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Top-up injection for FCC-ee

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Abstract

Top-up injection is essential for FCC-ee due to the very short luminosity lifetime especially for the Higgs and top-pair operation modes. Several schemes exist for topping up the collider rings. We investigate these schemes and identify the strongest candidates for FCC-ee.

1 Introduction

Top-up injection is essential for FCC-ee due to the very short luminosity lifetime especially for the Higgs and top-pair operation modes. In this note, we investigate various possible schemes and discard those that may not be applicable to FCC-ee because of obvious difficulties or disadvantages.

2 Booster

The injector booster is planned to be a full-energy, full-scale synchrotron situated in the same tunnel. The repetition rate is 0.1 Hz or lower (including flat bottom and top). The repetition rate of the top-up injection is half of this (<0.05 Hz) since the booster fills the pair of collider storage rings, alternatingly accelerating electrons and positrons.

Figure 1 (a) shows the normalized integrated luminosity as a function of the number of batches (or booster cycles) required to top up the entire bunch train in one of the collider rings. Figure 1 (b) presents the corresponding fractional number of particles accelerated by the booster with respect to the total number of particle in one of the collider rings.

The best integrated luminosity is naturally achieved when the entire bunch train in one of the collider rings is topped up at once. However the loss in the integrated luminosity is acceptable even when only half (two batches) or one third (three batches) of the bunch train is topped up because the booster repetition rate is high enough. A shorter injection batch relaxes the specifications on the booster extraction kicker (rise time and flat top) as well as for the collider ring injection kicker. Two-, three- or four-batch injection would therefore be an optimum choice for the Higgs operation mode. It is noted that the number of particles accelerated by the booster is approximately constant for these parameters as illustrated in Fig. 1 (b).

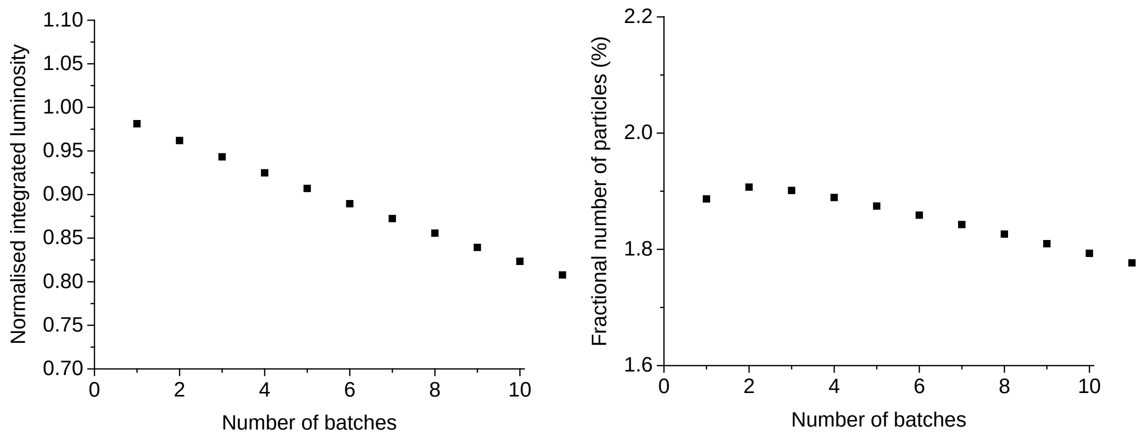

Figure 1. Normalized luminosity (a) and fractional number of particles (b) as a function of the number of batches. A luminosity life time of 21 min (Higgs operation mode) and a booster repetition rate of 0.04 Hz (25 sec) are assumed. The luminosity is computed with an approximation, i.e. it is taken to be proportional to the square of the average beam current, and it is normalized to the ideal case with a constant 100% beam current. The horizontal axis is the number of batches (or booster cycles) necessary to fill one of the collider rings. For example, when the number of batches is 2, half of all bunches in one of the collider rings are topped up, on each cycle. The fractional number of particles represents the amount of particles to be accelerated on one booster cycle relative to the number of particles stored in the collider ring.

The kicker flat top should be as long as the revolution period divided by the number of batches. Since the collider circumference is rather long, we need a large capacitor to realize so long a pulse (on the order of 100 μs). However, if the booster filling pattern can be controlled, the flat top can be further shortened by operating with multiple (separated) batches in a single booster cycle. These are then to be transferred to the collider ring one by one while the booster is at top energy. The kicker flat top must then equal the revolution period divided by the total number of batches. For example, when the collider ring is topped up with four booster cycles and four batches in each cycle, the kicker flat top is about 20 μs, which is a moderate value.

3 Lattice and relevant parameters

The relevant parameters for injection of the FCC lattice, taken from [1], are presented in Table 1 for the Higgs and top-pair operation modes. A lattice based on these parameters is under development by Bogomyagkov [2]. We use the latest version of this lattice [3] for our investigation.

Table 1. FCC-ee parameters relevant to top-up injection. The rf frequency may alternatively be 400 MHz; the choice of frequency changess some associated parameters such as the bunch length. The energy spread due to synchrotron radiation, important for our investigation, does not depend on the rf frequency.

Operation mode	**H**	**tt**
Circumference [km]	100	
Bending radius [km]	11	
Beam energy [GeV]	120	175
Beam current [mA]	30	6.6
Bunches / beam	1360	98
Bunch population [10^{11}]	0.46	1.4
Transverse emittance: - Horizontal [nm] - Vertical [pm]	 0.94 1.9	 2 2
Momentum compaction [10^{-5}]	0.5	0.5
Energy spread [%] - Synchrotron radiation - Total (including BS)	 0.10 0.14	 0.14 0.19
Bunch length [mm] - Synchrotron radiation - total	 0.81 1.17	 1.16 1.49
Energy loss / turn [GeV]	1.67	7.55
SR power / beam [MW]	50	50
Total RF voltage [GV]	5.5	11
RF frequency [MHz]	800	
Longitudinal damping time [turns]	72	23
Energy acceptance RF [%]	11.2	7.1
Synchrotron tune	0.096	0.10
Luminosity lifetime [min]	29	21

4 Injection options

In this section, different injection options for the FCC are briefly described. After their advantages or drawbacks are considered they are either discarded or further developed. Special attention is paid to subsection 4.6, devoted to the “multipole kicker injection +”, as it appears to be a strong option for the FCC top-up injection.

4.1 Conventional injection scheme

We call this injection scheme “conventional” as it has frequently been adopted in electron storage rings [4]. The conventional injection scheme employs a static septum and a dynamic magnetic chicane (or kicker bump). The latter rises to bring the closed orbit to the vicinity of the septum at the time of injection and falls within one electron beam revolution, or a few revolutions, to prevent the injected bunch from being lost at the septum. In the conventional scheme, the injected bunch is transversely separated from the circulating bunches, and thus it is referred to as off-axis injection.

Two drawbacks render implementation of this scheme undesirable for FCC: 1) the use of a kicker bump introduces adverse transverse oscillations of the beam at the interaction point (IP) which could cause unwanted background in the particle-physics experiment; thus the physics data acquisition might need to be gated during the injection and over the following few damping times, and 2) implementing this injection scheme requires a certain dynamic aperture of the ring in order to capture the off-axis injected beam, for which the non-linear optics has to be carefully optimized.

4.2 Synchrotron phase space injection

The synchrotron phase space injection scheme is an on-axis variant of the conventional injection scheme, already implemented in LEP [5]. It also employs a static septum and a kicker bump. However, in this case the beam is injected with a small momentum offset (requiring nonzero ring dispersion in the injection region), and the injection orbit is matched to the corresponding off-momentum closed orbit. In this manner the beam is injected transversely on axis, and the injected beam would merge into the circulating beam as the momentum deviation is damped.

The experience in LEP with this injection scheme was positive and better injection efficiencies were achieved despite of the off-momentum injection beam [5]. Studies of the application of this scheme to the FCC lattice have already been performed for a beam with a momentum offset of 1~2%, finding a 4σ clearance for a 5mm septum thickness [6]. Still, also this scheme also makes use of a magnetic chicane which is likely to introduce adverse transverse oscillations of the beam at the interaction point (IP). For this reason this scheme is a strong option, but may not be the best one. Thus, alternative schemes that do not make use of a dynamic chicane are also considered below.

4.3 Swap-out injection

The swap-out injection is a proposed injection scheme for the APS upgrade [7]. In this scheme full current bunches are injected onto the closed orbit and the circulating bunches, which are occupying the on-axis phase-space volume, are kicked out on the same turn. It can work in a bunch-by-bunch mode or even by swapping the entire bunch train at once when the beam current decreases below a threshold of the top-up injection [7]. A septum and a dipole kicker with a pulse length corresponding to the batch length are needed. We may discard this option because the injector chain may not be designed to provide a full charge injection batch.

4.4 Longitudinal injection

The longitudinal injection scheme is an alternative scheme, presented in [8], well suited for the modern ultra-low emittance ring in which the physical and dynamic aperture are such restricted that off-axis injection and accumulation may become impossible.

In this scheme the injected bunch is longitudinally separate from the circulating bunches, i.e., injected with a time offset. The bunch can be injected transversely on-axis because the separation is realized in the longitudinal phase space. The longitudinal phase space in the presence of synchrotron radiation exhibits a separatrix with the shape of a “golf-club” with its shaft extending towards the neighboring bucket. Not only the particles in the static bucket are stable, but also those on the shaft. When the height and width of the tilted shaft are sufficient to accept the energy and time spread of an incoming bunch, one can inject a new bunch at such a point, between two successive circulating bunches, together with a slightly higher energy from the injector. The injected bunch is finally merged with the circulating bunch through synchrotron radiation damping.

Longitudinal 1-D tracking simulations have been done for the Higgs mode parameters (see Table 1). The rf frequency and total voltage are assumed to be 400 MHz and 5.5 GV, respectively. The results show that the longitudinal phase space topology of FCc-ee is not optimum for this type of injection scheme, see Fig. 2, as the bucket height is too large and the momentum offset would reach values around 20%.

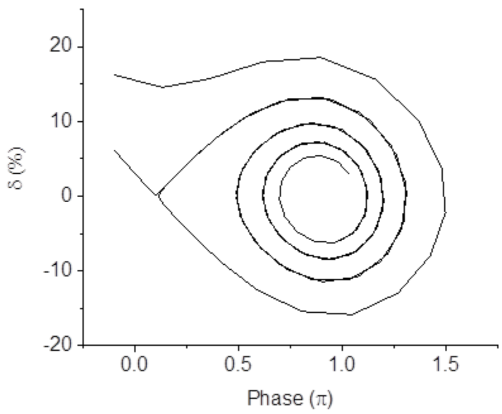

Figure 2: Longitudinal phase space topology for the Higgs mode parameters. The bucket height is too large and the momentum offset would reach values around 20%.

Another possible limitation for applying this scheme to a ring with an rf frequency of 400 MHz is the feasibility of a very short pulse kicker, with a fast decaying tail of approximately 1 ns. Moreover the short pulse kicker would have to fire repeatedly at a frequency corresponding to the bunch spacing (4 MHz for Higgs mode). This may not be feasible, or at least rather difficult, with present technology. Thus we may discard this scheme.

4.5 Multipole kicker injection

An injection scheme utilizing a multipole kicker and avoiding the inclusion of a kicker bump has been proposed and experimentally examined at the KEK Photon Factory storage ring in Tsukuba [9]. The injected bunch passes through a pulsed multipole magnet, typically a quadrupole or a sextupole, with an offset from the magnet center while the circulating bunches pass through the center. Therefore, the disturbance to the circulating bunches is significantly suppressed, and no adverse transverse oscillations of the beam at the IP should be expected. The scheme is compatible with top-up injection. Nevertheless, it is an off-axis injection by definition, and the necessary large dynamic aperture must be provided.

4.6 Off-momentum multipole kicker injection

Now we propose a new scheme for the injection into the FCC-ee, namely an on-axis version of the multipole kicker injection. This scheme also employs a static septum and a multipole kicker, but in this case the beam is injected with a momentum offset and the injection orbit is designed so as to cross the corresponding off-momentum closed orbit at the position of the multipole kicker. The kick brings the injected bunch onto the off-momentum closed orbit, which then merges into the circulating beam as the momentum offset is damped.

This option presents some advantages: the injection would be transversely on-axis, top-up compatible and would avoid the use of a kicker bump disturbing the beam. For this reason a more detailed study on the implementation of this scheme has been carried out for the FCC-ee lattice.

The FCC lattice has 12 arcs, each of which consists of 50 m long regular FODO cells with classical half-bend dispersion suppressors which expand over 2 cells at both ends of each arc. A possible injection lattice has been added at the beginning of an arc. The half bends in the dispersion suppressor cells have been integrated into single full bends to make room for the sextupole kickers. (The dispersion suppressor at the other end of the straight section should be modified as well to close the ring.) Additionally, the dispersion function has been locally modified at the location of the sextupole kickers to reach a value of approximately 0.3 m. The horizontal emittance increase due to the local enhancement of the dispersion function is marginal, as this modification expands only over 20 dipoles.

The enhancement of the dispersion function results in a larger offset of the off-momentum closed orbit at the position of the multipole kickers, thus enabling a smaller kicker gradient to bring the injection orbit onto the off-momentum closed orbit. The proposed injection lattice and the off-momentum (δ=-2%) orbit of the injected beam are shown in Fig. 3. For this example, we consider two 8-m long sextupole kickers with a sextupole gradient of $k_2 \approx 0.5$ m^{-3}, e.g. obtained with a pole tip field of 0.09/0.13 T at a radius r = 30 mm for a 120/175 GeV beam (corresponding to the Higgs/top-pair mode). Each kicker may consist of submodules (~30 cm) and would fit comfortably in the 10.5 m space created by rearranging the dispersion suppressors.

From the transverse point of view, the amplification factor, which is the product of the square root of the beta functions at the positions of the septum and multipole kicker, times the sine of the phase advance, would have a value of ~120 m/rad for this injection lattice.

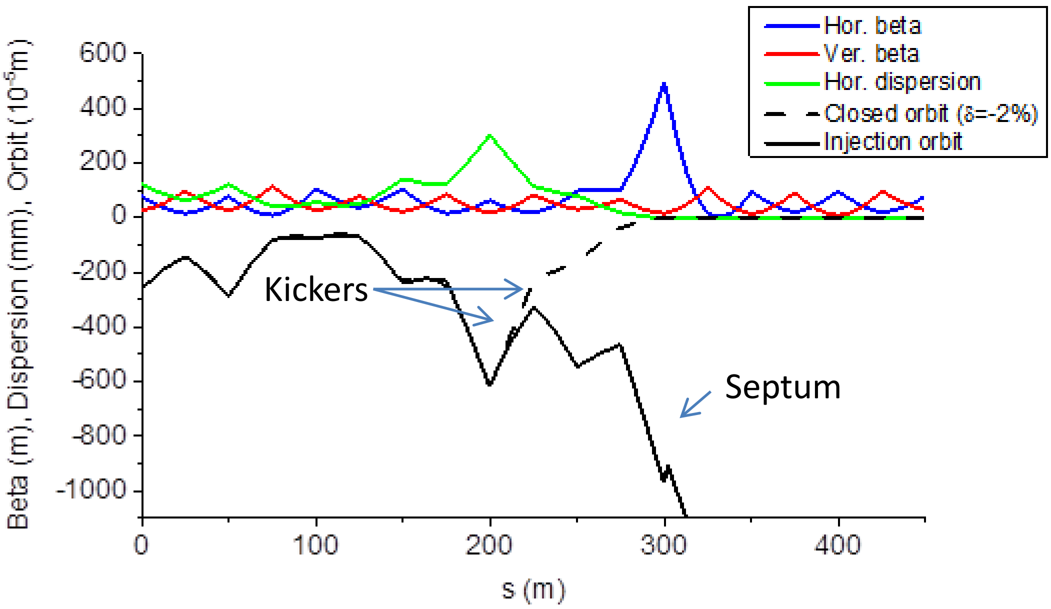

Figure 3. Injection lattice and off-momentum injection orbit for the proposed “off-momentum multipole kicker injection” scheme at the beginning of an arc. The dispersion function has been enhanced to a value of approximately 0.3 m at the position of the multipole kickers, where the injection orbit merges with the off-momentum closed orbit. Particle trajectories are from right to left. The kickers are situated between s=200 and 240 m, and the septum around s=300 m.

4.7 Kicker-less injection

The strong synchrotron radiation damping at high energy can be utilized to inject a beam without kicker. This possible option was proposed and studied by Talman for injection into the vertical plane [10]. We consider a similar injection scheme, but here exploit the (stronger) damping in the longitudinal plane, since the separation in the vertical plane may be rather small.

An injection scheme that would not need to use a kicker but instead would make use of the large energy variation per turn to jump over the septum, in a similar manner to the injection scheme in a cyclotron, would be the simplest and most robust option and a rather elegant one. The advantages are the same as for the "off-momentum multipole kicker injection" scheme: it would be on-axis, top-up compatible and would avoid the use of an injection chicane which would disturb the beam. In addition, any issues related to the kicker, such as stability or alignment, are removed.

Results from a longitudinal 1-D tracking simulation using the Higgs mode parameters and an initial momentum offset of -4% are shown in Fig 4 to illustrate the working principle of this injection scheme. The injection orbit is chosen such as to merge with the corresponding closed orbit after the septum. Because of the large energy loss per turn (e.g. 1.67 GeV for the Higgs mode), the amplitude of the bunch synchrotron oscillation significantly shrinks during one synchrotron period. The momentum variation of about 1% on the first turn, mainly due to the synchrotron motion of the injected bunch, results in a significant orbit separation between the first and second turn, shown in Fig. 5, which enables the bunch to jump to the other side of the septum. The injection time with respect to the rf phase has been optimized such that the beam momentum on the second turn equals the minimum after one full synchrotron oscillation.

The initial momentum offset can be also positive, and a similar separation may be obtained. However, a negative offset is preferable because of less radiation and less power consumption in the booster.

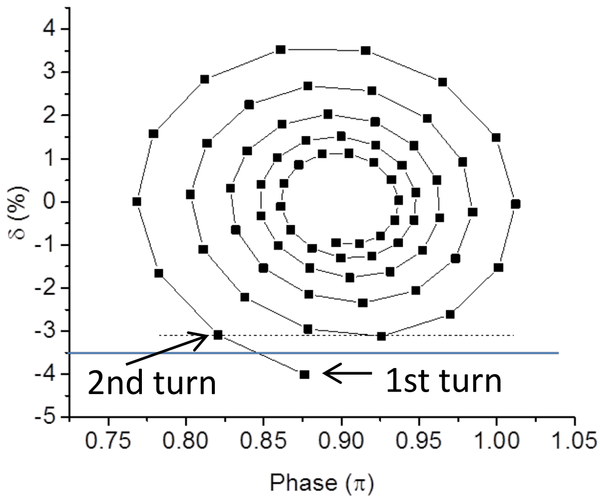

Figure 4. Longitudinal 1-D tracking with Higgs mode parameters. The initial momentum offset is -4%. Every point represents a consecutive turn in the ring. The black dotted line is added to guide the eye to see the approximately same beam momentum at the second turn and the minimum after one synchrotron

oscillation. The blue horizontal line indicates the place of the septum projected into the longitudinal phase space.

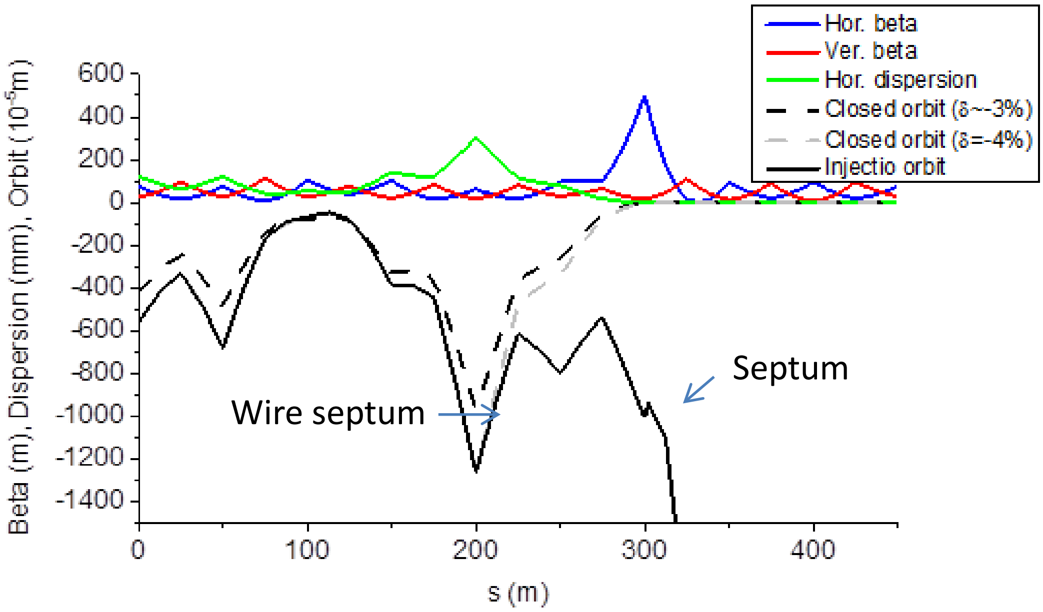

Figure 5. Proposed injection lattice and injection orbit for the kicker-less injection scheme. The particle trajectories are from right to left. The same lattice as the one shown in Fig. 3 is suitable and, therefore, a similar amplification factor can be expected. The dispersion function has been enhanced to approximately 0.3 m at the position of the septum. The injection orbit merges with the closed orbit for particles with δ = -4%. After one turn, due to the energy variation from synchrotron radiation and rf acceleration, the injected bunch has a momentum offset of δ ~ -3%. The corresponding closed orbit separation is ~3 mm for the dispersion of 0.3 m. Another (thick) septum is needed to fully separate the injection orbit from the ring. The thin septum (with a bending angle of 0.06 mrad) is situated in the vicinity of s=210 m and the thick septum around s=300 m.

When a wire septum is employed, the septum thickness is negligible (~60 μm) compared to the orbit separation or the beam size. A septum of this type has long been used for the SPS extraction [11]. For our lattice parameters, the rms beam size at the location of the thin septum is about 0.4 mm (assuming an rms emittance of 1 nm and a relative energy spread of 0.1%). Therefore the clearance can be more than 3σ on either side of the septum.

It has to be taken into account that this scheme is only valid for the Higgs and top-pair modes of the FCC-ee, due to their strong damping or large energy loss per turn. It would not work for the other modes (Z and W), since. due to their much more moderate values of energy loss per turn, the offset between the closed orbits on two consecutive turns would be too small to ensure adequate clearance at the septum and to avoid large losses on the septum wires. We also note that this scheme requires sufficient dynamic aperture for the relatively large momentum offset of the injection beam (-4%). Nevertheless this scheme is attractive because of the frequent top-up injection, for which robustness is highly important.

5 Summary

Top-up injection for the Higgs and top-pair operation modes of the FCC-ee has been investigated. Among all the options considered, the synchrotron phase space injection, the off-momentum multipole kicker injection, and the kicker-less injection appear to be the most promising options for FCC-ee. The properties of these three injection schemes are summarized in Table 2. It is noted that the first two options are compatible with off-axis, on-momentum injection, i.e. the same injection devices could also be used to inject a batch of bunches at nominal energy. Therefore, at the time of operation here one could still choose either on-axis or off-axis injection (or a combination thereof) for optimum injection efficiency. Finally the filling pattern of the booster needs to be further developed in order to determine the exact kicker specifications.

Table 2. Comparison of the synchrotron phase space injection, the off-momentum multipole kicker injection, and the kicker-less injection schemes.

	Synchrotron injection*	Multipole kicker +	Kicker-less injection
Kicker / septum strength	Kicker bump, 0.4 mrad	Sextupole magnet, k2·L~8 m^{-2}	Wire septum, 0.06 mrad
Amplification factor $\sqrt{\beta_{septum}\beta_{kicker}}\sin\mu$	100 m/rad	~120 m/rad	~120 m/rad
Dispersion at injection	2.5 m	~0.3 m	~0.3 m
Momentum offset of the injected beam	1.5%	~2%	~4%
Blind out due to kicker	3%?	~0%	0%
Compatibility with modes Z/W	Yes	Yes	No

* Parameters from [6]

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