ON-AXIS INJECTION WITH MULTIPOLE INJECTION KICKER IN FCC-ee

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Abstract

To reach and maintain its target luminosity despite a beam lifetime well below 1 h, the Future Circular Collider for electrons and positrons (FCC-ee) relies on top-up injection. The present baseline uses on-axis injection with a conventional one-turn orbit bump because of its robustness and its expected low impact on detector background. As an alternative, a multipole injection kicker (MIK) can provide on-axis injection without an orbit bump and can therefore reduce perturbations to the circulating beam.

This paper presents a first assessment of a pulsed conductor MIK for the FCC-ee injection scheme, with emphasis on the Z operation mode. The field requirements for an FCC-ee MIK are first established, and a preliminary pulsed conductor design is then presented. The beam-dynamics impact of the residual field is evaluated for both beams: a local compensation scheme based on a compensation MIK (CMIK) is studied for the circulating beam, while transfer-line optics correction is used for the injected beam. Other operation modes and alternative MIK topologies are beyond the scope of this work and remain to be studied in the future.

INTRODUCTION

The present Future Circular Collider for electrons and positrons (FCC-ee) baseline relies on on-axis, off-energy injection. The injected beam is placed on a chromatic orbit and separated from the circulating beam by the combined effect of the dispersion at the injection point and the injected beam energy offset. Since the dispersion at the interaction points (IP) is null, the injected beam overlaps with the circulating beam, thereby minimising additional synchrotron radiation photons near the experiment. The successful operation of on-axis injection in LEP also demonstrated reduced detector background and high injection efficiency [1].

A conventional local orbit bump is widely used in both light sources and colliders because of its maturity and robustness. Accordingly, the present FCC-ee baseline adopts on-axis injection with a conventional orbit bump, following the scheme successfully implemented in LEP [2]. However, a local bump is difficult to close perfectly, and residual orbit oscillations after injection have been observed in several light sources [3, 4]. In addition, a thin septum is required to minimize the separation between the circulating and injected beams.

To overcome these limitations, the multipole injection kicker (MIK) has been proposed as a bump free alternative. It was first demonstrated at the KEK Photon Factory in 2007 [3]. A MIK provides an approximately field free region around the beam pipe center, so that the circulating beam remains nearly unperturbed during injection, while a sufficiently strong field is generated at a transverse offset to deflect the injected beam into the ring. This concept can therefore relax the requirements on septum technology while reducing the impact of injection on the stored beam.

Among the possible MIK implementations, the pulsed conductor concept proposed at BESSY II [4] offers a particularly favourable field distribution and has since been adopted in several light sources either in operation or planned, including MAX IV [5], ALS-U [6], SOLEIL [7], ESRF-EBS [8], and ALBA [9].

In this contribution, the pulsed conductor concept is used as the reference MIK topology to evaluate the feasibility of on-axis top-up injection in FCC-ee. Two main points are addressed: first, the field requirements for an FCC-ee MIK are established; second, a local compensation scheme is studied for the circulating beam, while transfer-line optics optimization is used for the injected beam. This first study is restricted to the Z operation mode, which is used as the reference case for evaluating the feasibility of the scheme.

FIELD REQUIREMENTS FOR ON-AXIS INJECTION

For on-axis injection, the dispersion at the injection point and the injected beam energy offset must satisfy:

$$|D_x \times \Delta| = 5\sigma_{cir} + S + 5\sigma_{inj} \tag{1}$$

where D_x is the horizontal dispersion at the injection point, Δ is the energy offset of the injected beam, and S is the separation between the circulating and injected beams.

For this study, the 5σ envelopes of the circulating and injected beams are used to define the required apertures and the separation is chosen as $S = 2.8$ mm to maintain the comparison with the conventional scheme which uses a septum of that thickness. The magnetic field in the field free region should be as small as possible, whereas the field in the injection region should provide sufficient strength. In the FCC-ee Z operation mode, the beam sizes at the MIK are $5\sigma_{cir} = 8.8$ mm and $5\sigma_{inj} = 1.7$ mm [10].

The required MIK deflection angle is 100 rad, which is the same angle provided by the thin septum in the conventional injection scheme. The corresponding integrated magnetic-field strength is comparable to that used in light sources, even at the highest beam-energy mode (182.5 GeV). In general, the combination of a large field free region, a finite injection region, and a narrow separation zone, each varying across operation modes, makes the MIK topology for FCC-ee particularly demanding.

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PULSED CONDUCTOR MIK TOPOLOGY

For the preliminary pulsed conductor design, eight conductors are arranged in a left-right and up-down symmetric layout, with each group of four conductors carrying the same current magnitude and direction. The magnetic field is calculated from the Biot–Savart law, assuming infinitely long conductors. Figure 1 shows the conductor positions and the corresponding field distribution, and the integrated field is calculated for a 1 m-long pulsed conductor. This is a simplified conceptual design that does not yet include detailed technical constraints.

The calculated field quality in the field free region seems very good, indicating only a limited perturbation to the circulating beam. However, in the present design, the field transition region is limited to 2.8 mm, so a non-negligible field gradient remains in the injection point and requires pre-compensation of the injected beam in the transfer line.

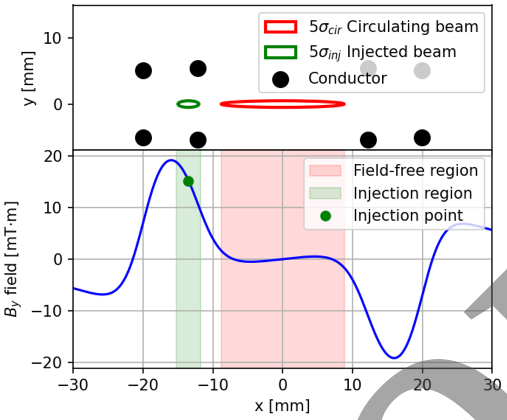

Figure 1: Conductor positions and field distribution of the pulsed conductor MIK in the Z mode.

LOCAL COMPENSATION OF THE CIRCULATING BEAM

For an ideal field distribution, the magnetic field should be exactly zero on the closed orbit of the circulating beam, while providing the required kick to the injected beam. In practice, the field can be made exactly zero only on the closed orbit, while particles at finite transverse amplitude still experience a non-zero field. As a result, particles away from the closed orbit can still receive a non-negligible deflection, especially for a large beam size. To mitigate this effect, a local compensation scheme is proposed to reduce the influence of the MIK on the circulating beam.

The basic idea is to install a compensation MIK (CMIK) upstream of the MIK in order to pre-distort the circulating beam [11, 12]. If the phase advance between the CMIK and the MIK is sufficiently small, the MIK, with an opposite field distribution, can both correct the disturbed circulating beam and deflect the injected beam onto its chromatic orbit.

INJECTION LAYOUT

In FCC-ee, the Point B (PB) straight section is dedicated to beam injection and extraction and has a length of about 2 km. Figure 2 shows the collider optics and the beam layout in the PB section for the Z mode, based on lattice version `LCC_V106.2` [10]. The injection area is located near the center of the section, and four bending magnets are used to create and then cancel the dispersion required for on-axis injection.

The CMIK and MIK are installed in the injection area with a separation of 100 m, indicated by the green elements in Fig. 2. The optics conditions at the CMIK and MIK are nearly identical: $\beta_x = 1100\,\text{m}$, $D_x = -1.4\,\text{m}$. Because of the large β_x, the horizontal phase advance between the two locations is very small. This indicates that the circulating beam distribution after the CMIK should be largely preserved when it arrives at the MIK and can therefore be corrected by the MIK with the opposite field distribution.

The lower plot in Fig. 2 shows the circulating and injected beam trajectories during injection. The circulating beam orbit should remain essentially unchanged with the MIK, thereby removing the perturbation to the reference orbit. The injected beam from the transfer line is deflected onto its chromatic orbit by the MIK and then gradually merges with the circulating beam through synchrotron radiation damping.

The CMIK and MIK should operate for only one turn in order to avoid a kick to the injected beam on the second turn. In the present layout, the CMIK should act only on the circulating beam and should not deflect the injected beam.

Circulating Beam Compensation in Z Mode

Since the MIK field in the field free region is not exactly zero, its effect on the circulating beam should be evaluated during injection.

Figure 3 shows the transformation of the circulating beam distribution between the CMIK and the MIK in horizontal phase space. Just before the CMIK, the circulating beam is a matched Gaussian distribution with an energy spread of 0.11%. After passing through the CMIK, the circulating beam becomes visibly distorted, indicating that compensation is still necessary even for the pulsed conductor topology, despite the low field in the field free region.

After a 100 m drift, the distorted beam reaches the MIK and is then partially corrected. The compensation performance depends strongly on the particle position. For particles in the core, the horizontal position changes only slightly, and the compensation is therefore effective. However, particles near or beyond the edge of $5\sigma_x$ experience a much larger deflection, leading to a significant position change upon arrival at the MIK. Because the magnetic field depends strongly on transverse position, the compensation in this region remains limited.

The circulating beam emittance is also evaluated by calculating the invariant of each particle within the ring periodic solution in order to estimate the overall effect of the compensation scheme. The horizontal emittance increases by

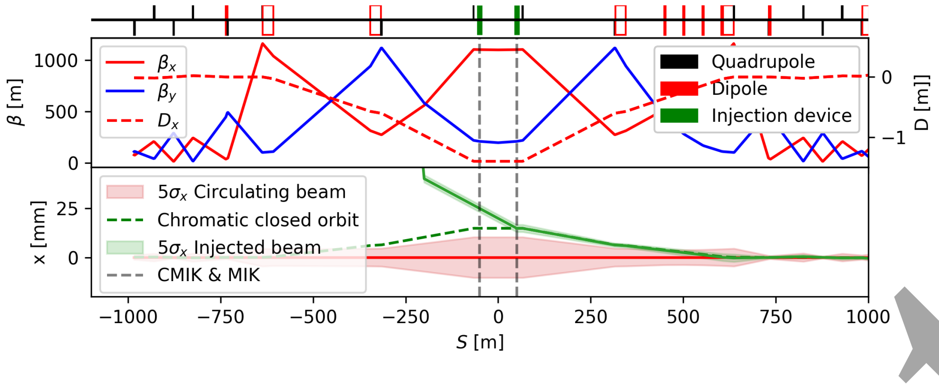

Figure 2: Collider optics in the PB section and the corresponding injection layout for Z mode.

about a factor of three after the CMIK and is reduced after the MIK correction, resulting in a final horizontal emittance growth of only 5 %.

The beam behaviour in the vertical phase space should also be considered. Because the vertical emittance is very small ($\epsilon_y = 2$ pm) and there is no vertical dispersion, the vertical beam size at $5\sigma_y$ is less than 0.1 mm. Tracking simulations show that the vertical emittance growth after local compensation remains below 2 %.

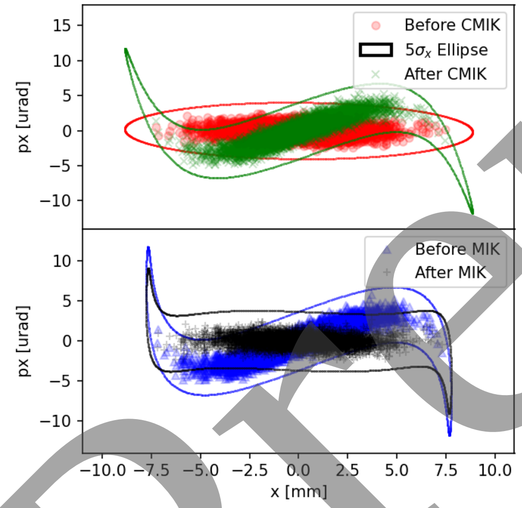

Figure 3: Circulating beam transformation between the CMIK and MIK in horizontal phase space.

Injected Beam Optics Compensation in Z Mode

According to the field distribution shown in Fig.1, a clear field gradient remains in the injection point. As a result, injected particles receive different deflections depending on their transverse position, which leads to a distortion of the injected beam. A correction scheme is therefore required to match optimally to the ring phase space.

Since such a correction cannot be implemented locally around the MIK without affecting the circulating beam, quadrupoles in the transfer line are used to optimise the Twiss parameters of the injected beam. Figure 4 shows the pre-compensated injected beam at the MIK in horizontal phase space, together with the the dynamics aperture (DA) at the corresponding energy offset. The DA is computed including synchrotron radiation only, in the absence of other beam effects. The 3σ and 5σ ellipses are used to represent the injected beam distribution.

For the injected beam optics at the end of the transfer line, i.e. just upstream of the CMIK, one preliminary optimized solution is $\beta_x = 850$ m and $\alpha_x = 17.6$. After a 100 m drift, the injected beam reaches the MIK and is then deflected onto the chromatic orbit. The DA indicates that most of the pre-compensated injected beam can be captured, and the beam performance could be further improved by using non-linear elements.

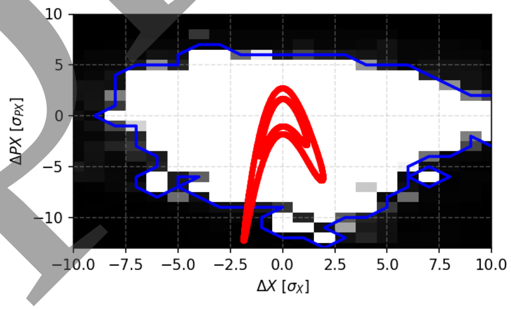

Figure 4: Pre-compensated injected beam at the MIK in the horizontal phase space.

CONCLUSION

This study shows that on-axis top-up injection with a multipole injection kicker is a promising option for FCC-ee. The field quality of the MIK is a key requirement, as it determines both the perturbation to the circulating beam and the capture of the injected beam.

The results indicate that the influence of MIK injection on the circulating beam can be kept very small by means of local compensation with a CMIK. In addition, despite the residual field gradient in the injection region, the injected beam can still be captured with suitable transfer-line optics manipulation.

The present study is limited to the Z operation mode and to a preliminary pulsed conductor topology. Further studies will extend the analysis to the other FCC-ee operation modes and to additional MIK topologies.

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