ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPMF002

PRE-BOOSTER RING CONSIDERATIONS 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 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 a completely new ring. The purpose of this paper is to explore the needs and parameters of the existing SPS machine and provide the conceptual design of an alternative accelerator ring with injection and extraction energies of 6 and 20 GeV, respectively. In this study, the basic parameters of both choices are established, including the optics design and layout updates. Consideration for non-linear dynamics optimization 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 and using the CERN Super Proton Synchrotron (SPS) as a damping and pre-booster Ring (PBR) [1]. Since there may be issues for using the SPS as pre-injector, such as machine availability, synchrotron radiation and RF system requirements, a "green field" alternative pre-booster ring (PBR) design was also undertaken [2]. In parallel, a linac study has also been progressing for the bunches to be injected in the pre-booster, based on the design approaches of the SUPERKEKB pre-injectors [3]. The layout of the FCC e^+e^- complex and the location of the pre-booster rings, are shown in Figure 1.

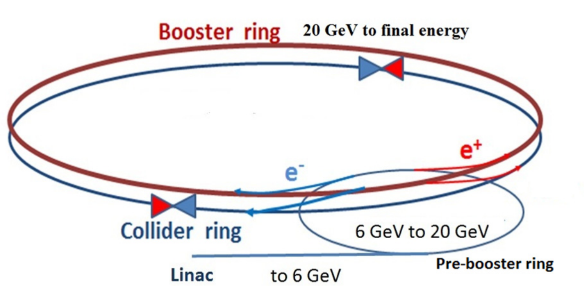

Figure 1: Layout of FCC e^+e^- complex.

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

Using the SPS as pre-booster for the FCC-e^+e^- injector chain imposes various constraints, as minimum modifications can be applied to the existing machine, following to the lepton collider requirements. Similar constraints were considered when the SPS was used as an injector for the LEP collider [4].

At first, the parameters that SPS can provide with the energy scale of FCC e^+e^- pre-booster (6 to 20 GeV) are estimated. The SPS is constructed by FODO cells and the dispersion suppression is achieved by keeping the total arc phase advance a multiple of 2π. Figure 2 shows the emittance value that SPS can achieve with different phase advance for a FODO cell, as the one in the present SPS. Although FODO cell is not a proper choice for low emittance, better values can be provided by arranging the horizontal phase advance of a cell to around 140^0. A geometrical emittance of 27 nm.rad can be achieved according to analytical calculation for a horizontal phase advance of 135^0, while satisfying at the same time the condition for the dispersion suppression [5].

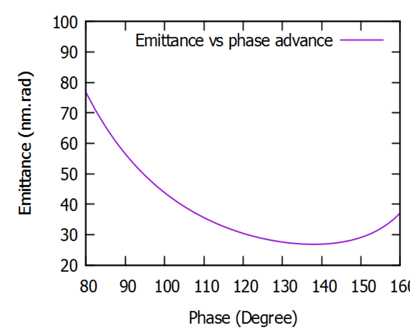

Figure 2: Parameterization of the horizontal geometrical emittance with the SPS FODO cell horizontal phase advance, at 20 GeV.

Another important parameter to be considered is the synchrotron radiation damping time, which is around 1.7 s for the SPS at 6 GeV. This damping time is quite long and will lengthen considerably the SPS injection flat bottom and thereby the whole injector cycle.

Wiggler Magnet and its Effects on Beam Properties

The equilibrium horizontal emittance in lepton rings is determined by the bending angle of the dipole magnets. In order to achieve the required emittance and shorten the damping times by roughly an order of magnitude, the employment of damping wiggler magnets are proposed to be installed in the straight sections of the SPS, like in the case of the CLIC damping rings design [6].

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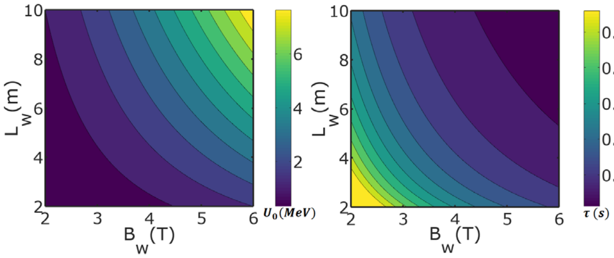

Figure 3: Parameterization of the Damping time (right) and energy loss per turn (left) with the total wiggler length, for different wiggler field.

In the meantime, wiggler magnets have different effects on beam properties as energy loss per turn, energy spread, bunch length, etc. The effects of wiggler magnets on damping time and energy loss per turn for SPS are shown in Figure 3. In these plots, analytical calculations are presented in order to evaluate the dependence of the damping time and energy loss per turn to the wiggler magnet total length and field. In order to obtain the desired damping time of 0.1 s, wigglers with 5 T field are necessary for a total length of 4.5 m. In Table 1 some parameters of the SPS are shown with and without wiggler magnets. In particular, the horizontal equilibrium emittance is reduced to 0.13 and 10 nm.rad at injection and extraction respectively, whereas the energy loss per turn is greatly increased to 2.7 and 47 MeV.

Table 1: Equilibrium Horizontal Emittance and Energy Loss per Turn, With and Without Wigglers for the SPS as Pre-booster of FCC-e^+e^-

	6 GeV		20 GeV	
	Without wiggler	W/wiggler	Without wiggler	W/wiggler
ε_x (nm.rad)	2.43	0.13	27	10
τ (s)	1.7	0.1	0.04	0.02
U_0 (MeV)	0.15	2.7	19	47

ALTERNATIVE PRE-BOOSTER RING CONSIDERATIONS

An alternative study of a green-field pre-booster ring has been also considered. Since the damping time of the main booster is long, the initial target was to extract the beams with a very low emittance which was around 0.7 nm.rad [2]. Following the decision to include wiggler magnets as well in the main booster in order to reduce the damping time at injection energy [7], the pre-booster target emittance can be relaxed, but still remain compatible with the dynamic aperture of the main booster. The relaxation of the extraction emittance requirement of the pre-booster ring provides more comfortable parameters in terms of quadrupole, sextupole strengths and chromaticity which are the factors that affect the dynamic aperture at injection. This updated design also provides a shorter circumference as well as better dynamic aperture comparing to the low extraction emittance option.

Based on analytic calculations and simulations, the basic structure of PBR has been achieved. A FODO type cell is chosen and the ring has a racetrack shape consisting of 2 arcs and 2 straight sections; each arc has 60 FODO cells with sextupole magnets in each main cell, whereas each straight section has two matching cells. The horizontal (black) and vertical beta (red) functions and horizontal dispersion (green) of a cell are presented in Figure 4.

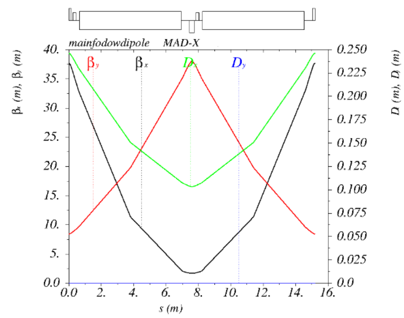

Figure 4: Beta functions and dispersion of the main cell.

A cell comprises two 6.3 m-long dipoles located between quadrupoles with 30 cm length. The dipoles have a $7x10^{-3}$ T field at injection. The chromaticity is controlled by two families of 20 cm-long sextupoles. The total circumference is 2280 m. Phase advance scanning is performed for a FODO to choose an optimum working point in terms of emittance, chromaticity and tune shift with different amplitude and thereby to have a good dynamic aperture.

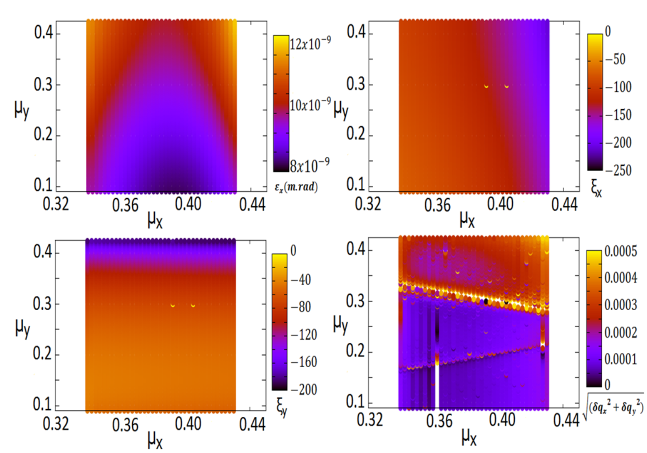

Figure 5: Parameterization of the horizontal and vertical phase advances with horizontal emittance (top, left), natural chromaticities (top, right and bottom, left) and tune shift with amplitude (bottom, right).

Figure 5 shows a parameterization of the equilibrium emittance at extraction (top, left), the horizontal (top, right) and vertical (bottom, left) chromaticities. The quadratic sum of the amplitude dependent tune shift (bottom, right) with the horizontal and vertical phase advance of the arc FODO cell is also shown in Figure 5 (bottom, right). The amplitude dependent tune shift was calculated using the

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anharmonicity values from MADX-PTC [8], based on [9]. An optimal choice of phase advances for achieving a small emittance at extraction, while keeping the chromaticities and the detuning with amplitude low, was chosen to be (μ_x, μ_y) = (0.38/2π, 0.134/2π), corresponding to a tune working point of (Q_x, Q_y) = (57.08, 20.24). Figure 6 shows the tune working point (left) on a resonance diagram up to 3rd order. The red and blue lines correspond to the systematic and non-systematic resonances respectively, while the solid and dashed lines to the normal and skew resonances respectively. In Figure 6 (left), the tune shift with amplitude up to 6 σ is shown in green. Since the anharmonicities are relatively low, the tune shift is very small.

Following these results, dynamic aperture simulations were undertaken and the results are shown in Figure 6 (right), i.e. the horizontal versus vertical DA for different momentum deviations using MADX-PTC. Considering that the injected horizontal emittance is around 1 nm.rad provided from the linac at the moment, the DA is around 50 beam size for up to ±1.5% momentum deviation in horizontal plane.

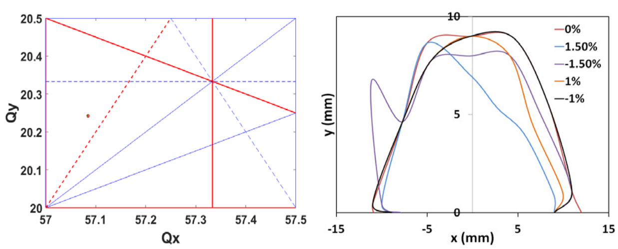

Figure 6: Tune working point on a resonance diagram up to 3th order. Systematic (red), non-systematic (blue), normal (solid) and skew (dashed) resonances are shown (left), Dynamic aperture for different momentum deviations (up to ±1.5%) (right).

Table 2: Main Parameters of Alternative Ring Design as Pre-booster of FCC e^+e^-

Parameters	20 GeV	6 GeV
Circumference [m]	2280	
Emittance [nm.rad]	8.34	0.75
Energy loss / turn [MeV]	50	0.4
Natural horizontal chromaticity	-96.71	
Natural vertical chromaticity	-44.03	
Dx max [m]	0.43	
Betax max [m]	49.85	
Betay max [m]	40.08	
Horizontal Damping times [ms]	7.2	268
Vertical Damping times [ms]	7.2	268
Longitudinal Damping times [ms]	3.6	134
Horizontal Tune	57.08	
Vertical Tune	20.24	

These updated studies show that the DA can accept up to 30 nm.rad emittance. The DA is quite comfortable, but the optimization study is still going on considering that the injected emittance may be increased and taking into account the effect of misalignment errors. Table 2 shows the updated main beam parameters of the pre-booster ring design.

Additional studies are also done to reduce the damping time to 0.1 s. Since this is a green field design, there is flexibility for arranging the damping by changing the circumference as well as adding wiggler magnets to the design. Both options were evaluated and it was decided to propose 2 T wiggler magnets with the total length of around 7 m, instead of making the circumference longer.

ENERGY ACCEPTANCE AND RF VOLTAGE ESTIMATIONS

The energy acceptance calculation is needed to confirm that the PBR can accept the incoming beam from the linac. The energy acceptance can be determined by the following Eq. (1):

$$\frac{\Delta E}{E} = \pm\sqrt{\frac{q.V}{\pi.h.\alpha_c.E_0}.(2cos(\emptyset_s) + (2.\emptyset_s - \pi)sin(\emptyset_s))} \quad (1)$$

where, E_0 is the beam energy, h is harmonic number, α_c is momentum compaction factor, $\emptyset_s$ is the RF stable phase and V is the RF voltage. Apart from the RF voltage and RF phase, all the other parameters are almost constant since they are determined during the optical design process. As also can be seen in Table 3, the energy acceptance is arranged to be ±1.5% so that the energy spread of the linac beam can be accepted.

Table 3: RF Voltages and Energy Acceptance

	SPS	Alternative
RF Voltage (inj./extr.) (MV)	23/55	4.2/67
RF Stable Phase at inj. (degree)	7	14
Momentum compaction fac.	$9.8x10^{-4}$	$4x10^{-4}$
Harmonic number	9214	2854
Energy acceptance (±%)	1.5	1.5

CONCLUSION

In this study, an update of the design options for the pre-booster ring of the FCC e^+e^- injector complex is presented. The insertion of damping wiggler magnets is proposed for the SPS lattice and the impact of the wiggler peak filed and total length on the final beam parameters is discussed. Updated studies for the alternative design option are also presented, providing an adequate on and off-momentum DA up to dp/p of ±1.5%. Optimal settings of RF voltage with respect to energy acceptance are proposed for both options. Further detailed studies are in progress, to identify the impact of magnet and alignment tolerances on the dynamic aperture and the vertical emittance tuning, the study of collective effects and synchrotron radiation handling.

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