

CONCEPTUAL DESIGN OF A PRE-BOOSTER RING FOR FCC e⁺e⁻ INJECTOR

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Abstract

The FCC-e⁺e⁻ injector complex needs to produce and to transport a high-intensity e⁺/e⁻ beam at a fast repetition rate of about 0.1 Hz for topping up the collider at its collision energy. A basic parameter set exists for all the collider energies, assuming a 10 GeV linac operating with a large number of bunches being accumulated in the existing SPS, which serves as pre-accelerator and damping ring before the bunches are transferred to the high-energy booster [1]. The purpose of this study is to provide the conceptual design of an alternative accelerator ring, replacing the SPS in the present scheme. This ring will have injection energy of 6 GeV and extraction energy of 20 GeV. In this study, the basic parameters of the ring are established, including the optics design and layout. Preliminary consideration for non-linear dynamics optimization and the impact of intra beam scattering are also presented.

INTRODUCTION

The initial basic parameters for FCC e⁺e⁻ pre-injector were established in order to satisfy the demanding collider flux requirements, especially for the full machine filling of the lowest energy collider flavour (45.6 GeV). This design is based, on a CLIC (Compact Linear Collider) based linac and using the CERN Super Proton Synchrotron (SPS) as a damping and pre-booster Ring. Since there may be issues for using the SPS as pre-injector, such as machine availability, synchrotron radiation and new RF system, just to name a few, a “green field” alternative pre-booster damping ring (PBDR) design was mandatory [2]. In parallel, another alternative linac study has also started [3], based on the design approaches of the SUPERKEKB pre-injectors. Additionally, a booster design study is also continuing [4]. Figure 1 shows the FCC e⁺e⁻ injector complex schematic layout.

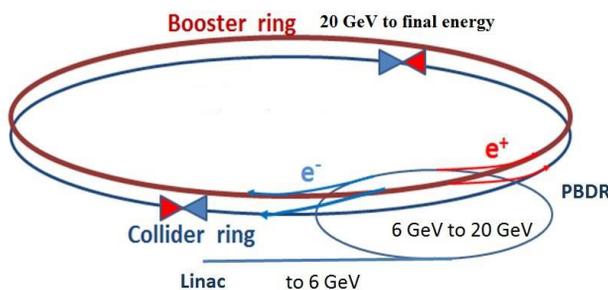


Figure 1: Layout of FCC ee injector complex.

The extraction energy of the PBDR has to be as high as possible, in order to raise as much as possible the field of the bending magnets of the main booster at injection. Based on parameter scaling and basic calculations, the extraction energy was established at 20 GeV, for having the lowest circumference within a reasonable energy loss per turn limits of around 50 MeV [5].

EMITTANCE AT EXTRACTION

The emittance at extraction of the PBDR has to satisfy the requirement for the injected emittance in the main booster ring, which in turn is established by the demands of the collider. The lowest injection emittance target of the collider ring is 0.09 nm.rad [6]. Assuming no extra blow-up effects, the emittance $\epsilon(t)$ at a certain instant t can be given by

$$\epsilon(t) = \epsilon_{inj} e^{-\frac{2t}{\tau}} + \epsilon_{equ}(1 - e^{-\frac{2t}{\tau}}) \quad (1),$$

where ϵ_{inj} and ϵ_{equ} are the injected and equilibrium emittances, respectively and τ the damping time. Taking into account that the different parameters are energy dependent, a parametric relation can be established connecting the injected emittance as a function of a linear ramping time t_r , for a given emittance at extraction. Figure 2 uses this relation to establish the injected emittance in the booster ring (or extraction in the PBDR assuming again no transfer blow-up). Taking into account that the cycle time of the main booster ring is around 12 seconds [1], and assuming equal ramp-up and down times and negligible injection and extraction plateaux, the emittance at the entrance of the booster ring should be about 1 nm.rad, corresponding to an accelerating time of 6 seconds.

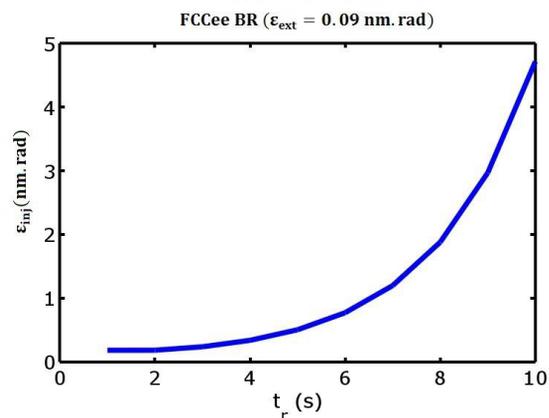


Figure 2: Injection emittance of booster ring with ramping time.

All the following calculations are made by targeting an extraction emittance of the PBDR of around 1 nm.rad. The same approach can be used for establishing the injection emittance in the PBDR. For a cycle of 1.2 s, the injected emittance obtained is 1.5 nm.rad. This may already point to the direction of needing an extra damping stage with a dedicated damping ring for both species.

PARAMETER SCALING AND LATTICE DESIGN

After fixing the extraction emittance of the PBDR as around 1 nm.rad, the scaling of parameters such as energy loss per turn, damping time, energy spread and emittance, as a function of the circumference C and ring filling factor FF (total dipoles' length over circumference) can be established, while constraining the energy loss to below 50 MeV/turn [5]. This is an important step to further determine the layout of the ring and provide the main lattice cell.

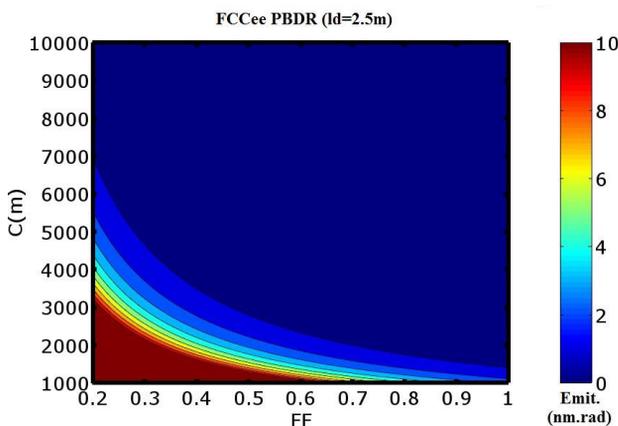


Figure 3: Scaling of emittance with filling factor and circumference.

Figure 3 shows an example of this parametrisation, between ring circumference and the filling factor color-coded with the emittance at extraction energy of 20 GeV, considering a reasonable dipole length of 2.5 m and FODO cells. As expected, the higher filling factor allows lower emittance for shorter ring circumference. For a filling factor of 0.7, the PBDR should have a circumference of around 3 km for obtaining around 1 nm.rad emittance at extraction. This choice is optimal, as it provides the minimum circumference for a limited RF power, while satisfying the transverse emittance requirements.

Additionally, there is a strict relation amongst emittance, phase advance and chromaticity for any given cell. Thus, the relations between these parameters are also checked. The basic idea is to find an adequate phase advance that satisfies the emittance requirement at extraction, while keeping the chromaticity low.

After analytic calculations and simulations, the basic structure of PBDR has been achieved. The ring is of race-track shape consisting of 2 arcs and 2 straight sections; each arc has 166 FODO lattice with sextupole magnets in

each main cell, whereas each straight section has two matching cells. The total circumference is 2736 m. Table 1 shows the main parameters of the magnets in PBDR.

The main cell is shown schematically in Figure 4. The cell consists of two 2.5 m-long dipoles sandwiched between quadrupoles with 30 cm length. The dipoles have a 70 Gauss field at injection. The chromaticity is controlled by two families of 10 cm-long sextupoles. The horizontal (red) and vertical (green) beta functions and horizontal dispersion (blue) of the cell are presented in Figure 5. The present cell employs separate function magnets, although combined function ones may be considered if found to be more cost-effective.

Table 1: Magnets in PBDR

Magnets	Num. of Magnets	Length	Field or Strength
Bending	700	2.5 m	0.07T/0.239T
FQ	362	0.3 m	-0.94 m ⁻²
DQ	362	0.3 m	1.59 m ⁻²
FS	332	0.1 m	109 m ⁻³
DS	332	0.1 m	-138 m ⁻³

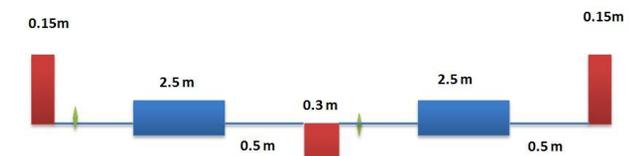


Figure 4: Main FODO cell of PBDR.

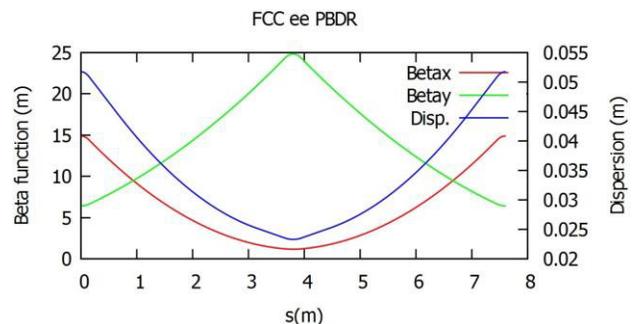


Figure 5: Beta functions and dispersion of the main cell.

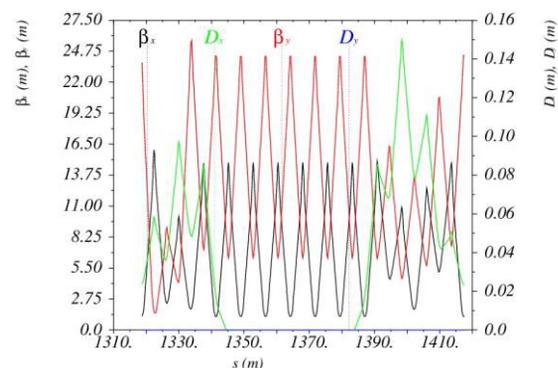


Figure 6: Straight section optics of PBDR.

Zero-dispersion straight sections with adequately allocated space for the RF, the injection and the extraction elements, are built with identical bending-free cells. They are connected to the arc with the help of matching cells. The optics functions of one such straight section including the matching cells is shown in Figure 6.

During the design process, three different codes, namely OPA [7], MADX [8] and ELEGANT [9] were used. A comparison of general ring parameters is presented in

Table 2. All three codes show very good agreement. For these design parameters, the emittance at 20 GeV is around 0.7 nm rad, which provides some margin with respect to the 1 nm rad target requirement. Note that a remarkably low equilibrium emittance of around 65 pm.rad is achieved at injection energy of 6 GeV. The energy loss per turn is 51 MeV and the damping times are quite short (a few ms).

Table 2: Main Parameters of PBDR

	OPA	MADX	ELEGANT
Energy [GeV]		20	
Circumference [m]		2736	
Emittance [pm.rad]	710	718	712
Energy loss / turn [MeV]	50.8	50.8	50.8
Natural chromaticity	-189/-110	-189/-110	-189/-108
Dx max [m]	0.149	0.156	0.149
Betax max [m]	16.0	16.0	16.0
Betay max [m]	25.7	24.6	25.8
Damping times [ms]	7.2/7.2/3.6	7.2/7.2/3.6	7.2/7.2/3.6

Chromaticity correction and dynamic aperture

The high chromaticity of the ring has to be controlled with a pair of sextupoles, which inevitably impact the rings dynamics aperture (DA). Figure 7 shows the horizontal versus vertical DA for different momentum deviations using the ELEGANT code [8].

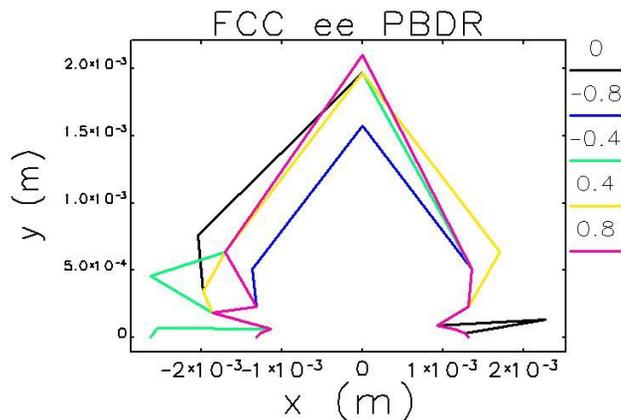


Figure 7: Dynamic aperture for different momentum deviations ($\pm 0.4, \pm 0.8$).

For the injected emittance of 1.5 nm.rad, the beam size is equal to 0.3 mm, so the minimum DA obtained is around 5σ . This is a preliminary study that needs further optimization (e.g. of the working point); this can be indeed improved by a better working point choice, which is not presently optimised.

Intrabeam scattering effect

The Intrabeam scattering (IBS) effect causes emittance growth in all three dimensions. It basically depends on the optics and beam properties and in particular with the

beam energy. The scaling of the horizontal emittance including the IBS effect using ELEGANT [9] is presented in Figure 8 (assuming no coupling or residual vertical dispersion and a bunch population is 8.3×10^9), along with the “zero-current” equilibrium emittance. The horizontal steady state emittance is IBS dominated at injection energy, with an almost 10-fold increase. At high energy, the effect of IBS is indeed negligible.

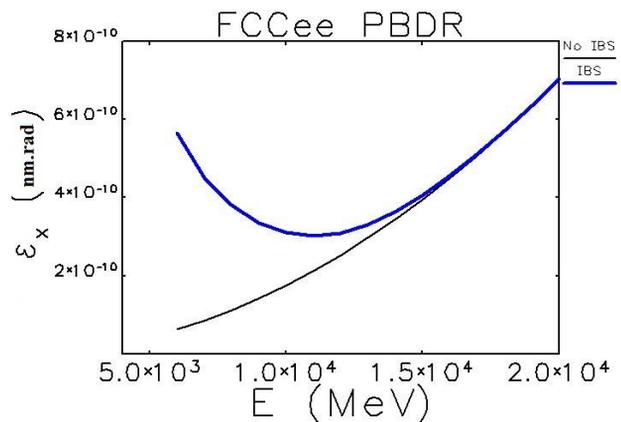


Figure 8: Emittance evaluation with energy changes by IBS effect.

CONCLUSION

In this study, a preliminary design of the pre-booster damping ring of the FCC e^+e^- injector complex is undertaken. Further detailed studies are in progress, in particular, the establishment of magnet and alignment tolerances impacting the vertical emittance and the dynamic aperture and the study of other collective effects and synchrotron radiation handling.

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