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STUDIES ON TOP-UP INJECTION INTO THE FCC-ee COLLIDER RING

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Abstract

In order to maximize the luminosity production time in the FCC-ee, top-up injection will be employed. The positron and electron beams will be accelerated to the collision energy in the booster ring before being injected with either a small transverse or longitudinal separation to the stored beam. Using this scheme essentially keeps the beam current constant and, apart from a brief period during the injection process, collision data can be continuously acquired. Two top-up injection schemes, each with on- and off-momentum sub-schemes, viable for FCC-ee have been identified in the past and are studied in further detail to find a suitable design for each of the four operation modes of the FCC-ee. In this paper, injection straight optics, initial injection tracking studies and the effect on the stored beam are presented. Additionally, a basic proxy error lattice is introduced as a first step to studying injection into an imperfect machine.

INTRODUCTION

The Future Circular Collider (FCC) study includes focus on a high energy and high brightness electron-positron collider (FCC-ee) to serve the international scientific community through the 21st century. Part of this proposed project is reaching unprecedented luminosity in an electron-positron collider. The FCC-ee design luminosity is to be more than 10,000 times greater than what was achieved at the Large Electron Positron collider (LEP), the previous highest energy electron-positron collider, when operating with a beam energy of 45.6 GeV [1].

Within the FCC-ee study there are four different working points for energy of the collisions, initially in the Z-pole energy range and moving through increasing operation energies to the $t\bar{t}$ threshold [1]. Some basic parameters of the four operation modes of the proposed machine are shown in Table 1. First studies, presented in the following, focus on operation in Z-mode (45.6 GeV beam energy) due to the importance of machine protection with its high, 20 MJ stored beam energy.

In order to maximize the luminosity of the FCC-ee top-up injection is required to maintain the beam current and allow for continuous, full-energy collisions [2]. LEP used fill and ramp injection which provides lower integrated luminosity due to the decay of the colliding beam current and lost collision time during injection and ramping of the ring. When using top-up injection beams are accelerated to collision energy in a booster ring before being injected into the collider ring. This allows the collider to stay in almost constantly in collision mode. Top-up injection has been successful in the colliders at both KEKB and SLAC and the integrated luminosity gain was as much as 50% [3]. Top-up is also a mainstay for modern lightsources.

Table 1: Selection of FCC-ee parameters for the four operation modes. From Table 1 in Ref. [1].

	Z	WW	ZH	$t\bar{t}$
Beam Energy (GeV)	45.6	80	120	175/182.5
Beam Current (mA)	1390	147	29	6.4/5.4
Horizontal Emit. ϵ_x (nm · rad)	0.27	0.84	0.63	1.34/1.46
Vertical Emit. ϵ_y (pm · rad)	1.0	1.7	1.3	2.7/2.9
Luminosity/IP (10^{34}cm^2 s)	230	28	8.5	1.8/1.55

Top-Up Injection Schemes for FCC-ee

Two viable top-up injection schemes have been identified for the FCC-ee: conventional orbit bump injection and multipole kicker injection (MKI) [2]. In the former, dipole kickers are used to introduce a bump in the orbit of the stored beam which brings it closer to the injection septum and reduces the separation of the stored and injected beams. Both beams are then bent back towards the design orbit within one turn, where the injected beam undergoes betatron oscillations until synchrotron radiation causes it to damp and join the stored beam.

In multipole kicker injection a specially designed magnet with a low-field region on-axis and significant off-axis field minimizes the disturbance of the stored beam while providing the kick required to store the injected beam which then damps to join the stored beam [4–6]. Though the stored beam passes through the low-field region of the MKI magnet, it is affected due to the finite width of the zero-field region. By introducing a compensation kicker upstream of the MKI magnet the emittance blow-up can be minimized. An MKI design for FCC-ee has been proposed previously, and studies of the feasibility of the injection hardware for each mode, including the injection septa and kickers are ongoing [2, 7].

Each of the two viable injection schemes also has an off-momentum option, where the injected beam has a fractional difference in energy compared to the stored beam. The injected beam is stored directly on a dispersive orbit to separate it from the stored beam. Damping occurs in the longitudinal

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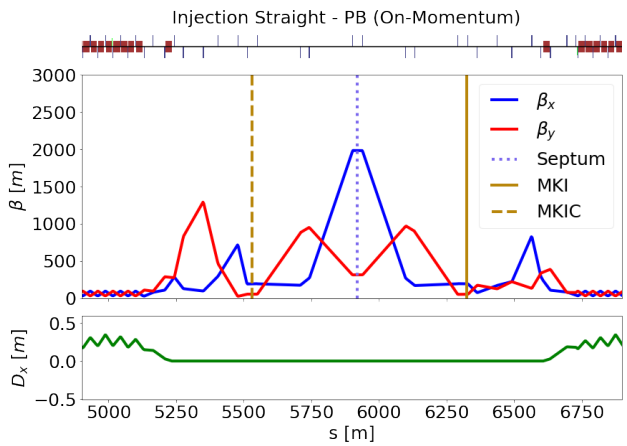

Figure 1: Injection straight optics for on-momentum orbit bump or multipole kicker injection with septum and kicker locations marked.

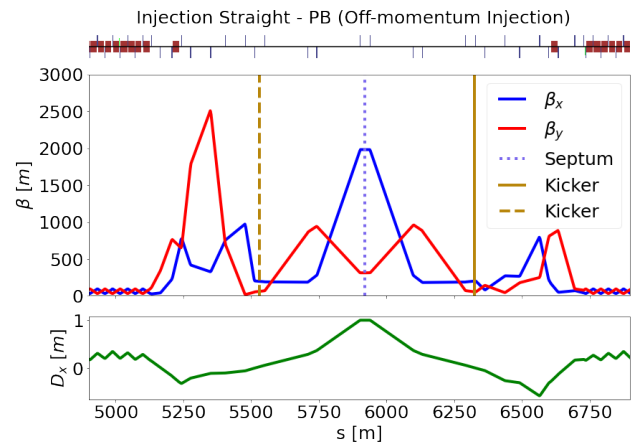

Figure 2: Injection straight optics for off-momentum conventional orbit bump injection with septum and kicker locations marked. Optics not suitable for off-momentum multipole kicker injection.

plane and the transverse oscillations of the injected beam will be minimized. Because of these flatter trajectories in the straight sections off-momentum injection also has the benefit of reducing radiation doses for the experiments, as observed at LEP [8]. In total with the orbit bump and multipole kicker injection for both the on- and off-momentum cases, four types of injection are considered. Studies are ongoing to quantify each of the injection schemes in terms of injection efficiency in the presence of errors.

SIMULATION OF INJECTION

The injection studies are performed on a 2 interaction point (IP) lattice similar to the one presented in the Conceptual Design Report [1]. The optics for the injection straight, suitable for both on-momentum orbit bump and on-momentum MKI are shown in Fig. 1 [9]. The injection straight's notable features are the large horizontal beta-function at the injection septum to minimize the effective size of the septum in terms of beam sigmas, and the matched beta functions at the planned locations for the kicker magnets [2].

Off-momentum orbit bump injection requires dispersion at the injection septum so that the injected beam can be placed directly on a dispersive orbit. Using MAD-X [10], the optics in the insertion was rematched to introduce dispersion at the septum, required for the off-momentum conventional injection. The same phase advance as for the on-momentum optics was kept, and matched to the arc optics. The dispersion is 1 m at the septum, which gives sufficient separation for injected beam with a momentum offset of $dp/p = 1\%$. These optics, shown in Fig. 2, are very similar to those in Fig. 1 except with the added dispersion peak at the septum.

For off-momentum MKI a larger dispersion at the multipole kicker is required. However, for the given layout no optics were found that provide a sufficiently large dispersion at the MKI.

First simulations have focused on on-momentum MKI injection. The horizontal phase advance between the septum and the MKI is 90° for compatibility with conventional injection. For the MKI, the beam is injected such that it interacts with the flat high-field region of the MKI field. As expected, with both the dynamic aperture and physical aperture above 15 σ_x [11] tracking of an on-momentum injected beam shows no losses around the ring.

Simulating the MKI's impact on the stored beam showed that an uncompensated MKI increases the stored beam size at the IP by a factor of 5. With the upstream compensation kicker active, the beam size at the IP is corrected to design stored beam levels. Figure 3 demonstrates how the compensation works by introducing the distortion upstream, which evolves 180° through phase space to the MKI where it receives an identical kick to eliminate the disturbance. These simulations show both the efficacy and the importance of the compensation kicker for MKI injection.

Misalignments and Magnet Errors

To evaluate the injection efficiency of the injection schemes in a more realistic machine, errors must be introduced to the simulations. Misaligned lattices, magnet errors, and their corrections are currently being studied in detail for the $t\bar{t}$ lattice [12]. For these injection studies in Z-mode, a simpler approach is chosen.

Small misalignments of the arc quadrupoles and bending dipole magnets are used to generate errors that approximate those after a full error implementation and correction. The tunes and chromaticities are then matched to the original values after the errors are applied. For one set of errors the RMS beta-beating is found to be 2.1% in both planes which is within the target range of 1-5% RMS beta-beating found in the full tuning studies. The maximum orbit error is 3 mm and the RMS orbit error is 300 µm, both of which are deemed too large compared to the 250 µm maximal orbit deviation in the tuning studies. Next steps will include a

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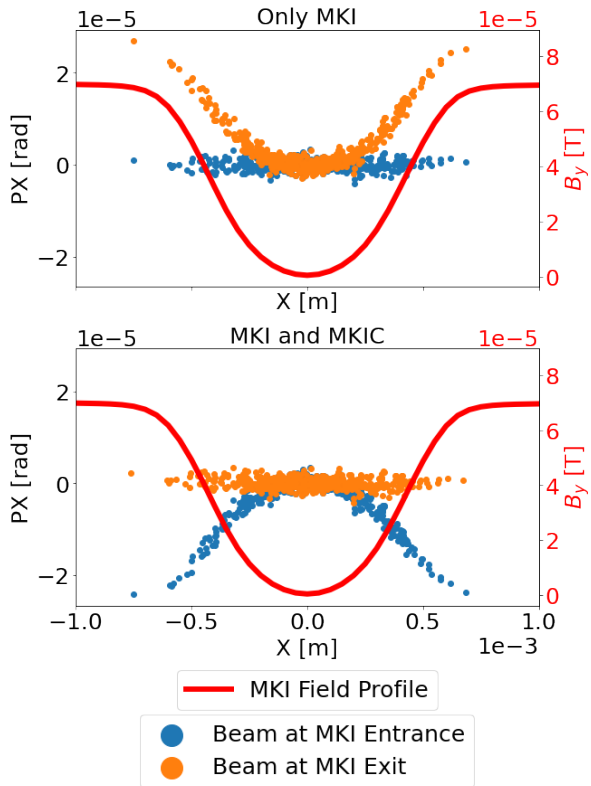

Figure 3: Stored beam distribution as it enters and exits the MKI magnet without the compensation (top) and with the compensation magnet (bottom). Without compensation the stored beam is distorted by the MKI. With the MKIC the distortion is introduced 180° phase advance upstream of the MKI which then flattens it, constraining the distortion to between the injection kickers.

simple orbit correction to reduce the orbit deviation in the lattice with simplified errors.

The dynamic aperture for the base optics (Fig. 4) was found to be greater than 30 σ in both the horizontal and the vertical which is much greater than the 15 σ required to store the 5 σ injected and stored beams for these injection approaches. When the proxy errors are included the DA drops to 20 σ in the horizontal (Fig. 5) which is still sufficient for injection. However, full tuning studies show that realistic errors are not yet able to be corrected to a point where the DA is sufficiently preserved [12, 13].

Dynamic aperture was determined using tracking of on-momentum particles for 2500 turns (one transverse damping time) through a thin, tapered lattice with a basic aperture model and synchrotron damping implemented in a MAD-X simulation.

Studies are ongoing to evaluate injection efficiency and disturbance of the stored beam in the presence of errors.

SUMMARY AND CONCLUSION

Top-up injection is required to maximize the integrated luminosity of the FCC-ee collider ring. Operation in the

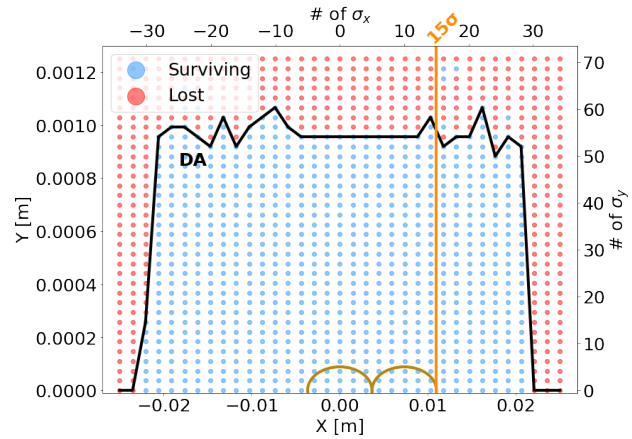

Figure 4: Dynamic Aperture for ideal lattice with on-momentum injection optics, as shown in Fig. 1. Dynamic aperture is greater than the 15σ requirement for injection.

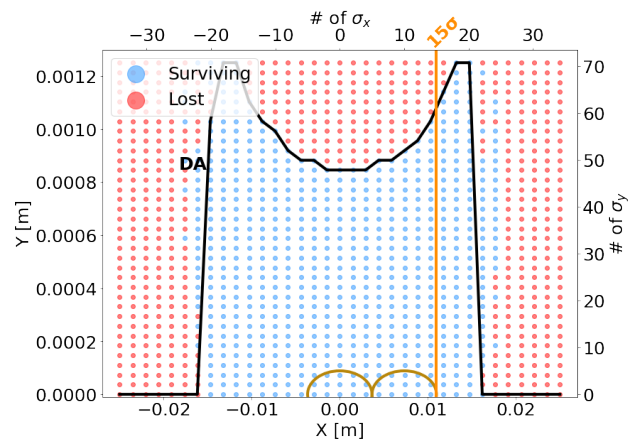

Figure 5: Dynamic Aperture for lattice with on-momentum injection optics, as shown in Fig. 1, with proxy errors included. Dynamic aperture is reduced but still greater than the 15σ requirement for injection. Full tuning studies show DA is not yet this well preserved [12, 13].

45.6 GeV Z mode has been chosen due to the machine protection concern resulting high stored beam current. We currently have developed optics for three of the four injection approaches considered for FCC-ee, and have successfully simulated injection into the ideal, 2 IP machine for Z mode. Further design of the injection straight is required to achieve optics for off-momentum MKI injection. Introduction of errors to the 2 IP lattice used in these studies to investigate the injection efficiency of the different methods is underway. Beyond this, study of beam-beam interaction with the injection process will be important to consider.

Studies will need to be repeated for higher energy operation modes, as well as for a 4 IP lattice. In a 4 IP lattice the layout of the injection insertion will need to be adapted to include a beam crossing.

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