [7] at CERN, from 45 to 175 GeV/beam, and the CEPC [9] at IHEP, from 45 to 120 GeV/beam. Both rely on Super Conducting cavities to cope with the large power consumption. Their large circumference (~100 Km) has been chosen in order to limit the beam power losses to about 50 MW/ring.

FCC-ee is a double ring, 2 IPs collider. Its design must comply the need to share the tunnel with the FCC-hh hadron collider and the booster for on-energy injection, therefore a wide tunnel is needed. Two tunnels are necessary around the IR, for ±1.2 km, where the beams collide with a horizontal crossing angle of 30 mrad, exploiting the LPA and CW collision scheme developed at LNF-Frascati. The beams must cross over through the common RF (at the tt production energy) to enter the IP from inside (see layout in Fig. 8). Only a half of each ring is filled with bunches. A MDI (Machine Detector Interface) task force has been established in order to study the IR design and the machine backgrounds, with detailed simulations of detector geometry and shielding, and description of all physical processes which can lead to non-collision produced particles to hit the detector. A workshop on this subject was held at CERN in January 2017 [23].

A new optics with updated parameters was presented [7] , which matches the FCC-hh layout, cures the BB instability and mitigates the microwave instability at the Z, and saves on power consumption. Electron beam polarization option is also considered for energy calibration at Z and W. A Conceptual Design Report is due to be published in 2018.

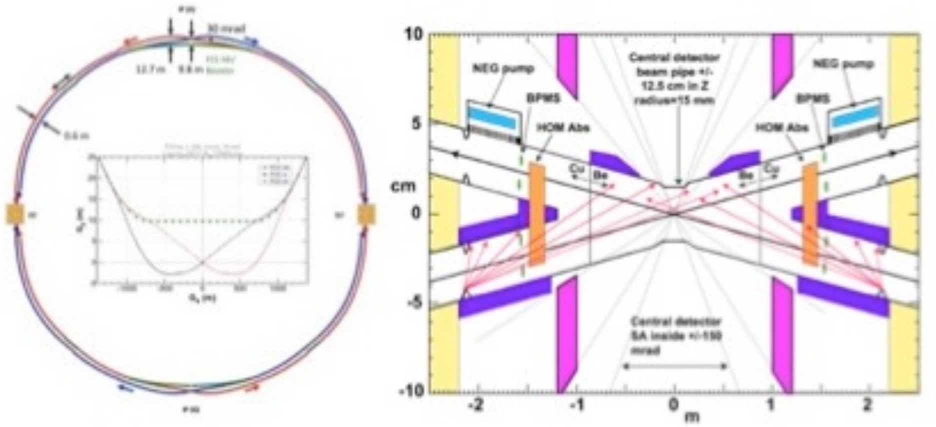

Fig 8: FCC-ee present layout (left) and IR layout (right).

The Chinese project CEPC has evolved from a 50 Km single ring collider with pretzel orbits to finally converge on a design very similar to the FCC-ee one, called “fully partial double ring” (see Fig. 9 left) [9]. For the Higgs operation mode, the RF cavities will be in common between the two beams, with bunches filled only in half of the rings, while for the W and Z production there will be independent RF cavities (650 MHz) and all bunches will be filled (see Fig. 9 right). Beam loading and beam transient in the RF cavities may be an issue and should be carefully studied for both machines, see for example [24]. Maximum beam power in CEPC is 32 MW/beam. Dynamic Aperture studies have been performed with the code MODE (Multi-Objective optimization by Differential Evolution) and SAD [25]. Detailed studies of IR backgrounds are in progress, as well as design of a Superconducting IP doublet.

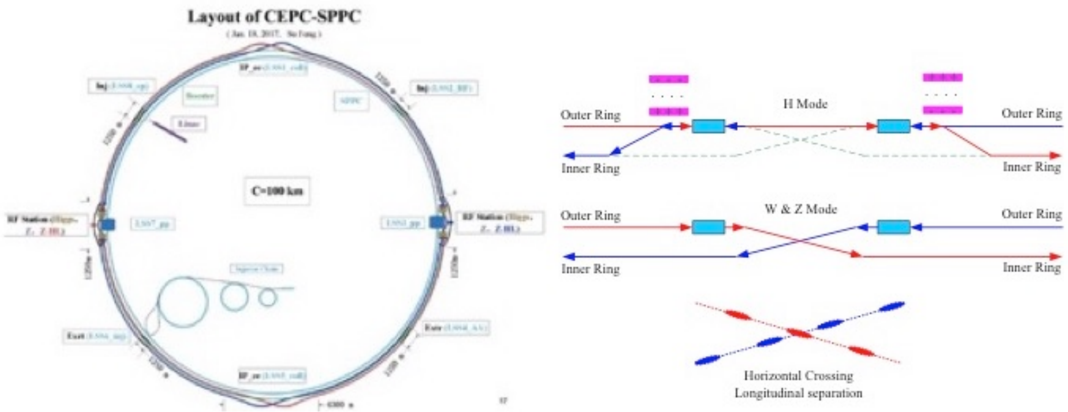

Fig 9: CEPC present layout (left) and RF cavities layout (right).

4.3 Technology and beam dynamics related challenges

A number of issues rise when pushing colliders to their limit in energy and/or luminosity. Some on them, beam dynamics or technology related, will be listed in the following.

The performances of high luminosity circular Factories rely on the efficiency of the injection complex. Top-up (continuous) injection, - which is mandatory since beam lifetimes are very short due to the nano-beam dimensions, the BB interaction and the beamstrahlung for the high energy beams,- requires high reliability and resistance to stresses for non-stop operation, as well as a high repetition rate. The beam lifetimes with the BB effects and the CW sextupoles scheme are a concern that poses stringent constraint on the injection system. Moreover, the injection induced beam oscillations can badly affect the IP collisions and therefore the luminosity, and should be carefully studied. From simulations performed for the *SuperB* project it seems that the CW sextupoles can damp these oscillations [26].

A booster at full energy in same tunnel is needed for the circular colliders, then the layout becomes more complicated and costly due to the huge detectors to bypass.

For all designs, a photo-injector (RF) for low emittance/high charge electrons is needed to assure the number of particles needed to achieve high currents. A Damping Ring for positrons, but maybe for electrons too, is also needed to meet the accelerator acceptance.

An efficient and powerful positron source, with the option to have polarized positrons, is mandatory to deliver the high number of particles requested by all designs.

For the circular colliders the beam pipe and the vacuum system design, in terms of pipe material choice, surface coating, low impedance budget, High Order Modes suppression and pumping system, are requiring large simulation and R&D efforts, in order to suppress or mitigate the ion instability in the electron rings and the e-cloud instability in the positron rings (also present in the LC Damping Rings).

Saving power is one of the key issues recently raised. Since the beams require significant RF drive power (180 MW for CLIC, 100 MW FCC-ee and CEPC, 88 MW for ILC) an RF source with high efficiency is preferable to minimize the overall power required: high efficiency klystrons are needed. Klystrons with the current state of the art are operating at efficiencies of up to 70%, but novel bunching methods, such as: “congregated bunch”, “bunch core oscillation”, “BAC method”, are being investigated and promise to deliver 90% efficiency. An international collaboration for high efficiency klystrons R&D is in place. High field accelerating sections (X-band) are the base of the CLIC project, a strong R&D program is also in place worldwide.

For FCC-ee the design of “twin aperture arc magnets” for the arc cells quadrupoles and dipoles is being developed [27] to save power consumption: the result of simulations is a saving of half the power with respect to single quadrupoles. This results in less units to manufacture, transport, install, and align, with remarkable costs saving.

The Superconducting RF cavity design (single/multi-cells, cryogenics, frequency 400/650/800 MHz) also require a worldwide R&D effort. The large energy range the circular colliders plan to operate at, requires different RF layouts to cope with the different power losses. At FCC-ee for example 400 MHz single-cells cavities are preferred for the Z running and the FCC-hh collider (few MV/m), while for ZH, tt and WW running multi-cells cavities at 400 or 800 MHz are preferred. Cavity coating and high Q are the R&D key topics.

Civil engineering represents a good fraction of costs. Studies are being done to optimize assembly (underground or on surface), access shafts, equipment transportation and tunnel sizing.

As mentioned before, the IR design is an extremely hard task. The detector requirement for a large solid angle must trade-off with the dimensions of IP quadrupole doublet (QD-QF), the distance L* from IP to first QD entrance and the quadrupoles aperture, which is a big issue at large gradients. R&D on compact quadrupoles (PM, SC or hybrid) is going on for all projects.

The control of beams at the IP is a particularly delicate matter for nano-beams collisions. Efficient and fast IP feedbacks are needed, vibrations of the IP magnets have to be kept at a minimum, alignment errors avoided, since all these can have a strong impact of luminosity performances. The work done for beam tuning, jitter characterization, beam instrumentation, fast extraction kickers tests at the ATF and ATF2 (KEK), where a 41 nm beam size has been measured, is extremely important (foe ex. the FONT5 feedback system) [8].

For what concerns the circular colliders, beam dynamics poses several challenges on the lattice design. A short summary is given below.

At very high energies (FCC-ee ad CEPC) due to the large synchrotron radiation power losses and non-zero dispersion function, the closed orbit shifts progressively in the ring, to be abruptly corrected by the RF cavities: this is called saw-tooth orbit. To overcome this problem, which otherwise results in a serious mismatch of the optical functions, the fields in quadrupoles and dipoles in the cells need to be tapered following the energy losses. Of course this requires to have the beams circulating in two different rings. This adjustment has to be taken into account when simulating the Dynamic Aperture (DA) and applying the low emittance tuning procedures, needed to correct for unavoidable magnet errors, misalignments and imperfect solenoidal detector field compensation, to keep the vertical beam emittance to the minimum required by the luminosity requirements.

A large energy acceptance is required in all lattice designs. It is very important that DA simulations include all the possible reduction causes: the crab sextupoles effect, since a reduction (~20% or more) is expected; synchrotron motion and radiation losses in dipoles and quadrupoles, as they can reduce or increase DA; magnet tapering; solenoids, even if they are compensated; BB effects for stored and injected beam. These effects are all being included in the SAD code [26].

The choice of the collision parameters, such as beam dimensions, β-value in both planes, L* distance from the IP, betatron tunes working point, bunch currents, need to be checked through detailed simulations. For example, unwanted IP non-linearities (NL), affecting the DA, are a consequence of the large quadrupole gradients needed to have the low-β at the IP. These NL are due to both kinematical terms and Maxwellian fringe fields, and are unavoidable but they can be decreased by a careful choice of the β_y value (should be increased), L* and gradient (both should be decreased). These requirements are in general conflicting with the design parameters to achieve the design luminosity.

It is mandatory that BB simulations include these NL, the Space Charge linear tune shift, which is about same order than the BB one but with reverse sign, and the CW sextupoles, which can be armful if the conditions on betatron phase advance, beta and dispersion, are not perfectly matched.

Finally, BB instabilities, as the coherent BB instability induced by a IP large crossing angle, and the recently discovered 3D flip-flop instability, due to the combined effect of the beamsstrahlung and the bunch current asymmetry [28], are to be seriously taken into account.

Conclusions

The future of lepton colliders, linear and circular, depends on solving both the pending technological issues and the beam dynamics ones. Efforts are being put in optimize the design in order to minimize the costs of these large machines. Worldwide collaborations are in place to help solving the most important technological issues in the next 20 years or so. Two linear and two circular projects are being proposed and the synergy between their communities, as well as with the Synchrotron Light Sources one, will be crucial for the chance to build at least one of each type.

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