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CONCEPTS AND CONSIDERATIONS FOR FCC-ee TOP-UP INJECTION STRATEGIES

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Abstract

The Future Circular electron-positron Collider (FCC-ee) is proposed to operate in four modes, with beam energies from 45.6 GeV (Z-pole) to 182.5 GeV ($t\bar{t}$ production) and luminosities up to 4.6×10^{36} cm^{2}s^{-1}. At the highest energies the beam lifetime would be less than one hour, meaning that top-up injection will be crucial to maximise the integrated luminosity. Two top-up injection strategies are considered here: conventional injection, employing a closed orbit bump and septum, and multipole-kicker injection, with a pulsed multipole magnet and septum. On-axis and off-axis injections are considered for both. We present a comparison of these injection strategies taking into account aspects such as spatial constraints, machine protection, disturbance to the stored beam and injection efficiency. We overview potential kicker and septum technologies for each.

INTRODUCTION

The FCC-ee

The FCC-ee [1] is a proposed, high-luminosity, circular lepton collider; the parameters for the FCC-ee at lowest and highest energy are given in Table 1. The short lifetime of the beam requires it to be continuously topped up, where this top-up process is planned via a separate, full-energy booster ring, located in the same tunnel as the collider ring.

Table 1: FCC-ee parameters [1] for Z- and $t\bar{t}$-operation. The beam lifetime is given as that from radiative Bhabha scattering/beamstrahlung, and the quoted energy spread includes effects of beamstrahlung.

Parameter	Unit	Z	$t\bar{t}$
Beam energy	GeV	45.6	182.5
Beam lifetime	min	68/>200	39/18
Beam current	mA	1390	5.4
# bunches/beam		16 640	48
Magnetic rigidity	Tm	152.1	608.7
Emittance (x/y)	nm/pm	0.27/1.0	1.46/2.9
Energy spread	%	0.132	0.192

Injection Into the Collider

In these proceedings we consider two methods of top-up injection: conventional bump injection and multipole kicker injection (MKI) [2]. For beam tracking studies of these two methods see [3]. Conventional bump injection, depicted in Fig. 1(a), uses a dynamic π-orbit-bump created with dipole kickers, to bring the beam close to the septum blade. MKI (Fig. 1(b)) incorporates a 'multipole' kicker providing a kick to the injected bunch, which passes off-axis, and a field-free region on-axis for the stored beam.

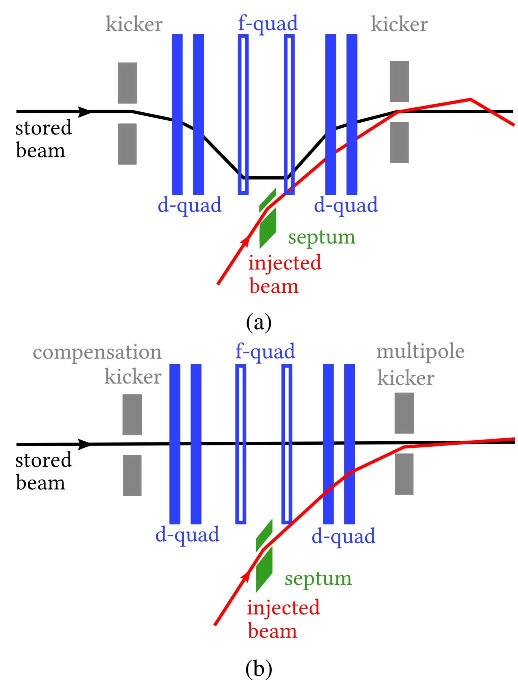

Figure 1: Schematic of (a) conventional bump injection and (b) multipole kicker injection.

As specified by Liouville's theorem [4], the density of the particles in phase-space stays constant while under conservative forces, hence you cannot inject particles into the phase-space of the stored bunches. Instead, beams are injected with a separation from the stored beams and merge via synchrotron radiation damping. For *off-axis* injection, bunches are injected with a separation from the stored beam in betatron phase (transverse offset). For *on-axis* injection, bunches are injected with a separation in synchrotron phase (momentum offset) onto the off-momentum closed orbit, thus requiring a non-zero dispersion at the septum (Fig. 2(b)). A large β_x-value at the septum reduces the impact of the septum width as it would be smaller compared with the beam size.

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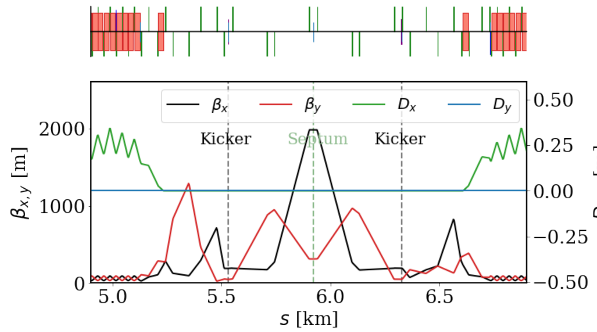
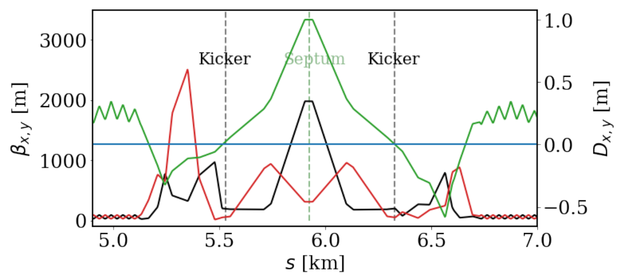


(a)



(b)

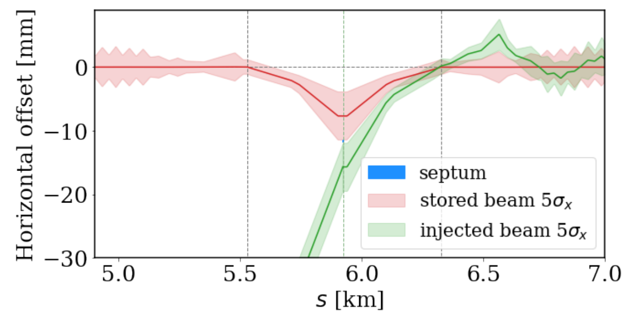
Figure 2: Z-operation optics around the injection region, with Twiss functions β_x (black), β_y (red) and dispersion D_x (green), D_y (blue) showing (a) off-axis injection and (b) on-axis, conventional bump injection. A synoptic overview of the beamline is shown above (a).

CONVENTIONAL BUMP INJECTION

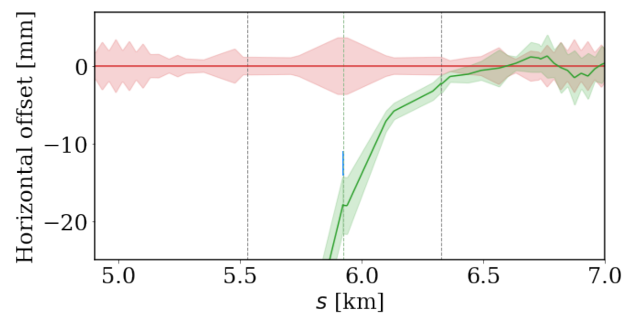
For conventional bump injection, kickers are placed at π-phase-advance so as to produce a closed orbit bump with only two kickers. Ideally, the orbit bump rises and falls within one revolution to minimise beam loss on the septum. This restricts the kicker rise and fall times to fit within the abort gap of the collider ring. To ensure a robust injection with minimal losses the separation between the injected and stored beams at the septum should be more than $5\sigma_i + S + 5\sigma_s$, where σ denotes the r.m.s beam size, the subscripts i and s denote the injected and stored beams, and S is the septum width. The bump amplitude must be $> 10\sigma_i + S$, such that, once the bump is collapsed, the injected beam is not lost on the septum for subsequent revolutions.

This method requires a thin septum to keep the injected beam within the $15\sigma_s$ dynamic range. From the optics (Fig. 2(a)) and emittance (Table 1), a bump amplitude of 7.6 mm and injected beam offset of 15.7 mm are required at the septum. This would be achieved with kicker deflection of 12.5 rad and septum deflection 65 rad. The beam trajectories and envelopes are shown in Fig. 3(a).

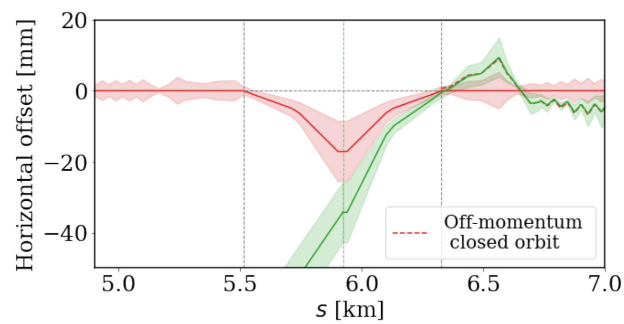
On-axis conventional bump injection is shown in Fig. 3(c). The dispersion needed for on-axis injection leads to larger beam sizes at the septum requiring a larger bump amplitude, 17.1 mm, and a larger injected beam offset of 34.2 mm at the septum. These values correspond to a kicker deflection of 27 rad. The momentum offset for the injected bunch,



(a)



(b)



(c)

Figure 3: Beam envelopes for off-axis (a) conventional bump injection and (b) multipole kicker injection, and (c) on-axis conventional bump injection. The kicker and septum locations are denoted with dotted lines.

$\delta = -1.9\%$, is selected such that the separation between stored and injected beams is $|D_x\delta|$.

Dipole Kickers

Considering even the highest beam energy ($t\bar{t}$-operation), a stripline kicker would be suitable to meet the deflection requirements. A magnetic length of 3 m and plate separation of 20 mm would mean a voltage of ±7.5 kV and an integrated electric field of 2.28 MV. Ideally, the two kickers would be powered in series so that any ripples or jitter in the power supply cancel due to the π-phase-advance between them.

The necessary kicker pulse length depends on how many batches are used for injection. For single-batch injection, the repetition rate for these kickers is set by the booster cycle time, which for Z-operation is 50.95 s and for $t\bar{t}$-operation is 5.6 s. With the alternation of e^- and e^+ injection, the

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repetition rate for these kickers would be 0.01-0.09 Hz. The pulse flat-top should be the full train length divided by the number of batches injected, i.e. 304 µs for single-batch.

Electrostatic Wire Septum

Conventional bump injection necessitates a very thin septum such as an electrostatic wire septum [5], which can achieve septum widths of the order of 100s of microns. This septum uses many contiguous wires under tension, forming a plane to separate the high-field and free-field regions. Electrostatic septa risk the possibility of sparking caused by incident synchrotron radiation (SR). Due to the geometry of the orbit bump, the septum would be exposed to the SR fans only from the >4σ beam envelopes from upstream bending magnets. Further studies are planned to ascertain the effect of X-rays on electrostatic septa sparking rates as a function of voltage.

A septum deflection angle of 65 rad could be achieved at highest energies with two 3-m-long modules with electric field strength 1.9 MV/m. Here, we assume a septum width of 200 µm. More detailed studies are needed to establish the feasibility of such a design. If the voltage would need reducing, the wire septum could be preceded by a thicker magnetic septum to increase the total deflection angle.

MULTIPOLE KICKER INJECTION

For MKI, the minimum permissible separation of the injected and stored beams at the septum ($> 5\sigma_i + S + 15\sigma_s$) is larger than for conventional bump injection. This is because the beam is injected with a $10\sigma_x$-offset at the kicker and thus undergoes betatron oscillations. A proposal for off-axis MKI injection is shown in Fig. 3(c), with kicker deflections of 29 rad and septum deflection of 65 rad.

For MKI, an ideal multipole kicker would have zero field for the stored beam and constant field for the injected beam, i.e. a step-function. A proposal for a multipole kicker design is described in [2], based on two opposing, similarly powered, C-shaped dipoles. A compensation kicker would be placed upstream with π-phase-advance to compensate the perturbation to the stored beam distribution.

MKI does not require as thin a septum blade as for conventional bump injection and a magnetic eddy-current septum with a blade width of a few millimetres would be sufficient, here we assume 3 mm. A magnetic eddy-current septum exploits that when a magnetic field changes inside a conductor eddy currents will be induced to oppose the change, by using these eddy currents to shield the free-field region. The septum should have a deflecting field region gap width of at least 8 mm.

Machine Protection

For Z-operation there will be 20.6 MJ of stored energy per beam, which if not properly handled would damage the machine. The appropriate protection methods depend on the time-scale on which the failures occur. Slower failures, e.g. changes in the septum field, could be mitigated using an active system, where the beam is dumped if the septum current varies by more than a few per mille. If there is a fault in the septum power supply the magnetic field, B, will decay as $\Delta B/B = 1 - e^{\frac{-t}{\tau}}$, with τ the magnet decay constant. For example, if $\tau = 1$ s and we could tolerate a 0.2‰ change, we would need to abort within 7 turns. For MKI, if the septum field varies more than a few percent then the injected beam will be within the low-field region of the multipole kicker and passive beam intercepting devices would also be needed.

Kicker failure, either failure to fire or erratic firing, would occur on a very short timescale and therefore both injection methods will require passive protection such as an absorber. The absorber should be placed at $\frac{\pi}{2}$-phase-advance from the kicker so as to be furthest from the stored beam. An example scenario for MKI where the kicker fails to fire is shown in Fig. 4; the absorber would be placed at 6.6 km. For both injection methods, other failure modes and potential protection schemes should be considered, including for example protection against the failure of dipoles in the transfer line from the booster to the collider.

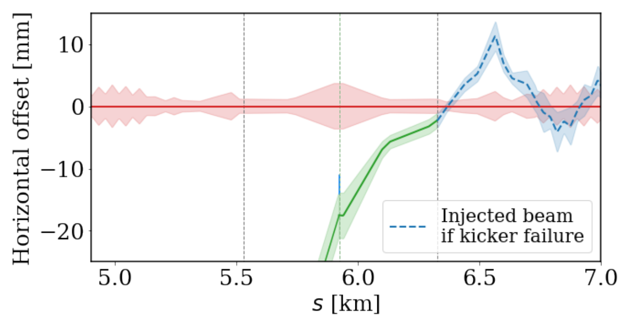

Figure 4: The injected beam trajectory if the MKI injection kicker fails to fire.

CONCLUSION

Two options for the top-up injection of the collider ring were discussed, conventional bump injection and multipole kicker injection. Conventional bump injection would require R&D for the electrostatic septum, whereas for the MKI injection it would be the multipole kicker which needed investigating. Injection optics will need developing for the W-, H- and t̄t-operations and also for on-axis MKI injection. We will need studies of the performance and sparking probability of electrostatic wire septa in the presence of synchrotron radiation in order to establish whether this could be a suitable means of injection for such a high-energy lepton machine. Here we have described the injection of only one beam and we will develop this scheme for injection of both the electron and positron beams.

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