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HYBRID ON-AXIS AND OFF-AXIS TOP-UP INJECTION AT THE FUTURE CIRCULAR LEPTON COLLIDER

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Abstract

The integrated luminosity target of the future circular lepton collider (FCC-ee) requires a continuous injection scheme due to the limited beam lifetime in collisions, well below 1 h[1]. At each injection, up to 10 % of the collider's maximum bunch intensity will be injected. The interval between injections of positron and electron beams ranges from 40 s to 10 s, varying according to the operation mode. Among the four operation modes, the Z mode is particularly challenging, storing approximately 20 MJ of beam energy per collider ring at an energy of 45.6 GeV. This mode exhibits the most significant constraints for injection, making it the current focal point for designing the injection scheme. Due to the limited dynamic aperture in the ring and the synchrotron radiation (SR) cone at the interaction points (IP), the conventional off-axis injection scheme is not favored. The on-axis scheme is chosen as the baseline injection scheme. However, it requires a large dynamic aperture while the energy acceptance in the collider ring is presently limited to ~±1 %. This contribution presents the baseline injection design and proposes a hybrid off-axis with off-energy injection scheme to optimise the baseline with particular focus on the Z mode.

INTRODUCTION

In the off-axis scheme, the injected beam (beamlet) has a transverse offset with respect to the circulating beam at the injection point. This brings the beamlet beside the circulating beam in the transverse phase space. The beamlet experiences large amplitude betatron oscillations until it merges completely with the circulating beam.

The horizontal off-axis injection was explored in FCC-ee [2]. However, the horizontal betatron amplitude of the injected beamlet results in a physical offset at the IPs. Such offset in turn causes increased SR cone size around the whole ring, and in particular near IPs. This is critical because the high beta regions near the IP are equipped with superconducting magnets, necessitating precisely designed SR absorbers to prevent energy deposition in the cold masses. Modelling of the beamlet SR cones towards an IP revealed an unacceptable photon flux impacting these SR absorbers from the injected beam [3]. Furthermore, the beamlet may also increase the experiment background.

For on-axis injection, the beamlet has an energy offset with respect to the circulating beam. However, the zero dispersion design at the IPs ensures that the beamlet's SR cone aligns with that of the main beam's one[3]. That suggests that no additional photons deposited in the IP region, and less background. Therefore, the on-axis injection is chosen as the baseline scheme, which is already applied in the LEP [4], instead of off-axis injection. This contribution will introduce the on-axis injection method used in FCC-ee, and explore the possibility of a hybrid on-axis and off-axis injection scheme for optimisation.

ON-AXIS INJECTION

In on-axis injection, the beam is injected onto the chromatic closed orbit, where the energy offset together with the ring's optics dispersion provides the separation between the injected and circulating beams. When the injected beam reaches an IP, it overlaps with the circulating beam due to zero dispersion, thus preventing any increase to the SR cones or experiment background. Due to the SR damping, injected beamlet synchrotron oscillations will decay twice as fast as the betatron oscillations. In the Z operation mode, the longitudinal damping time is approximately 1200 turns, corresponding to 0.36 s.

The requirements on energy offset and dispersion in on-axis injection can be expressed as [5]:

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

where D_x is the dispersion at the injection point, Δ is the relative energy offset of the injected beam, S is the blade thickness of septum, σ_{cir} and σ_{inj} are the beam size of circulating and injected beams at the injection point. Beam size can be expressed as $\sigma = \sqrt{\beta \times \epsilon + (D_x \times \delta)^2}$, where β is the beam twiss parameter, and ϵ is the beam emittance.

According to Eq. 1, to achieve sufficient separation between the injected and circulating beams to place the septum blade, a large dispersion and momentum offset together with small beam sizes are required. Therefore, the electrostatic septum with a thickness of 0.3 mm was considered in the initial design. However, the risk of electrostatic breakdown, induced by SR, has led to a preference for a magnetic septum, despite its thicker blade. In the following, we will focus on optimising the dispersion and beta functions at the injection point to ensure the sufficient separation for the blade of magnetic septum.

Optics at the Injection Point

According to Eq. 1, a quadratic equation describing dispersion and beta function can be derived:

$$\left(D_x\Delta - (S + 5\sigma_{inj})\right)^2 = 25 \times (\beta_x\epsilon_{cir} + (D_x\delta_{cir})^2) \tag{2}$$

There are three assumptions in Eq. 2. Firstly, the circulating beam emittance remains constant. Although changes in optics can influence the equilibrium emittance in the collider ring, it has already been shown to be negligible [6]. Secondly, the dispersion of injected beam is assumed to be zero,

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and lastly we assume that the injected beam's beta function equals that of the circulating beam.

The physical solution of the quadratic equation is:

$$D_x = \frac{(S+5\sqrt{\epsilon_{inj}\beta_x})\Delta}{\Delta^2 - 25\delta_{cir}^2} + \frac{5\sqrt{\epsilon_{cir}\beta_x(\Delta^2 - 25\delta_{cir}^2) + (S+5\sqrt{\epsilon_{inj}\beta_x})^2\delta_{cir}^2}}{\Delta^2 - 25\delta_{cir}^2} \tag{3}$$

In Z mode, the beam equilibrium horizontal emittances for the collider and booster rings are 0.71 nm and 0.26 nm, respectively [7]. Considering an energy offset of the injected beam of 1 %, we represent the relationship between β_x and D_x for various septa blade thicknesses in Fig. 1. This figure shows a monotonic relationship where a larger β_x leads to a larger beam size, necessitating increased dispersion to enhance the separation between the injected and circulating beams at the injection points, while maintaining the constraints of Eq. 1.

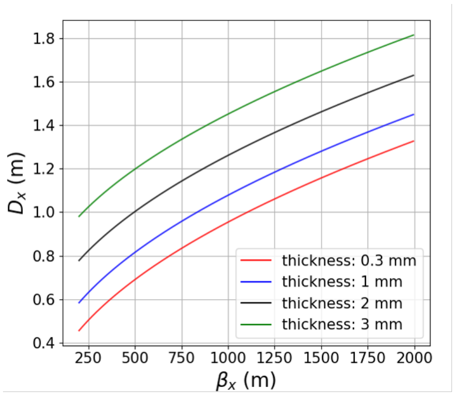

Figure 1: Relation between β_x and D_x for difference septa blade thicknesses which respects the aperture constraints of Eq. 1.

At a fixed β_x, a linear relationship can be derived between dispersion and septum thickness. This relation can also be seen in Fig. 1, which shows that a thinner septum can reduce the required dispersion, thereby motivating the initial choice of an electrostatic septum for the collider injection. However, due to the strong SR, photons hitting the high voltage electrodes can increase the risk of electrostatic breakdown, as previously observed in the SPS when it was used to accelerate positrons [8]. Therefore, further optics studies were performed and showed that a larger dispersion can be achieved thanks to the kilometer-long straight section, allowing for the use of a magnetic septum with a thickness of about 3 mm.

INJECTION LATTICE DESIGN

The FCC-ee collider ring is designed around 4 experimental IPs, and due to the required crossing schemes, the other 4 technical straight sections also feature crossings. The optics of the technical straight section in point B are shown Fig. 2.

This optics makes use of the dispersion created by the crossing dipoles near the center and enhances it by a doublet quadrupole arrangement near 1250 m. Optimisation of the lattice aimed at reaching larger values of D_x and β_x in order to maintain the required energy offset below the lattice acceptance of ~1 % while allowing sufficient space for the magnetic septum blade of ~3 mm.

The final optics uses several quadrupole magnets on both sides of the crossing. The perturbation to the lattice on the upstream side (up to s=1000 m) is minimal but necessary to match all the optical parameters and phase advance across the straight section to the reference ones. The optics, as shown in Fig. 2, achieve a dispersion of −1.44 m and β_x = 1000 m at the injection point, located at s=1550 m.

Vertical equilibrium emittances in the booster and collider are very small, thus vertical mismatch caused by vertical dispersion may be critical and the transfer from booster to collider has to be achromatic in that plane.

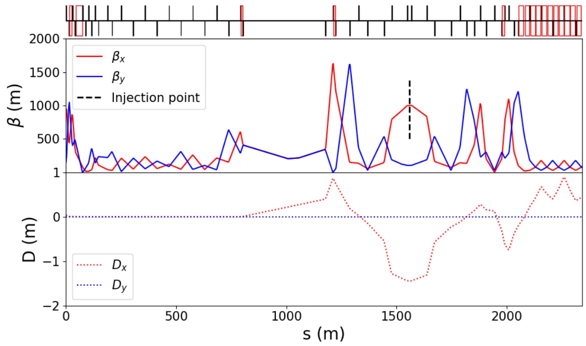

Figure 2: The collider injection optics in PB. The top synoptic displays dipoles (red) and quadrupoles (black) magnets.

Figure 3 shows the envelopes of the circulating and injected beams during the injection process. Two stripline kicker magnets placed at a relative phase advance of π are used to produce an orbit bump with a height of $10\sigma_{inj} + S$ in order to bring the circulating beam close to the injection septum. The thickness of the septum is 2.8 mm and represented by the blue box marking the separation between injected and circulating beams. This scheme injects the beamlet onto the axis of the chromatic closed orbit represented by the dashed line. After injection, the local orbit bump collapses and the injected beam slowly damps towards the circulating beam.

In this scheme the injected beam is much smaller than the circulating one, partly because the injected beam dispersion is kept at zero. While the zero-dispersion condition was necessary to simplify the solution to Eq. 2, it also introduces betatron oscillations for particles of the injected beam away from the injected beam reference energy. However, the effect remains moderate, as the momentum spread of the injected beam (δ_{inj} = 3.9×10^{-4}) is significantly smaller than that of the circulating beam (δ_{circ} = 8.9×10^{-4}). Therefore, further optimisation of the optics will be required to account

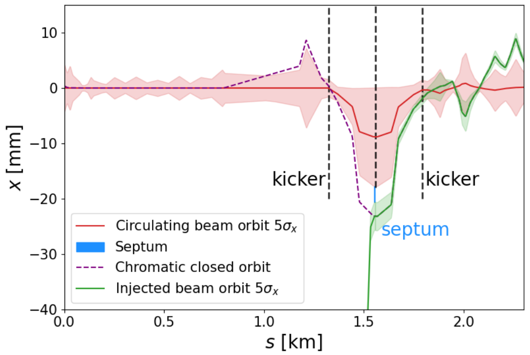

Figure 3: Beam envelopes of injected (green) and circulating (red) beams along the PB straight section. The black dashed line represents the location of kicker and septa magnets.

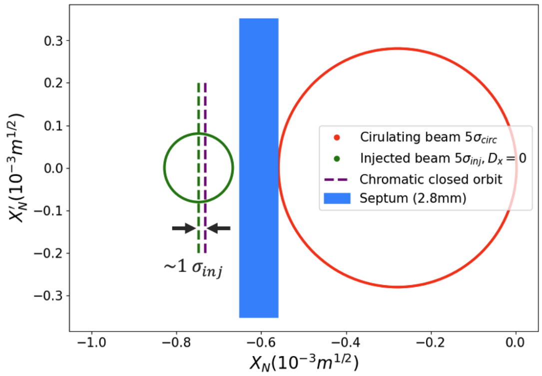

Figure 4: Normalized horizontal phase space at the injection point. The green circle shows an injected beam without dispersion injected on a trajectory (green dashed line) offset from the chromatic closed orbit (purple dashed line).

for the dispersion matching and associated size increase of the injected beam.

HYBRID INJECTION SCHEME

Due to the limitations of dynamic aperture and RF acceptance, the maximum energy offset of the injected beam is ~1 %. However, the injection scheme must also account for provision for possible sub-optimal beam or machine conditions. For instance, the limited damping time during the booster cycle may cause the injected beam's emittance to exceed its equilibrium emittance. Other limitations may arise due to the circulating beam emittance or energy spread, which may deviate from the design expectation.

One possible solution is to move the injected beam away from the chromatic closed orbit. This increases the separation between injected and circulating beams at the expense of causing betatron oscillations to the injected beam. The injected beam oscillates around the circulating beam in both horizontal and longitudinal phase spaces, hence the scheme may be referred to as hybrid on-axis and off-axis.

Figure 4 shows the normalized phase space at the injection point where the 5σ envelopes need sufficient separation to clear the septum blade. The injected beam has a shift of 0.5 mm ($\sim 1\sigma_{\text{inj}}$) away from the septum, which allows to increase the space between the injected beam contour in green and the septum. These values are chosen arbitrarily to illustrate the concept while the maximum offset will be limited by the energy deposited by the SR cone around the experimental IPs [3] as well as the background induced on the detector but not quantified yet.

Injection Scheme at Other Modes

To use the same kicker and septa system design in all the operation modes, the lattice configuration of the injection section remains the same for all energies, with minor adjustments in optics matching. However, the collider's and booster's equilibrium emittances in W and ttbar modes are significantly larger than those in the Z mode discussed here [7]. This makes the on-axis injection scheme unlikely to provide a sufficient clearance for the 2.8 mm septum blade without significant increase of the injected beam energy offset. In the W mode, the energy acceptance remains limited to ±1 %, which may require using the hybrid injection as the baseline injection scheme. In Higgs and ttbar modes, the energy acceptance of ±1.6 % and -2.8/+2.5 % respectively, allows for increased energy offset of the injected beam, which should suffice for the on-axis injection scheme.

CONCLUSION

Because it carries the highest beam power and presents the strongest machine protection challenges, the current design focuses on the Z mode. Due to the limitations of the SR energy deposition around IPs, the baseline scenario for top-up injection into the collider ring uses on-axis conventional. Considering the risk of electrostatic breakdown due to SR photo-electrons, the initially considered thin electrostatic septum has been replaced by a magnetic septum. An approximation of the relation between optics parameters at the injection point has been established in the absence of injected beam dispersion and the lattice has been optimised to the settings that allow sufficient clearance for the magnetic septum.

However, the approximations made by neglecting the dispersion of the injected beam do not provide an accurate representation of the clearance and apertures at the injection point for the on-axis injection scheme. Therefore, a more detailed model of the on-axis injection scheme, utilizing numerical tools, is required for the baseline design.

The design of a unique on-axis injection scheme working at every operation mode seems particularly challenging. Therefore, a dedicated design for every mode will need to be established with associated optimisation prospects such as the hybrid-scheme on- and off-axis. Each scheme will need to be evaluated with comprehensive tracking, not only to ensure sufficient clearance at the injection point but also to estimate the injection efficiencies and possible drawbacks of optimisation techniques.

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