OVERVIEW OF HIGH ENERGY e^+e^- FACTORIES

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Abstract

Designs of e^+e^- colliders from the Z-pole and above are introduced. Two projects, CEPC and FCC-ee, are discussed. If we compare their schemes, a partial double ring (CEPC) and a full double ring (FCC-ee), find several important differences that affect the performance. On the other hand, there are a number of similarities in both designs, such as the crab-waist scheme, crossing angle, optimization of the dynamic aperture, etc.

INTRODUCTION

At least there are two plans have been studied for high energy e^+e^- circular collider factories. One is CEPC in China, which consists of a circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel. Another is FCC-ee, which is an e^+e^- collider as potential intermediate step or a possible first step for a 100 TeV pp-collider (FCC-hh). The design of CEPC has been considering several schemes: single-ring with pretzel, partial double-ring (PDR), and full double-ring. Although CEPC has not decided the scheme yet, the main efforts have been focused on the PDR scheme in this year. Thus we pick PDR for CEPC in this article. On the other hand, FCC-ee has chosen a full double ring scheme.

DESIGN PARAMETERS

Table 1 compares important design parameters of two machines at several beam energies. The parameters are as of this workshop.

PROGRESS

As for FCC-ee, a baseline beam optics [1] has been chosen, characterized by:

- A highest-energy circular e^+e^- collider ultra-low β^* of 1 mm and more than ±2% dynamic momentum acceptance.
- Features a local chromatic correction for the vertical plane. The dynamic aperture was optimized by varying the strengths of about 300 independent $-I$ sextupole pairs in the arcs.
- A crab-waist scheme was implemented by reducing the strength of an existing sextupole in the chromatic correction section with proper betatron phases, instead of adding another dedicated sextupoles.
- Synchrotron radiation is accommodated by tapering the magnet strengths in the arcs, and by a novel asymmetric IR/final-focus layout.
- The RF system is concentrated in two straight sections. A common system provides maximum voltage for $t\bar{t}$ running, where operation requires only few bunches. Two separate RF systems, one for either beam, are used at lower beam energies.
- The optics was designed to match the footprint of a future hadron collider (FCC-hh) along the arcs. Due to the asymmetric interaction region (IR) layout the e^+e^- interaction point (IP) is displaced transversely by about

Table 1: Design Parameters of FCC-ee and CEPC(PDR) together with LEP2. SR: synchrotron radiation, BS: beamstrahlung. FCC-ee has two options at Z.

	FCC-ee				CEPC(PDR)		LEP2
Beam energy [GeV]	45.6		120	175	45.6	120	105
Beam current [mA]	1450		30	6.6	67.6	16.9	3
Bunches/beam	91500	30180	770	78	1100	107	4
Energy loss/turn [GeV]	0.03		1.67	7.55	0.061	2.96	3.34
SR power for two beams [MW]	100				8.2	100	22
RF voltage [GV]	0.2	0.4	3	10	0.11	3.48	3.5
Bunch length (SR) [mm]	1.6	1.2	2.0	2.1	3.78	2.7	12
Bunch length (+BS) [mm]	3.8	6.7	2.4	2.5	4.0	2.95	12
Emittance $\varepsilon_{x,y}$ [nm, pm]	0.1, 1	0.2, 1	0.6, 1	1.3, 2.5	0.88, 8	2.05, 6.2	22, 250
$\beta^*_{x,y}$ [m, mm]	1, 2	0.5, 1	1, 2	1, 2	0.1, 1	0.27, 1.3	1.5, 50
Long. damping turns	1320		72	23	748	41	31
Crossing angle [mrad]	30				30		0
Beam lifetime [min]	185	94	67	57	79	20	434
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	70	207	5.1	1.3	4.5	3.1	0.0012

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COMMISSIONING OF SuperKEKB

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Abstract

After five and half years upgrade works from KEKB to SuperKEKB, the Phase 1 commissioning of SuperKEKB was conducted from February to June in 2016. This paper describes the progress of the Phase 1 commissioning. Brief plans of the Phase 2 commissioning are also described.

INTRODUCTION

The purpose of SuperKEKB is to search a new physics beyond the standard model of the particle physics in the B meson regime. SuperKEKB consists of the injector linac, a damping ring for the positron beam and two main rings; *i.e.* the low energy ring (LER) for positrons and the high energy ring (HER) for electrons, and the physics detector named Belle II. The beam energies of LER and HER are 4GeV and 7GeV, respectively. The design beam currents of LER and HER are 3.6A and 2.6A, respectively. The design luminosity is $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Design machine parameters are shown in Table 1. More details of SuperKEKB are described elsewhere [1].

The main issues for SuperKEKB are listed below.

- IR design and dynamic aperture
- Optics corrections and low emittance tuning
- Magnet alignment strategy
- Beam-beam related issues
- Orbit control to maintain beam collision
- Beam loss and beam injection
- Effects of electron clouds
- Injector upgrade for low emittance and high intensity beams
- Detector beam background

Some of those are studied in the Phase 1 commissioning this year.

BEAM COMMISSIONING

Commissioning Strategy

The beam commissioning will proceed in three steps; *i.e* Phase 1, 2 and 3. The Phase 1 commissioning has been already done for 5 months this year. In Phase 1, the superconducting final focus doublets and other correction coils (called QCS) and the physics detector (called Belle II) were not installed and no beam collision was performed. The idea of Phase 1 is that we conduct sufficient vacuum scrubbing and other beam tuning such as beam injection before installing the Belle II detector. The commissioning of the damping ring, which is newly introduced for SuperKEKB, will start in November 2017. The Phase 2 commissioning of main rings will start in January 2018 and continue for about 5 months. In Phase 2, the QCS magnets and the main part of the Belle II detector will be installed. But the vertex detector will not be installed in Phase 2. This is based on an idea that the vertex detector, which is very sensitive to the beam background, should be installed after sufficient beam tuning with the QCS magnets. From the viewpoint of the accelerator tuning, we can make tuning on condition that hardware components are fully installed except for the beam background tuning to the vertex detector. The target luminosity in Phase 2 is $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The Phase 3 commissioning will start in autumn 2018. In this phase, the vertex chamber will be installed and we will continue beam tuning aiming at the design luminosity in parallel with the physics experiment.

Table 1: Design machine Parameters of SuperKEKB (Values in parentheses of the emittances correspond to those at zero bunch currents).

	LER	HER	Units
Beam Energy	4.000	7.007	GeV
Beam Current	3.6	2.6	A
# of Bunches	2500		
Circumference	3016.315		m
Hor. Emittance	3.2(1.9)	4.6(4.4)	nm
Ver. Emittance	8.6(2.8)	11.5(1.5)	pm
β-function at IP(H/V)	32/0.27	25/0.30	mm
Moment. compaction	3.25	4.55	$\times 10^{-4}$
Energy spread	8.08	6.37	$\times 10^{-4}$
RF voltage	9.4	15.0	MV
Hor. tune ν_x	44.53	45.53	
Ver. tune ν_y	46.57	43.57	
Synchrotron tune ν_s	-0.0247	-0.0280	
Energy loss / turn	1.87	2.43	MeV
Damping time $\tau_{x,y}/\tau_s$	43/22	58/29	ms
Bunch length	6.0	5.0	mm
Beam-beam param. H	0.0028	0.0012	
Beam-beam param. V	0.0881	0.0807	
Luminosity	8×10^{35}		/cm^2/s

Results of Phase 1 Commissioning

Missions in Phase 1 After five and half years of upgrade work from KEKB, the Phase 1 beam commissioning of SuperKEKB started on Feb. 1st this year and finished at the end of June this year. Missions of the commissioning in

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OVERVIEW OF THE LOW ENERGY COLLIDERS*

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Abstract

The low energy colliders cover the beam energy from 500 MeV to 2.5 GeV or more, with relatively small sizes from several ten meters to several hundred meters in circumference. The physics requirements on phi particle, charm quark, tau lepton, Ds, XYZ particles, and R value measurement. Since the beam energies are close to the low energy synchrotron radiation light sources, these machines could be used as parasitic light sources. In this paper, we will investigate some selected beam dynamics issues of the low energy colliders like DAFNE [1], VEPP -2000 [2], BEPCII [3], and CESRc [4], the ways on how to enhance the luminosity at these colliders, the operation and some upgrades during operation, and the future possible super charm tau factory.

INTRODUCTION

Colliders for high energy physics study, have been developed from the pioneer AdA, built in Frascati in 1962, to the LHC, which started its operation at CERN from 2008, within the past five decades. During this half a century, General speaking, the higher beam energy, the larger collider size. Most of the low energy collider could be run at an energy range, and some could be used as a parasitic synchrotron facility. For example, BEPCII keeps running for 10 years as a parasitic light source with the E_b =2.5GeV and I=250mA, and can provide photons to users with 14 beam lines. Figure 1 gives the luminosity evolution of different lepton colliders during the past 40 years.

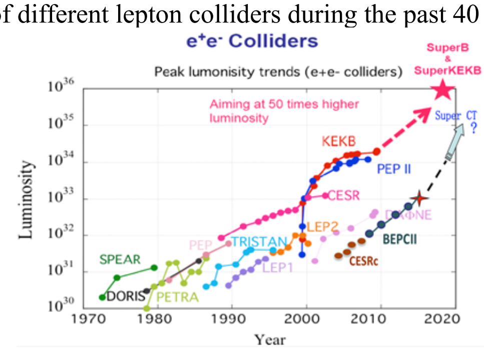

Figure 1: Lepton colliders' luminosity evolution within the past 40 years.

In this paper, low energy colliders, such as DAFNE, VEPP-2000, BEPCII and CESRc will be reviewed from their beam dynamics studies, luminosity tuning and enhancements, operation with some upgrades on the machines, to the future development to super charm-tau factory. Beam dynamics study covers such a large field that we cannot overview all of these machines and topics in this paper, so we just select several important issues. Since they are all operational machines, the topics like dynamic aperture, error effects, and interaction region design, which are all design topics, will not be included.

DAFNE is a phi-factory collider with double-ring, running at the E_{cm} = 1 GeV for phi particle with the design luminosity of 5x10^{32}cm^{-2}s^{-1}, locates at the LNF/INFN, Italy. The two rings of the collider are placed in parallel, with one collision point where the detector KLOE/ SINDDHARTA stays. Table 1 lists the main parameters of the DAFNE ring, and Fig. 2 shows the layout and a bird-view of the collider. From 2001 to 2009, the luminosity of DAFNE was enhanced gradually, and even doubled after the crab-waist scheme was applied to the machine with the modification of the IR in 2007 to 2008. The highest luminosity was reached as high as 4.5×10^{32}cm^{-2}s^{-1}.

Table 1: Main Parameters of the DAFNE Ring

Energy per beam	510 MeV
Machine length	97 m
Maximum beam current (KLOE run)	2.5(e-) /1.4(e+) A
No. of colliding bunches	100-111
RF frequency	368.67 MHz
RF voltage	100-250 kV
Harmonic number	120
Bunch spacing	2.7 ns
Max ach. Luminosity (SIDDHARTA run)	4.5×10^{32} cm^{-2} s^{-1}

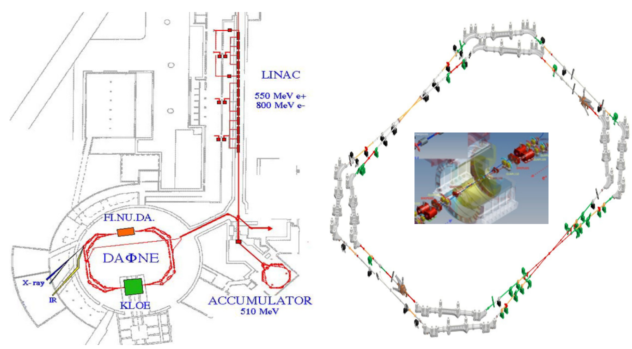

Figure 2: Schematic layout of the DAFNE machine (left) and rings with the detector (right).

The VEPP-2000 is the upgrade machine of the VEPP-2M in BINP, and started its operation from 2010, with the beam energy range from 200 MeV to 1 GeV. Figure 3 is the layout of the VEPP-2000, and its main parameters are given in the Table 2.

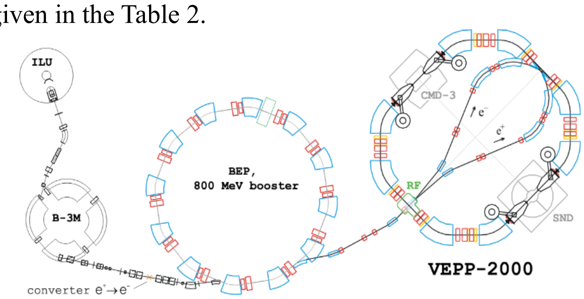

Figure 3: Layout of the VEPP-2000, and its boosters.

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PERFORMANCE AND PERSPECTIVE OF MODERN SYNCHROTRON LIGHT SOURCES

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Abstract

The first synchrotron radiation was used in a so called parasitic mode from high energy machines (1st generation). At the end of the 1970s and the beginning of 1980s accelerators dedicated to the production of synchrotron radiation were built (2nd generations). With the investigation and developments of insertion devices in the middle of 1980, the 3rd generation synchrotron radiation sources were built and emittances down to some nmrad could be reached. At present around 50 Synchrotron Radiation sources are existing around the world. All of these sources reached there the specification (energy, current, emittance, beam stability, etc.) very soon after the commissioning. With the 4th generation, emittances of down to around 100 pmrad should be reached. This is still a factor of 10 away from the requirement of a diffraction limited light source. According to the expertise in designing and operating of synchrotron radiation sources this should be reachable in the future, but only with circumferences of some kilometers like Petra III or PEP-X. Overall the performances and perspective of synchrotron light source are remarkable.

INTRODUCTION

The layout of the European Synchrotron Radiation Facility (ESRF) [1] (see Fig.1) is an example of a modern Synchrotron Light Source. It starts with an electron Linac with an energy of 200 MeV, which will be injected via a transfer line into the booster synchrotron and accelerated up to 6 GeV. From the booster synchrotron the beam goes over another transfer line into the storage ring. With a repetition frequency of 10 Hz the beam will be accumulated in the storage ring until reaching its final value of 200 mA (for the ESRF).

The ESRF exist of 32 achromat's with the magnet sections and the straights for the installation of the ID's.The characteristics of the Linac, Booster and Storage-ring are changing for the different light sources. At the Swiss Light Source, ALBA and TPS [2-4] the booster is located in the storage ring tunnel in order to reduce the emittance. For these facilities the emittance of the beam is smaller as 10 nmrad. Details of all Light Sources can be found under "www.lightsources.org" within the rubric "Light sources of the world". Overall there are 47 Light Sources in the world.

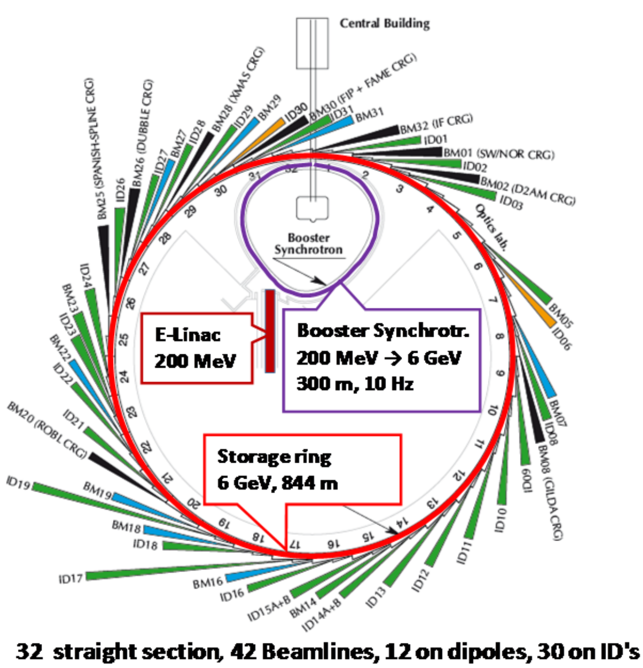

Figure1: General layout of a synchrotron light source with the Linac, Booster Synchrotron, Storage-Ring and the beam lines around the storage ring.

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HIGGS FACTORY CONCEPTS*

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Abstract

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

PAST AND FUTURE

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

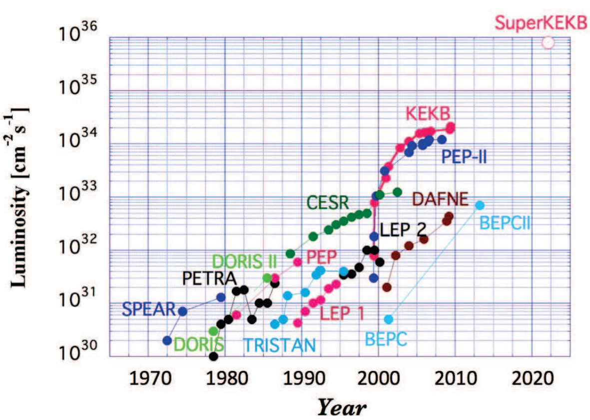

Figure 1: Luminosity trends of circular e^+e^- colliders (Courtesy Y. Funakoshi).

HIGGS FACTORY PHYSICS

In order to support extremely high precision tests of the standard model along with unique searches for rare decays, the proposed "Higgs factories" should operate over a wide range of high beam energies, from about 35 GeV to above ~175 GeV, For comparison, the maximum beam energy reached at LEP2 was 104.5 GeV. The FCC-ee physics programme [5] may include: (1) $\alpha_{\rm QED}$ studies (with energies as low as 35 GeV) to measure the running coupling constant close to the Z pole; (2) operation on the Z pole (45.5 GeV/beam), where FCC-ee would serve as a "Tera-Z" factory for high precision M_Z and Γ_Z measurements and allow searches for extremely rare decays (also enabling the hunt for sterile right-handed neutrinos); (3) running at the H pole (63 GeV/beam) for H production in the s channel, with mono-chromatization, e.g. to map the width of the Higgs and measure the electron Yukawa coupling; (4) operation at the W pair production threshold (~80 GeV/beam) for high precision M_W measurements; (5) operation in the ZH production mode (maximum rate of H's) at 120 GeV; (6) operation at and above the $t\bar{t}$ threshold (~175 GeV/beam); and (7) operation at energies above 175 GeV per beam, should a physics case for the latter be made. Scaling from LEP, at FCC-ee some beam polarization is expected for beam energies up to about 80 GeV [6], permitting an extremely precise energy calibration for the Z and W modes of operation.

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

LESSONS LEARNT

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

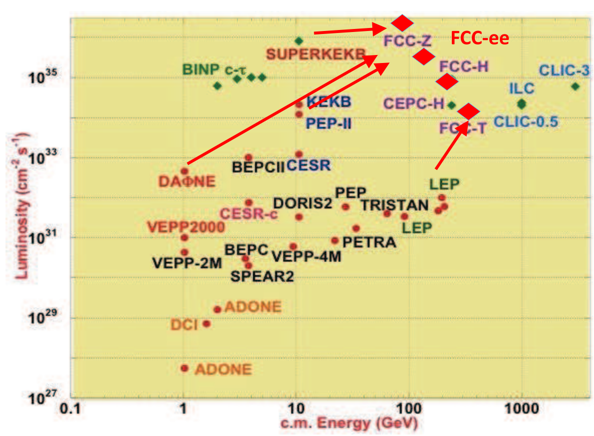

Figure 2: Luminosity as a function of c.m. energy for past, present and future e^+e^- colliders. The proposed FCC-ee and CEPC exploit lessons and recipes from precedent colliders.

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

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IMPLEMENTATION OF ROUND COLLIDING BEAMS CONCEPT AT VEPP-2000

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Abstract

VEPP-2000 e^+e^- collider at Budker Institute of Nuclear Physics was commissioned in 2009 and collected data during three runs in whole designed energy range of 160-1000 MeV per beam. The Round Colliding Beams concept was implemented at VEPP-2000 to get a significant enhancement in beam-beam limit. The beam-beam parameter value as high as $\xi = 0.12$ per IP was achieved at intermediate energy. To obtain more intensive beams and achieve target luminosity at top energies the injection chain upgrade was done during 2013-2016. Presently VEPP-2000 is recommissioned and ready to start data taking.

ROUND COLLIDING BEAMS

The VEPP-2000 collider [1] exploits the round beam concept (RBC) [2]. The idea of round-beam collisions was proposed more than 25 years ago for the Novosibirsk Phi-factory design [3]. This approach, in addition to the geometrical factor gain, should yield the beam-beam limit enhancement. An axial symmetry of the counter-beam force together with the *X*–*Y* symmetry of the transfer matrix between the two IPs provide an additional integral of motion, namely, the longitudinal component of angular momentum $M_z = x'y - xy'$. Although the particles' dynamics remain strongly nonlinear due to beam–beam interaction, it becomes effectively one-dimensional. The reduction of degrees of freedom thins out the resonance grid and suppress the diffusion rate resulting finally in a beam-beam limit enhancement [4].

Thus, there are several demands upon the storage ring lattice suitable for the RBC:

1. Head-on collisions (zero crossing angle).
2. Small and equal β functions at IP ($\beta^*_x = \beta^*_y$).
3. Equal beam emittances ($\varepsilon_x = \varepsilon_y$).
4. Equal fractional parts of betatron tunes ($\nu_x = \nu_x$).

The first three requirements provide the axial symmetry of collisions while requirements (2) and (4) are needed for *X*–*Y* symmetry preservation between the IPs.

A series of beam–beam simulations in the weak–strong [5, 6] and strong–strong [7] regimes were done. Simulations showed the achievable values of beam–beam parameters as large as $\xi \sim 0.15$ without any significant blow-up of the beam emittances.

First experimental tests of RBC were carried out at CESR collider with use of linear coupling resonance and specially adopted lattice to fulfil mentioned requirements. The tests showed promising results of beam-beam parameter increase up to 0.09 but could not provide high luminosity due to large β^* value in this test regime [8].

VEPP-2000 OVERVIEW

The layout of the VEPP-2000 complex as it worked before shutdown for upgrade in 2013 is presented in Fig. 1.

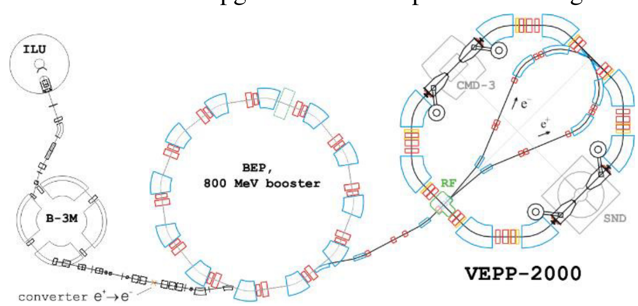

Figure 1: VEPP-2000 complex layout.

VEPP-2000 collider used the injection chain of it's predecessor VEPP-2M [9]. It consisted of the old beam production system and Booster of Electrons and Positrons (BEP) with an energy limit of 800 MeV. Collider itself hosts two particle detectors [10], Spherical Neutral Detector (SND) and Cryogenic Magnetic Detector (CMD-3), placed into dispersion-free low-beta straights. The final focusing (FF) is realized using superconducting 13 T solenoids. The main design collider parameters are listed in Table 1. In Fig. 2 one can find a photo of the collider ring.

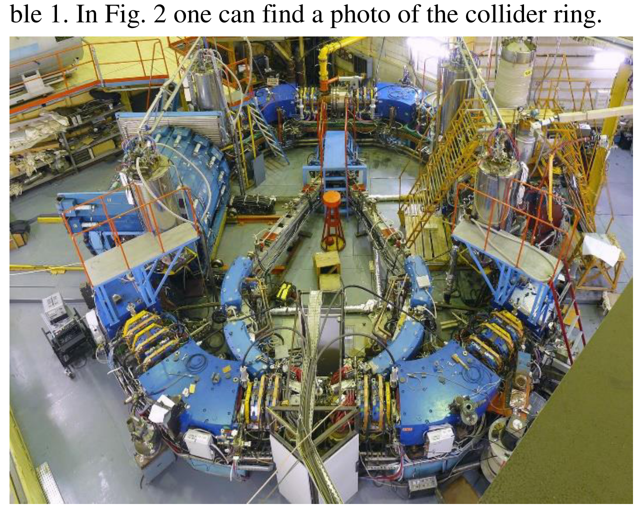

Figure 2: VEPP-2000 collider photo.

The density of magnet system and detectors components is so high that it is impossible to arrange a beam separation in the arcs. As a result, only a one-by-one bunch collision mode is allowed at VEPP-2000.

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ISSUES IN CEPC PRETZEL AND PARTIAL DOUBLE RING SCHEME 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 50-70 km. The single ring scheme and the partial double ring scheme are now both under study. In the single ring scheme, the electron and positron beam will share the beam pipes, thus a special orbit is needed to avoid the beam colliding at positions except the Interaction Points (IPs). While in the partial double ring scheme, the two beams will be separated into two beam pipes in the parasitic collision positions. This paper will show the latest design of the CEPC lattice, including both the pretzel and partial double ring scheme. Some critical issues that we encountered when designing the lattices will be discussed.

INTRODUCTION

CEPC (a Circular Electron Positron Collider) has been proposed by IHEP to study the Higgs boson [1].At the end of the 2014, the Preliminary Conceptual Design Report of CEPC was published, with single ring (pretzel) scheme as the baseline design [2]. As the design work move on, especially the demand to increase the luminosity at Z-pole, we started to study a new scheme, e.g. the so called ąřPartial double ring schemeąś. Then, the RF system raised that the RF efficiency could be too low to assure a constant voltage at the cavity for all bunches, so another scheme called ąřAdvanced double ring schemeąś was proposed to mitigate the low RF efficiency effect.

Another scheme, which is relatively less complicated but more costly, the double ring scheme, is also under study. The pretzel and partial double ring scheme will be introduced in this talk.

PRETZEL SCHEME DESIGN

As described in the Pre-CDR [2], the ring is using 60/60 degrees phase advance FODO cells, with interleaved sextupoles. The pretzel orbit is designed for 50 bunches per beam, every 4π phase advance has one parasitic collision point. A schematic drawing of the pretzel orbit is shown in Fig.1.

In our design, the horizontal separation scheme is adopted to avoid big coupling between the horizontal and the vertical. The orbit is generated such that there is no off-center orbit in RF sections to avoid beam instability and High Order Modes(HOMs) in the cavities. There will be one pair of electrostatic separators for each arc, and for each arc, the first separator will be placed before the first parasitic collision point in this region to generate the orbit, and the second separator will be placed after the last collision point in this region to remove the orbit.

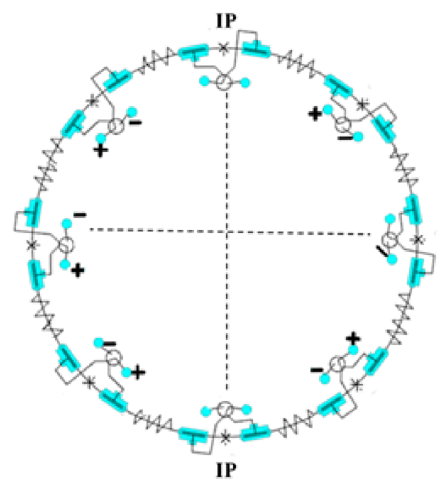

Figure 1: A schematic drawing of the pretzel orbit scheme, the beams are separated by electrostatic separators.

A schematic drawing of the pretzel orbit and the place of electrostatic separators for one arc is shown in Fig.2.

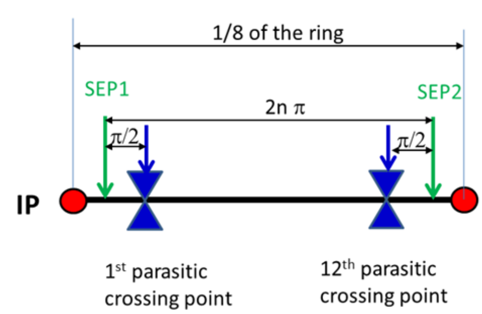

Figure 2: A schematic drawing of the positions of the electrostatic separators for 1/8th of the ring. SEP1 and SEP2 in the drawing means the first and second electrostatic separators.

ISSUES WITH PRETZEL ORBIT

Beams with off-centered orbit, will experience extra fields in magnets. To be specific, in quadrupole magnets, the beam will see an extra dipole filed when it is off-centered.

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SIMULATIONS OF POLARIZATION LEVELS AND SPIN TUNE BIASES IN HIGH ENERGY LEPTONS STORAGE RINGS*

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Abstract

The use of resonant depolarization has been suggested for precise beam energy measurements in the 100 km long Future Circular Collider e+e-. The principle behind resonant depolarization is that a vertically polarized beam excited through an oscillating horizontal magnetic field gets depolarized when the excitation frequency is in a given relationship with the beam energy. In this paper the possibility of self-polarized leptons at 45 GeV (Z resonance) and 80 GeV (WW physics) in presence of quadrupole vertical mis-alignment is investigated.

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 storage rings 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 obeys to the Thomas-Bargmann-Michel-Telegdi (Thomas-BMT) equation [2] [3]

$$\frac{d\vec{S}}{dt} = \vec{\Omega}\times\vec{S} \qquad (1)$$

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

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

with $\vec{\beta}\equiv\vec{v}/c$ and $a=(g-2)/2$=0.0011597 (for $e^{\pm}$).

In a planar machine the *periodic* solution, $\hat{n}_0$, to Eq.(1) is vertical and, neglecting the electric field, the number of spin precessions around $\hat{n}_0$ 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*). Using a semiclassical approach, Derbenev and Kondratenko [4] found that the polarization is oriented along $\hat{n}_0$ and its asymptotic value is

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

with $\hat{b}\equiv\hat{v}\times\dot{\hat{v}}/|\dot{\hat{v}}|$ and $\delta\equiv\delta E/E$. $\hat{n}$ the *invariant spin field* [5], i.e. a solution of Eq.(1) satisfying the condition $\hat{n}(\vec{u};s)$=$\hat{n}(\vec{u};s+C)$, C being the machine length. The <> brackets indicate averages over the phase space. The term $\partial\hat{n}/\partial\delta$ quantifies the depolarizing effects resulting from the trajectory perturbations due to photon emission.

The corresponding polarization rate is

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

In a perfectly planar machine $\partial\hat{n}/\partial\delta$=0 and $P_{\rm DK}$=$P_{\rm ST}$. In presence of quadrupole vertical misalignments (and/or spin rotators) $\partial\hat{n}/\partial\delta\neq0$ and it is particularly large when spin and orbital motions are in resonance

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

For FCC-e^+e^- with $\rho\simeq 10424$ m, fixed by the maximum attainable dipole field for the hadron collider, the polarization time at 45 and 80 GeV are 256 and 14 hours respectively.

Here it is assumed that beam polarization of about 10% is sufficient for an accurate depolarization measurement. The time, $\tau_{10\%}$, needed for the beam to reach this polarization level is given by

$$\tau_{10\%} = -\tau_p\times\ln(1-0.1/P_\infty)$$

At 80 GeV it is $\tau_{10\%}$=1.6 hours, but $\tau_{10\%}$= 29 hours at 45 GeV.

At low energy the polarization time may be reduced by introducing properly designed wiggler magnets i.e. a sequence of vertical dipole fields, $\vec{B}_w$, with alternating signs.

FCC-e^+e^- maximum synchrotron radiation power is set to 50 MW per beam and the beam current at the various energies as been scaled accordingly. This limits the integrated wiggler strength. Moreover the wiggler increases the beam energy spread for which the effect on polarization must be investigated.

At 80 GeV wigglers are not needed. However the energy dependence of the spin motion makes the attainable polarization level more sensitive to machine errors.

Preliminary studies for a FCC-e^+e^- by using a"toy" ring [6] have shown that even in presence of quadrupole vertical

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IDEAS FOR SIBERIAN SNAKES AND SPIN ROTATORS IN VERY HIGH ENERGY e^+e^- RINGS

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Abstract

The high value of the radiated power in synchrotron radiation in very high energy e^+e^- storage rings presents unique challenges for the design of Siberian Snakes and spin rotators in such machines. This paper presents some ideas which may lead to a feasible design of such devices. The idea is to employ solenoids interleaved with the arc dipoles, to yield a set of noncommuting spin rotations, which can rotate an initially vertical spin to any desired direction. The solenoids should be (approximately) optically transparent, and can be 'spin matched' to the ring using known procedures. Preliminary numerical studies indicate the design may be feasible.

SPIN ROTATOR AND SNAKE SCHEMATIC

For a general review of spin dynamics in accelerators and for a review of Siberian Snakes and spin rotators in accelerators, we direct the reader to [1] and [2], respectively. The concern here is e^+e^- rings of very high energy, where the very high synchrotron radiation (SR) radiated power places serious constraints on the design of Siberian Snakes and spin rotators. The subject has of course been studied by others already, see, e. g. [3]. The present work also draws on an analysis by the author for FCC-ee [4]. The prototype ring below is FCC-ee, although the essential ideas apply to any very-high energy e^+e^- collider. The subject of beam polarization in such rings falls naturally into two sections: (i) transverse polarization, for energy calibration, and (ii) longitudinal polarization at the interaction point (IP), for tests of the electroweak theory and other tests/searches for new physics. We discuss these in turn.

For energy calibration via the resonant depolarization (RD) of transversely polarizaed beams, it is envisaged that a set of 'pilot' non-colliding e^+ and e^- bunches will be circulated in each ring. (The colliding bunches for HEP will be unpolarized.) The polarized bunches will be produced at low energy in polarized electron and positron sources and then accelerated to high energy for injection into the main ring. Hence the polarized bunches must be accelerated across a large number of intrinsic and imperfection depolarizing spin resonances. To avoid depolarization via the Froissart-Stora formula [5], one or more Siberian Snakes are required in the booster ring. The basic scenario for FCC-ee is to employ full-energy injection, and this is likely to be case for other rings also. The booster ring will occupy the same tunnel as the main ring, i. e. it will have the same circumference and top energy. Hence the designs of Snakes or spin rotators will apply equally to the booster ring and the main ring.

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Longitudinally polarized colliding beams are usually envisaged at the Z^0 peak, to test the electroweak theory, However, they could be useful to explore physics at other energies. It is also possible that, at a later stage, a hadron ring may be installed for an $e-p$ collider option. In such a case, a longitudinally polarized lepton beam would be a natural choice. Longitudinally polarized colliding beams require the e^+ and e^- bunches to be polarized *in situ* in the main rings. This almost certainly requires the use of polarization wigglers, which will increase the SR radiated power. Some details of polarization wigglers for FCC-ee were analyzed in [4]. Since the polarization must be preserved during storage, Siberian Snakes will be required in the main ring. In addition, longitudinally polarized colliding beams require the use of spin rotators.

Hence we are led to consider designs for Siberian Snakes and spin rotators in the booster and/or main ring. We treat a particle of charge e, mass m, with velocity $\vec{v}$, Lorentz factor $\gamma = 1/\sqrt{1-v^2/c^2}$ and spin $\vec{s}$. The magnetic moment anomaly will be denoted by $a = \frac{1}{2}(g-2)$. The externally prescribed electric and magnetic fields of the accelerator are denoted by $\vec{E}$ and $\vec{B}$, respectively. The Thomas-BMT (Bargmann, Michel and Telegdi) equation [6, 7] is given by $d\vec{s}/dt = \vec{\Omega}\times\vec{s}$. Treating only motion in magnetic fields, the spin precession vector is

$$\vec{\Omega} = -\frac{e}{\gamma mc}\left[(\gamma a+1)\vec{B}_\perp + (a+1)\vec{B}_\parallel\right]. \qquad (1)$$

Here $\vec{B}_\parallel = (\vec{B}\cdot\vec{v})\vec{v}/v^2$ and $\vec{B}_\perp = \vec{B}-\vec{B}_\parallel$ are the components parallel and orthogonal to the particle velocity, respectively. Because of eq. (1), Snakes and rotators built using transverse bending fields have traditionally been considered as the superior choice for use at high energies.

However, the above conclusion is derived by considering only the spin rotation angle in a magnet and neglects the synchrotron radiation generated. The above view is therefore applicable to hadron rings, where synchrotron radiation is negligible, but must be reexamined for very high energy e^+e^- colliders. It was argued in [4] that Snakes and rotators built from transverse field dipoles produce an unacceptable SR load, or else entail unacceptably large beam orbit excursions. This includes the so-called 'Steffen Snakes' (see [2] for details) and the Derbenev-Grote Snake/rotator design [8]. The use of helical field Snakes and rotators was analyzed in [4], where it was argued that the closed orbit beam excursions might be tolerable. However, helical field Snakes also generate SR, which is a disadvantage of the design.

Hence in this note, we consider the possibility of employing solenoids to design Snakes and spin rotators. Solenoids do not add to the SR power load. They also have the advantage that they are optically transparent and techniques

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ISSUES ON IR DESIGN AT SuperKEKB

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Abstract

The design of the interaction region is one of the most important issue in SuperKEKB. The lattice design with the final focus system and the local chromaticity correction as well as the dynamic aperture under the influence of beam-beam interactions are presented.

SUMMARY OF INTERACTION REGION

The machine parameters of SuperKEKB [1] are shown in Table 1. The final focus system is designed to achieve the extremely low beta function at the IP. In order to squeeze the beta functions, doublets of a vertical focusing (QC1) and a horizontal focusing quadrupole magnet (QC2) are adopted. Figure 1 shows the layout of the final focus system. The magnet system consists of superconducting magnets to make strong focusing strength. Those magnets have an iron yoke or a permendure yoke to shield the magnetic field to the opposite beam line except for the most inner magnets QC1Ps in the LER. Cancel coils for the leakage field of sextupole, octupole, decapole, and dodecapole filed from QC1s in the LER are installed in the HER. The dipole and quadrupole leakage fields are used in the lattice design of the interaction region in the HER. The dipole, skew dipole, skew quadrupole coils are quipped with the main quadrupole magnets to adjust X-Y couplings and vertical dispersions induced by solenoid field, although the 1.5 detector solenoid field is almost corrected by compensation solenoid magnets. The octupole coils are also installed to make dynamic aperture large, especially in the transverse direction. In addition to the coils for the lattice design, skew sextupole coils to correct imperfections of the main quadrupole magnet.

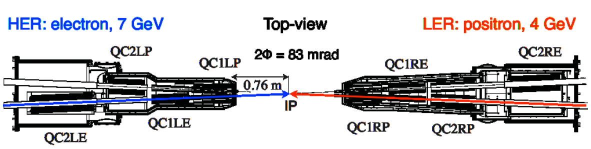

Figure 1: Top View of the Final Focus System.

The natural chromaticity is ξ_x =-105 and $\xi_y = -776$ in the LER, ξ_x =-171 and $\xi_y = -1081$ in the HER. Since approximately 80 % of the linear chromaticity in the vertical direction is induced in the final focus system, a local chromaticity correction (LCC) is adopted to correct the large chromaticity near the final focus system. There are 2 pairs for the vertical direction (Y-LCC) and another 2 pairs of sextupoles for the horizontal direction (X-LCC) in the IR. The phase advance between QC1 and the Y-LCC is π in the vertical direction and between QC2 and X-LCC is 2π in the horizontal direction for each side of the IP. Horizontal dispersions are created at the LCC by using several dipole magnets. Figures 2 and 3 show the lattice design of the LCC region.

Table 1: Machine Parameters (with Intra-beam Scattering) for the Final Design of SuperKEKB

	LER	HER	Unit
E	4.000	7.007	GeV
I	3.6	2.6	A
n_b	2500		
C	3016.315		m
ε_x	3.2	4.6	nm
ε_y	8.64	12.9	pm
β_x^*	32	25	mm
β_y^*	270	300	µm
$2\phi_x$	83		mrad
α_p	3.19×10^{-4}	4.53×10^{-4}	
σ_δ	7.92×10^{-4}	6.37×10^{-4}	
V_{RF}	9.4	15.0	MV
σ_z	6	5	mm
ν_s	-0.0245	-0.0280	
ν_x	44.53	45.53	
ν_y	46.57	43.57	
U_0	1.76	2.43	MeV
τ_x	45.6	58.0	msec
ξ_x	0.0028	0.0012	
ξ_y	0.0881	0.0807	
L	8×10^{35}		$cm^{-2}s^{-1}$

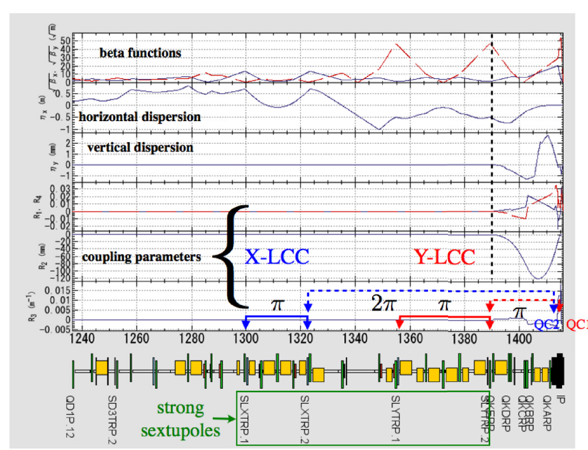

Figure 2: Local Chromaticity Correction in the LER.

NONLINEAR TERM IN FINAL FOCUS

Nonlinear effects in the final focus system decreases the dynamic aperture significantly. In addition to the nonlinear magnetic field, the drift space is not linear system as

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DESIGN OF INTERACTION REGION AND MDI AT CEPC*

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Abstract

The CEPC is a proposed circular electron positron collider to study the Higgs boson more accurately. The interaction region and the machine detector interface must be well designed to make sure the machine and the detector can work well after they are integrated together. Important factors that will affect the design of the CEPC interaction region are reviewed, such as the beam induced background, the interference of the magnetic field between the machine and the detector, etc. Several rules are summarized to steer the design of the interaction region. The progress on the machine detector interface of CEPC are presented.

INTRODUCTION

The CEPC [1] is a proposed circular electron positron collider to study the Higgs boson more accurately. It will be operated at the center of mass energy of 240 GeV with an instantaneous luminosity of $2 \times 10^{34} cm^{-2} s^{-1}$. One of the most important advantages of the e^+e^- collider is that the produced Higgs events will be much cleaner than those produced at the proton collider, e.g. the LHC. However, if the interaction region (IR) isn't designed well, the potential of the e^+e^- collider will not be fully exploited. For instance, the luminosity might be highly suppressed by the detector solenoid field if the beam coupling is not well cancelled and the Higgs events might be "heavily polluted" by the beam induced backgrounds if the shielding of the IR is not well designed. Thus, the interface between the machine and the detector must be carefully designed to achieve the required luminosity and background level.

Two kinds of problems must be well understood to find reasonable solutions of IR design. Firstly, the mutual influence between the machine and the detector must be well studied. It includes the interference of magnetic field between detector solenoid and machine magnets, the sources of beam induced backgrounds and so on. Secondly, the interface between the machine and the detector, such as the mechanical supporting and the procedure to assemble the interaction region, must be well designed. In this paper, we present the recent progress of the IR design and machine detector interface (MDI) study of CEPC. The dominant sources of beam induced background have been studied and some preliminary results are obtained. A compensating solenoid and anti-solenoid will be used to suppress the influence on the beam status from the detector solenoid. A global design of the interaction region is undergoing to balance the conflict of performance between the machine and the detector.

MAGNETS AND LAYOUT OF THE INTERACTION REGION

The luminosity is one of the most important parameters of CEPC. The accelerator design are trying to increase the luminosity as much as possible, however, the detector solenoid might decrease the luminosity. The luminosity is given by:

$$L = \frac{N_e^2 n_b f_0}{4\pi\sigma_x^*\sigma_y^*} F H \quad (1)$$

Here, N_e is the bunch population, n_b is the number of bunches, f_0 is the revolution frequency, σ_x^* and σ_y^* are the transverse size of bunches at the inter action point. F is the geometric luminosity reduction factor due to the crossing angle at the interaction point (IP). H is the hourglass factor giving the luminosity reduction due to the change of β^* along the bunch. To improve the luminosity of CEPC, the bunch size should be as small as possible, which means the final focusing magnets should be as close to the IP as possible. At current design, the distance between IP and the final quadrupole magnet L^* is set as 1.5 m. As a result, the final focusing magnets QD0 and QF1 will be inside the field of the detector solenoid. At CEPC, the bunch shape is set to be flat with large horizontal bunch size and very small vertical bunch size, which is helpful to reduced some kinds of beam induced backgrounds such as beamstrahlung meanwhile keep the multiply of σ_x and σ_y to be small. In this case, the detector solenoid will cause the coupling between the horizontal and vertical betatron motion and increase the bunch size in the vertical direction, which will further decrease the luminosity. To achieve the required luminosity, compensating solenoids are designed to cancel the beam coupling before the beam enter quadrupole magnets and anti-solenoids are designed around quadrupole magnets to prevent the beam coupling inside quadrupole magnets. Figure 1 shows the preliminary layout of the interaction region.

BEAM INDUCED BACKGROUNDS

The most important influence on the detector from the machine is the beam induced backgrounds. The major backgrounds at CEPC are the synchrotron radiation, the beam lost particles and the beamstrahlung.

Synchrotron Radiation

Because the beam energy of CEPC is very high and the number of beam particles in one bunch is very large, the synchrotron radiation (SR) emitted from the beam in the dipole and quadrupole magnets will be the most serious

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THE FCC-ee INTERACTION REGION MAGNET DESIGN

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Abstract

The design of the region close to the interaction point of the FCC-ee [1] [2] experiments is especially challenging. The beams collide at an angle (±15 mrad) in the high-field region of the detector solenoid. Moreover, the very low vertical β^* of the machine necessitates that the final focusing quadrupoles have a distance from the IP (L^*) of around 2 m and therefore are inside the main detector solenoid. The beams should be screened from the effect of the detector magnetic field, and the emittance blow-up due to vertical dispersion in the interaction region should be minimized, while leaving enough space for detector components. Crosstalk between the two final focus quadrupoles, only about 6 cm apart at the tip, should also be minimized.

INTRODUCTION

FCC-ee incorporates a "crab waist" scheme to maximize luminosity at all energies [3]. This necessitates a crossing angle between the electron and positron beams which is ±15 mrad in the horizontal plane in the current baseline design. No magnetic elements can be present in the region approximately ±1 m from the interaction point (IP) to leave space for the particle tracking detectors and the luminosity counter. Furthermore, the area outside the forward and backward cones of 100 mrad defined from the IP and along the longitudinal axis of the experiment is reserved for detector elements, leaving only the two narrow cones for machine elements. Therefore, beam electrons experience the full strength of the detector magnetic field in the vicinity of the IP. The resulting vertical kick needs to be reversed and this is performed in the immediate vicinity. This vertical bump, however, leads to vertical dispersion and an inevitable increase the vertical emittance of the storage ring. Since FCC-ee is a very low emittance machine (with an emittance budget of the order of 1 pm), the emittance blow-up in the vicinity of the IP needs to be minimized.

THE MAGNETIC ELEMENTS AROUND THE IP

We now have a preliminary conceptual design of the magnetic systems close to the IP which fits our requirements. It comprises the following elements:

The *detector solenoid* is assumed to have a magnitude of 2 T and extend to ±6 m from the IP.

The *screening solenoid* is a thin solenoid producing a field equal and opposite to the detector solenoid and screens the final focus quadrupoles from the detector solenoid field. It starts at 1.65 m from the IP and extends all the way to the endcap region of the detector. In the current design the screening is such that at the face of the final focus quadrupoles (2.2 m from the IP) the longitudinal magnetic field strength is 0.013 T (attenuated from 2 T)

The *compensating solenoid* sits in front of the screening solenoid, has a field higher than that of the detector solenoid, so that the magnetic field integral seen by the beam is zero. In our design the length of this solenoid is 0.65 m and its inner edge is at 1.0 m. Its maximum field along the axis is -4.95 T.

The *final focus quadrupoles* in our current design sit at a distance of 2.2 m from the IP and are 3.2 m long. The focusing strength in the current design is 92 T/m at 175 GeV [4]. The distance between the centres of the two quadrupoles is 6.6 cm at the tip closest to the IP and 16.2 cm at the far end.

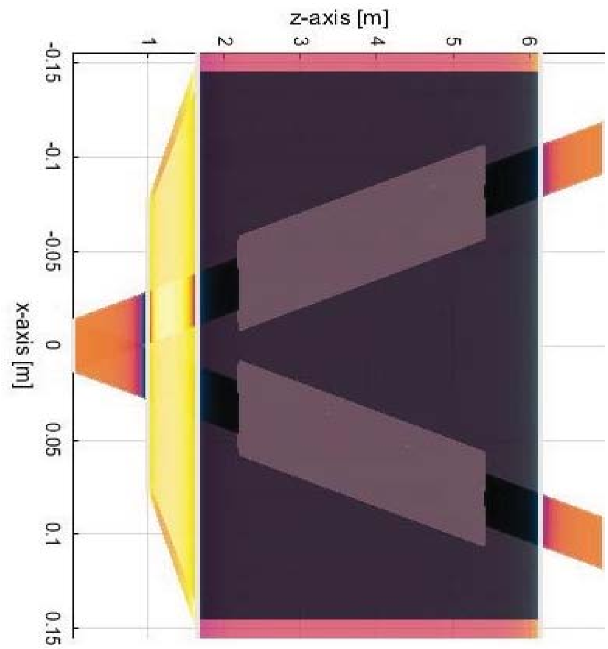

Figure 1: The conceptual design of the magnetic elements close to the IP, looking on the x-z plane. The IP is at (0,0). Please note the elongated scale in x. The opening angle of the (schematic) beam pipes is 30 mrad. The final focus quadrupoles surround the two beam pipes whereas the rest of the elements are aligned to the longitudinal axis of the experiment. The compensating solenoid (yellow) is tapered and is in front of the screening solenoid (pink). The detector solenoid is outside this picture.

The different elements of the design can be seen in Figure 1, as seen from above the detector. Please note the elongated view along the x-axis. Figure **2** shows the magnitude of the magnetic field, whereas Figure 3 shows the components of the magnetic field along the path of the electron. The longitudinal field varies from +2 T to -3 T, whereas the fringe horizontal field varies from +0.26 T to

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STUDY OF COHERENT HEAD-TAIL INSTABILITY DUE TO BEAM-BEAM INTERACTION IN CIRCULAR COLLIDERS BASED ON CRAB WAIST SCHEME

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Abstract

Coherent motion of colliding beam-beam system has been studied mainly for transverse modes. π and σ modes are We dicuss coherent head-tail instability for beam-beam collision with a large Piwinski angle. The instability seems serious for colliders based on the crab waist scheme.

INTRODUCTION

Recent and future e^+e^- colliers adopt collision with large crossing angle $\sigma_z\theta_c \gg \sigma_x$, where θ_c is half crossing angle. The vertical beta function is squeezed smaller than the bunch length, $\beta_y^* < \sigma_z$, while the crossing angle (θ_c: half angle) is chosen $\sigma_x/\theta_c \leq \beta_y$ to avoid the hourglass effect. Crab waist using based on a transformation $H = xp_y^2/2\theta_c$ at collision point suppress hourglass effect for particles with a large horizontal amplitude.

The beam-beam effects in the crab waist collision has been studied using the weak-strong simulation. Strong-strong simulation recenlty showed a strong coherent head-tail instability in the crab waist collision [?]. The instability is studied in detail in this paper.

STRONG-STRONG SIMULATION

A strong-strong bam-beam simulation code "BBSS" is used to study coherent effects in the crab waist collision. Two colliding bunches are represented by many macro-particles, $\approx 1,000,000$. Each bunch is sliced into several or many pieces, depending on Piwinski angle. Figure 1 shows schematic view of collision simulation for a large Piwinski angle. Typically the number of slices is chosen $n_{sl} \approx 10\sigma_z\theta_c/\sigma_z$. Collision order is given by sorting $z_{+,i} + z_{-,j}$, where z is the arrival time advance of $i(j)$-th slice of $e^{+(-)}$ beam multiplied by the light speed c. The collision point of a slice pair is given by $s_\pm = \pm(z_{+,i} - z_{-,j})/2$ for $e^\pm$ beam. A slice pair with $z_{+,i} \approx z_{-,j}$ collides at similar horizontal position, $x_{+,i} \approx x_{-,j} \approx z_{\pm,ij}\theta_c$ at $s \approx s^*$. While a pair with a large difference in z collides at $s = (z_{+,i} - z_{-,j})/2$ deviating from s^* with a large horizontal offset $(s - s^*)\theta_c$.

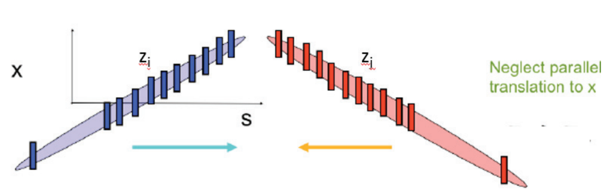

Figure 1: Schematic view of collision simulation for a large Piwinski angle.

In the strong-strong simulation, particles in a beam move with experience of electro-magnetic field induced by another beam. The motion of two beams (slice pair) are solved self-consistently. Strong-strong simulations are performed based on Particle In Cell method usually. The particle distribution is mapped on a transverse grid space (cell). Electric potential due to the particle distribution is calculated by solving Poisson equation in the two dimensional grid space. The potential calculation is simplified by assuming Gaussian distribution in transverse.

The code "BBSS" [3,4] eqipps several options to calculate electro-magnetic force between slice pair.

1. Gaussian approximation using rms value. Transverse Rms sizes of slice pair are calculated at $s_\pm = \pm(z_{+,i} - z_{-,j})/2$. Beam-beam force is evaluated by Bassetti-Erskine formula.

2. Gaussian approximation using fitting value. Transverse sizes of slice pair are calculated by Gaussian fitting at $s_\pm = \pm(z_{+,i} - z_{-,j})/2$. Beam-beam force is evaluated by Bassetti-Erskine formula.

3. Combined of PIC and Gaussian approximation. PIC is used for collision with small offset, namely $z_{+,i} \approx z_{-,j}$, while Gaussian approximation is used for collision with a large offset.

4. Full PIC using shifted Green function. Every collisions of slice pairs are evaluated by PIC method. Shifted Green function makes possible to evaluate potential for collision with a large horizontal offset.

Computing is harder for later options.

The strong-strong beam-beam simulation has been performed for FCC-ee. We discuss for Z and H, which parameters are listed in Table 1. Coherent instability has been seen in the simulation. Study of the coherent beam-beam instability is main thema of this paper.

Coherent beam-beam mode has been studied for a long time. Typical mode is π and σ modes, in which two beams collide with corrective frequency of transverse betatron frequency shifted by the coherent beam-beam tune shift. Here we discuss head-tail mode induced by beam-beam interaction with a large Piwinski angle. Two beams oscillate coherently with a head-tail mode.

The simulation calculate luminosity and beam distribution turn-by-turn Beam-beam parameter, which is normalized luminosity, is used for index of the beam-beam limit. The

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TOP-UP INJECTION FOR A FUTURE ELECTRON-POSITRON COLLIDER*

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Abstract

Top-up injection was developed in PEP-II and KEKB both using a linac injector to allow nearly constant luminosity with the BaBar and Belle detectors, respectively, being fully operational in data taking mode during injection [1-13]. This note will cover injection parameters, injection hardware, detector background masking, background detection, and top-up injection commissioning. For this paper top-up injection, continuous injection, trickle injection and trickle charging all refer to the same injection technique.

The positron beam top-off in PEP-II (Figure 1) was first developed in fall 2005. The positron beam lifetime (3 GeV) was the shortest and thus made the luminosity much more constant after top-up injection. Second, the electron beam top-off (9 GeV) was developed making the luminosity fully constant in spring 2006. For PEP-II either electrons or positron could be injection up to 30 Hz each if needed, deciding pulse-by-pulse which beam (i.e. bunch) was desired. The typical injection rate for each beam was a few Hz.

Top-up injection for KEKB (Figure 2) for both electrons and positrons was developed in winter 2005. Which beam was injected was determined by the configuration of the linac and transport lines at the moment. The switching time between injected beams was a about a minute.

REQUIRED INJECTION PARAMETERS FOR A CIRCULAR $e^+ e^-$ FACTORY

Future e+e- colliders such as CEPC or FCCee will store about 2 to 6 x10^{13} e- and e+ per beam at the Higgs beam energy. The lifetime is expected to be about 0.5 hr lifetime, thus, needing about 3 to 7 x10^{13} e- and e+ per hour or about 0.5 to 2 x10^{10} e+ and e- per second at full energy (75% capture). These rates compare well with previous particle generation rates such as those CERN delivered from the LEP injection complex ~10^{11} e+ per second and SLAC delivered from the SLC injection complex ~6 x 10^{12} e+ per second.

The requirements for top-up injection involve all aspects of injection and detector operation: One must measure each bunch's charge in real time and determine when it needs refilling. In the injector, the accelerator will initiate a bunch generation to deliver it to the needed particular bunch (bucket) in the ring. Then one must inject the bunch(es) into the collider with very low losses. Then one determines the injected beam backgrounds in the particle physics detector and find cures using collimation and steering. Next, one develops methods to monitor relevant backgrounds in real time for accelerator operators to tune on. Finally, one develops trigger masking for the detector physics data taking with trigger vetoes by the number of turns and within azimuthal locations within the ring.

Figure 1: PEP-II tunnel with LER above the HER with injection in the vertical plane.

Figure 2: KEKB tunnel with LER and HER side-by-side with injection in the horizontal plane.

Top-up injection into each ring can be provided by stacking into an existing bunch as in PEP-II and KEKB (Figure 3) or by full bunch charge exchange (Figure 4). Most rings use the stacking method but some newer light sources are using charge exchange as the stored dynamic aperture is small making the injection aceptance small.

Listed here are typical lattice parameters at the injection septum for the stacking of bunches in the ring.

β_x at injection septum (stored) = ~200m
β_x at injection septum (injection) = ~30m

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INJECTOR LINAC UPGRADE AND NEW RF GUN DEVELOPMENT FOR SuperKEKB

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Abstract

The SuperKEKB commissioning has finally started. The final goal of luminosity is 40 times higher than KEKB. The injector upgrade is required to obtain the low emittance and high charge beam corresponding to the short beam life and small injection acceptance of the SuperKEKB ring. In the injector linac, several new instruments have been installed. Flux Concentrator (FC) was developed for high charge positron beam capture. The target of positron bunch charge is 4 nC. The new damping ring will be used for positron beam to reduce beam emittance to 10 mm-mrad. However, electron beam must be reached to 20 mm-mrad normalized emittance at 5 nC beam charge without damping ring. Thermionic gun was used for KEKB injector and it was able to generate enough beam charge. However, its emittance is too large. Therefor we developed photo cathode S-band RF gun. This new RF gun has unique accelerating cavity which called quasi-traveling wave side coupled cavity. Laser system for this photo cathode has been also developed. The laser system is constructed with Yb:YAG thin disk for high power and pulse shaping.

INTRODUCTION

The upgrade of KEKB to SuperKEKB is going on. Since high luminosity is required in SuperKEKB, improvement of beam emittance and high charge is necessary. The injector linac has many challenging issues. Table.1 is upgrade parameter of electron and positron beam.

Table 1: Electron and Positron Beam Parameter

	KEKB (e+/e-)	SuperKEKB (e+/e-)
charge [nC]	1 / 1	4 / 5
Emittance [mm-mrad]	2100 / 300	20 / 20

In the positron beam, SuperKEKB beam charge is 4 times higher than KEKB beam charge. Primary electron beam for positron beam generation is 10 nC. It is same charge as KEKB. Therefore new Flux Concentrator (FC) and capture section was developed for efficient positron generation [1]. Since generated positron beam has large emittance, new damping ring has been constructed to reduce beam emittance.

In the other hand, the RF gun is developed to realize both of high charge and low emittance electron beam. Since we have no damping ring for electron beam, high charge beam generation with low emittance is essential in the gun. We are developing a photo cathode S-band RF gun for high charge (5 nC) low emittance (20 mm-mrad) beam generation. A thermionic cathode DC gun was used in KEKB for both of electron injection beam and positron primary electron beam. However this conventional gun does not have potential of low emittance generation. The new RF gun development is very important issue for electron beam.

Emittance preservation is one of the big issues. Total length of our linac is 600 m. In SuperKEKB, the beam charges are not small enough to ignore wakefield effect. Precise alignment of beam line is required to avoid transverse wakefield effect. However, small misalignment is remained. This small misalignment may be cancelled to using offset injection. The misalignment should be less than 0.1 mm in locally and 0.3 mm in globally. Target value of emittance will be able to be achieved with performing precise alignment and offset injection.

Optimum optics and magnet adjustment is required for both of electron and positron beam offset injection. The KEK injector is required simultaneous injection for HER, LER, PF and PF-AR ring at 50 Hz. The pulse quadrupole magnet and pulse steering magnet has been developed for pulse-to-pulse modulation [2].

Several new devices such as RF gun, FC and pulse magnets have been developed for achieve low emittance high charge electron and positron beam. The SuperKEKB Phase 1 commissioning had been carried out from February to June 2016. We had been able to confirm the performance of the new devices in KEK injector linac.

NEW RF GUN DEVELOPMENT

We are developing a photo cathode S-band RF gun for high charge (5 nC) low emittance (20 mm-mrad) beam generation. A thermionic cathode DC gun was used in KEKB. Since it is difficult to make a low emittance beam with the thermionic gun, the new RF gun must be installed to realize required electron beam parameter. However the standard on-axis coupled 1.5 cell RF gun is not suitable for this high charge beam, because standard gun is used up to about 1 nC by ordinary. If we obtain 5 nC in the gun, beam size will be too large. We have to consider both beam focus and emittance preservation. Thus it is necessary to make a focusing field against the space charge in the cavities. In this on-axis coupling cavity, however, it is difficult to arrange the field freely on the axis. Since beam hole is also the coupling hole. Thus annular coupling is required.

We are developing a new advanced RF gun. It has new acceleration scheme, we call it as a quasi-traveling wave. In this method, higher accelerating field and stronger focusing field are expected. It is very efficient accelera-

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DESIGN STUDY OF CEPC BOOSTER*

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Abstract

CEPC is next generation circular collider proposed by China. The design of the full energy booster ring of the CEPC is especially challenging. The ejected beam energy is 120GeV, but the injected beam only 6GeV. In a conventional approach, the low magnetic field of the main dipole magnets creates problems. we have two ways to solve this problem, Firstly, we propose to operate the booster ring as a large wiggler at low beam energy and as a normal ring at high energies to avoid the problem of very low dipole magnet fields. Secondly, we implement the orbit correction and correct the earth field to make booster work.

INTRODUCTION

CEPC (Circular Electron and Positron Collider) was proposed as an electron and positron collider ring with a circumference of 50-100km to study the Higgs boson[1][2][3]. CEPCB(CEPC Booster) is a full energy booster ring with the same length of CEPC which ramp the beam from 6Gev to 120Gev. At the injected beam energy, the magnetic field of the main dipole is about 30Gs, the low magnetic field will create problems for magnet manufacturing[4].

In the Pre-CDR[5], a preliminary design is proposed, but the problems of earth field correction and dynamic aperture are not solved.

In this paper, we focus on those problems and find a reasonable solution. In the wiggler scheme, which split the normal dipole to several pieces with different magnet field direction to avoid the problem of very low dipole magnet fields[6][7][8], because low field magnet manufacture is difficult.

In the normal bend scheme, we implement the first turn orbit correction and closed orbit correction to correct the earth field effect.

An analytic map method(Differential algebra)[9] is used to derive the twiss functions of arbitrary order of energy spread, such as β function, phase advance function, dispersion function. Those functions are all analytic functions dependent of sextupole strength. Optimize the high order chromaticities, then a good dynamic aperture for both on-momentum and off-momentum particles are got.

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DESIGN GOAL

At present, the emittance of CEPC is about $2.0 \times 10^{-9} m * rad$, it is much lower than the Pre-CDR because of the crab waist scheme. That makes the CEPCB harder to design because emittance of CEPCB at high energy is also reduced, which cause the chromaticities much stronger and pose challenges to our design at the same time.

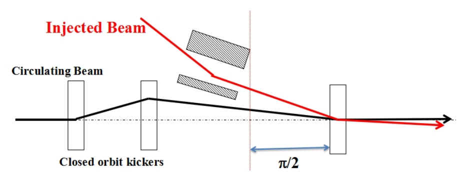

Figure 1: Injection scheme.

Fig. 1 shows the X direction injection scheme for mainring. Asume that the dynamic aperture of CEPC mainring at 0.5% energy spread is 15 times of sigma and the β function is about 200m.

The total space for injection:

$$\begin{aligned} & \sqrt{\epsilon_x \times \beta_x} \times 15 \\ = & \sqrt{2.0 \times 10^{-9} \times 200} \times 15 \\ = & 9.49(mm) \end{aligned}$$

5 sigma is retained for revolution beam to get enough quantum life time:

$$\begin{aligned} & \sqrt{\epsilon_x \times \beta_x} \times 5 \\ = & \sqrt{2.0 \times 10^{-9} \times 200} \times 5 \\ = & 3.16(mm) \end{aligned}$$

Asuming that the emittance of CEPCB at 120Gev is $3.5 \times 10^{-9} m * rad$, and 3 sigma is retained for injection beam to loss less particles:

$$\begin{aligned} & \sqrt{\epsilon_x \times \beta_x} \times 3 \\ = & \sqrt{3.5 \times 10^{-9} \times 200} \times 3 \\ = & 2.51(mm) \end{aligned}$$

The design goals of CEPCB are listed:

1. The emittance of CEPCB at 120Gev is about $3.5 \times 10^{-9} m * rad$.

2. 1% energy acceptance for enough quantum life time.

3. The dynamic aperture results must better than 6 sigma (Normalized by emittance, which is decided by the beam from linac) for both on-momentum and off-momentum(1%) particles.

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TOP-UP INJECTION SCHEMES FOR HEPS*

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Abstract

Top-up injection has become standard mode of operation for most third generation light sources, and has also been succesfully applied in electron-positron circular colliders like KEKB and PEP-II. For next generation ultra-low emittance storage rings approaching the diffraction limit of X-rays, take the High Energy Photon Source (HEPS) for example, top-up injection is a basic requirement but non-trivial to implement. The very small dynamic aperture is insufficient for traditional off-axis injection scheme, instead, a novel on-axis injection scheme was recently proposed for HEPS, based on RF gymnastics of a double-frequency RF system. This paper will describe the physical mechanism of this scheme, related RF issues and the implications for top-up injection.

INTRODUCTION

First implemented in APS [1] and SLS [2] for user exmperiments, top-up injection has become standard mode of operation in most third generation light sources. Frequent beam injection ensures the relative beam current fluctuation within a few 10^{-3}, which significantly improves the photon beam stability and efficiency in user exmperiments. This mode of operation was also realized in electron-positron circular colliders KEKB [3] and PEP-II [4], which greatly enhanced the average luminosity and the almost constant beam current made luminosity tuning much easier.

With these success in existing machines, top-up injection is considered to be a basic requirement in the design of next generation electron (positron) storage rings, but this also brings new challenges. In particular, in the next generation synchrotron light sources with ultra-low emittances approaching the diffraction limit of X-rays, the implementation of top-up injection is somewhat non-trivial.

These diffraction-limit storage rings normally adopt multibend achromat (MBA) cells [5] in the lattice design, and utilize high-gradient quadrupoles to achieve a ultra-low beam natural emittance of tens of picometers. Therefore, very strong sextupoles are required to compensate for the large natural chromaticities and thus lead to great challenges in optimization of the dynamic aperture (DA) and the momentum aperture (MA). Take the High Energy Photon Source (HEPS, its major parameters are listed in Table 1) for example, a nominal lattice design has achieved a natural emittance of 59.4 pm, while an effective DA of 2.5 mm (horizontal) and 3.5 mm (vertical) and an effective MA of 3.0% are obtained with great effort[1] [6]. Such a small DA is insufficient for traditional off-axis injection schemes, which typically requires a DA on the order of 10 mm. Therefore, we have to seek alternative on-axis injection schemes.

Inspired by various on-axis injection schemes [7–9] suitable for ultra-low emittance storage rings, we proposed a new injection scheme based on RF gymnastics of an active double-frequency RF system [10] and applied it in HEPS. In this paper, the physical mechanism of this injection scheme will be overviewed, followed by the discussion on the control of RF cavities, finally implications for top-up injection will also be presented.

Table 1: HEPS Parameters [6]

Parameter	Value
circumference C(m)	1295.616
beam energy E_b(GeV)	6
beam current I_0(mA)	200
natural emittance ϵ_0(pm)	59.4
betatron tunes ν_x/ν_y	116.155/41.172
momentum compaction α_c	3.74×10^{-5}
rms energy spread σ_ϵ	7.97×10^{-4}
harmonic number h_f/h_h	720/2160
SR energy loss U_0(MeV/turn) [2]	1.995
damping times(ms) $\tau_x/\tau_y/\tau_s$	18.97/25.99/15.95

PHYSICAL MECHANISM OF THE INJECTION SCHEME

Without synchrotron radiation, a particle's longitudinal motion with a double-RF system is described by the Hamiltonian

$$H(\phi,\delta;t) = \frac{h_f\omega_0\eta}{2}\delta^2 + \frac{e\omega_0}{2\pi E_b\beta^2}\left[\sum_{i=1}^{N_f} V_f^i\cos(\phi+\phi_f^i) + \frac{h_f}{h_h}\sum_{j=1}^{N_h} V_h^j\cos(\frac{h_h}{h_f}*\phi+\phi_h^j) + \phi\frac{U_0}{e}\right], \quad (1)$$

where ϕ and δ are a pair of canonical variables with respect to the time variable t, $\omega_0 = 2\pi c/C$ is the angular revolution frequency of the synchronous particle, e is the electron charge, γ is the relativistic factor, $\eta = \alpha_c - 1/\gamma^2$,

[1] The "effective" DA (or MA) means the boundary within which, not only particles survive in the ideal lattice tracking, but also the amplitude-dependent tunes are bounded by the nearest integer and half-integer resonances of the nominal tunes.

[2] Insertion devices are not included.

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TOWARDS A PRELIMINARY FCC-ee INJECTOR DESIGN

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Abstract

The Future Circular Collider-ee aims to get high luminosity which mainly relies upon high charge and low geometric emittance in the collider. The FCC-ee is a future project of CERN to operate as Z, W, H and tt factories with varying energies between 45.6 to 175 GeV. Among those, the total charge requirement is peaked for Z-operation (i.e. 91500 bunches of electron and positron with 3.3E10 particles per bunch) meanwhile this mode targets the smallest geometric emittance in the Collider. To reach the goal, the normal conducting S-band Linac has been designed to accelerate 4E10 particles in a bunch to 6 GeV and send two bunches per RF pulse within a repetition of 100 Hz. The FCC-ee positrons will also be created inside the linac at 4.46 GeV and accelerated to 1.54 GeV. These positrons are damped at the designed Damping Ring at that energy, and then transferred back to the Linac to meet the same characteristics of electrons. Therefore, in this paper, we'd like to discuss the transmission and robustness of the Linac and the dynamic aperture of the Damping Ring which has to be large enough to accept the incoming beam and cover the probable shrink due to the misalignments.

INTRODUCTION

CERN's leading role over the world in the fields of the particle and accelerator physics has brought about thinking of ambitious post-LHC (Large Hadron Collider) projects. As a 100 km-machine, FCC-ee has been proposed to supply ever increasing demand of high luminosity machines for new physics search and the precision study of the particle physics. Nowadays, FCC-ee is being designed to operate as Z, W, H and tt factories. However, in the design of pre-injectors, the total charge and the equilibrium emittance are determinant. Therefore, we will be following Z-operation which has the highest total charge and lowest final emittance at 45.6 GeV to study pre-injectors, some parameters of Z-operation is tabulated in Table 1.

Table 1: FCC-ee Baseline Parameters for Z-operation Mode

Parameter	Value
Final Energy [GeV]	45.6
Number of Bunches per Beam	91500
Bunch Population	3.3×10^{10}
Horizontal Emittance	0.09 nm
Vertical Emittance	1 pm

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The detailed version of the table and the preliminary design parameters of the pre-injectors are already discussed in details in our earlier proceedings [1] and [2], respectively. In this paper, however, we'd like to discuss the followings: i) improvements on the Linac transmission, and ii) enlargement of dynamic aperture of the Damping Ring.

IMPROVEMENTS ON LINAC

The designed Linac for FCC-ee is an S-band normal conducting accelerator operating at frequency 2.856 GHz. The optics before the correctors were tightly allocated as presented in Fig. 1.

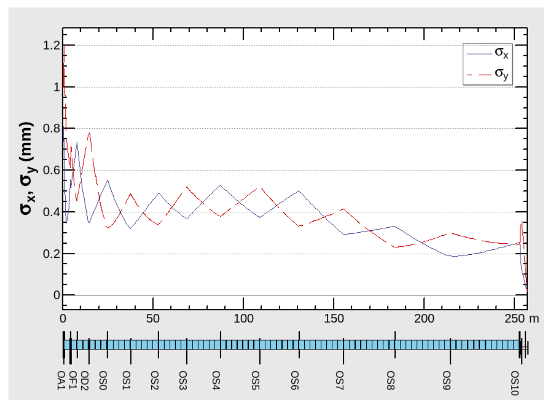

Figure 1: Linac optics before the misalignments.

After the idealistic design of the Linac, the study of errors is crucial in a sense to determine probable and inevitable misalignments through the commissioning of the accelerator. Therefore, we have given some misalignment to the elements both horizontally and vertically as tabulated in Table 2. The study has been done as a Monte-Carlo simulation where the tabulated errors represents one-sigma, and no truncation has been made.

Table 2: Misalignment Study

Element	Simulated Error
Injectional Error (h/v)	0.1 mm
Injectional Momentum Error (h/v)	0.1 mrad
Quadrupole Misalignment (h/v)	0.1 mm
Cavity Misalignment (h/v)	0.1 mm

After introducing errors, the Linac transmission has dropped dramatically down to 33%. The cavities of the Linac are with length of 28 + 1/3 wavelengths which correspond to 3 meters approximately. The wakefields of the cavities are similar to ATF-Linac [3] and the cavity geometry

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ELECTRON SOURCES AND POLARIZATION

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Abstract

In this presentation the present electron sources and the relevant issues will be discussed. For the electron positron colliders and accelerator based light sources, the electron gun and injector design, are arguably the most critical part. There are a variety of electron source designs: DC guns, normal-conducting RF guns, superconducting RF gun and hybrid guns. All variants have their own advantages and difficulties. We will overview the typical sources around the world, and compare their advantages and main challenges. The polarization production will also be discussed.

INTRODUCTION

For most of the electron accelerator facilities, design of electron gun and injector is arguably the most critical work. The quality of guns determines the ultimate performance of whole machine: current, bunch charge, bunch structure, repetition rate, transverse and longitudinal emittance. Certain applications require polarized electron beams. These parameters can only be degraded in subsequent beam line, will never become better [1].

High brillant beams are required by electron based colliders and high energy free electron lasers (FELs) [2]. Obviously, higher bunch charge in smaller transverse phase space and in smaller longitudinal phase space leads to higher brilliance. This gun must not work in continuous wave mode (CW), but provide very high electrical field at emission to overcome the space charge effect in the low energy stage.

Energy Recovery Linac (ERL), high power FELs and some other accelerator-based facilities place extra emphasis on high average current and low emittance, which needs robust cathodes with high emission efficiency, and high acceleration field in CW or high duty factor pulsed mode [1].

For microscopes and some accelerator applications, cold beams with extremely low emittance are request. Thermal emittance of the emitted electrons determines the limit of the lowest emittance of the beam. During the acceleration and transportation the emittance can only be degraded. So it is important to modify the cathode emission process and to optimize the accelerating structure to maintain the low emittance in the electron source [3].

Polarized beams are required by some high energy particle physics experiments, thus the spin-polarized electron sources are specially stimulated by the application of e+ e- colliders and electron-hadron colliders. For this case cathode materials with high spin-polarization rate and the good operation vacuum are the essential issue [4].

The main challenges of electron sources are to provide high efficient emitters, to deal with severe space charge effect and normally to work in the limited space. Although different facilities have their own focus, stability and reliability are the common requirement to ensure the routine operation, and also low dark current is request to reduce the damage risk and radiation doses for the downstream beam line.

EMITTERS

According to the different electron emitters, electron sources can be classified as thermal emission sources, photoemission sources, field emission sources and hybrid sources.

Thermionic cathodes, like Hexaborides, will emit when the temperature reach the threshold, when thermalized electrons can overcome the work function and finally escape the cathode surface [5]. Because of the high working temperature (for example 2500 K for LaB_6), thermal emitters can only work in direct current (DC) guns and in normal conducting radio frequency (NC RF) guns. With high electric fields, they are able to produce high current, but the time structure of bunches cannot be as short as those from photo-emitters and the emittance will be high due to the thermal emission process.

Photo-induced emission is up to now the best candidate for low emittance sources. Photocathodes can locate in DC guns, NC RF guns and lately in Superconducting RF guns (SRF guns). Photo-guns have produced beams with sufficient quality for many accelerator facilities [6]. But the critical gun vacuum and the expensive drive lasers increase greatly machine cost. In the next section the photo emission sources will be discussed.

Electron sources with cold field emission cathodes, like diamond field emitter and multiwall carbon nanotubes, are very common used in the field of electron microscopy, Gabor holography and also the accelerator facilities [7]. Due to the Fowler-Nordheim theory, the high fields built at the tips of emitter surface will induce stable field emission [8]. There are some new ideas inspired from field emission, for example, photo-induced field emission cathode or field enhanced photocathode [9], thermal field emission cathode [10], Schottky emission cathode [11], combining two emission models by using one method to reduce the work function of material and then extract the electrons with another method.

AVAILABLE ELECTRON SOURCES

Photoemission based electron sources (photo guns) have reached the best beam quality. For electron positron colliders, photo guns have the biggest potential to produce high current and low emittance beam. In this section we will overview the various on-going photo gun types, DC guns, NC RF guns and SRF gun projects.

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COLLECTIVE EFFECTS ISSUES FOR FCC-ee

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Abstract

The Future Circular Collider study, hosted by CERN to design post-LHC particle accelerator options in a worldwide context, represents a great challenge under several aspects, which require R&D on beam dynamics and new technologies. One very critical point is represented by collective effects, generated by the interaction of the beam with self-induced electromagnetic fields, called wake fields, which could produce beam instabilities, thus reducing the machines performance and limiting the maximum stored current. It is therefore very important to be able to predict these effects and to study in detail potential solutions to counteract them. In this paper the resistive wall and some other important geometrical sources of impedance for the FCC electron-positron accelerator are identified and evaluated, and their impact on the beam dynamics, which could lead to unwanted instabilities, is discussed.

INTRODUCTION

The new CERN project, called High Luminosity LHC [1], aims to increase the number of collisions accumulated in the experiments by a factor of ten from 2024 onwards. While the project is well defined for the next two decades, CERN has started an exploratory study for a future long-term project based on a new generation of circular colliders with a circumference of about 100 km. The Future Circular Collider (FCC) study [2] has been undertaken to design a high energy proton-proton machine (FCC-hh), capable of reaching unprecedented energies in the region of 100 TeV, and a high-luminosity e+e- collider (FCC-ee), serving as Z, W, Higgs and top factory, with luminosities ranging from about 10^{34} to 10^{36} cm^{-2}s^{-1} per collision point as a potential intermediate step towards the realization of the hadron facility. The design of the lepton collider complex will be based on the same infrastructure as the hadron collider.

At high beam intensity, necessary to reach the high luminosity foreseen for FCC-ee, the electromagnetic fields, self-generated by the beam interacting with its immediate surroundings and known as wake fields [3], act back on the beam, perturbing the external guiding fields and the beam dynamics. Under unfavorable conditions, the perturbation on the beam further enhances the wake fields; the beam-surroundings interaction then can lead to a reduction of the machine performance and, in some cases, also to instabilities.

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The theory of collective beam instabilities induced by the wake fields is a broad subject and it has been assessed over many years by the work of many authors, such as F. Sacherer [4], A. W. Chao [5], J. L. Laclare [6], B. Zotter [7], C. Pellegrini [8], M. Sands [9] and others [10].

To simplify the study of collective effects, in general it is convenient to distinguish between short range wake fields, which influence the single bunch beam dynamics, and long range wake fields, where high quality factor resonant modes excited by a train of bunches can last for many turns exciting, under some conditions, coupled bunch instabilities. In both cases the bunch motion is considered as a sum of coherent oscillation modes perturbed by these wake fields.

In this paper we will focus on the FCC-ee collective effects induced by wake fields. In particular we will first evaluate the wake fields induced by the finite resistivity of the beam vacuum chamber (resistive wall). Due to the 100 km length of the beam pipe, the resistive wall plays a non negligible role among the sources of wake fields for this accelerator, and the choice of the pipe geometry, material, and dimensions is particularly important. We then discuss the collective effects induced by the resistive wall for both the short range and long range wake fields, and for both longitudinal and transverse planes. For some instabilities we will resort to the linear theory, while for other cases and for more accurate predictions, we need to use simulation codes.

We finally dedicate the last part of the paper to other important sources of wake fields, such as the RF system, the synchrotron radiation absorbers, and smooth transitions, in order to reduce their impact on the beam dynamics. Finally, concluding remarks and outlook will end the paper.

For reference we report in Table 1 the list of beam parameters for the two lowest energies that we have used for evaluating the effects of wake fields on the beam dynamics. At the 45.6 GeV energy, two options are foreseen, with the same total beam current and a different bunch spacing, 7.5 ns and 2.5 ns. It is important to observe that the 7.5 ns option is more critical, from the single bunch point of view, with respect to the 2.5 ns option, having a triple bunch current and a shorter bunch length.

RESISTIVE WALL WAKE FIELDS, IMPEDANCES, AND EFFECTS ON BEAM DYNAMICS

The electromagnetic interaction of the beam with the surrounding vacuum chamber, due to its finite resistivity, produces unavoidable wake fields, which, for FCC-ee, result

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INSTABILITY ISSUES IN CEPC*

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Abstract
The CEPC is a high-energy circular electron-positron collider under design. Large bunch population is required to achieve the design luminosity. Instabilities driven by the coupling impedance are possible limitations for reaching high machine performance. An updated impedance model, including the resistive wall and the main vacuum components, has been obtained for the main ring. Based on the impedance model, the collective instability issues of the beam with the partial-double ring design are discussed.

INTRODUCTION

In high-energy circular e+e- colliders, large efforts have been made to increase the bunch intensity in order to reach high luminosity. Meanwhile, large circumferences are often chosen due to restricted synchrotron radiation power, which means a further enhancement of the machine impedance. The interaction of the beam with the impedances may lead to collective instabilities, which can induce beam quality degradation or beam losses. Moreover, the large bending radius and small horizontal dispersion in dipoles will generate small momentum compaction factor, which can make the beam more sensitive to the collective instabilities. Therefore, collective instability becomes a potential restriction for the machine performance. In this paper, the instability issues for the partial double ring design of CEPC are studied. The impedance budget for the CEPC main ring is first given. Based on the impedance studies, the single bunch and coupled bunch instabilities are investigated. The main parameters used in the calculation are listed in Table. 1.

Table 1: Main Parameters

Parameter	Symbol, unit	Value
Beam energy	E, GeV	120
Circumference	C, km	54
Beam current	I_0, mA	16.9
Bunch number	n_b	50
Bunch length	σ_z, mm	4.1
RF frequency	f_{RF}, GHz	0.65
Energy spread	σ_e	1.3E-3
Slipping factor	α_p	2.5E-5
Betatron tune	ν_x/ν_y	319.21/318.42
Synchrotron tune	ν_s	0.08
Damping time	$\tau_x/\tau_y/\tau_z$, ms	14/14/7

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IMPEDANCE BUDGET

The impedance and wake are calculated with both analytical formula and numerical simulations. The vacuum components considered in the calculation include resistive wall, RF cavities, flanges, shielded bellows, BPMs and pumping ports. The short range wake at nominal bunch length is shown in Fig. 1. The impedance budget of the objects considered is listed in Table 2, where $Z_{||}/n$ is the longitudinal effective impedance, k_l is the loss factor, R and L are effective resistance and inductance of the components obtained by fitting the wake potential with the analytical formula [1]

$$W(s) = -Rc\lambda(s) - Lc^2\lambda'(s). \quad (1)$$

Here, c is the speed of light, and $\lambda(s)$ is the bunch line density.

Table 2: Summary of Impedance Budget

Objects	R, kΩ	L, nH	$Z_{\|}/n$, mΩ	k_l, V/pC
Resistive wall	6.7	487.7	17.0	138.4
RF cavity	14.9	-132.7	-	307.5
Flange	0.7	165.5	5.8	15.1
Bellows	5.9	331.5	11.6	122.3
BPM	0.6	21.4	0.7	11.6
Pumping port	0.007	3.1	0.1	0.1
Total	28.8	876.5	35.2	595.0

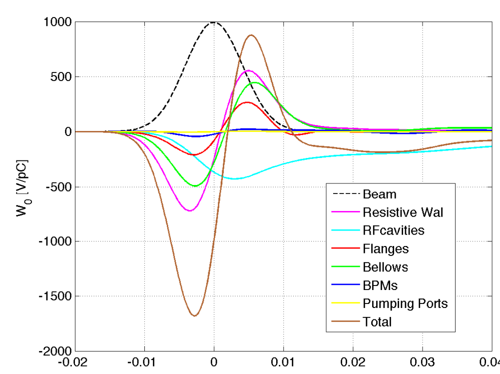

Figure 1: Longitudinal wake potential at nominal bunch length of 4.1 mm.

From the impedance budget we can conclude that the longitudinal impedance is dominated by the resistive wall and the vacuum components with large quantity, such as flanges and bellows. A more complete impedance budget

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BEAM-BASED IMPEDANCE MEASUREMENT TECHNIQUES *

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Abstract

Characterization of a vacuum chamber impedance is necessary to estimate stability conditions of a particle beam motion, to find a limit of the beam intensity and characteristic times of single-bunch and multi-bunch instabilities. For a new accelerator project, minimization of the impedance is now the mandatory requirement for the vacuum chamber design. For an accelerator in operation, the impedance can be measured experimentally using various beam-based techniques. The beam-impedance interaction manifests itself in measurable beam parameters, such as betatron tunes, closed orbit, growth rates of instabilities, bunch length and synchronous phase. The beam-based techniques developed for measurement of the longitudinal and transverse impedance are discussed, including theoretical basics and experimental results.

WAKE FUNCTIONS AND IMPEDANCES

In a theory of collective effects, the interaction of a particle beam with electromagnetic fields induced by the beam itself is described in terns of wake functions. These electromagnetic fields are called wake fields because they never propagate ahead of a relativistic particle. The wake function is defined as a normalized integral of the Lorentz force that acts on a test particle moving behind a leading particle which excites the wake fields. To analyze the beam stability in most practical cases, it is enough to consider only monopole longitudinal $W_\parallel$ and dipole transverse $\mathbf{W}_\perp$ wake functions. The longitudinal wake function is obtained by integrating the electric field component E_z, which is parallel to the velocity $\mathbf{v}$ ($|\mathbf{v}| = c$) of the particles moving on the same trajectory [1]:

$$W_\parallel(\tau) = -\frac{1}{q}\int_{-\infty}^{\infty} E_z(t,\tau)\,\mathrm{d}t\,, \qquad (1)$$

where q is the charge of leading particle, $\tau = s/c$, s is the distance between the leading and trailing particles, c is the speed of light. The dipole transverse wake function is determined similarly to the longitudinal one as an integral of transverse electromagnetic forces normalized by the dipole moment qr of the leading particle (r is the transverse offset); it is a vector with horizontal and vertical components:

$$\mathbf{W}_\perp(\tau) = -\frac{1}{q\,r}\int_{-\infty}^{\infty} [\mathbf{E}(t,\tau) + \mathbf{v}\times\mathbf{B}(t,\tau)]_\perp\,\mathrm{d}t\,. \qquad (2)$$

The longitudinal and transverse wake functions are related to each other by the Panofsky-Venzel theorem [1, 2].

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For a beam with arbitrary charge distribution, its interaction with wake fields is described by the wake potential V, which is a convolution of the wake function W and the longitudinal charge density $\lambda(t)$:

$$V(\tau) = \int_0^{\infty} W(t)\lambda(\tau - t)\mathrm{d}t\,, \qquad (3)$$

where $\lambda(t)$ is normalized as $\int_{-\infty}^{\infty} \lambda(t)\mathrm{d}t = 1$.

In the frequency domain, each part of the vacuum chamber is represented by a frequency-dependent impedance. Longitudinal $Z_\parallel$ and transverse $Z_\perp$ impedances are defined as Fourier transforms of the corresponding wake functions:

$$Z_\parallel(\omega) = \int_{-\infty}^{\infty} W_\parallel(\tau)\,e^{-i\omega\tau}\,\mathrm{d}\tau\,,$$
$$Z_\perp(\omega) = i\int_{-\infty}^{\infty} W_\perp(\tau)\,e^{-i\omega\tau}\,\mathrm{d}\tau\,. \qquad (4)$$

The main contributors to the total impedance of the vacuum chamber are: finite conductivity of the walls (resistive-wall impedance), variations of the chamber cross section, high-order modes of accelerating RF cavities, electrostatic pickup-electrodes, strip-lines, flanges, bellows, synchrotron radiation ports, etc. If there is no interference of the wake fields excited by the beam in different components of the vacuum chamber (the components are far away from each other or the wake fields are rapidly damping), the impedances are additive at any frequency. In this case, the total impedance of the vacuum chamber can be represented as a sum of impedances of its components. For almost any component of a vacuum chamber, the impedance can be approximated by equivalent resonators with proper resonance frequencies, shunt resistances and quality factors. Since a narrowband oscillation mode is more long-living than the broadband mode, the beam interaction with the narrowband impedance and with the broadband one can be analyzed separately. We can assert that the narrowband impedance leads to the bunch-by-bunch interaction and can result in multi-bunch instabilities, whereas the broadband impedance leads to the intra-bunch interaction and can cause single-bunch instabilities. The beam stability is analyzed using the computed impedance or its simplified representation by resonators and resistive-wall impedance calculated analytically.

To compute the impedance of complex components of vacuum chambers, 3D finite-difference simulation codes [3, 4] are used. These codes solve Maxwell equations with the boundary conditions determined by the chamber geometry. The fields are excited by a bunched beam with pre-defined charge distribution, usually Gaussian. The simulation code

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ELECTRON CLOUD AND ION EFFECTS AND THEIR MITIGATION IN FCC-ee

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Abstract

High current and high repetition beam causes electron cloud and ion build-up, which result in two stream type of instability. We discuss build-up of electron cloud and ion, and related instabilities in FCC-ee. Latest result of ion instability in SuperKEKB is reported.

INTRODUCTION

Electron cloud and ion effects in FCC-ee is preseneted in this paper. These effect is serious for storage rings operated with high current and high repetition beam. FCC-ee is designed so that total synchrotron radiation loss is 50 MW. The effects in FCC-ee Z is most serious, because bunches are stored every 2.5 or 7.5 ns with total current of 1.45 A. In high energy FCC-ee; H and t options, the number of bunch is limited by hundreds due to the total radiation loss. These instability is less serious in W, H and t options.

Ion effects in SuperKEKB is discussed, while electron cloud effects in SuperKEKB is discussed in Ref. [1].

ELECTRON CLOUD EFFECTS

We first evaluate threshold of fast head-tail instability caused by electron cloud, and then how the electron cloud build-up compare with the threshold value.

Threshold of Electron Density for Fast Head-Tail Instability

The fast head-tail instability is caused by the electron cloud moving in a positron bunch with a frequency

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}, \qquad (1)$$

where λ_p is a positron line density in a bunch, namely $\lambda_p = N_p/(\sqrt{2\pi}\sigma_z)$. Beam, which is modulated by the electron oscillation, experiences the fast head-tail instability above a threshold density of the electrons. The threshould density of electron cloud is expressed by [2]

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_e\langle\beta_y\rangle L}, \qquad (2)$$

where $K = \omega_e\sigma_z/c$ and $Q = min(\omega_e\sigma_z/c, 7)$. Table 1 shows beam parameters, the fequency in Eq.(1) and the threshold density in Eq.(2) for FCC-ee.

Coherent Head-Tail Instability in the Simulation

The fast head-tail instability caused by the electron cloud is simulated by a code "PEHTS" [3]. Electrons with a density distribution are placed in a beam line, and interaction with beam is calculated in every passage of a bunch. The bunch is transffered by a revolution matrix for the next interaction. Figure 1 shows evolution of the vertical beam size and the beam-electron centroid along a bunch after 500 turns at the electron density $\rho_e = 1.0\times10^{10}$ m^{-3}. The threshold density in the simulation, $\rho_{e,th,sim} = 0.8 \times 10^{10}$ m^{-3}, agrees with that in Table 1.

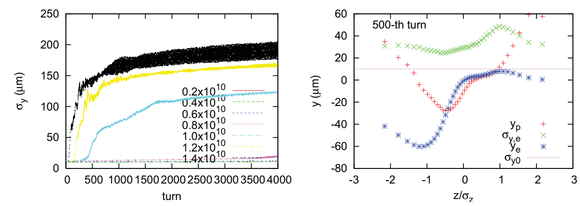

Figure 1: Evolution of the vertical beam size (left) and beam-electron centroid along a bunch after 500 turn (right).

Electron Cloud Build-up

We next discuss how high density of the electron cloud is built-up. The electron cloud is formed by photo-electrons and their secondary electrons. Photon production rate per revolution per positron is given by

$$n_\gamma = \frac{5}{2\sqrt{3}}\frac{\alpha\gamma}{\rho_{bend}}, \qquad (3)$$

where $\alpha = 1/137$ is the fine structure constant. The critical energy is

$$u_c = \frac{3\hbar c}{2}\frac{\gamma^3}{\rho_{bend}}. \qquad (4)$$

Electrons are created by photons hitting a chamber wall with a quantum efficiency around $Y_1 \approx 0.1$. Electron production by a bunch per meter passage is given by

$$n_{e,1} = n_\gamma Y_1 N_p \qquad (5)$$

For FCC-ee-Z, $\rho_{Bend} = 11.3$ km and $N_+ = 3.3 \times 10^{10}$, the eletrcon production is $n_{e,1} = 1.8 \times 10^8$ m^{-1}. Assuming the chamber cross section of 0.005 m^2, increment of the electron density by a bunch passage is $\Delta\rho_e = 3.5 \times 10^{10}$ m^{-3}. This density after a passage of a bunch is already 4.4 times higher than the threshold $\rho_{e,th} = 0.8 \times 10^{10}$ m^{-3} in Table. 1. An ante-chamber protect the density increment, because most of electrons are produced at the chamber slot. The effective increment of the density near the beam is order of 1% of the above value. Secondary emission amplifies the electrons even the number of initial electrons are small. To evaluate the electron density more precisely, a simulation in which

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ELECTRON CLOUD AT SuperKEKB

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Abstract

Several measures such as TiN coated aluminum ante-chambers, clearing electrodes and grooved structure have been taken to mitigate the electron cloud effects in the SuperKEKB positron ring. During phase 1 operation of SuperKEKB, where solenoid windings were not applied as a measure against the electron cloud, the electron cloud effects such as the beam size blowup, the nonlinear pressure rise, the betatron tune shift along a bunch train and the transverse coupled bunch instability were observed. Permanent magnets attached at aluminum-bellows-chambers that generate longitudinal magnetic field in the chambers were effective to reduce the electron cloud. In case of no solenoid windings, the threshold linear current density of the blowup was increased from 0.04mA/RF bucket in KEKB to 0.17mA/RF bucket in SuperKEKB owing to the measures mentioned above. This paper covers following subjects about the electron cloud at SuperKEKB, 1) mitigation methods against the electron cloud, 2) observation of the electron cloud effects in phase 1 operation and 3) measures against the EC toward phase 2 operation which will start in the late FY2017.

MEASURES AGAINST THE ELECTRON CLOUD IN SUPERKEKB

SuperKEKB is the upgraded electron-positron collider of the KEKB B-factory [1]. The design luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ will be achieved by so called nano-beam scheme. Machine upgrades include the replacement of round copper chambers in LER to aluminum TiN coated ante-chambers so as to withstand large beam currents and mitigate the electron cloud effects.

A threshold electron density of the strong head-tail instability caused by the electron cloud (EC) in SuperKEKB Low Energy Ring (LER) is estimated to be 2.7×10^{11} m^{-3} by an analytic estimate [2]. A threshold electron density of 2.2×10^{11} m^{-3} calculated by a simulation [3] is consistent with the analytic estimate. Growth time of the coupled bunch instability (CBI) due to the EC is estimated to be 50 turns at the threshold electron density of the single bunch instability [3], which is larger than an expected damping time of the transverse bunch by bunch feedback system. Thus the target electron density near the beam against the EC instabilities was taken to be less than 1×10^{11} m^{-3}.

The electron density near the beam in SuperKEKB was estimated to be 5×10^{12} m^{-3} based on results from measurements at KEKB assuming a round copper chamber with a diameter of 94 mm, no solenoid field, 4 ns bunch spacing and the bunch current of 1 mA [4]. Main contribution comes from the drift space. Based on studies at KEK following measures were considered at the SuperKEKB LER [4], TiN coated aluminum ante-chambers and solenoid windings in the drift space in arc sections, TiN coated aluminum ante-chambers with grooved surface in dipole chambers and copper ante-chambers with clearing electrodes in wiggler chambers. Taking these measures, the electron density near the beam is expected to be less than 1.0×10^{11} m^{-3}[4].

OBSERVATION OF THE ELECTRON CLOUD EFFECTS IN PHASE 1

Phase 1 operation of SuperKEKB was carried out from February 2016 to June 2016 without final focus quads and the Bell-II detector. The main purposes of the phase 1 were vacuum scrubbing, optics tuning to achieve small emittance beams and a background study with Beast detectors. Measures against the EC taken until the start of phase 1 operation were TiN coated aluminum ante-chambers, grooved surface in dipole chambers and clearing electrodes in wiggler sections. Solenoid windings which were assumed at the initial design were not applied in this stage of the commissioning.

EC Related Events

The vertical beam size blowup was observed at LER by an x-ray beam size monitor. At the same time, pressures at whole LER ring showed a nonlinear behavior against the beam current above ~500 mA [5]. The fill pattern was one long train of 1576 bunches with average bunch separation of 3.06 RF buckets. A separation of adjacent

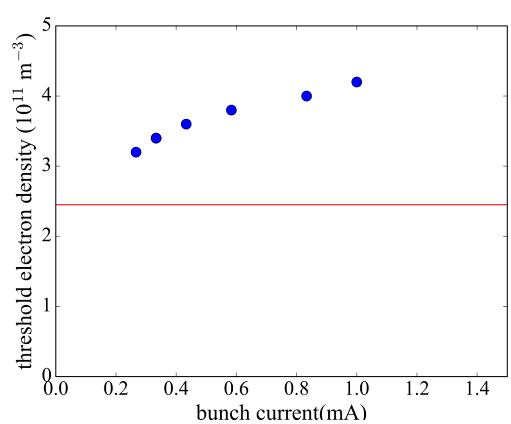

Figure 1: Simulated threshold electron density of the strong head-tail instability caused by the electron cloud as a function of the bunch current. A red line shows an analytic estimate.

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ELECTRON CLOUD AND COLLECTIVE EFFECTS IN THE INTERACTION REGION OF FCC-ee

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Abstract

The FCC-ee is an e^+e^- circular collider designed to accommodate four different experiments in a beam energy range from 91 GeV to 350 GeV and is a part of the Future Circular Collider (FCC) project at CERN. One of the most critical aspects of this new very challenging machine regards the collective effects which can produce instabilities, thus limiting the accelerator operation and reducing its performance. The following studies are focused on the Interaction Region of the machine. This paper will present preliminary simulation results of the power loss due to the wake fields generated by the electromagnetic interaction of the beam with the vacuum chamber. A preliminary estimation of the electron cloud buildup is also reported, whose effects have been recognized as one of the main limitations for the Large Hadron Collider at CERN.

INTRODUCTION

The Future Circular Lepton Collider FCC-ee has been designed as an e^+e^- collider with a centre-of-mass energy from 91 to 350 GeV and 100 km circumference. In this paper we will focus on the Interaction Region (IR) of the machine, whose proposed layouts are shown in Fig. 1. While the symmetric layout [1] has synchrotron radiation (SR) masks to shield the two final focusing quadrupoles and a 12mm pipe radius , the asymmetric layout [2] presents two ingoing pipes with 13mm radius and two outgoing pipes with a larger radius of 20mm. In particular, this latter design will allow high order modes that remain trapped in the IR to escape to the outside through the outgoing pipes, whose cutoff frequancy is the same as the IP. Moreover, in the asymmetric optics the final quadrupole closer to the IP is thinner and stronger. High Order Modes (HOMs) and electron cloud studies presented in this paper will be focused on both the layouts, since there are still many open questions. Regarding all the FCC-ee beam pipes (including those at IR), it was decided to use them at room temperature as in the case of KEKB, SuperKEKB and other lepton colliders. However, even if there will be no cryogenic systems, the beam heat load represents one of the major issues to be analyzed in the machine, in order to avoid extra heating and eventual damage of the background.

By considering a uniformly filled machine, i.e. a train of M bunches covering the full ring circumference ($M = h$ with h the harmonic number) with bunch spacing $\tau_b = \frac{2\pi}{h\omega_0}$ where ω_0 is the revolution frequency, the total power loss of the beam depends only on the real part of the longitudinal component of the coupling impedance [3]:

$$P_{loss} = I^2 \sum_{p=-\infty}^{+\infty} |\Lambda(pM\omega_0)|^2 Re[Z_\parallel(pM\omega_0)] \quad (1)$$

where Λ is the bunch spectrum, $Re[Z_\parallel]$ is the real part of the longitudinal impedance and $I = \frac{MNe}{T_0}$ is the average beam current with N the bunch population and T_0 the revolution period of the machine.

Possible beam heat load sources in the IR are the resistive wall wake fields, geometric wake fields due to the step transitions of the SR masks, the HOMs that remain trapped in the IR and the electron cloud in the two final focusing quadrupoles.

IMPEDANCE STUDIES

This section will present preliminary results of the power losses due to geometrical and resistive wall impedances and trapped modes carried out by analytical tools and simulation codes.

Heat Load due to Resistive Wall Impedance

The resistive wall impedance is produced by the finite resistivity of the beam pipe. If we consider a circular pipe with radius b the classic analytic formula for the power loss per unit length due to resistive wall is given by:

$$\frac{P_{loss}}{L} = \frac{1}{T_0}\frac{N^2e^2c}{4\pi^2 b\sigma_z^{\frac{3}{2}}}\sqrt{\frac{Z_0}{2\sigma_c}}\Gamma\left(\frac{3}{4}\right)n_b \quad (2)$$

where N is the bunch population, e the elementary charge, σ_z the bunch length, σ_c the conductivity of the material, Z_0 the vacuum impedance and n_b the number of bunches. In the evaluation of the resistive wall impedance, we considered a beam pipe with 12mm radius and three layers: a first layer of aluminum or copper with 2mm thickness, then 2mm of dielectric and finally stainless steel with resitivity $6.89 \cdot 10^{-7}\Omega m$. Simulations were performed by using the Impedancewake2D code [4] and results are shown in Fig. 2, for both the aluminum (with a conductivity $\sigma_{Al} = 3.77 \cdot 10^7 S/m$) and copper (with conductivity $\sigma_{Cu} = 6 \cdot 10^7 S/m$). The results for the power loss are summarized in Table 1 for the two energy cases of 45.6 GeV and 175 GeV at the nominal beam parameters.

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FEEDBACK SYSTEMS FOR FCC-EE

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Abstract

In this paper, some preliminary considerations on the feedback systems for FCC-ee are developed. Bunch-by-bunch feedback systems have been designed in the last years for other e+/e- colliders like PEP-II, KEKB, DAFNE, SuperB and SuperKEKB. In all these cases, similar approaches have been implemented, even if some design variations have been suitable or necessary for different reasons. Bunch-by-bunch feedback systems are based on the concept that the barycenter of each bunch moves with harmonic motion around the equilibrium point in three planes (L, H, V). The feedback copes with the forcing excitation by producing damping correction for each individual bunch. This is possible managing every single bunch by a dedicated processing channel in real time. For FCC-ee the very high number of stored bunches requires much more power in terms of processing capability for the feedback systems. Ring length (100 Km) and very low fractional tunes must be also considered requiring for a more effective strategy in the feedback system design.

INTRODUCTION

A new tunnel with a circumference of 100 Km around the CERN area could host the proposed FCC-ee (Future Circular Collider e-/e+), in the past also called TLEP (Triple LEP). As alternative, the tunnel can host FCC-hh, a 100 TeV center-of-mass energy-frontier hadron-hadron collider or FCC-he, a proton-electron collider. Beside the lepton accelerator, the hadron one faces additional challenges, such as high-field magnet design, machine protection and effective handling of large synchrotron radiation power in a superconducting machine [1] [2].

FCC-ee [3][4], operating at four different energies for precision physics of Z, W, and Higgs boson and top quark, represents a significant push in terms of technology and design parameters. Pertinent R&D efforts include the RF system, top-up injection scheme, optics design for arcs and final focus, effects of beamstrahlung, beam polarization, energy calibration, and power consumption. Finally, feedback systems in the three oscillation planes (H, V, L) are necessary, and some preliminary considerations are carried on in this paper.

To achieve this goal, in the following a fast sketch of the foreseen instabilities impacting the possible design of the FCC-ee feedback systems is reported.

In the past two decades, bunch-by-bunch feedback systems have been designed for several e+/e- colliders like PEP-II [5] [6] [7], DAFNE [8], KEKB [9] and more recently for SuperB [10] (feedback built and installed at DAFNE [11]) and SuperKEKB [12].

In all these cases, very similar or identical approaches have been implemented, even if some design variations have been possible for technological progress or convenient for specific reasons.

All these feedback systems are based on the concept that the barycenter of each bunch moves with harmonic motion around the equilibrium point in each of the three planes (H, V, L).

The feedback copes with the forcing excitation by calculating individual damping correction kicks for each bunch. This is possible by managing in real time every single bunch by a dedicated processing channel implementing a FIR (Finite Impulse Response) filter at n taps, with n from 1 to 32, chosen by the operator. In each system, the phase response must be found experimentally with great care to give the best correction kick for each bunch. Betatron and synchrotron phase advance at pickups and kickers determines the filter setup along with other parameters.

For the FCC-ee feedback systems, a similar design is proposed in this paper taking also in consideration the peculiarities of the collider: a very high number of stored bunches and a huge harmonic number, fast instability growth rates and remarkable ring length.

Figure 1: Parameter list from FCC Week 2015 M.Migliorati's talk with arrows indicating the most relevant parameters for a feedback design point of view.

Parameter list - FCC-ee Z-pole, crab waist, 2 IPs

parameter	Z	W	H	t
Circumference (km) →	100	100	100	100
Beam energy (GeV)	45.5	80	120	175
Beam current (mA) →	1450	152	30	6.6
RF frequency (MHz) →	400	400	400	400
RF Voltage (GV)	0.2	0.8	3	10
Mom compaction [10^{-5}]	0.7	0.7	0.7	0.7
Bunch length [mm](*)	1.63	1.98	2.0	2.1
Energy spread(*)	3.7×10^{-4}	6.5×10^{-4}	1.0×10^{-3}	1.4×10^{-3}
Synchrotron tune	0.025	0.037	0.056	0.075
Bunches/beam →	90300	5162	770	78
Bunch population [10^{11}]	0.33	0.6	0.8	1.7
Betatron tune	350	350	350	350

(*) without beamstrahlung (no collision)

FORESEEN INSTABILITIES

The preliminary evaluation of the foreseen instabilities is based on the talks held by M. Migliorati at the FCC Week 2015 (First Annual Meeting of the Future Circular Collider Study) [13] and in a March 2016 CERN meeting (First Annual Meeting of the Future Circular Collider Study) [14]. In the following Fig. 1 a parameter list is shown with the arrows indicating the most relevant parameters for a feedback design point of view.

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OPTICS CORRECTION AND LOW EMITTANCE TUNING AT THE PHASE 1 COMMISSIONING OF SuperKEKB

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Abstract

The SuperKEKB collider has finally come to the first commissioning, Phase 1 without the final focus system and before Belle II detector roll-in. In order to accomplish a extremely high luminosity of 8x10^{35} $cm^{-2}s^{-1}$, the nano-beam scheme is adopted. Since the vertical emittance is one of keys in this scheme, optics corrections for low emittance tuning are applied. The non-interleaved sextupole scheme is utilized in the arc section. Skew quadrupole-like corrector is equipped for each sextupole. These skew quadrupole-like correctors can correct both X-Y coupling and physical vertical dispersions which induce the vertical emittance. Beta function and physical horizontal dispersion are corrected by fudge factors of quadrupoles and/or horizontal orbit bumps at the sextupoles. Overall optics performance as well as the strategy of low emittance tuning is also presented.

INTRODUCTION

The SuperKEKB collider [1] is an asymmetric-energy and a double-ring electron-positron collider. The energy of the electron ring is 7 GeV(HER) and the positron ring is 4 GeV(LER). The collision point is one and the circumference is 3 km. The target luminosity is 8×10^{35} $cm^{-2}s^{-1}$, which is 40 times as high as the predecessor KEKB collider [2]. In order to accomplish the extremely high luminosity, a nano-beam scheme [3] is adopted.

There are three stages for the commissioning of SuperKEKB; Phase-1, Phase-2, and Phase-3. The initial commissioning was done during Phase-1 without the final focus system before Belle II roll-in. The Phase-1 commissioning was started in February 2016 and operated until the end of June 2016 for about 5 months. The commissioning for Phase-2 will start in November 2017 and will operate for 5 months with the final focus system and Belle II detector. The first collision will be performed in Phase-2, however, the vertex detector will not be installed. The physics run with the full detector in Phase-3 will start October 2018, then the luminosity will increase gradually by squeezing the beta function at the IP and increasing the beam currents toward the target luminosity.

The vertical emittance is one of the most important issues in Phase-1 since the luminosity performance significantly depends on the coupling parameter in the nano-beam scheme. Table 1 shows machine parameters in Phase-1.

Table 1: Machine Parameters in Phase-1 (Without Intrabeam Scattering)

	LER	HER	Unit
E	4.000	7.007	GeV
I	1.01	0.87	A
n_b	1576		
ε_x	1.8	4.6	nm
α_p	2.45×10^{-4}	4.44×10^{-4}	
σ_δ	7.52×10^{-4}	6.30×10^{-4}	
V_{RF}	7.56	12.61	MV
σ_z	4.6	5.3	mm
ν_s	-0.0192	-0.0253	
ν_x	44.53	45.53	
ν_y	46.57	43.57	
U_0	1.76	2.43	MeV
τ_x	46	58	msec

OPTICS MEASUREMENTS AND CORRECTIONS

The lattice for Phase-1 is the same lattice as those of Phase-2 and Phase-3 except for the interaction region(IR). Since there is no final focus magnet in the vicinity of the IP, the field strengths of quadrupole magnets in the IR are adjusted so as to connect the arc lattice. The optics tuning [4] without the final focus, the solenoid field, and the local chromaticity corrections can be performed for Phase-1. The lattice designs of the so-called interaction region in the LER and the HER are shown in Fig. 1.

The optical functions such as beta functions, dispersions, and X-Y couplings were measured and corrected in the LER and HER, respectively. The beta functions are obtained by orbit responses induced by six kinds of dipole correctors for each x and y direction [5]. The physical dispersions are measured by orbit displacements for the rf frequency shifts between -500 Hz and +500 Hz. Note that the dispersions are physical and different from normal mode dispersions. In the case of the X-Y couplings, vertical leakage orbits from horizontal orbits induced by six kinds of horizontal dipole correctors are used to correct the X-Y couplings instead of four X-Y coupling parameters of r_1 - r_4. The number of BPMs is 438 in the LER and 460 in the HER to measure closed orbits. The BPM gain mapping and the beam based alignment(BBA) have been performed before the optics tuning.

In order to correct the beta functions, the measured beta functions and phase-advance are compared with those calculated by the reference optics and amount of the correc-

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LUMINOSITY TUNING AT KEKB

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Abstract

KEKB achieved the world's highest luminosity. One of the key issues for the high luminosity at KEKB was a luminosity tuning which was done almost all the time even during the physics run to suppress the beam-beam blowup. In this talk, those experiences are summarized.

INTRODUCTION

KEKB [1] was an energy-asymmetric double-ring collider for B meson physics. KEKB consisted 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 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 experiences on the luminosity tuning. Some of them may be useful in future colliders such as SuperKEKB or a high-luminosity circular e+e- Higgs factory. Achievements of KEKB and details of commissioning are described elsewhere [2] [3].

MACHINE PARAMETERS RELATED TO LUMINOSITY

As is well known, the luminosity is expressed as

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}.$$

Here, γ and r_e are the Lorentz factor and the electron classical radius and the index of ± denotes the positron or electron. σ_y^* and σ_x^* are the vertical and horizontal beam sizes at the IP, respectively. I, ξ_y and β_y^* denote the total beam current, the vertical beam-beam parameter and the vertical beta function at the IP, respectively. R_L and R_{ξ_y} are the reduction factors for the luminosity and the vertical beam-beam parameter due to the hourglass effect and the crossing angle, respectively. In usual cases, the beam size ratio is much smaller than unity and the two reduction factors are not much different from unity. Therefore, the luminosity is almost determined by the three parameters; *i.e.* the beam current (I), the beam-beam parameter (ξ_y) and the vertical beta function at the IP (β_y^*). Table 1 shows machine parameters of KEKB at the time when the highest luminosity was achieved.

Table 1: Machine Parameters of KEKB

Parameters	LER	HER	Units
Energy	3.5	8.0	GeV
Circumference	3016		m
I_{beam}	1.637	1.188	A
# of bunches	1585		
I_{bunch}	1.03	0.75	mA
Ave. Spacing	1.8		m
Emittance	18	24	nm
β_x^*	120	120	cm
β_y^*	5.9	5.9	mm
Ver. Size@IP	0.94	0.94	μm
RF Voltege	8.0	13.0	MV
ν_x	.506	.511	
ν_y	.561	.585	
ξ_x	.127	.102	
ξ_y	.129	.090	
Lifetime	133	200	min.
Luminosity	2.108		10^{34}cm^{-2}s^{-1}
Lum/day	1.479		fb^{-1}

BEAM CURRENTS AND VERTICAL BETA FUNCTIONS AT THE IP

The HER beam current of 1.188 A in Table 1 is near the hardware limit. The design beam current of HER was 1.1 A. On the other hand, the design beam current of LER was 2.6 A and there was large room to increase LER beam current from the viewpoint of the hardware limit. There are evidences that this saturation of the luminosity against the LER beam current is caused by the effects of the electron clouds [3]. Based on these experiences, we will take more fundamental countermeasures against the electron clouds effect at SuperKEKB such as adoption of antechmbers with TiN coating. As for the vertical beta function at the IP (β_y^*), the minimum values are determined by the hourglass effect. Although lower values than 5.9 mm were possible from the viewpoint of the dynamic aperture and the detector beam background, the lower β_y^* did not bring a higher luminosity.

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COUPLING AND DISPERSION CORRECTION FOR THE TOLERANCE STUDY IN FCC-EE

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Abstract

The FCC-ee study is investigating the design of a 100 km e+/e- circular collider for precision measurements and rare decay observations in the range of 90 to 350 GeV center of mass energy with luminosities in the order of $10^{35} cm^{-2} s^{-1}$. In order to reach such performances, an extreme focusing of the beam is required in the interaction regions with a low vertical beta function of 2 mm at the IP. Moreover, the FCC-ee physics program requires very low emittances never achieved in a collider with 1.3 nm for ϵ_x and 2 pm for ϵ_y at 175 GeV, reducing the coupling ratio to around 2/1000. With such requirements, any field errors and sources of coupling will introduce spurious vertical dispersion which degrades emittances, limiting the luminosity of the machine. This study describes the status of the tolerance study and the impact of errors that will affect the vertical emittance. In order to preserve the FCC-ee performances, in particular ϵ_y, a challenging correction scheme based on dispersion free steering and linear coupling correction is proposed to keep the coupling and the vertical emittance as low as possible.

INTRODUCTION

Electron-positron circular colliders profit from small vertical beam size due to vertical emittances close to the quantum excitation. The FCC-ee machine is foreseen to run at 4 different energies in order to perform precision measurements of the Z and W resonance and the Higgs and top. In order to produce a high luminosity, an extreme focusing of the beam is required in the interaction regions with a low vertical beta function of 2 mm at the IP. The baseline foresees very low emittance never achieved in a collider with 1.3 nm for ϵ_x and 2 pm for ϵ_y at 175 GeV, bringing down the coupling ratio to 2/1000. The main parameters are presented in Tab. 1. With such performances, the chromaticities reach several hundred units and the high beta functions in the interaction regions cause the machine to be very sensitive to lattice errors, resulting in large distorsion of the vertical dispersion. As a consequence, the vertical emittance will be enlarged, since

$$\epsilon_y = \left(\frac{dp}{p}\right)^2 (\gamma D^2 + 2\alpha DD' + \beta D'^2) \qquad (1)$$

where D is the vertical dispersion, D' the dispersion derivative with s, $\frac{dp}{p}$ the momentum spread, γ, β, α are the lattice parameters. This article present the status of the tolerance of the FCC-ee lattice to errors such as magnet misalignements, rolled angles, which are the main cause of vertical dispersion and emittance blowup. The main challenge is to establish an optics correction methodology suitable for large machines with such challenging beam parameters baseline such as FCC-ee.

FCC-EE RACETRACK LAYOUT

The FCC-ee machine is foreseen to run at 4 different energies and in term of tolerance, the biggest challenge comes from the 175 GeV case, due the 8 GeV energy loss per turn by synchrotron radiation, as shown in Tab. 1. A constraint being that the lepton and hadron collider layout should fit together, several lattice scenarios with different interaction regions and sextupole layouts are under study (See [1] [2]). This paper will show mainly results about a racetrack lattice, with 2 RF sections and a LEP-like interaction region, where the final doublet quadrupoles focus the beam down to 2 mm β_y^*. The IR and arc optics are shown in Fig. 1. In this lattice, the chromaticity is corrected with sextupoles in the arcs including a matching from arc to IP of the Montague functions, whereas another lattice option provides as well a local chromaticity correction at the IPs [2]. The two layouts are shown in Fig. 2 for a lattice with the LEP-like IR and chromaticity correction in the arcs and Fig. 3 for a lattice with a local chromaticty correction at the IPs.

Table 1: Baseline Beam Parameters in FCC-ee

Beam Energy (GeV)	**120**	**175**
Beam current (mA)	30	6.6
Bunch/beam	780	81
Bunch population (10^{11})	0.8	1.7
Horizontal ϵ (nm)	0.61	1.3
Vertical ϵ (nm)	0.0012	0.0025
Momentum compaction (10^{-5})	0.7	0.7
Hor. β^* at the IP (mm)	1000	1000
Vert. β^* at the IP (mm)	2	2
Energy loss/turn (GeV)	1.67	7.55
Total RF Voltage (GV)	3	10

For FCC-ee, the so-called sawtooth effect is particulary important at 175 GeV: with 8 GeV of energy loss per turn, the off-momentum particles are following the dispersive orbit until they reach the next RF section. This effect causes an orbit distorsion of about 1.5 millimeter, which is very problematic when the beam goes off center through the strong sextupoles. Two options are foreseen to alleviate this problem: the FCC-ee lattice can be tapered either fully or partially. In the fully tapered option, every magnet strength (dipole, quadrupole, sextupole) is adapted to the current energy loss. In the partially tapered option - or sectorwise version- the machine

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BEAM INSTRUMENTATION NEEDS FOR A FUTURE ELECTRON-POSITRON COLLIDER BASED ON PEP-II OBSERVATIONS*

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Abstract

Instrumentation for e+e- colliders is very important to monitor collider operations, detector data taking quality, accelerator physics, hardware status, and beam error analysis. The required instrumentation grows with the complexity of the collider and must be constantly advanced to higher functionality.

Future e+e- colliders will operate with many bunches, short bunch lengths, small emittances, high currents, and small interaction point betas. The stability of the colliding beams with these characteristics will depend on detailed, high precision, and continuous measurements. The various beam measurement requirements and techniques will be discussed with using PEP-II observations [1-13].

PEP-II BEAM MEASUREMENTS

The topics covered will be:

- Beam parameter overview
- Beam position (single pass and stored)
- Bunch transverse and longitudinal instabilities
- Beam tunes
- Beam size
- Bunch length
- Beam loss rates
- Beam lifetime
- IP luminous size
- HOM measurements
- Chamber vacuum pressure

Table 1: PEP II Parameters and Ultimate Potential

Parameter	Units	Design	April 2008 Best	2008 Potential
I+	mA	2140	3210	3700
I-	mA	750	2070	2200
Number bunches		1658	1722	1740
β_y*	mm	15-25	9-10	8.5
Bunch length	mm	15	11-12	9
ξ_y		0.03	0.05-0.06	0.07
Luminosity	$x10^{33}$	3	12	20
Int lumi / day	pb^{-1}	130	911	1300

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The parameters of PEP-II are shown in Table 1. PEP-II operated until April 2008. The general layout of the instrumentation in the HER ring is shown in Figure 1. The LER layout is similar but reversed relative to IR 2 where the BaBar detector was located. The instrumentation needs of PEP-II covered every possible beam and accelerator parameter and most were crucial to the ultimate operation of the accelerator and the detector. During the design of PEP-II, the instrumentation was integrated into the collider design. For construction, the desire was to be as inexpensive as possible but as broad as possible. For operations, the need was for low power costs, reliable running, and low maintenance costs with as many standard units as possible.

BEAM POSITION

The beam position monitors BPM for PEP-II were button type feedthroughs as shown in Figure 2. The diameter was 15 mm and resolution 20 microns. They worked well except at the highest currents (>3 A) as the button heads could fall off. The BPMs were used to make many measurements: initial turn observations (Figures 3 and 4), tune measurements in the longitudinal and transverse planes of stored beams (Figures 5 and 6), orbit corrections and feedback, and feedback of the tunes with beam current (Figure 7) which was done automatically by computer.

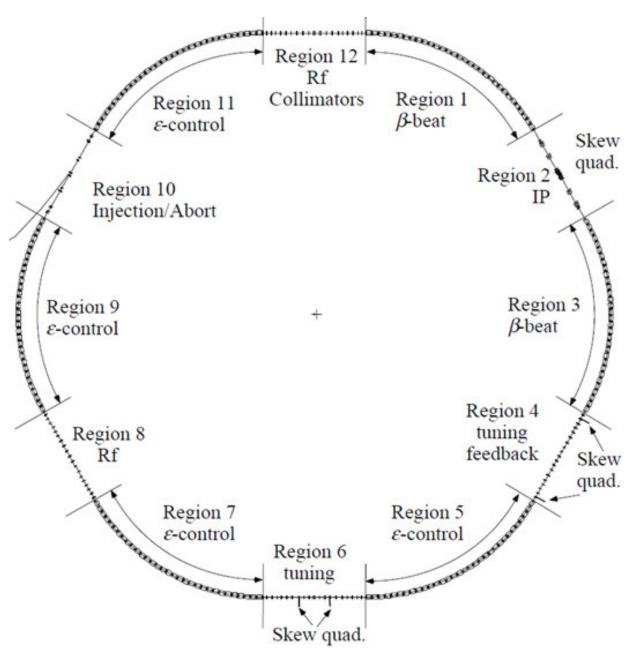

Figure 1: PEP-II layout with insturmentation.

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BEAM INSTRUMENTATION IN SUPERKEKB

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Abstract

SuperKEKB is the upgraded collider of the KEK B-factory (KEKB). Beam instrumentation of KEKB has been commissioned in phase 1 operation which has just finished in this June. A beam position monitor system consists of super heterodyne detectors, turn by turn log-ratio detectors with fast gates and detectors for the orbit feedback to maintain stable collision. New x-ray beam profile monitors with the coded aperture method are installed. A bunch-by-bunch feedback system is upgraded using low noise frontend electronics and new 12 bits iGp digital filters. An introduction of instrumentation of SuperKEKB and its performance in phase 1 operation will be given here briefly.

INTRODUCTION

SuperKEKB is the upgraded electron-positron collider of the KEKB B-factory [1]. The design luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ will be achieved using so-called nano-beam scheme. Main machine upgrades include the replacement of cylindrical copper chambers in LER to those with aluminum TiN coated ante-chambers so as to withstand large beam current and also mitigate the electron cloud effect, a new final focus system in order to adopt the nano-beam scheme and the construction of a positron damping ring. Phase 1 operation has just finished in June 2016 [1].

This paper introduces the beam instrumentation in SuperKEKB and shortly comments on its performance in phase 1 operation. Detailed reports to which this paper often refers are appeared in [2, 3, 4, 5] and their references.

BEAM POSITION MONITOR SYSTEM [2,3]

The number of beam position monitors (BPMs) in SuperKEKB is 445 in the low energy ring (LER) and 466 in the high energy ring (HER). The BPM chambers and button electrodes in HER are reused from KEKB. New button electrodes whose diameter is 6mm are installed on new LER vacuum chambers. The electrode is a flange type for easy replacement. A pin-type inner conductor is adopted for tight electrical connection.

A narrowband detector system which follows that in KEKB is a main detection system. A new narrowband detector with a detection frequency of 509 MHz has been developed and used in LER since the cutoff frequency of the new LER ante-chamber is below the detection frequency of the KEKB detector of 1 GHz. Analogue

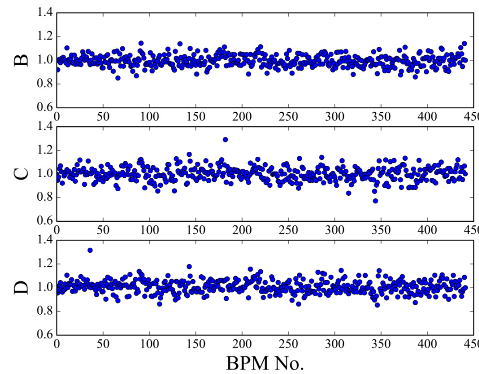

Figure 1: BPM gain mapping of LER relative to electrode A [3].

circuits are housed in an aluminum shield case. An isolator is put in front of a variable attenuator to reduce change of signal level upon switching of the attenuator. Discrete PIN diodes with DC coupling are used in a multiplexer and the attenuator to improve transient characteristics such as spike and ringing. S/N ratio larger than 90 dB is achieved by 2048 points FFT and averaging of 8 points data with CW signal, which corresponds to position resolution better than 0.5μm.

Gain calibration [6] has been applied by the narrowband detection system. Imbalance of signal level of four channels was measured by beam and then corrected in position calculation. Figure 1 shows measured relative signal levels with respect to that of the electrode A. Dispersion of the LER gain is slightly larger than that of HER, which probably reflects the difference of flange-type connection (LER) and brazing (HER) to fix the BPM to the chamber.

Beam based alignment [7] has been applied to measure the BPM position offset against the center of an adjacent quadrupole. The rms values of the measured offset (x/y) were 0.570 mm/0.222 mm in LER and 0.505 mm/0.392 mm in HER [8]. Rotation angle of BPMs was measured prior to the operation to correct the position data of the beam. The rms values of rotation were 0.62 mrad and 0.78 mrad in HER and LER respectively.

Position resolution of the narrowband system was measured by the three BPM method. The obtained resolution is better than 3μm and 5μm in LER and HER, respectively, for most of the BPMs. The result represents upper bound of the resolution because the measurement could be affected by beam movement between switching interval of a multiplexer. The beam current dependence of BPM resolution was small because signal voltage was adjusted by the variable attenuator as a function of the beam current. Anti-correlation between resolution and signal level was seen.

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MEASUREMENT OF BEAM POLARISATION AND BEAM ENERGY IN ONE DEVICE*

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Abstract

Electron beam interaction with the monochromatic laser radiation produces scattered photons and electrons due to the Compton effect. Both types of scattered particles carry the information about the polarisation (if any) and the energy of initial electrons in the beam. In this report we focus on the properties of the scattered electrons. After a bending magnet these electrons leave the beam and their X-Y space distribution is measured by the 2D pixel detector. We show that if the electron beam vertical emittance is sufficiently small, the shape of this distribution is an ellipse. Measurement of the length of the X-axis of this ellipse allow to calibrate accurately the bending field integral seen by the beam. The distribution of the electrons within the ellipse depends on the initial beam polarisation, allowing to measure the its degree and direction. So we propose a universal Compton polarimeter with a unique feature of precise calibration of the LEP-style beam energy spectrometer. The approach is thought to be useful for the future high-energy e+/e- colliders, while the feasibility tests may be performed on existing accelerators.

INTRODUCTION

An illustration for the process of Inverse Compton Scattering (ICS) is presented in Fig. 1:

Figure 1: Inverse Compton scattering: the thickness of the arrows qualitatively represents the energies of the particles.

Considering the case when $\varepsilon_0, \varepsilon, \omega \gg \omega_0$ let's introduce the scattering parameter

$$u = \frac{\omega}{\varepsilon} = \frac{\theta_\varepsilon}{\theta_\omega} = \frac{\omega}{\varepsilon_0 - \omega} = \frac{\varepsilon_0 - \varepsilon}{\varepsilon}, \qquad (1)$$

where $u \in [0, \kappa]$ and $\kappa = 4\omega_0\varepsilon_0/mc^2$ is twice the ratio between the photon and electron energies in the electron rest frame. The photon and electron scattering angles are:

$$\eta_\omega \equiv \gamma\theta_\omega = \sqrt{\frac{\kappa}{u} - 1}; \quad \eta_\varepsilon \equiv \gamma\theta_\varepsilon = u\sqrt{\frac{\kappa}{u} - 1}. \qquad (2)$$

Further we consider an ICS of monochromatic laser radiation on the beam of ultra-relativistic electrons. ICS cross section is sensitive to the polarisation of initial electron and photon beams:

$$\frac{d\sigma}{du\,d\varphi} = \frac{r_e^2}{\kappa(1+u)^2} \times \qquad (3)$$

$$\times\left\{\left(2 + \frac{u^2}{1+u} + 4\frac{u}{\kappa}\left[\frac{u}{\kappa} - 1\right]\left[1 - \xi_\perp \cos(2(\varphi - \varphi_\perp))\right]\right) + \right.$$

$$\left. + \xi_\circlearrowright \left(\zeta_\parallel \frac{u(u+2)(\kappa - 2u)}{\kappa(1+u)} - \zeta_\perp \frac{2u^2\sqrt{\kappa/u - 1}}{\kappa(1+u)} \sin\varphi\right)\right\},$$

where

- φ is the azimuthal angle of scattered electron relative to horizon,
- $\xi_\perp$ and $\varphi_\perp$ are the degree and direction of laser beam linear polarisation,
- $\xi_\circlearrowright$ is the degree and sign of laser circular polarisation,
- $\zeta_\parallel$ and $\zeta_\perp$ are the signs and degrees of longitudinal and vertical transverse electron beam polarisations.

Figure 2: ICS cross section for small and large κ. The dashed lines illustrate the influence of $\xi_\circlearrowright\zeta_\parallel$.

Experiments with polarised e± beams were performed at many facilities (ACO, VEPP-2, SPEAR, DORIS, TRISTAN, VEPP-4, CESR, LEP, HERA...). Compton polarimeters usually dealt with scattered photons. General layout of ICS

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NEW CAVITY TECHNIQUES AND FUTURE PROSPECTS*

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Abstract

In the recent decades, Superconducting cavities have been widely used to accelerate electron, positron, and ions. Most SRF cavities are made from bulk niobium till now, which has developed fast in the past years and is hard to advance more. Take 1.3 GHz 9-cell cavity for example, the quality factor (Q) can keep above 1e10 when the accelerating field (E_{acc}) reach 40 MV/m, which nearly touch the theoretical limitation of Q and E_{acc} for bulk niobium. For large superconducting accelerators in future (FCC, CEPC, etc), Q and E_{acc} should be increased significantly compared to now, which can reduce the cryogenic power and use fewer cavities. So new cavity material and techniques are being studied at accelerator laboratories, while Nitrogen doping (N-doping) and Nb_3Sn have developed quickly and been paid attention to mostly [1]. N-doping can increase Q by one time for 1.3 GHz 9-cell cavity, which have been adopted by Linac Coherent Light Source II (LCLS-II) at SLAC [2].

INTRODUCTION

In recent years, N-doping technology has been proposed and proven to increase Q of superconducting cavity obviously, which lowers the BCS surface resistance. It was discovered in 2012 at FNAL, which has been promoted by FNAL, JLAB and Cornell together. Since 2013, there have been over 60 cavities nitrogen doped in USA laboratories. After N-doping, Q of 1.3 GHz 9-cell cavities increased to $3*10^{10}$ at $E_{acc}=16$ *MV/m*, while $1.5*10^{10}$ without N-doping [3].

Besides, thin film technologies have also developed very quickly, which include Nb_3Sn/Nb, Nb/Cu et al. There've been many good results of vertical tests. And superconducting cavities made of thin film would be more practical in future.

RESEARCH OF N-DOPING

Theory

N-doping of niobium can create a niobium nitride layer, which is about 2-micron deep and harmful to Q value. So this layer is removed by 5-micron electro polishing. Then, the diffraction pattern of transmitted electron microscope shows only clean niobium phase without nitride. It indicates that the interstitial nitrogen contributes to the increase of Q value.

N-doping has been proven to prevent Q-slope at medium accelerating fields for superconducting cavities, which is found to reduce the BCS surface resistance compared to ILC/XFEL standard by 50%. The non-trapped flux related residual resistance can also be reduced to 2 nΩ with N-doping [4]. But it also results to undesirable lower quench field. The levels of N-doping affect R_{BCS}, R_0, R_{MAG} and quench field, which is important and needs deeper research.

Achievements

The experiments of N-doping succeeded on the 1.3 GHz cavities firstly. And then it was applied to 650 MHz cavities.

Based on the research achievements above, the N-doping technique has been adopted by the LCLS-II project. To transfer it to industrial vendors, the protocol of N-doping has been optimized, as Table 1 [5].

Table 1: N-doping Parameters

Step	Temperature (℃), Pressure (Pa)	Duration (min)
Hydrogen degassing	800 ± 10, 0	180 ± 5
N-doping	800 ± 10, 3.5 ± 10	2 ± 0.1
Vacuum annealing	800 ± 10, 0	6 ± 0.1

Table 1 shows the latest recipe of N-doping adopted by LCLS-II, which is known as "2/6". It stands for 2-minute nitrogen injection and 6-minute annealing, both at 800C. Then, 5 microns of cavity inner surface are removed by electro polishing [6]. So it's different from the standard protocol of 1.3 GHz 9-cell cavities for XFEL. The 120C baking is cancelled, which may cause a decrease in Q and quench fields for cavities nitrogen doped.

Details of N-doping for LCLS-II are deeply analysed in [7]. Figure 1 shows the vertical test results of LCLS-II cavities adopted 2/6 recipe at FNAL and JLAB. All cavities meet the design target of 2.7e10@16MV/m at 2K. Average Q is 3.5e10@16MV/m at 2K, and average quench field reach 22 MV/m [2, 4].

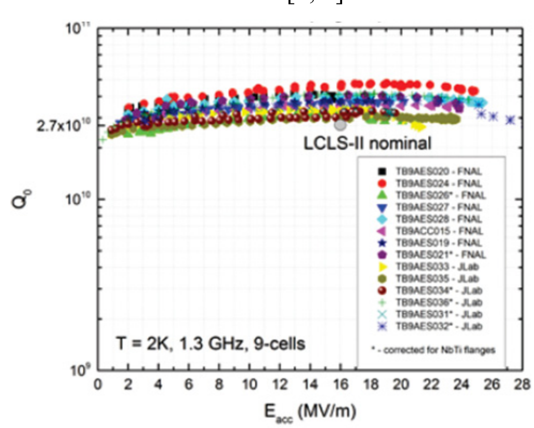

Figure 1: Performance of 1.3 GHz 9-cell cavities for LCLS-II.

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LLRF CONTROLS INCLUDING GAP TRANSIENTS AT KEKB AND PLANS FOR superKEKB

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Abstract

Features of LLRF control systems in KEKB and SuperKEKB will be reviewed, and the evaluation of the bunch gap transient effect on beam phase will be presented for SuperKEKB. The RF systems of KEKB are being reinforced to handle triple as large beam power for upgrade to SuperKEKB. Furthermore, a new LLRF control system, which is based on a recent digital control technique, has been developed. They were worked successfully in the Phase-1 commissioning.

Bunch phase shift along the bunch train due to a bunch gap transient is a concern in a high intensity circular collider. In KEKB operation, a rapid phase change was observed at the leading part of the train in the bunch phase measurement, which was not predicted. Our new simulation study of the bunch gap transient effect on beam phase clarified that the rapid phase change is caused by a transient loading in the three-cavity system of ARES. The new simulation for SupeKEKB shows that the phase change due the bunch gap will be significantly large at the design beam current operation. The main issue is the difference in beam phase change between the two rings for the asymmetry colliding. The measures for mitigation of the relative beam phase difference between the two rings will be also suggested.

INTRODUCTION

KEKB is an asymmetric energy collider consisting of an 8 GeV electron ring (high-energy ring, HER) and a 3.5 GeV positron ring (low-energy ring, LER), which was operated from 1998 to 2010 [1]. It obtained the world record in luminosity of 2.11×10^{34} $cm^{-2}s^{-1}$. To increase the luminosity, a high-current beam is needed in both rings, which is accomplished by filling bunches into a number of buckets. One serious concern for high-current storage rings is the coupled-bunch instability caused by the accelerating mode of the cavities. This issue arises from the large detuning of the resonant frequency of the cavities that is needed to compensate for the reactive component of the beam loading [2]. Two types of cavities that mitigate this problem are used in KEKB [3, 4]: one is the ARES normal conducting three-cavity system [5, 6] and the other is the superconducting cavity (SCC) [7, 8]. The detuning frequency of these cavities is reduced owing to the high stored energy in these cavities.

The ARES is a unique cavity, which is specialized for KEKB. It consists of a three-cavity system operated in the $\pi/2$ mode: the accelerating (A-) cavity is coupled to a storage (S-) cavity via a coupling (C-) cavity as shown in Fig. 1 [9]. The A-cavity is structured to damp higher-order modes (HOM). The C-cavity is equipped with a damper to damp parasitic 0 and π -modes. The $\pi/2$ mode has a high Q-value even with a C-cavity with a very low Q-value of about 100. In LER, where a higher beam current is stored than in HER, only the ARES cavities were used. For details regarding the RF systems of KEKB, see Refs. [3, 4]. The RF issues to be considered for the heavy-beam current storage are summarized in Ref. [10].

KEKB is being upgraded to SuperKEKB, which is aiming at a 40 times higher luminosity than KEKB [11, 12]. The RF related machine parameters are shown in Table 1. The RF systems are being reinforced to handle twice as large stored beam currents in both rings and much higher beam power (compared to KEKB) [13]. ARES and SCC will be reused with the reinforcements. The RF power source systems, including klystrons, waveguides, and cooling systems, also need to be reinforced to increase the driving RF power to provide larger beam power. Furthermore, a new low-level RF (LLRF) control system, which is based on a recent digital control technique using field-programmable gate arrays (FPGAs), has been developed to realize higher accuracy and greater flexibility [14]. For nine RF stations, among a total of thirty, the LLRF control system used in KEKB has been replaced with new ones.

The first beam commissioning of SuperKEKB (Phase-1) was accomplished in 2016. The RF systems and the new LLRF control systems were soundly worked. The desired beam current of 1A for Phase-1 was successfully achieved and the vacuum scrubbing was sufficiently progressed.

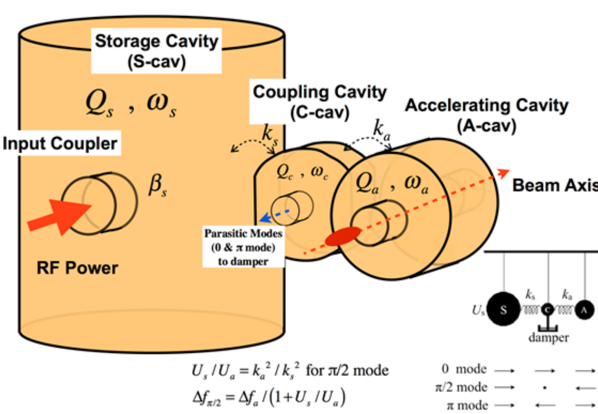

Figure 1: Illustration of the ARES cavity structure.

RF SYSTEM ARRANGEMENT

RF related parameters of SuperKEKB are shown in Table 1 in contradistinction with those of KEKB. The RF system layout of KEKB is shown in Fig. 2. The planed arrangement for SuperKEKB at the design beam current is also shown in the figure (lower side). We have about

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HIGH EFFICIENCY KLYSTRON DEVELOPMENT FOR PARTICLE ACCELERATORS

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Abstract

Presently, state-of-the-art klystrons operate at efficiencies of up to 65%. Through the use of novel bunching mechanisms, it is possible to improve the efficiency towards 90%, which will be beneficial for reducing the power consumption of future particle accelerators. An overview of these bunching schemes, supported by results from numerical simulation and experiment are presented.

INTRODUCTION

Upcoming large scale particle accelerators, such as the Future Circular Collider (FCC-ee) [1], the Compact Linear Collider (CLIC) [2,3], the International Linear Collider (ILC) [4], and European Spallation Source (ESS) [5] are expected to require RF powers in the 10-100 MW range. For comparison, the currently operational, Large Hadron Collider (LHC) [6], has a total RF drive of 5 MW. Due to the significant increase in RF power, it is advantageous to maximise the efficiency of the RF source, in order to reduce their running costs.

Klystrons are an attractive RF source for such applications, owing to their stability, operating frequencies, output powers, and efficiencies. In terms of efficiency, current state of the art klystrons can deliver a maximum of approximately 65%. The limiting factor lies with the profile of the electron bunch, as it approaches the output cavity of klystron, as well as the velocity of the slowest electron leaving the output gap. In order to maximise the efficiency of the tube, the spatial and phase profile of the bunch should be such, that, after it is decelerated by the output gap, each electron has identical velocity.

The High Efficiency International Klystron Activity (HEIKA) collaboration seeks to make improvements to the overall efficiency of klystrons by considering these issues. To that end, a number of novel electron bunching mechanisms have been proposed. In this paper, a brief discussion, along with numerical and experimental results of these novel schemes in operation, will be presented.

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BUNCHING MECHANISMS

In traditional klystrons, electrons are monotonically brought towards the centre of a single bunch along the length of the device. At the output gap, the final bunch does not contain all available electrons within it, with some being contained in a so called ‘anti-bunch’. Therefore, these electrons do not provide any energy to the output RF signal. As a result, the overall efficiency of the device is limited by the number of un-bunched electrons contained in the anti-bunch. The novel bunching mechanisms investigated by HEIKA will be discussed.

Core Oscillation Method (COM)

The core oscillation method (COM) [7,8] is based on the non-monotonic bunching technique, where, along the length of the klystron, electrons at the periphery of the bunch gradually approach the bunch centre. Simultaneously, the core of the bunch experiences an oscillation in its phase, due to its space charge causing it to expand, and the momentum delivered by successive bunching cavities causing it to contract. The cavity RF fields have a weak effect on the periphery electrons (phase of $\pm\pi$ with respect to the core); therefore, COM klystrons require a substantial increase in their interaction length to capture all electrons in the bunch. However, very high efficiencies (> 90%) have been observed in 1-D simulations.

This process can be seen in Figure 1, which shows electron trajectories in phase space, modelled in AJDISK [9]. Here, the de-bunching of the core can be observed between successive cavities (shown by vertical lines in Figure 1), as a contraction and expansion of the centre of the beam, while the outlier electrons move into the bunch.

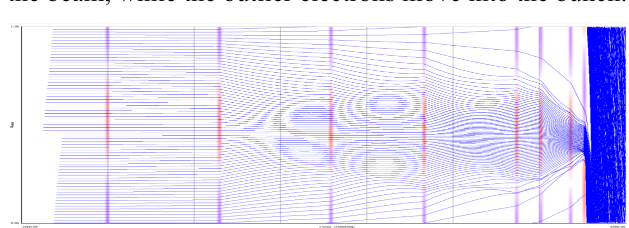

Figure 1: Electron phase profile of an 800 MHz klystron employing the Core Oscillation Method (COM).

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EXTRACTION LINE AND BEAM DUMP FOR THE FUTURE ELECTRON POSITRON CIRCULAR COLLIDER*

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Abstract

The conceptual design of an extraction line and beam dump for the future electron positron circular collider is presented. The proposed extraction line, consisting of abort kicker system, spoilers and beam diagnostics apparatus transports the electron and positron beams to the main beam dumps. The beam must be spread over a large surface in order not to damage the beam dump and the window, which separates the ring from the dump. The extraction line redistributes bunches at different location on the face of beam dump. Monte Carlo simulations using FLUKA have been performed to estimate the distribution of energy deposition on the window and beam dump to find the optimal absorber and its dimensions.

INTRODUCTION

The Future Circular Collider (FCC) is a high-luminosity and high-precision e^+e^- storage ring collider. The FCC-ee study includes the design of a high-luminosity e^+e^- collider serving as Z, W, Higgs and top factory, with luminosities ranging from $\approx 10^{36}$ to $\approx 10^{34}\text{cm}^{-2}\text{s}^{-1}$ per collision point at the Z pole and $t\bar{t}$ threshold, respectively.The design of FCC-ee provides separate e^+e^- channels allowing very large luminosities to be considered in up to four interaction points. In a 100 km tunnel, the accessible centre of mass energy range spans from the Z pole (90 GeV) to above the top pair threshold (350 GeV) [1].

The key part of modern high energy colliders operation is the machine-protection system. Safe operation requires systems for beam dumping, beam instrumentation and absorbers, etc. One of the important collider systems is the extraction line directing the particle bunches to the beam dump. It is important to be able to dump the electron and positron beams in a controlled way in the main collider. The function of the beam dump system is to reliably absorb the power from the electron and positron beams. For safe, long-term operation, the beam dump must be able to withstand the thermal stress and possible fatigue stress.

We have considered several actually implemented or proposed concepts of beam dump systems for various past and future e^+e^- colliders, such as LEP [2], KEK [3] and CLIC [4]. Both solid [2, 3] and water based [4] absorbers are considered for use in the FCC-ee beam dump system.

The FCC-ee design is a part of the global Future Circular Collider (FCC) study. The FCC-ee will be a potential intermediate step towards a 100 TeV hadron collider, FCC-hh, sharing the same tunnel infrastructure. Therefore, it is reasonable to assume that part of the FCC-hh beam dump infrastructure [5], e.g. the tunnel for the extraction line or galleries hosting powering systems, may be shared with the FCC-ee beam extraction system. Also key concepts of the existing LHC beam dump [6] may be adopted and adapted for the FCC-ee.

The proposed FCC-ee beam dump system must have the capability to absorb an energy ranging from 0.4 MJ/beam (for $t\bar{t}$) to 22 MJ/beam (for Z factory). A preliminary beam dump design for the lower current operation mode of FCC-ee (Higgs factory) was discussed at the FCC Week 2016 [7]. In this paper, we include the most challenging operation mode, namely the Z factory. After discussing the components and the magnet parameters of the extraction line, we will present results of Monte-Carlo shower simulations, comparing the energy deposition in various beam-absorber candidate materials.

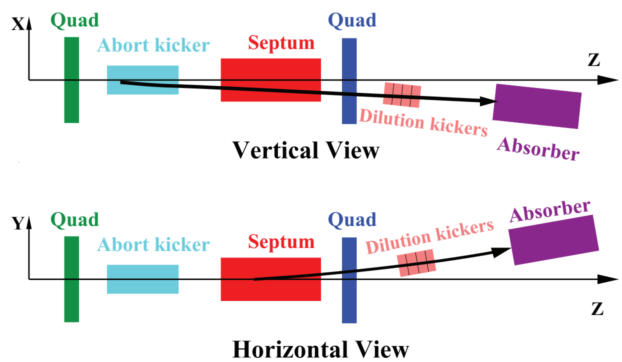

Figure 1: Schematic layout of the extraction system. The horizontal extraction kicker and vertical bending septum magnet are marked in yellow and red, respectively.

EXTRACTION LINE

The extraction line is designed to transport the electron and positron beams from the main ring to the main beam dump. The concept of the beam dump system has been adopted from CERN LHC [6] as baseline for the FCC-ee dumping system where energy of 22 MJ of high current beam must be absorbed. We can use one of the six straight sections with a length of 1.4 km for the extraction line. The layout of the extraction line system consists of abort kicker, septum magnet, dilution kickers system and absorber as shown in Fig. 1.

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IMPROVEMENT OF EFFICIENCY OF KLYSTRON TO APPLY THE CPD METHOD

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Abstract

A high power RF system for the particle accelerators needs large electrical power in the operation. Improvement of efficiency is also always required as a technology component for the energy saving.

To improve efficiency of a high-power rf source, the CPD (Collector Potential Depression) method already was applied a Gyrotron to recovery the electrical energy form the dissipated power in the collector. The CPD is an energy-saving scheme that recovers the kinetic energy of the spent electrons after generating rf power. A proto-type klystron (E37703 CPD) was fabricated at 2013, to recycle an existing klystron of Toshiba E3786. The purpose of our study is to demonstrate the proof-of-principle of the CPD method to apply a klystron. A plane of R&D at KEK is reported in this meeting.

INTRODUCTION

Two examples to obtain the high efficiency of the klystron are shown as following, (1) more strong bunching on the output cavity to optimize rf design (increase number of cavities compare with existing model) and electron gun (chose multi-beam gun)[1], (2) dissipated power on the collector reuses to do the energy recovery by CPD (Collector Potential Depression) method. The CPD method already was applied a Gyrotron to recovery the electrical energy form the dissipated power in the collector. It was worked very well [2].

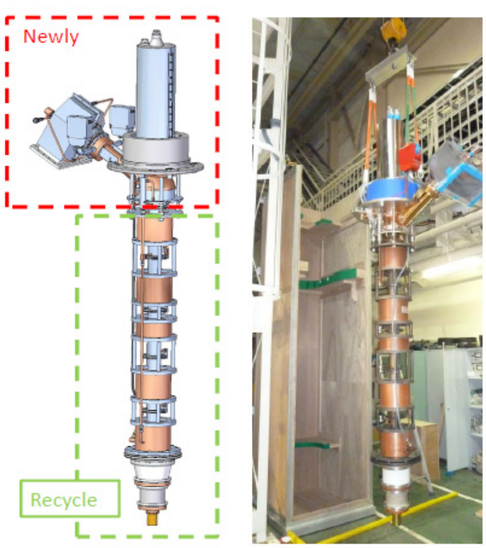

Figure 1: the proto-type CPD klystron (E37703 CPD).

At KEK, a proto-type CPD klystron (CW, 508.88 MHz) was fabricated using by existing klystron (it was used at TRISTAN and KEKB.) at 2013, to demonstrate the proof-of-principle of this method to apply a klystron (see figure 1). In the fabrication, the recycled components were the electron gun, the input cavity and the middle cavities in drift tube. Newly fabricated components were the output cavity, the output coupler and the collector with CPD gap. These parts were bonded by brazing. The parameters of the existing and newly klystrons are shown in Table 1. The range to apply CPD for a klystron is restricted to the un-saturate situation. Then, the efficiency of klystron has the possibility that 10~20 % is improved. However, at present three issues are assumed for the operation. We must design and build an experiment setup in consideration of the health hazards by exposure of the electromagnetic wave and the radiation. We are estimating the amount of field level of rf leakage from the prototype klystron to design rf shield with some access port by the CST-studio (Particle studio). Moreover, commercial viability of CPD klystron is required development of KPS (Klystron Power Supply) to optimize it. At present, it is not the category of this examination. This is a future task.

Table 1: Parameters compared with E3732 and E37703 CPD

Item	E3732 (E3786)	E37703 CPD
Frequency	508.89 MHz	508.89 MHz
Maximum rf output power	1.2 MW (saturation)	500 kW (un-saturation)
Efficiency	20~65%	w/o CPD 20~60% w/ CPD 40~80%
Collector	1 MW	500 kW
Cooling method of collector	Vapor cooling (130 l/min + AFC)	Water cooling (360 l/min)
Cooling items	Klystron body Output coupler Focusing coil	Klystron body Output coupler Focusing coil Ceramics insulator Microwave absorber
KPS	B-type x 1	B-type x 1 PS for CPD
Vk	47~90 kV	47~90 kV
Va	25~60 kV Ib max = 20 Adc	25~60 kV Ib max = 20 Adc
Vc (CPD)	none	0 ~ -50 kV

SUMMARY OF DESIGN CONCEPTS*

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Abstract

This paper summarizes the session on design concepts at the ICFA workshop on future circular electron-positron factories "eeFACT2016" [1] held at the Cockcroft Institute, Daresbury, from 24 to 27 October 2016.

OVERVIEW

The eeFACT2016 [1] session on design concepts featured the following four presentations:

1. Crab Waist Concept [2], by Pantaleo Raimondi, ESRF;
2. Higgs Factory Concept [3], by Frank Zimmermann, CERN;
3. Implementation of Round Colliding Beams Concept at VEPP-2000 [4], by Dmitry Shwartz, BINP; and
4. New Concept of a very Compact e^+e^- Collider with Monochromatization and Maximum Beam Energy of around 200 MeV [5], by Anton Bogomyagkov, BINP.

Another important design concept is maximizing the synergies between kepton and hadron colliders, which was highlighted by Alain Blondel, U. Geneva, during the summary session.

CRAB WAIST CONCEPT

The crab-waist scheme overcomes, or exploits, the classical limitations from hourglass and beam-beam effect, allowing for much lower values of β^* and gaining luminosity with a large Piwinski angle [2]. Its key feature is the crab-waist compensation, a new idea from 2006. Positive and useful experience comes from an actual implementation at the DAFNE collider, where the crab-waist scheme significantly increased the luminosity, as is illustrated in Figs. 1 and 2. The price to pay is a more challenging final-focus system design/construction, in particular the realization of particular phase advances and the possible impact of crab waist sextupoles on the dynamic aperture. Regardless, DAFNE experience and several designs for future have proven the feasibility of this novel approach. Now crab waist is a key concept for the next generation of high luminosity colliders, such as FCC-ee or the Super charm-tau factory at BINP.

At eeFACT2016, the possible conversion of DAFNE into a test facility for studies on the large Piwinski angle and the crab waist scheme was discussed. While this would be useful, it was not entirely clear if there was an added value

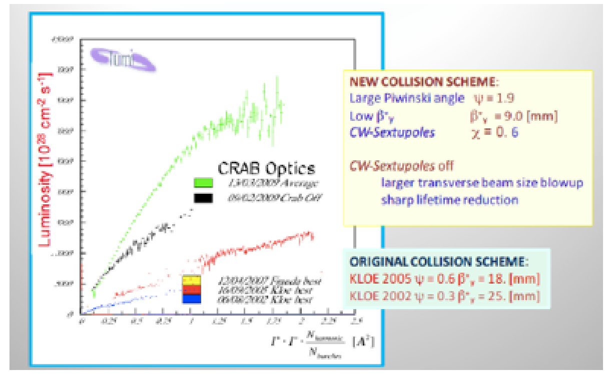

Figure 1: DAFNE luminosity versus product of beam currents for the classical and crab-waist collision scheme [2].

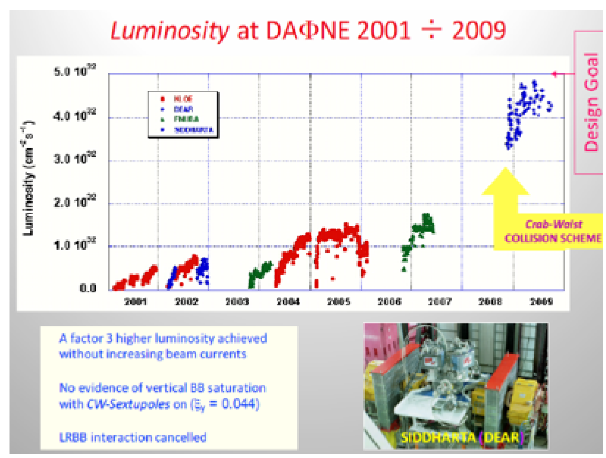

Figure 2: DAFNE luminosity versus time, showing a step-like increase at the moment the crab-waist was introduced, together with a photograph of the DAFNE installation [2].

beyond the SuperKEKB experience and whether this would not interfere with the DAFNE physics programme. The resource needs and the benefits would need to be analysed.

Discussion: The limit on β^* in the crab waist scheme was addressed including the question whether such limit would be consistent with the FCC-ee design. The subsequent discussion revealed that other limits in the final focus design (e.g. dynamic aperture) must also be considered.

HIGGS FACTORY CONCEPTS

The designs of FCC-ee & CEPC exploit lessons or recipes from past and present e^+e^- and pp colliders: combining successful ingredients of recent colliders leads to extremely high luminosity at high energies (Fig. 3), up to and beyond 10^{36} cm^{-2}s^{-1} [3]. Crab waist is successfully implemented in the design of the proposed new machines. Obtaining a low

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SUMMARY OF OPTICS ISSUES

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There were three talks in this session:

1. “Review of IR Designs with CW" by Anton Bogomyagkov – Budker Institute of Nuclear Physics,
2. “FCCee La5ce with Errors and Misalignment" by Sergey Sinyatkin – Budker Institute of Nuclear Physics
3. “Issues in CEPC pretzel and parAal double ring scheme design" by Huiping Geng – Institute of High Energy Physics,

The first talk by A. Bogomyagkov analyzes the nonlinearities associated with a crab-waist optics, evaluated the effects on the dynamic aperture. It can explain the reduction of the dynamic aperture due to crab-waist sextupoles in many machines. Then he proposes a new layout for the location of the crab-sext to reduce those nonlinearities. This idea can help the issue on any machines, including SuperKEKB.

The second talk by S. Sinyatkin will be summarized in the Machine Tuning session.

The third talk by H.P. Geng introduces the progress of the lattice design for CEPC, since single-ring pretzel to the partial double ring scheme. Now they have a consistent design that involves the arc, IR, RF, etc. They have optimized the dynamic aperture using an advanced multi-objective optimization method, then it nearly reaches the goal. They are still in progress.

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SUMMARY OF IR AND MDI SESSION

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Abstract

A brief summary of talks in IR and MDI session is given. Also features and issues on the IR design in the future colliders are summarized.

INTRODUCTION

In this session, 5 talks were given on 4 colliders; *i.e.*, SuperKEKB, CEPC, FCC-ee and eRHIC. The talks are listed below.

- “Issues on IR Design at SuperKEKB" by Yukiyoshi Ohnishi (KEK)
- “IR Design and MDI at CEPC" by Qinglei Xiu (IHEP)
- “FCC-ee Interaction Region Magnet Design" by Michael Koratzinos (Unige)
- “The eRHIC Interaction Region Magnets and Machine Detector Interface" by Brett Parker (BNL)
- “FCC-ee MDI" by Manuela Boscolo (INFN-LNF)

In this summary, a brief summary for each talk is given firstly and then a summary of the whole session is given.

SUMMARY OF EACH TALK

Issues on IR Design at SuperKEKB

SuperKEKB has a relatively large (full) crossing angle of 83 mrad to squeeze the IP vertical beta function down to ~ 0.3 mm with “Nano-Beam Scheme". L* is chosen as ~0.76 m. The strength of the detector solenoid is 1.5 T and the field is cancelled with compensation solenoid magnets so that the integral of the field along the beam line is zero on both sides of the IP. A challenge is to keep enough dynamic aperture and the enough Touschek beam lifetime with the extremely small IP beta functions. For this purpose, many corrector coils are installed in IR including the cancelling coils of the leakage field from the opposite beam. Octupole and skew-sextupole coils are also wounded for wider dynamic aperture. In the simulation, the target beam lifetime of ~ 600 s from the Touschek effect has been obtained for both rings without the beam-beam effect by optimizing many parameters including the octupole , skew-sexupole and sexupole magnets. A serious issue presented is that the dynamic aperture in the horizontal direction shrinks largely with the beam-beam effect particularly in LER. The beam lifetime can be decreased down to less than 100 s. A particle with a large horizontal offset collides with the other beam at the position where the vertical beta function is large and the vertical oscillation is induced when the particle is lost in the simulation. This phenomena can be suppressed with the crab waist scheme. But the nonlinearity of the sexutpoles for the crab waist scheme reduces the dynamic aperture very seriously combined with other IR nonlinearity particularly with the fringe field of the final focus quadrupoles. This is an unsolved problem and the conclusion of the speaker is “ The transfer map between the IP and the crab waist sextupole should be linear. Development of a cancellation technique for the nonlinear field is necessary."

IR Design and MDI at CEPC

A preliminary IR design of CEPC was shown. The (full) crossing angle is 30 mrad. The vertical beta function at the IP is 1.2 ~ 1.3 mm. The strength of the detector solenoid is 3.5 T and the field is cancelled with compensation solenoid and is shielded with the screening solenoid. L* is chosen as ~1.5 m. A preliminary design of the final focus quadrupole (QD0) with Serpentine coil layers was shown. The problem with the present design is the cross talk of the two QD0’s for the two beams. The cross talk should be decreased by adding shield coils. The simulations on the beam background were done on the three types of the background, the synchrotron radiation (SR), the beam loss and Beamstrahlung. Of the 3 types of background, the SR background is the most serious. The critical energy of SR is assumed to be ~ 1 MeV. If this value is for the SR from the last bending magnet, this seems too high considering the experiences at LEP. Collimators for synchrotron radiation from the dipole are designed. The particle loss from the radiative Bhabha process was simulated and the preliminary design of collimator for this background was made. The energy deposition to the collimator should be estimated. In the talk, it was stressed that the mechanical support may be a new challenge for IR design due to the limited space for the support.

FCC-ee Interaction Region Magnet Design

The IR magnet design of FCC-ee was shown. The (full) crossing angle is 30 mrad. The vertical beta function at the IP is 1 ~ 2 mm. The strength of the detector solenoid is 2 T. L* is chosen as ~2.2 m. A border between the accelerator and the detector has been set at ±100 mrad. Two big challenges for the IR magnet design are vertical emittance creation from the IR vertical dispersion and very tight space for two final focus quadrupoles sitting ~6 cm apart. As for the vertical emittance, the emittance budget is very tight and is 1 pm for most of energies. By introducing two magnetic elements; *i.e.* the screening solenoid and compensating solenoid and localizing the dispersion near the IP as much as possible, the emittance blowup has been successfully suppressed to only 10 % of the emittance budget for 2 IPs. As for very tight space for the final focus quadrupoles, the influence of one quadrupole to the other beam might be problem. To

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SUMMARY BEAM-BEAM SESSION, eeFACT2016 WORKSHOP

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Abstract

There are two talks in the beam-beam session. But beam-beam is an issue that permeates in several other sessions. So in this summary I have taken the liberty to include some materials extracted also from other sessions.

FLIP-FLOP

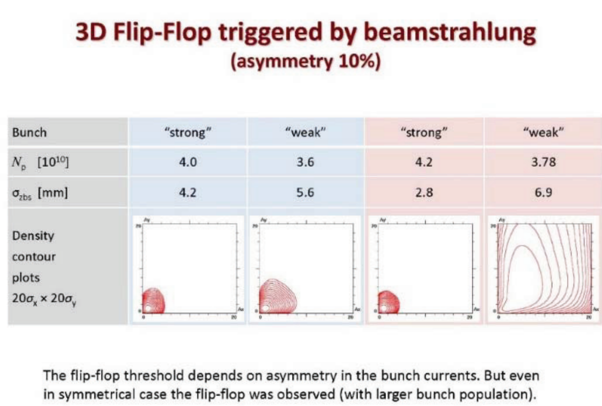
The first talk was “Flip-flop instability in FCC-ee at low energies” by Dmitry Shatilov.

The old flip-flop as we know it is a 1D effect. A new intriguing 3D flip-flop is now discovered for strong-weak cases when the beam intensity asymmetry exceeds ~10%. The instability mechanism is rather involved, requiring several ingredients. Missing one of them removes the instability. Ingredients include:

1. asymmetry in beam intensities
2. beamstrahlung
3. crossing beams
4. x-y coupling

This flip-flop instability has a beam intensity threshold. Below a certain threshold, even asymmetric beams do not become unstable. The threshold can be increased by lowering □x* (and raising □x holding luminosity fixed).

A slide from Dmitry Shatilov:



Bunch	“strong”	“weak”	“strong”	“weak”
N_p [10^{10}]	4.0	3.6	4.2	3.78
σ_{zbs} [mm]	4.2	5.6	2.8	6.9
Density contour plots $20\sigma_x \times 20\sigma_y$				

SIMULATIONS

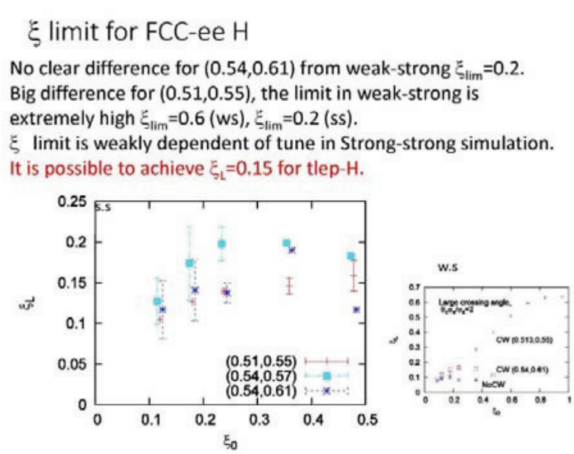
The second talk was “FCC-ee beam-beam strong-strong simulations for all working and mitigation” by Kazuhito Ohmi.

For FCCee at Higgs energy, it was found that the beam-beam limit behaves rather differently for a strong-weak case and a strong-strong case. For a strong-weak case, it was found that the beam-beam limit ξ depends sensitively on the choice of the working point. For one working point, it can be as high as ξ = 0.6, while for another working point it is 0.2. Two observations can be made:

- The fact that a strong-weak case can have large beam-beam limit is in sharp contrast with the prediction by 3D flip-flop (as in the previous talk), where it was observed that a small asymmetry in beam intensities leads to a strong instability. The present-day beam-beam is a subtle subject involving multiple parameters and multiple physical mechanisms. Careful and complete considerations are necessary to draw final conclusions.
- The sensitivity to working point apparently appears when the working point is in the proximity to ½ tunes.

In contrast to the strong-weak case, the strong-strong cases seem to converge to a beam-beam limit ξ = 0.2 at the Higgs energy, insensitive to the choice of working point. Very interesting is the observation that in the FCCee case with crossing beams, there is a strong beam-beam-induced high-mode coherent x-z oscillation, while the lowest x-z mode is stable. This oscillation becomes more serious at the Z energies, when the beam-beam limit is reduced to 0.06. It was further observed that these x-z oscillations can be removed by substantially lowering β_x^* and raising ε_x, curiously the same trick to cure the 3D flip-flop instability.

Two slides from Kazuhito Ohmi showing the beam-beam limits:



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SUMMARY OF INJECTOR AND BEAM INJECTION*

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Abstract

This summary covers the Injection and Sources Session of the e+e- Factories Workshop held at Daresbury Laboratory, UK, October 24-27, 2016, which had six presentations. Here we discuss the goals for top-up injection for a collider and their sources and then covers the highlights, discussion topics, and future plans for each presentation. The talks [1-6] will be covered in alphabetical order by author's name.

INJECTION AND SOURCES GOALS

Extracted from the six talks in this session, the required qualifications for injection and sources for present and future e+e- colliders can be broken down into three general areas: parameters, construction, and operation. The desired parameters are full energy injection (up to 175 GeV), varied injected bunch charges (quanta), short fill times from scratch, low detector backgrounds while injecting while taking data, polarization of about 80% for electrons and, if possible, for positrons (under development), well integrated into the collider design, and well instrumented. For construction, the desire is to be inexpensive as possible using existing technology if possible. For operations, the need is for low power costs, reliable running, low maintenance costs with many common-standard units, and bunch number flexibility.

The goals for the injector for an e+e- collider are shown in Table 1 where 50 to 90000 overall bunches are needed and 6 to 1450 mA per beam of stored currents are needed. The injection rates depend on how many bunches are to be injected per booster cycle, the expected beam lifetimes (~10 to 60 min) and the charge per bunch needed to maintain the luminosity near the maximum.

Table 1:Injection Parameters for a Future e+e- Collider

parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**5**	**1.3**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5

FCC-ee: 2 separate rings & 2 IPs   CEPC: single beam pipe version

TIANJIAN BIAN (IHEP): DESIGN STUDY OF CEPC BOOSTER

The injector of the proposed CEPC e+e- collider in China has been studied for several years with a converging design. It consists of a linac, positron source, damping ring and, finally, a full energy booster ring in the same tunnel as the collider with a circumference of 63.8 km. The injected bunches go through a septum and then a kicker to be stacked onto (top-up) an existing bunch in the collider. The highest energy of the booster would be 120 GeV for the Higgs energy with an injected emittance of 3.5 nm-rad. A booster optical lattice has been generated which looks acceptable in term of tunability, chromatic corrections, earth's field correction, element error tolerances, and magnet technical features.

The very low magnetic field in the booster at injection energy is a concern with several cures being studied including shielding of the earth's field, reverse bends, special steel, and low energy orbit corrections. A reverse (wiggling) bend scheme is the primary choice at the present (See Figure 1) to boost the magnet field about a factor of 6 (25 gauss to (-129 and +180) gauss).

A computer code has been developed (MOOLA) to optimize the design of a ring lattice. It uses Hamilton canonical coordinates and has fourth order symplectic integration. This code has been used to maximize the properties of the CEPC injector booster lattice and the HEPS light sources lattice.

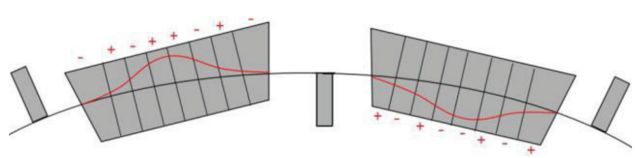

Figure 1: Proposed booster dipole magnet layout to increase the low energy fields in China CEPC.

Further work and discussion:

1) Construct a real model of the 25 gauss dipole magnet and test the reproducibility of the low filed state.
2) Construct a working model of the reverse bend dipole magnet and measure the remnant fields through field reversal.
3) Further work on lattice dynamic aperture optimization with MOOLA is ongoing.
4) Study if the partial double ring collider design changes the requirements for the CEPC injector.

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SUMMARY OF IMPEDANCE ISSUES AND BEAM INSTABILITIES*

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Abstract

This paper summarizes the session on impedance issues and beam instabilities at the ICFA workshop on future circular electron-positron factories "eeFACT2016" [1] held at the Cockcroft Institute, Daresbury, from 24 to 27 October 2016. This session also covered active beam stabilization by feedback systems. Beam-beam effects and coherent beam-beam instabilities were addressed separately and, therefore, are not included here.

OVERVIEW

The eeFACT2016 [1] session on impedance issues and beam instabilities featured the following ten presentations:

1. Low SEY Engineered Surface for Electron Cloud Eradication [2], by Reza Valizadeh, STFC;
2. Collective Effects Issues for FCC-ee [3], by Mauro Migliorati, University of Rome La Sapienza;
3. Impedance Measurement Techniques and Lessons from Light Sources [4], by Victor Smalyuk, Brookhaven National Laboratory;
4. Coherent Wave Excitation in a High Current Storage Ring [5], by Alexander Novokhatski, SLAC National Accelerator Laboratory;
5. Electron Cloud and Fast-Ion Instability plus Mitigation Methods for Future Factories [6], by Kazuhito Ohmi, KEK;
6. Electron Cloud at SuperKEKB [7], by Hitoshi Fukuma, KEK;
7. Electron Cloud and Collective Effects in the Interaction Region [8], by Eleonora Belli, CERN and La Sapienza;
8. An Overview of Active Coupled-Bunch Instability Control [9], by Dmitry Teytelman, Dimtel, Inc.;
9. Feedback Experience at DAFNE [10], by Alessandro Drago, INFN/LNF;
10. Instability Issues in CEPC [11], by Na Wang, Institute of High Energy Physics, Chinese Academy of Sciences.

The topics and presentations can be classified according to three grand themes: (1) classical wake fields and instabilities, (2) electron cloud, and (3) ion instability. The focus was on forecasts for the proposed future large circular colliders, CEPC [12] and FCC-ee [13, 14], recent experience during the commissioning of SuperKEKB [15], and lessons from DAFNE [16] and PEP-II [17].

Concerning classical wake fields and instabilities, in the transverse plane the resistive-wall driven coupled-bunch instability is of greatest concern [3, 11]. Assuming a fractional betatron tune above an integer, for FCC-ee the expected growth time of the fastest growing mode is about 7 turns, but there are many modes with a growth rate of order 10 turns. Fortunately, advanced transverse feedbacks could control instabilities with a damping time of about 1–2 turns. Such feedbacks can be realized either by using multiple BPMs ("folding the ring") [9], by doubling or quadrupling the feedback system [10], by multiple feedforward systems, or by a combination thereof.

Longitudinally, the potential single-bunch microwave instability driven by the broadband impedance appears to be the most dangerous effect [3, 11]. In addition to the resistive wall, the broadband impedance contains noticeable contributions from the RF cavities, photon stops, etc.

Indeed, many elements are contributing to the total impedance, both transversely and longitudinally. First models of total wake fields are available for FCC-ee and CEPC [3, 11]. Experience from the light sources suggests, however, that reality often differs from expectation [4].

When operating with high beam current and/or with short bunches higher-order mode (HOM) heating and HOM driven instabilities need to be controlled [5]. HOM heating destroyed numerous beam-pipe components at PEP-II and at many other storage rings. A particular topic of ongoing research is HOM excitation around the interaction point [8], where — depending on the various beam-pipe dimensions — a cavity-like object may be formed.

Nowadays powerful codes are available for solving Maxwell's equations inside the beam pipe. Such codes can compute the combined effects of sychrotron radiation, space charge, and wake fields [5].

The electron cloud is a potential threat to positron beams, especially for the Z-pole operation of FCC-ee [6, 8], where even the photoelectrons created by a single bunch passage yield an average electron density above the single-bunch instability threshold. Electron cloud is still an issue for SuperKEKB despite numerous countermeasures incorporated in the design [7], and even after installing additional permanent magnets in the short uncoated aluminium bellows chambers. One reason is that the TiN coating applied for most the vacuum chambers has proven insufficient to reduce the secondary emission yield to the required low level. A potential, highly efficient cure for future and present machines is the laser surface treatment LASE developed in the UK [2], which can dramatically reduce the secondary emission yield.

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SUMMARY OF MACHINE TUNING SESSION*

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Abstract

This paper summarizes the work presented at the Machine Tuning session on the low emittance tuning for low emittance lattices and luminosity tuning at colliders.

SESSION TALKS

Optics correction is a key tool to achieve desired performances in an accelerator. It is very important to have a good lattice model so to be able to operate on the real machine in a reliable way. Unavoidable magnet errors, such as displacements, tilts or field errors, will affect the closed orbit, H-Y betatron coupling, H-V dispersion, H-V emittance. Their correction is crucial for reaching the design performances. Beam polarization is also heavily affected by errors, as shown in [1]. For the new generation of e^+e^- accelerators, where low emittance beams are needed to achieve the design luminosity, this is a very important topic to be addressed and solved.

Five talks have been presented on Optics correction (for LHC and SuperKEKB), Errors correction (for FCC-ee) and Luminosity tuning (for KEKB):

1. A. Langner (CERN), "Optics correction at large accelerators",
2. Y. Ohnishi (KEK), "Optics correction and low emittance tuning at the Phase 1 commissioning of SuperKEKB",
3. Y. Funakoshi (KEK), "Luminosity tuning at KEKB",
4. S. Sinyatkin (BINP), "FCC lattice with errors and misalignment",
5. S. Aumon (CERN), "Coupling and dispersion correction in FCC-ee".

ERRORS SIMULATION

Errors simulations are needed in order to provide a model of what can be the *real* accelerator. The impact of different errors, such as magnet misalignments, magnet field errors, magnet tilts, BPM gain and position errors, have to be modelled to be able to perform corrections and prepare the online tools needed when running. Also, tolerances to these errors should be computed, in order to set up what are the requirements for the accelerator alignment and magnets quality. Most of the errors are impacting betatron coupling and vertical dispersion, which are particularly important to minimize since modern accelerators, both colliders and synchrotron light sources, aim to very low emittances in both planes.

For the FCC-ee project a study of the errors and misalignments at 175 GeV [2] showed that in the Arcs quadrupoles need to be aligned at 100 μ. Final Focus (FF) quadrupoles were studied separately, due to the high gradients and β-functions behaviour in the Interaction Region (IR). For these elements there is a strong vertical dispersion excitation due to errors. A tolerance of 25 μ to quadrupole misalignments has been found. This seems a very low value that must be checked with the alignment experts. The use of MADX code turned out not to be ideal for this study since is time consuming and in presence of errors it was difficult to find the closed orbit for a displacement of 100 μ in Arc quadrupoles. However, after closed orbit, betatron coupling and vertical dispersion correction the average ratio between the vertical and horizontal emittances was reduced from an initial 15% to a final 1.4%, as shown in Fig.1 below.

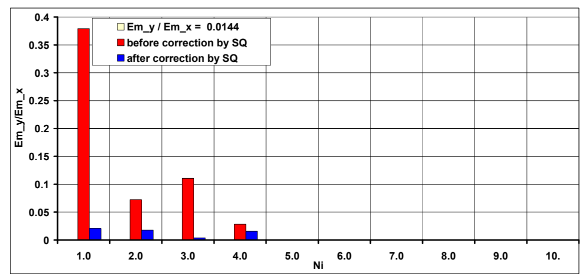

Figure 1: Emittance ratio as a function of optics correction iterations (in red before, in blue after correction).

Another study of betatron coupling and vertical dispersion correction for the FCC-ee 175 GeV [3] was presented. The energy losses in the Arcs at 175 GeV are so large (the so called saw-tooth effect) that a tapering of dipoles, quadrupoles and sextupoles fields is needed. However, this is an expensive requirement, so a study was performed to see if closed orbit correction was still possible by tapering dipoles only, so called "sector-wise" method. The lattice studied was a racetrack type with a "LEP-like IR" with sector-wise tapering. This scheme has shown to have some issues. A quadrupole misplacement tolerance of 20 μ in quadrupoles (here the FF quadrupoles are included in the simulation) has been found after a combination of dispersion free steering and Interaction Point (IP) betatron coupling correction. Fig. 2 shows the dependence of vertical emittance from quadrupole misalignments for this lattice. Future work will be needed to implement the real lattice and full magnets tapering.

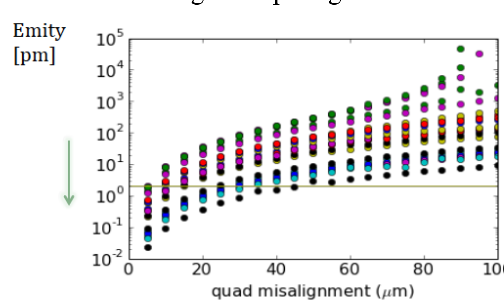

Figure 2: Vertical emittance vs quads misalignments.

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SUMMARY OF BEAM INSTRUMENTATION AND BEAM DIAGNOSTICS SESSION

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Abstract

This report is a summary of the beam instrumentation and beam diagnostics session of the eeFACT2016 workshop.

LIST OF PRESENTATIONS

Talks presented in the beam Instrumentation and beam diagnostics session are:

- Beam Instrumentation Needs for a Future e+e- Collider Based on PEP-II Observations, J. Seeman, SLAC,
- Beam Position Measurements at Synchrotron Light Sources, V. Smalyuk, BNL,
- Beam Instrumentation in SuperKEKB, H. Fukuma, KEK,
- Measurement of Beam Polarization and Beam Energy in One Device, N. Muchnoi, BINP.

SUMMARY OF THE PRESENTATIONS

Beam Instrumentation Needs for a Future e+e- Collider Based on PEP-II Observations

J. Seeman presented needs for various beam measurement requirements and techniques for a future e+e- collider using PEP-II observations.

Future e+e- colliders will operate with many bunches, short bunch lengths, small emittances, high currents, and small beta functions at an interaction point (IP). The stability of the colliding beams with these characteristics will depend on detailed, high precision, and continuous measurements. Since beam parameters of a future e+e- collider are not far from B-factories, observations at PEP-II are useful as a starting point of the discussions.

Various measurement techniques for beam position, beam size, bunch length and beam lifetime were used at PEP-II. IP luminous region parameters such as beam sizes and beta functions were measured using data from PEP-II and BaBar together. Beam instabilities were analyzed and suppressed by the sophisticated bunch-by-bunch feedback system.

HOM generated by the beam with high current and short bunch length causes following serious effects:

- Heating of the vacuum elements
  Temperature and vacuum rise
  Chamber deformations and vacuum leaks
  Decreasing the pumping speed
  Out gassing
- Multipacting, sparking and breakdowns
  Vacuum leaks
  Melting thin shielded fingers
  Longitudinal instabilities
  High backgrounds (high radiation level in the detector)
- Electromagnetic waves outside vacuum chamber
  Interaction with sensitive electronics

Many HOM related events such as damage of a cavity tuner and a SiC tile in IR and an overheated vacuum valve occurred at PEP-II. A lot of measurements, for example, an estimation of HOM power from RF power measurements, temperature monitoring and modeling and moderate/fast real-time vacuum pressure monitoring were necessary for identifying damaged parts.

The talk was summarized as:

- Many complicated measurements are needed in a high-power, high-current collider,
- Measure and record versus time as many parameters as possible to diagnose issues,
- Find new innovative measurement techniques,
- Many measurements relate to potential hardware damage to the accelerator,
- Many measurements need to automated and computer monitored to make the accelerator operation safe.

Beam Position Measurements at Synchrotron Light Sources

V. Smalyuk presented beam position measurements at synchrotron light sources mainly based on beam position monitors (BPMs) at NSLS-II.

Modern light sources demand following severe performances for the BPM system:

- Beam stability of 5-10% of the beam size,
- Active interlock system which damps the beam to protect the storage ring and the frontend components from damage by synchrotron radiation if its orbit exceeds the safety limits (e.g. 0.5 mm and 0.25 mrad at insertion devices),
- Fast data transfer and processing for fast orbit feedback systems,
- Flexibility of the system for machine commissioning, lattice optimization and beam studies.

Recent BPM signal processing is mainly based on digital signal processing. A list of BPM signal processing electronics in major light sources shows two third use the Libera digital processor of Instrumentation Technologies, while one third use homemade processors. NSLS-II BPM module is a homemade module whose architecture of analog frontend is based on under-sampling of the signal

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SRF WORKING GROUP SUMMARY *

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Abstract

This working group focussed on the status and challenges of superconducting Radio Frequency (SRF) cavities and systems for present and future high luminosity lepton colliders, the so-called "factories". Submissions covered the state of the art of SRF cavity designs, HOM damping, high power couplers, operational experiences and the needs of future colliders. Active work on similar SRF systems for the electron complex of a future electron ion collider (EIC) was presented. Much of this technology is also useful for next generation high brightness light sources and other applications.

OVERVIEW

The session contained nine talks covering:

- SRF cavities
- High level parameter optimization
- LLRF controls
- Power couplers
- HOM damping
- New materials and processes

The talks were all of a high standard and packed with useful information but all speakers managed to stay on schedule.

SRF CAVITIES

The success of existing high current SRF cavity designs at CESR and KEK-B, figures 1, 2, which continue to operate reliably after many years of service, prove that the technology is mature and can be relied upon for future applications. However the increasing demands for higher voltage, higher currents, better HOM damping, higher efficiency, lower cost and more compact installations is driving the development of new and more specialized designs. These designs expand upon this experience but are increasingly specialized and optimized for different operating scenarios [1]. Table 1 shows the main parameters of the operating scenarios of FCC-ee.

Looking forward to the highest energy future circular colliders such as FCC and CEPC it is clear that:

- One solution doesn't fit all needs.
- Operating at the Z and W (high current, lower energy) needs 1 or 2 cell cavities, probably 400 MHz).
- Operating at the Higgs or Top energy (lower current, higher energy), could probably benefit from multi-cell cavities, higher frequency.

*Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.

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NEW DESIGNS

New design concepts were shown that are under consideration for the JLab EIC collider rings and cooler ERL [2] and the FCC-ee rings, figures 3-5. In these designs the cavity shape should be optimized to avoid harmful HOMs being resonant with harmonics of the RF frequency, to minimize the HOM power. The number of cells is determined by the maximum power per coupler and the HOM damping requirements. The higher-current machines favour one or two-cell low frequency cavities, while the higher energy lower current machines may use more cells per cavity and higher frequency. Total RF power is capped and therefore the higher energy machines must run at lower current due to synchrotron radiation.

Table 1: Main Parameters of the FCC Operating Modes

	V_tot	n_bunch	I_beam	σ	E_turnloss
FCC-hh	0.032		500		
Z	0.4 / 0.2	30180 / 91500	1450	0.9/1.6	0.03
W	0.8	5260	152	2	0.33
H	3	780	30	2	1.67
t	10	81	6.6	2.1	7.55

Figure 1: CESR-B type 500 MHz cavity cryomodule produced by Industry.

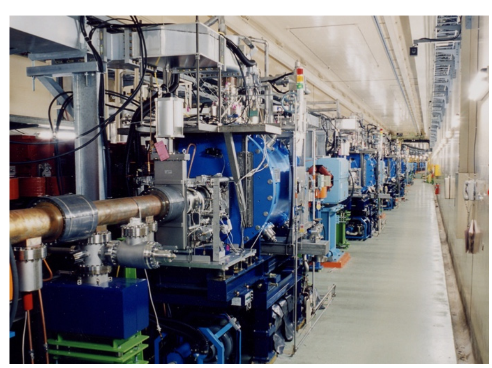

Figure 2: KEK-B type 508 MHz cavity cryostat produced by Industry.

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SUMMARY: JOINT SESSION OF OTHER TECHNOLOGIES AND ENERGY EFFICIENCY

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Abstract

This paper summarizes the presentations and discussions at the joint session of "Other Technologies" and "Energy Efficiency." It also highlights several key issues for R&D in these fields.

INTRODUCTION

For future high energy high luminosity e+e- colliders such as FCC-ee and CEPC, power consumption is a critical issue. The synchrotron radiation power for the two machines is 100 MW each in their present design. Due to limited efficiency to deliver energy to the beam, the wall plug power would be substantially higher than 100 MW. For example, Figure 1 shows the relative power consumption of each system in the CEPC design [1].

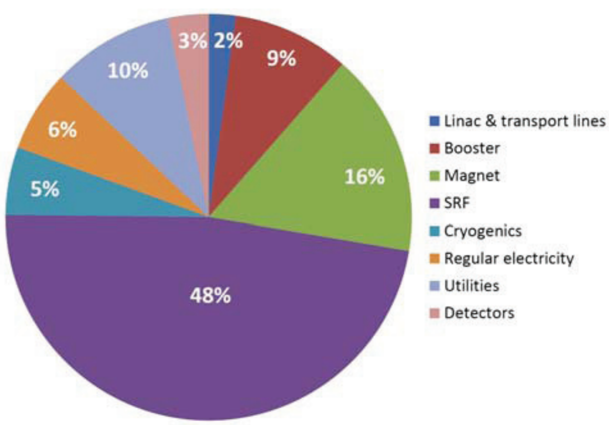

Figure 1: Relative power consumption of each system in the CEPC.

The total power is about 500 MW, which is almost an order of magnitude higher than the power consumption at Fermilab during Tevetron running (58 MW), and three times as high as that at CERN during the 2012 LHC running (183 MW). Assuming 4,000 hours for annual collider operation (i.e., 1.5 Snowmass unit), the electricity alone would cost RMB 1 billion (about USD 150 million). Apparently this is a key R&D item and one has to find a more efficient way to deliver power to the beam.

From Figure 1, it can be seen that the two biggest power consuming systems are SRF (48%) and magnet (16%). This session has two presentations on improving SRF system efficiency (high efficiency klystrons by David Constable and Ken Watanabe, respectively). And one presentation on improving magnet efficiency (Frank Zimmermann).

This session also has two presentations on beam dump, one by Armen Apyan on traditional beam dump, another by Alex Chao on a novel beam dump concept based on beam-plasma interaction. The latter has the potential to recycle the dumped beam energy so the overall energy efficiency of the collider would be improved.

This session also has a presentation by Oleg Malyshev discussing NEG coating and its recent progress.

HIGH EFFICIENCY KLYSTRON

The wall power is delivered to the beam through a number of steps: modulators, klystrons, waveguides, SRF power coupler, cavity, etc. Among them, the klystron efficiency is the key because it is relatively low (40-50%) compared to other components. Therefore, in order to reduce the collider power consumption, one needs to focus on improving the klystron efficiency.

Constable presented the work of the HEIKA collaboration [2]. Its goal is to increase the efficiency of the FCC-ee HEKCW tube to 90%. The klystron uses multiple beams (16) and employs non-traditional bunching mechanism: one called core oscillation method (COM), another called bunching-alignment-collection (BAC) method. Figure 2 is an illustration of COM. As a proof-of-principle test, a SLAC 5045 S-band klystron has been retrofitted using the BAC scheme and is scheduled for testing in 2016. The efficiency is expected to increase from current 45% to 62.5%.

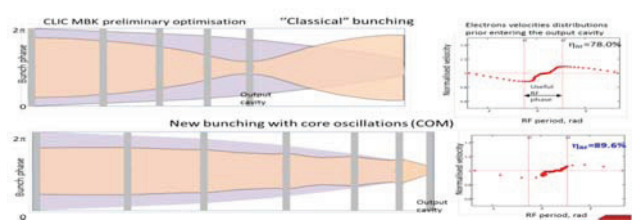

Figure 2: Comparison of the traditional bunching (top) and core oscillation method (COM, bottom). The simulation shows the latter has an efficiency of 89.6% (bottom right).

Watanabe reported the work at KEK in collaboration with Toshiba [3]. It uses a different method called collector potential depression (CPD), which was developed for gyrotron. An insulator is inserted between the body and the collector so a high voltage of Vc (30 kV) can be applied to the body for energy recovery. (Figure 3) A Toshiba E37703 tube was tested and the efficiency was increased from 42% (without CPD) to 62% (with CPD).

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