

# LONGITUDINAL TOP-UP INJECTION FOR SMALL APERTURE STORAGE RINGS

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## Abstract

Future light sources aim at achieving a diffraction limited photon beam both in the horizontal and vertical planes. Small magnet apertures and high magnet gradients of a corresponding ultra-low emittance lattice may restrict physical and dynamic aperture of the storage ring such that off-axis injection and accumulation may become impossible. We investigate a longitudinal injection, i.e. injecting an electron bunch onto the closed orbit with a time-offset with respect to the circulating bunches. The injected bunch will be merged to a circulating bunch thanks to longitudinal damping.

## INTRODUCTION

The performance of light sources has been progressively approaching one of its ultimate goals, i.e. achieving a double plane diffraction limited photon beam. The fundamental approach for this is lowering the transverse beam emittances to tens of pico-meters. A storage ring realising such ultra-low emittances is normally composed of quadrupoles with rather high gradient, and thus the available physical aperture decreases. The dynamic aperture as well may become small because of strong sextupoles necessary to compensate for the chromatic effects arising from those strong quadrupoles.

At the same time, one of the most important features of light sources is high stability of the photon beam. The so-called top-up injection is incorporated in most third generation light sources, where a frequent beam injection on top of the circulating bunches is carried out to keep the electron beam current essentially constant. The relative current fluctuation is within a small range (dead-band) of the order of  $10^{-3}$ . Our primary goal is therefore to establish a top-up on-axis injection scheme, which is transparent to the circulating bunches.

The conventional injection scheme for electron storage rings employs a static septum and a dynamic, magnetic chicane. The latter rises and falls within several electron beam revolutions to bring the closed orbit to the vicinity of the septum at the time of injection. The injected bunch is spatially separate from the circulating bunches, and thus it is referred to as off-axis injection. It is noted that, though this scheme is in principle transparent to the circulating bunches, the magnetic chicane unfortunately introduces detectable disturbances to the photon beam even when intensive efforts are made to close the orbit bump.

Another important goal is therefore to avoid an inclusion of the injection chicane for the photon beam stability. Moreover, the straight section can then be

utilised for an accommodation of one more beamline instead of the injection chicane.

The conventional injection scheme can be improved to be an on-axis injection when the injection chicane is situated in a dispersive section [1]. This improved scheme achieves the primary goal but still requires the injection chicane.

An injection scheme utilising a multipole kicker and avoiding a magnetic chicane has been proposed and tested [2]. The injected bunch passes through a pulsed multipole magnet off-axis while the circulating bunches pass through the centre. Therefore, the disturbance to the circulating bunches is significantly suppressed. The scheme is compatible with top-up injection. It is, however, an off-axis injection by definition.

It has been proposed in [3] to swap the circulating bunches for full current bunches bunch-by-bunch or even the entire bunch train at one time when the beam current decreases below a threshold of the top-up injection. In such a swap injection scheme, the prepared bunches can be injected onto the closed orbit by kicking out the circulating bunches occupying the on-axis phase space volume.

One of the disadvantages in the bunch-by-bunch swapping is that a full charge injector is required. The dead-band would be larger than that of normal top-up injection since it may not be straightforward to generate full charge injection bunches with small bunch charge fluctuation. In addition, the bunch train swapping requires another ring to store the beam and keep it ready for swapping. Given the higher initial construction cost of the facility and significant increase in electricity consumption during operation, this option is not so attractive.

Instead we propose a *longitudinal injection* scheme, where the injected bunch is separate longitudinally, i.e. injected with a time-offset, from the circulating bunches and it is transversely on-axis injection.

## LONGITUDINAL INJECTION SCHEME

The longitudinal motion in an electron storage ring can be described with the following equations of motion:

$$\frac{dz}{dt} = -c\alpha\delta, \quad (1)$$

and

$$\frac{d\delta}{dt} = \frac{eV-U}{ET_0}, \quad (2)$$

where  $z$  is the longitudinal coordinate with respect to the reference particle with the nominal momentum,  $c$  is the speed of light,  $\alpha$  is the momentum compaction factor of the storage ring,  $\delta$  is the relative momentum deviation,  $e$  is the electron charge,  $E$  is the nominal beam energy,  $T_0$  is

the revolution period,  $V$  is the rf voltage, and  $U$  is the energy loss per turn due to synchrotron radiation. The operation point of electron storage rings is normally above transition, and thus  $\alpha$  is positive. The synchronous phase is lower than 180 degrees because of the synchrotron radiation loss. The reference particle with the nominal momentum of the ring is considered to stay at the synchronous phase, where the synchrotron radiation loss equals the energy gain from the rf field. It is noted that the relative momentum deviation can be approximated by the relative energy deviation for relativistic beams.

The second equation contains higher order terms ( $\delta^2$  and  $\delta^3$ ) because the synchrotron radiation loss is proportional to third power of the energy for a ring with an isotropic bending field. A numerical integration of these equations still allows us to draw longitudinal phase space topologies (Fig. 1).

One sees in Fig. 1 that the acceptance phase space plot has the shape of a “golf-club” with its “shaft” extending towards the neighbouring bucket. It is well known that such a golf-club shape appears when the rf-acceleration is taken into account (see e.g. [4]). In this case, it originates from the synchrotron radiation loss and the energy recovery from the rf field.

When the height and width of the tilted shaft is sufficient for the energy and time spread of the bunch generated by an injector, one can inject it at a point equidistant to two circulating bunches at the expense of a slightly higher energy from the injector. The injected bunch will be merged into the circulating bunch thanks to the longitudinal synchrotron radiation damping.

Since the injected bunch can be separate longitudinally from the circulating bunches, it can be injected on-axis transversely with a pulsed *dipole kicker* as in a common fast injection. When the pulse length of the kicker is shorter than the bunch separation, the kicker field is fully transparent to the circulating bunches, fulfilling our goal.

## APPLICATION TO MAX-IV 3 GEV RING

We present an application of the longitudinal injection scheme to the MAX-IV 3 GeV storage ring [5]. The relevant parameters are summarised in Table 1. We used the Elegant code [6] and a lattice with two damping wigglers [7] for our investigation.

The rf voltage is chosen to realise a bucket height of ~5% including a bunch prolongation due to a third harmonic cavity. We assume that the normalised rms transverse emittance of the injected beam is 10  $\mu\text{m}$  (corresponding to a geometrical emittance of 1.7 nm at 3 GeV) in both planes, a relative energy spread of 0.1% and a bunch length of 5 ps. These values are taken from Ref. [8]. Since the MAX-IV injector linac is planned to be used also for driving a free electron laser (FEL) [8], the energy and timing jitter must be negligibly small.

The above described bunch is injected with a time offset of -5 ns (the middle of two circulating bunches), and a relative energy offset of +4.3%.

The following random machine errors have been introduced to investigate the robustness of the longitudinal injection scheme:

- sextupole vertical misalignments of 50  $\mu\text{m}$  rms and quadrupole roll errors of 0.2 mrad rms, exciting linear coupling resonances
- beta-beating of 3~6% rms through quadrupole gradient errors, exciting normal resonances
- sextupole and octupole roll errors of 0.2 mrad rms, exciting skew resonances

The bunch is injected with a transverse offset of -0.5 mm with respect to the closed orbit at the middle of straight section, where the horizontal and vertical beta functions are ~9 m and ~2 m, respectively.

We generated 40 machines with different random error distributions and confirmed an injection efficiency of 100% for those except for one case with 95% efficiency. Figure 2 shows one of the simulation results, the particle distributions in the longitudinal and the transverse planes.

Finally, we present a fast injection orbit with two short pulse kickers (Fig. 3). An orbit separation about 10 mm is achieved with a kick of 1.8 mrad each, allowing a use of a common magnetic septum.

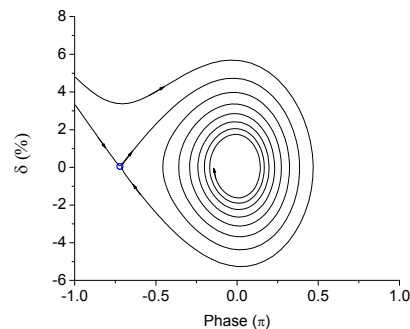


Figure 1: Longitudinal acceptance with synchrotron radiation loss. The origin of phase corresponds to the synchronous phase. This example is for the synchronous phase of 155 degrees and the bucket height of 5% (without damping). The blue open circle corresponds to an unstable fixed point.

Table 1: MAX-IV 3 GeV Ring Parameters with two Damping Wigglers. It is noted that the values are from our Elegant simulation [7].

Parameter	Value	Unit
Circumference	528	m
Beam energy	3.0	GeV
Momentum compaction	$3.07 \times 10^{-4}$	-
Radiation loss per turn	0.58	MeV
Damping time, Hor./Ver./Longi.	12 / 18 / 12	ms
RF frequency	100	MHz
RF voltage (Fundamental/3HC)	1.42 / 0.423	MV
Hor. equilibrium emittance	0.25	nm
Betatron tune, Hor./Ver.	40.20 / 16.28	-

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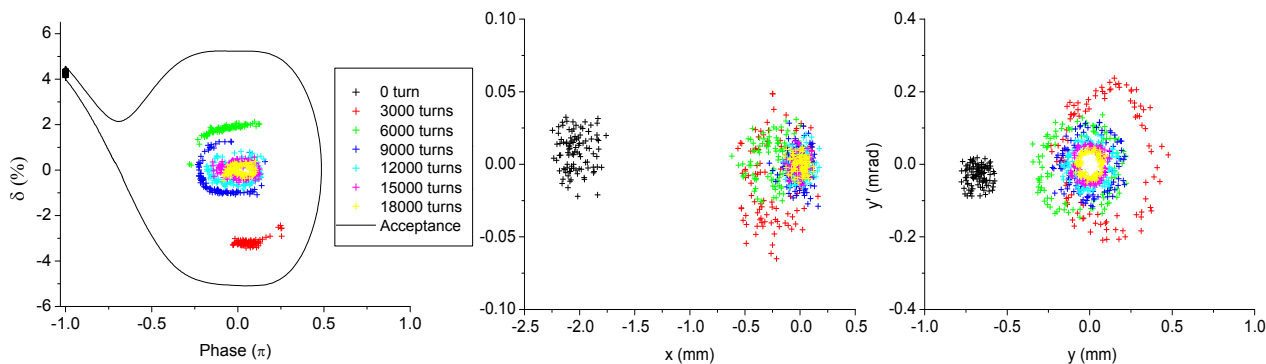


Figure 2: Particle distribution in the longitudinal (left) and transverse planes (centre and right) up to 18000 turns. Tracking result with machine errors (see text). The closed orbit for the off-momentum injected beam (4.3%) is horizontally/vertically shifted by -1.4/-0.2 mm due to higher order dispersion terms and the introduced machine error.

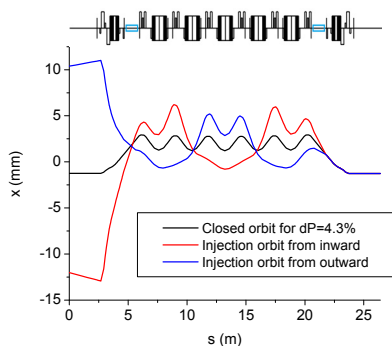


Figure 3: Fast injection orbit with two short pulse kickers (1.8 mrad each). Blue boxes in the schematic lattice layout correspond to the location of the kickers.

## DISCUSSION

We find from the simulations that the injection scheme works with reasonable machine errors. This is consistent with the fact that the multipole magnets are properly located and tuned in the lattice to ensure the necessary dynamic aperture [9]. Light source storage rings should be capable to accept Touscheck scattered particles so as to realise a reasonable beam lifetime. Therefore the dynamic aperture necessary for the longitudinal injection is not an additional requirement but a pre-requisite for the storage ring for user operation.

One technical challenge in the longitudinal injection scheme is the short pulse kicker used to situate the injected bunch on-axis. It is noted that the pulse length should be about the bunch spacing while, in a bunch-by-bunch swapping injection, it can be about twice the bunch spacing. There are a few strip-line type kickers in operation whose pulse length are short enough for an rf system of 100 MHz [10, 11]. Sufficient kick angle (1.8 mrad at ~3GeV for MAX-IV case) can be obtained by optimizing the geometry of the strip-lines.

The rf frequency of MAX-IV 3 GeV ring was selected, taking into account higher order mode issues, initial cost, ease of operation and so on [5]. On the other hand, it excludes time-resolved experiments. In the future, some of these experiments may move to FEL facilities, but

others may stay at 3rd generation light sources. The proposed injection scheme is presently available only for rings with a low frequency rf. Research and development of “nano-second kicker”, with a pulse length of ~1 ns, is necessary to adapt the injection scheme to rings with a common 500 MHz rf system. Nowadays, a pulser capable to generate such a very short pulse is commercially available, and such a kicker may be technically feasible.

## SUMMARY

We presented a new injection scheme for small aperture electron storage rings. The injection scheme is on-axis transversely and transparent to the circulating bunches, and thus compatible with a top-up injection.

## ACKNOWLEDGEMENTS

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