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REVIEW OF TOP-UP INJECTION SCHEMES FOR ELECTRON STORAGE RINGS

Masamitsu Aiba*, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

Abstract

Top-up operation, which nowadays is the norm for lepton colliders and synchrotron light sources, has been in continual development over the past few decades, resulting in a drastic improvement in the performance of accelerators. Future electron storage rings, which aim to further increase performance, are, however, designed to operate with strong nonlinear magnetic fields that may restrict their dynamic aperture. Consequently, conventional off-axis injection and accumulation may prove impossible. New injection schemes have therefore been proposed, with others under development, to overcome the expected difficulties and limitations associated with these machines. This paper reviews the various top-up injection schemes including recently proposed novel ideas.

INTRODUCTION

In earlier times, prior to establishing a new fill, beams in lepton colliders would be dumped once the total beam current fell below a critical value. It took some time to refill the machine and re-establish stable collisions, with inevitable detriment to the integrated luminosity.

In the 1980's, an improved operation mode, *Top-up-and-Coast* [1], was established in, e.g., PEP [2], wherein the beams were no longer dumped, but rather electrons and positrons were injected atop of the remaining stored beam, so as to compensate for the missing beam current. A full-energy injector was essential for this task. Although the physics detectors were required to be powered down during the injection phase to avoid possible damages, the turn-around time was effectively reduced. The injection was performed when the beam current dropped by typically about 30%, see, e.g., Fig. 7 of [2].

In the 2000's, the technique was further developed, mainly at the KEKB [3] and PEP colliders [4]. It then became possible to keep the physics detectors powered on during top-up injection, while providing a mask to the data acquisition during the relatively short injection period [4]. Without having to repeatedly power the detectors on and off, injection could be frequently enabled, and the beam current essentially kept constant.

Top-up injection was applied to SORTEC [5], for the first time to the light source, and it has since been applied in most modern light sources. The photon beam flux is thus stabilized as a consequence of the constant electron beam current. In addition, the transverse electron beam stability, which is equivalent to the photon beam stability, can also be increased by maintaining a steady synchrotron radiation heat load to the accelerator components. A summary of the historical development in light sources is found in [6] and references therein.

These first realizations of top-up injection utilized a septum and a dynamic *kicker bump* (a series of dipole kickers). 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 blade 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 within the inside of septum channel to the outside. Thanks to synchrotron radiation damping, the injected beam is merged into the stored beam after several damping times.

For the sake of clarification, top-up injection, top-off injection, trickle injection and continuous injection all refer to the same technique [4], with *top-up injection* being the most commonly used term. Furthermore, the described injection scheme is often referred to as the *conventional injection scheme*, not only because of the fact that it has been in use since a long time, but also because of the emergence of new injection schemes.

This paper gives an overview of top-up injection in lepton (electron/positron) colliders and synchrotron light sources.

DEMAND IN HIGH PERFORMANCE ACCELERATORS

The performance of colliders and light sources has vastly increased through top-up operation. However, it has been recognized that the conventional injection scheme has a few limitations or adverse effects.

Firstly, the orbit bump in the conventional injection scheme may not be fully closed, hence the stored beam is disturbed. The leakage of the bump is intrinsic where sextupole or higher multipole magnets are located, for unavoidable reasons, between the first and last kicker. Even when only linear elements are involved in the orbit bump, the bump may not be closed perfectly when the phase advance between kicker deviates from the design value and/or due to kicker imperfections, e.g., the kickers are not identical in temporal field profile. The disturbance (or transient) of electron/positron beam results in a deterioration of photon beam stability in light sources and might be an issue for colliders if it is significant. Some beamlines in the light source receive a trigger from the accelerator control system whenever injection occurs, and suspend data acquisition for this period. The same is true for the collider as discussed earlier. Our ultimate aim is to eliminate this disturbance altogether.

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* masamitsu.aiba@psi.ch

Secondly, the injected beam particles oscillate around the closed orbit (betatron oscillation) and require a large enough dynamic aperture. It has been recognized, especially within the light source community [7], that the dynamic aperture required for the top-up injection can be a bottleneck when a very high performance, i.e., the natural emittance of about 100 pm or less, is targeted in the next generation light source. In order to lower the emittance, it is efficient to introduce a large number of bending magnets with small deflection angles together with tight focusing to regulate the dispersion function at each bending magnet. To this end, storage rings based on *multi-bend achromat lattice* have been under intensive development. A drawback of small emittance is the limited dynamic aperture, since strong sextupoles have to be installed to correct chromaticity despite the low dispersion function. This is also true for colliders in general: the higher performance, the smaller the dynamic aperture will be, although a large fraction of chromaticity arises from collision optics which include very small beta functions at the collision point.

To overcome these issues, several injection schemes have been invented as described in the following.

TOP-UP INJECTION SCHEMES

This section describes injection schemes other than the conventional injection.

Synchrotron Phase Space Injection

Synchrotron phase space injection, a modified conventional injection, was examined at the LEP [8, 9]. In the conventional injection scheme, the injected beam is spatially separated from the stored beam with septum blade in between. This separation results in a betatron oscillation of injected beam. The injection beam energy is, in synchrotron phase space injection, shifted slightly, and finite dispersion function is introduced to the ring optics at the location of the septum such that the injection beam is placed onto the corresponding off-energy closed orbit. Such a configuration results in a synchrotron oscillation of injected beam but no betatron oscillation. This injection scheme was successful in two aspects:

- Higher injection efficiency was achieved.
- Adverse radiation doses to the physics detectors during injection period were lowered.

The former is attributed to the fact that (1) the synchrotron oscillation may be more robust than the (large amplitude) betatron oscillation and (2) the injection efficiency may be less sensitive to the injection beam position and angle jitters since the injection beam is placed transversely *on axis*. The lower radiation dose is then achieved as a consequence of the higher injection efficiency, but it is noted that the design dispersion at the detector is zero so that both stored beam and off-energy injected beam follow the vacuum chamber center. This scheme may be therefore preferable for lepton colliders.

Synchrotron phase space injection, requires a finite, but small dynamic aperture, (ultimately, barely accepting the injection beam) over a range of energy deviation, which corresponds to the synchrotron oscillation of the injected beam. The dynamic aperture limitation is consequently overcome. It is, however, difficult, if not impossible, to introduce a large enough dispersion function into the low-emittance multi-bend-achromat lattices of the next generation light sources, while the collider optics may, on the other hand, offer more flexibility.

Multipole Kicker Injection

Multipole kicker injection (MKI), has been proposed and developed at the KEK photon factory (PF) [10, 11], and is actually in use for user operation at the KEK PF ring [12]. A multipolekicker, e.g., sextupole kicker as in [11], is used as an injection kicker. Therefore, the stored beam centroid, passing through the kicker axis, is not deflected whereas the injection beam passing off-axis is deflected into the machine aperture. The primary goal of multipole kicker injection was to minimize disturbance to the stored beam. The minimization of disturbance was excellently demonstrated in [12]: the beam position and profile were measured during and after the injection period for the conventional injection and MKI. The measurement showed almost no movement of stored beam centroid with MKI.

MAX-IV is the first light source constructed based on a compact multi-bend achromat lattice (7 bend achromat) [13]. The dynamic aperture of MAX-IV is, however, still sufficient to apply the conventional injection scheme or multipole kicker injection. The latter is selected, and MAX-IV is the first machine, where MKI is incorporated at the design stage [14].

A pure multipole kicker with transverse field profile proportional to x^n, where x is the horizontal position and n is a natural number ($n = 1$ for quadrupole, $n = 2$ for sextupole etc.), strongly defocuses the injection beam. Depending on the parameters, such as septum thickness and available dynamic aperture, the injection efficiency may deteriorate due to defocusing. This can, to some extent, be dealt with by adjusting the injection beam parameters [15, 16]. Also, developments to the *nonlinear kicker* were undertaken with a field profile that is better than that of a pure multipole kicker, as will be later discussed in more detail.

Swap-out Injection

The dynamic aperture limitation may simply be overcome by swapping the stored beam and the injection beam: the injection beam is prepared with the design charge and injected into the storage ring, and at the same time, the stored beam that is missing a fraction of charge is kicked out from the storage ring. The required dynamic aperture is smallest in this *swap-out injection* [17, 18]: a dynamic aperture which barely accepts either the injected beam or stored beam, whichever has the larger emittance, is sufficient and an off-energy dynamic aperture is not required in contrast to the synchrotron phase space injection. Nevertheless, some off-energy dynamic aperture is still necessary to ensure a reasonable beam lifetime.

Swapping-out is performed either bunch by bunch or bunch-train by bunch-train. The former requires a short pulse kicker (shorter than twice the bunch spacing) which kicks out only one bunch and inserts the injection bunch. Such a bunch-by-bunch swap-out injection is planned for the APS upgrade [19]. The latter may require an accumulator ring to prepare the injection beam and a kicker with flat-top corresponding to the length of the bunch train. Swap-out injection with an accumulator ring is also planned for the ALS upgrade [20].

The stored beam extracted from the storage ring may be treated in various ways, brought to a beam dump, re-injected into the accumulator ring for recycling, etc. In principle, swap-out injection is also applicable to lepton colliders. However, it may not be practical at least for very high energy colliders [21].

The injection kicker deflection angle is adjusted to minimize or eliminate ideally the betatron oscillation of injected beam. In the bunch-by-bunch swapping-out, the residual oscillation may hardly affect the photon beam of a light source when the number of bunches in the storage ring is high. On the other hand, the fluctuation in kicker flat-top is reflected to the photon beam position stability in the bunch-train swap-out injection.

Longitudinal Injection

Yet another injection scheme, *longitudinal injection*, has been proposed [22]. The injection beam energy is shifted, and the off-energy injection beam is placed onto the corresponding off-energy closed orbit by a dipole kicker. It is noted that the dispersion function is not necessary in contrast to synchrotron phase space injection. The injection timing is also shifted by a fraction of the rf period, typically a half: the injection beam is inserted between two stored bunches (or two rf buckets). Due 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. When the pulse length of the dipole kicker is shorter than the bunch spacing, the injection is fully transparent to the stored beam.

The dynamic aperture requirement is qualitatively the same as that of the synchrotron phase space injection whereas quantitatively the injection beam energy offset (amplitude of injection beam synchrotron oscillation, in other words) may be larger in the longitudinal injection.

The longitudinal injection scheme was simulated for the MAX-IV storage ring, equipped with a 100 MHz rf system. It was shown that the injection beam was trapped into the rf bucket and its synchrotron oscillation was damped after a few radiation damping times [22]. 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 the above simulation, 100% injection efficiency was observed for the beams with small longitudinal emittance, generated by a linac injector.

The necessity of small longitudinal emittance can be practically removed by applying rf gymnastics with two rf systems of fundamental and second harmonic frequencies [23, 24]. The second harmonic cavity creates rf buckets between the ones from the fundamental frequency rf. The injection beam with nominal energy can be injected into these newly created empty rf buckets. Afterwards, the phases and voltages of two rf systems are varied to merge the injected bunch into the stored bunch. Such a bunch merging (and conversely splitting) technique is well established in hadron machines, see, e.g., [25] and references therein. It is noted that the bunch length is significantly varied during the rf gymnastics, which potentially is an issue of instabilities.

Third harmonic cavity is widely used in light sources to prolong the bunch and thus increasing instability threshold. When a higher harmonic cavity, e.g., 2nd harmonic, in addition to 3rd harmonic cavity is employed, the bunch can be further prolonged. The rf bucket is then largely expanded toward the space between bunches. Therefore, a bunch can be injected between two stored bunches and still within the bucket [26]. The necessity of small longitudinal emittance is then removed as in the bunch merging approach, and moreover no rf gymnastic is involved in this case.

One more interesting approach, improving the longitudinal injection, has been proposed for the SOLEIL upgrade [27]. The fraction of bucket area occupied by the stored bunch is rather small. Therefore, the rf bucket shape can be modified by varying the fundamental and 3rd harmonic cavity phases and voltages, keeping the potential of synchrotron oscillation constant locally around the stored beam bunch. The modification of rf bucket is performed so as to quickly damp the injected beam synchrotron oscillation. This may be explained as an analogy to transverse resonance injection where multipole and/or quadrupole magnets are utilized to control the particle trajectory in the transverse phase space. Similarly, the third harmonic cavity together with the fundamental cavity is used here, as a *longitudinal nonlinear kicker*, to control the particle trajectory in the longitudinal space.

CATEGORIZATION

The previous section presented a number of top-up injection schemes. A breakdown of these schemes into their beam dynamics components would serve to facilitate our present understanding and to stimulate future proposals.

Firstly, the injection beam should be separated in phase space from the stored beam at the time of injection (this is referred to as *separation* in the following), for it cannot overlap with the stored beam according to Liouville's theorem, although it is merged to the stored beam later through synchrotron radiation damping.

Secondly, there are various types of kicker available for injection. The injection schemes reviewed in the last section

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can be regarded as a variety of combinations of the separation and kicker type to be used.

In the conventional injection and MKI, the separation is in the transverse plane whereas it is in the longitudinal plane in synchrotron phase space injection and longitudinal injections. However, the separation in MKI can be also in the longitudinal plane [28]. This requires a finite dispersion function at the kicker (not at a septum as in synchrotron phase space injection) such that the injection beam is deflected by a multipole kicker and put onto the off-energy orbit.

Regarding the injection scheme using longitudinal nonlinear kicker previously described, it has also been proposed to combine this with the off-energy multipole kicker injection. Although, in the low-emittance multi-bend-achromat lattice, the dispersion function cannot be so large [27], it may be covered by a rather larger energy offset. Due to the fact that the injected beam synchrotron oscillation is quickly damped, the injection efficiency can be high enough even for the injected beam with an initial large energy offset. In this combination, the short pulse kicker, which is not straightforward for 352 MHz rf used in SOLEIL and 500 MHz rf commonly in light sources, can be replaced by a multipole kicker while overcoming the dynamic aperture limitation by the feature of longitudinal injection.

Table 1 lists the injection schemes together with their features to summarize this section. The schemes with a separation in the transverse plane, resulting in a betatron oscillation of injection beam, is often referred to as *off-axis injections* and with a separation in the longitudinal plane (beam energy and/or rf phase), resulting in a synchrotron oscillation of injection beam, as *on-axis injections*.

Kicker and Septum Developments

Kicker developments have been intensively conducted for top-up injection as well as for beam injection and extraction in general.

Short pulse kicker is necessary for bunch-by-bunch swap-out injection and longitudinal injections. The pulse length of kicker needs to be on the order of 10 ns or even shorter than 10 ns, depending on the rf frequency. Many research and developments in this field have been performed as found in [29–32], and more literature may be found elsewhere.

In order to improve MKI, *nonlinear kicker* has been developed [33], aiming at a wider region with zero/small field around the axis and zero/small gradient at the location where the injection beam passes. The former is to be more transparent for the stored beam, and the latter is to avoid defocusing the injection beam. It consists of several conductors (typically eight) to realize such a field profile. A nonlinear kicker has been tested at BESSY-II, and has been installed into MAX-IV.

Another type of kicker has been proposed recently for MKI [34]. It consists of two C-shaped (ferrite) dipole kickers, which are facing each other, with a copper plate in-between. The copper plate suppresses the fringe field of dipole kickers with an eddy current induced on its surface. The two dipole kickers can be excited oppositely such that dipole, sextupoles and higher components are excited [21], or similarly with quadrupole, octupole and higher components [34]. The dipole or quadrupole component can be suppressed by narrowing the gap of dipole kicker. However, the gap tends to be too small for a full suppression. Additional kickers/conductors are likely required to suppress dipole/quadrupole component for a kicker with reasonable geometry. Nevertheless, this type of kicker can easily provide a wide plateau in the profile for the injection beam.

Anti-septum has been proposed, for the upgrade of SLS, to enable the conventional injection even with a small dynamic aperture [35]. In the SLS, four bump kickers are all placed in one straight section. The third kicker, placed right downstream of the septum, deflects both stored and injection beam. When the third kicker field is masked around the injection beam orbit with a metal conductor, the injection beam is not deflected. The field masking virtually generates a septum field inside the kicker. The septum blade of an ordinary eddy-current septum is suppressing the field outside of the injection beam channel whereas, in the above configuration, the conductor is suppressing the field inside the injection beam channel. The septum thickness (thickness of masking conductor) can be thinner than that of an ordinary septum since the kicker excitation pulse is much shorter than the septum one. Moreover, the stray field leaking to the injection beam channel, which is induced after the injection beam passes, is irrelevant.

INJECTOR

Apart from, or in addition to, new injection schemes, efforts may be applied to the injector to lower the injection beam emittance. A full energy linac injector is normally capable of generating injection beams with smaller emittances than those of an injector synchrotron. There is a trend that light source facilities build a linac based free electron laser at the same site. The newly built linac could be used as an injector to existing light sources provided the beam energy is sufficient. For instance, a new beam transport line was built to connect SACLA and SPring-8 to utilize the SACLA linac as an injector [36]. Another example is MAX-IV facility, where 1.5-GeV and 3-GeV rings are both filled with a linac, which is designed to serve as an injector and as an FEL linac at the same time [13]

The horizontal emittance of injection beam from an injector synchrotron can be significantly reduced through a transverse emittance exchange [37]. The vertical emittance is normally one or more order of magnitudes smaller than in the horizontal plane. An emittance exchange can be performed in the injector synchrotron using coupling resonance or possibly in the transfer line from the injector to the storage ring.

SUMMARY

An overview of top-up injection schemes has been presented. New injection schemes have been developed both to overcome the weaknesses and limitations of the conventional

Table 1: Summary of Injection Schemes

Injection Scheme	Separation	Kicker Type	Dispersion Requirement
Conventional injection	Transverse	Kicker bump	None (Zero at septum)
Synch. phase space inj.	Beam energy	Kicker bump	Finite at Septum
Multipole kicker inj.	Transverse	Multipole/Nonlinear kicker	None
MKI, off-energy	Beam energy	Multipole/Nonlienar kicker	Finite at kicker
Swap-out injection,	Transverse	Short/Long pulse (dipole) kicker	None
Long. inj.	Beam energy and RF phase	Short pulse kicker	None
Long. inj., 2 rf	RF phase	Short pulse kicker	None
Long. inj., 3 rf	RF phase	Short pulse kicker	None
Long. inj., long. NLK	Beam energy and RF phase	Multipole/Short-pulse kicker	None

injection, as revealed through the experiences of numerous machines, and to fulfill the stringent demands being imposed by the new generation accelerators. A number of kicker and septum developments are underway to support and/or improve these new injection schemes. The various injection schemes have been categorized according to their components to facilitate a systematic understanding and instigate future proposals. A welcome reduction in the emittance of the injection beam can also be achieved through alternative injector systems.

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