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UPDATES ON ALTERNATIVE PRE-BOOSTER RING DESIGN AND WIGGLER MAGNET CONSIDERATIONS OF SPS FOR THE FCC e^+e^- INJECTOR

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Abstract

The Future Circular e^+e^- Collider (FCC-e^+e^-) injector complex needs to produce and to transport a high-intensity e^+e^- beam at a fast repetition rate for topping up the collider at its collision energy. Two different options are under consideration as pre-accelerator before the bunches are transferred to the high-energy booster: using the existing SPS and designing a completely new ring. The purpose of this paper is to explore the needs and parameters of the existing SPS, to investigate wiggler magnet options for SPS, and provide an updated study of alternative accelerator ring design with injection and extraction energies of 6 and 20 GeV, respectively. In this study, the parameters of both choices are established, including the optics design, layout update and considerations for non-linear dynamics optimization.

INTRODUCTION

FCC-e^+e^-, a high-luminosity e^+e^- circular collider of around 100 km, is under design. The injector complex of the FCC-e^+e^- consists of an e^+e^- linac, up to 6 GeV energy, a pre-booster synchrotron ring (PBR), accelerating from 6 to 20 GeV, and a full energy booster synchrotron ring (BR), integrated in the collider tunnel [1]. A schematic layout of the injector complex can be seen in Figure 1.

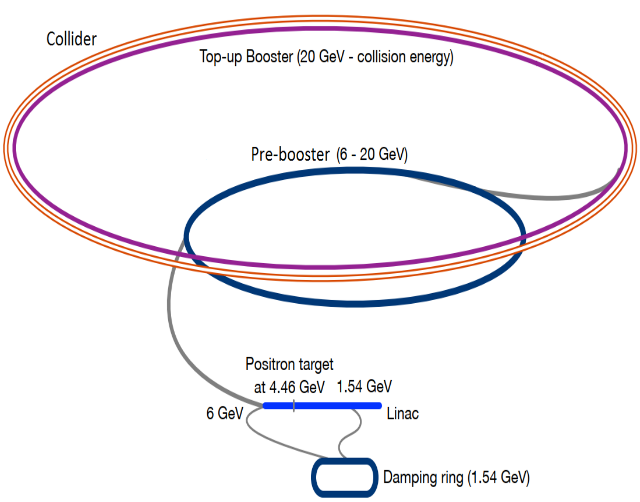

Figure 1: Layout of the FCC-e^+e^- injector complex [1].

Currently, the existing SPS is considered as the baseline for the PBR. However, since there could be limitations such as machine availability, synchrotron radiation and RF system requirements, a "green field" alternative PBR design was also proposed [2, 3].

Table 1: Design Requirements for the PBR

Parameter	Injection	Extraction
Energy [GeV]	6	20
Damping time (hor.) [s]	0.1	-
Emittance (hor.) [nm.rad]	-	5
Energy loss per turn [MeV]	-	50
Energy acceptance [%]	1.5	-
Dynamic aperture (hor.) [mm]	7	-
Energy spread [%]	-	0.3

The PBR needs to accept the beam from the linac [4] and increase the energy up to 20 GeV. The required beam characteristics, defined by the BR [5] and the linac, are summarized in Table 1.

In this paper, optics design considerations and limitations are presented for both options.

ALTERNATIVE PRE-BOOSTER RING DESIGN

Optics Design and Layout

The alternative design of the PBR composes of 4 arcs and 4 straight sections [6]. Each arc consists of 35 FODO cells while the straight sections consist of 5 FODO cells each, with adequately allocated space for the RF, damping wigglers, injection and extraction elements.

Minimum emittance is ensured by choosing the phase advance of a FODO in the arc. The optimum phase advance of a cell in the arc is chosen to be (μ_x,μ_y)=(0.383, 0.11) in order to achieve the required 5 nm.rad emittance at extraction. The phase advance of a FODO in the straight section is tuned for the working point optimization.

Damping Wiggler Magnets

The PBR needs to accept the beam from the linac and dump it to the equilibrium state, in less than half of a second, otherwise it will lengthen the PBR injection flat bottom and thus the whole injector cycle. In this respect, damping wiggler (DW) magnets are proposed for achieving the desired damping time. The damping time of the PBR is reduced to 0.1 s from 0.26 s with a wiggler peak field of 1.3 T and a total wiggler length of 16.2 m. Two DW magnets per cell are installed in each straight section.

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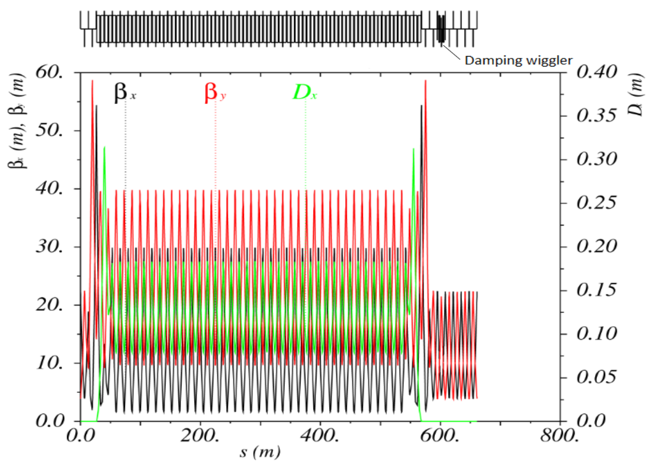

Figure 2: Optics functions of one super-period of the alternative PBR.

Figure 2 shows the horizontal (black) and vertical (red) beta functions and the horizontal dispersion (green) of one of the four super-periods.

RF Voltage and Energy Acceptance

The value of the maximum momentum deviation, for which a particle may have and still undergo stable synchrotron oscillation, is called the momentum acceptance of the accelerator [7]. Considering the maximum energy spread of the beam extracted from the linac, the energy acceptance is aimed to be 1.5% for the PBR design at injection energy. Figure 3 shows the dependence of the energy acceptance and energy loss per turn with the RF voltage and the energy of the PBR. Therefore, the minimum RF voltage is calculated as 3.6 MV to assure 1.5% energy acceptance at injection and it increases up to 62 MV at extraction energy.

Dynamic Aperture Optimization

The dynamic aperture (DA) is defined as the maximum phase-space amplitude within which particles do not get lost as a consequence of single-particle effects. The working

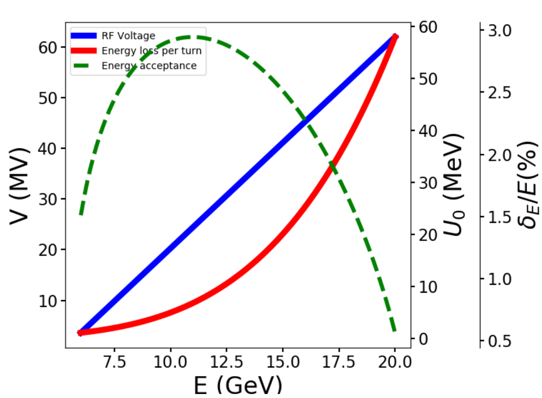

Figure 3: The energy loss per turn (red), RF voltage (blue) and energy acceptance (green) 6–20 GeV energy.

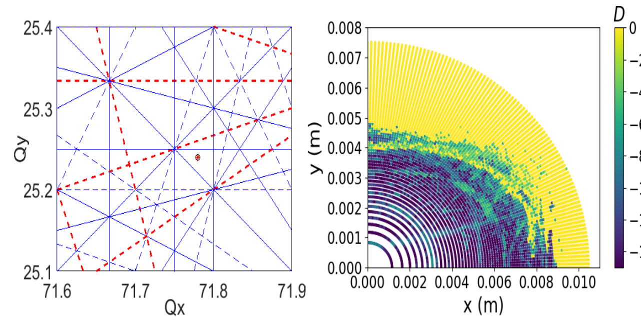

Figure 4: Tune working point on a resonance diagram up to 5th order. Systematic (red), non-systematic (blue), normal (solid) and skew (dashed) resonances are shown (left), dynamic aperture (right).

point of a ring is chosen to be away from resonance lines. Different resonance lines have different effects on DA and the effect generally becomes weaker with the increasing order [7, 8]. The horizontal and vertical phase advances in the straight sections of the PBR are selected to be $(\mu_x, \mu_y) = (0.248/0.249)$ in order to choose a proper working point, provide minimum beta functions in the straight sections, and maximum efficiency for injection and extraction elements. The working point of the PBR is $(Q_x, Q_y) = (71.78/25.24)$ as it is shown in Figure 4 (left) with the phase advance optimizations in the arcs and in the straight sections.

The injection method to the PBR puts the main requirement for the DA in the horizontal plane. An off-axis (on-energy) injection is proposed due to the number of bunches needed to be stored in the PBR [9]. Therefore, the PBR is required to provide a large dynamic aperture [10]. Thus, the need of minimum 7 mm DA is imposed to the PBR.

DA simulations were carried out with MADX-PTC [11]. Particles with different initial conditions were tracked for 10000 turns (around 1 damping time). The calculation is performed including sextupoles and fringe fields for on-momentum particles without magnet errors. Figure 4 (right) shows the initial positions of the particles with the color coded diffusion coefficient (D=$log\sqrt{(Q_{x1}-Q_{x2})^2+(Q_{y1}-Q_{y2})^2}$) which is a measure of the frequency change in time. Large negative values of D indicate better stability whereas close to zero values shows chaotic motion [8]. As a result, the DA is calculated around 8 mm in horizontal plane for the determined working point as satisfying the requirement of the DA for the PBR.

Based on all the previous considerations, the beam parameters of the PBR design are summarized in Table 2.

SPS AS PRE-BOOSTER OF FCC-e^+e^-

Using the SPS as a pre-booster for the FCC-e^+e^- imposes some extra constraints, as minimum modifications can be applied to the existing machine. Similar constraints were also considered when the SPS was used as an injector for the LEP collider [12]. The SPS lattice is designed with FODO cells and the dispersion suppression is achieved by keeping

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Table 2: Beam Parameters of the Alternative PBR

Parameter	20 GeV / 6 GeV
Circumference [m]	2644
Emittance (hor.) [nm.rad]	5.01 / 0.20
Energy loss per turn [MeV]	57.8 / 1.025
Damping time (hor.) [s]	0.06 / 0.1
Field of bending magnet [T]	0.24 / 0.07
Horizontal natural chromaticity	-118
Vertical natural chromaticity	-61
Equilibrium energy spread	0.0012 / 0.0009
RF voltage [MV]	62 / 3.6
Momentum comp. factor [10^{-3}]	0.28
Energy acceptance [%]	0.57 / 1.5
Tune h/v	71.78 /25.24
Transverse acceptance h/v [mm]	3.5 /0.5
Dynamic aperture h/v [mm]	8.0 /4.0
Field of damping wiggler [T]	1.3
Length of damping wiggler [m]	16.2

the total arc phase advance a multiple of 2π. Minimum emittance can be achieved for a FODO cell horizontal phase advance of around 135^0 ($3\pi/4$) [13]. The emittance at the extraction and the damping times at the injection are two of the main limitations for the SPS. The emittance at the extraction energy, even with the optimum phase advance, exceeds 50 nm.rad and the damping time at injection energy is around 1.8 s, which are far from the requirements of the PBR.

Damping and Robinson Wiggler Magnets

Damping wiggler magnets have different effects on damping time, emittance, energy spread and energy loss per turn [14]. The required emittance can be reached with around 6 T magnetic field and 23 m damping wiggler for the SPS. However, the energy loss per turn becomes very high and around 200 MeV according to the analytical calculations. In this respect, the use of a Robinson wiggler in combination to the damping wigglers are being investigated. The Robinson wiggler (RW) is composed by a series of combined function magnets and theoretically changes the damping partition ($D = I_4/I_2$) by modifying the 4^{th} synchrotron radiation integral (I_4) [15, 16]. Figure 5 shows an analytical parametrization of the horizontal emittance and energy spread with the damping partition. The damping partition is 0.0014 without RW and it becomes negative depending on the added RW: the horizontal emittance can be significantly decreased with Robinson wiggler, whereas it introduces a growth of the energy spread which puts a limit on the number of the RW.

Even though it is possible to achieve the required horizontal emittance with a combination of damping and Robinson wiggler magnets, the energy spread and energy loss per turn become still high at 20 GeV extraction energy of the SPS.

In this respect, different extraction energy options have been considered and the impact on the extracted beam parameters, based on MAD-X, is summarized in Table 3. From

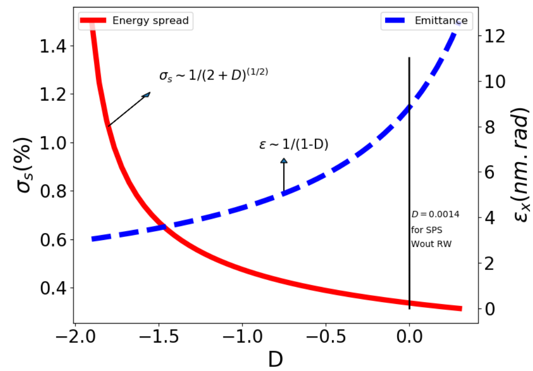

Figure 5: Parameterization of the emittance (blue) and energy spread (red) with D for the effect of RW in addition to DW at 20 GeV.

this, it becomes clear that the 16 GeV option provides a reasonable energy spread, energy loss per turn and emittance at the same time. This energy is similar to the one considered for using the SPS with electrons for dark matter searches (LDMX) [17].

CONCLUSIONS

In this study, an update for the alternative pre-booster ring design study of the FCC-e^+e^- injector chain is presented under the specified requirements. Damping wiggler magnets are added to reduce the damping time. Phase advance optimizations are provided in order to have minimum emittance and obtain optimized working point for a good dynamic aperture. The RF voltage is calculated as ensuring the required energy acceptance.

The insertion of the damping and Robinson wiggler magnets are introduced and compared for the SPS by analytical calculations and MAD-X results. Additionally, the different extraction energies are discussed to assure the required emittance, energy loss per turn and energy spread for the SPS. Further detailed studies are in progress, including extraction energy selection, DA optimization for the SPS and estimation of collective effects for both choices.

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Table 3: Beam Parameters for Different Energies

Parameter	20 GeV	18 GeV	16 GeV
	inj./ext.	inj./ext.	inj./ext.
Emittance [nm.rad]	1.0/5.9	0.9/5.6	0.7/5.6
E. loss per/turn [MeV]	9.9/128	6.9/73.9	3.4/31.5
Damping time (hor.) [ms]	12/3	10/5	30/10
Eq. energy spread [%]	0.3/0.6	0.35/0.5	0.3/0.38
RF voltage [MV]	35/160	30/90	25/40
Field of DW [T]	6	5	3.5
Field of RW [T]	0.5	0.5	0.5

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