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Injection: Electron Beams

M. Aiba
Paul Scherrer Institute, Villigen, Switzerland

Abstract
Beam injection into electron (or positron) rings is the subject of this paper. Through synchrotron radiation damping, top-up injection is realized: the beam current is kept essentially constant by injecting electrons or positrons atop of the stored beam to compensate for particle loss. This top-up operation mode maximizes the output of the accelerator, namely the integrated luminosity in lepton colliders and the photon flux in light sources. The history of top-up injection is briefly reviewed, and Liouville's theorem and synchrotron radiation damping are expounded from the viewpoint of top-up injection. Finally, various top-up injection schemes are explained, together with advantages and disadvantages.

Keywords
Beam injection; electron beam; lepton circular colliders; light sources; top-up injection.

1 Introduction

In lepton circular colliders and light sources, beam particles are continuously lost through collisions, Touschek scattering, and so on. The outputs of these accelerators, namely the luminosity and the photon beam flux, decrease as the beam current drops. To maximize the output, the beam current is kept essentially constant by injecting electrons or positrons atop of the stored beam, i.e. *top-up injection*. Top-up injection is important, not only to maximize the output but also to stabilize the beams. As discussed in the following, top-up injection is enabled through synchrotron radiation damping. The synchrotron radiation, conversely, heats up the accelerator components; thus top-up injection increases the beam stability by keeping the thermal load constant.

This paper specifically covers top-up injections. For those accelerators that do not necessitate top-up injection, other lectures in this series may be referred to; for most of these beam injections, injection schemes used there are commonly applicable to lepton and hadron beams. The technical and engineering aspects of injection devices, namely kickers and septa, are also not covered here but may be found in the other lectures and in the literature elsewhere.

2 Brief history of top-up injection

In early times, the beams in lepton colliders were dumped for the next filling, as in hadron colliders, when the beam current significantly decreased. It took some time to refill the machine and re-establish stable collisions after the beam dump. The luminosity production was not very efficient then.

In the 1980s, an improved operation mode was established in lepton colliders, e.g. PEP [1], where the beams were no longer dumped but electrons and positrons were injected atop of the stored beam left in the machine so as to compensate for the missing beam current. It is noted that a full-energy injector was necessary for this. Although the physics detectors had to be turned off during the injection to avoid possible damage, the turn-around time was successfully reduced. The injection was typically performed when the beam current dropped by about 30%.

In the 2000s, the technique was further developed, mainly at the KEKB [2] and PEP colliders [3], to top-up operation mode. It was possible to keep the physics detectors turned on during the top-up

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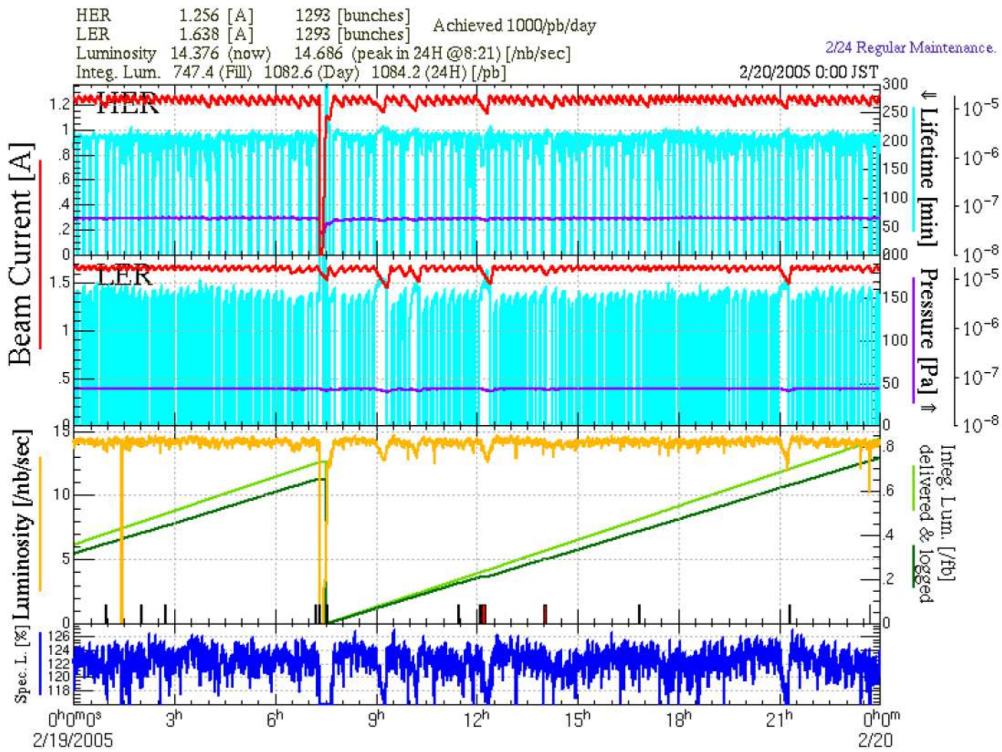

Fig. 1: Top-up operation at KEKB in 2005. Top and middle plots show beam currents in high-energy ring (HER, electron) and low-energy ring (LER, positron), respectively. The beam currents are kept essentially constant with a regular sawtooth pattern, where top-up injection is repeated approximately every 12 min. It can be seen that the current drops from time to time for various reasons. The bottom plot shows approximately constant luminosity with its integral linearly increasing. The beam current stability has been further improved after an injector linac upgrade in 2009; see Ref. [2], from where the figure is taken.

injection, with a mask to the data acquisition for a short time [3]. Without turning the detectors on and off, the injection could be repeated frequently, and the beam current could be kept essentially constant. Figure 1 shows the various parameters during top-up operation of the KEKB.

In light sources too, the stored beam was dumped and refilled before the emergence of top-up injection. A number of light sources were operated in energy-ramping mode, where the beam was injected with lower energy and accelerated to the operation beam energy in the storage ring. In 1990, top-up injection was first applied to the light source SORTEC [4]. The top-up operation mode was able to maintain the full beam current and so the maximum photon flux. Furthermore, the electron beam stability is of importance in providing a stable photon beam to the beamlines. Constant beam current helps to achieve micrometre level electron-beam position stability with orbit feedback, see e.g. Ref. [5]. The top-up operation became standard for light sources in the 2000s [6].

3 Physics behind top-up injection

According to *Liouville's theorem*—'Under the influence of conservative forces the density of the particles in phase space stays constant,' [7]—the injection beam particles cannot be put into the phase space volume occupied by the stored beam particles by an injection kicker. At the same time, it is preferable, if not essential, that the injection process does not disturb the stored beam. Therefore, the injection beam is placed with finite initial betatron or synchrotron oscillation amplitude, being separated from the stored beam at the origin of these oscillations.

Betatron and synchrotron oscillations are damped through *synchrotron radiation damping* in the ring. When a charged particle is accelerated, photons are emitted. The longitudinal acceleration, for instance by RF field, is normally negligible in terms of photon emission. For transverse acceleration with a bending magnetic field, the energy loss for the charged particle due to the emission is proportional to γ^4/ρ, where γ is the Lorentz factor corresponding to the beam energy and ρ is the bending radius. For electron and positron beams, it can be significant.

The energy loss is compensated by RF acceleration turn by turn. Because the radiation energy loss reduces the transverse and longitudinal momenta by the same fraction, whereas the RF acceleration only compensates for the longitudinal component, the betatron oscillation is damped. At the same time, the energy loss depends on the particle energy, i.e., there is greater energy loss for higher-energy particles and vice versa. Hence, synchrotron oscillation is also damped.

The injection beams initially separated in the betatron or synchrotron phase space are merged to the stored beam after several damping times. Since the synchrotron radiation, i.e., photon emission, acts on beam particles as a non-conservative force, Liouville's theorem does not apply here. Hence, the density of the particles in phase space is increased by the injected beam particles. Without synchrotron radiation damping, the entire phase space volume within the machine aperture is to be filled, and thus the top-up injection cannot be repeated indefinitely.

In fact, in hadron machines, top-up injection is not applicable because the radiative energy loss is typically marginal; thus the damping time is too long. It is, however, worth noting that the synchrotron radiation damping can be replaced by other means; for instance, electron cooling is applied to hadron beams, enabling an injection atop of the stored beam. Interested readers are led to literature elsewhere, e.g. Ref. [8].

The oscillations of the injected beam are not harmful for user experiments in light sources, since the injection beam current is negligible compared with the stored beam current. However, betatron oscillations are unfavourable for physics detectors in the collider, as discussed shortly.

4 Top-up injection schemes

There are several ways to perform top-up injection, depending on how the injection beam is separated from the stored beam and which type of kicker is employed. This section describes various injection schemes, together with their advantages and disadvantages.

4.1 Conventional injection scheme

The conventional injection scheme is performed with a static septum and a dynamic *kicker bump* (a series of dipole kickers). The former can be a pulsed magnet but is regarded as a static element for the time scale where the injection beam passes. The latter is turned on and off within one or a few revolution periods, depending on the ring circumference and the field required. The stored beam is brought to the vicinity of the septum wall by the kicker bump, and the injection beam is synchronized to arrive at the septum at the same time. The stored beam is brought back to the closed orbit when the kicker bump is turned off, while the injection beam is brought from the inside of septum channel to the outside. The radio frequency is normally much higher than the ring revolution frequency, accommodating a large number of RF buckets and beam bunches in lepton colliders and light sources. To place the injection beam in the target RF bucket, the precision of synchronization in time should be much shorter than the RF period. For a typical RF frequency of 500 MHz, corresponding to 2 ns RF period, the required precision would be about 100 ps or less. The conventional injection scheme has been used widely, including the first realizations of top-up injection mentioned in Section 3.

Figure 2 shows the configuration of the injection devices and the beam orbits. In Fig. 2, all kickers are located within the straight section. Other configuration, for instance two kickers with several quadrupoles in between, may be employed when a sufficiently long straight section is not afford-

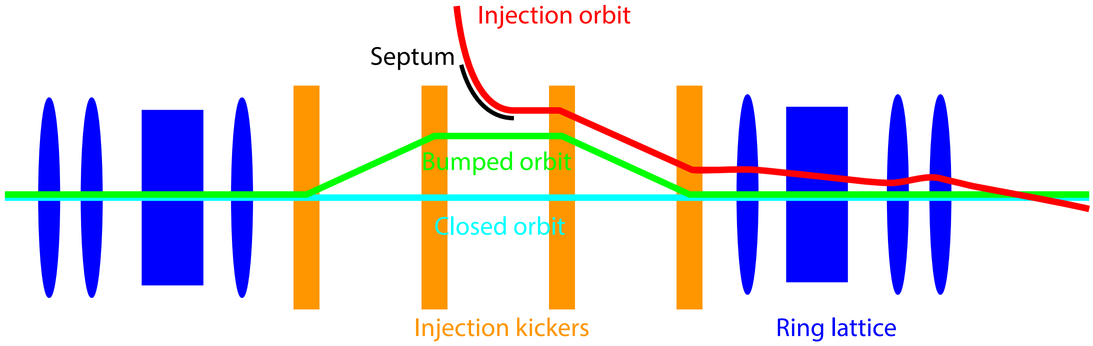

Fig. 2: Conventional injection scheme

able. Also, in high-energy rings, the orbit bump may be formed with the latter configuration, since the quadrupole field is useful to enhance the bump height efficiently for the high-energy beams.

The bump height is determined by the geometry in the former configuration, while it is expressed in the latter case as

$$x_{\mathrm{bump}} = \theta\sqrt{\beta_{\mathrm{k}}\beta_{\mathrm{s}}}\sin\mu, \tag{1}$$

where θ is the kick angle of the first kicker, β_{k} is the beta function at the first kicker, β_{s} is the beta function at the septum location between the two kickers, and μ is the betatron phase advance between the first kicker and the septum. The beta functions at the two kickers may not always be of the same value, and the kick angle of the second kicker is then different from that of the first kicker and adjusted to close the orbit bump. When the second kicker cannot be located at the phase advance of 180° (or its multiple), a third kicker is necessary to close the orbit bump.

The orbit bump excited by the kicker may not, in practice, be fully closed, despite being provided by design. Hence, the stored beam centroid is transversely misplaced. Such a beam disturbance (or transient) is minimized by tuning the kicker strengths. Additional kickers may also be installed to improve the closure of the orbit bump. It is noted that the bump closure deteriorates when sextupoles are located within the orbit bump, which distort the orbit bump through the off-axis field proportional to the horizontal position squared. Such a configuration should be avoided if at all possible.

The injection beam performs a betatron oscillation for many turns until damped through synchrotron radiation. The kicker bump must therefore be turned off before the injection beam hits the septum wall after a few turns, at which point the betatron phase advance at the septum approximately corresponds to a multiple of 360°.

Figure 3 shows the beams positions during the injection process; σ_{s} and σ_{i} are the r.m.s. beam sizes of the stored and injection beams, respectively, S is the septum wall thickness, and n_{s} and n_{i} are the clearances for the stored and injection beams, respectively, i.e., how much the beam centroids are separated from the septum wall in units of r.m.s. beam size.

It can be seen in Fig. 3 that the bump height of $2n_{\mathrm{i}}\sigma_{\mathrm{i}} + S$ and the separation of $n_{\mathrm{s}}\sigma_{\mathrm{s}} + S + n_{\mathrm{i}}\sigma_{\mathrm{i}}$ are required to achieve the given clearances. From the bottom figure, the machine aperture required to accept the injection beam particles within $n_{\mathrm{i}}\sigma_{\mathrm{i}}$ is found to be $n_{\mathrm{s}}\sigma_{\mathrm{s}} + S + 2n_{\mathrm{i}}\sigma_{\mathrm{i}}$. The injection beam size, σ_{i}, can be optimized to minimize the required machine aperture, or conversely to maximize n_{s} and n_{i} for a given machine aperture and septum thickness. Note that it is the injection beam shape in the betatron phase space (Twiss parameters) that is optimized [9], and not the beam size itself. The bump height may be set to a higher value so as to keep the septum away from the closed orbit, in order to, e.g., reduce the beam impedance due to the septum wall if needed.

Instead of placing the injection beam with a separation from the stored beam in the betatron phase

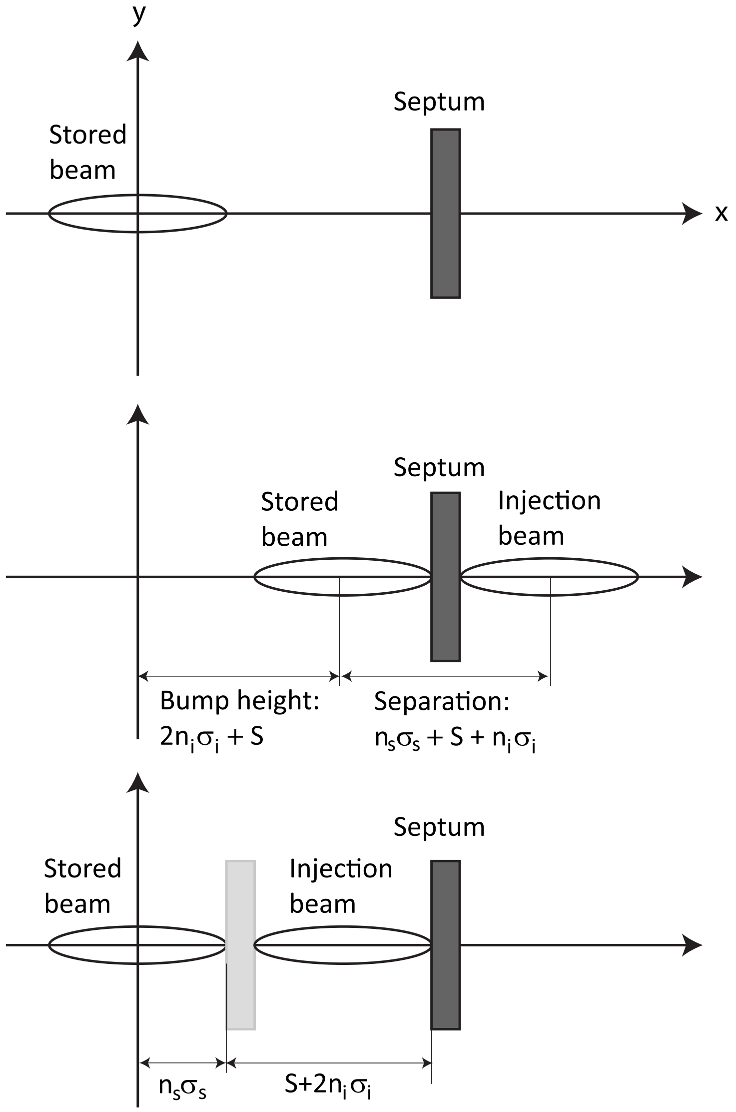

Fig. 3: Beam positions in real space at the exit of the septum: (top) during the injection process before the injection; (centre) at the time of injection with maximum bump height; (bottom) after the injection. The beam position after injection corresponds to the critical case, where the injected beam is closest to the septum, i.e., the number of turns multiplied by the fractional part of horizontal betatron tune is an integer. See text for symbols.

space, the beam energy can be slightly shifted, resulting in a separation in the longitudinal phase space. This alternative conventional injection scheme, *synchrotron phase space injection* [10], was applied to the LEP collider. The dispersion function at the septum location and the injection beam energy were adjusted such that the off-energy injection beam was placed in the corresponding off-energy closed orbit. Therefore, the injected beam performed a synchrotron oscillation rather than a betatron oscillation. The dispersion function at the collision points were essentially zero; thus, adverse radiation doses to the detectors were reduced. Moreover, a higher injection efficiency was achieved [10]. This is attributed to the fact that the injection efficiency may be less sensitive to the injection beam position and angle jitters, since the injection beam is placed transversely on-axis.

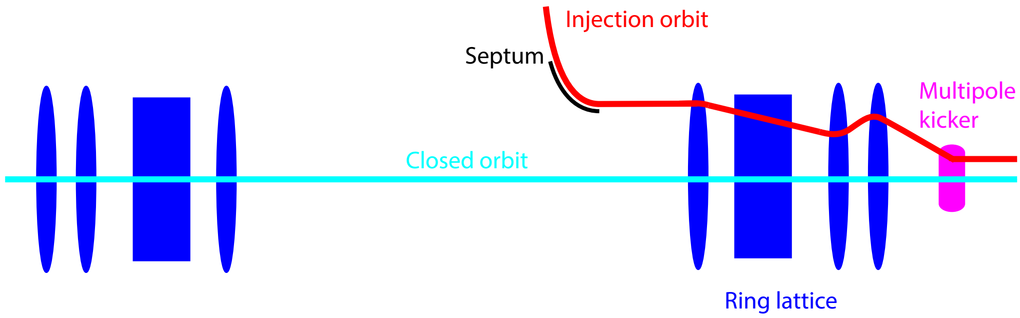

Fig. 4: Multipole kicker injection scheme

4.2 Multipole kicker injection

Multipole kicker injection [11] is developed with the motivation of eliminating the beam disturbance in the conventional scheme. A multipole kicker—quadrupole or higher multipole—excites a magnetic field proportional to x^n, where x is the horizontal position with respect to the magnetic axis of the kicker, and n is an integer: $n = 1$ represents quadrupole, $n = 2$ sextupole, and so on. Since the field is zero on-axis ($x = 0$), the stored beam centroid is not affected, whereas the injection beam passing through off-axis ($x \neq 0$) is deflected. The injection kicker must be turned off within one or a few revolutions in order not to kick the injection beam particles out of the machine aperture. Figure 4 shows the configuration of the injection devices and the beam orbits.

The disturbance to the stored beam is brought to higher order, depending on the kicker employed. A sextupole kicker may be the preferred choice; the disturbance arising from a quadrupole kicker may still be visible as a quadrupolar oscillation (beam size oscillation) while the field strength is rather limited in higher multipoles than sextupole.

The injection beam passing the kicker off-axis is defocused by the feed-down quadrupole components, which may potentially deteriorate the injection efficiency. A *non-linear kicker* that has a plateau in its field profile is proposed to avoid this issue. When the plateau covers the injection beam orbit, the injection beam receives approximately a dipole kick and is not defocused. At the same time, the region with zero or negligibly small field around the magnetic axis can be expanded in the non-linear kicker. It is, however, to be noted that the physical aperture of the non-linear kicker becomes smaller when the field plateau is brought closer to the axis. This may cause an aperture bottle-neck or beam impedance issues, and the plateau may not be set to overlap with the injection orbit in such cases. Figure 5 shows a non-linear kicker and typical field profile, compared with sextupole and octupole kicker profiles.

Like synchrotron phase space injection, a multipole kicker injection can be performed with off-energy injection beams. The dispersion function is adjusted at the location of the kicker, where the injection beam is placed in the corresponding off-energy closed orbit.

4.3 Resonance injection

The kicker in the conventional and multipole kicker injection schemes must be turned off after injection within a few revolution periods, as already discussed. In small rings, however, the fall time of the kicker cannot be so short. Resonance injection may be employed in such small rings (see e.g. Ref. [14]).

When the betatron tune is close to a resonance condition, the betatron phase space topology can be arranged such that the injected beam placed off-axis moves first towards the origin in the following turns and then gets away afterwards. The phase space topology can be varied during this movement, either by moving the working point away from the resonance condition or exciting the resonance less. The quadrupoles to control the tune or multipole magnets to control the resonance excitation are used as the injection kicker equivalently.

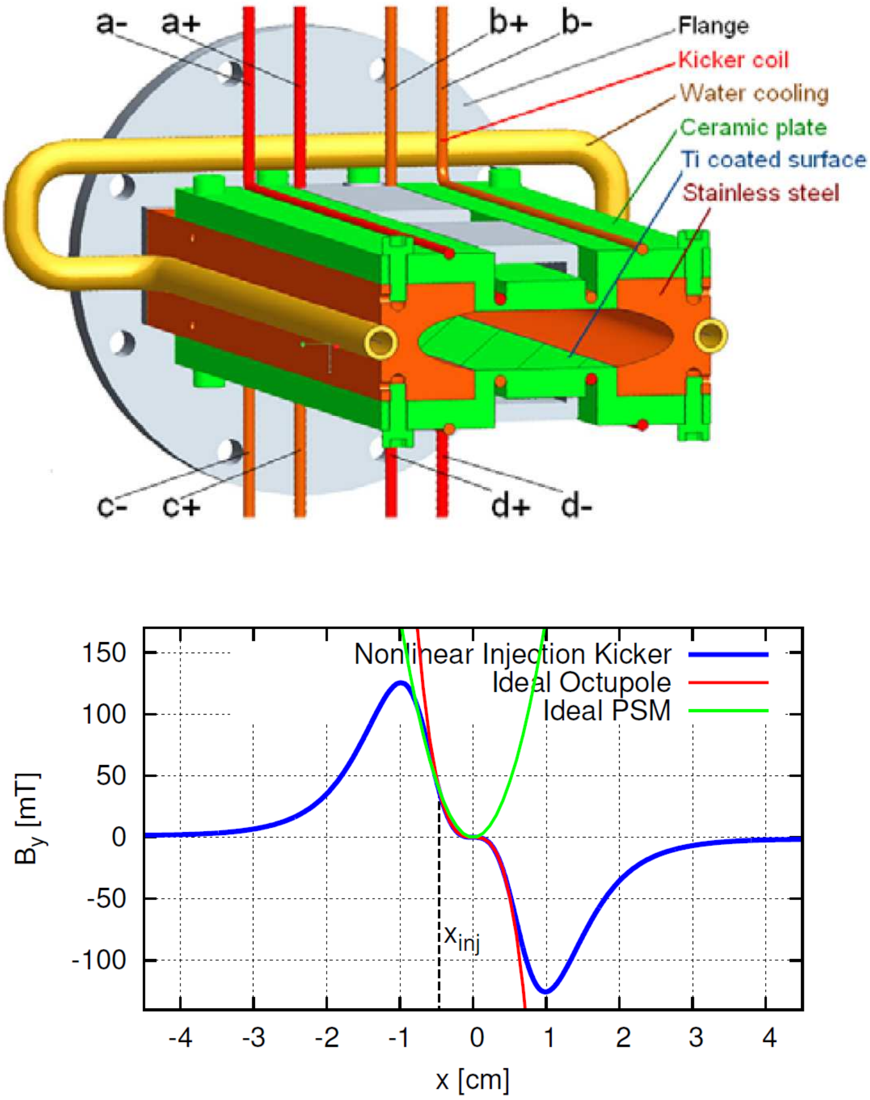

Fig. 5: Non-linear kicker [12] and its field profile [13] compared with sextupole and octupole kickers

4.4 Swap-out injection

For rings with a very small dynamic aperture, where the injected beam separated in the betatron phase space from the stored beam will be partly or fully lost, it is proposed to *swap out* the injection and stored beams [15]. The injection beam is prepared with the design charge and injected into the storage ring. At the same time, the stored beam that is missing a fraction of charge is kicked out from the storage ring.

Such a small aperture ring may be a consequence of aiming at the best performance of the accelerator, e.g., very small equilibrium emittance in a light source. To apply the aforementioned off-energy injections, where the off-energy injection beam is placed in the corresponding off-energy closed orbit (and thus accepted within the small aperture), a finite dispersion function at the septum or the kicker is required. It may be difficult, if not impossible, to realize this in the very low emittance ring. Swap-out injection, however, has no requirement on the dispersion function, since the stored beam is kicked out and the injection beam can then be injected into the nominal-energy closed orbit that *was* occupied by the stored beam.

Swapping-out is performed either bunch by bunch or bunch-train by bunch-train. The former re-

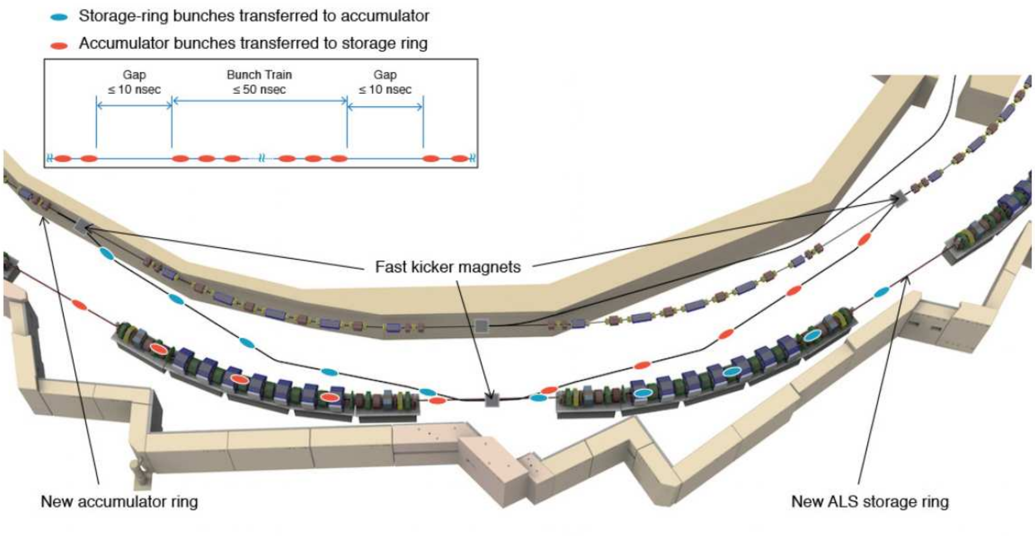

Fig. 6: Swap-out injection (bunch-train swapping) [16]

quires a short pulse kicker (shorter than twice the bunch spacing), which kicks out only one bunch and inserts the injection bunch. The latter may require an accumulator ring to prepare the injection beam and a flat-top kicker. The stored beam kicked out from the storage ring may be treated in various ways, e.g. re-injected into the accumulator ring for recycling or brought to a beam dump. Figure 6 shows the swap-out injection planned for the ALS upgrade project.

The injection kicker strength (kick angle) is adjusted to minimize or, ideally, eliminate the betatron oscillation of the injected beam. In the bunch-by-bunch swapping-out, the residual oscillation may hardly affect the photon beam of light source when the number of bunches in the storage ring is high. However, bunch-train swapping-out requires a stable flat-top kicker to minimize the oscillation.

4.5 Longitudinal injection

Longitudinal injection is also proposed for small aperture rings [17]. The injection beam energy is shifted, and the off-energy injection beam is placed in the corresponding off-energy closed orbit to fit the limited aperture by a dipole kicker. As in the swap-out injection, no requirement on the dispersion function is imposed. The injection timing is also shifted by a fraction of the RF period, typically one-half: the injection beam is inserted between two stored bunches (or two RF buckets). When the pulse length of the dipole kicker is shorter than the bunch spacing, the stored beam remains undisturbed.

Owing to the energy dependence of synchrotron radiation loss, there is a narrow channel of the longitudinal acceptance that extends to the space between RF buckets. An injection beam, with adjusted energy and timing, fitting this channel can be trapped into the RF bucket and merged to the stored beam.

Figure 7 shows the result of a tracking study, where the longitudinal injection scheme is applied to the MAX IV storage ring, equipped with a 100 MHz RF system. It is seen that the injection beam is trapped in the RF bucket and its synchrotron oscillation is almost damped at 18,000 turns (the radiation damping time is about 6900 turns). The injection efficiency strongly depends on the longitudinal injection beam emittance, since the injection beam should fit the narrow channel of the longitudinal acceptance. In this simulation, 100% injection efficiency was observed for the beams with small longitudinal emittance, generated by linac injector.

Most light sources are equipped with a 500 MHz RF system, requiring a kicker pulse length shorter than 2 ns. It is noted that such a short pulse kicker is technically challenging.

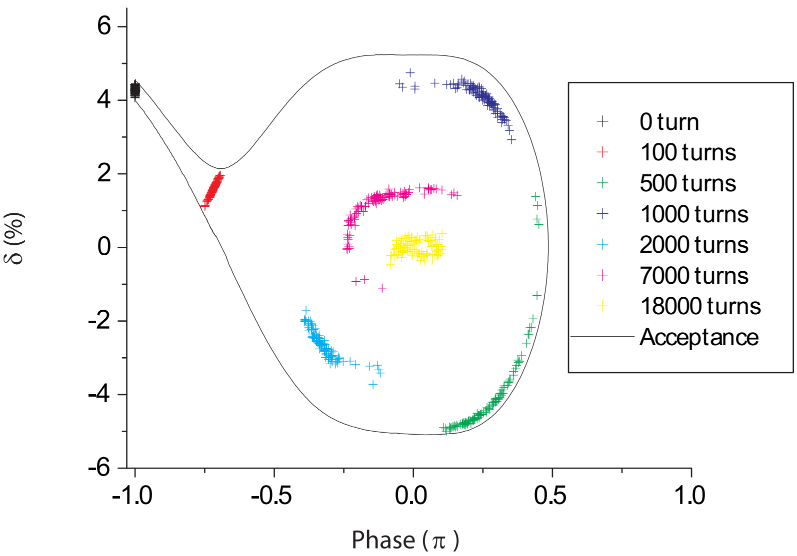

Fig. 7: Injected beam particles in longitudinal phase space, tracked through the MAX IV storage ring lattice up to 18,000 turns. The black solid line represents the longitudinal acceptance, taking into account the energy dependence of synchrotron radiation energy loss. The tracking is six-dimensional, including transverse planes.

Table 1: Top-up injection schemes

Injection scheme	Kicker	Separation
Conventional scheme	Kicker bump	Transverse position
Synchrotron phase space injection	Kicker bump	Beam energy[a]
Multipole kicker injection	Multipole or non-linear kicker	Transverse position
Multipole kicker injection, off-energy	Multipole or non-linear kicker	Beam energy[a]
Resonance injection	Multipole kicker	Transverse position
Swap-out injection	Dipole kicker[b]	Transverse position[c]
Longitudinal injection	Dipole kicker (short pulse)	Beam energy + timing

[a] The beam is also separated transversely at dispersive sections.

[b] Pulse length depends on whether swapping-out is performed bunch by bunch or bunch-train by bunch-train.

[c] Stored beam is kicked out.

4.6 Remarks

The top-up injection schemes described in Section 4 are summarized in Table 1. They are also categorized as off-axis injection or on-axis injection, depending on whether the separation is in betatron phase space (transverse position) or longitudinal phase space (beam energy and/or timing).

So far, the conventional injection scheme has been widely used in colliders and light sources. Among the new schemes, for instance, the multipole kicker injection has been used at the KEK-PF storage ring since 2011 [18] and also implemented in MAX IV as the design injection scheme [19]. The upgrade projects of APS [20] and ALS [21], and the HEPS project [22] are based on swap-out injection to enable beam injection into a small dynamic aperture. Longitudinal injection has been further studied, and possible variants or improvements are proposed [23, 24].

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