Nuclear Inst. and Methods in Physics Research, A 880 (2018) 98–106

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Top-up injection schemes for future circular lepton collider[☆]

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ARTICLE INFO

Keywords:
Future circular collider
Lepton collider
Top-up injection

ABSTRACT

Top-up injection is an essential ingredient for the future circular lepton collider (FCC-ee) to maximize the integrated luminosity and it determines the design performance. In ttbar operation mode, with a beam energy of 175 GeV, the design lifetime of ∼1 h is the shortest of the four anticipated operational modes, and the beam lifetime may be even shorter in actual operation. A highly robust top-up injection scheme is consequently imperative. Various top-up methods are investigated and a number of suitable schemes are considered in developing alternative designs for the injection straight section of the collider ring. For the first time, we consider multipole-kicker off-energy injection, for minimizing detector background in top-up operation, and the use of a thin wire septum in a lepton storage ring, for maximizing the luminosity.

1. Introduction

The FCC-ee is conceived as a double ring storing electron and positron beams. The two beams collide with a crossing angle at two (or four) interaction points, where the physics detectors are installed. Four operation modes are planned, and the stored beam energy is varied accordingly from 45.6 GeV (Z pole) to 175 GeV (ttbar threshold). The collider ring is under active study, and recent design parameters are found in Ref. [1,2].

Beam particles are continuously lost due to radiative Bhabha scattering in the collision. The design lifetime is shortest in the ttbar operation mode, ∼1 h, and it may be even shorter in actual operation, e.g., due to beam–beam effects. Therefore, top-up injection is essential to maximize the integrated luminosity, and at the same time, it is of importance to establish a highly robust injection scheme because of the necessary frequent topping up.

In early times, the beams in lepton colliders were often dumped for the next filling, as in the hadron colliders, when the beam current significantly decreased, before ramping the accelerator down in energy for the next injection. It took some time to refill the machine, re-accelerate and establish again stable collisions after the beam dump. The luminosity production was not very efficient then. *Top-up-and-Coast* [3] operation mode was applied at the PEP collider in the 1980s [4]: when the beam currents dropped significantly, electrons and positrons were injected on top of the circulating beams. Although the physics detectors were turned off, and thus there was no increase in the integrated luminosity during the injection, the turn-around time was largely shortened. It is noted that a full-energy injector was necessary for this. Later at the start of the 21st century, for the two B factories KEKB and PEP-II complete top-up injection was established, where the physics detectors remained turned on during injection (though with certain triggers or read-out masks applied during the turns immediately following an injection turn or for the bunches affected). Ref. [3] presents some details on top-up injection for KEKB and PEP-II.

Top-up injection has been applied also in most modern light sources. A brief summary of the historical development in light sources is found in Ref. [5] and references therein. Although the conventional injection scheme based on a kicker bump, which generates a closed orbit bump, is transparent to the stored beam in principle, the stored beam is misplaced due to a non-closure (or leakage) of the orbit bump in practice. In order to minimize the disturbance (or transient), *multipole kicker injection* has

☆ This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No 730871.
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https://doi.org/10.1016/j.nima.2017.10.075
Received 27 June 2017; Received in revised form 23 October 2017; Accepted 24 October 2017
Available online 3 November 2017

been proposed and experimentally demonstrated at the KEK photon factory (PF) [6,7], and used during the user operation at the KEK PF ring [8]. Further development was conducted at BESSY II to improve the scheme by applying a *nonlinear kicker* [9]. Afterwards, it was proposed to employ this advanced injection scheme at SOLEIL and MAX IV [10]. A few newer injection schemes, as discussed later, are under investigation or development for future light sources. Among these injection schemes, we first select those potentially suitable for FCC-ee, and then study the corresponding designs of the injection straight section.

Although the top-up injection scheme must be compatible with all the operation modes, the most difficult case is the ttbar mode, where the beam energy is highest and the geometric beam emittance is largest (since, for a constant optical lattice, the geometric emittance is proportional to the square of the beam energy). Therefore, our investigation focuses on the ttbar operation mode. The various injection designs will, however, also be applicable to the other operation modes of the collider. It is noted that the baseline design considers the use of the same lattice for all operation modes [1,2,11].

In Section 2, the constraints and assumptions for the injection are discussed. In Section 3, we describe a selection procedure for suitable schemes. Possible designs of the injection straight are presented in Section 4. In Section 5 we discuss a few important issues related to the injection. Finally we draw conclusions in Section 6.

2. Constraints and assumptions

The injection scheme must satisfy several constraints. Firstly, the available straight section is assumed to be about 1.5 km (1.57 km in the present design), which is sufficiently long, and needs to be compared with the overall circumference of about 100 km. Secondly, the beam clearance, i.e., the distance between the stored (injection) beam orbit and the septum must be larger than or equal to 5σ of the stored (injection) beam size. The injection system of SuperKEKB, for example, is designed with 3σ and 2.5σ clearances for the stored and injection beams, respectively [12]. The rather large clearances in our design have been chosen to ensure a robust injection with low losses. Thirdly, the thickness of the magnetic septum is assumed to be 5 mm, including mechanical tolerance. Alternatively, a much thinner electrostatic wire septum [13,14] may be considered, in which case the thickness can be as low as 0.2 mm, again including the mechanical tolerances.

We assume that the available dynamic aperture of the collider ring is at least about 15σ of the (stored) beam size for the nominal beam energy and 5σ for ±2% off-energy particles. Although the collider optics is still being refined, these assumptions are fulfilled for the present design [1,11,15], in which the number of interaction points is limited to two, while the maximum could be four. Sufficient off-energy aperture is required not only for the injection process, but also for providing a reasonable beam lifetime in the presence of beamstrahlung at the interaction points [16]. It is noted that the top-up injection into FCC-ee is constrained by the limited dynamic aperture.

Acceleration of the injection beam to the collider beam energy, which is a prerequisite for top-up injection, is performed by a booster. To profit from the existing tunnel and to minimize the energy loss due to synchrotron radiation, the booster ring is installed in the same tunnel as the collider rings; otherwise synchrotron radiation energy loss per turn would be too high, demanding an unrealistic rf voltage. Then it is natural to assume that the booster provides injection beams with a horizontal emittance similar to the equilibrium emittance of the collider. Therefore, in the following study we will assume that the booster beam emittance has the same value of 1.3 nm as for the collider. Such a booster generates injection beams with a bunch length similar to that of the stored beam, and also similar energy spread, resulting in a good matching in the longitudinal phase space. The booster can potentially provide beams with smaller emittance, e.g., if the beam does not reach its equilibrium state thanks to rapid acceleration and fast extraction. Our injection designs, therefore, include additional margins and tuning flexibility in order to optimally adapt to, and to benefit from, such a situation. The energy spread of the injection beam may be determined by the synchrotron radiation in the booster (equilibrium rms spread 0.14% at top energy), while the energy spread of the colliding stored beam is larger due to the effect of beamstrahlung [17,18]. The FCC-ee collider parameters for the ttbar operation mode at 350 GeV c.m. energy are summarized in Table 1.

Table 1
FCC-ee collider beam parameters for the ttbar operation mode, relevant to top-up injection. The collider parameters are taken from Refs. [1,11]. The injection beam parameters are explained in the text.

Parameters	Values
Circumference	~ 100 km
Luminosity lifetime	57 min
Beam energy	175 GeV
Hor. geometric emittance, rms	1.3 nm
Energy spread, rms (with/without beamstrahlung)	0.17%/0.14%
Number of bunches	81
Bunch population	1.7×10^{11}
Longitudinal damping time	23 turns
RF energy acceptance	6.7%
Radiation power/beam	50 MW

For the purpose of the injection study, we separate the injection straight from the rest of the collider ring. The optical functions of the regular arc cell are taken as boundary conditions on either side of the injection straight. This separation simplifies our investigation, but the chromatic and higher order terms are ignored, i.e., the beta functions are assumed to be constant over the considered beam energy deviation (±2%) and the off-energy closed orbit is determined by $D_x\delta$, where D_x is the linear horizontal dispersion and δ is the relative beam energy deviation. The neglected higher-order terms will eventually have to be taken into account, but they are not stable yet since the collider ring is still under design. The impact of these terms, however, is expected to be rather marginal for our beam clearance considerations.

3. Top-up Injection schemes suitable for FCC-ee

We investigated various top-up injection schemes listed in Table 2 and concluded that both conventional injection and multipole-kicker injection are suitable for FCC-ee. In the following we describe the arguments for the down-selection.

The conventional injection scheme into electron storage rings employs a septum and a dynamic orbit bump (see e.g. [19]). The latter is turned on only at the time of injection and is turned off afterwards such that the injected beam is brought to the other side of the septum wall.

According to Liouville's theorem, a bunch cannot be injected into the same phase-space volume occupied by the stored beam at the time of injection although it will later be merged into the stored beam thanks to synchrotron radiation damping. In the conventional injection scheme, the injected bunch is transversely separate from the stored beam.

When the energy of the injection beam differs from the stored beam energy and the dispersion function at the location of the septum is nonzero, the injection beam can be placed on the off-energy closed orbit. In this case the separation between injected and stored beam is in the longitudinal phase space. This scheme, *synchrotron phase space injection* [20], was successfully used in the LEP collider, as a variant of the conventional injection. A higher injection efficiency was observed when this off-energy, on-axis injection was employed. Energy offsets of an injected beam do not perturb the experiments as much as betatron oscillations, since there is no dispersion at the collision points. Since the beam is injected onto the off-energy closed orbit, the injection efficiency may also be less sensitive to transverse position and angle errors as mentioned in Ref. [20]. Finally, the longitudinal damping time is two times shorter than the horizontal one. As we will see in Section 4.1, the conventional injection scheme with both on- and off-energy injection beams is suitable for FCC-ee.

Table 2
Top-up injection schemes. Suitability and "remark" are discussed in the text.

Schemes	Suitability	Remark
Conventional injection	Yes	Both on- and off-energy injection considered
Multipole-kicker injection	Yes	Both on- and off-energy injection considered
Swap-out injection	No	Strong difficulties
Longitudinal injection	No	Limited off-momentum dynamic aperture
Kickerless injection	No	Limited off-momentum dynamic aperture

In the aforementioned multipole-kicker injection, the injection beam passes off-center through a pulsed multipole magnet (quadrupole or higher multipole), while the stored beam passes through the center of the pulsed magnet. In consequence, only the injection beam is deflected by the multipole, so as to be finally captured into the collider ring aperture. The injection bunch is transversely separated from the stored beam as in the on-energy conventional injection. Similar to synchrotron phase space injection in the conventional scheme, also here an off-energy injection beam can be situated on the off-energy closed orbit when the dispersion function is nonzero at the location of the kicker [21]. In Section 4.2 we discuss multipole-kicker injection for both on- and off-energy injection. It appears that multipole-kicker off-energy injection has not previously been proposed.

For future light sources with a small aperture, it has been proposed to swap the stored beam bunches with injected bunches either bunch by bunch or even the entire beam at once [22]. In such a *swap-out injection*, the prepared, full-charge bunches can be injected onto the closed orbit by kicking out the stored bunches, which are occupying the on-axis phase-space volume. The upgrade projects of APS [23] and ALS [24], and the project of HEPS [25] are based on swap-out injection to enable the beam injection into a small dynamic aperture. However, it is difficult, if not impossible, for the FCC-ee injector chain to provide full-charge bunches for injection. Even if the injector chain were capable of providing the needed intensity for a single injection, the kicked-out stored bunches would have to be extracted from the collider ring, and be dumped or re-injected into the booster for deceleration. It is noted that the total stored beam energy is about 0.4 MJ for the ttbar operation mode but it is more than 20 MJ for the Z-pole operation mode [1]. Furthermore, the FCC-ee collider is designed such that the synchrotron radiation power is limited to 50 MW per beam. In order to maximize the integrated luminosity under these conditions, the top-up injection for the ttbar operation mode should be performed over one or a few booster cycles per beam. The acceleration of full-charge bunches with the booster would then result in a large variation in the peak electric-power consumption. A significant effort would likely be required to stabilize the entire facility against the impact of so large a variation. Also, the synchrotron radiation from the booster would be noticeably increased in case of full-charge acceleration, necessitating an increase of the booster rf power and a reinforcement of its shielding and cooling systems. We conclude that swap-out injection is not suitable for FCC-ee in view of these practical difficulties.

Longitudinal injection has also been proposed for future light sources [26]. Particle trajectories in the longitudinal phase space are not closed when the synchrotron radiation damping is taken into account. The so-called "golf club" acceptance is then formed [26,27], and an injected bunch can be captured if its energy offset and phase (or timing) are precisely adjusted. A fast dipole kicker places the injected bunch onto the corresponding off-energy closed orbit. This scheme is, however, not suitable for FCC-ee since the injected beam performs large synchrotron oscillations close to the rf bucket (see Fig. 1). The bucket height of FCC-ee is about 5% or more, depending on the specific operation mode, and with so large an oscillation, extending well beyond the off-energy dynamic aperture, the injected beam would be lost before the synchrotron oscillation is damped.

One more injection scheme has been considered for FCC-ee: *kickerless injection* in the longitudinal phase space [28]. Since in the higher energy operation mode the synchrotron radiation damping is fast, an off-energy beam can be injected without a kicker, as in cyclotrons. This scheme is also not suitable for FCC-ee, again because of the limited off-energy dynamic aperture. Kickerless injection in the vertical plane [29] does not appear to be a viable option either, since the optimum betatron tune with regard to beam–beam effects is close to the half integer (or integer), so that parts of the injected beam would hit the septum on the turns following the injection. The situation is further aggravated by the fact that the transverse damping is half as strong as the longitudinal one.

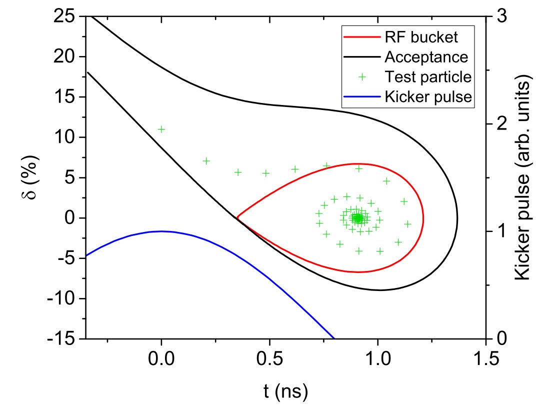

Fig. 1. Longitudinal phase space plot describing longitudinal injection scheme. The relevant parameters (momentum compaction factor, rf frequency and voltage, energy loss per turn) are the ones of the ttbar operation mode. (Red) rf bucket is computed with synchrotron radiation loss constant over the beam energy whereas (black) "golf club" acceptance is computed taking into account the beam energy dependence of radiation loss. The kicker pulse length (blue) needs to be short to fit to the 400 MHz rf, and it is assumed here to be 1.6 ns. Trajectory of a test particle (green) injected at $t = 0$ with a momentum deviation of about 11% is also shown. As it is seen, the momentum deviation needs to be well beyond the off-energy dynamic aperture (smaller than 5%), and thus this scheme is not suitable for FCC-ee. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The two viable options which we have identified, namely conventional injection and multipole-kicker injection, are further developed in the following sections.

4. Design of the injection straight section

We here present possible designs of the injection straight section for the conventional and multipole-kicker injections with emphasis on the optical parameters and the specifications for kickers and septa.

A design strategy common to these schemes is increasing the beta function in the injection straight section, so as to decrease the effective septum thickness measured in units of beam size as well as to relax the technical requirements for the kickers and septa.

Between the injection straight and the first regular arc cell (50 m long) on either side, two FODO cells with the same length as the regular arc cell, but half the bending angle can be placed to function as dispersion suppressor. To increase the beta function in the straight section, longer FODO cells are employed. Several quadrupoles in the dispersion suppressor and the straight section are used to match the beta functions from the regular arc cells to the regular cells of the injection straight. At the same time, for on-energy injections the dispersion function is suppressed, while it needs to be maximized for the off-energy injections. These optical functions are computed using the MAD-X code [30].

We will assume that the injection beam is matched to the collider ring optics, i.e., $\sigma = \sigma_s = \sigma_i$ at all locations with zero horizontal dispersion, where σ_s is the stored beam size, and σ_i is the injection beam size. This is further discussed in Section 5.

4.1. Conventional injection scheme

We have previously reported that the conventional injection scheme is based on an injection septum and a kicker bump. The latter can consist of solely three or four dipole kickers located within the same drift space, but such a design may not be efficient for the high energy ring. Instead, two dipole kickers are installed with FODO quadrupoles in between, which enhance the bump height. The phase advance of the straight section FODO cells is adjusted to 90 degrees such that the orbit bump is closed over two cells. The choice of the phase advance is important not only for closing the bump, but also for radiation issues (see Section 5). The FODO cell length is set to be 200 m, resulting in a large beta function at the kicker and septum of about 310 m.

In the conventional injection scheme, the separation between the stored beam and injection beam is required (for 5σ clearance) to be $5\sigma_s + S + 5\sigma_i$, and the bump height is $10\sigma_i + S$, where S is the septum thickness including the mechanical tolerance (see Fig. 2). Orbit and trajectory variations are not considered as these will be controlled at a high degree of precision by feedback/feedforward systems. The clearance of 5σ provides margin for some residual orbit variation.

Since a septum of 5 mm thickness corresponds to an rms beam size of 7.9σ for a beta function of 310 m (1σ ∼ 0.64 mm), it seems impossible to inject the beam within the available dynamic aperture (15σ). Therefore, a thin wire septum is required for these parameters. This is true also in the vertical plane. The dynamic aperture can be about 60σ [11], which, in units of beam size, is much larger than that of the horizontal plane. However, this value corresponds to only 3.1 mm even for a beta function as large as 1 km since the vertical emittance is of a small value, 2.6 pm (0.2% coupling assumed).

With this proviso, the conventional injection scheme is feasible, fulfilling all the constraints. The required separation is $\sim 10.3\sigma$ with a septum of 0.2 mm thickness (5σ clearance for both beams and 0.3σ corresponding to 0.2 mm). The injected beam of 5σ full beam size then lies within 15.3σ from the center of the stored beam, essentially compatible with the assumed dynamic aperture. The required bump height is 6.6 mm achieved with a deflection angle of 21 μrad. The corresponding integrated field of the kicker is then ∼0.012 Tm for 175 GeV beam, which is feasible using conventional kicker technology (for example, magnetic length of 0.4 m and field of 0.03 T). The deflection angle of the wire septum is set to be 65 μrad. This results in more than 5σ clearance at a thick septum located upstream of the wire septum, and reduces the beam impedance of the thick septum for the stored beam. The integrated deflecting voltage of the wire septum is then about 11 MV for 175 GeV beam, which is much lower than that of the existing device, e.g. SPS ZS septum (∼170 MV) [32]. The optical functions and the beam orbits are shown in Fig. 3.

For the off-energy injection, the required separation shown in Fig. 2 determines the dispersion function at the septum and the energy deviation of the injection beam, i.e., $5\sigma_s + S + 5\sigma_i = |D_x\delta|$. When this condition is fulfilled, the injection beam is situated on the off-energy closed orbit. It is noted that the beam sizes, σ_s and σ_i, are enlarged at the septum location due to the finite dispersion and beam energy spread. The same bump height requirement, $10\sigma_i + S$, applies but with the enlarged beam size.

The arc dispersion can be leaked into the straight section and enhanced to about 0.8 m at the location of septum. However, the energy offset needed to fulfill the separation requirement with a septum thickness of 5 mm is then −2.4%, whereas in Section 2 we had only required that the off-energy dynamic aperture of 5σ is achieved within ±2%. Therefore, a thin septum is required also for the off-energy injection. The energy deviation can be −1.8% with a septum thickness

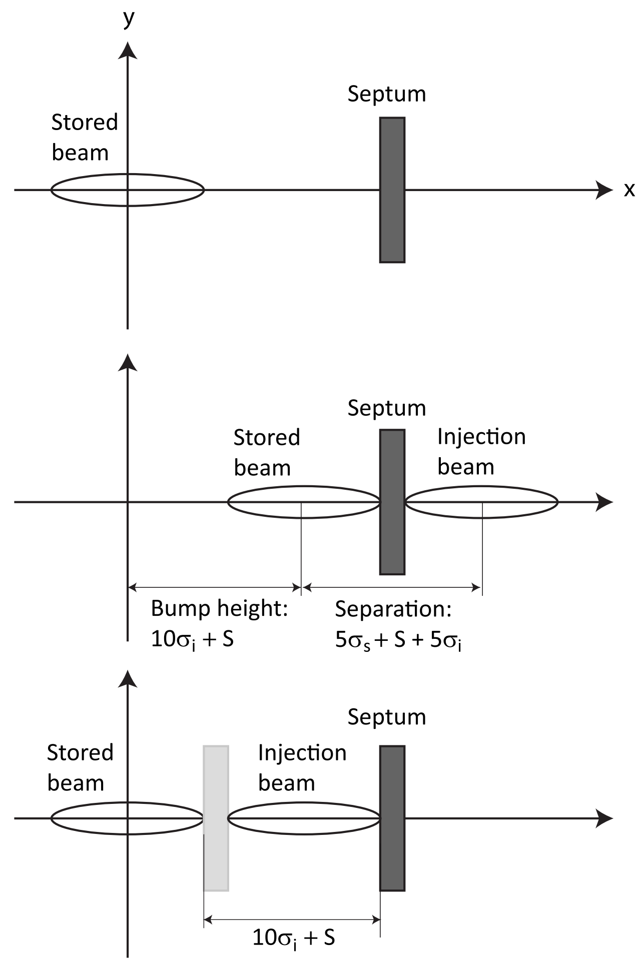

Fig. 2. Required separation and bump height to realize 5σ clearance. Beam positions at the location of the septum before the injection (top), at the time of injection with maximum bump height (middle) and after the injection (bottom) are shown in the real space. The beam position after injection corresponds to the worst case, where the injected beam is closest to the septum, i.e., the number of turns multiplied by the fractional part of tune is an integer. See text for symbols. A similar illustration is found e.g. in [31].

of 0.2 mm. The off-energy injection also satisfies all the constraints. The optical functions and the beam orbits are shown in Fig. 4. The integrated field of the kicker for the off-energy injection is ∼0.025 Tm for 175 GeV beam, which is still feasible technologically.

4.2. Multipole-kicker injection scheme

The length of straight section FODO cells is set to 200 m as in the conventional injection to increase the beta function and to reduce the injection kicker strength. The FODO phase advance is set to about 35 degrees such that the separation at the septum, which is located two cells upstream of the kicker, is enlarged. It is noted that the optimum phase advance between septum and kicker is not 90 degrees because the injection point is off-axis in on-energy multipole-kicker injection. A phase advance of about 70 degrees (one cell between the septum and the kicker) is also a possible choice but it results in a smaller beta function.

Beam positions at the location of the septum and kicker in the normalized phase space are schematically shown in Fig. 5. The injection beam orbit at the location of the kicker is adjusted to 10σ to fit the dynamic aperture of 15σ.

The feed-down quadrupole component of a sextupole kicker induces a significant mismatch of the injected beam from the ring optical parameters. This may be solved by adjusting the injection beam optical parameters. However, it turns out that the beta function becomes too

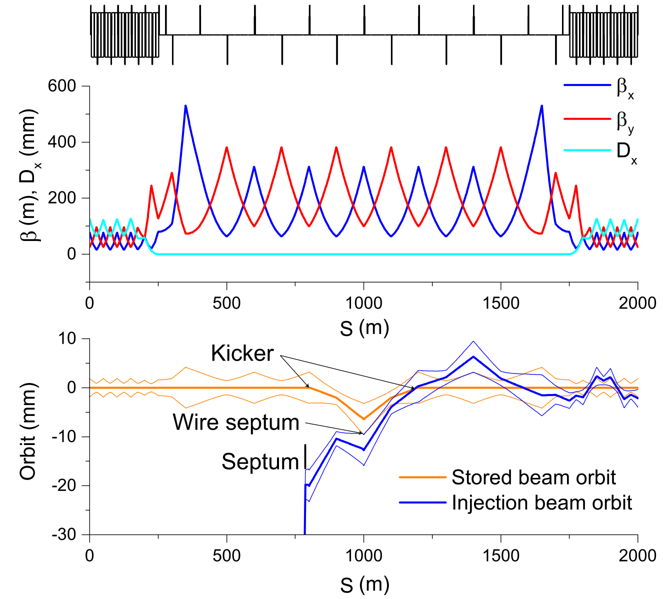

Fig. 3. Injection straight section for the conventional injection scheme (on-energy). The optical functions (top) and the beam orbits together with 5σ envelopes (bottom) are shown. The integrated kicker field is 0.012 Tm. The integrated wire septum voltage is 11 MV.

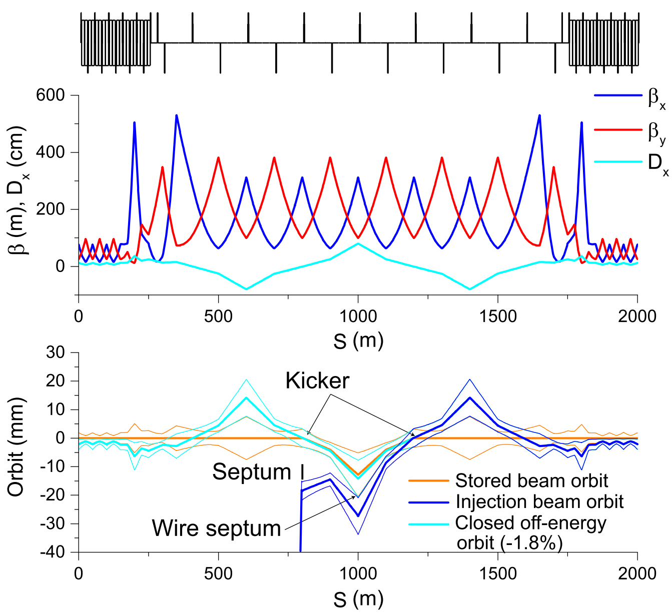

Fig. 4. Injection straight section for the conventional injection scheme (off-energy). The optical functions (top) and the beam orbits together with 5σ envelopes (bottom) are shown. The integrated kicker field is 0.025 Tm. The integrated wire septum voltage is 11 MV.

large in the injection beam line, which makes the injection tuning difficult. With non-zero field around the axis, it is inevitable to disturb the stored beam, i.e., the emittance of the stored beam is increased at the time of the injection. A *nonlinear kicker* is proposed [9] to mitigate these problems. Ultimately, the nonlinear kicker aims at realizing an ideal field profile as shown in Fig. 5. However, such a field cannot be generated exactly, and the actual field profile may have a smooth transition from zero to the peak, resulting in distortions of the stored and injection beams. This will be discussed later in this section.

The separation between the stored beam and the injected beam at the location of the septum must not be smaller than $15\sigma_s + S + 5\sigma_i$.

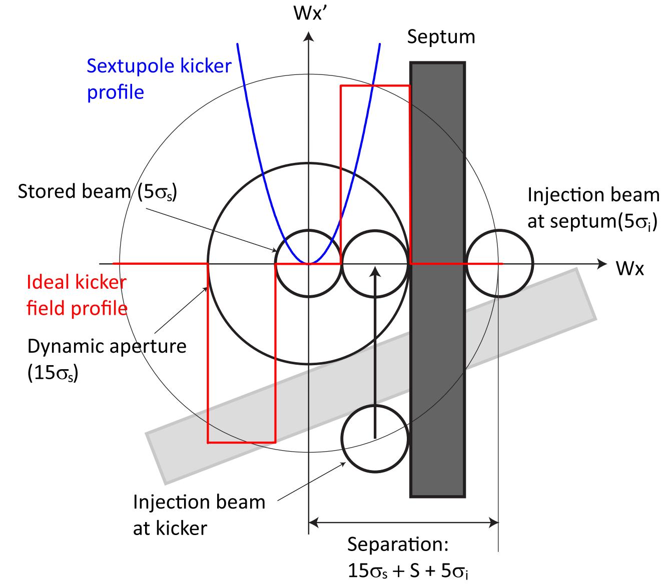

Fig. 5. Beam positions at the location of the septum and kicker are shown in the normalized phase space. A field profile of sextupole kicker (blue) and an ideal profile (red) are also shown. The ideal profile keeps the injection beam and stored beam shapes unchanged. See text for symbols. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The kicker strength is determined so as to realize this requirement. The first term in the above sum (i.e., 15σ) is required to keep a clearance of 5σ for the injected beam, since the injected beam performs a betatron oscillation with 10σ amplitude, corresponding to the injection point of 10σ. Although the stored beam particles at large betatron amplitude are significantly perturbed by the multipole kicker, they will not be lost as long as they stay within the dynamic aperture or within the physical aperture of the septum, both about equal to 15σ. (In practice, the physical aperture is likely to be set by a collimation system in such a way that it will be slightly smaller than the septum aperture.)

The injection orbits together with the optical parameters in the straight section are shown in Fig. 6. The injection beam envelope follows the ring optics when the kicker field profile is close to the ideal one. With a sextupole kicker, the horizontal beta function of the injection beam at the septum needs to be more than 10 km when we adjust the injection beam optical parameters so as to match to the ring optics after passing the kicker. Such a large beta function is not only difficult to handle and generate, but it will also render the beam extremely sensitive to nonlinear field errors at the septum.

For the off-energy injection, the phase advance of the FODO cell is adjusted to 45 degrees, corresponding to a phase advance between the kicker and the septum of 90 degrees. This is optimum since the off-energy injection is on-axis. The dispersion function at the kicker is set to be 0.8 m. The injection orbits together with the optics in the straight section are shown in Fig. 7. The required field at the plateau is about 0.025 Tm/0.03 Tm for on- and off-energy injections, respectively.

We now discuss how we realize a kicker field profile suitable for the injections discussed above. Fig. 8 shows a typical nonlinear kicker profile with eight conductors. It is seen that there is a region around the axis where the field is zero or negligibly small. On the other hand, the plateau is not wide enough for the given injection beam size. The number of conductors must be increased to enlarge the plateau, and the complexity of the kicker is then increased. It may not be straightforward to devise a nonlinear kicker, which realizes a good field profile, only with conductors.

We consider a different approach: two C-shaped dipole (ferrite) kickers are facing each other, and a suitable field profile is formed with the fringe fields [33,34]. Such a kicker can be installed within a vacuum

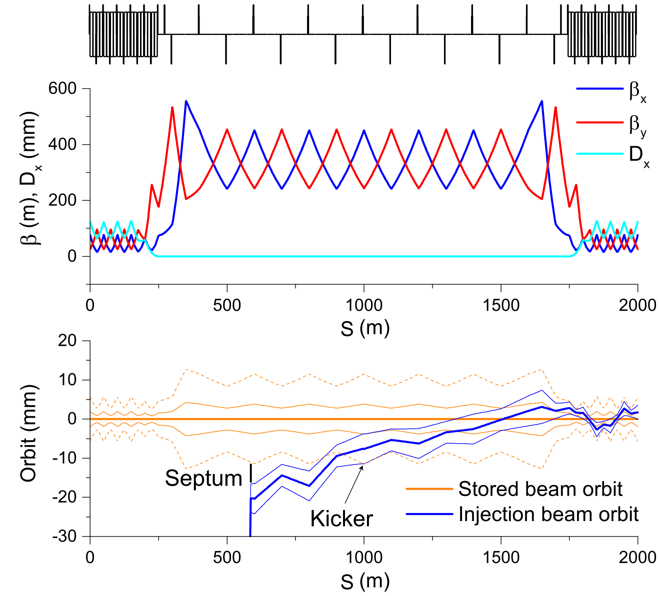

Fig. 6. Injection straight section for the multipole-kicker injection scheme (on-energy). The optical functions (top) and the beam orbits together with 5σ envelopes are shown. The stored beam envelope of 15σ (dashed line), which corresponds to 10σ betatron oscillation for the injection beam plus 5σ clearance, is also shown. The integrated field of nonlinear kicker plateau is 0.025 Tm.

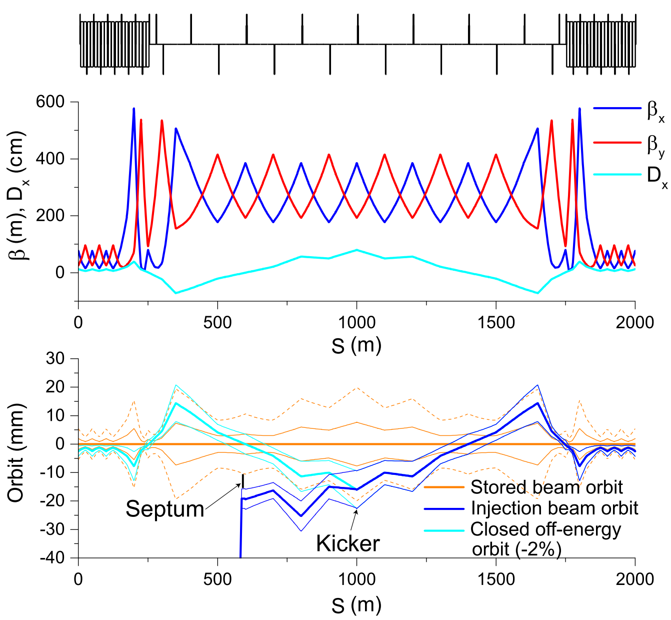

Fig. 7. Injection straight section for the multipole-kicker injection scheme (off-energy). The optical functions (top) and the beam orbits together with 5σ envelopes are shown. The stored beam envelope of 15σ (dashed line), which corresponds to the dynamic aperture, is also shown. The integrated field of nonlinear kicker plateau is 0.03 Tm.

chamber. When the two kickers are powered oppositely, quadrupole, octupole and higher multipole components are excited around the axis. The quadrupole component may not be preferred since it results in an emittance increase in both planes. Narrowing the gap is effective to suppress the quadrupole component. The horizontal spacing between the two kickers is mainly determined by the injection beam orbit. On the one hand, the gap should be much smaller than the spacing to realize a field profile close to the ideal one, on the other, the gap should be reasonably large. It is then comparable to the spacing for the injection orbit at −7.6 mm (on-energy injection). Therefore, the

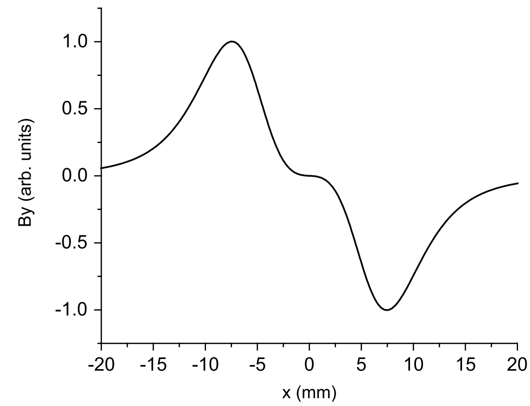

Fig. 8. Typical nonlinear kicker field profile with eight conductors. The four inner conductors are placed at $|x| = |y| = 5.7$ mm and the outer ones at 7.2 mm. This configuration sets the plateau at the injection point of 7.6 mm (on-energy injection). The field profile is normalized to the value at the peak.

quadrupole component may not be fully suppressed with a reasonable gap. It is proposed to insert a copper plate between the two kickers that assists in the suppression. Also the image charge of the beam is conducted through the copper plate [34]. However, a full suppression may still not be achieved for the given spacing and gap.

When the two kickers are powered similarly, dipole, sextupole and higher multipole components are excited around the axis. A copper plate also suppresses the dipole component to some extent. An effective, full suppression can be achieved by placing a dipole kicker near by. Fig. 9 shows a cross section of such a kicker and the field profile obtained. The half vertical aperture at $x = 0$ is 12 mm, and the half gap of C-shaped dipole is 4 mm. These numbers may be reasonable due to the fact that several 100 mA beam current is achieved in light sources where insertion devices with a half gap of around 2 mm are installed. It is noted that only the injection beam goes through the 4-mm gap of C-shaped dipole, and that the maximum injection beam current may be at most 100 mA.

With the profile of Fig. 9, an injection efficiency of almost 100% can be achieved as is shown in Fig. 10. The stored beam is distorted, and its emittance is increased by about 40%. For the off-energy injection, a similar kicker but with a different copper plate thickness realizes an injection efficiency of almost 100%, and the emittance increase is evaluated to be about 30%.

The required field on the plateau can be obtained with a (single turn) coil current of about 700 A and 500 A for the on-energy and off-energy injection, respectively, for a 50-cm long kicker (without counting additional dipole kicker). These values are technologically feasible.

5. Discussion

In this section we discuss some issues related to top-up injection for the designs of the straight section presented in Section 4.

We have assumed that the injection beam is matched to the collider ring optics. For the on-energy conventional injection, lowering the beam size of the injection beam and making it much smaller than that of the stored beam by intentionally mismatching the beta function allows us to bring the injection point down to about $8\sigma_s$. A higher injection efficiency may then be expected. On the other hand, for the on-energy multipole kicker injection, an injection point closer to the closed orbit obtained by optics mismatch may not necessarily be beneficial since the required kicker strength is increased, and consequently the emittance increase of the stored beam is enhanced. For the off-energy injection schemes, a transverse optics mismatch of the injection beam will not improve the injection efficiency. It may even deteriorate the efficiency, since the injection beam is situated on the off-energy closed orbit. Instead

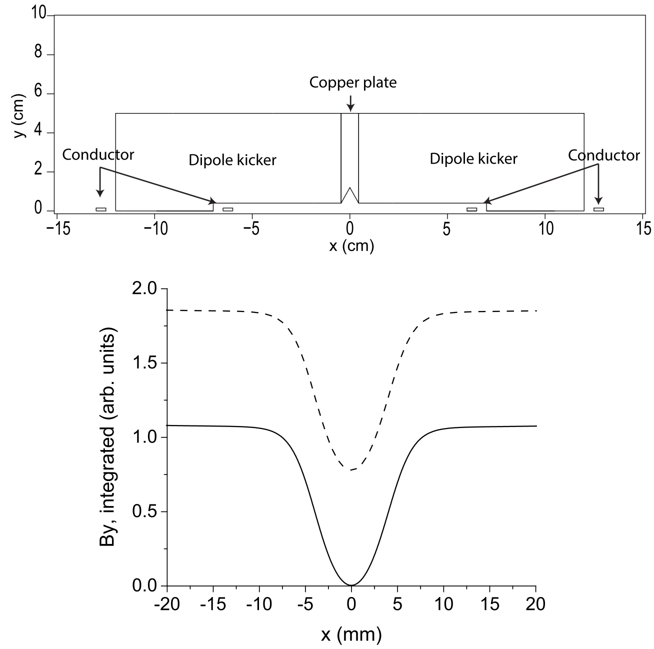

Fig. 9. Upper half geometry of a kicker with two C-shaped dipoles (top) and its field profile (bottom). A copper plate of 9 mm thickness is inserted in between. The half vertical aperture at $x = 0$ is 12 mm, and the half gap of C-shaped dipole is 4 mm. The field profile is normalized to the value at the injection point of −7.6 mm (on-energy injection). Dashed line is the field profile of the kicker and solid line is an effective profile with a pure dipole kicker attached. The field profile is computed with Poisson [35] as a static field, but the effect of eddy currents on the copper plate is approximated by a boundary condition imposed on the copper surface.

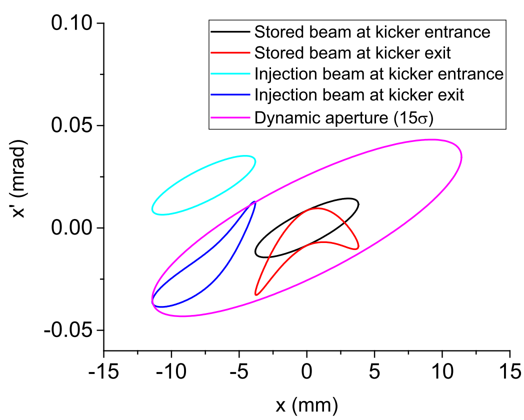

Fig. 10. Beam shapes (5σ) in the horizontal phase space. The injection beam almost fits the dynamic aperture although it is distorted due to the non-ideal kicker profile. The stored beam is also distorted.

the matching of the injection beam would be important for maximizing the injection efficiency, when the off-energy dynamic aperture may be limited to 5σ. Obviously, injection beams with smaller emittance, if provided from the booster, would yield additional margins for all the injection schemes considered. In the on-energy conventional injection scheme, for example, the bump height can be lower, increasing the clearance for the stored beam while preserving a 5σ clearance for the injection beam. We note that the beam clearance of 5σ corresponds to the design injection efficiency of ∼100% for the injection schemes presented in Section 4, and thus we have discussed mitigation for the hypothetical cases that it drops below 100% in real operation.

As demonstrated in Section 4, a wire septum is required for the conventional injection scheme at a beta function of ∼300 m. If we increase the beta function to ∼1 km and use a mismatched beam (with

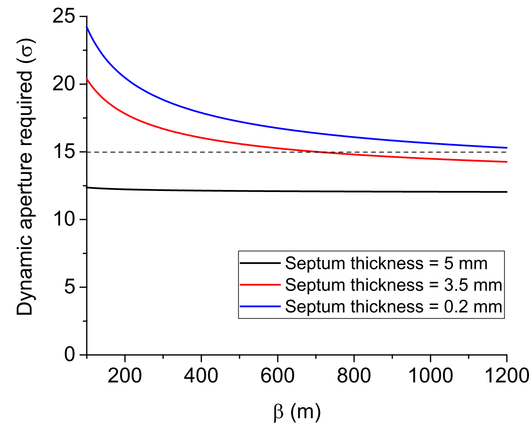

Fig. 11. Required dynamic apertures as a function of beta function at the septum for various septum thicknesses. They are computed for a beam emittance of 1.3 nm and the optimum injection beam sizes.

$\sigma_i \sim 0.5\sigma_s$), the required separation is achieved within the dynamic aperture of $\sim 15\sigma$ even with a septum of 5 mm thickness for the on-energy injection. For the off-energy injections, the injection beam should be matched as discussed above, and thus the beta function needs to be further increased to be compatible with a septum of 5 mm thickness. The required beta function is estimated to be ∼1.8 km, assuming the same value of the normalized dispersion as the one in Section 4.1 ($D_x/\sqrt{\beta_x} = 0.8/\sqrt{310}$ m$^{1/2}$). Such a large-beta injection straight may also be an option provided that it fits with the collider optics design. The assumption of a septum thickness of 5 mm might be a little too conservative, although it was for the purpose of achieving a robust injection. For instance, a septum with an effective thickness of 3.5 mm is being implemented for the injection system of SuperKEKB, whereas the septum used for KEKB had an effective thickness of 5.5 mm [12]. Fig. 11 shows the required dynamic aperture as a function of beta function at the septum for various septum thicknesses. It is seen that a beta function of about 700 m is enough when the septum thickness is 3.5 mm. The required beta function for an off-energy injection at −2% injection beam energy is also evaluated, and it is about 900 m with a 3.5-mm-thick septum. Therefore, a medium-beta injection straight with a thinner septum may also be an attractive option.

When a wire septum is employed, sparking induced by synchrotron radiation photons is a potential risk, reducing the reliability of the injection system. We found that the direct radiation fans from the stored beam do not overlap with the wire septum when the FODO phase advance is 90 degrees. Other phase advances, for example 45 degrees, result in significant overlap. Fig. 12 shows the orbit bump for these phase advances together with the radiation fans.

The main synchrotron radiation illuminating the wire septum is then from the injection beam, which has much lower intensity than the stored beam. It can be limited by applying a longer quadrupole magnet in the straight section if necessary. Also, the risk of sparking naturally reduces with lowering the field of the wire septum. From the experience in the SPS and LEP, the rate of sparking was tolerable when the field was 30 kV/cm or lower [36]. For FCC-ee, such a low field can be achieved when two 3-m-long wire-septum modules are installed, to be compared with five modules installed in the SPS. With a careful design, the sparking rate may be reasonably low.

There may be a significant energy deposition to the wire septum from the stored beam. The wakefields excited by the beam can be trapped in the form of higher order modes (HOMs), depending on the detailed geometry of the septum region. The HOM heating can be strong enough to destroy the thin wires. This issue needs to be quantitatively investigated in case a wire septum is employed since the beam current is quite high, especially in the Z-pole operation mode.

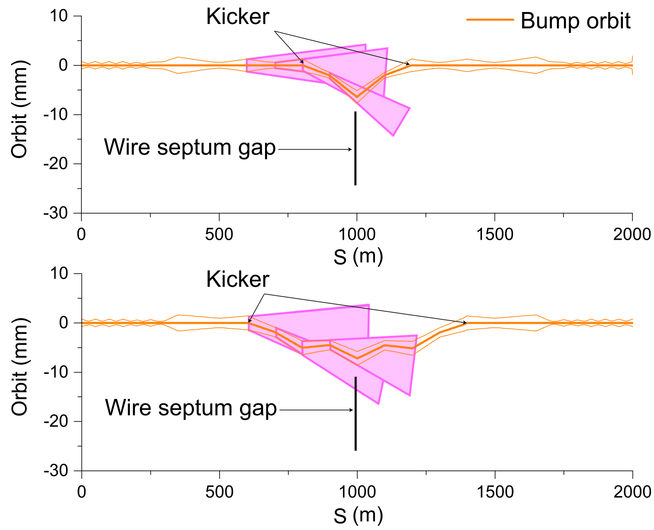

Fig. 12. Bump orbit and radiation fans for the FODO phase advance of 90 degrees (top) and 45 degrees (bottom). Radiation from a 2σ beam and from the magnets upstream of the wire septum up to 400 m are considered.

One of the important issues in top-up injection is the disturbance of the stored beam. Light sources generally face this very same problem, and an excellent experimental study of beam disturbances in the KEK PF is reported in Ref. [8]. The conventional injection scheme results in a dipolar disturbance to the stored beam due to a non-closure of the orbit bump in practice. Additional kickers are to be installed and fine-tuned to accomplish a satisfactory bump closure. It is noted that the roll errors of the injection kickers should be well corrected not to excite a vertical oscillation of the stored beam. These tunings may take a significant effort.

Reducing the disturbance was the primary motivation for the multipole-kicker injection. It was demonstrated in Ref. [8]. However, in FCC-ee the perturbation cannot be fully mitigated since the injection point has to be rather close to the stored beam. The temporary emittance increase due to the injection kicker is estimated to be about 30%–40% for the kicker considered. The disturbance occurs only at the time of injection, after which the stored beam emittance is quickly recovered, e.g., after a few synchrotron radiation damping times. The emittance increase, however, can be suppressed when an identical kicker, which acts only on the stored beam, is placed at an upstream location with a phase advance of 180 degrees and the same Twiss parameters [37]. As discussed in Section 4.2, it is necessary to install an additional dipole kicker nearby to effectively suppress the dipole components of the injection kicker. It may be difficult to achieve the same pulse shape in time for the dipole kicker and the multipole kicker. The residual dipole kick results in a closed orbit bump when an identical kicker is installed upstream.

The beam disturbance might be important for beam–beam effects. Some betatron or synchrotron oscillation of the injection beam is inevitable, and qualitatively the off-energy injection with residual synchrotron oscillation is preferable, since the dispersion at the collision point will be zero or very small. The off-energy injection also lowered undesired radiation doses to the detectors at LEP [20].

For the conventional injection scheme, both on- and off-energy injections can be examined with the same kickers and septa. On the other hand, the multipole-kicker injection may require a dedicated kicker for either case since the transverse injection point depends on whether the injection beam is on-energy or off-energy. The physical positions of the septa need to be adjustable not only to switch between on- and off-energy injections, but also to maximize the injection efficiency, which is very important for the frequent top-up injection.

There will always be differences in bunch charges of the circulating stored beam since the top-up is performed at the repetition rate of the booster. The tolerance for the charge difference has to be studied taking into account beam–beam effects [38]. A filling pattern feedback to keep the bunch charges as constant as possible has to be implemented in the injector chain.

6. Conclusion

We have investigated the top-up injection for FCC-ee. The beam lifetime of the collider is rather short, and it is important to establish a highly robust injection scheme.

Although the top-up injection into FCC-ee is constrained by the limited dynamic aperture [11], we found and presented feasible designs of the injection straight using conventional injection and multipole-kicker injection schemes for both on-energy and off-energy injection. We assumed dynamic apertures of 15σ and 5σ for on- and off-energy (2%), respectively, consistent with the present optics design. A larger aperture and/or smaller injection beam emittance would increase the reliability of the injection. A concrete application for off-energy multipole-kicker injection was discussed for the first time. The on- and off-energy injections could use the same, or at least similar, kickers and septa.

The various injection schemes have their respective advantages and disadvantages. One of the important issues is the disturbance of the stored beam. In principle, the conventional scheme can be fully transparent for the stored beam, but in practice the required orbit bump may not be fully closed. A significant effort will then be required to mitigate the disturbance. On the other hand, the multipole-kicker injection may not affect the stored beam orbit if the kicker is well aligned. A beam-based alignment of the kicker can be performed with little effort. A certain temporary emittance increase due to the kicker is induced in this scheme but it can be suppressed when an identical kicker is installed upstream.

Synchrotron phase space injection with off-energy injection beams reduces the background and is likely to increase the injection efficiency, while multipole kicker injection avoids any disturbance of the stored-beam orbit. Combining these two schemes may simultaneously realize all the aforementioned advantages, i.e., provide a high efficiency injection with low experimental background and a small perturbation of the circulating beam — three essential merits for a collider running in top-up mode.

A very thin electrostatic wire septum is helpful for the conventional injection with limited aperture unless the beta function is significantly increased. It would be the first ever use of this type of septum with a lepton beam. For such a wire septum, we found that the optimum phase advance in the injection region is 90 degrees per FODO cell. This phase advance minimizes the amount of synchrotron radiation from the stored beam hitting the septum, which could result in sparking and voltage breakdown. The collider luminosity can be increased by further lowering β^{*}, provided that the dynamic aperture remains adequate for injection. In this sense, wire septa allow for the highest possible collider luminosity.

To finalize the top-up injection scheme for FCC-ee, several dedicated studies are still necessary, such as completing the optics designs of the collider and booster rings, studies of beam–beam effects at injection, examining the possible effects on the beam polarization, the definition of the overall injector chain, that will determine the bunch pattern of the injection beam, and the hardware design for the top-up injection components, which again largely depends on the bunch pattern. These topics are all beyond the scope of the present paper, but some preliminary results (partly from the same authors) are found in Refs. [11,15,38–42]. It may also be necessary to validate the final design with tracking simulations, taking into account all the effects which could potentially deteriorate the injection efficiency.

Finally, the injection designs presented in Section 4 and discussion of Section 5 are summarized in Table 3.

Table 3
Summary of injection schemes (for 175 GeV beam). The parameters of the conventional injection scheme are based on a thin electrostatic wire septum. A thicker magnetic septum can be used with a larger beta function. The nonlinear kicker for multipole kicker injection consists of two C-shaped dipole kickers.

Parameters	Conventional (on-/off-energy)	Multipole kicker (on-/off-energy)
β_x at kicker and septum (m)	310/310	450/380
D_x at kicker and septum (m)	0/0.8	0/0.8
Type of kicker	Dipole kickers	Nonlinear kicker
Integrated kicker field (Tm)	0.012/0.025	0.025/0.03 (Plateau)
Wire septum integrated volt. (MV)	11/11	Not required
Beam disturbance	Coherent oscillation	Emittance increase
Injection beam oscillation	Betatron/Synchrotron	Betatron/Synchrotron
Required aperture (σ_s)	$\sim$ 15/5 (at −1.8%)	15/5 (at −2%)

Acknowledgments

We are grateful to M. Benedikt, T. Garvey, L. Rivkin, T. Schietinger, A. Streun and J. Wenninger for continuous support and encouragement. We appreciate C. Calzolaio, S. Dordevic, and C. Gough for valuable discussions on the injection kicker.

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