A NEW PARADIGM: ROLE OF ELECTRON-POSITRON AND HADRON COLLIDERS

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Abstract

In 2012, a light scalar boson (denoted as H(125) in this paper) was discovered at the LHC. We explore the possible correlation between the lightness of H(125) and the smallness of CP-violation based on the Lee model, namely the spontaneous CP-violation two-Higgs-doublet-model. It is a new way to understand why H(125) is light. Based on this we propose that it is the much heavier scalar boson-s, instead of the H(125), which need to be understood. This opens a new paradigm that one tries to understand the electro-weak symmetry breaking and CP violation. For the new paradigm, similar to many other physics beyond the s-tandard model, one need both electron-positron and higher energy hadron collider, as well as the low energy experiments, in order to pin down the whole picture.

INTRODUCTION

The organizers of HF2014 invited me to give an overview on physics, especially the physics beyond the s-tandard model (BSM), which can be investigated at Higgs Factories (HF). Since a new scalar (denoted as H(125) in this paper) was discovered in 2012, LHC is an obvious HF. For one hand, LHC can do much more in the future run, on the other hand, LHC precision is limited by its hadron-ic environment. Next generation electron-positron collid-er and higher energy hadron collider are under extensive discussion. One predominant example is the CEPC (circu-lar electron and positron collider) with $\sqrt{s} = 240$ GeV or so, plus the possible update to super proton-proton collider (SPPC) with $\sqrt{s} = 50 - 100$ TeV or higher. It is quite nat-ural to expect that CEPC can reach much higher precision that those of LHC, and SPPC can detect the much higher BSM scale than that of the LHC.

In principle, the whole BSM picture can usually be re-vealed via the combination efforts of LHC, CPEC/ILC, SP-PC, FCC and other high energy colliders, as well as the low energy experiments which have certain unique opportunity, for example, CP violation and/or rare processes. There are numerous BSM, how to give the audience a relative glob-al, objective and persuasive picture is a challenging task. In the end we decide to firstly give a brief overview on B-SM motivations, then discuss a possible new paradigm as an example, which need high energy electron-positron and hadron colliders to pin down the whole picture.

MOTIVATION FOR BSM

The discovery of H(125) is revolutionary. For the fist time in the history of particle physics, we have a complete theory to describe the electro-weak and strong interactions. If the H(125) is really the SM one, as many people believe, SM can be applicable to a very high scale, much higher than the weak scale. However we also have many reasons that BSM should exist. In this section, the motivations for BSM are categorized into 4 classes.

Motivation(I): Test New Types of Interactions

In the SM, there are 3 types of interactions:

- Gauge interaction
- Yukwa interaction
- Higgs self interaction

Gauge interaction, which can describe the strong and electro-weak interactions excellently, is well-tested for most cases. The Yukawa interaction and Higgs self-interaction are new types of interactions, and which need to be checked in HF. In the SM Yukawa interaction is the origin of fermion mass, and induce the flavor changing pro-cesses. BSM can easily affect Yukawa interaction. For the Higgs self interaction in the SM, once Higgs boson mass is fixed, the triple h^3 and quartic h^4 interactions are also fixed. One motivation to measure the Higgs self couplings is related with electro-weak phase transition. In order to account for the matter dominant Universe, the Higgs self couplings are usually greatly altered. Another popular mo-tivation is that Higgs potential might be more complicated than that in the SM. Therefore measuring the Higgs self interaction is the way to reconstruct the Higgs potential, though quite challenging.

Motivation (II): Account for Astrophysical Obser-vations

There are several astrophysical observations (dark mat-ter (DM), baryon asymmetry, and inflation) which may be related to BSM at O(TeV). There is not suitable DM can-didate in the SM. In order to keep DM stable or pseudo-stable, one usually introduces new symmetry, and one pop-ular example is the supersymmetry (SUSY). SUSY can provide a natural SM candidate is thought as one of its suc-cesses. In order to construct a complete theory, one likely

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FCC-*ee* OVERVIEW

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Abstract

The *FCC-ee* is a proposed circular e^+e^- collider installed in a new 100 km tunnel delivering high luminosity to four experiments at centre-of-mass energies ranging from 91 GeV (Z pole) over 160 GeV (*W* threshold) and 240 GeV (*H* production) to 350 GeV (*t* physics). The *FCC-ee* design is pursued as part of the global Future Circular Collider (*FCC*) study, which regards the *FCC-ee* as a potential intermediate step towards a 100-TeV hadron collider, called *FCC-hh*, sharing the same tunnel infrastructure. We here report the *FCC-ee* design status.

INTRODUCTION

Since 1960 about 30 ring colliders have been successfully built and operated. Many more $e^{\pm}$ storage-ring light sources have been constructed, with ever smaller transverse emittances. In short, storage rings and storage-ring colliders represent a well understood technology, typically exceeding their design performance within a few years. LEP was the highest energy lepton collider built so far. Its maximum c.m. energy reached 209 GeV, and its total synchrotron radiation power rose up to 23 MW. Figure 1 shows the evolution of the LEP-1/-2 peak-luminosity performance compared with the respective design values, and Figure 2 the vertical-to-horizontal emittance ratio towards the end of LEP-2. Both figures demonstrate better performance at higher beam energy (increasing over the years).

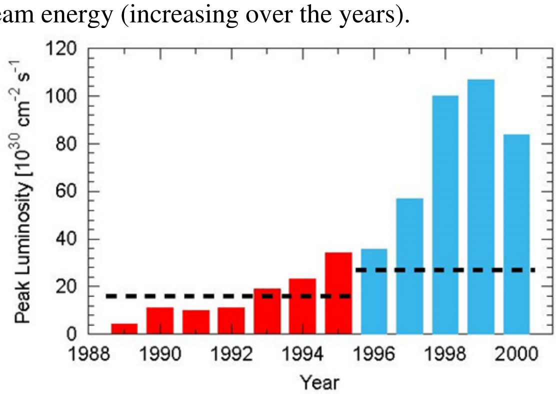

Figure 1: Peak luminosity of LEP-1 (red) and LEP-2 (blue) as a function of year, compared with the respective design values (dashed lines) [1].

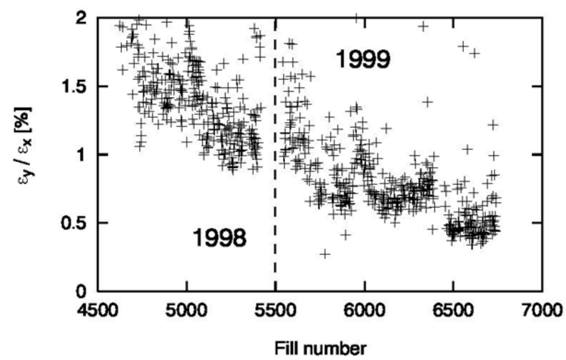

Figure 2: Vertical-to-horizontal emittance ratio at LEP in 1998 and 1999 [1]. The decrease reflects both changes in the damping partition numbers and improved steering [2].

In 1976, B. Richter foresightedly wrote that "An e$^+$-e$^-$ storage ring in the range of a few hundred GeV in the centre of mass can be built with present technology [and] ...would seem to be ... most useful project on the horizon" [3]. Figure 3, from the same reference, shows the cost-optimized circumference according to 1976 prices as a function of c.m. energy. For 300 GeV c.m. the cost optimum corresponds to a ring of about 90 km in size. This suggests that the 100 km tunnel for a 100-TeV hadron collider also is a good choice for hosting a circular e^+e^- collider operating at up to 350-400 GeV.

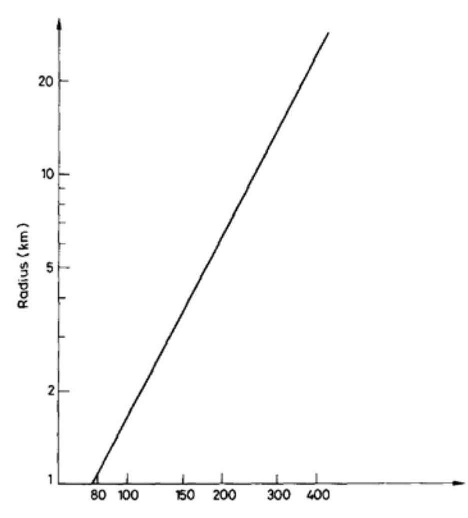

Figure 3: Cost-optimized circumference of a circular e^+e^- collider versus centre-of-mass energy as of 1976 [3].

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OVERVIEW OF THE CEPC ACCELERATOR

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Abstract

A circular electron positron collider (CEPC) was proposed in IHEP after the Higgs boson was discovered at LHC two years ago. In the meantime, some possible ring-based Higgs factories, were also proposed in different labs around the world. In these two years, studies focusing on the preliminary design of the ring, and the considerations on injectors, were carried out in IHEP. Some results on beam physics and hardware will be given in this paper.

INTRODUCTION

Two years ago, CERN declared the discovery of the 126 GeV/c^2 Higgs boson, which is much less than expected before, causing the big possibility to build ring-based Higgs factory for further fine measurement of the new particle. Although muon collider, γ-γ collider, and linear collider were proposed to be the candidates of Higgs factory more than 10 years ago, some ring-based Higgs factories, such as LEP3 [1], TLEP [2], Super-Tristan [3], FNAL site-filter [4], etc., were suggested in different labs due to the relatively mature accelerator technology of circular machine. IHEP also proposed a circular e^+e^- collider (CEPC) as a Higgs factory in September 2012 [5], which can be converted to a super proton-proton collider (SppC) in the future as a machine for new physics and discovery, shown as Figure 1 [6].

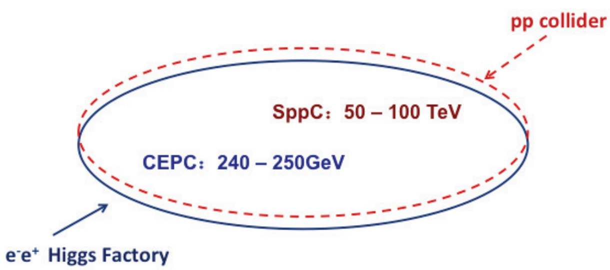

Figure 1: Schematic graph of the CEPC + SppC.

In the CEPC, the electron beam energy can be 120-125 GeV, and in the SppC, the proton beam energy can reach 25-50 TeV. The CEPC then can be thought as a natural extension of the BEPC, Beijing electron positron collider, which was built in 1980's and upgraded as BEPCII 10 years ago. From the BEPC and BEPCII, experiences on lepton machine's design, construction and operation are gradually accumulated. Accelerator technologies are also developed in IHEP, and other Chinese labs as well. Thus the CEPC becomes a very important direction in the field of high energy physics in China, and is the one we can do as a future high energy facility. In recent two years, we did some studies on the CEPC machine design, aiming on the pre-CDR to be finished by the end of 2014.

The current IHEP site is too small to accommodate the future CEPC and its auxiliary facilities. A candidate site for such a big machine is Funing of Qinhuangdao, a coast city northeast of Beijing and 300 km in between, shown in Figure 2.

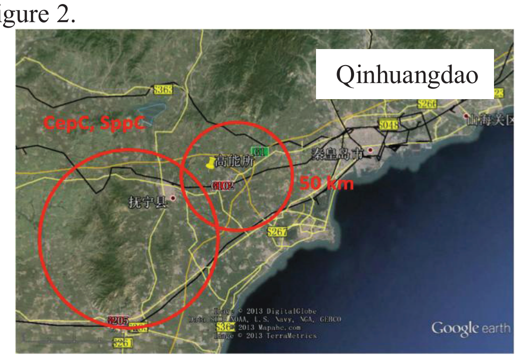

Figure 2: Possible location for future CEPC and SppC.

In this paper, the main studies on accelerator physics, such as main parameter determination, lattice design, final focus system, dynamic aperture simulation, beam-beam effect, injection chains, collective effects, etc., and some hardware system considerations of CEPC, are discussed. A preliminary overall time schedule will be given, and a summary of all studies is given at last.

MAIN PARAMETERS AND LAYOUT

Since the energy loss due to synchrotron radiation is proportional to the fourth power of beam energy, a relatively low beam energy will save the RF power and make the ring more flexible. Beam energy of 120 GeV is thus chosen, because the cross-section of Higgs at that energy is similar as that of 125 GeV. The beam power compensated by the RF will be limited as 50 MW in a general design of such a big ring. Such a large amount synchrotron radiation also causes a strong beamstrahlung [7], which makes the bunch size at the interaction point (IP) diluted and the beam energy spread enlarged. Finally, it brings the beam lifetime to reduce dramatically, and the luminosity decrease as well. General speaking, if we keep the beam power unchanged, the bigger the ring, the more the beam current can be stored, and thus the higher the peak luminosity. Considering a possible p-p collider in the same tunnel of the CEPC in the future for much high energy of proton beams, at least 50 km is necessary for the circumference of the CEPC ring. As a Higgs factory, a peak luminosity of $1\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ is the lower limit to fit the physics requirement of CEPC.

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CEPC DESIGN PERFORMANCE CONSIDERATIONS[1]

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Abstract

In this paper I will commend on the early CEPC design as of October 2014. In particular I will comment on the choice of circumference, minimum and maximum energy, number of collision points and target luminosity. I will finish with suggestions to increase performance with minimum incremental cost.

CEPC DESIGN PHILOSOPHY

The design of the CEPC revolves around the philosophy of keeping costs low while achieving as much of the performance of an ultimate machine. For this reason the scope has been limited to primarily a Higgs factory, operating at a beam energy of 120GeV. Tunnel size has been kept to 54.8 kms, approximately twice as big as LEP. Two experiments are envisaged for e^+e^- operation and a single beam pipe design has been chosen.

We will try to quantify the cost of these choices in terms of performance. In the late part of the paper we will also make suggestions to improve the performance of the baseline design.

LUMINOSITY OF A CIRCULAR COLLIDER

The luminosity of a circular collider is given by

$$\mathcal{L} = \frac{3}{8\pi}\frac{e^4}{{r_e}^4}P_{tot}\,\frac{\rho}{{E_0}^3}\xi_y\frac{R_{hg}}{\beta_y^*} \qquad (1)$$

where r_e and e are the classical radius of the electron and its charge, P_{tot} the total SR power dissipated by one beam, ρ the bending radius, E_0 the beam energy, ξ_y vertical beam-beam parameter, β_y^* the vertical beta function at the interaction point and R_{hg} the geometric hourglass factor.

The maximum achievable ξ_y depends on if a specific machine is beam-beam or beamstrahlung dominated [1].

The Beam-beam Limit

The beam-beam limit depends on the damping decrement λ_d, the amount of energy loss when electrons move from one IP to the next:

$$\lambda_d = \left(\frac{U_0}{E}\right)\frac{1}{n_{IP}} \qquad (2)$$

Where U_0 is the energy loss per electron in one turn. The LEP data has been used to derive this number following the formulation in [2]:

$${\xi_y}^{max} \propto {\lambda_d}^{0.4} \qquad (3)$$

which when fitted to the maximum beam-beam parameters achieved at LEP yields the approximate formula

$${\xi_y}^{max} \approx 0.86\cdot{\lambda_d}^{0.4} \qquad (4)$$

We need to stress here that the above formulation is only based on a limited amount of LEP data and should be taken with a grain of salt. Beam-beam simulations and ultimately measurements on a real machine would provide a more accurate estimation, but for the purposes of this paper we consider the approach above adequate.

The Beamstrahlung Limit

The beamstrahlung limit [3] is due to the fact that at high energies and luminosities beamstrahlung, the synchrotron radiation emitted by an incoming electron in the collective electromagnetic field of the opposite bunch at an interaction point, reduces beam lifetimes to values where the top-up injector cannot cope. The effect of beamstrahlung is very implementation specific and can be mitigated by small vertical emittance and large momentum acceptance.

Two analytical calculations exist for computing beam lifetimes due to beamstrahlung [3] [4] offering fast estimates of the effect. Analytical simulations assume Gaussian distributions (i.e. without non-Gaussian tails) and have other approximations. Therefore it is important to be checked against a complete simulation such as the one by K. Ohmi [5]. The comparison between the two analytical calculations and the simulation for two different energies (where beamstrahlung plays a crucial role in defining the beam lifetime) and for the specific implementation of FCC-ee [6] is shown in Figure 1 and Figure 2. Care is taken to use the effective β_x^* coming out of the simulation, rather than the design value.

Both analytical calculations show reasonable agreement for momentum acceptances of interest here (between 1.5% and 2%) at beam energies of both 120GeV and 175GeV. This justifies the use of the analytic formulas instead of the much more accurate but time-consuming simulation for the purposes of this work.

The two regimes (the beam-beam dominated and the beamstrahlung dominated one), for the specific implementation of FCC in [6], can be seen in **Figure 3**. Such a machine would be beamstrahlung dominated at

[1] Talk title: Choice of circumference, minimum & maxim energy, number of collision points, and target luminosity

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RING CIRCUMFERENCE AND TWO RINGS VS ONE RING

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Abstract

The natural next future circular collider is a circular e+e- Higgs Factory and, after that, a post-LHC p,p collider in the same tunnel. The main Higgs factory cost-driving parameter choices include: tunnel circumference C, whether there is to be one ring or two, what is the installed power, and what is the "Physics" for which the luminosity deserves to be maximized. This paper discusses some of the trade-offs among these choices, and attempts to show that the optimization goals for the Higgs factory and the later p,p collider are consistent.

GENERAL COMMENTS

The quite low Higgs mass (125 GeV) makes a circular e+e- collider (FCC-ep) ideal for producing background-free Higgs particles. There is also ample physics motivation for planning for a next-generation proton-proton collider with center of mass energy approaching 100 TeV. This suggests a two-step plan: first build a circular e+e- Higgs factory; later replace it with a 100 TeV pp collider (or, at least, center of mass energy much greater than LHC). This paper is devoted almost entirely to the circular Higgs factory step, but keeping in mind the importance of preserving the p,p collider potential.

The main Higgs factory cost-driving parameter choices include: tunnel circumference C, whether there is to be one ring or two, what is the installed power, and what are the physics priorities. From the outset I confess my prejudice towards a single LEP-like ring, optimized for Higgs production at $E = 120$ Gev, with minimum *initial* cost, and highest possible eventual p,p energy. This paper discusses some of the trade-offs among these choices, and attempts to show that electron/positron and proton/proton optimization goals are consistent.

Both Higgs factory power considerations and eventual p,p collider favor a tunnel of the largest possible radius R. Obviously one ring is cheaper than two rings. For 120 GeV Higgs factory operation (and higher energies) it will be shown that one ring is both satisfactory and cheaper than two. But higher luminosity (by a factor of five or so) at the (45.6 GeV) Z_0 energy, requires two rings.

Unlike the Z_0, there is no unique "Higgs Factory energy". Rather there is the threshold turn-on of the cross section shown, for example, in Figure 1 of my WG 2 paper "Single Ring Multibunch Operation and Beam Separation".

We arbitrarily choose 120 GeV per beam as the Higgs particle operating point and identify the single beam energy this way in subsequent tables. Similarly identified are the Z_0 energy (45.6 GeV), the W-pair energy of 80 GeV, the LEP energy (arbitrarily taken to be 100 GeV) and the $t\bar{t}$ energy of 175 GeV to represent high energy performance.

SCALING UP FROM LEP TO HIGGS FACTORY

Scaling Radius and Power Inversely Conserves Luminosity

Most of the conclusions in this paper are based on scaling laws, either with respect to bending radius R or with respect to beam energy E. Scaling with bend radius R is equivalent to scaling with circumference C. (Because of limited "fill factor", RF, straight sections, etc., $R \approx C/10$.)

Higgs production was just barely beyond the reach of LEP's top energy, by the ratio 125 GeV/105 GeV = 1.19. This should make the extrapolation from LEP to Higgs factory quite reliable. In such an extrapolation it is increased radius more than increased beam energy that is mainly required.

One can note that, for a ring three times the size of LEP, the ratio of E^4/R (synchrotron energy loss per turn) is $1.19^4/3 = 0.67$—i.e. *less than final LEP operation*. Also, for a given RF power $P_{\rm rf}$, the total number of stored particles is proportional to R^2—doubling the ring radius cuts in half the energy loss per turn and doubles the time interval over which the loss occurs. These comments deflate a long-held perception that LEP had the highest practical energy for an electron storage ring.

There are three distinct upper limit constraints on the luminosity. Maximum luminosity results when the parameters have been optimized so the three constraints yield the same upper limit for the luminosity. For now we concentrate on just the simplest luminosity constraint $\mathcal{L}^{\rm RF}_{\rm pow}$, the maximum luminosity for given RF power $P_{\rm rf}$. With n_1 being number of stored particles per MW; f the revolution frequency; N_b the number of bunches, which is proportional to R; σ_y^* the beam height at the collision point; and aspect ratio σ_x^*/σ_y^* fixed (at a large value such as 15);

$$\mathcal{L}^{\rm RF}_{\rm pow} \propto \frac{f}{N_b}\Big(\frac{n_1 P_{\rm rf}[\rm MW]}{\sigma_y^*}\Big)^2. \qquad (1)$$

Consider variations for which

$$P_{\rm rf} \propto \frac{1}{R}. \qquad (2)$$

Dropping "constant" factors, the dependencies on R are, $N_b \propto R$, $f \propto 1/R$, and $n_1 \propto R^2$. With the $P_{\rm rf} \propto 1/R$ scaling of Eq. (2), $\mathcal{L}$ is independent of R. In other words, the luminosity depends on R and $P_{\rm rf}$ only through their product

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SINGLE RING MULTIBUNCH OPERATION AND BEAM SEPARATION

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Abstract

The counter-circulating electrons and positrons in a circular Higgs Factory have to be separated everywhere except at the N^* intersection points (IP). The separation has to be electric and, to avoid unwanted increase of vertical emittance ϵ_y, the separation has to be horizontal. This paper considers only head-on collisions at $N^* = 2$ IP's, with the beams separated everywhere else (but with nodes at RF cavities) by closed electric bumps.

ELECTRIC BUMP BUNCH SEPARATION

Operating Energies

Typical energies for "Higgs Factory" operation are established by the cross sections shown in Figure 1. We arbitrarily choose 120 GeV per beam as the Higgs particle operating point and identify the single beam energy this way in subsequent tables. Similarly identified are the Z_0 energy (45.6 GeV), the W-pair energy of 80 GeV, the LEP energy (arbitrarily taken to be 100 GeV) and the $t\bar{t}$ energy of 175 GeV to represent high energy performance.

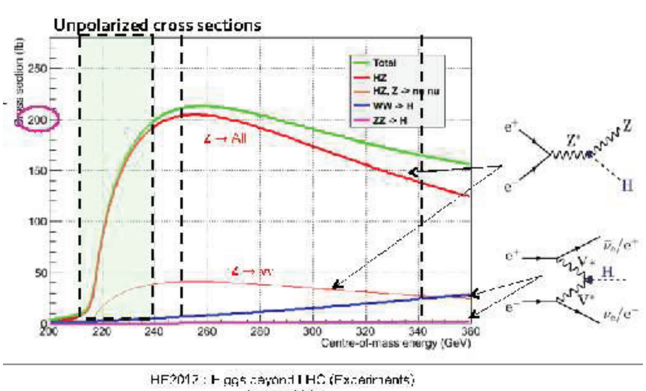

Figure 1: Higgs particle cross sections up to $\sqrt{s} = 0.3$ TeV (copied from Patrick Janot); $\mathcal{L} \geq 2 \times 10^{34}$ /cm^2/s, will produce 400 Higgs per day in this range.

Bunch Separation at LEP

Much of the material in this section has been drawn from John Jowett's article "Beam Dynamics at LEP" [1]. When LEP was first commissioned for four bunches (N_b=4) and four IPs (N^*=4) operation, bunch collisions at the 45 degree points were avoided by vertical electric separation bumps. It was later realized that vertical bumps are inadvisable because of their undesirable effect on vertical emittance ϵ_y, which needs to be minimized. We therefore consider only horizontal separation schemes.

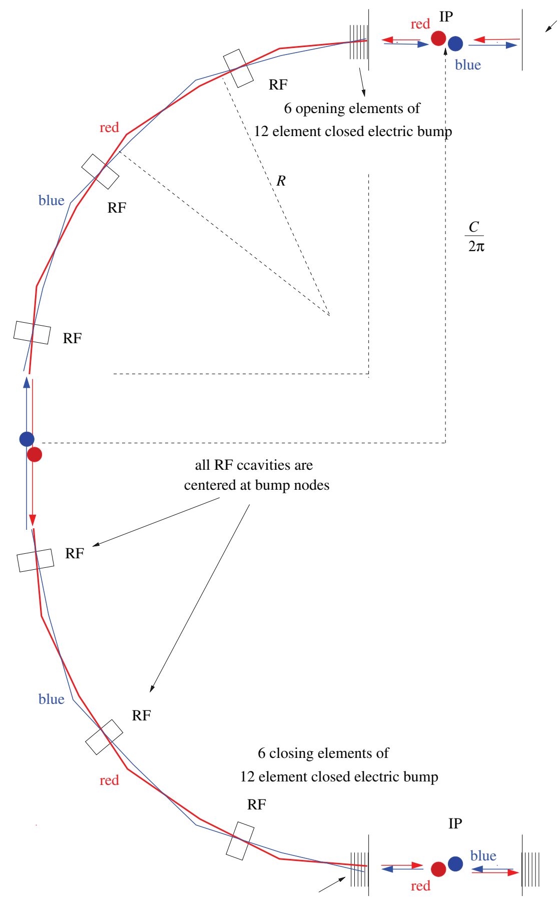

Figure 2: Cartoon illustrating beam separation in one arc of a Higgs factory. There are N_b=4 bunches in each beam and N^*=2 interaction points (IP). The bend radius R is significantly less than the average radius $C/(2\pi)$; roughly $C = 3\pi R$. For scaling purposes R and C are taken to be strictly proportional. Far more separation loops and crossovers are actually needed than are shown.

Various horizontal pretzel separation schemes were tried at LEP. They were constrained by the need to be superimposed on an existing lattice. LEP investigations in the early 1990's mainly concentrated on what now would be called quite low energies, especially the Z_0 energy, $E = 45.6$ GeV. For a Higgs factory we need to plan for energies four or five times higher. The required product of separator length multiplied by electric separator field has to be greater by the same factor to obtain the same angular separation. Actually the factor may have to be somewhat greater than this because of the larger bunch separation needed with increased ring circumference.

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CHALLENGES AND STATUS OF THE FCC-*ee* LATTICE DESIGN

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Abstract

Following the recommendations of the European Strategy Group for High Energy Physics, CERN started the Future Circular Collider Study (FCC), a design study for possible future circular collider projects to investigate their feasibility for high energy physics research. One part of this study is FCC-ee, an e+e- collider with a circumference of 100 km. Challenges for the lattice design result from operation at four different beam energies ranging from 45.5 GeV to 175 GeV. Very high beamstrahlung effects at high energies and the beam-beam limit at low energies request emittance parameters that rise with decreasing beam energy. This paper will present the status of the lattice design and the lattice modifications needed to achieve the requested emittance parameters.

INTRODUCTION

The Large Electron Positron Collider (LEP) was the most powerful lepton machine that was ever build. Its maximum beam energy was limited by the available power of the RF cavities that fed back the high amount of energy lost by synchrotron radiation. When LEP finished operations in 1995 investigations of lepton machines with even higher beam energy moved to linear accelerators (e.g. CLIC, ILC). After nearly 20 years CERN launched a design study for the feasibility of circular colliders for future high energy physics research, called FCC. One part of the study, FCC-hh, is a possible proton discovery machine with 100 TeV center of mass energy. The circumference would be about 80 km-100 km based on Nb_3Sn technology with magnetic fields of 16 T-20 T [1]. Given the technical infrastructure and the large bending radius of 10.6 km a future circular lepton collider for precision studies in the energy range of 90 GeV to 350 GeV could still be operated with an acceptable amount of synchrotron radiation loss. This part of the study, which could bring the come back of circular high energy lepton colliders, is called FCC-ee. As a third part, a proton electron option called FCC-he is considered. Deep inelastic scattering could basically be studied in two options: a LHeC like linac-ring option and a ring-ring option. In this paper the status of the FCC-ee lattice design and its modifications in order to achieve the requested emittance parameters are discussed in detail.

Physics Goals

FCC-ee is designed to provide highest possible luminosity for precision studies of a wide physics program. This covers four different center of mass energies: 91 GeV for measurements of the Z pole, 160 , which is the W pair production threshold, 240 GeV for H production and the $t\bar{t}$ threshold at 350 GeV. To reach the goal of highest possible luminosity, for each of the physics programs a set of baseline parameters was assembled shown in Table 1.

CHALLENGES

The limit of luminosity performance in a lepton storage ring strongly depends on the energy of the colliding beams. Thus the machine has to be designed and optimized for each of the four energies separately while using the same hardware. At high energies the luminosity lifetime is limited to 15-20 min by beamstrahlung [2]. This requires on the one hand top up injection from a full energy booster and on the other hand a very high momentum acceptance of 1-2 %. At low energies the luminosity is limited by the beam-beam effect, which creates a tuneshift of the working point. Assuming two equal beams sizes the beam-beam parameter is given by [3]

$$\xi_q = \frac{N r_e}{\gamma} \frac{\beta_q^*}{2\pi\sigma_q(\sigma_x + \sigma_y)}, \tag{1}$$

where q stands for x or y and N is the bunch population. To keep the tuneshift small, the beam size σ must be increased by a larger emittance. However in electron storage rings the horizontal equilibrium emittance is proportional to γ^2 [4], so the emittance is decreasing with lower energy. Consequently the lattice needs to be modified between operation at different energies. At the same time a very small ration of vertical and horizontal emittance of 0.1 % must be achieved for highest luminosity. The vertical emittance of 1 pm corresponds to performances of synchrotron light sources and sets serious constraints on the alignment requirements of the machine.

At 175 GeV beam energy very high synchrotron radiation losses of 7.5 GeV per turn will require a sophisticated absorber design to protect the vacuum chamber. Furthermore equally distributed RF sections will be needed to keep the energy sawtooth effect on a reasonable level. At 45.5 GeV beam energy the high beam current and the large number of bunches make it mandatory to use two separated vacuum chambers instead of a common one and a crossing angle in the interaction region to avoid multiple bunch crossings inside the detector. A further challenge for the interaction region design is the very small vertical beta function at the interaction point $\beta^* = 1$ mm. Very strong focusing is required, which creates high chromaticity. Therefore a local chromaticity correction scheme is foreseen before entering the arcs [5]. Still the strong sextupoles must provide sufficient dynamic aperture for momentum deviations of up to 2 % created by the beamstrahlung.

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STATUS OF CEPC LATTICE DESIGN

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Abstract

IHEP has proposed a circular electron and positron collider (CEPC) to study the properties of the Higgs boson. In the baseline design, the circumference of CEPC will be taken as 50km, and a sing ring scheme will be adopted, e.g., the electron and positron beam will share the beam pipes. This paper will show the latest design of the CEPC lattice, including the design of the main ring lattice and the pretzel scheme. Some critical issues that we encountered when designing the lattice will also be discussed.

INTRODUCTION

After the discovery of Higgs-like boson at CERN [1-3], many proposals have been raised to build a Higgs factory to explicitly study the properties of the particle. One of the most attractive proposals is the Circular Electron and Positron Collider (CEPC) project in China [4,5].

CEPC is a ring with a circumference of 50-70 km, which will be used as electron and positron collider at phase-I and will be upgraded to a Super proton-proton Collider (SppC) at phase-II. The designed beam energy for CEPC is 120 GeV, the main constraints in the design is the synchrotron radiation power, which should be limited to 50 MW, the target luminosity is ~10^{34}cm^{-2}s^{-1}.

As beam energy is high, CEPC favors more arcs which enables RF cavities to compensate the energy loss in the straight section, thus can reduce energy variation from synchrotron radiation. SppC needs long straight sections for collimators etc. To compromise between CEPC and SppC, the ring is decided to have 8 arcs and 8 straight sections, RF cavities will be distributed in each straight section.

In this paper, we will show the latest design of the CEPC lattice, including the design of the main ring lattice and the pretzel scheme. Some critical issues that we encountered when designing the lattice will also be discussed.

LATTICE DESIGN OF THE RING

The circumference of the ring is 54km with 8 arcs and 8 straight sections. The layout of the ring is shown in Fig. 1. There are four IPs in the ring, IP1 and IP3 will be used for CEPC, while IP2 and IP4 will be used for SPPC. The RF sections are distributed in each straight section. At the IP section, the RF cavities will be symmetrically placed at the two ends of the section, at the other straight sections, the RF cavities can be located together at the middle of each straight section.

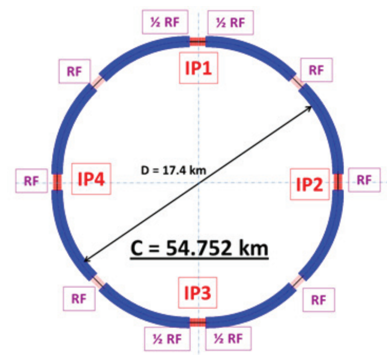

Figure 1: Layout of the CEPC ring.

FODO Cells

The lattice for CEPC ring has been chosen to use the standard FODO cells with 60 degrees phase advances in both transverse planes. The FODO cell structure is chosen to have a maximum filling factor. The 60 degrees phase advance is chosen to have a relatively large beam emittance, so that a relatively longer beamstrahlung beam lifetime, than the 90 degrees phase advance lattice cells.

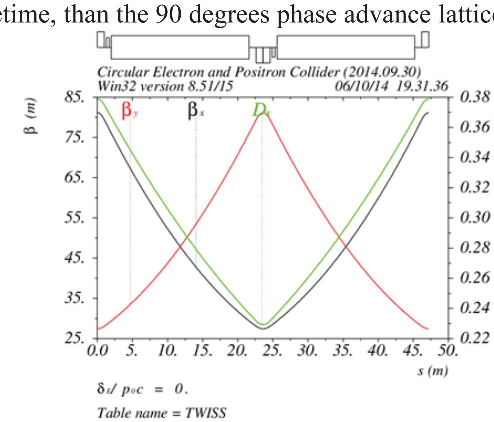

Figure 2: Beta functions and dispersion function of a standard FODO cell with 60/60 degrees phase advance in CEPC ring.

A standard FODO cell with 60 degrees phase advance is shown in Fig.2. The length of each bend is 19.6m, the length of each quadrupole is 2.0m. There is one sextupole, with a length of 0.4 m, next to each quadrupole for chromatic corrections. The distance between the sectupole and the adjacent magnet is 0.3 m, while the distance between each quadrupole and the adjacent bending magnet is 1.0 m. The total length of each cell is 47.2 m.

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A GREEN CEPC USING THE POWER OF NUCLEAR WASTE

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Abstract

China is proposing to build an efficient Higgs factory, CEPC, a 52 km ring under the ground, to search the mysteries of the particle physics. This large circular collider would allow the Higgs boson to be studied with greater precision than at the much smaller Large Hadron Collider (LHC) at CERN. However, several hundreds of MW wall power is needed to run such a huge machine. With the development of China's nuclear power, a huge amount of long-lived nuclear waste needs to be safe disposed. The nuclear waste can be safely disposed by Accelerator Driven Sub-critical System (ADS) and provide electric power at the same time. Both CEPC and ADS are based on the superconducting accelerator technology and the power of the CEPC can be fully covered by the ADS. A green CEPC running in China is possible in the future.

INTRODUCTION

The Standard Model (SM) of particle physics can describe the strong, weak and electromagnetic interactions under the framework of quantum gauge field theory. The theoretical predictions of SM are in excellent agreement with the past experimental measurements. After the discovery of the Higgs particle, it is natural to measure its properties as precise as possible, including mass, spin, CP nature, couplings, and etc., at the current running Large Hadron Collider (LHC) and future electron positron colliders, e.g. the International Linear Collider (ILC). The low Higgs mass of ~125 GeV makes possible a Circular Electron Positron Collider (CEPC) as a Higgs Factory, which has the advantage of higher luminosity to cost ratio and the potential to be upgraded to a proton-proton collider to reach unprecedented high energy and discover New Physics. CEPC is the development in energy frontier of particle physics, and the next step of BEPC and BEPCII. As the energy is about 125GeV for the circular machine, it is a huge machine that ever built in china in fundamental research. The machine will be in a ~50km tunnel underground to keep electron and positron colliding. As the project is only for the fundamental research, it is a large non-profit and high operation cost machine. The construction cost will be much larger than the BEPCII. Huge energy consuming is a problem must be in concern as the machine will consume several hundred MW wall power in operation.

CEPC POWER CONSUMING

The CEPC is large circular collider with ~50km ring. Figure 1 shows the schematic layout of CEPC. The booster, CEPC and SppC will share the same tunnel. Table 1 shows the main parameters of the CEPC. The beam SR loss will be 51.7MW/turn. As there will be two beams in the ring, about 100MW/turn beam power will be lost. Considering the RF power source, cryogenic system and so on, the total power consuming will be about 300MW. Comparing will LHC and ILC, it is about two times of the LHC power consuming and about the same as ILC [1].

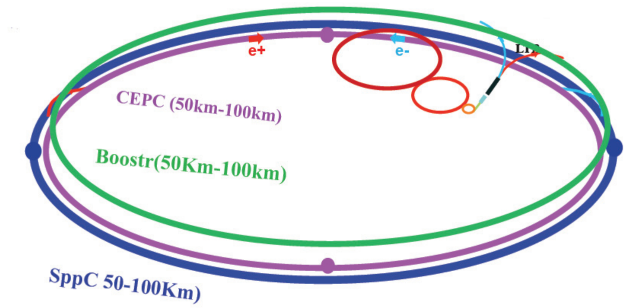

Figure 1: The road map of ADS linac project.

ENERGY PROBLEM IN CHINA

China has a population of about 1.3 billion. Now the average energy consumption per person is less than one half of the world level and less than one tenth of the developed country's level. However, the fast development of economy at annual rate of 7-10% has been kept for more than 20 years, and it will last for much more years. China will keep the fast development country for a long time. China has been the second largest energy producing and consumption country [2]. The population of China will be 1.5 billion at 2050, conservatively predicted capacity of electricity will be 1200~1500GWe. China will probably be the first largest CO_2 producer at 2025 [2]. And in the near future, China will become the first largest energy producing and consumption country. Therefore, China faces serious pollution and energy shortage in the future. Renewable energy, sustainable energy and nuclear energy must be considered to solve the pollution problem and energy shortage. Now China has made great effort to develop renewable energy, sustainable energy and nuclear energy. Figure 2 shows the renewable and sustainable energy that mainly used in China.

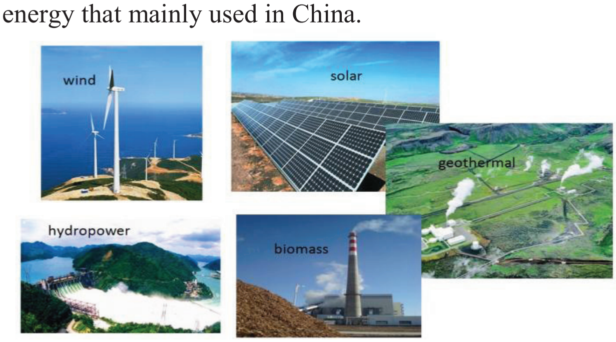

Figure 2: Renewable and sustainable energy in China.

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GREENING FOR BOSONS

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Abstract

Throughout history, scientific advancement has been dependent upon advances in the technologies of research. However, branches of research that today rely on Research Infrastructures (RIs) such as accelerators require technological investments so large that multi-nation collaborations are required to fund them. Modern accelerator science also has massive (and increasing) energy needs, yet the very provision of secure, equitable, clean and cost effective energy is one of the greatest sustainability challenges facing society. Modern energy provision systems are fundamental to development, yet also constitute one of the greatest threats to sustainability via their contribution to environmental degradation and climate change. This paper works from a premise that any new proposal for investment in an RI should credibly demonstrate that it would deliver more value than cost to society. As our understanding of the negative impacts of energy use grows, the demonstration of overall value creation has become more complex; it must now include consideration of an RI's 'energy system footprint'. Programs to reduce the energy footprint can help address this delicate balance. This paper uses experiences in the development of the European Spallation Source (ESS) in Sweden to demonstrate how credible programs to improve the energy performance of an RI can take form.

THE REASON FOR GREENING

Research Infrastructure

We use the term "Research Infrastructure" (RI) to denote scientific facilities of such magnitude that they are comparable to other infrastructure such as airports, bridges or tunnels. Many of these facilities are based on accelerators, but there are also telescopes, supercomputers, reactors, wind tunnels, and more.

The funding of scientific RIs is also an issue that can be compared with that of bridges and airports. Such investments are often necessarily financed by governments, but are motivated by explicit expectations that the benefits they provide to society, both in the medium and long-term, far outweigh their costs. There is thus, a strong social element in the argument for investments in RIs such as particle accelerators. This social argument element includes the societal value of knowledge as a goal in itself.

Costs and Benefits of RIs

Just as each breakthrough in the crafting of lenses has paved the way for new scientific discovery with telescopes and microscopes that can see further, or 'smaller', each generation of accelerator-based RI required for the next level of knowledge needs to be more powerful. While technological improvements help ameliorate the situation, for the most part, each RI generation with increased performance also needs increased energy input – and the overall energy consumption (and operational cost) increases.

In order to attract governments to join the financing of new RIs, scientists and other proponents must successfully argue that benefits continue to (significantly) outweigh the costs. Cost/benefit assessments however, are complex; both the benefits and the costs are likely to contain a large proportion of intangible or contingent items. As positives, these can include the effects of creativity and innovation; as negatives, there may be fear of (potential) accidents, concern about radiation or simply NIMBYism. It can therefore be a difficult task to demonstrate net benefit. It is perilous to disregard stakeholder concerns however. Proponents of scientific infrastructure, often themselves scientists, may tend to undervalue risk vectors that seem irrational, or factually unfounded, such as the concerns of neighbours of the potential dangers of the research to be conducted (e.g. the 'creation of a black hole', the potential of a meltdown, etc.). Even if concerns are unfounded, they can still be real, both in the minds of neighbours, and even in law. In Swedish environmental legislation, as one example, the concerns of neighbours are considered as an 'environmental impact' and must be managed; just as emissions are.

SUSTAINABILITY

Humankind places an increasing burden on the planet. Despite our gains in efficiency, the effects of population growth and economic growth consume increasing amounts of resources [1], [2]. Scarcity of resources leads to price volatility – and to 'security of supply' challenges that are most serious for those most sensitive to price. Food, water and energy can always be produced and distributed to those who can afford them. This is not the central challenge for sustainability. A very important challenge however, is to do so for the world's poor.

Science can substantially contribute to both the knowledge needed to lower the cost of supplying life essentials, and to the growth needed for the poorest to access them. This is an important argument for investment in science. However, it is also important to recognise that an initial investment of resources to create large RIs places additional stress on supply systems. It can contribute to energy poverty by raising prices, and also competes directly for potentially scarce energy with such sectors as food production.

In addition to its highly publicized links to climate change [3], energy also plays important roles in the

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PARAMETER OPTIMIZATION IN HIGGS FACTORY DESIGN

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Abstract

In this paper, parameter optimization of Higgs factories is discussed focusing on the designs of CEPC and FCCee. The total beam current in Higgs factories is limited by synchrotron radiation power, and then the machine size and cost; maximum linear tune shift is limited by beam-beam interaction; reduction of beta-function at interaction point is restricted by the distance of the final focusing quadrupole to the interaction point, bunch length, "hour glass" effect and dynamic aperture. Beamstrahlung effects beam energy spread and lifetime in the colliders, limiting luminosity reach. High luminosity in the Higgs factories requires optimization of parameters.

LUMINOSITY

Discovery of Higgs boson of 125 GeV, shown in Fig.1, not far from the LEPII reached energy, makes it feasible to build circular e$^+$e$^-$ colliders of 120 GeV and neighbouring energies as Higgs factories with high luminosity.

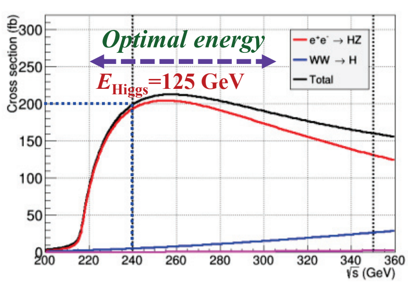

Figure 1: Energy of Higgs boson and Higgs factories.

The luminosity in circular collider is given in Eq. (1) assuming beam aspect ratio $r=\sigma_y/\sigma_x<<1$, σ_x and σ_y being horizontal and vertical beam size at interaction point (IP).

$$L = \frac{1}{2e \cdot r_e E_0} \cdot \xi_y \frac{E \cdot k_b I_b}{\beta_y^*} H_g \tag{1}$$

Where e is electron charge, r_e is classical radius of electron, E_0 is rest energy of electron, E is colliding beam energy, k_b and I_b are bunch number and current respectively, ξ_y is vertical beam-beam parameter, β_y^* is beta function at IP and H_g is hour glass factor expressed as:

$$H_g = \frac{L}{L_0} = \frac{\beta_y^*}{\sqrt{\pi}\sigma_z} \exp\left(\frac{\beta_y^{*2}}{2\sigma_z^2}\right) K_0\left(\frac{\beta_y^{*2}}{2\sigma_z^2}\right) \tag{2}$$

Here σ_z is bunch length. The formula is applies to the zero crossing angle case.

It can be seen in Eq. (1) that the luminosity is closely related to total beam current, beta function at IP, maximum beam-beam parameter, hour glass factor which always less than 1. And all parameters are correlated. The correlation of the parameters are illustrated in Figure 2.

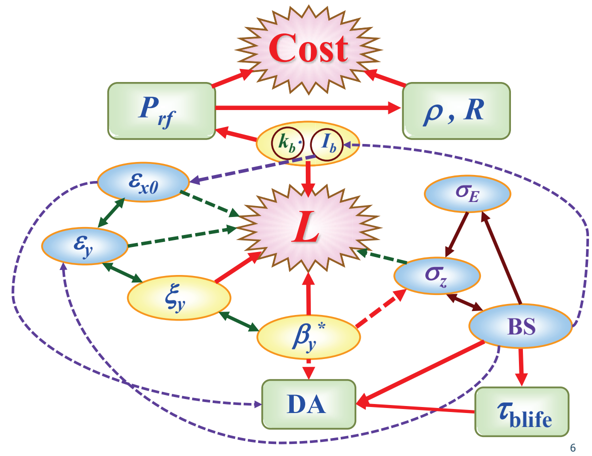

Figure 2: Correlation of parameters in colliders.

As shown in Fig. 2, luminosity is in the centre of the correlation net while the cost of the collider is the top concern especially for such a high energy e$^+$e$^-$ collider like Higgs factories. In following sections optimization of the parameters related to luminosity and cost are discussed based on the designs of CEPC [1] and FCCee [2].

BEAM-BEAM PARAMETER

Beam-beam parameter, or linear beam-beam tune shift, characterizes the strength of the beam-beam force [3]:

$$\xi_{x,y} = \frac{r_e}{2\pi e} \frac{I_b \beta_{x,y}^*}{\gamma \cdot f_0 \sigma_{x,y}(\sigma_x + \sigma_y)} \tag{3}$$

here γ is relativistic energy and f_0 is revolution frequency. The larger the beam-beam parameters, the higher the luminosity will be reached. The maximum achievable beam-beam parameter strongly depends on the radiation damping in storage rings. The LEP beam-beam performance gives the following scaling law [4]:

$$\xi_y^{\max} = 0.5\tau_E^{-0.4} \tag{4}$$

Taking advantage of the LEP scaling law of Eq. (3), the maximum vertical beam-beam parameters for CEPC and FCCee are calculated in comparison with their designed values in Table 1 and Fig. 3.

Table 1: Calculated and Designed Maximum Vertical Beam-beam Parameters for CEPC and FCCee

Parameter		CEPC	FCCee			
E (GeV)		120	45.5	80	120	175
τ_E (turns)		39	1320	243	72	23
$\xi_y^{\max}$	Cal.	0.15	0.028	0.056	0.090	0.143
	Des.	0.083	0.03	0.059	0.093	0.092

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POLARIZATION ISSUES IN THE $e\pm$ FCC

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Abstract

After the Higgs boson discovery at LHC, the international physics community is considering the next energy frontier circular collider (FCC). A *pp* collider of 100 km with a center of mass energy of about 100 TeV is believed to have the necessary discovery potential. The same tunnel could host first a e^+e^- collider with beam energy ranging between 45 and 175 GeV. In this paper preliminary considerations on the possibility of self-polarization for the $e^\pm$ beams are presented.

INTRODUCTION

$e^\pm$ beams in a ring accelerator may become vertically polarized through the Sokolov-Ternov effect [1]. A small part of the radiation emitted by particles moving in a constant homogeneous field is accompanied by spin flip wrt the field direction. The probability of spin flip in the direction parallel to anti-parallel and from anti-paralle to parallel to the field are slightly different and this results in a polarization of 92.4 %, independently of energy. The polarization rate is given by

$$\frac{1}{\tau_{ST}} = \frac{5\sqrt{3}}{8}\frac{r_0 h}{2\pi m_0}\frac{\gamma^5}{|\rho|^3}$$

which strongly depends upon energy and radius. In actual ring accelerators there are not only dipoles. Quadrupoles for instance are needed for beam focusing. When a particle emits a photon it starts to perform synchro-betatron oscillations around the machine actual closed orbit experiencing extra possibly non vertical fields. The expectation value $\vec{S}$ of the spin operator moves according to the Thomas-Bargmann-Michel-Telegdi (Thomas-BMT) equation [2] [3]

$$\frac{d\vec{S}}{dt} = \vec{\Omega}\times\vec{S}$$

$\vec{\Omega}$ depends on machine azimuth and phase space position, $\vec{u}$. In the laboratory frame and MKS units it is given by

$$\vec{\Omega}(\vec{u};s) = -\frac{e}{m_0}\Big[\Big(a+\frac{1}{\gamma}\Big)\vec{B}-\frac{a\gamma}{\gamma+1}\vec{\beta}\cdot\vec{B}\vec{\beta}-\Big(a+\frac{1}{\gamma+1}\Big)\vec{\beta}\times\vec{E}\Big]$$

with $\vec{\beta} \equiv \vec{v}/c$ and $a = (g-2)/2$=0.0011597 ($e^\pm$). The T-BMT equation describes a precession of $\vec{S}$ around $\vec{\Omega}$. In a planar machine the *periodic* solution, $\hat{n}_0$, is vertical. The number of precessions per turn, the "naive" spin tune, in the rotating frame is $a\gamma$. Photon emission results in a randomization of the particle spin directions (*spin diffusion*). Polarization will be therefore the result of the competing process, the Sokolov-Ternov effect and the spin diffusion caused by stochastic photon emission. The problem has been studied and solved in a semiclassical approximation by Derbenev and Kondratenko [4]. They found that the polarization is oriented along the *periodic* solution, $\hat{n}_0$, of the Thomas-BMT equation along the *closed orbit* and its value is

$$P_{DK} = P_{ST}\frac{\oint ds < \frac{1}{|\rho|^3}\hat{b}\cdot(\hat{n}-\frac{\partial\hat{n}}{\partial\delta}) >}{\oint ds < \frac{1}{|\rho|^3}\Big[1-\frac{2}{9}(\hat{n}\cdot\hat{s})^2+\frac{11}{18}(\frac{\partial\hat{n}}{\partial\delta})^2\Big] >}$$

with

$$\hat{b} \equiv \vec{v}\times\dot{\vec{v}}/|\vec{v}\times\dot{\vec{v}}|$$

The <> brackets indicate averages over the phase space. The term $\partial\hat{n}/\partial\delta$, with $\delta \equiv \delta E/E$ quantifies the depolarizing effects resulting from the trajectory perturbations due to photon emission.

The corresponding polarization rate is

$$\tau_{DK}^{-1} = P_{ST}\frac{r_e\gamma^5\hbar}{m_0 C}\oint < \frac{1}{|\rho|^3}\Big[1-\frac{2}{9}(\hat{n}\cdot\hat{s})^2+\frac{11}{18}(\frac{\partial\hat{n}}{\partial\gamma})^2\Big] >$$

In a perfectly planar machine $\partial\hat{n}/\partial\delta$=0. In presence of quadrupole vertical misalignments (and/or spin rotator) $\partial\hat{n}/\partial\delta \neq 0$ and large when

$$\nu_{spin} \pm mQ_x \pm nQ_y \pm pQ_s = \text{integer}$$

Polarization in an actual ring accelerator has been observed for the first time at ACO in Orsay in 1968. The self polarization mechanism has been exploited more recently in large accelerators, namely HERA-e and LEP. While in LEP beam polarization was used for precise energy measurement through RF resonant depolarization, at HERA the provision of beam polarization was an integral part of the physics program and 3 pairs of spin rotators were build-in for turning the direction of polarization of the lepton beams from vertical to longitudinal at the HERMES, H1 and ZEUS experiments. HERA-e was operating at 27.5 GeV and the dipole bending radius was about 600 m, corresponding to a polarization time of the order of 30 minutes. The maximum transverse polarization achieved at HERA-e was about 75%. LEP dipole bending radius was about 3000 m and energy ranged between 40 and 100 GeV. The polarization level strongly decreased with energy and above 65 GeV no polarization was detected [5]. Qualitatively this can be explained by the increasing of spin diffusion with energy.

Both at HERA-e and LEP the high level of polarization was obtained through

- Optimization of energy;
- Choice of orbital tunes: small values of the fractional part result in a larger region free from low order resonances;

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ANALYSIS OF BEAM DYNAMICS IN A CIRCULAR HIGGS FACTORY*

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Abstract

We design a circular Higgs factory with a center-of-mass energy of 240 GeV residing in a 50-km tunnel. Aside from two strong focusing systems and a low-emittance lattice in arcs that are required to achieve a factory luminosity of $1.0 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a large momentum aperture of 2% is absolutely necessary to mitigate the effect of beamstrahlung and retain an adequate beam lifetime. This turns out to be the most challenging aspect in the design. We comprehensively study the single-particle dynamics and identity many nonlinear aberrations that limit the performance of the optics.

INTRODUCTION

Since the discovery of the Higgs particle at LHC, the recent results for ATLAS and CMS have shown that the discovered particle resembles the Higgs boson in the standard model of elementary particles. Because of this remarkable discovery, it becomes increasingly important to precisely measure the property of the particle that gives the mass to all and to study the nature of the spontaneous symmetry breaking in the standard model.

The relatively low mass of the Higgs boson provides an opportunity to build an e^+ and e^- collider to efficiently and precisely measure its properties. In the production channel of $e^+e^- \rightarrow HZ$, the beam energy required for such a collider is about 120 GeV, which is only 15% higher than the energy reached about two decades ago at LEP2. Can we design and build a circular Higgs factory (CHF) within a decade? What are the major challenges in the design? In this paper, we will address these questions.

LUMINOSITY

In a collider, aside from its energy, its luminosity is the most important design parameter. For Gaussian beams, we can write the bunch luminosity as

$$\mathcal{L}_b = f_0 \frac{N_b^2}{4\pi\sigma_x\sigma_y} R_h, \tag{1}$$

where f_0 is the revolution frequency, N_b the bunch population, $\sigma_{x,y}$ transverse beam sizes, and R_h is a factor of geometrical reduction due to a finite bunch length σ_z and is given by

$$R_h = \sqrt{\frac{2}{\pi}} a e^{a^2} K_0(a^2), \tag{2}$$

$a = \beta_y^*/(\sqrt{2}\sigma_z)$, β_y^* is the vertical beta function at the interaction point (IP), and K_0 the modified Bessel function. In order to avoid R_h becoming too small, we shall require $\sigma_z \approx \beta_y^*$. Obviously, for a number of n_b bunches, the total luminosity is $\mathcal{L} = n_b \mathcal{L}_b$.

In general, the beam sizes in the luminosity formula are not static variables. They are subject to the influence of the electromagnetic interaction during the collision. Typically, for flat beams, the vertical beam size will be blown up by the beam-beam force. To take this effect into account, we introduce the beam-beam parameter as [1]

$$\xi_y = \frac{r_e N_b \beta_y^*}{2\pi\gamma\sigma_y(\sigma_x + \sigma_y)}, \tag{3}$$

where γ is the Lorentz factor and r_e the classical electron radius. Using this formula for ξ_y, we can rewrite the luminosity as [2]

$$\mathcal{L} = \frac{cI\gamma\xi_y}{2r_e^2 I_A \beta_y^*} R_h, \tag{4}$$

where I is the beam current and $I_A = ec/r_e \approx 17045$ A, the Alfven current. Since ξ_y is limited below 0.1 in most colliders, this formula is often used for estimating an upper bound of the luminosity.

Table 1: Main Parameters of a Circular Higgs Factory

Parameter	LEP2	CHF
Beam energy, E_0 [GeV]	104.5	120.0
Circumference, C [km]	26.7	47.5
Beam current, I [mA]	4	14.4
SR power, P_{SR} [MW]	11	50
Beta function at IP, β_y^* [mm]	50	2
Bunch length, σ_z [mm]	16.1	1.5
Hourglass factor, R_h	0.98	0.76
Beam-beam parameter, ξ_y	0.07	0.07
Luminosity/IR, $\mathcal{L}$ [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	0.0125	1.01

In Table 1, we tabulated a set of consistent parameters for a CHF. In contrast to the B-factories [3,4], the beam current is severely limited by the power of synchrotron radiation at very high energy. To reach the factory luminosity, we need to have very strong final focusing systems and a very low emittance lattice. This combination makes the design of optics much more difficult compared with that of the B-factories.

SYNCHROTRON RADIATION

When an electron is in circular motion with a bending radius ρ, its energy loss per turn to synchrotron radiation is given by

$$U_0 = \frac{4\pi r_e mc^2\gamma^4}{3\rho}. \tag{5}$$

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DYNAMIC APERTURE OPTIMIZATION IN SuperKEKB

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Abstract

Colliders squeeze a beam spot at an interaction point(IP) to obtain higher luminosity. Large natural chromaticity generated in a final focus system should be corrected by strong sextupole magnets. Nonlinear effects in the sextupole field and the final focusing magnets decreases the dynamic aperture significantly. Optimization of the dynamic aperture is based on a numerical particle-tracking simulations since aberrations of particle motions due to nonlinear and higher-order effects are treated. In particular, low emittance and low beta functions at IP in SuperKEKB, the dynamic aperture is one of the important issues for both Touschek lifetime and injection efficiency. We present an optimization procedure of the dynamic aperture in SuperKEKB.

INTRODUCTION

The target luminosity of SuperKEKB is 8×10^{35} cm^{-2}s^{-1} which is 40 times higher than the peak luminosity of KEKB. In order to achieve the target luminosity, the vertical beta function at the interaction point (IP) is necessary to be squeezed down to about 300 μm and the beam current needs to be increased 3.6 A in LER with keeping the same beam-beam parameter in the vertical direction, $\sim$0.09 as KEKB.

A bunch length is 5$\sim$6 mm which is much longer than the vertical beta function to suppress coherent synchrotron radiation (CSR). "Nano-beam scheme" proposed by P. Raimondi[1] is adopted to avoid a luminosity degradation due to an hourglass effect. A large Piwinski angle is introduced in the nano-beam scheme. The crossing-angle is 83 mrad in the horizontal direction between a positron low energy ring (4 GeV, LER) and an electron high energy ring (7 GeV, HER). The horizontal emittance is reduced to 3.2$\sim$4.6 nm and the horizontal beta function is also squeezed to 25$\sim$32 mm to realized the nano-beam scheme. A small vertical emittance is necessary to obtain a higher luminosity in the nano-beam scheme. The ratio of the vertical emittance to the horizontal emittance is required to be less than $\sim$0.27 % under an influence of the beam-beam interaction as well as including machine error. The machine parameters will be found in elsewhere[2].

Touschek lifetime will be expected to be very short and the linac injector will need to be improved to provide enough injection beams to compensate short lifetime. A dynamic aperture is one of important issues at SuperKEKB because the dynamic aperture will affect both of the lifetime and the injection efficiency.

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LATTICE DESIGN

The linear chromaticity of focusing magnets in a ring is written by

$$\xi_{x,y} = \frac{\partial \nu_{x,y}}{\partial \delta} = -\frac{1}{4\pi}\int K(s)\beta_{x,y}(s)ds, \tag{1}$$

where $\nu_{x,y}$ is betatron tune and $\delta = \Delta p/p_0$ the momentum deviation from the design momentum p_0, $K(s)$ the focusing strength, $\beta_{x,y}(s)$ the beta function as a function of location s. The linear chromaticity is $\xi_x = -105$ and $\xi_y = -776$ in the LER and $\xi_x = -171$ and $\xi_y = -1081$ in the HER, respectively. The linear chromaticity is corrected with noninterleaved sextupoles at SuperKEKB. The noninterleaved chromaticity corrections in the arc section are shown in Figures 1 and 2.There are 50 pairs of sextupole

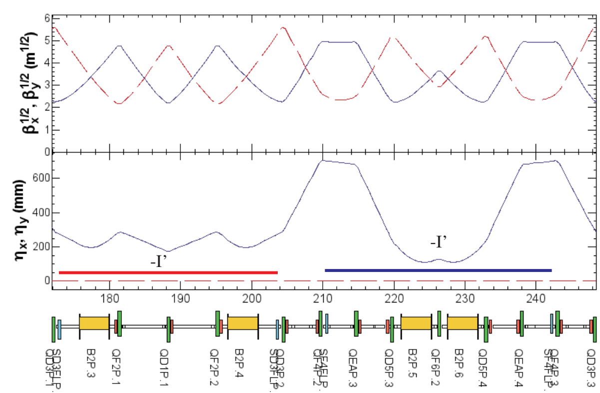

Figure 1: Arc cell in LER.

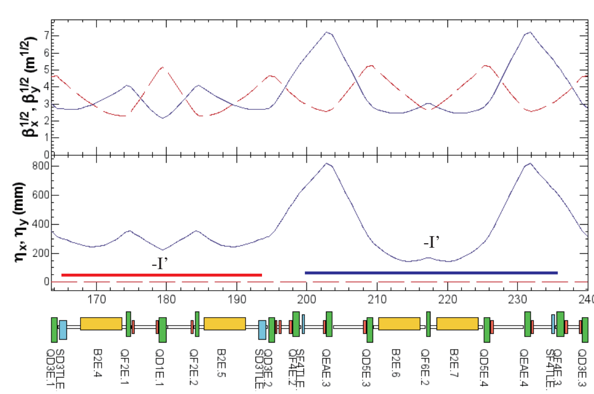

Figure 2: Arc cell in HER.

magnets in the arc section and 4 pairs in the interaction region (IR). The transfer matrix between two identical sextuple magnets is $-I'$ to compensate a nonlinear kick due

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THE EFFECT OF IR IMPERFECTION ON DYNAMIC APERTURE IN SUPERKEKB/ DYNAMIC APERTURE STUDY OF CEPC

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Abstract

Interaction region (IR) is the most critical part of colliders to optimize the dynamic aperture because a detector solenoid and strong final focus magnets give rise to complicated nonlinear beam dynamics. Design of the SuperKEKB IR has been carried out with considering the effect of a possible IR imperfection on the machine performance. In this paper, degradation of dynamic aperture due to error fields from the final focus magnets is discussed. We also present a preliminary study of dynamic aperture of CEPC based on the experience of the SuperKEKB lattice design.

INTRODUCTION

The KEKB accelerator [1] is being upgraded to a SuperB accelerator named SuperKEKB [2]. SuperKEKB consists of 7 GeV electron (HER) and 4 GeV positron (LER) storage rings with a injector linac and a positron damping ring. The target luminosity of $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is obtained by 2 times higher beam current (3.6 A for e^+ and 2.6 A for e^-), 1/20 times smaller vertical beta function β_y^* (0.3 mm), and larger crossing angle of 83 mrad. This approach also requires the low emittance optics to realize the nano-beam collision. The Touschek effect is enhanced in such a low emittance beam and restricts the beam lifetime. Meanwhile squeezing the beta function at the interaction point (IP) results the huge natural chromaticity and makes the chromaticity correction difficult. Furthermore the huge beta function enhances the undesired nonlinear effects in IR likely restricts the beam stability. Therefore the optimization of the dynamic aperture is one of the most challenging topic of the SuperKEKB lattice design.

A large number of feedback procedures between hardware and optics group have been repeated with consideration on detailed hardware specifications to obtain the sufficiently wide dynamic aperture. Overview of the lattice design and effects of the error fields due to the IR imperfection are reported in this paper.

Optimization of the dynamic aperture is a common issue on future high energy circular colliders. Sufficiently wide momentum acceptance is especially important requirement because the beamstrahlung is critical in such a high energy collider. We recently started the optimization of the dynamic aperture for the CEPC project proposed in China. In this paper, a preliminary study of the dynamic aperture of the CEPC lattice is also presented.

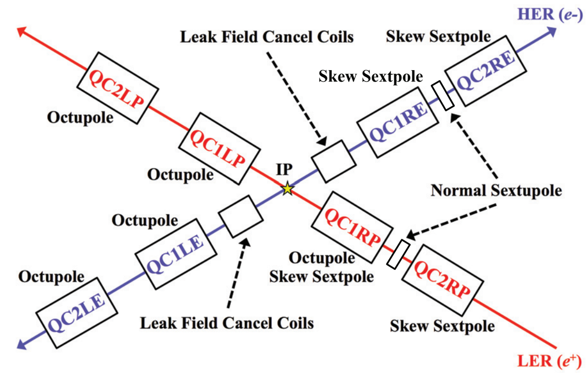

Figure 1: IR schematic view and arrangement of higher-order corrector coils. All magnets have superconducting corrector coils of a dipole, a skew dipole and a skew quadrupole.

SUPERKEKB IR DESIGN OVERVIEW

Figure 1 shows schematic view of the SuperKEKB IR [3]. Each storage ring has 4 superconducting magnets to squeeze the beam size at IP. All quadrupole magnets except for QC1Ps have iron or permendur yoke for preventing leakage fields to the opposite beam line. The HER beam line has cancel coils of sextuple, octupole, decapole and dodecapole in order to compensate the leakage filed from QC1Ps of the LER beam line.

The SuperKEKB IR has a detector solenoid of 1.5 T, and this solenoid field is troublesome in the design of the beam optics and optimization of the dynamic aperture. For example, the finite crossing angle between the beam line and the solenoid axis generates the vertical emittace due to the solenoid fringe field. Therefore, the angle between solenoid axis and two beam lines should be chosen by compromising the vertical emittance generation in HER and LER. In the SuperKEKB IR design, this angle is chosen to be half of the crossing angle. Compensation solenoids are installed in order to suppress the effect of the solenoid field on the beam optics as much as possible. The field distribution is optimized so that the solenoid field integral from IP to each side of IR vanishes, $\int B_z(s)\,ds = 0$ for coupling matching, and reduce the peak of $\partial B_z/\partial s$ for vertical emittance suppression.

All quadrupole magnets have superconducting corrector coils of a dipole, a skew dipole and a skew quadrupole. Horizontal or vertical offset of the quadrupole magnets from the beam line is adopted to reduce required field strength of the dipole corrector in orbit matching. In addition to these

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LIFE TIME AND INJECTION CONSIDERATIONS FOR CEPC

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Abstract

To make a precise study on the Higgs bosons, CEPC ,a circular storage ring collider is being proposed in China. The beam lifetime calculation results in CEPC are shown in this paper. Due to the fact of short lifetime, a top-up injection scheme is needed and some considerations on the injection design is presented.

INTRODUCTION

After the discovery of Higgs bosons at LHC, e+e- collider working as a Higgs factory for further studies has been in consideration throughout the world. CEPC is such a circular e+e- collider proposed in China. The electron and positron energy are chosen to be 120 GeV, which is optimized for a Higgs research. This Collider has a circumference of 50 km, which is about twice the size of LHC, the existing world largest circular collider. Synchrotron radiation energy loss power is 50 MW, and the budget should be more than 20B CNY. The main parameters are listed below in Table 1.

Table 1: Main Parameters of CEPC

Beam Energy	**120 GeV**
Circumference	54.75 km
Luminosity	2.0E34 cm-2s-1
SR power/beam	50 MW
Number of IPs	2
Number of Bunches/beam	50
Momentum compaction factor	3.39E-5
Energy acceptance	0.01
Beam current	16.6 mA
Horizontal emittance	6.12E-9 m.rad
Bunch length	0.00253 m
Beam-Beam parameters(x/y)	0.116/0.082
Emittance coupling	0.003

BEAM LIFETIME

Beam lifetime in a storage ring is a parameter to describe the losing rate of particles, it is defined to be [1]:

$$\frac{1}{\tau}=-\frac{1}{N}\frac{dN}{dt}. \tag{1}$$

In storage rings many effects could reduce the beam intensity, so that the beam life time should include many parts, the total lifetime and the lifetime due to a single beam loss mechanism have a relation as:

$$\frac{1}{\tau_{total}}=\sum\frac{1}{\tau_i} \tag{2}$$

For the CEPC lifetime study lifetime from these effects are taken into account [2]:

(i) Beam-Gas scattering
(ii) Quantum fluctuation of radiation
(iii) Touschek effects
(iv) Radiative BaBar
(v) Beamstrahlung effect

The beam lifetime of CEPC is shown in Table 2, in the calculation a gas consists of 80% H2 and 20% CO with a vacuum pressure of 1E-8 Torr, and a 1.5 cm vacuum chamber radius is assumed.

Table 2: Lifetime of CEPC Due to Different Effects

	Lifetime	**Unit**
Elastic H2 scattering	189	Hours
Elastic CO scattering	15	Hours
Inelastic H2 scattering	149	Hours
Inelastic CO scattering	14	Hours
Transverse quantum	2218	Hours
Longitudinal quantum	Infinity	Hours
Touschek	530	Hours
Radiative BhaBha	51	Min
Beamstrahlung	80	Min
Total lifetime	30	Min

INJECTION DESIGN

The current baseline design of CEPC injection is chosen to use a ramping booster as the main injector. The system consists of one Linac which accelerates the electrons and positrons to 6 GeV, a booster ring which ramps from 6GeV up to high energy of 120 GeV. A sketch of the system is shown in Figure 1.

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CONSTRAINTS ON THE FCC-*ee* LATTICE FROM THE COMPATIBILITY WITH THE FCC HADRON COLLIDER

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Abstract

Following the recommendations of the European Strategy Group for High Energy Physics, CERN launched the Future Circular Collider Study (FCC), a design study for possible future circular collider projects to investigate their feasibility for high energy physics research. The FCC Study covers three different machines with a circumference of 100 km: an electron positron collider with collision energies in the range of 90 GeV to 350 GeV (FCC- ee), a proton proton collider with a maximum energy of 100 TeV (FCC-hh) and an electron proton option (FCC-he). This paper will present the constraints on the design of the FCC-ee lattice and optics from geometry and lattice considerations of the hadron machine.

INTRODUCTION

With the discovery of a Higgs boson all particles of the standard model of particle physics have been found. In order to discover new physics CERN started to study a future discovery machine called FCC-hh with proton proton collisions at 100 TeV center of mass energy. Considerations presented in this paper will show that such a machine will need to have a circumference of 80 km-100 km given by the achievable technology. Having this tunnel available it is obvious to think about an electron positron collider for precision measurements as well [1]. The large circumference allows operation with an acceptable amount of synchrotron radiation losses and the costs for a second machine decrease drastically, as no extra tunnel has to be built. However straight sections for RF installation have to be provided to deal with the synchrotron radiation loss in such a storage ring. This part of the design study, earlier known as TLEP, is called FCC-ee. The third part of the study, FCC-he, covers the investigation of future electron proton collisions in order to study deep inelastic scattering. This comprises two options: a LHeC like linac-ring option and, in case FCC-hh and FCC-ee can be hosted and operated in the tunnel at the same time, a ring-ring option. Each machine of the FCC study has special requirements, that have to be considered in the design phase. This paper focuses on the constraints on the FCC-ee lattice design from the compatibility with FCC-hh. Contrary to FCC-ee, for a beam energy of 50 TeV in the hadron machine a new magnet technology has to be developed. The maximum bending radius in the arcs and consequently the circumference of the machine directly depends on the achievable magnetic field. The length of the long straight sections needed for insertions also contributes to the circumference. They must provide enough space to house RF installation, collimators, kickers for injection and beam dump and the detectors. If LHC is used as an injector, the circumference and harmonic number of FCC should be rational multiples of the LHC's to allow bunch to bucket transfer. Furthermore the FCC-hh and LHC tunnels should be close to each other to guarantee a reasonable length of the transfer lines. For locating a 100 km circular collider also geologic aspects play a major role. The constraints arising from the requirement of hosting both machines in the tunnel at the same time and from the compatibility with FCC-he are not covered in this paper.

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BENDING RADIUS AND CIRCUMFERENCE

The beam rigidity of a 50 TeV proton beam is

$$B\rho = p/e \approx 1.67 \times 10^5 \,\mathrm{Tm}. \tag{1}$$

To bend such a stiff beam in a reasonable radius a new technology of superconducting magnets needs to be developed. A prototype dipole based on Nb_3Sn technology could reach a magnetic field of B =16 T [2]. Such a magnet would define a bending radius of ρ = 10.7 km. If even higher magnetic fields of B =20 T could be achieved, the bending radius could be reduced to ρ =8.5 km. Assuming 16 T magnets and 67 % of the whole circumference including long straight section being occupied by bending magnets the circumference C would approximately be 100 km. As mentioned before, if LHC is used as an injector, the circumference of FCC should be a multiple of the LHC circumference, which is 26.66 km [3]. For 16 T magnets approximately 106.64 km should be taken as circumference and 79.98 km for the 20 T version. Both possibilities are studied, the final choice will depend on the technical progress in magnet technology.

Table 1: Circumference and Ending Radius for Different Magnetic Felds of the Bending Magents

B in T	ρ in km	C in km
16	10.7	106.64
20	8.5	79.98

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POLARIZATION ISSUES AND SCHEMES FOR ENERGY CALIBRATION

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Abstract

The paper presents an overview of problems related to production, acceleration and subsequent utilization of the polarized electron and positron beams for the precise energy calibration in the future FCC-ee storage rings. Advantages and disadvantages of the proposed method of free precession spin frequency measurement are discussed.

INTRODUCTION

As truly stated in [1], the polarized beams can be of interest for two reasons: they allow for an accurate energy calibration using resonant depolarization, which will be a crucial advantage for measurements of M_Z, G_Z, and M_W, with expected precisions of order 0.1 MeV; and they are necessary for physics program with longitudinally polarized beams. Taken seriously into consideration the last request we came to the following polarization scenario:

- No use of self-polarization in a collider - too slow with r=11 km: τ=190 hours at Z-peak.
- Polarized electrons acceleration chain started from a Ga-As photo-gun illuminated by a circularly polarized laser light, followed by acceleration to the energy of an intermediate damping ring (1-2 GeV) and then after cooling by SR again acceleration by a linac up to 20 GeV. After then they will be accelerated by a synchrotron up to the top beam energy of a collider (45 – 175 GeV).
- Positrons produced by the conversion of the accelerated to 5-10 GeV electrons are injected into a damping ring. Main part of the cooled via SR-damping positrons will be utilized for the un-polarized collisions. The remaining fraction of positron bunches will spent much longer time, about few minutes, in a special damping ring equipped by the polarization wigglers. These positrons, after became polarized to 10-40% degree, will be accelerated similarly to electrons via the linac and the synchrotron.
- Preservation of the polarization in the booster synchrotron should be guaranted by the installation there of a number of Siberian Snakes.
- The equilibrium spin direction in both collider rings is vertical. But the spin precession frequency could be determined using two methods: by the resonant depolarization technique, see [2-3], and, alternatively, by measuring a free precession Fourier spectrum.
- In the last approach the injected beam polarization vector is perpendicular to the vertical axis.
- The Compton backscattering longitudinal laser polarimeter we propose to use for detection of a coherent spin precession.
- Our estimations reveal a possibility to measure the average beam energy with the accuracy of the order 10^{-6} in single injection shot.

One should keep in mind that resonant depolarization is limited for the use of up to 80-100 GeV per beam. At higher energies the non-polarization methods of the energy monitoring should be considered. Such two possibilities are discussed in [4, 5]. Still calibration by the resonant depolarization shall validate these techniques for the use at higher energies.

POLARIZED BEAM ACCELERATION WITH SIBERIAN SNAKES

When polarized electron beam is accelerated say from 20 GeV to 80 GeV it crosses more than 130 of integer spin resonances spaced by 440.65 MeV. Due to small field errors it will become fully depolarized even by a single cross of such a resonance.

In 70-th Derbenev and Kondratenko have suggested an idea of the Siberian Snake [6]. This is some kind of a spin rotator which rotates spin by 180^0 around any axis which is perpendicular to the vertical one. In a ring with equally spaced odd number of snakes the closed spin orbit looks like it is shown in the Fig.1: everywhere in arcs spins are lying in the medium plane of an accelerator.

Another remarkable fact is that with the odd number of snakes the fractional part of the spin tune always equals to ν=0.5, thus all the spin resonances became eliminated! Still strong enough spin perturbation may destroy the regular spin motion making it non-adiabatic. It may happen, if any k-th harmonic amplitude of a perturbation exceeds or approaches to w_k~0.5.

Other mechanism, which one should take into account, is the radiative depolarization. More details on that are presented in [7]. Here we want announce only the rough depolarization time estimates, achieved analytically and by running the code ASPIRRIN [8]. With 3 snakes in the isomagnetic ring with the bending radius r=11 km τ_p =320 s at E=45 GeV and τ_p =6 s at E=80 GeV.

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COST CONSIDERATION AND A POSSIBLE CONSTRUCTION TIMELINE OF THE CEPC-SPPC

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Abstract

This paper discusses the cost consideration and a possible construction timeline of the CEPC-SPPC study based on a preliminary conceptual design that is being carried out at the Institute of High Energy Physics (IHEP) in China.

INTRODUCTION

The discovery of the Higgs boson in 2012 at CERN was not only a milestone in particle physics, but also a trigger in the world high-energy physics (HEP) strategic planning for a renewed interest in future circular colliders. Because the Higgs mass is low (125 GeV), a circular *e+e-* collider can be built to serve as a Higgs factory. But the ring size must be big in order to combat the synchrotron radiation problem. Such a large size ring would be ideal to house a *pp* collider with an energy much higher than that of the LHC. Based on this consideration, the IHEP proposed to build a 50-100 km ring in China. It would first be used as a Higgs factory with the name Circular Electron-Positron Collider (CEPC), then as a 70-100 TeV Super Proton-Proton Collider (SPPC).

A preliminary conceptual design study of the CEPC-SPPC started in earnest in early 2014. In order to be considered as a line item listed in the Chinese government's next Five-Year Plan (2016-2020), the study was put on a fast track – a preliminary conceptual design report is due the end of 2014.

A general description of the CEPC-SPPC can be found in another presentation at this workshop [1]. This paper will discuss the cost consideration and a possible construction timeline of a 50 km ring.

Table 1 and 2 list the top level parameters of the CEPC and SPPC, respectively. Please note that the luminosity of the SPPC has not yet specified because there is an ongoing debate in the world HEP community about the required luminosity of a future high energy *pp* collider [2].

Table 1: Top Level Parameters for CEPC

Parameter	Design Goal
Particles	*e+, e-*
Center of mass energy	240 GeV
Integrated luminosity (per IP per year)	250 fb^{-1}
No. of IPs	2

Table 2: Top Level Parameters for SPPC

Parameter	Design Goal
Particles	*p, p*
Center of mass energy	70 TeV
Integrated luminosity (per IP per year)	(TBD)
No. of IPs	2

Figure 1 is a layout of the CEPC. The circumference is about 54 km. There are 8 arcs and 8 straight sections. Four straight sections, about 1 km each, are for the interaction regions and RF; another four, about 800 m each, are for the RF, injection, beam dump, etc. The lengths of these straight sections are determined when the future need of large detectors and complex collimation systems of the SPPC are taken into account. The total length of the 8 straight sections is about 14% of the ring circumference, similar to the LHC. Among the four IPs, IP1 and IP2 will be used for *e+e-* collision, whereas IP2 and IP4 for *pp* collision.

The tunnel will be underground, about 50-100 m deep. It will accommodate three ring accelerators: the CEPC collider, the SPPC collider, and a full energy booster for the CEPC. Therefore, the tunnel must be big, about 6 m in width as shown in Figure 2. While the two colliders will sit on the floor, the booster will hang on the ceiling, similar to the Recyler in the Main Injector tunnel at Fermilab.

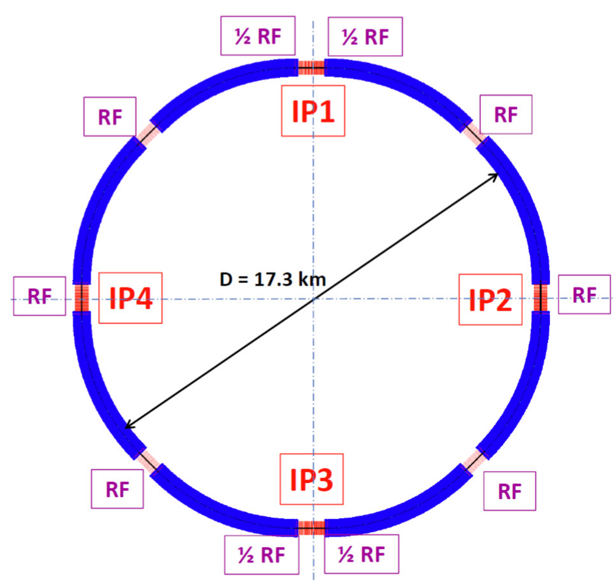

Figure 1: CEPC layout.

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STATUS OF THE FCC-ee INTERACTION REGION DESIGN

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Abstract

The FCC-ee project is a high-luminosity circular electron-positron collider envisioned to operate at center-of-mass energies from 90 to 350 GeV, allowing high-precision measurements of the properties of the Z, W and Higgs boson as well as the top quark. It is considered to be a predecessor of a new 100 TeV proton-proton collider hosted in the same 80 to 100 km tunnel in the Geneva area.

Currently two interaction region designs are being developed by CERN and BINP using different approaches to the definition of baseline parameters. Both preliminary designs are presented with the aim of highlighting the challenges the FCC-ee is facing.

INTRODUCTION

FCC-ee is foreseen to run at four different center-of-mass energies: the Z-pole at 90 GeV, the W pair production threshold (160 GeV), Higgs resonance (240 GeV) and $t\bar{t}$ threshold (350 GeV). From the accelerator point of view, the Z-pole and $t\bar{t}$ threshold are the most challenging setups due to the high number of bunches per beam and high luminosity target (Z) and beamstrahlung ($t\bar{t}$) so these will be the driving forces of the lattice design. In Table 1 the relevant baseline parameters for the 100 km option of FCC-ee are shown. The parameters are in part determined by the design limit of 50 MW of synchrotron radiation per beam. Another constraint for the design of FCC-ee, in particular of the Interaction Region (IR), is the required compatibility with a possible proton-proton collider (FCC-hh) in order to allow a reuse of the tunnel for both machines. Since not only length, but also diameter of the tunnel are a major cost driver of projects of that kind, the design of both machines has to be closely connected and optimized.

Table 1: FCC-ee Baseline Parameters at Z and $t\bar{t}$ Energy for CERN Design at the 100 km Option [1]

	Z	$t\bar{t}$
Beam energy [GeV]	45.5	175
Crossing angle [mrad]	11	
Bunches / beam	16700	98
Bunch population [10^{11}]	1.8	1.4
Energy loss / turn [GeV]	0.03	7.55
Beta function at IP β^*		
- horizontal [m]	0.5	1
- vertical [mm]	1	1
Transverse emittance ϵ		
- horizontal [nm]	29.2	2
- vertical [pm]	60	2
Beam size at IP σ^*		
- horizontal [µm]	121	45
- vertical [µm]	0.25	0.045
Luminosity / IP [10^{34}cm^{-2}s^{-1}]	28.0	1.8

CERN IR DESIGN

The CERN interaction region design is based on a generic lattice originally designed for linear accelerators [2]. This is in part due to the fact that the strong focusing required to reach the high luminosity goals induces high chromaticity that will require a local correction, especially in the vertical plane. The design is shown in Fig. 1 together with the optical functions. It consists of a Final Focus System (FFS), Vertical and Horizontal Chromatic Correction Sections (CCSV, CCSH) and a Matching Section (MS). Each chromatic correction section consists of 4 FODO cells forming two opposed missing dipole dispersion suppressors. All functions are spatially separated which makes the whole lattice very modular. In addition to the sextupoles for chromaticity correction, weaker sextupoles for local correction of nonlinearities were inserted. Currently the CERN design is still in a very early stage of development and only the $t\bar{t}$ settings have been matched.

In the final focus quadrupole, the chromaticity is proportional to $\xi_{x,y} \sim \frac{L^*}{\beta^*_{x,y}}$, thus the length of the last drift L^* should be as small as possible while still leaving enough space to host the detector. At this stage of the design, $L^* = 2$ m is considered reasonable.

From the high number of bunches at lower energies, it is clear that a crossing angle is required to ensure an adequate bunch separation after the IP. While the crossing angle must be large enough to separate the bunches to several σ_x, a large crossing angle requires either a broad tunnel -a major cost driver- or strong dipole magnets close to the IP bending the beam back. The latter will produce high doses of synchrotron radiation close to the detector, increasing the background noise and potential radiation damage. Thus a compromise has to be found.

A first approach is to choose the crossing angle as small as possible to achieve a certain beam separation and have both beams share the same quadrupoles of the final focus system. In this case, the beams pass the first quadrupole off axis and are deflected due to the magnetic field being non-zero, producing considerable amounts of synchrotron radiation. In

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CRAB WAIST INTERACTION REGION FOR FCC-*ee* (TLEP) *

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Abstract

Design study of the accelerator that would fit 80-100 km tunnel called Future Circular Colliders (FCC) includes high-luminosity e^+e^- collider (FCC-ee aka (TLEP)) with center-of-mass energy from 90 to 350 GeV to study Higgs boson properties and perform precise measurements at the electroweak scale [1–3]. Crab waist interaction region provides collisions with luminosity higher than 2×10^{36} $cm^{-2}sec^{-1}$ at beam energy of 45 GeV. The small values of the beta functions at the interaction point and distant final focus lenses are the reasons for high nonlinear chromaticity limiting energy acceptance of the whole ring. The present paper presents estimations of nonlinear effects and describes practical solutions implemented in the design of the interaction region for correction of linear and nonlinear chromaticity of beta functions, and of betatron tune advances, of second and third order geometrical aberrations from the strong sextupoles pairs. The given design embraces realistic design of final focus quadrupoles, satisfies geometrical constraints of the tunnel layout.

INTRODUCTION

One of the limiting factors of high energy e^+e^- collider (FCC-ee aka (TLEP)) is beamstrahlung [4, 5], which limits the beam life time. Consideration of this effect by different authors gave several sets of parameters to achieve high luminosity and feasible beam lifetime. The first one is based on head-on collisions [6], the second is relying on crab waist collision scheme [7, 8] with crossing angle $2\theta = 30$ mrad. Both sets implement the same values of beta functions at the interaction point (IP): $\beta_x^* = 0.5$ m, $\beta_y^* = 0.001$ m and require energy acceptance of the ring more than ±2% to provide feasible beam life time. Advantages of the crab waist set are higher luminosity (7.5 times at 45 GeV) and crossing angle that provides natural separation of the bunches. The list of parameters relevant to present work is given in Table1.

Table 1: Relevant Parameters for Crab Waist IR [7]

	Z	W	H	tt
Energy [GeV]	45	80	120	175
Perimeter [km]		100		
Crossing angle [mrad]		30		
Particles per bunch [10^{11}]	1	4	4.7	4
Number of bunches	29791	739	127	33
Energy spread [10^{-3}]	1.1	2.1	2.4	2.6
Emittance hor. [nm]	0.14	0.44	1	2.1
Emittance ver. [pm]	1	2	2	4.3
β_x^*/β_y^* [m]		0.5 / 0.001		
Luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	212	36	9	1.3
Energy loss / turn [GeV]	0.03	0.3	1.7	7.7

Lattice of the interaction region (IR) should satisfy several requirements:

1. Since successor to FCC-ee is proton accelerator, the IR tunnel should be as straight as possible;
2. Small values of IP beta functions produce large chromaticity, which should be compensated as locally as possible in order to minimize excitation of nonlinear chromaticity;
3. Synchrotron radiation power loss should be significantly smaller than in the arcs;
4. Synchrotron radiation at high energy will produce flux of high energy gamma quanta, therefore the lattice should minimize detector background;
5. Small beta functions at IP enhance effects of nonlinear dynamics, decreasing dynamic aperture and energy acceptance of the ring, therefore the lattice should be optimized to provide large dynamic aperture and energy acceptance.

ESTIMATIONS

The following estimations are performed for vertical plain and marked with subindex y. Assuming that action of the first final focus (FF) quadrupole Q0 changes the sign of α function the quadrupole strength could be estimated as $K_1L = -2/L^*$, where L^* is distance from the interaction point (IP). Chromaticity of beta function is best described by Montague functions [9]

$$b = \frac{1}{\beta}\frac{\partial\beta}{\partial\delta}, \qquad (1)$$

$$a = \frac{\partial\alpha}{\partial\delta} - \frac{\alpha}{\beta}\frac{\partial\beta}{\partial\delta}, \qquad (2)$$

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SUPERKEKB BACKGROUND SIMULATION, INCLUDING ISSUES FOR DETECTOR SHIELDING

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Abstract

The Belle experiment, operated on the KEKB accelerator in KEK, had accumulated a data sample with an integrated luminosity of more than 1 ab^{-1} before the shutdown in 2010. We are preparing upgraded accelerator and detector, called SuperKEKB and Belle-II, to achieve the target luminosity of $8 \times 10^{35} cm^{-1} s^{-1}$. With the increased luminosity, we expect more beam background which might damage our detector components, hide event signals under noise hits, max out readout bandwidth, etc.

Detector shielding is a key to cope with the increased background and protect Belle-II detector. We present how we estimate the impact from each beam background sources at SuperKEKB, such as Touschek-scattering, beam-gas scattering, radiative Bhabha process, etc. We also present our countermeasures to mitigate the beam background, such as tungsten shields installed in the detector to stop shower particles, beam collimators to stop stray beam particles before they reach interaction region, dedicated beam pipe design around interaction point to stop synchrotron radiation, and so on.

INTRODUCTION

The Belle experiment, operating at an asymmetric electron positron collider KEKB, finished its operation in June 2010. The Belle experiment had accumulated a data sample corresponding to an integrated luminosity of 1 ab^{-1}. KEKB recorded the world's highest peak luminosity, $2.1 \times 10^{34} cm^{-2} s^{-1}$. Numerous results of the Belle experiment have confirmed the theoretical predictions of the Standard Model. Especially, measurement of large CP violation in the B meson system has demonstrated that the Kobayashi-Maskawa (KM) mechanism is the dominant source of CP-violation in the standard model,

SuperKEKB, an upgraded of the KEKB collider, will provide a prove to search for new physics beyond the Standard Model, thanks to much larger data sample. The target luminosity of SuperKEKB, $80 \times 10^{34} cm^{-2} s^{-1}$, is 40 times higher than that of KEKB. The upgrade is based on so-called "Nano-beam scheme", which is first proposed by SuperB project planned in Italy [1]. The basic idea of this scheme is to squeeze the vertical beta function at the interaction point (IP). The luminosity of the collider is expressed by the following formula, assuming flat beams and equal horizontal and vertical beam size for two beams at IP:

$$L = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_y \pm}\right)\frac{R_L}{R_{\xi_y}}, \qquad (1)$$

where $\gamma, e, andr_e$ are the Lorentz factor, the elementary electric charge and the electron classical radius, respectively. I, ξ_y, β^*_y are the beam current, the beam-beam parameter and the vertical beta function at IP. The suffix $\pm$ specifies the positron (+) or the electron (-) beam. The parameters R_L and R_{ξ_y} represent reduction factors for the luminosity and the vertical beam-beam parameter, which arise from the crossing angle and the hourglass effect. At SuperKEKB, the vertical beta function at IP is 20 times smaller than KEKB in the Nano-beam scheme. In addition, the total beam currents will be doubled to achieve 40 times higher luminosity. The basic parameter of SuperKEKB is summarized in Table 1.

Belle II detector, an upgrade of the Belle detector, has better vertex resolution with new pixel detector, better particle identification performance with new type sensors, and better tolerance for the background particles. Details of the Belle II detector are described in [2].

Table 1: Basic parameters of SuperKEKB and KEKB. The former number is for the Low Energy Ring(LER) and the latter for the High Energy Ring(HER).

	KEKB achieved	SuperKEKB
Energy [GeV]	3.5/8.0	4.0/7.007
Beam current [A]	1.637/1.188	3.6/2.62
Number of bunch	1584	2503
ξ_y	0.129/0.090	0.0869/0.0807
σ^*_y [nm]	940/940	48/63
β^*_y [mm]	5.9/5.9	0.27/0.30
σ^*_x [μm]	147/170	10/10
β^*_x [mm]	1200/1200	32/25
Luminosity [$cm^{-2}s^{-1}$]	2.1×10^{34}	80×10^{34}

BEAM BACKGROUND SOURCES

At SuperKEKB with higher luminosity, the beam-induced background will also increase. Major background sources at SuperKEKB are shown in this section.

Touschek Effect

The first background source is Touschek effect, which is one of dangerous background sources at SuperKEKB with "Nano-beam" scheme. Touschek effect is an intra-bunch scattering. Coulomb scattering between two particles in a same beam bunch changes their energy to deviate from the beam bunch, one with too much and the other with too little energy. The scattering rate of the Touschek effect is proportional to the inverse beam size, third power of the beam energy, the number of bunches and second

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ANALYTICAL ESTIMATION OF MAXIMUM BEAM-BEAM TUNE SHIFTS FOR ELECTRON-POSITRON AND HADRON CIRCULAR COLLIDERS*

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Abstract

In this paper we will make a brief review of the existing analytical formulae for the beam-beam tune shift limits for electron-positron and hadron circular colliders. The comparison of the estimated beam-beam tune shifts from these formulae with those obtained from existing machines has been made and the validity comparison among these formulae are given as well. Finally, the formulae from J. Gao have been applied in CEPC and SppC parameter optimizations.

INTRODUCTION

The luminosity of an electron-positron circular collider can be expressed as

$$L = \frac{I_{beam}\gamma\xi_y}{2er_e\beta_y^*}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)F_h \tag{1}$$

where r_e is the electron radius (2.818×10^{-15} m), β_y^* is the beta function value at the interaction point, γ is the normalized beam energy, σ_x^* and σ_y^* are the bunch transverse dimensions at the interaction point, respectively, I_{beam} is the circulating current of one beam, F_h is Hourglass reduction factor, and ξ_y is defined as

$$\xi_y = \frac{N_e r_e \beta_y^*}{2\pi\gamma\sigma_y^*(\sigma_x^*+\sigma_y^*)} \tag{2}$$

is the vertical beam-beam tune shift, N_e is the particle population inside a bunch.

$$\begin{aligned} L &= 2.17\times10^{34}(1+r)\xi_y \times \\ &\quad \frac{E_0(GeV)N_b I_{bunch}(A)F_h}{\beta_y^*(cm)}[cm^{-2}s^{-1}] \end{aligned} \tag{3}$$

where E_0 is the beam energy, $r=\sigma_y^*/\sigma_x^*$, N_b is the number of bunches inside a beam, I_{bunch} is the average current of a bunch, and $I_{beam}=N_b I_{bunch}$.

In fact, since ACO [1], it is found that for all circular colliders ξ_y is not a free parameter, and for a given collider, there is a maximum ξ_y, or $\xi_{y,max}$, which could not be surpassed no matter how to make working point optimization [2], and beyond $\xi_{y,max}$, the colliding bunch transverse dimensions blow-up and bunch lifetime drops drastically (exponentially in fact). These beam-beam interaction induced phenomena are called beam-beam effects. To understand the beam-beam effects is one of the key subjects for particle accelerator physicists. For a long time, in a collider design, $\xi_{y,max}$ is chosen as a constant value according to some experiences from previous machines independent of specific machine parameters, i.e., regardless whether $\xi_{y,max}$ is a function of the machine energy, damping time, number of interaction points and particle revolution period, etc. In fact, as we know from Ref. [3], for flat colliding electron-positron beams, $\xi_{y,max}$ can be expressed as (without top-up injection)

$$\xi_{y,max} = \frac{H_0}{2\pi}\sqrt{\frac{T_0}{\tau_y\gamma N_{IP}}} \tag{4}$$

where $H_0=2845$, τ_y is the transverse damping time, T_0 is the revolution period, and N_{IP} is the number of interaction points. Or, for isomagnetic case, one has

$$\xi_{y,max,iso} = H_0\gamma\sqrt{\frac{r_e}{6\pi R N_{IP}}} \tag{5}$$

where R is the local dipole bending radius.

Knowing the analytical expression of maximum beam-beam tune shift, $\xi_{y,max}$, one could has luminosity expressed as

$$\begin{aligned} L_{max}[cm^{-2}s^{-1}] &= 2.17\times10^{34}(1+r)\xi_{y,max}\times \\ &\quad \frac{E_0[\mathrm{GeV}]N_b I_{bunch}[\mathrm{A}]F_h}{\beta_y^*[\mathrm{mm}]} \end{aligned} \tag{6}$$

or

$$\begin{aligned} L_{max}[cm^{-2}s^{-1}] &= \frac{0.158\times10^{34}(1+r)}{\beta_y^*[\mathrm{mm}]}\times \\ &\quad I_{beam}[\mathrm{mA}]\sqrt{\frac{U_0[\mathrm{GeV}]}{N_{Ib}}}F_h \end{aligned} \tag{7}$$

where U_0 is the energy loss due to synchrotron radiation per turn, or

$$\begin{aligned} L_{max}[cm^{-2}s^{-1}] &= \frac{0.158\times10^{34}(1+r)}{\beta_y^*[\mathrm{mm}]}\times \\ &\quad \sqrt{\frac{I_{beam}[\mathrm{mA}]P_{sr}[\mathrm{MV}]}{N_{Ib}}}F_h \end{aligned} \tag{8}$$

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BEAM-BEAM EFFECTS IN CEPC AND TLEP

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Abstract

Higgs particles are discovered in LHC at the mass of 126 GeV. The mass is in possible range for circular Higgs factory. Two proposals for high energy electron positron colliders are being submitted from Europe and China. The colliders are called TLEP and CEPC, respectively. It was considered that very high energy lepton colliders are inefficient for two reasons; high beam power loss and strong beamstrahlung in the beam-beam interaction. We discuss the beamstrahlung in two colliders theoretical and simulations.

INTRODUCTION

Studying the beam-beam effects is essential to determine the beam parameters in colliders. In Higgs factories, beamstrahlung, which is synchrotron radiation emitted by beam-beam collision, seriously affects the bunch length. To get high luminosity $L \sim 10^{34}$ cm^{-2}s^{-1}, vertical beta function at the interaction point (IP) is squeezed strongly, since the successes and ongoing project of B factories, PEP-II, KEKB and SuperKEKB. The bunch lengthening may break hourglass condition $\beta_y > \sigma_z$. The design parameter should be determined with taking into account the bunch lengthening. The colliders, PEP-II and KEKB, have operated with the condition $\beta_y \le \sigma_z$. Simulations of beam-beam interaction have worked as powerful tool for optimization of the operating condition. For Higgs factories, highly qualitative design based on the simulations can be made possible. Table 1 shows the parameters of CEPC and TLEP.

Beamstrahlung is inevitable subject in very high energy e+e- circular colliders [1, 3]. Energy of photon emitted by beam-beam force, which is called beamstrahlung, is much harder than that of bending magnet, because of orbit radius is smaller than the bending radius. High relativistic factor γ shift photon energy higher. We discuss beam-beam interaction with considering beamstrahlung as a key subject.

BEAMSTRAHLUNG

Beamstrahlung is synchrotron radiation emitted during the beam-beam interaction. The curvature of beam orbit during the beam-beam interaction is far smaller than that of bending magnets. Energy of emitted photon during the interaction is very high and the number is less than one per collision. Energy spread of the beam is damaged by the emission, which is hard and stochastic.

We first sketch the beamstrahlung using analytic formulae. Linearized Beam-beam force is written as follows,

$$(\Delta p_x, \Delta p_y) = \frac{2N_e r_e}{\gamma} \frac{1}{\sigma_x + \sigma_y} \left(\frac{x}{\sigma_x}, \frac{y}{\sigma_y} \right). \quad (1)$$

where N_e is the bunch population, r_e the classical electron radius, and $\sigma_{x/y}$ is horizontal/vertical beam size at IP. $p_{x,y}$, which is normalized by total momentum p_0, is $(1+\delta)dx/ds$, where $\delta = \Delta E/E_0$ is energy deviation for the design beam energy. Substituting $x = \sigma_x$ and $y = \sigma_y$ as typically numbers, the momentum change is expressed by

$$\Delta p_{xy} = \frac{2N_e r_e}{\gamma(\sigma_x + \sigma_y)} \quad (2)$$

The beam-beam force acts during the interaction $\Delta s = \sqrt{\pi/2}\sigma_z$, where it is notified that the colliding beam also moving light speed. The curvature of a beam particle is expressed by

$$\frac{1}{\rho} \approx \frac{\Delta p_{xy}}{\Delta s} = \frac{2Nr_e}{\sqrt{\pi/2}\gamma\sigma_x\sigma_z}. \quad (3)$$

The orbit radii are 23.3 and 38.7 m for CEPC and TLEP-H, respectively. While the radii of bending magnets are 6,094 and 11,000 m, respectively. The radii during the beam-beam interaction are far smaller than those of bending magnets.

The synchrotron radiation is emitted by the beam particles moving with curvature $1/\rho = \sqrt{1/\rho_x^2 + 1/\rho_y^2}$. Characteristic energy of the synchrotron radiation is expressed by

$$u_c = \hbar\omega_c = \frac{3\hbar c\gamma^3}{2\rho}. \quad (4)$$

The energies are 0.16 and 0.099 GeV for CEPC and TLEP-H, respectively. The energies is far less than the beam energy, $E_0 = 120$ GeV.

Spectrum of the synchrotron radiation is expressed using K Bessel function

$$\frac{dn_\gamma(\omega)}{d\omega} = \frac{\sqrt{3}\alpha\gamma\Delta s}{2\pi\rho\omega_c} S(\omega/\omega_c) \quad (5)$$

where

$$S(\xi) = \int_\xi^\infty K_{5/3}(y)dy. \quad (6)$$

K is K-Bessel function and $\alpha = e^2/4\pi\epsilon_0\hbar c \approx 1/137$ is the fine structure constant.

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INTERACTION REGION MAGNETS

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Abstract

The magnets of the very final focus are among the most challenging devices of a collider. They must be very compact to leave large acceptance for the surrounding detectors still providing strong focusing power together with excellent field quality not to degrade the collider dynamic aperture. Being all placed very close one respect each other and well inside the detector (which is usually a magnetic spectrometer) several strategies to compensate the cross talk of the leaking field and the coupling introduced by the detector field had been recently proposed and some are now in the construction phase. In this paper I will shortly review these novel compensation techniques, the present status of the interaction region magnets now under construction and the main concepts of their design together with a summary of some of the research and development project in the field.

MAIN ISSUES OF THE INTERACTION REGION MAGNETS IN e^+e^- HIGH INTENSITY COLLIDERS.

The main strategy followed by the e^+e^- collider community in the last decade to increase the luminosity is to decrease the beam size at the Interaction Point (IP). The recipe seems deceptively simple and straightforward but in reality it implies major advances in almost each aspect of the collider. The prototypical example of the last generation high luminosity e^+e^- colliders based on this approach are SuperKEKB [1] which is now in an advanced construction phase and which is expected to start the first phase of commissioning by 2015, together with its main competitor SuperB [2] whose fate was doomed by the economical crisis in Italy and the shortcoming of the promised funding. Both machines are based on the large Piwinski angle collision scheme [3] in which very low emittance beams are demagnified down to a vertical size of roughly 30 nm and brought in collision with a large crossing angle. The main requirements from the machine designers that are hard to met from the perspective of the magnet builders are the quadrupoles of the final doublet. These magnets must be very short and strong to ease the problem of chromaticity correction, they must provide excellent field quality over a large aperture since the horizontal and vertical beta functions are usually reaching their maxima in the final doublet and any spurious sextupolar component will be detrimental for the dynamic aperture of the ring. Additional complications arise from the requirements of the users (i.e. the detector community). The final doublet must be as compact as possible to leave space for the detector surrounding the IR, moreover the losses near the IP must be kept at a minimum to reduce the detrimental effects of machine backgrounds on the performances and life span of the detector. The most worrisome source of background that must be carefully considered in the design of the magnets of the IR are radiative Bhabha (i.e. beam-strahlung) and Touschek that, at least for SuperKEKB and SuperB, are the driving terms of the loss rate near the IP. It turns out that a conventional design with the two quadrupoles closest to the IP shared among the electron and positron rings in the final doublet is not viable since it is not possible to meet at same time the requirement to have the incoming beam on the magnetic axis to reduce the synchrotron radiation fan impinging on the detector and the requirement to have the outgoing beam on the magnetic axis to reduce the radiative Bhabha losses. In essence each beam line must be equipped with its own set of focusing quadrupoles. The main challenge is the limited amount of space available in between the two beam lines that require a very thin magnet design.

THE SUPERKEKB IR MAGNETS.

The SuperKEKB collider is a major upgrade of the KEKB Bfactory. It will collide 4 GeV positrons on 7 GeV electrons aiming for a final luminosity of $8 \cdot 10^{35}$ Hz/ cm^2, that is a 40-fold increase with respect to its ancestor. The final doublet [4] (see Fig. 1) consists of several superconducting magnets: 8 main quadrupoles, 4 compensation solenoids, 35 corrector coils and 8 coils to cancel the leaking field of quadrupoles facing the IP on the Low Energy Ring (LER) that perturbs the High Energy Ring (HER) (see Table 1).

Table 1: SuperKEKB IR magnets name and main parameters. GL is the integrated gradient, Z is the distance of the pole face from the IP, r_{in} is the inner radius of the coil, r_{out} is the outer radius of the collar.

Magnet	GL, T(T/m × m)	Type	Z, mm	r_{in}/r_{out}, mm
QC2RE	13.04 (31.12×0.419)	Yoke	2925	59.3/115
QC2RP	11.54 (28.15×0.410)	Yoke	1925	53.8/93
QC1RE	25.39 (68.07×0.373)	Yoke	1410	33.0/70
QC1RP	22.96 (68.74×0.334)	no Yoke	935	25.0/35.5
QC1LP	22.96 (68.74×0.334)	no Yoke	-935	25.0/35.5
QC1LE	26.94 (72.23×0.373)	Yoke	-1410	33.0/70
QC2LP	11.48 (28.00×0.410)	Yoke	-1925	53.8/93
QC2LE	15.27 (28.44×0.537)	Yoke	-2700	59.3/115

The quadrupoles closer to the IP are the QC1RP and QC1LP, two vertical focusing magnets acting on the LER. They are quite strong (68.74 T/ m) and very thin (the coil thickness is less than 6 mm). The small crossing angle (83 mrad) together with the small $l^\star$ (935 mm) does not allow to shield the magnet with a return yoke surrounding it

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BROAD-BAND LONG-FOCUS MIRROR OPTICAL SYSTEM FOR INFRARED DIAGNOSTICS

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Abstract

The characteristics of special optics [1] and their use in experiments with IR synchrotron radiation are exemplified by a diagnostics of ring bunches in the compressor at JINR. For the diagnostics of ring bunches of electrons, which use the IR spectrum of synchrotron radiation, the windows to guide radiation out of the accelerator chamber and two variants of long-focus broadband optical channels to focus IR radiation on the sensitive elements of the detector unit were designed and constructed. The difference between the variants is that lenses are used as an objective in one and as spherical mirrors, in the other.

In our article we describe the Mirror Optics.

If a detector should not be exposed to the electromagnetic and radiation fields of an accelerator (this especially relates to high-sensitive detectors with a filled Dewar flask), a special optical channel with the active reflective elements (spherical mirrors) pro-viding the broadband efficiency of the whole channel and allowing for synchrotron radiation to be recorded in a spectral range of Δλ ~ 0.3–40 μm was designed and constructed.

One of the chief requirements necessary for multi-cell detectors is that they are screened from pulsed electromagnetic and radiation disturbances of an accelerator. The main source of disturbances is a magnetic field of an accelerator. In order to eliminate the influence of disturbances, a position-sensitive detector where the image of a source is focused at a scale of 1 : 1 should be set no less than two meters from this source. This required an optical channel with long-focus elements to be design.

The spectral broadband efficiency of a tract is implemented by using the reflecting elements (mirrors) only. The reflecting elements were made of the optical glass, had the given curvature, and were coated with a layer of silver evaporated in vacuum. As the temperature and humidity in the laboratory is constant, the evaporated metal was not coated with a protective cover, because it would increase the losses in the optical channel. The short-wave cut-off of a spectral range is determined by the quality of the reflecting surfaces and by a material of coating. The long-wave range is limited by diffraction, and the edge depends on the values of an aperture ratio of a system forming the image. In addition, the long-wave cut-off is connected with the limited number of windows to guide synchrotron radiation out of an accelerator and depends on the sensitivity of detectors.

A principal optical diagram of a mirror channel is shown in Figure 1.

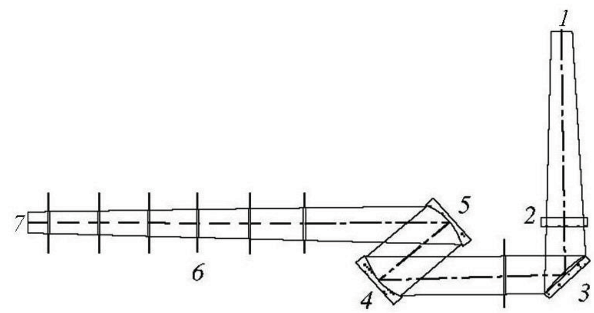

Figure 1: Principal optical diagram of a mirror channel.

As the synchrotron radiation is emit ted into a narrow cone, not all of the electron ring but only its cross section normal to the optical axis of a system is apparent. The synchrotron radiation from the minor cross section (~1/60 part) of an electron ring 1 is extracted from the vacuum chamber of the compressor through IR window 2 in close vicinity to which plane mirror 3 is positioned to deflect the divergent beam of the synchrotron radiation. The first spherical mirror 4 is set so that the object would be in its focus, for the diverging radiation beam would be transformed into the parallel one relative to the optical axis, and thus enabling it to transport it to any distance. The image of an observed object (the cross section of an electron bunch, in our case) is formed in focal plane 7 of second mirror 5 where the sensitive surface of a detector unit is situated. A focal length of both mirrors is the same and equal to 1850 mm. The elements 4 and 5 are concave spherical mirrors, the focal planes of which coincide with the investigated object and its image, which moves along the surface of a position-sensitive multicell photodetector during the compression of an electron ring in an accelerator. Diaphragms 6 limit the influence of glares and stray light.

Deflecting mirror 3 turns the optical axis by 90°. Its surfaces initially had a cylindrical form to correct the spherical mirrors for astigmatism due to oblique beams. Later, in order to obtain optimal image quality, the optical system was analyzed, with the help of computer, frequency-contrast characteristics. It was shown that the best image quality gave plane, not cylindrical, deflecting mirror. The influence of astigmatism seemed to be less

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BEAM-BEAM LIMIT, NUMBER OF IP'S AND ENERGY

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Abstract

FCC-ee has been designed for factories of top (175 GeV), Higgs (120 GeV), W and Z (45 GeV). Number of IP is 4. CEPC has been designed for H with two IP. Limit of the beam-beam tune shift depends on the damping time. Number of IP affects the beam-beam performance, because the superperiodicity between is broken in real accelerators. We discuss beam-beam limit based on LEP experiences.

INTRODUCTION

Systematic study for energy/damping time and number of IP's are performed for LEP. LEP had been operated in several energy. The beam-beam tune shift limit is measured in each energy. The experiences should be helpful for FCC-ee design.

We study the beam-beam limit of LEP using simulations and compare the results with experimental results. LEP had operated with several energies. The number of IP is 4. Difference between LEP and FCC-ee is the fact that the bunch length (σ_z) is longer than vertical beta at IP (β_y^*). The effects of the difference will be discussed elsewhere.

Table 1 summarizes parameters of LEP. LEP had been operated at three stages with energy of 45.6, 60 and 100 GeV which are called LEP1, LEP1.5 and LEP2, respectively. The radiation damping time is faster for increasing the beam energy with cubic dependence. Luminosity and beam-beam tune shift limit increase for the energy increase.

SIMULATION RESULTS

We executed beam-beam simulation for LEP. Both of strong-strong and weak-strong simulations was performed using the code named BBSS [2, 3] and BBWS [3, 4]. Beam particles are tracked during 10 damping time under the beam-beam interaction. The number of macro-particles are 1,000,000 for the strong-strong and 65,536 for the weak-strong simulation. Though the bunch length is shorter than β_y, the bunch is sliced into 7 pieces. Because beam-beam induced head-tail instability is sometimes seen in the simulations.

Figure 1 shows the evolution of the luminosity for LEP2. The radiation damping time is 300 turns/IP. Equilibrium value is realized around 1-2 damping time Luminosity for several cases of bunch populations is plotted in the figure.

The beam-beam tune shift per IP is evaluated by the equilibrium luminosity per IP,

$$\xi_y = \frac{2r_e\beta_y L}{\gamma N_e f_0}. \tag{1}$$

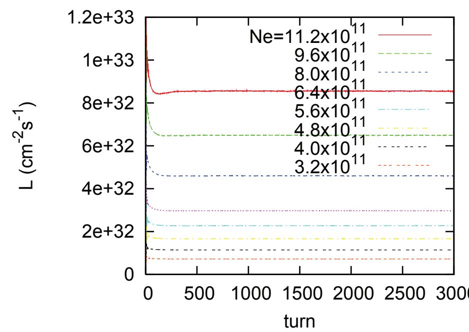

Figure 1: Evolution of luminosity for LEP2. The turn number is 4 times of actual turn number.

Figure 2 shows ξ_y per IP and vertical beam size evolution as function of the equilibrium bunch population. The vertical beam size evolutions are for (ν_x, ν_y)=(0.5775,0.0425)/IP. There are no remarkable signal related to luminosity degradation in x, σ_x. The beam-beam tune shift per IP is saturated at 0.12 for (ν_x, ν_y)=(0.5775,0.0425)/IP, while is not saturated over 0.18 at (0.51,0.57). The fractional tune operating point (0.5775,0.0425) is given by the tune in Table 1 divided by 4. LEP had been operated at the tune area (0.57,0.04) in every energy. CESR, KEKB, PEPII, BEPC-II had operated at the tune area (ν_x, ν_y)=(0.51,0.58). The electron positron colliders were successful by adopting the tune operating point.

At (ν_x, ν_y)=(0.5775,0.0425)/IP, beam-beam limit is seen ~ 0.12 at $N_e = 3 \times 10^{11}$. This value is very higher than experimental value 0.044 at $N_e = 1.2 \times 10^{11}$ in Table 1.

Figure 3 shows evolutions of $\langle y \rangle$ and $\langle yz \rangle$ at $N_e = 3 \times 10^{11}$. Coherent oscillation of π mode is seen in $\langle y \rangle$ motion (1st and 2nd pictures). $\langle yz \rangle$ (3rd) of two beams, which is related to head-tail motion, oscillate with an opposite phase.

Figure 4 shows the results for LEP15; beam-beam parameter (1st) as function of the bunch population and coherent motion in $\langle y \rangle$ (2nd) and $\langle yz \rangle$ (3rd).

Figure 5 show ξ_y as function of bunch population for LEP2 and LEP2.1. The tune shift is saturated at 0.3 for both cases. Coherent motion was not seen in LEP2 and 2.1. Fast radiation damping may suppress the coherent motion. Figure 6 shows evolution of the vertical beam sizes. Flip-flop of two beam sizes are reason of the beam-beam limit.

Weak-strong simulation is performed using LEP pa-

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LONG-RANGE BEAM-BEAM INTERACTION WITH THE BUNCH TRAIN OPERATION*

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Abstract

For the past three decades, colliders have realized increased luminosity by adding beam bunches beyond the traditional $N_{interaction\ points}$ / 2. CESR has operated since 1983 with pretzel orbits to realize substantial improvements in luminosity. In 1994 bunch trains with horizontal crossing angle were introduced. We review some of the fundamentals of the long-range beam-beam effects, including bunch trains, and suggest some guidelines in the design of a circular e+e- Higgs Factory.

MULTI-BUNCH OPERATION IN E+E- CIRCULAR COLLIDERS

Ideally a circular colliding beam facility should have full flexibility in number of bunches to maximize performance with attention to bunch charge limits (head-on beam-beam effects, TMCI and other single bunch effects), total current limitations (RF, instabilities), and beam-beam tune shift limits. There are, unfortunately, also effects on performance resulting from the choice of adding bunches.

Where separate rings are not practical, the counter-rotating beams share a common vacuum chamber and guide fields with separation at crossing points provided by electrostatic or RF separators. The resulting closed orbits are generally referred to as pretzel orbits (Fig. 1).

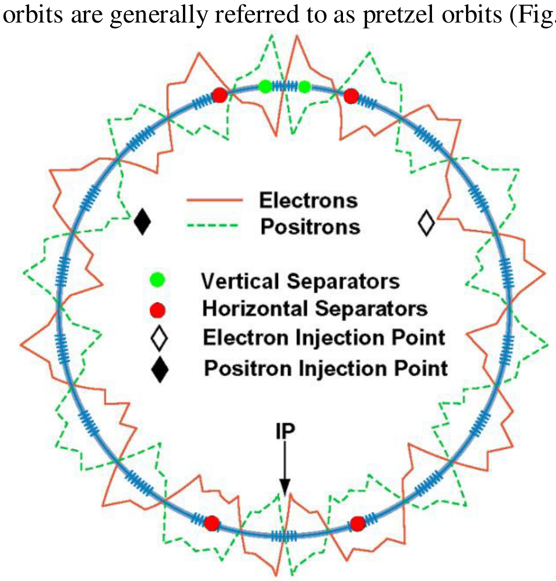

Figure 1: Pretzel orbits in CESR. Blue tic marks show crossing points for 9 trains of 5 bunches each.

Both the pretzel orbit and the multiple crossings where bunches experience the electromagnetic fields from the opposing beam impact the beam dynamics.

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PRETZEL AND PARASITIC CROSSING EFFECTS

Overview

We start with a brief outline of potential pretzel optics and parasitic crossing effects outlined in Table 1. The pretzel orbits themselves bring about multiple changes in optics. These are inherently different for electrons and positrons, but some effects are mitigated by choosing the appropriate symmetry in the ring.

The electromagnetic fields from the opposing beam cause multiple beam-beam effects (long range beam-beam interaction, or LRBBI) at each parasitic crossing. The effects of the LRBBI include kicks, tune and chromaticity shifts, and nonlinear coupling. The magnitude of the effects of these parasitic crossings depends on local pretzel amplitudes, twiss parameters and dispersion, as well as the charge in the opposing bunch and therefore do not affect all bunches uniformly.,. The variation of the lattice parameters at the parasitic crossing as well as the non-uniformity in the intensities of the opposing bunches makes mitigation difficult as compared with the usual head-on beam-beam effects, or impossible in many cases.

The distortion of the closed orbit distorts the optics of a single beam. If the separation scheme has the appropriate symmetry, the change in global parameters like tune and chromaticity is common to both beams. But local distortions are generally different for electrons and positrons. There is therefore a tension between minimizing pretzel effects (smaller pretzel amplitude) and minimizing LRBBI effects (larger pretzel amplitude).

Table 1: Pretzel and Long Range BBI Effects

Type	Source
Pretzel Optics	
Betatron phase errors	Sextupoles
Dispersion errors	Sextupoles
Damping partition #'s	Quadrupoles
Enhanced Synch. Rad.	Quadrupoles
H_V coupling	Sextupoles, etc.
Instr. Nonlinearities	BPMs
Parasitic Crossings	(Opposing beam -)
Orbit distortion	Far E&M fields
Coherent tune split	Far E&M fields
Nonlinearity	Core E&M fields
Chromatic Effects	Far E&M + Dispersion

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MONTE-CARLO SIMULATION OF SYNCHROTRON RADIATION IN THE DESIGN OF CEPC VACUUM CHAMBER

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Abstract

The circular electron positron collider (CEPC) has been proposed by IHEP. Two 120GeV beams circulate around the 54km accelerator rings, which produce intense synchrotron radiation with photon energies up to a few of mega-electron volts. It is very important to analysis the source of synchrotron radiation. Two techniques of designing vacuum chamber which are contained Al covered by Pb and totally by Cu are put forward to protect sensitive machine components. A Monte-Carlo program called MCNP has been used to calculate dose rate, heat and energy spectrum of synchrotron radiation in the tunnel in former two designing cases. The results including dose rate, heat and energy spectrum which performed in various components of the CEPC are shown in this article.

INTRODUCTION

Synchrotron radiation (SR) is a kind of electromagnetic radiation which is released by charged particles, when the speed of particles is close to the speed of light (v ≈ c), while particles are moving in the magnetic field along the arc track. In CEPC, 120GeV electrons and positrons pass through the dipole magnets and focusing (quadrupole) magnets, which are always accompanied by the emission of SR. The spectrum of SR extends from the region of visible light through the energy range of ordinary diagnostic X-rays (hundreds of kilo-electron volts) up to ten mega-electron volts in the vacuum chamber. By calculation, the power of SR emitted per unit length is huge, which is up to 1KW/m. Hence, SR can bring about very high radiation dose rates in many components of accelerator and Air of the tunnel, which will induce the problems of heating of the vacuum chamber, radiation damage to machine elements, formation of ozone and nitrogen oxides in the air, further lead to corrosion of machine components and act [1],[2]. At present, two methods of designing vacuum chamber are proposed, there are including manufactured by Aluminum material [3],[4] and covered by lead shield, or fabricated totally by copper. Therefore, it is essential to confirm relevant parameters of these two choices, such as energy deposition, energy spectrum in every part of the tunnel, which could be used to calculate heat quantity, dose rate, the amount of harmful gases.

ANALYSIS OF SYNCHROTRON RADIATION SOURCE

In the accelerator, the spectrum of SR depends on the charge, the mass and energy of the particle and the bending radius. When determining the effects of SR, there are two important parameters including: the radiated power per unit beam path and the critical energy. The power of the synchrotron radiation emitted by the electrons and positrons per unit length is given by the simple expression:

$$P(W/m) = 14.08\frac{E(GeV)^4 I(mA)}{\rho(m)^2} \tag{1}$$

With P, the synchrotron power loss is in W/m;
E, the energy of electrons and positrons is in GeV;
I, the current of the circulating particles is in mA;
ρ, is the bending radius in meter.

The critical energy of synchrotron spectrum divides the emitting radiation power in two halves, which is defined by the following expression:

$$E_c(keV) = 2.218\frac{E(GeV)^3}{\rho(m)} \tag{2}$$

With E_C, the critical energy is in keV.

The energy spectrum of synchrotron radiation can be calculated by the following formula:

$$S\left(\frac{\omega}{\omega_c}\right) = \frac{9\sqrt{3}}{8\pi}\frac{\omega}{\omega_c}\int_{\omega/\omega_c}^{\infty} K_{5/3}(\eta) \tag{3}$$

With ω, the angular frequency of the synchrotron radiation photon in rad/s;
ω_c, the angular frequency of the critical energy photon in rad/s;
S, the relative share of spectrum in different frequency separation;
K, Bessel function.

992 blocks of magnets will be equipped in the main ring of CEPC, the bending angle would be given in this condition. Meanwhile, synchrotron radiation itself distributes as a solid degree, and the half angle of light cone is 1/γ, which is focused by 85% power of synchrotron radiation, γ can be expressed as:

$$\gamma = \frac{E_e}{mc^2} = 1957E_e(GeV) \tag{4}$$

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VACUUM SYSTEM REQUIREMENTS FOR A HIGGS FACTORY e+e- COLLIDER

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Abstract

Several proposals for a new class of accelerators called Higgs Factories (HF) have been made in the recent years. The LEP machine, formerly installed in what is today the 26.7 km LHC tunnel, had already given a glimpse of the issues which such machines would have to face. Since the stop and dismantling of LEP, big advancements have been made by the accelerator physics community to develop smart ways of increasing the luminosity. At the same time, the synchrotron radiation (SR) community has worked towards the development of so called "ultimate light sources", which have lately been grouped under the name of "ultra-low emittance" light sources. The merging of the two fields has allowed the development of new magnetic lattices which would allow a HF machine to obtain a very low beam emittance, which in turn would generate, with proper design of the interaction regions (IRs) unprecedented values of the luminosity at center of mass energies in excess of several hundred GeVs. These state-of-the-art accelerators necessarily need state-of-the-art implementation of technologies for their sub-systems, such as radio-frequency (RF), vacuum, feedback and control, etc…

The paper looks into the specific vacuum system requirements stemming from the large size of any HF, its high beam energy, its rather large beam currents and attendant synchrotron radiation losses and loads, just to name a few. It is shown that an optimization of the vacuum system based on discrete, localized absorbers would allow a minimization of the number and size of the pumps, especially if implemented in conjunction with distributed pumping along most of the machine, like was done in LEP. Localized absorbers would also allow concentrating the radiation background generated by the MeV-range critical energy of the SR, and minimizing the radiation damage and material activation in the tunnel.

Delving into the details, and taking into account what has been done for the Long Straight Sections (LSS) of the LHC, it becomes clear that a cost-optimization of the vacuum system is possible under the assumption that an industrial-scale development of the vacuum chamber fabrication and preparation could be carried out.

In principle, there seems to be no major technological show-stopper, since modern B-factories and light sources have already found solutions for dealing with extremely high linear photon flux and power densities.

Based on LEP experience, particular care must be taken in case damping- and beam-polarization- wigglers are installed on the rings.

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This paper does not address any specific vacuum issues relevant to the IR regions or to the injectors, which are treated in separate talks.

BACKGROUND

A wealth of information on the vacuum issues relevant to very high energy e- e+ accelerators has been accumulated during the 12 years of operation of LEP, under its various forms ([1-10], and references therein). In addition to those seen on LEP, a new class of vacuum issues can be expected in HFs due to the extremely low emittance specifications for these machines, which call for narrower gaps in the magnets and stronger focusing gradients. These effects have already appeared in all their magnitude in B-factories, in particular the electron-cloud generated in the e^+ ring, an effect which had not affected LEP since it hosted both e^- and e^+ beam in the same vacuum chamber.

For the sake of clarity, the well documented case of LEP is taken as a guideline for the discussion, and extrapolations to the design and performance of future HFs are made.

SYNCHROTRON RADIATION AND GAS LOADS

Synchrotron Radiation

Any multi-GeV e^+ and/or e^- accelerator is bound to generate a huge amount of synchrotron radiation (SR). Standard formulae [11] show that the total flux varies linearly with the beam energy, while the total power varies with the 4^{th} power of the energy and is inversely proportional to the radius of curvature. For reasons related to obtaining a very low emittance, the radius of curvature of the dipoles for the proposed HFs is always very large, as is the number of dipoles. In the case of the FCC-ee versions proposed by CERN (FCC-ee Z, W, H, tt), the radius of curvature is presently ~ 11 km, i.e. ~3.5x that of LEP (3096 m) [12]. This helps with keeping down the linear flux and power densities, in ph/s/m and W/m respectively, which dictate the local vacuum conditions along the ring. As explained in the nice retrospective review paper [4], SR-induced desorption is the main source of residual gas in the vacuum chamber of a LEP-like accelerator, and is also the source of other different problems. All photons with energies above 4 eV are considered capable of inducing the emission of molecules from the surface of the vacuum chamber, and migration/diffusion from the bulk of it. These molecules in turn move randomly around the chamber until either they reach a pump and are removed or are hit by one of the circulating e^-/e^+. In that case the collision can lead to beam losses following different well known mechanisms, and energy deposition, both locally and away from the

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SHIELDING OF ELECTRONICS IN THE TUNNEL

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Abstract

Radiation to Electronics (R2E) represents a crucial issue to be taken into account as design criterion of any high energy and intensity machine. The different effects on the concerned equipment and the microscopic mechanisms underneath are reviewed. Evaluation and mitigation strategies are presented, based on the support of dedicated Monte Carlo calculations. In the specific context of a future e+e- HF, the relevant radiation sources and their possible impact are discussed.

INTRODUCTION TO R2E

The study of the electronics sensitivity to radiation requires a multi-disciplinary approach, spanning from the knowledge of the electronic components, to the radiation environment, and to the physics models that describe the interaction of the radiation with the matter. The goals are: (1) to define and quantify the effects of the radiation on the electronics; (2) to monitor and/or estimate the radiation levels in the concerned area; (3) to test and develop radiation-hard or sufficiently tolerant electronics; (4) to implement mitigation options.

R2E is often considered for space applications, where application design, test and monitoring standards are already well defined. However, it is important to note that the radiation environment encountered in a high energy and intensity accelerator, the high number of electronic systems and components exposed to radiation, as well as the actual impact of radiation-induced failures on the machine operation, pose challenges that might strongly differ from the context of space applications.

For a high intensity and energy machine, typical sources of radiation are luminosity debris, direct losses on collimators and dumps, and beam interactions with the residual gas inside the vacuum chamber all along the accelerator, as well as with dust fragments falling into the beam path. But, for the specific case of a lepton machine, an additional main source of radiation in the tunnel is represented by the synchrotron radiation.

In order to evaluate the impact of the radiation on the machine equipment, Monte Carlo simulations represent an indispensable tool. They need to rely both on a refined implementation of physics models of the particle interaction with matter and an accurate 3D-description of the region of interest.

Typically the mixed particle type and energy field of interest in a high-energy environment is composed of charged and neutral hadrons (protons, pions, kaons and neutrons), photons, electrons and muons ranging from thermal energies up to the GeV range. This complex field has been extensively simulated by the FLUKA Monte Carlo code [1,2] and benchmarked in detail for radiation damage issues at the LHC [3,4].

The proportion of the different particle species in the field depends on the distance and on the angle with respect to the original loss point, as well as on the amount (if any) of installed shielding material. In this environment, electronic components and systems exposed to a mixed radiation field will experience three different types of radiation damages:

- damage from the Total Ionizing Dose (TID).
- displacement damage (DD) or non-ionizing dose.
- so-called Single-Event-Effects (SEEs).

The latter ones range from single or multiple bit upsets (SEUs or MBUs), transients (SETs) up to possible destructive latch-ups (SELs), destructive gate ruptures or burn-outs (SEGRs and SEBs).

The first two groups are of cumulative nature and are measured through TID and non-ionizing energy deposition (NIEL [1], generally quantified through accumulated 1-MeV neutron equivalent fluence), where the steady accumulation of defects cause measurable effects which can ultimately lead to device failure.

Being of stochastic nature, SEE failures form an entirely different group. They are due to the direct ionization by a single particle, able to deposit sufficient energy through ionization processes in order to perturb the operation of the device. They can only be characterized in terms of their probability of occurring as a function of accumulated High Energy (> 5 ÷ 20 MeV) Hadron (HEH) fluence. The probability of failure will strongly depend on the device as well as on the flux and nature of the particles.

For accelerator applications, the installed control systems are either fully commercial or often based on so-called COTS (Commercial-Off-The-Shelf) components, both possibly affected by radiation. This includes the immediate risk of SEE with a possible direct impact on beam operation, as well as in the long-term, cumulative dose effects (impacting the component/system lifetime) which additionally have to be considered.

As example, for the tunnel equipment in the existing LHC, radiation was only partially taken into account as design criteria prior to construction, and most of the equipment placed in adjacent and partly shielded areas was not conceived nor tested for their actual radiation environment. Therefore, given the large amount of electronics being installed in these areas, during the past years a CERN wide project called R2E (Radiation To Electronics) [5] was then initiated to quantify the risk of radiation-induced failures and to mitigate the risk for nominal beams and beyond to below one failure a week for all exposed electronic systems together. The respective

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[1] Non-Ionizing Energy Losses.

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CHOICE OF L*: IR OPTICS AND DYNAMIC APERTURE(*)

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Abstract

A design of interaction region (IR) optics from the viewpoint of nonlinear motion and dynamic aperture limitation is discussed for the FCCee Crab Waist collision scheme. We use the first order tune-amplitude shift as a figure of merit to characterize the strength of nonlinear perturbation caused by different sources including the final focus kinematic terms, quadrupole fringe field, octupole field error in QD0 and chromatic sextupoles. Theoretical prediction is compared with the tracking results. Dynamic aperture limited by different nonlinearities in the IR is presented and analyzed.

INTRODUCTION

A drift L_* from the interaction point (IP) to the first quadrupole (QD0) in the collider final focus (FF) is an important parameter not only from the viewpoint of a machine detector interface or detector background condition. This drift length also influences the beam optics and dynamics and hence determines the design of the whole IR and beyond. It is essential especially for the Crab Waist (CW) beam-beam collision [1] because this approach assumes that the bulk of luminosity increase comes from an extremely low vertical beta at the IP ($\beta_y^* \le 1$mm), resulting in large chromaticity (for both vertical betatron tune and function) and ~1÷10-km beta in the FF quadrupoles.

Large chromaticity must be corrected by strong sextupole magnets which usually are arranged in pairs and separated by the –I optical transformation [2]. For the ideal kick-like sextupoles such a scheme cancels all geometrical aberrations. For the realistic length sextupoles, the second order aberrations are cancelled exactly while the higher order terms remain and spoil the DA [3].

Very large beta in QD0 amplifies influence of nonlinear imperfections in quadrupole fields (including the fringe fields and the field errors inside) on nonlinear beam dynamics. These effects can also provide the DA reduction.

One more source of the DA shrink is kinematic terms which originated from the fact that due to a large transverse momentum in the first drift, usual paraxial approximation is not still valid and the next momentum terms should be taken into account.

All the above-mentioned effects are discussed and estimated below. The problem is that there is no general criterion to evaluate relative contribution of a particular nonlinear perturbation to the DA size. Fortunately all important effects are of the forth power (octupole-like) in Hamiltonian canonical variables. Basing on this fact we suggest using vertical nonlinear detuning coefficient as a figure of merit to compare different effects depending on L^*. Numerical simulation of the DA shows strong and weak points of such approach.

IR ARRANGEMENT

Typical CW IR consists of several optical modules as it is shown in Figure 1. Strong FF quadrupole doublet squeezes the beam at the IP. The final focus telescope (FFT) matches the IP lattice functions to the rest of the IR. The chromaticity correction section YXCCS consists of the sextupoles Y1-Y2 and X1-X2 combined in two pairs with –I transformation inside of each pair.

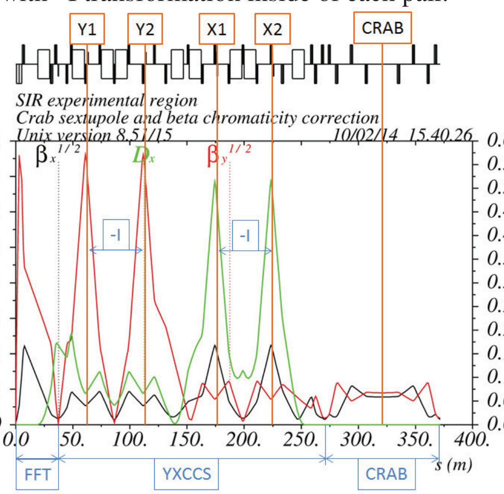

Figure 1: Optical arrangement of the FCCee IR (one half) in the CW mode for L^*= 0.7 m.

Dispersion function in the chromaticity correction section is excited by a dipole magnet (BM in Figure 2) and the vertical beta in the Y sextupole pair is as large as in the QD0. Finally the crab sextupole is placed at the end of IR at the proper phase advance with respect to the IP.

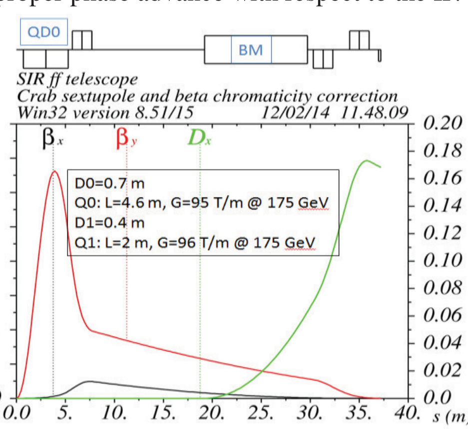

Figure 2: Final focus arrangement.

For the FF parameters shown in Figure 2, $\beta_y^* = 1$ mm yields almost 7 km beta in the middle of QD0.

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SYNCHROTRON RADIATION ISSUES FOR THE CEPC IR*

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Abstract

This is a preliminary investigation of some of the issues concerning Synchrotron Radiation (SR) generated in and nearby the Interaction Region (IR) of the CEPC e+e- Higgs Factory design. Background issues are discussed as well as power levels and power absorption of the SR in this region. Implications as to final focus magnet parameters, including L*, and nearby bending magnet strengths and positions are explored.

INTRODUCTION

The IR of any collider is one of the more difficult sections of the accelerator. There are several conflicting requirements related to this area that need to be satisfied. The ultimate performance of the accelerator (the luminosity) is manifest here by the event rate of the physics coming out of the collision between the beams. Low β* values are needed which in turn requires large beta functions in the final focus magnets (usually a doublet). The distance from the final focus magnets and the Interaction Point (IP) called L* plays an important role. The physics detector prefers as much space as possible around the collision point in order to collect as much physics as it can. However, areas close to the beams and to the vacuum beam pipes are populated with backgrounds from the beam particles directly (lost beam particles through various mechanisms: Beam-Gas scattering (BGB), Coulomb scattering, Touschek scattering, Inter-bunch scattering (IBS), beamstrahlung, to name a few. In this paper, I will concentrate on the backgrounds and implications of the large amount of SR generated in this area.

CEPC INTERACTION REGION

The high energy of the colliding beams (120 GeV) makes high power fans and beams of SR. This radiation must be controlled and designed to either be absorbed in local masks and shields or to pass harmlessly through the IR to be absorbed at some location away from the IP. The intensity of the SR generated in this area is high enough to instantly (seconds to minutes) destroy unprotected detectors if it is not properly controlled. Usually at least 4 orders of magnitude (and in some cases much more) suppression is needed in order to create an environment suitable for detectors to collect the physics from the collision point.

Table 1 lists some of the accelerator parameters important for the study of SR backgrounds in the IR. This is not a complete parameter list but emphasizes features important to IR designs.

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Table 1: Some accelerator parameters important for SR background studies in the interaction region.

Accelerator Parameters related to IR designs	
Beam energy (GeV)	120
Current (mA)	16.6
Number of bunches	50
Particles/bunch	3.79×10^{11}
L* (m)	1.5
Emittance x/y (nm-rad)	6.12/0.018
β* x/y (mm)	800/1.2
QD0 L(m) and G(T/m)	1.25/300
QF1 L(m) and G(T/m)	0.72/300

SYNCHROTRON RADIATION SOURCES

The sources of SR come from nearby magnets. The important magnets are the final focus magnets and the last bend magnet before the collision point. We will first take a look at the last bend magnet in the design.

Last Bend Magnet before the IP

In an earlier design, the last bend magnet from the local chromaticity correction block had the following parameters: length 3.375 m and a bend angle of 4.416 mrad. These values gave a field strength of 5.275 kG for this bend magnet. This is a very intense magnetic field for this beam energy (the arc bend magnets have a field strength of about 600 G). This bend magnet would have generated 8965 kW of SR power. This was quickly recognized as too much local power and a new design has emerged in which the bend magnet has been lengthened to 15.5 m and the strength has been reduced to 1 kG. This reduces the SR fan power from this magnet to 47 kW, still a significant amount of power, but greatly reduced from the initial design. The new bend magnet also starts 30 m from the IP which is about 15 m farther away from the IP.

Figure 1 shows a drawing of a possible beam pipe with a 2 cm radius for the pipe outboard of the final focus (FF) quads. There is a 1.5 cm radius cryogenic pipe under the final focus quads and the collision point beam pipe has a 1.5 cm radius and is ±0.1 m long. As one can see, the SR fan from the last bend magnet passes entirely through the region and the detector beam pipe and the cryogenic beam pipes under the FF quads must be shielded from this fan. The power incident on the beam pipe from the SR fan is shown. The power density for each section of the fan and for various surfaces of the beam pipe is listed in Table 2. For reference, an acceptable beam pipe surface power is usually about 10 W/mm. The highest beam pipe wall power that can be absorbed is about 20 W/mm and a material called GlipCop™ which is dispersion strengthened copper is one of the few materials that can stand up under this power density.

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LOST PARTICLES IN THE IR AND ISSUES FOR BEAM INDUCED BACKGROUNDS IN HIGGS FACTORIES

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Abstract

The loss of beam particles has to be well under control in high energy and high luminosity e+e- colliders -namely Higgs Factories- especially at the interaction regions. In the design stage the main beam related effects causing particle losses need to be studied in details by means of full simulation to check that machine induced background rates are tolerable for the experiments and, if not, conceive an efficient collimation system to intercept particles that would eventually be lost in the Interaction region (IR). These studies can also give a realistic evaluation of beam lifetime.

We will review how main beam backgrounds have been handled at SuperB and DAΦNE and we will mention the LEP experience. A first tracking simulation of the Touschek and radiative Bhabha particles for the CEPC IR case are presented as a starting point for losses evaluation.

Synchrotron Radiation, essentially determined by the beam energy, is a key issue for the IR design of Higgs Factories. A first description of the tools under development for the SR evaluation in view of the FCC-ee design study is given.

INTRODUCTION

We can distinguish backgrounds from two main sources: losses of beam particles and synchrotron radiation (SR). Particle effects that cause beam losses can be generated by single beam effects -mainly Touschek and beam-gas scattering- or they can be generated at the IP -mainly beamstrahlung, radiative Bhabha, e^+e^- pairs production- usually referred to as *IP backgrounds*.

Both sources have been deeply studied for past and present machines; beam particles effects have been studied extensively for upgrades of B factories; on the other hand LEP has been the highest energy lepton collider, experience on this machine can be very helpful.

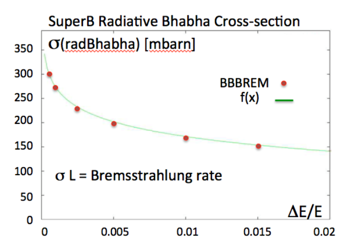
Unlike linear colliders, circular machines have to cope also with beam halo. For lepton high-energy colliders this issue has to be considered particularly for the vertical plane, where the emittance is low. An off-momentum halo at the IR may be generated by beam-beam effects and by beamstrahlung, which gets stronger as the beam energy increases.

The first concern for particle losses is the implication of beam degradation itself, with a consequent loss of luminosity, lifetime reduction and need of increase the frequency injection. The second concern is the background that beam losses can generate at the IR: particle losses may shower into detectors causing damages and they may fake triggers.

BEAM PARTICLE LOSSES

In this section a short description of the main effects for beam losses is presented, with a summary of the approach used for SuperB factories and LEP. First considerations for future high energy colliders, such as the Chinese HF CEPC [1] and FCC [2] are also presented.

Depending on machine's parameters such as energy, beam density and energy spread, the beam particle losses will be driven by one of the processes mentioned in the introduction. We can say that for rings with beam energies of E_{beam}=120 GeV such as CEPC and even higher (maximum energy foreseen for FCC-ee is 175 GeV), beamstrahlung will typically be the dominant effect, followed by radiative Bhabha, e+e- pairs production, beam-gas and Touschek.



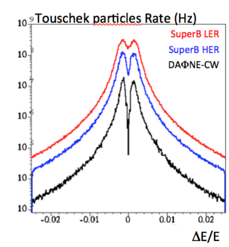


Figure 1: Left: SuperB radiative Bhabha cross-section vs ΔE/E; right: rate of Touschek particles in SuperB LER (red), HER (blue) and DAFNE Crab-waist (black) for 1 single bunch nominal current (1.49 and 10 mA, respectively).

For CEPC and FCC which are in the design phase, dedicated calculations for backgrounds are planned. As an example in Table 1, we report the lifetime evaluation performed for the SuperB factory with a Monte Carlo numerical tracking code developed for this purpose. SuperKEKB used an analogous approach [3].

Table 1: Lifetime Contributions at SuperB Calculated with the Code, Beam Parameters in [4] and Collimators at Set.

Loss effect	HER Lifetime (s)	LER Lifetime (s)
Radiative Bhabha	290*/280+	380*/420+
Touschek	1320	420
Elastic beam-gas	3040	1420
Inelastic beam-gas	72 hrs	77 hrs
Total Lifetime	220	180

* 1% momentum acceptance assumed in integrated formula;
+ momentum acceptance calculated with tracking MonteCarlo

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SYNCHROTRON RADIATION ABSORPTION AND VACUUM ISSUES IN THE IR*

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Abstract

The PEP-II B-Factory (3.1 GeV e+ x 9.0 GeV e-) at SLAC operated from 1999 to 2008, delivering luminosity to the BaBar experiment. PEP-II surpassed by four times its design luminosity reaching 1.21x10^{36} cm^{-2} s^{-1}. It also set stored beam current records of 2.1 A e- and 3.2 A e+ in 1732 bunches. Continuous injection was implemented with BaBar taking data. PEP-II was constructed by SLAC, LBNL, and LLNL with help from BINP, IHEP, the BaBar collaboration, and the US DOE OHEP [1, 2].

The interaction region at PEP-II had to bring the multi-ampere beams into collisions at one point, produce small vertical beta functions (~1 cm), provide beam separation for parasitic beam crossings, provide low backgrounds to the detector, and remove heat generated by synchrotron radiation and higher order modes. All of these constraints made the IR design very complicated. The synchrotron radiation generated by the many dipole and quadrupole magnets had to be absorbed without generating a lot of emitted gas which would cause beam-gas interaction, lost particles, and detector backgrounds. A complication was the permanent magnet dipoles and quadrupoles near the collision point inside the Babar detector used to focus the beam and to provide the beam separation [3, 4]. The IR region extended away from the collision point by about 65 m on each side to accomplish all the needed requirements.

Table 1: PEP-II Collision Parameters

Parameter	Units	Design	April 2008 Best	Gain Factor over Design
I+	mA	2140	3210	x 1.50
I-	mA	750	2070	x 2.76
Number bunches		1658	1732	x 1.04
β_y*	mm	15-25	9-10	x 2.0
Bunch length	mm	15	11-12	x 1.4
ξ_y		0.03	0.05 to 0.06	x 2.0
Luminosity	10^{34} /cm^2/s	0.3	1.2	x 4.0
Int lumin per day	pb^{-1}	130	911	x 7.0

*Supported by US DOE contract DE-AC02-76SF00515.
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PEP-II PARAMETERS

In PEP-II the Low Energy Ring (LER) was mounted 0.89 m above the High Energy Ring (HER) in the 2.2 km tunnel as shown in Figure 1. The interaction region is shown in Figure 2 where the beams were collided head on. Figure 3 shows the Be vacuum chamber inside the detector with the permanent magnet dipoles on either side. The interface cone angle at the IR between BaBar and PEP-II was at 300 mrad. To bring the beams into collision, LER was brought down 0.89 m to the HER level and then with a horizontal deviation for both rings were made to collide. Since both rings have the same circumference, each bunch in one ring only collides with one bunch in the other ring making the beam-beam interaction much easier. Parameters are shown in Table 1.

Figure 1:PEP-II tunnel with LER above the HER.

The high beam currents were supported large RF systems consisting of 1.2 MW klystrons at 476 MHz and high power copper cavities with HOM absorbing loads. An RF cavity had three HOM loads with the capability of 10 kW each. At the peak currents the HER cavities each received 285 kW and the LER cavities 372 kW. The average klystron power was 1.01 MW. An overhead of about 20% in power was needed to allow the RF feedback systems to be stable. The power from synchrotron radiation was ultimately deposited in the walls of the vacuum system and had to be removed by water cooling.

The vacuum systems were extruded copper in the HER arcs and extruded aluminium with antechambers and photon-stops in the LER arcs. Both rings had stainless steel double walled chambers in the non-IR straight

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INFRARED SYNCHROTRON METHODS AND SYSTEMS FOR MONITORING AND CONTROLLING PARTICLE BEAMS IN REAL TIME

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Abstract

We present the methods and infrared position-sensitive detection systems for nondestructive diagnostics and study of charged-particle beams or bunches based on the use of their synchrotron radiation in a wide spectral range. The detection systems contains of the optoelectronic and spectral detectors working in real time with the computer system.

The synchrotron radiation spectrum that is used mainly in the infrared region (wavelength range > 1 µm). The radiation is detected in the spectral region 0.3-45 µm by infrared detectors operating at low temperature or room temperature. Results are presented on the measurement of the number of electrons in the ring bunch, the equilibrium radius and dimensions of the small cross section of bunch, and the angular divergence of the synchrotron radiation relative to the median plane of the ring bunch.

The extension of the spectral range of positively diagnosed synchrotron radiation opens up new possibilities and prospects for solving scientific and applied problems.

INTRODUCTION

Synchrotron radiation of relativistic charge-particles is a well-known effect observed in electron-ring accelerators and storage systems and is widely used in various experiments and investigations, in particular, for passive, nondestructive diagnostics of electron bunches during formation and acceleration of the bunches [1,2]. Synchrotron radiation can be used to measure the current, energy, and geometrical dimensions of electron and proton beams and bunches without affecting the accelerated particles, as well as for nondestructive studies of fast processes. The objectives of this work are as follows – we present the methods and systems of nondestructive diagnostics and study of charged-particle (electron, electron-ion, and proton) bunches (beams) based on the use of their magnetic-bremsstrahlung (synchrotron) radiation in a wide spectral range, from the ultraviolet to the far long-wave infrared region. In this paper, we describe the infrared one-element integration detectors and position sensitive one-coordinate detectors (the sensitive elements are arranged in line) and present the results of measurements with these detectors.

The extension of the spectral range of positively diagnosed synchrotron radiation opens up new possibilities and prospects for solving scientific and applied problems.

INFRARED SOURCES

Synchrotron radiation is a well understood effect which is widely used at electron ring accelerators and storage rings. All charged particles, including protons, emit synchrotron radiation as they move along a curved trajectory in a magnetic field. However, since the proton rest energy E0p (938 MeV) is larger than the electron rest energy E0e (0.511 MeV) by a factor of 1835.6, the intensity of the synchrotron radiation for protons is lower by the same factor for a given particle energy and curvature of the trajectory. Therefore, for the energies available until recently at proton accelerators, synchrotron radiation has hardly been used at all. This explains the limited number of publications on this topic. Such publications have begun appearing only since the late 1970s and deal with the production of synchrotron radiation by the 400 GeV SPS proton synchrotron at CERN (synchrotron radiation at the edges of the displacement magnets at wave-lengths 0.6 µm). The construction of accelerator-storage-ring complexes like SSC or LHC for protons of energy 3-20 TeV may significantly effect the monopoly of electron ring accelerators as the main producers of synchrotron radiation. Analysis of the synchrotron radiation spectra of proton ring accelerators at the leading accelerator laboratories around the world shows that the bulk of the spectral distribution of the radiation for protons of energy up to 1 TeV lies in the infrared region. Estimating the intensity of the proton radiation and comparing it with that of the synchrotron radiation of low-energy electrons at, for example, the JINR accelerator – compressor electron-ring bunch (see we find that the techniques and systems of infrared synchrotron diagnostics developed for the JINR accelerator and later used in accelerator experiments may also be useful for the diagnostics of proton beams with energies above 100 GeV. So far we know of no cases of diagnostics of proton beams with proton energy above 400 GeV. The calculation of the characteristics of synchrotron radiation and the choice of techniques and diagnostics systems have been made and demonstrated for the example of the ring-shaped bunches during bunch compression in the high-current low-energy accelerator – compressor of ring-shaped electron (electron-ion) bunches are based on the measurements of synchrotron radiation [1]. The spectrum of synchrotron radiation from the compressor (electron energy ΔE ≈

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DETECTOR BEAM BACKGROUND SIMULATIONS FOR CEPC

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Abstract

Detector backgrounds of different sources expected at the Circular Electron Positron Collider are reviewed. Their potential impacts on the interaction region design and detector performance are discussed. The backgrounds originating from beam-beam interactions are evaluated with Monte Carlo simulation and preliminary results are presented.

INTRODUCTION

The Circular Electron Positron Collider (CEPC), proposed by the Chinese High Energy Physics community, is designed to operate at the center-of-mass energy of $\sqrt{s}$ = 240 GeV, with an instantaneous luminosity of 2×10^{34} cm^{-2}s^{-1}. The CEPC e^+e^- collider will produce millions of clean Higgs events over a period of 10 years, allowing for detailed studies of the properties of the Higgs boson discovered at the LHC experiments [1,2].

To fully exploit the physics potential of machine and to optimise the detector performance, it is important to understand the detector backgrounds at the CEPC, which is among the most critical issues for the project. Different sources of backgrounds can give rise to either primary particles that enter the detector directly or generate secondary debris that ultimately hit the detector. It is mandatory to study thoroughly those backgrounds and their impacts on detector performance with Monte Carlo simulation. In this report, results of the main backgrounds from the beam-beam interactions, including beamstrahlung, electron positron pair production, hadronic backgrounds and radiative Bhabha events, are presented and their impacts on the CEPC detector are discussed. Other critical backgrounds, in particular synchrotron radiation, beam-gas interactions and beam loss, are important topics for future studies.

THE INTERACTION REGION LAYOUT

The interaction region (IR) of the CEPC consists of the beampipe, the surrounding silicon detectors, the luminosity calorimeter and the interface to the last final focus quadrupoles, namely QD0 and QD1. Its preliminary IR layout is depicted in Figure 1. The current design features a rather short focal length of $L^* = 1.5$ m, *i.e.* the distance between QD0 and the interaction point (IP). Such short L^* allows for the realisation of high luminosity without large chromaticity corrections, but at the same time it imposes certain constraints on the CEPC detector layout and can have significant impact on the choice of detector technologies. Therefore thorough understandings of the effects of the short L^* on both detector and machine performance will be a critical topic for future studies.

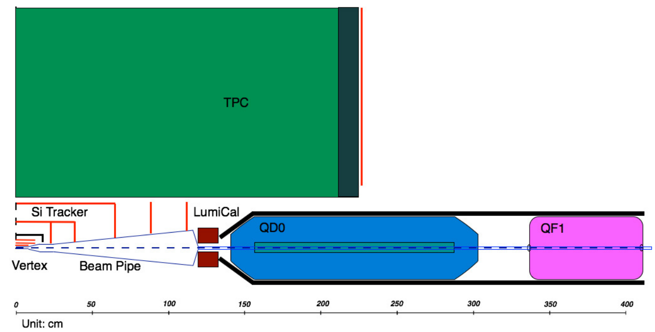

Figure 1: Preliminary layout of the interaction region for the CEPC.

BACKGROUNDS FROM THE BEAM-BEAM INTERACTIONS

At the IP of the e^+e^- collider, the two crossing bunches of opposite-charge attract each other, called "Pinch Effect", which is illustrated in Figure 2. The self-focusing effect during this process leads to higher luminosity for head-on collisions. However, the charged particles deflected by the strong forces will emit radiation called "beamstrahlung". The actual beam-beam effects can be estimated with Monte Carlo simulation, which shall take into account the dynamically changing bunch effects, reduced particle energies and their impacts on the fields. The GUINEA-PIG [3] program has been adopted to simulate the beam-beam interactions for the CEPC. The machine and beam parameters used as the input into the program are listed in Table 1.

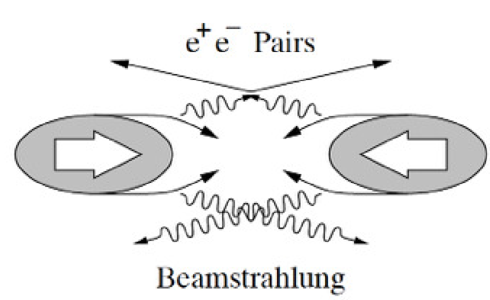

Figure 2: Illustration of the Pinch Effect between two crossing bunches of opposite-charge.

The main backgrounds from the beam-beam interactions are beamstrahlung, electron positron pair production,

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DESIGN STUDY OF THE CEPC BOOSTER

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Abstract

Design study of the CEPC booster is reported. The booster provides 120 GeV beams for the collider with top-up injection frequency of 0.1 Hz. To save cost, energy of the linac injector for the booster is chosen as 6GeV, corresponding to the magnetic field of 30 Gs. In this paper, lattice of the booster is described; the low injection energy issues are studied; beam transfer from linac to booster and from booster to collider are discussed.

GENERAL DESCRIPTION

Soon after discovery of the Higgs boson, the Circular Electron-Positron Collider (CEPC) was proposed. The Super Proton-Proton Collider (SPPC) could be installed later in the same tunnel of CEPC for e^+e^-, pp, ep and ion collisions [1].

The booster is in the same tunnel of the collider with about same circumference, while bypasses are arranged to keep away from detectors in IP1 and IP3. Electron and positron beams are injected from the linac to the booster through the transfer line LTB (Linac To Booster) in one of the 850 m long straight sections. The beam extraction at top energy takes place in other two straight sections. Electron and positron beams are injected to the collider through BTCe$^+$ and BTCe$^-$ (Booster To Collider) transfer lines. Figure 1 illustrates the layout of the booster on the upside of the CEPC collider.

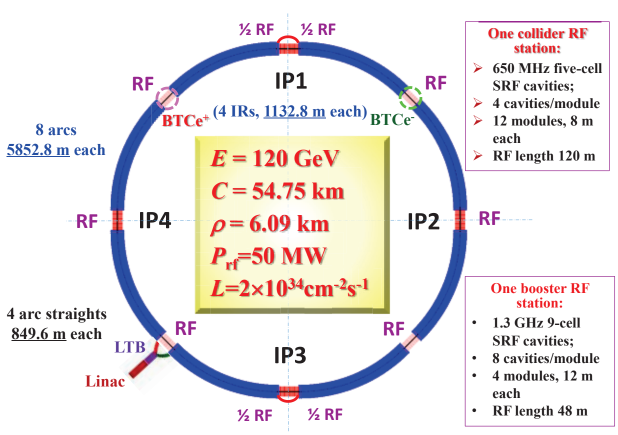

Figure 1: Layout of CEPC and its booster.

As shown in Fig.1, the collider is designed with four interaction points, where IP1 and IP2 are for e^+e^- collisions of luminosity $2\times10^{34}cm^{-2}s^{-1}$ each, while other two IP's are reserved for future pp collider SPPC. The circumference of CEPC collider is 54.75 km, including 8 arcs of 5852.8m, 4 arc straights of 849.6 m each and 4 interaction region straights of 1132.8 m each. The RF frequency of the booster is chosen as 1.3 GHz, factor of two higher than that in the collider. There are eight RF stations in the booster, providing total RF voltage of 5.12 GV. One RF station consists of 4 cry-modules of 12 m long each, each of them contains eight 9-cell super-conducting cavities. Table 1 lists the main parameters of the CEPC booster.

Table 1: Main Parameters of the CEPC Booster

Parameter		Unit	Value
Injection energy		GeV	6
Ejection energy		GeV	120
Circumference		km	52.75
Bending radius		km	6.519
Bending field	@ 6 GeV	T	0.0614
	@ 120 GeV		0.00307
SR loss/turn		GeV	2.814
Bunch number			50
Bunch population		10^{10}	2.0
Beam current		mA	0.87
RF frequency		GHz	1.3
Total RF voltage		GV	5.12
SR power @ 120GeV		MW	2.46
SR power density @120GeV		W/m	45

The bunch number in the booster is chosen the same as in the collider. The bunch population is based on the assumption of 5% current decay in the collider between two top-ups. Synchrotron radiation power density of 45W/m at 120 GeV in CEPC booster is much lower than in BEPCII of 415W/m [2].

For the very low synchrotron radiation damping rate, a scheme of single bunch injection from linac to booster is adopted. The electron and positron beams with bunch population of 2×10^{10} and emittance of 0.3 mm·mrad are injected into central orbit of the booster. Overall transfer efficiency from linac to the collider is assumed to be 90 %.

The booster operates with a repetition frequency of 0.1 Hz, the typical magnetic cycle is given in Fig. 2. Shown in Fig.2, the beam injection from the linac to the booster takes 1 second, the energy ramp takes 4 seconds, 1 second flat top is for beam extraction to the collider, and 4 seconds for magnets ramping down.

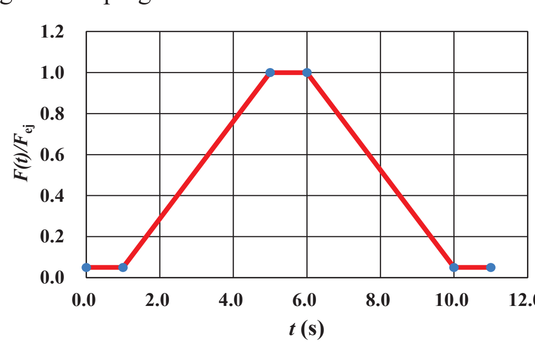

Figure 2: Typical magnetic cycle in the booster.

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MAINTAINING POLARIZATION IN SYNCHROTRONS

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Abstract

The paper describes a method of the preservation of the polarization of the electron beam during the acceleration in a synchrotron. It is proposed to install in the ring equally spaced Siberian Snakes. Advantages to use the odd number of snakes are discussed. Preliminary results of the analytical estimations and of numerical spin tracking simulation are shown.

INTRODUCTION

The polarized beams are needed, first of all, for precise energy calibration using either resonant depolarization or free precession frequency measurement technique; and they are necessary for physics program with longitudinally polarized beams. Acceleration of polarized beams in a synchrotron has many advantages in comparison with the use of self-polarization directly in the collider: 1) full intensity polarized of up to 80%-90% electron beam could be accelerated and used for the experiments; 2) a polarized up to 50%-70% positron beam with only about 10 times lower intensity also should be available – it will become polarized in about 5 min in a 1-1.5 GeV wiggler damping ring; 3) free spin precession frequency measurement technique [1] is much faster and robust method of the energy determination – it measures every injection shot not only the average beam energy with the accuracy in the order of 10^{-6} , but also many other parameters, such as spin de-coherence rate, strength of first and high order synchrotron spin resonances etc.

A method of Siberian Snakes for preservation of the polarization during acceleration in a synchrotron was proposed by Derbenev and Kondratenko in 70-th [2]. They suggested install along a circumference the odd number of 180^0 spin rotators. We will briefly discuss the applicability of that approach for acceleration of the polarized electron and positron beams in a booster synchrotron of FCC-ee collider.

POLARIZED BEAM ACCELERATION WITH SIBERIAN SNAKES

When polarized electron beam is accelerated say from 20 GeV to 80 GeV it crosses more than 130 of integer spin resonances spaced by 440.65 MeV. Due to small field errors it will become fully depolarized even by a single cross of such a resonance. A Siberian Snake may help to solve this problem quite radically.

It is some kind of a spin rotator which rotates spin by 180^0 around any axis which is perpendicular to the vertical one. In a ring with equally spaced odd number of snakes the closed spin orbit looks like it is shown in the Fig. 1 - everywhere in arcs spins are lying in the medium plane of an accelerator.

Another remarkable fact is that with the odd number of snakes the fractional part of the spin tune always equals to ν=0.5, thus all the spin resonances became eliminated! Still strong enough spin perturbation may destroy the regular spin motion making it non-adiabatic. It may happen, if any k-th harmonic amplitude of a perturbation exceeds or approaches to w_k~0.5.

Other mechanism, which one should take into account, is the radiative depolarization. The spin relaxation rate is described by the famous DK formula [3]:

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8} \lambdabar_e r_e c\gamma^5 \left\langle \frac{1-\frac{2}{9}\left(\vec{n}\vec{\beta}\right)^2 + \frac{11}{18}\vec{d}^2}{|r^3|} \right\rangle$$

Here $\vec{n}(\theta)$ is a unity vector aligned along the equilibrium spin direction of a reference particle, $\vec{d}(\theta) \equiv \gamma \frac{\partial \vec{n}}{\partial \gamma}$ is the so-called a spin-orbit coupling vector, which describes the dependence of $\vec{n}$ from the energy, r is the bending radius and other symbols have the obvious meaning.

In a flat normal ring without snakes $\vec{n}(\theta)$ is vertical and $\vec{d}(\theta) = 0$. In the ring with the odd number of snakes $\vec{n}(\theta)$ is horizontal in arcs, as shown in the Figure 1, $|\vec{d}|$ scales $\sim \gamma$ and $\tau_p^{-1} \sim \gamma^7$.

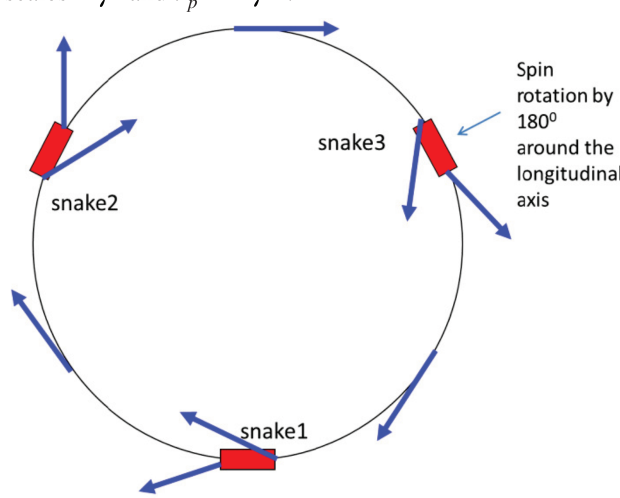

Figure 1: Schematic of spin rotation in a ring by 3 solenoid type snakes.

The averaged over the azimuth θ value of the spin-orbit coupling vector depends on the number of snakes N as follows:

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HOM DAMPER HARDWARE CONSIDERATIONS FOR FUTURE ENERGY FRONTIER CIRCULAR COLLIDERS*

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Abstract

Future high luminosity energy frontier e^+e^- circular colliders CEPC and FCC-ee will operate with high average beam currents. Radio-frequency systems in these machines utilize superconducting RF (SRF) structures with strong damping of higher order modes (HOMs). In this paper I will consider HOM damping options for the colliders under consideration, review HOM damper hardware, both existing and under development, and outline R&D necessary to develop efficient HOM damping in the future circular colliders.

INTRODUCTION

Superconducting RF systems of the future energy frontier e^+e^- circular collider CEPC and FCC-ee will have to deal with high average current particle beams consisting of a large number of short bunches [1]. The machines will be very big with a circumference between 50 and 100 km. As a result, the beams will have very wideband spectra with densely spaced frequency lines. Therefore HOM damping schemes for future colliders are quite challenging. Any selected scheme will have to be capable of handling kilowatts of HOM power via a combination of HOM couplers and beam pipe absorbers, see [2], for example. The latter are required to intersect the high-frequency part of HOM power, which propagate through the beam pipes. Typically required loaded quality factors of HOMs are in the 10^2 to 10^4 range. In this paper I review HOM dampers, existing and under development, with an emphasis on their applicability to the future energy frontier circular colliders.

COUPLER TYPES

There are a large variety of HOM damper designs for SRF cavities, many of them reviewed in references [3]-[4]. However, very few of those dampers are designed to handle high average HOM power and even fewer demonstrated this in operation. The three main HOM damper configurations are based on different transmission lines and coupling circuits. These are: beam pipe absorbers, rectangular waveguide HOM couplers and loop/antenna HOM couplers to a coaxial line [4]. In this section we discuss pros and cons of different HOM damper types and consider existing designs.

*Work is supported by Brookhaven Science Associates, LLC under contract No. DE-AC02-98CH10886 with the US DOE.
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Beam Pipe Absorbers

The beam pipe absorbers (HOM loads) are arguably the most efficient in HOM damping and will be required to absorb the high frequency part of HOM power, which propagates along the beam pipe. The absorber is a section of beam pipe with its inner surface covered by a layer of microwave-absorbing material, e.g. lossy ferrite or ceramics. Drawbacks of the beam pipe absorbers are: i) most absorber materials are brittle, can create particulates that contaminate SRF cavities; ii) parasitic beam-absorber interaction is significant and contributes to the overall HOM power; iii) the main disadvantage for large SRF systems is that the HOM loads occupy real estate along the beam axis and thus reduce the SRF system fill factor.

Room temperature HOM loads were originally developed at Cornell University and KEK for very high average power HOM absorption in the high-current e^+e^- colliders CESR and KEKB [5]-[6]. These HOM loads utilize lossy ferrite materials and demonstrated capacity to absorb several kilowatts of HOM power in operation: 2.9 kW per load at CESR and 8 kW per load at KEKB. In both cases the loads were used in conjunction with single cell SRF cavities as illustrated in Figure 1.

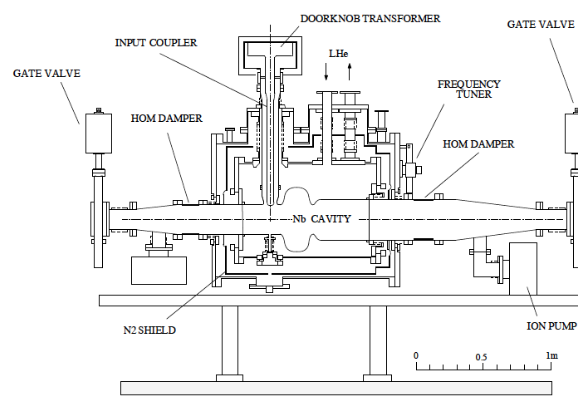

Figure 1: Single cell KEKB SRF cavity with beam pipe HOM dampers [7].

The CESR HOM loads, as the one shown in Figure 2, are used in many high-current storage rings around the world as well as in the R&D ERL at BNL [8]. The KEKB loads are installed in BEPC-II and are planned to be used at SuperKEKB, where the HOM power is expected to reach 15 kW per absorber.

The beam pipe absorbers operating at cryogenic temperatures have dissipation capacity of ~100 W [4] and are not suitable for the future circular colliders.

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FREQUENCY TUNERS, OPERATING EXPERIENCE AND PERFORMANCE RECOVERY

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Abstract

Several important issues for the SRF cavity system will be discussed. One issue is a tuner system. Recent tuner systems have significantly advanced at many laboratories and a number of tuner technologies now exist for a variety of requirements. We will review those tuner systems and discuss applicability.

The second issue is stability of cavity operation. The SRF systems for the Higgs factory must have as low trip rate as possible. Maintenance work is necessary to keep the trip rate at low level. The SRF cavity design that takes into account the ease of maintenance is required. Operational experience of KEKB is an useful example for practical considerations.

The third issue is performance degradation and its recovery method. In a long-term operation, cavity performance gradually degrades. A recovery method with a low risk, low cost and in a short period of time is desirable. We have developed a horizontal high pressure rinsing that can be applied directly to the cavity in a cryomodule. Our degraded cavities successfully recovered using this method.

In this paper, we will report the tuner systems for SRF cavities for appropriate design choice, the operating experience and cavity performance recovery.

INTRODUCTION

There are several important issues for designing SRF cavities and cryomodules. In this report three main issues will be discussed. Those are frequency tuners, operating experience and performance recovery.

Frequency tuner is an important system for the cavity. Its functions are to tune the cavity to its resonant frequency, detune to compensate the beam loading, and help to stabilize its RF amplitude and phase. At an early stage of the SRF cavity development, many types of tuners were tried and applied. Now frequency tuners have advanced for a variety of requirements. One can select an appropriate tuner design for one's cavity. It is useful to review tuner designs developed at many laboratories.

Operating experience gained elsewhere provides very useful information for designing suitable system for the machine operation. Since the Higgs factory requires high integrated luminosity, RF trip rates and down time of the SRF cavities should be as low as possible. In order to keep the low trip rate, maintenance works are essential. Cavity performance degradation in a long term operation also gives a useful information. As an example, cavity RF trip rates, maintenance work, troubles of the cavity operation and performance degradation of the SRF cavities at KEKB are presented.

Performance recovery is needed or desired for a long-term operation. A recovery method should be low risk, low cost and in short period of time. KEK recently developed a horizontal high pressure rinsing method that can be directly applied to a cavity in a cryomodule. Two degraded KEKB cavity modules successfully recovered after the horizontal high pressure rinsing. The R&D effort, details of horizontal high pressure rinsing and application to cryomodules are presented.

FREQUENCY TUNERS

Tuners at An Early Stage

Four frequency tuner systems at an early stage of development are reviewed [1]. The TRISTAN tuner at KEK had a lever system. The lever was driven by a screw jack with a stepping motor. The jack has a piezoactuator for fine tuning. The CESRIII tuner at Cornell University had a flex hinge system with no backlash driven by a stepping motor. The CEBAF tuner system at JLab had a gear shaft system driven by a stepping motor and harmonic gear combination exterior to the cryomodule. The LEPII tuner system at CERN utilized thermal expansion and contraction of three Ni bars. He gas cools the bars for contraction while coil heater warm up the bars for expansion. Exciting coils surrounded those bars to produce magnetostrictive effect for fine tuning. There were a variety of mechanism of the main tuners. The fine sub-tuner was a piezoactuator or a magneto-strictive tuner. Table 1 summarises tuner parameters.

Table 1: Tuner Parameters

	CEBAF	TRISTAN	CESR III	LEP II
Frequency (MHz)	1500	508	500	325
Mechanism	Drive shaft	Lever arm	Flex hinge	Ni bars
Driver	Stepping motor	Stepping motor	Stepping motor	He cooling and coil heating
Sub-tuner		Piezo 4kHz		Magneto-strictive ±1kHz
Sensitivity (kHz/mm)	500	80	320	40
Frequency range (kHz)	400	800 (10 mm)	600	50 (10Hz/s)
Precision (Hz)	2	20	10	-

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TOP UP INJECTION AT PEP-II AND APPLICATIONS TO A CIRCULAR e+e- HIGGS FACTORY*

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Abstract

The PEP-II B-Factory at SLAC (3.1 GeV e+ x 9.0 GeV e-) operated from 1999 to 2008, delivering luminosity to the BaBar experiment. The design luminosity was reached after one and a half years of operation. PEP-II surpassed by four times its design luminosity reaching 1.21 x 10^{36} cm^{-2} s^{-1}. It also set stored beam current records of 2.1 A e- and 3.2 A e+ in about 1732 bunches.

Top-off injection, or continuous injection, was developed in PEP-II using the linac injector to allow constant luminosity with the BaBar detector being fully operational during injection. The electron beam top-off was developed initially as its lifetime was the shortest and thus made the luminosity nearly constant. Second, the positron beam top-off was developed making the luminosity fully constant. Either electrons or positron could be injection up to 30 Hz if needed, deciding pulse-by-pulse which beam (bunch) was needed. Technical details of PEP-II top-off will be discussed. The implications for top-off into a circular Higgs factory are also presented. For this article top-up injection, top-off injection, trickle injection, and continuous injection mean the same thing [1-9].

The SLAC linac as built for the SLC was used for the injector of PEP-II with up to 30 Hz of either positrons or electron injected into the two rings. The injections for top-up typically were about 3 to 10 Hz for HER and 5 to 15 Hz for LER in steady state operations.

Table 1: PEP-II Collision Parameters

Parameter	Units	Design	April 2008 Best	Gain Factor over Design
I+	mA	2140	3210	x 1.50
I-	mA	750	2070	x 2.76
Number bunches		1658	1732	x 1.04
β_y*	mm	15-25	9-10	x 2.0
Bunch length	mm	15	11-12	x 1.4
ξ_y		0.03	0.05 to 0.06	x 2.0
Luminosity	10^{34} /cm^2/s	0.3	1.2	x 4.0
Int lumin per day	pb^{-1}	130	911	x 7.0

*Supported by US DOE contract DE-AC02-76SF00515.
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PEP-II PARAMETERS

In PEP-II the Low Energy Ring (LER) was mounted 0.89 m above the High Energy Ring (HER) in the 2.2 km tunnel as shown in Figure 1. To bring the beams into collision at the single IP, LER was bent down 0.89 m to the HER level and then with horizontal deviations for both rings are made to collide. Since both rings had the same circumference, each bunch in one ring only collides with one bunch in the other ring.

The high beam currents were supported large RF systems consisting of 1.2 MW klystrons at 476 MHz and high power cavities with HOM absorbing loads. Each cavity had three HOM loads each with the capability of 10 kW. At the peak currents the HER cavities received 285 kW and the LER cavities 372 kW. The average klystron power was 1.01 MW. An overhead of about 20% in power was needed to allow the longitudinal bunch-by-bunch RF feedback systems to be stable.

Figure 1: PEP-II tunnel with LER above the HER.

TECHNICAL ITEMS FOR TOP-UP

There are seven technical items that need to be accomplished to achieve successful top-up injection. 1) Each bunch charge in real time must be measured and determined when it needs to be refilled. 2) In the ring and injector, a timing signal is produced to generate a bunch so to deliver it after all the transport gymnastics (gun, linac, damping rings, transport lines) to the needed particular bunch (bucket) in the ring. 3) The linac bunch or bunches need to be injected into the collider with very low losses. 4) The injected beam backgrounds in the

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INJECTION WITH PRETZELS AT CESR*

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Abstract

CESR has operated with pretzel orbits since 1983. With separation in the horizontal plane, the parasitic crossings reduce the acceptance for horizontal betatron stacking of injected particles. Furthermore, both coherent and incoherent long range beam-beam effects reduce tune plane working space. Each bunch will have a particular coherent tune shift depending on parasitic crossing points and bunch currents in the opposing beam. We present the experience at CESR and discuss applicability to the circular Higgs factories.

CESR RING AND INJECTOR

CESR operated as an electron-positron collider from 1979 to early 2008. Ring and injector parameters are listed in Table 1. The synchrotron ring circumference is precisely 60/61 times the CESR circumference, permitting filling of many CESR bunches each injector cycle.

Table 1: CESR Ring and Injector Parameters

Parameter & Units	Value
CESR Ring	
Circumference [m]	768.44
Operating beam energy [GeV]	1.8-6
Transverse damping time [ms]	24
Current per beam (mA)	400
Number of bunches	40
RF Frequency [MHz]	499.7594
CESR Injector	
Injector repetition rate [/s]	60
Linac Energy (e+/e-) [MeV]	160/300
Linac max bunch number	24
Linac charge/bunch (e+/e-) [nc]	
Linac RF frequency [MHz]	2855.77
Synchrotron Circumference [m]	755.84
Synchrotron RF frequency [MHz]	713.943
Highest common frequency [MHz]	71.394
Smallest common bunch spacing [ns]	14.007

The numerology of the various RF systems in the injector chain enables acceleration and injection of bunches spaced at 14 ns intervals (7 CESR RF buckets) in a single injection cycle. The maximum number of bunches is limited to about 24 by loading of the linac RF accelerating cavities. Intercalary buckets may be filled by shifting the injector RF phases between injection cycles. Bunch currents in CESR are monitored and the linac bunch pattern adjusted to equalize the bunch currents.

* Work supported by multiple grants from the U.S. National Science Foundation

Figure 1 below shows a layout of the CESR accelerator complex. Two important features of CESR are critical to optimization of injection with pretzeled orbits:

1. All quadrupoles and sextupoles are independently powered, enabling total flexibility in designing optics and creating group knobs for orthogonal adjustment of specific accelerator physics parameters.
2. The linac/synchrotron provide trains of bunches each (60 Hz) cycle for rapid filling in multi-bunch mode.

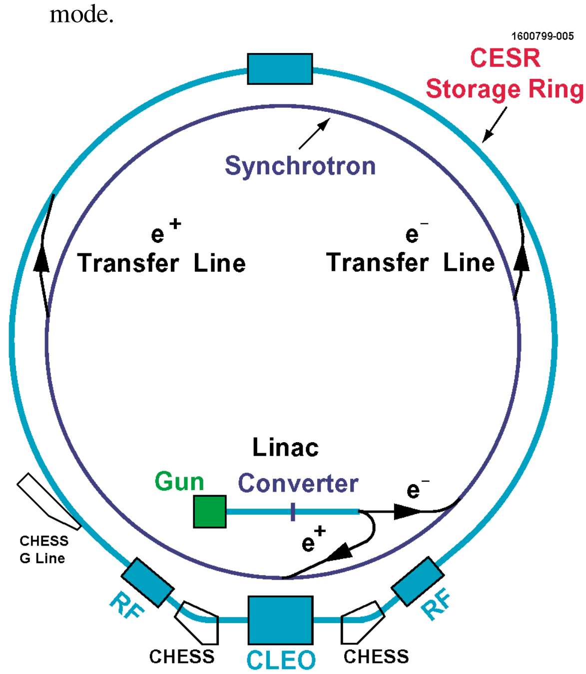

Figure 1: CESR accelerators layout.

Injection into CESR takes place, nominally at least, in the horizontal plane. The beam is extracted from the synchrotron in a single turn by a fast (2.5 µsec) kicker and a pair of septum magnets to bring the beam through the synchrotron fringe field into transfer lines shown above. The transfer lines (Figure 2) have five quadrupoles each (two of them off-center), three horizontal bending magnets and two or three steering trim magnets in each plane. A pulsed septum magnet provides a final bend to bring the injected bunches roughly parallel to the stored beam that has been brought next to the septum magnet by three pulsed kicker ("bumper") magnets forming a closed orbit bump. Injection efficiency can be as high as 90% for a single beam, but is reduced significantly in the presence of a counter-rotating beam as described below.

When all of the beam sizes and hardware parameters are accounted for, the center of the injected bunch has an

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LATTICE OPTIMIZATION FOR TOP-OFF INJECTION

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Abstract

This paper discusses Higgs factory injection. Full energy, top-off injection is assumed. Vertical injection seems preferable to horizontal and kicker-free, bunch-by-bunch injection concurrent with physics running may be feasible. Achieving high efficiency injection justifies optimizing injector and/or collider lattices for maximum injection efficiency. Stronger focusing in the injector and weaker focusing in the collider improves the injection efficiency. Scaling formulas (for the dependence on ring radius R) show injection efficiency increasing with increasing ring circumference. Scaling up from LEP, more nearly optimal parameters for both injector and collider are obtained. Maximum luminosity favors adjusting the collider cell length L_c for maximum luminosity and choosing a shorter injector cell length, $L_i < L_c$, for maximizing injection efficiency.

INJECTION STRATEGY: STRONG FOCUSING INJECTOR, WEAK FOCUSING COLLIDER

Introduction

I take it as given that full energy top-off injection will be required for the FCC electron-positron Higgs factory. Without reviewing the advantages of top-off injection, one has to be aware of one disadvantage. The cost in energy of losing a full energy particle due to injection inefficiency is the same as the cost of losing a circulating particle to Bhabha scattering or to beamstrahlung or to any other loss mechanism. Injection efficiency of 50% is equivalent to doubling the irreducible circulating beam loss rate. To make this degradation unimportant one should therefore try to achieve 90% injection efficiency.

Achieving high efficiency injection is therefore sufficiently important to justify optimizing one or both of injector and collider lattices to improve injection. The aspect of this optimization to be emphasized here is shrinking the injector beam emittances and expanding the collider beam acceptances by using stronger focusing in the injector than in the collider. What are the dynamic aperture implications? They will be shown to be progressively more favorable as the ring radius R is increased relative to the LEP value. The dynamic-aperture/beam-width ratio increases as $R^{1/2}$ and is the same for injector and collider. Before addressing this optimization other injection issues will be surveyed.

Handling the synchrotron radiation at a Higgs Factory is difficult and replenishing the power loss is expensive. Otherwise the RF power loss is purely beneficial, especially for injection. Betatron damping decrements δ (fractional amplitude loss per turn) are approximately half the energy loss per turn divided by the beam energy, (e.g. $\delta \approx 0.5\times2.96/120 = 1.25$ %.) Also the energy dependence is large enough for injection efficiency to improve significantly with increasing energy.

According to Liouville's theorem, increasing the beam particle density by injection is impossible for a Hamiltonian system. The damping decrement δ measures the degree to which the system is *not* Hamiltonian. Usually bumpers and kickers are needed to keep the already stored beam captured while the injected beam has time to damp. If δ is large enough one can, at least in principle, inject with no bumpers or kickers.

Advantages of Vertical Injection and Bumper-Free, Kicker-Free, Top-Off Injection

The most fundamental parameter limiting injection efficiency is the emittance of the injected beam. The vertical emittance in the booster accelerator can be very small, perhaps $\epsilon_y < 10^{-10}$ m. This may require a brief flat top at full energy in the booster. For injection purposes the beam height can then be taken to be effectively zero. The next most important injector parameter is the septum thickness. For horizontal injection this septum also has to carry the current to produce a horizontal deflection. Typically this requires the septum thickness to be at least 1 mm. For vertical injection, with angular deflection not necessarily required, the septum can be very thin, even zero. The remaining (and most important) injection uncertainty is whether the ring dynamic aperture extends out to the septum. If not, it may be possible to improve the situation by moving the closed orbit closer to the wall using DC bumpers. (However this may be disadvantageous for vertical injection as vertical bends contribute unwanted vertical emittance to the stored beams.)

A virtue of top-off injection is that, with beam currents always essentially constant, the linear part of the beam-beam tune shift can be designed into the linear lattice optics. One beam "looks", to a particle in the other beam, like a lens (focusing in both planes). Large octupole moments makes this lens far from ideal. Nevertheless, if the beam currents are constant the pure linear part can be subsumed into the linear lattice model. And the octupole component, though nonlinear, does not necessarily limit the achievable luminosity very severely.

With injection continuing during data collection there would be no need for cycling between injection mode and data collection mode. This could avoid the need for the always difficult "beta squeeze" in transitioning from injection mode to collision mode. Runs could then last for days, always at maximum luminosity. This would improve both average luminosity and data quality.

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IMPEDANCE AND COLLECTIVE EFFECTS STUDIES IN CEPC*

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Abstract

Circular electron-positron collider (CEPC) is a 120GeV storage ring-based collider. Due to the small beam size and high single bunch population, the collective effects may bring new challenges to the physical design of the machine. A thorough evaluation of the coupling impedance is necessary in controlling the total impedance of the ring, which can accordingly prevent the occurrence of the beam instability. The primary studies on the impedance and collective effects in CEPC are presented.

INTRODUCTION

Interaction of an intense charged particle beam with the vacuum chamber surroundings may lead to collective instabilities. These instabilities can induce beam quality degradation or beam loss, and finally restrict the luminosity of the machine. Therefore, beam instability study is essential for designing a new machine. In this paper, the primary calculations of the impedances are first given. Based on the impedance studies, beam instabilities due to single bunch and multi bunch effects are estimated. Instabilities due to interaction of electron beam with the residual ions and positron beam with the electron cloud are also investigated. The main parameters used in the calculation are listed in Table 1.

Table 1: Main Parameters of CEPC

Parameter	Symbol, unit	Value
Beam energy	E, GeV	120
Circumference	C, m	54752
Beam current	I_0, mA	16.6
Bunch number	n_b	50
Bunch length	σ_z, mm	2.65
RF frequency	f_{rf}, GHz	0.65
Energy spread	σ_e	1.63×10^{-3}
Slipping factor	α_p	3.36×10^{-5}
Betatron tune	ν_x/ν_y	179.08/179.22
Synchrotron tune	ν_s	0.18
Damping time	$\tau_x/\tau_y/\tau_z$, ms	14/14/7

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IMPEDANCE

Since most of the engineering designs of the vacuum objects are not done yet, only the RF cavities and the resistive wall impedance are considered here. A more complete impedance budget will be obtained as more vacuum components are designed.

RF Cavities

A five cell superconducting RF cavity structure with RF frequency of 650 MHz will be used in CEPC. Given an accelerating gradient of 15.5 MV/m, 384 cavities will be needed. Since the RF cavities are axisymmetric, the impedance and wake are calculated with the code ABCI [1]. The short range wake at nominal bunch length is shown in Fig. 1. We fit the bunch wake with the analytical model [2]

$$W(s) = -Rc\lambda(s) - Lc^2\lambda'(s), \qquad (1)$$

where L and R are effective inductance and resistance, respectively. The calculated loss factor for one RF cavity is k_l=2.332 V/pC.

Resistive Wall

The resistive wall wake for a Gaussian bunch in a cylindrical beam pipe is calculated analytically [3]

$$W(s) = \frac{cl}{8\sqrt{2}\pi a}\frac{1}{\sigma_z^{3/2}}\sqrt{\frac{Z_0}{\sigma_c}}f(s/c), \qquad (2)$$

where

$$f(x) = \sqrt{|x|^3}e^{-x^2/4}\left(I_{1/4} - I_{-3/4} \pm I_{-1/4} \mp I_{3/4}\right)\Big|_{x^2/4}, \qquad (3)$$

and $I_n(x)$ is the modified Bessel function of the first kind.

Aluminium beam pipes will be used in CEPC. The beam pipe has an elliptical cross section with half height of dimension of a_x=52 mm and a_y=28 mm. We use the vertical aperture in the calculation and obtain the longitudinal wake as shown in Fig. 1.

Impedance budget of the objects considered is given in Table 2.

Table 2: Summary of the Impedance Budget

Objects	R, kΩ	L, nH	k_{loss}, V/pC
RF cavities	28.1	--	895.5
Resistive wall	9.7	126.8	309.6
Total	37.8	126.8	1205.1

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TRANSVERSE POLARIZATION FOR ENERGY CALIBRATION AT THE Z PEAK

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Abstract

In this paper we deal with aspects of transverse polarization for the purpose of energy calibration of proposed circular colliders like the FCC-ee and the CEPC. The main issues of such a measurement will be discussed. The possibility of using this method to accurately determine the energy at the WW threshold as well as the Z peak will be addressed. The use of wigglers for reducing long polarization times will be discussed and a possible strategy will be presented for minimising the energy uncertainty error in these large machines.

INTRODUCTION

Accurate energy determination is a fundamental ingredient of precise electroweak measurements. In the case of LEP1 the centre of mass energy at and around the Z peak was known with an accuracy of around 2×10^{-5}. The exact contribution of the energy error to the mass and the width of the Z are presented in [1].

The proposed circular colliders FCC-ee [2] and CEPC [3] are capable of delivering statistics a factor ~10^5 larger than LEP at the Z and WW energies, therefore there is a need not only to achieve similar performance as far as energy determination is concerned, but to do significantly better.

The only method that can provide the accuracy needed is the so-called resonant depolarization technique, each measurement of which has an instantaneous accuracy of $O(10^{-6})$.

The resonant depolarization technique [4] is based on the fact that the spin precession frequency of an electron in a storage ring is proportional to its energy, E. More precisely the spin tune ν will precess $a\gamma$ times for one revolution in the storage ring, where a is the anomalous magnetic moment and γ the Lorenz factor of the electron

$$\nu = a\gamma = \frac{aE}{mc^2} = \frac{E[MeV]}{440.6486(1)[MeV]} \quad (1)$$

The average of all spin vectors in a bunch is defined as the polarization vector $\vec{P}$.Therefore the average energy of a bunch can be computed by selectively depolarizing a bunch of electrons or positrons which have been polarized to an adequate level and measuring the frequency at which this depolarization occurs. A polarimeter measures the change of polarization level. The accuracy with which the instantaneous average energy of the bunch is computed using this method is O(100KeV) – a value much smaller than the beam energy spread of the storage rings considered here.

TRANSVERSE POLARIZATION

Electron and positron beams in a storage ring naturally polarize due to the Sokolov-Ternov effect [5]. For the purposes of energy calibration important figures of merit are the asymptotic value of polarization that can be reached and the time constant of polarization build-up.

Asymptotic Polarization Value

The maximum achievable polarization value is given by the theory as

$$P_{max} = \frac{8}{5\sqrt{3}} \cong 0.924 \quad (1)$$

however machine imperfections usually limit this number to lower levels. There can be numerous depolarizing effects in a storage ring.

Polarization Time Constant

For a beam with zero polarization the time dependence for build up to equilibrium is

$$P(t) = P_{max}\left[1 - \exp(-t/\tau_{pol})\right] \quad (2)$$

Where the built up rate is (in natural units)

$$\tau_{pol}{}^{-1}[s^{-1}] \approx \frac{2\pi}{99}\frac{E[GeV]^5}{C[m]\rho[m]^2} \quad (3)$$

Where C is the circumference of the storage ring and ρ its bending radius. Therefore polarization times increase dramatically with the machine circumference and decrease with energy. The use of wigglers [6] can decrease this time if needed, at the expense of increasing the energy spread and the synchrotron radiation (SR) budget of the machine.

Polarization times for relevant machines and energies can be seen in Table 1.

Table 1: Polarization Times without the Help of Wigglers

Storage ring	Circumference (kms)	E (GeV)	τ_{pol} (hours)
LEP	27	45	5.8
FCC-ee	100	45	290
FCC-ee	100	80	16
CEPC	55	45	48

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LONGITUDINAL POLARIZATION AND ACCELERATION OF POLARIZED BEAMS

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Abstract

The paper describes a scheme of creation of the longitudinally polarized electron beam at the collision point of the future FCC-ee collider. A scheme is based on use of two 90-degrees spin rotators placed in appropriate points of the interaction region. The solenoid type spin rotators are proposed to use for that purpose. Advantages and disadvantages of the proposed approach are discussed.

INTRODUCTION

There is a clear request for the longitudinal polarization at Z-peak [1]. Even collisions of un-polarized positrons with polarized electrons are of interest for the Weinberg angle measurement experiment, as it was done at SLC.

Still, a positron beam polarization would help very much in study and minimization of different systematics. In principle, a polarized of up to 50%-70% positron beam with only about 10 times lower intensity should be available – it can become polarized in about 5 min in 1-1.5 GeV wiggler damping ring and then be pre-accelerated in a linac to 20 GeV and finally ramped to a full energy by the booster synchrotron.

The full intensity polarized of up to 80%-90% electron beam will be produced like at SLC by a photoemission gun. After acceleration in a linac to 20 GeV it similarly to positrons will be accelerated in a booster synchrotron. Maintaining of the polarization in a synchrotron is discussed briefly in [2].

The effective control of the polarization in the collider and in a synchrotron will be provided by the longitudinal Compton backscattering polarimeter [3, 4]. In contrast to the transverse case the longitudinal one has an extremely large analyzing power, approaching to 75% at Z-peak and almost to 100% at W-threshold.

Below we will discuss two possibilities of organizing of the longitudinal orientation of the stable spin direction at the IP. In both cases the solenoid type spin rotators are proposed to be used.

LONGITUDINAL POLARIZATION AT Z-PEAK

A combination of two $\pm 90^0$ spin rotators and an anti-symmetric horizontal chicane in between with 15 mr deflection angle at IP (relative to the solenoid axis) provides the needed longitudinal spin direction in the collision point, see the Figure 1. Such setup does not disturb the global spin motion due to mirror symmetry of all spin rotations. Therefore the stable spin axis remains a vertical all around a ring, as also the spin tune remains be as same $\nu=\nu_0=\gamma a$, as without any spin rotators. So, a spin precession frequency measurement can be used further for monitoring of the energy stability and for the energy calibration.

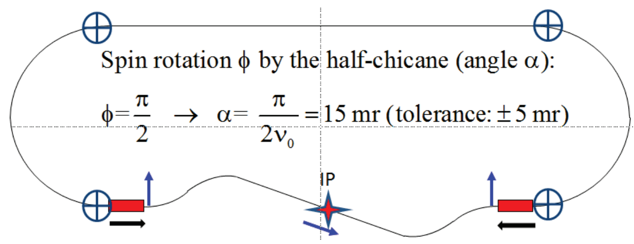

Figure 1: Top view on anti-symmetric layout of a set of 90^0 spin rotations produced by solenoids and by bends in horizontal plane. The orbit deflection angle 15 mr provides 90^0 spin rotation exactly at E=45.5 GeV.

The radiative depolarization rate is expected to be very small because of zero value of the spin-orbit coupling vector $\vec{d}$ everywhere in arcs, except the chicane bends. The spin relaxation rate is described by the famous DK formula [5]:

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8} \lambda\!\!\!^{-}_e r_e c \gamma^5 \left\langle \frac{1 - \frac{2}{9}\left(\vec{n}\vec{\beta}\right)^2 + \frac{11}{18}\vec{d}^{\,2}}{|r^3|} \right\rangle$$

Here $\vec{n}(\theta)$ is a unity vector aligned along the equilibrium spin direction of a reference particle, $\vec{d}(\theta) \equiv \gamma \frac{\partial \vec{n}}{\partial \gamma}$ is the so-called a spin-orbit coupling vector, which describes the dependence of $\vec{n}$ from the energy, r is the bending radius and other symbols have the obvious meaning.

In a flat normal ring $\vec{n}(\theta)$ is vertical independently of energy, hence $\vec{d}(\theta) = 0$. Some small contribution to $\vec{d}$ from dipoles of the chicane will decrease depolarization time from 190 hours to about 24 hours, if the field strength in these bends is same as in arcs.

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FCC-ee BEAM ENERGY MEASUREMENT SUGGESTION*

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Abstract

An approach for beam energy calibration at future circular electron-positron collider (FCC-ee) is suggested. The method is based on a magnetic spectrometer, but does not require absolute knowledge of its bending field. Inverse Compton scattering of laser radiation on the electron beam provides accurate calibration of the bending force. Due to scattering kinematics, the beam energy determination is based on the laser wavelength together with accurate measurement of the ratio of deflection angles. The approach has no serious limitations in the electron beam energy range. The same apparatus allows to measure the electron beam polarization.

INTRODUCTION

Accurate knowledge of the beam energy in experiments on lepton colliders provides direct access to collision energy. This knowledge has always been a tremendous advantage for performing precise measurements of particle masses, shapes of the resonance structures, etc.

The present accuracy of the mass scale in high-energy physics is established mostly due to the resonant depolarization technique, which had been used at various e^+e^- colliders like VEPP-2M, SPEAR, DORIS, CESR, VEPP-4(M), LEP. The resonant depolarization approach provides ultimate precision ($\Delta E_0/E_0 \simeq 10^{-6}$) for instant beam energy determination through measurement of the spin precession frequency. However, preparation of and control over polarized beams is not always possible and usually consumes significant amount of time and decreases the overall luminosity integral. At high beam energies the beam polarimetry is usually based on laser backscattering, a process which is sensitive to both transverse and longitudinal polarization of electrons [1, 2].

In case when an experiment requires precise measurement of the beam energy, it is very important to have several complementary approaches possessing high sensitivity at least to relative beam energy changes. This helps to determine the beam energy behaviour during data acquisition time as well as to perform various cross-checks and eliminate possible errors. In storage rings the beam energy is usually derived from continuous measurements of the bending fields in a number of dipoles. The relationship between the measured fields and the beam energy is defined via magnetic model of the storage ring, which is calibrated against precise measurements of the beam energy, e. g. by resonant depolarisation [3, 4].

At LEP 2 the beam energy "was verified by three independent methods: the flux-loop, which is sensitive to the bending field of all the dipoles of LEP; the spectrometer, which determines the energy through measurements of the deflection of the beam in a magnet of known integrated field; and an analysis of the variation of the synchrotron tune with the total RF voltage".

Compton Backscattering of Laser Radiation

Here let us make a brief introduction to another approach for the absolute beam energy determination. It was implemented for the last ten years at e^+e^- colliders VEPP-4M [3], BEPC-II [5] and VEPP-2000 [6, 7].

When the photon with energy ω_0 is scattered towards the relativistic electron with energy E_0, this electron gives significant part of its energy to the scattered photon, even in case when $\omega_0 \ll E_0$. Maximum energy loss of the electron occurs when the scattered photon propagates exactly along the electron momentum, carrying out ω_{max} energy:

$$\omega_{max} = E_0 \frac{\kappa}{1+\kappa}, \qquad (1)$$

where $\kappa = 4\omega_0 E_0/m^2$. Electron mass m is a well established parameter, $\Delta m/m \simeq 2 \cdot 10^{-8}$. If one uses a laser as a source of photons for scattering, the order of about 1 ppm relative accuracy for the ω_0 value is practically not a problem. Thus, if one can measure ω_{max} in absolute units, electron energy E_0 could be easily obtained from Eq. 1 with roughly twice better relative precision than ω_{max} measurement.

The particular case when this approach is good enough is when ω_{max} belongs to the energy range between 100 keV and 10 MeV. Here the HPGe[1] detectors possess *high energy resolution* and *sufficient efficiency*. What is also very important is that in this energy range the *absolute scale calibration is possible* due to well-known energies of nuclear γ-sources. By now the backscattering of laser radiation is a well established approach for beam energy measurement with an accuracy $\Delta E_0/E_0 \lesssim 5 \cdot 10^{-5}$, but its application is limited for the beam energies $E_0 \lesssim 2$ GeV.

For further consideration we note that for a relativistic electron one can neglect ω_0 in the energy balance of scattering, i. e. the minimal electron energy after scattering $E_{min} = E_0 - \omega_{max}$, and from Eq. 1 one has:

$$E_{min} = E_0 \frac{1}{1+\kappa}. \qquad (2)$$

THE SUGGESTION

One of the beam energy measurement approaches at LEP (1997-2000) was the LEP spectrometer [4]. The similar concept was proposed for the ILC upstream beam energy spectrometer [2]. When the electron beam passes through

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[1] HPGe – High Purity Germanium detector

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POSSIBLE APPLICATIONS OF WAVE-BEAM INTERACTION FOR ENERGY MEASUREMENT AND OBTAINING OF POLARIZATION AT FCCee

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Abstract

Possibility to monitor beam energy in FCCee with an accuracy of 10^{-4} using Compton scattering on a waveguide wave is under consideration. Methods based on interaction of a beam with circularly polarized photons for obtaining beam polarization, proposed and theoretically substantiated in the past but not yet approved anywhere, are briefly discussed in regard to parameters of FCCee.

INTRODUCTION

The aim of the work is an attempt to imagine some new possibilities which a beam-wave interaction can impart to the FCCee project development in regard to beam energy monitoring and obtaining of spin polarization.

One of them is an application of waveguide wave for a beam energy determination by the Compton scattering.

The precision beam energy calibration with an accuracy of 10^{-6} using the resonant depolarization technique will be applied at FCCee in the experiment of the Z mass measurement [1]. Such calibration procedures will be conducted periodically depending on the timing cycles of obtaining and utilization of beam polarization. The gained experience of the similar experiments (see, for example, [2]) shows an acute need to continuously monitor a beam energy in the intervals between these procedures with an accuracy of at least the order of a beam energy spread. The reason for this is a long-term instability of guide field and violations of a storage ring geometry due to temperature changes and tidal effects.

Compton Back Scattering (CBS) on a relativistic electron beam in a storage ring is applied now to monitor the beam energy with an accuracy of up to a fraction of the beam energy spread which makes diffuseness of the Compton spectrum edge. In the top quark experiments the Compton scattering may be considered as a main method for beam energy determination because of growing problems [1] with obtaining spin polarization at energies >100 GeV.

Accuracy of the VEPP-4M CBS monitor of beam energy with the working laser wavelength of 10 μm amounts 2.5×10^{-5} at the beam energy spread of 3×10^{-4} [2]. Question of possibility to apply a similar CBS monitor at 45-175 GeV FCCee turns on the issue of the use of significantly longer wavelengths of incident waves providing a limit of scattered photon energy of the order of 5 MeV which is feasible for detecting [3]. Taking into account such limitation we should take the wavelength $\lambda > 8$ mm. Such a problem definition looks like obvious but the corresponding possibility still has not been studied.

In the past the original proposals to obtain spin polarization in storage rings of the LEP energy range using laser waves were developed at Budker Institute [4, 5]. But no experiments have been performed to approve these proposals anywhere till now. We briefly discuss them in regard to the FCC project general parameters.

WAVEGUIDE COMPTON MONITOR OF BEAM ENERGY

Compton Scattering Kinematics in Waveguide Mode

According to the Compton kinematic scheme in Figure1 a momentum k_2 of a scattered photon is related to an analogous parameter before scattering (k_1) by the equation (the useful formulae on the Compton effect are presented in [6])

$$k_2 = \frac{k_1(1-\beta\cos\theta_1)}{1+\frac{k_1}{E}[1-\cos(\theta_2-\theta_1)]-\beta\cos\theta_2}, \qquad (1)$$

where $E = m\gamma$ and β are the initial energy and velocity of an electron. When a microwave radiation with a frequency

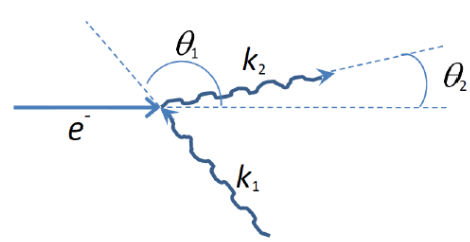

Figure 1: Kinematic scheme of Compton scattering.

$\omega = 2\pi c/\lambda$ induced in the FCC vacuum chamber propagates towards the beam one can observe the Compton Back Scattering of the corresponding photons. In the limit of very small wavelengths $\lambda << \lambda_c$ (λ_c is a critical wavelength) the incident photons fly practically along an axis of the chamber-waveguide ($\theta_1 = \pi$) and energy of scattered photons equals to

$$\omega' \approx \frac{4\gamma^2\omega}{1+\gamma^2/\theta_2^2}, \qquad (2)$$

or $\omega' = 4\gamma^2\omega$ at $\theta_2 = 0$. This is valid for laser beam because of its high directedness. In the general case a geometric description of Compton scattering of waveguide waves undergoes change. The easiest way to consider this change is to use the Brillouin approach based on partial plane waves (see Figure 2). Direction of the partial waves are given by the angle

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LESSONS LEARNED FROM THE B-FACTORIES AND IMPLICATIONS FOR A HIGH-LUMINOSITY CIRCULAR e+e- HIGGS FACTORY

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Abstract

Experiences on the electron clouds, optics corrections, an orbit feedback at IP and luminosity tuning at KEKB are described. An emphasis is placed on the beam instrumentations and the beam control.

INTRODUCTION

KEKB [1] is an energy-asymmetric double-ring collider for B meson physics. KEKB consists of an 8-GeV electron ring (the high energy ring: HER), a 3.5-GeV positron ring (the low energy ring: LER) and their injector, which is a linac-complex providing the rings with both of the electron and positron beams. The construction of KEKB started in 1994, utilizing the existing tunnel of TRISTAN, a 30 GeV × 30 GeV electron-positron collider. The machine commissioning of KEKB started in December 1998. The physics experiment with the physics detector named Belle was started in June 1999. The peak luminosity surpassed the design value of 1.0 $\times 10^{34}$cm^{-2}s^{-1} in May 2003. The maximum peak luminosity of KEKB is 2.11 $\times 10^{34}$cm^{-2}s^{-1}, which was recorded in June 2009. This value has been the world-record since then. The KEKB operation was terminated at the end of June 2010 for the works to upgrade KEKB to SuperKEKB. The commissioning of SuperKEKB is expected to start in autumn in 2015. The total integrated luminosity collected by the Belle detector was 1041 fb^{-1}. The history of KEKB is shown in Figure 1. In this report, some experiences at KEKB are described. An emphasis is places on the beam instrumentation and the beam control. Some of them may be useful in future colliders such as a high-luminosity circular e+e- Higgs factory. Achievements of KEKB and details of commissioning are described elsewhere [2] [3].

ELECTRON CLOUDS

A beam size enlargement depending on the beam current in the LER has given one of the most serious luminosity restrictions to KEKB. This type of beam-blowup was not considered in the design phase of KEKB. It turned out that the cause of the blowup is the electron clouds. Although the electron clouds are formed by the bunch train, the blowup is induced by a single bunch instability. The mechanism of this blowup has been studied theoretically by F. Zimmermann and K. Ohmi. They showed by simulations that the blowup can be explained by a fast head-tail instability caused by wake fields by the passage of the bunch particles though the electron clouds [4]. This explanation has been experimentally confirmed by observing vertical betatron sideband due to the electron clouds at KEKB LER [5]. Figure 2 shows a typical results of the sideband measurements. More detailed explanations and an experimental setup for this measurement are described in [5].

To suppress this instability, solenoid coils have been wound around approximately 95% of the drift space in the LER ring with a maximum field at the center of the beam pipe of ~60 Gauss [6]. Although the solenoids drastically improved the luminosity, performance of KEKB was still affected by the effects of electron clouds with a higher beam current of the LER than about 1.6 A. The luminosity of KEKB did not increase with a higher LER beam current than about 1.6 A. It is believed that this is due to the effects of electron clouds. For this reason, the operation beam current in LER of 1.6 A is much lower than the design beam current, 2.6 A. Another impact of the electron clouds to the beam operation at KEKB is the choice of bunch spacing. In the design, the bunch spacing is one RF bucket, which means that every RF bucket is filled with beam particles. However, in the actual operation, the bunch spacing is approximately 3 RF buckets. With shorter bunch spacing, the specific luminosity lowered. This restriction to bunch spacing is also believed to come from the effects of the electron clouds. Figure 3 shows a result of an experiment on bunch spacing carried out on March 21st 2008. For the experiment, a special filling pattern was used. In the beam filling pattern of KEKB, the same pattern should be repeated every 49 RF-buckets to be compatible with the two bunch injection. Due to the synchronization problem between the injector linac and the KEKB rings, only the two bunches in 49 RF-buckets in the rings can be injected from linac to the rings. In the filling pattern used in the experiment, 17 RF-buckets out of 49 RF-buckets were filled with the beam and the same patterns repeated 99 times. Most of bunch spacing between adjacent bunches was 3 RF-buckets but only 2 bunches out of 17 bunches in a unit of 49 RF-buckets followed the preceding bunches at a distance of 2 RF-buckets. In Fig. 3, the specific luminosity per bunch is plotted as function of bunch ID in a unit of 49 RF-buckets. Note that the specific luminosity of each bunch ID in the figure is the average of 99 bunches in the equivalent position in the units of 49 RF-buckets. The error bars in the graph show the standard deviations of the 99 bunches. As is seen in the figure, the specific luminosity after 2 RF-buckets is ~15 % lower than that of the other bunches. It is believed that this degradation in the specific luminosity comes from the effects of the electron clouds. In the case of short bunch trains, this degradation was not observed and then we can deny the possibility that the degradation in the specific luminosity after short bunch spacing is caused by the effects of the parasitic collisions.

Another instrument for the electron clouds measurement used at KEKB is an retarding field analyzer (RFA) [7]. A

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CHALLENGES IN BEAM INSTRUMENTATION AND DIAGNOSTICS FOR LARGE RING COLLIDERS – BASED ON THE LHC EXPERIENCE

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Abstract

An overview on some of the major challenges for beam instrumentation and diagnostics for large ring colliders is given. In the Introduction the general challenges are listed, independent of particle type and accelerator specifics. After a short LHC introduction, examples from the LHC experience are presented, related to observed issues, and to the present upgrade and improvement efforts, made during the long shutdown 1. A list, however not comprehensive, of relevant beam instrumentation R&D activities closes this summary.

INTRODUCTION

The next generation of a ring collider for high energy physics (HEP) will have >50 km circumference, and collide leptons, as a Higgs factory, or hadrons, for beyond standard model physics exploration, at highest energies (up to 100 TeV center-of-mass) and luminosities. At the time of this article we operate the Large Hadron Collider (LHC) at CERN (Geneva, Switzerland) for the HEP community at the energy frontier, colliding proton beams with up to 7+7 TeV [1].

Table 1: Large Ring Colliders for HEP

Collider	Years of operation	Circumference *[km]*	Beam type	Beam Energy *[GeV]*	Luminosity *[cm^{-2}s^{-1}]*
Tevatron	1983-2011	6.3	p-$\overline{\text{p}}$	980-980	4e32
LEP	1989-2000	27	e^+-e^-	104.5-104.5	2.1e31
HERA*	1992-2007	6.3	p-e	920-27.5	5.1e31
LHC	**2008-…**	**27**	**p-p/Pb^{82+}**	**4000-4000****	**7.7e33****

* achieved >50 % longitudinal polarization of the e-beam
** achieved performance in 2012

Table 1 summarizes recent large ring colliders, which all have common goals, i.e. highest center-of-mass (CoM) energy, high integrated luminosity (reliable operation), reasonable low investment and operation costs, and in case of leptons high spin polarization. All these ring accelerators made heavy use of superconductive technologies for magnets, RF or both. For any future large ring accelerator project the time span from the initial concept to the first stored beam will be large, 20 years, or more. With the LHC now in operation, the case for a future HEP machine has to be made, this also includes first thoughts on the challenges for the beam instrumentation.

The beam instrumentation and diagnostics systems have to characterize mission critical beam parameters, e.g.:

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Intensity Beam and bunch intensities, beam life time, abort gap, etc.

Orbit and Position Beam position monitors (BPM) with bunch-by-bunch, turn-by-turn and high resolution beam orbit measurement capabilities. All BPMs integrated into the orbit feedback system, some BPMs integrated into technical interlock systems. Special BPMs for specific tasks, e.g. BPMs integrated into collimator jaws.

Beam Losses The beam loss monitors (BLM) are the central element of the machine protection system (MPS).

Tunes and Instabilities Monitoring and feedback of the betatron tunes should be accomplished with no or minimum beam excitation. The measurement on the tunes of individual bunches (single bunch tunes) is desirable. A system for the early detection of instabilities, e.g. head-tail motion is of great benefit.

Beam Profile (Emittance) and Halo A non- or minimum invasive measurement of the transverse beam profile, with single bunch capability is essential to monitor the beam emittance. Techniques with high dynamic range have to be developed to monitor the transverse beam halo, which need to be eliminated.

Chromaticity measurement based on a direct, non-invasive measurement technique, e.g. monitoring of the *Schottky* bands.

Challenges

Regardless of beam type and exact machine layout, all future large ring accelerators will have some major challenges for the beam instrumentation in common:

- The large physical size requires a large number of components and subsystems, thus a tight control on costs and reliability. E.g. the use of copper cables over long distances is not adequate, optical fibers have to replace copper wherever possible.
- Low temperatures for superconductive operation of magnets and/or RF give additional challenges for nearby beam monitors, e.g. cryogenic RF vacuum feedthroughs, RF cables, beam monitors (BPMs, BLMs) inside the cryostat.
- High order mode (HOM) and wakefield effects of beam detectors have to be well understood to minimize their impact on the accelerator's impedance budget, and to prevent damages e.g. due to RF heating.
- Basically all beam detection methods have to be non-invasive as of the damage and residual loss potential of high intensity, high brilliance beams.
- An early observation and damping of beam instabilities, e.g. head-tail, e-cloud, etc. will be crucial.

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SUMMARY OF HF2014 WORKING GROUP 1 – “PARAMETERS”

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Abstract

The ICFA Higgs Factory workshop (“HF2014”) was held in Beijing from 9 to 12 October 2014. Here we summarize the presentations and discussions from the three sessions of Working Group no. 1, which looked after the “Parameters.”

INTRODUCTION

The HF2014 WG1 sessions featured the following nine presentations:

1) Physics motivation and requirements, Alain Blondel (U. Geneva)
2) Choice of circumference, minimum & maxim energy, number of collision points, and target luminosity, Michael Koratzinos (U. Geneva)
3) Ring circumference and two rings vs. one ring, Richard Talman (Cornell U.)
4) Beam-beam effects in high-energy colliders: crab waist vs. head-on, Dmitry Shatilov (BINP)
5) Optimizing beam intensity, number of bunches, bunch charge, and emittance, Chuang Zhang (IHEP)
6) Polarization issues in *FCC-ee* collider, Eliana Gianfelice (FNAL)
7) Constraints on the *FCC-ee* lattice from the compatibility with the *FCC* hadron collider, Bastian Haerer (CERN)
8) Polarization issues and schemes for energy calibration, Ivan Koop,
9) Optimizing costs of construction and operation, possible construction time line, Weiren Chou (FNAL)

PHYSICS REQUIREMENTS

Alain Blondel reviewed the physics requirements for the next generation of high-energy e^+e^- colliders [1].

Table 1 presents a sample of essential physics studies.

For FCC-ee and CepC the precision of the luminosity measurement will be improved compared with LEP-2. As systematic errors are likely to dominate the need for small-angle measurement should be revisited.

The duration of the desired e^+e^- runs is of order ~20 years, including staging. A possible *FCC-ee* physics programme conceived in 2013 (for the then *TLEP*) would be as follows:

1. ***ZH* threshold scan and 240 GeV running** (covering energies from 200 GeV to 250 GeV): more than 5 years at 2 x 10^{35} cm^{-2}s^{-1} would produce 2×10^6 *ZH* events. Later one will need to return to the *Z* peak with the *FCC-ee-H* configuration for the detector and beam energy calibration. The physics programme includes Higgs boson *HZ* studies, while running at the *ZH* measuring of cross sections and decay rates of the copiously produced *WW* and *ZZ* pairs, etc.
2. **Top threshold scan and 350 GeV running:** more than 5 years at 2×10^{34} cm^{-2}s^{-1} would produce 10^6 $\bar{t}t$ events. Also this configuration should be operated at the *Z* peak for calibration purposes. The physics covered would include top quark mass, *WW* fusion (with *H* and two neutrinos in the final state), etc.
3. ***Z* peak scan and peak running in the *FCC-ee-Z* configuration** delivering more than 10^{12} (possibly 10^{13}) *Z* decays. This running mode includes transverse polarization of ‘single’ bunches for precise E_{beam} calibration. At least 2 and preferably 4 years of running in this configuration are required to accomplish the physics goals related to M_z, Γ_Z, R_b etc, with emphasis on precision tests and searches for rare decays.
4. ***WW* threshold scan for precision *W* mass measurement and *W* pair studies** during another 1-2 years would yield some 10^8 *W* pairs. Again energy and beam energy calibration would be accomplished by operating with the same configuration at the Z peak.
5. **Operation with polarized beams** (requiring spin rotators) at the *Z* peak during 1 year at a beam-beam tune shift of 0.01 per IP would yield 10^{11} *Z* decays, enabling precision measurements of A_{LR}, A_{FB}^{pol} etc.

Achieving polarization will be more difficult for *CepC* than for *FCC-ee,* due to the intrinsically larger energy spread of a smaller machine.

For precision studies of the *Z* pole and of various thresholds mono-chromatization schemes (see e.g. [2]) could be of interest. Such schemes could provide a 10 times smaller collision energy spread, probably at the expense of lower luminosity.

Table 1: Sample of *FCC-ee* Physics Studies [1]

X	physics	present precision		FCC-ee stat//syst. precision	FCC-ee key	challenge
M_Z MeV/c^2	Input	91187.5 ±2.1	Z line shape scan	0.005 MeV/ <±0.1 MeV	E_{cal}	QED corrections
Γ_Z MeV/c^2	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495.2 ±2.3	Z line shape scan	0.008 MeV/ <±0.1 MeV	E_{cal}	QED corrections
R_l	α_s, δ_b	20.767 ± 0.025	Z peak	0.0001/ ± 0.002 - 0.0002	statistics	QED corrections
N_ν	unitarity of PMNS, sterile ν’s	2.984 ±0.008	Z peak Z+γ (161 GeV)	0.00008/ ±0.004 0.001/-	lumi meas. statistics	QED corrections to Bhabha scattering
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003/ ±0.000020 – 60	statistics, small IP	hemisphere correlations
A_{LR}	$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)	0.1514 ±0.0022	Z peak, polarized	-/±0.000015	4 bunch scheme	design experiment
M_W MeV/c^2	$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$ (T, S, U)	80385 ± 15	tThreshold (161 GeV)	0.3 MeV/ <1 MeV	E_{cal} & statistics	QED corections
m_{top} MeV/c^2	Input	173200 ± 900	threshold scan	10 MeV/-	E_{cal} & statistics	theory limit at 100 MeV?

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SUMMARY OF WORKING GROUP 2: OPTICS*

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INTRODUCTION

We had four sessions of optics in the Higgs Workshop 2014, Beijing. The first section was dedicated to the overall consideration of optics in circular Higgs factory (CHF), and the existing designs from IHEP and CERN. The second one focused on single-particle beam dynamics, in particular dynamic aperture in SuperKEKB and CHF. The third session was a joined one together the working group 3: interaction region (IR) and machine detector interface. The topic was final focus system (FFS) and local chromatic compensation. Three approaches by IHEP, CERN, and BINP were presented. In the final session we had a discussion of beamstralung, beam-beam interaction, and IR magnets.

TALKS

There were 15 talks in the optics sessions:

1. "Overall consideration, main challenges and goals", Yunhai Cai (SLAC)
2. "Single ring multi-bunch operation and beam separation", Richard Talman (Cornell)
3. "Challenges and status of the FCC-ee lattice design", Bastian Harer (CERN)
4. "Status of the CEPC lattice design", Huiping Geng (IHEP)
5. "Analysis of nonlinear dynamics", Yunhai Cai (SLAC)
6. "Dynamic aperture optimization in SuperKEKB", Yukiyoshi Ohnishi (KEK)
7. "The effect of IR imperfection on dynamic aperture in SuperKEKB / dynamic aperture study of CEPC", Hiroshi Sugimoto (KEK)
8. "Beam lifetime and Injection consideration", Cui Xiaohao (IHEP)
9. "CEPC IR optics", Yiwei Wang (IHEP)
10. "Status of the FCC-ee interaction region design", Roman Martin (CERN)
11. "Crab waist interaction region", Anton Bogomyagkov (BINP)
12. "Beamstrahlung and energy acceptance", Kazuhito Ohmi (KEK)
13. "Interaction region magnets", Eugenio Paoloni (INF)
14. "Beam-beam effects in the CEPC", Yuan Zhang (IHEP)
15. "Wide-band long-focus optics for detection systems infrared synchrotron accelerator diagnostics", Marina Maltseva (TENZOR)

Here are our conclusive remarks on the optics in CHF.

MAIN CHALLENGES

Compared with LEP2, we need a factor of 100 increase of luminosity at beam energy of 120 Gev with an affordable cost. Without any major technology advances, we have put all burdens squarely on the optics:

- Low emittance lattice at high energy,
- High packing factor of magnets,
- Strong final focusing,
- Large momentum acceptance,
- Short bunches.

Any one of the listed item represents a significant challenge. With all of them combined, we have not yet found any solution since the last workshop two years ago. Most likely, something has to give or new concept has to be discovered.

ARC LATTICE

To reduce synchrotron radiation of the bending magnets, we all use FODO cell in CHF because of its large packing factor. It lacks of flexibility in optics. Specifically, the interlaced sextupoles generated huge tune shifts at high betatron amplitudes. As a result, any perturbation will degrade the dynamic aperture, mostly noticeable with a pretzel orbit or insertion of the IR. A way to mitigate this effect is to consider increase circumference to accommodate other type of cells with non-interlace sextupoles in arcs.

FINAL FOCUS SYSTEM

Many progresses have been made since the last meeting (Feb, 2014), but the momentum aperture of the collider with realistic arcs remains too small. Possible solutions:

- Add octupoles near the final doublet,
- Consider asymmetric dispersion at the paired sextupole in FFS,
- Simplify the transition between CCY and CCX to reduce the phase advance from 3π to 2π

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SUMMARY OF WORKING GROUP 3*

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Abstract

This is a brief summary of the talks and issues that came up in Working Group 3 (IR and MDI). There were many excellent presentations and several issues were raised regarding the CEPC design and the FCC-ee design.

INTRODUCTION

The working group looked at issues for backgrounds in the detector from synchrotron radiation and from beam particles. In addition, the needs of the detector were also addressed and several discussions were entertained that revolved around these various issues. The CEPC interaction region design is quite challenging and there were many points of interest raised that will require further study. The interaction region of the FCC-ee design is equally challenging and has its own set of unique issues.

PRESENTATIONS

There were a total of 6 sessions and 14 presentations. We also had 3 joint sessions with working groups 2 and 4. We list the presentations here.

1. CEPC IR Optics, Y. Wang (IHEP)
2. Status of FCC-ee Interaction Region Design, R. Martin (CERN) **FRT2B2**
3. Crab Waist Interaction Region, A. Bogomyagkov (BINP) **FRT2B3**
4. SuperKEKB Background Simulations, H. Nakayama (KEK) **FRT3A1**
5. Beam-beam limit vs. number of IPs and Energy II: scaling law, M. Xiao (IHEP) **FRT3A2**
6. Beam-beam limit vs. number of IPs and Energy I: beam-beam simulation, K. Ohmi (KEK) **FRT4A1**
7. Long-Range beam-beam interaction with the CESR bunch train operation, D. Rice (Cornell U.) **FRT4A2**
8. Choice of L* I and SR in the HF IR, M. Sullivan (SLAC) **SAT1B1**
9. Choice of L* II: IR optics and dynamic aperture, E. Levichev (BINP) **SAT1A2**
10. Choice of L* III: requirement from the detector, G. Li
11. Lost particles in the IR and Touschek effects, M. Boscolo (INFN-LNF) **SAT1B2**
12. Infrared synchrotron methods and systems for monitoring and controlling particle beams in real time, M. Maltseva (TENZOR) **SAT1B4**
13. Detector beam background simulations for CEPC, H. Zhu (IHEP) **SAT2A2**
14. Synchrotron radiation absorption and vacuum issues in the IR, J. Seeman (SLAC) **SAT1B3**

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HIGHLIGHTS

- The CEPC IR optics has been improved. The L* value has been lowered from 2.5 m to 1.5 m and the strength of the bend magnets in the chromaticity correction blocks on either side of the IP have been lowered. The Synchrotron Radiation (SR) power from the previous bends had been exceptionally large and now the values, though large, are looking manageable.
- The FCC-ee interaction region design is being studied. The design includes an 11 mrad crossing angle with two complete storage rings for the electrons and positrons. The overall design is quite ambitious with an energy range that goes from the Z0 to the ttbar threshold E_{cm}: from 92 GeV to 355 GeV
- A crab waist design was presented for the FCC-ee IR which looks quite promising.
- There was a very comprehensive presentation from the SuperKEKB background group. They have gone to great effort to model every detail of the detector hardware and the beam line components both inside and outside of the detector in order to get as accurate a simulation as possible. They have used this detailed simulation to study the effects of adding shielding in almost all possible remaining space inside the detector.
- There were two very interesting studies presented about beam-beam limits. One study collected all the available information about beam-beam limits from present and past machines and compared these numbers against some standard scaling laws and typical simulations. The other presentation showed a study of the CEPC IR design and concluded that a β_y^* design of 2 mm gave more luminosity than the current β_y^* of 1.5 mm.
- There was presentation on bunch trains and using pretzel orbits that revealed many of the difficulties of maintaining a good orbit and luminosity with such a design. This is the plan for the CEPC design. The issues of the pretzel design were difficult to handle even with a very flexible machine.
- There were three presentations on choices of L* values. The first presentation concentrated on the issues of SR coming from the final focus quadrupoles. Due to the very high strength of these quads, there is a very significant amount of SR

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SUMMARY OF WORKING GROUP 4: SR AND SHIELDING

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Abstract

In this paper a summary of the work done in Working Group 4, Synchrotron Radiation and Shielding, is presented. A short description of the topics discussed and future issues to be addressed in this field by high energy circular colliders designers is given.

TALKS PRESENTED

The talks presented in WG4 two sessions and summarized in this paper are the following:

1. Monte Carlo Simulations of Synchrotron Radiation for CEPC Vacuum System, by Z. Ma (IHEP);
2. Vacuum System requirements for a HF e+e- Accelerator, by R. Kersevan (CERN);
3. Synchrotron Radiation Effects in the HF Injector, by Y. Papaphilippou (CERN)
4. Electronics shielding in the tunnel, by L. Esposito (CERN);
5. Infrared Synchrotron Methods and Systems for Monitoring and Controlling Particle Beam in Real Time, by M. Maltseva (TENZOR);
6. Lost Particles in the IR and Beam Induced Backgrounds in a Higgs Factory, by M. Boscolo (INFN);
7. Synchrotron Radiation Absorption and Vacuum Issues in the IR, by J. Seeman (SLAC).

VACUUM AND SR

Talks 1 and 2 addressed the impact of the SR on the design of the vacuum system.

CEPC

Radiation protection topics addressed were:

- synchrotron radiation shielding;
- thickness of the main tunnel;
- shielding for straight tunnel, beam dump, collimate station, injection section, maze, duct, shielding doors, RF station, etc…;
- induced radioactivity analysis: cooling water, ventilation air, accelerator component, local shielding concrete, ground water, environmental samples, etc…;
- personal safety interlock system;
- radiation dose monitoring system.

Since there are different radiation thresholds for different operational zones, like inner and outer tunnel, all areas should be clearly defined after the functional structures are determined.

A Monte Carlo simulation of the Synchrotron Radiation (SR) in the CEPC beam pipe has started. A model of the beam pipe similar to the LEP design was assumed for the first calculations (see Figure 1) with two material options: a few millimeters of Al covered by 3 or 8mm of Pb or only a few millimeters of Cu.

A comparison between LEP2 and CEPC SR parameters is shown in Table 1.

Table 1: SR Parameters for CEPC and LEP2

Parameter	CEPC	LEP2
Beam Energy (GeV)	120.	100.
Beam current (mA)	16.6	5.5
Bending radius (m)	6094.	3104.
Power/unit length (W/m)	1305	805
Critical energy (keV)	629.	709.
Bending angle (mrad)	3.17	6.4
Solid angle (μrad)	4.3	5.1

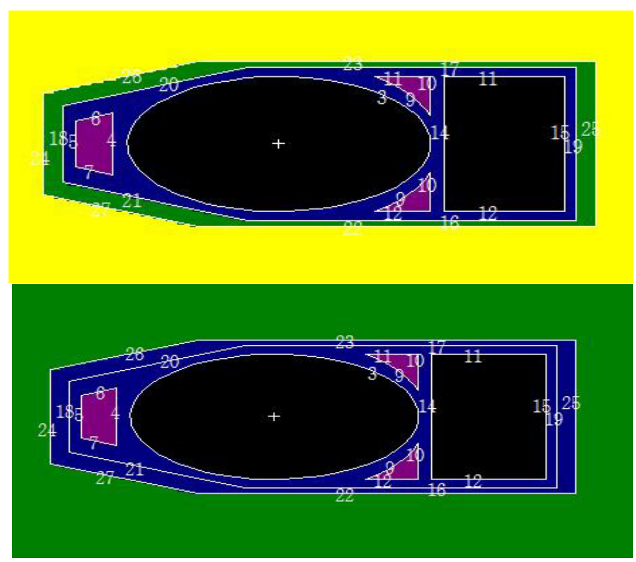

Figure 1: Cross section of the simulated beam pipe, Al&Pb (upper), Cu (lower).

The dose rate in the tunnel for CEPC is mainly dominated by synchrotron radiation. Copper seems to be a good material for beam pipe from the point of radiation protection, but manufacture/price and other points of view

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HF2014 REPORT OF WORKING GROUP 5: SUPERCONDUCTING RF*

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Abstract

This report summarizes presentations and discussions that took place during two sessions of the Working Group 5 (WG5) of the HF2014 workshop. In WG5 we reviewed Superconducting RF (SRF) systems of FCC-ee and CEPC and considered SRF structures, peripheral components and other issues relevant to the future circular colliders. In particular, we discussed the validity of cavity parameters and cavity design (frequency, voltage, input RF power, coupling, and HOM damping scheme), high power couplers, HOM dampers, frequency tuners, operating experience and other issues. As the result of WG5, we have come up with a list of important issues that have to be addressed in future studies.

INTRODUCTION

The two proposed future high luminosity energy frontier e^+e^- circular colliders, Circular Electron-Positron Collider (CEPC) in China and Future Circular Collider (FCC-ee) at CERN, would operate as Higgs Factories as well as at other energies of interest (Z, W, top quark) for precision measurements and search for rare processes. Circumference of these machines will be in the range of 50 to 100 km. Radio-frequency systems of these colliders will utilize superconducting RF structures and will have to compensate energy loss of several GeV due to synchrotron radiation with an RF power limit set to ~100 MW. As a result, these systems will have a large number of SRF cavities equipped with high-power RF input couplers and with strong damping of higher order modes (HOMs). Working Group 5 of the 55th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders – Higgs Factory (HF2014) was dedicated to discuss topics relevant to the SRF systems. In this report we summarize the discussions and outline important R&D issues.

SRF SYSTEM PARAMETERS AND REQUIREMENTS

Both CEPC and FCC-ee would use large superconducting RF systems as the energy loss to synchrotron radiation is very high and the systems would have to compensate power loss of ~50 MW per beam. As a result, requirements to the RF input power couplers are quite demanding. The systems need SRF cavities with strong HOM damping to avoid multi-bunch instabilities and reduce parasitic beam power loss to HOMs. These and some other considerations lead to selecting relatively low operating RF frequencies. Table 1 lists key parameters of the two colliders relevant to the SRF

Table 1: Key Parameters of the CEPC and FCC-ee SRF Systems

Parameter	CEPC	FCC-ee
Beam energy	120 GeV	120 GeV (175 GeV)
Energy loss per turn	3.11 GeV	1.67 GeV (7.5 GeV)
Synchrotron radiation power	103.4 MW	100 MW
Bunch charge	60.56 nC	59.2 nC (13 nC)
Bunch length	2.65 mm	N/A
Beam current (two beams)	33.2 mA	60 mA (13.2 mA)
RF voltage	6.87 GeV	2.7 GeV (11.2 GeV)
RF frequency	650 MHz	400 MHz
Number of cavities	384	568
Number of cells per cavity	5	5
E_{acc}	15.5 MV/m	2.53 MV/m (10.5 MV/m)
Q_0	$2\cdot10^{10}$ at 2 K	$2\cdot10^{10}$ at 2 K
Number of cryomodules	96	71
RF power per cavity	260 kW	176 kW
HOM power per cavity	3.5 kW	N/A

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SUMMARY OF WORKING GROUP 6 – INJECTORS AND INJECTION HF2014

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Abstract

We present a summary of presentations made in Working Group 6, *Injectors and Injection*, at the 55th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders – HF2014 in Beijing, China. The workshop was held October 9-12, 2014.

PAPERS PRESENTED

Contributions covered planned injectors and injection for CEPC (Chuang Zhang) and FCC-ee (Yannis Papaphilippou), polarization preservation in synchrotrons (Ivan Koop), top-up injection (John Seeman and Richard Talman), and injection with pretzels (Dave Rice).

We cover the highlights from each presentation then offer our summary of injection highlights and challenges at the end of this paper.

CEPC PLANS (IHEP)

Both CEPC and FCC-ee are planning on a full energy injector that is necessarily similar in size to the full ring, and thus sharing the same tunnel. Chuang Zhang presented a conceptual design for the CEPC full injector. Because the CEPC design anticipates building a newly constructed injector complex, the booster injection energy is 6 GeV from a linear accelerator, limited by cost considerations, though 10 GeV was mentioned as a possibility. The low energy of the injector is a primary issue for development.

An injection interval of 10 seconds, with intensity of 5% of the stored beam, simultaneously filling all 50 bunches in the collider ring will conservatively meet the needs of the predicted 25 minute collider beam lifetime, giving a factor of 3.75 combined margin for injection efficiency and beam lifetime.

A 6 GeV linac provides both electrons and positrons to the booster ring. A target at the 4 GeV point produces positrons that are accelerated to 200 MeV for return to the front end of the linac. Plans are to construct the linac on the surface with a sloped transfer line to the level of the booster.

The booster is filled with 50 bunches at 6 GeV by 50 linac pulses (operating at 100 Hz) then ramped to 120 GeV in 4 seconds. The plan presented did not include a positron damping ring, rather a booster dwell period at 120 GeV is expected to provide sufficient damping.

The beam is transferred from the booster to the storage ring 2 m below with horizontal bends and vertical Lambertson magnets. The beam is injected in the horizontal plane via a segmented septum magnet. Injection in the vertical plane is considered to ease concerns about the pretzel configuration, but this is complicated by the large β_V^* needed for local chromaticity correction in the IR.

The booster employs a 1300 MHz RF system with details still in design process.

Primary concerns are stability of the net magnetic field (30 Gauss) at injection into the booster and beam stability (125 seconds damping time), and injection into the pretzel orbits. A "wiggling-bend" layout (Figure 1) with half of the bends being bipolar to decrease damping time at 6 GeV is being considered as is higher injection energy (longer linac) and a pre-booster ring.

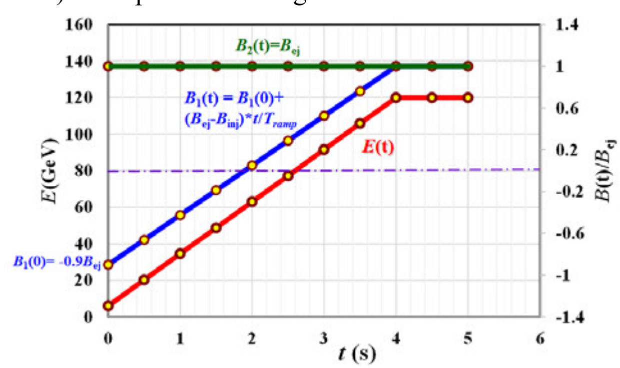

Figure 1: CEPC wiggling bend ramp program.

FCC-ee PLANS (CERN)

Yannis Papaphilippou described the FCC-ee injector, which is being designed to provide e+/e- for Z, W, Higgs, and $t\bar{t}$ (45.5 – 175 GeV) compatible with the expected 20 minute lifetime at $t\bar{t}$ energy. (Table 1) The availability of the SPS as a 20 GeV pre-booster would allow higher energy injection into the booster compared to the 6-10 GeV CEPC plans.

Following the proposed CLIC design, a new linac operated at 50Hz would accelerate 1360 bunches (in the case of the Higgs production) in a 2GHz structure. Eight linac batches are injected into a 50MHz RF system in the SPS at 10GeV to be accelerated and injected into the booster ring at 20 GeV. Five SPS accelerating cycles of 1.2 s are used providing the total 1360 bunches in the Booster flat bottom. With the addition of wigglers, the SPS can also serve as a damping ring.

Both the linac injector and booster ring are designed to provide low emittance beams (~1 nm at 120 GeV) for improved injection efficiency (~ 80%). New RF systems are needed throughout the injector chain – linac (2000 MHz, SPS (50 MHz) and booster (50 MHz).

Alternative injection schemes were presented, including synchrotron injection (both Δp and Δt) and pulsed sextupole injection.

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SUMMARY FROM WORKING GROUP 9: INSTRUMENTATION AND CONTROL*

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Abstract

Since the discovery of the Higgs particle at the Large Hadron Collider at CERN in 2012, feasibility studies for a very large future circular collider are ongoing for two designs in particular: the FCC in Europe and the CEPC-SppC in China. Both designs aim for initial operation as a Higgs factory. This workshop on High Luminosity Circular e+e- Colliders (HF2014), held in Beijing, China and hosted by the Institute of High Energy Physics (IHEP) and the Chinese Academy of Sciences (CAS), included a Working Group on Instrumentation and Control to consider important issues associated with these systems. While instrumentation and control designs are just starting, HF2014 provided the opportunity to discuss these systems and their challenges.

INTRODUCTION

Instrumentation and Control are vital subsystems for a future e+e- collider operating for high luminosity Higgs boson production and beyond. The applied technologies must guarantee the challenging design parameters and collider luminosity. As the accelerator parameters are stabilizing, the diagnostic designs have recently started. These developments are expected to direct control system design, the technology for which is rapidly evolving and expected to continue so.

As instrumentation designs were anticipated by the working group conveners (M. Minty and H. Schmickler), prior to the workshop, as being quite similar to those demonstrated at existing accelerators with new challenges pertaining to the large-scale aspects of a future Higgs factory, presentations were solicited with the aim of understanding essential features, challenges and solutions based on experiences at existing accelerators most similar to those of a future e+e- collider.

PRESENTATIONS

The working group activities consisted of invited talks and a discussion session starting with an additional talk on instrumentation in the CEPC design (instrumentation design for the FCC project has yet to start).

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Y. Funakoshi (KEK) presented "Lessons learned from the B-Factories and implications for a high-luminosity circular e+e- Higgs factory" [1]. M. Wendt (CERN) presented "Challenges in beam instrumentation and diagnostics for large ring colliders – based on the LHC experience" [2]. The B-Factories have in common with the accelerator designs under consideration similar particle species while the LHC shares similarities in the context of the overall scale (many 10's of kilometre circumference). Concerning instrumentation and control (as well as many other aspects) both accelerators share certain similar challenges with technological developments of great importance for future large ring colliders ongoing.

M. Wendt's presentation contained an overview of instrumentation design challenges common to all future large ring colliders including:

(1) Large physical size of accelerator and correspondingly large number of instrumentation devices, impact on reliability and costs
(2) Issues associated with low temperatures in superconducting environments
(3) Higher-order modes and wakefields generated by the instrumentation
(4) For high power beams, the need for non-invasive beam detection methods
(5) Need for early observation and damping of beam instabilities
(6) Large dynamic range of instrumentation and compatibility with different particle species, need to anticipate changes as learned from operational experiences
(7) Damage potential from beams with high stored energy and impact on machine protection system (MPS) including all related components

Other challenges and motivations for requirements addressed by the presentations are given below.

Beam position monitors (BPMs) – The stringent tolerances on beam orbit stability, with rule-of-thumb scaling as ~ $1/10^{th}$ the beam size σ, imply the need for commensurately high accuracy beam position data. Real life experiences were presented showing susceptibility to ambient temperature variations which introduced significant systematic errors in the beam position

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