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SYNCHROTRON ACCUMULATION ON OFF-ENERGY CLOSED-ORBIT WITH ANTI-SEPTUM OR NONLINEAR KICKER*

Yipeng Sun†, ANL, Argonne, IL 60439, USA

Abstract

Off-axis accumulation on off-energy closed-orbit (so-called synchrotron injection/accumulation) was studied and implemented in the 1990s for LEP [1] at CERN. The idea of using pulsed multipole injection on off-energy closed-orbit was first proposed in 2014 [2] and then developed for Swiss Light Source (SLS) upgrade in 2015 [3]. In 2017, the anti-septum [4] was proposed for SLS upgrade injection. In this paper, two similar injection schemes are proposed which combine off-axis accumulation on off-energy closed-orbit (no betatron oscillations), with the anti-septum or pulsed nonlinear kicker schemes. Preliminary lattice solutions are developed for Advanced Photon Source upgrade (APS-U) [5] where a special injection straight (with length of 5.8 m) is designed with horizontal dispersion of 0.15m. The impact on the ring emittance is relatively small. The injection elements are all placed in this injection straight, including 1 thin septum and 3 slow kickers (or 1 pulsed nonlinear kicker). No fast kickers are needed.

INTRODUCTION

Typically, transverse accumulation is achieved in storage rings with a 4-kicker-bump plus septums, which requires large dynamic acceptance (DA). Even with a closed bump for stored beam, it generates transient effects on stored beam during top-up operations due to kicker timing errors, waveform imperfections, and other effects. For next-generation storage rings with small round (or horizontal) insertion device (ID) apertures, this scheme is harder to implement. It may be possible to employ small-β IDs to host narrow IDs, and provide large-β insertions to host septums. Nonlinear beam dynamics performance is then more challenging due to greatly reduced symmetry in the linear optics.

For next-generation storage rings with small round/horizontal IDs, the DA is smaller and limited by physical apertures. Alternative injection schemes are proposed to accomodate this. The swap-out scheme [5–7] replaces a whole bunch by a fresh full-charge bunch, but needs very fast kickers and high bunch charge from the injectors. Longitudinal accumulation at RF bucket edge [8] may need lower frequency RF for a longer RF bucket, and requires even faster kickers than swap-out scheme to only kick the injected bunch between two adjacent RF buckets.

Transverse accumulation with pulsed multipole injection kickers [9, 10] (pulsed nonlinear kicker) was first implemented at Photon Factory (PF) of KEK from 2007, which worked well for top-up operation mode with reduced transient effects on photon users.

For presently operating storage rings, the motivations to study injection schemes may include achieving injection which is transparent to photon users during top-up mode and improving injection efficiency. It is also important to find workable schemes for future synchrotron light sources, with smaller emittance, smaller DA, and possible narrower ID apertures in both vertical and horizontal planes.

SYNCHROTRON INJECTION ON OFF-ENERGY CLOSED-ORBIT

Synchrotron injection [1] was studied and implemented in the 1990s for LEP (Large Electron–Positron Collider) at CERN, with 20-GeV injected beams and a 27-km circumference. Synchrotron accumulation [1] on off-energy (-0.6% energy offset) closed-orbit was achieved with good efficiency (6 mm separation between stored and injected beam). The second injection kicker (3-kicker-bump) and thin septum are located in the arc section with high dispersion [1].

The idea of using pulsed multipole injection of off-energy electron beam (on off-energy closed-orbit) was first proposed in 2014 [2], with promising simulation results presented for SLS upgrade in 2015 [3]. Similar as the multipole injection scheme in [11], the off-energy injected beam performs betatron ocsillations (after passing the septum) in some arc sections with strong quadrupoles/sextupoles magnets, which is then kicked on the closed orbit by two pulsed multipole magnets (located in arc dispersive regions) [3].

In this paper similar schemes are proposed with specific high dispersion (D_x=0.15 m) injection section designed at ID straight, where the off-energy injected bunch does not need to perform any betatron ocsillations.

SYNCHROTRON ACCUMULATION ON OFF-ENERGY CLOSED-ORBIT WITH PULSED NONLINEAR KICKER

Off-axis accumulation on off-energy closed-orbit with pulsed nonlinear kicker [2, 3] is another option for accumulation, with the following features compared to swap out: needs only one nonlinear kicker (placed at large dispersion location) plus septums; no requirement for high charge injectors; no need for fast kickers; no need for a swap-out dump; similar DA requirement as swap-out; transparent or small impacts to stored beam with high charge; low charge injected bunch has large dispersive orbit (only in dispersive regions), which may be prefered by collective effects.

Figure 1 shows the scheme, using the APS-U lattice [5] as an example. The following assumptions are made: 1.0-

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† yisun@aps.anl.gov

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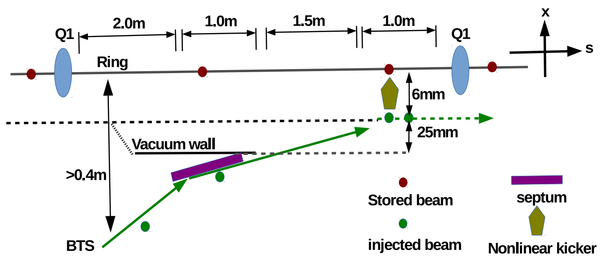

Figure 1: Sketch for synchrotron accumulation on off-energy closed-orbit with a single pulsed nonlinear kicker. APS-U example in one 5.8 m insertion.

m long 0.3 T in-vacuum pulsed nonlinear kicker [12] giving a 15 mrad kick. 6 mm separation in x between stored and injected beam at nonlinear kicker; 1.5 m between nonlinear kicker and septum; 1.0-2.0 m thin septum (150 mrad kick), strong superconducting magnet, 30 mm separation in x at septum end; 1.0-2.0 m distance from septum to first quad magnet, larger than 0.4 m clearance in x.

OFF-ENERGY SYNCHROTRON ACCUMULATION WITH ANTI-SEPTUM

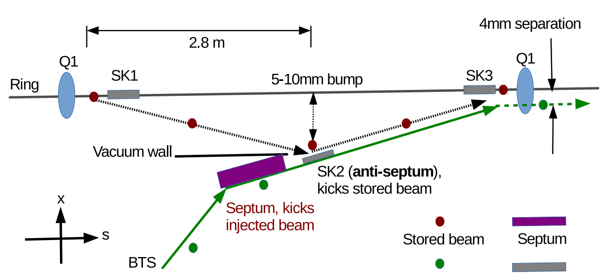

Figure 2: Sketch for synchrotron accumulation on off-energy closed-orbit with anti-septum [4] in 3-slow-kicker scheme. APS-U example in one 5.8 m ID.

Anti-septum scheme [4] was recently proposed for the SLS upgrade injection systems [4]. The so-called anti-septum (the second kicker in a 3-slow-kicker scheme as shown in Figure 2) only kicks the stored beam, since its magnetic field is shielded from the injected beam [4]. By employing a residual horizontal angle (after septum, before anti-septum end) between the stored- and injected-beam's longitudinal direction of motion, it is possible to reduce the minimum horizontal separation between these two beams, from nominally more than 5mm to less than 3mm [4]. Another benefit is that only 2 kickers and 1 anti-septum are required instead of 4 kickers, which saves some space.

Here we propose an injection scheme that combines synchrotron accumulation on off-energy closed-orbit (as in LEP [1]), with anti-septum scheme. Figure 2 illustrates the concept in a way appropriate to the APS-U lattice. The following assumptions are made: 3-kicker-bump with 5-10mm bump height in x; 2nd slow-kicker (SK2) serving as anti-septum; 2-4mm separation between stored beam and injected beam, after SK2, with the same separation after SK3.

LATTICE SOLUTIONS FOR BOTH SCHEMES

The requirement on the position and angle (relative to stored beam) of injected beam is (at injection point, which is the end of anti-septum, or pulsed nonlinear kicker for single nonlinear kicker accumulation scheme) listed below.

$$X_{inj} = D_x \cdot \frac{\Delta p}{p} + D_{x(2)} \cdot \left(\frac{\Delta p}{p}\right)^2 + ... \quad (1)$$

$$X'_{inj} = D'_x \cdot \frac{\Delta p}{p} + D'_{x(2)} \cdot \left(\frac{\Delta p}{p}\right)^2 + ... \quad (2)$$

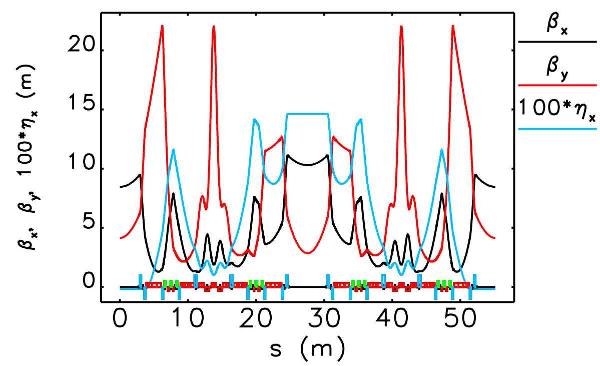

Figure 3: High horizontal dispersion (D_x=0.15 m) injection ID. Blue blocks represent quadrupoles, red blocks represent dipoles, and green blocks represent sextupoles.

It may be hard to place the injection elements inside arc, since there is no space available and dispersion may not be large enough. The injection section will be placed in one special straight section (with length of 5.8 m), where the horizontal dispersion is increased from zero to 0.15 m. The chicane or dogleg beamlines can not be employed here, as they are not compatible with the low emittance requirement. The linear optics solution is shown in Figure 3 with two modified sectors, where the magnet lengths and drift space lengths are identical to the original APS-U 42pm lattice [5]. The matching variables are the gradients in all the quadrupoles and transverse gradient dipoles. Only 2 sectors out of total 40 sectors are modified. The design of the transverse gradient dipoles may need some modifications in these 2 sectors near the injection straight.

Figure 4 shows two alternating-beta [13] APS-U storage ring sectors, plus these 2 sectors near the injection straight. The APS-U storage ring is composed of 38 nominal alternating-beta sectors plus these 2 injection sectors. The dispersion is zero at all other 39 IDs. The effective ring emittance is increased from 42 pm [5] to 58 pm (at 39 nominal IDs), with these 2 injection sectors. The lattice solution works for off-energy synchrotron accumulation with either

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pulsed nonlinear kicker or anti-septum schemes as shown in Figure 1 and Figure 2.

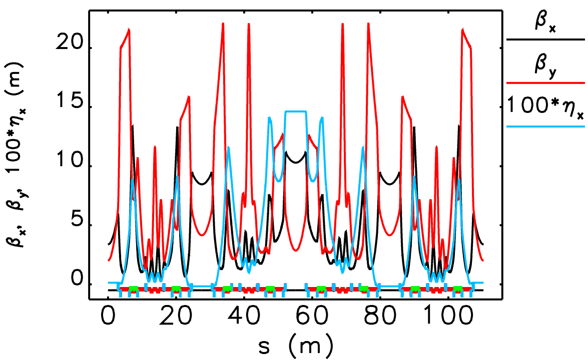

Figure 4: Two alternating-beta APS-U storage ring sectors, plus these 2 sectors near the injection ID straight.

SIMULATIONS

The injection simulation results shown here are applicable for both nonlinear kicker or anti-septum schemes, assuming that the off-energy injected beam is on closed-orbit at the injection point (nonlinear kicker or anti-septum).

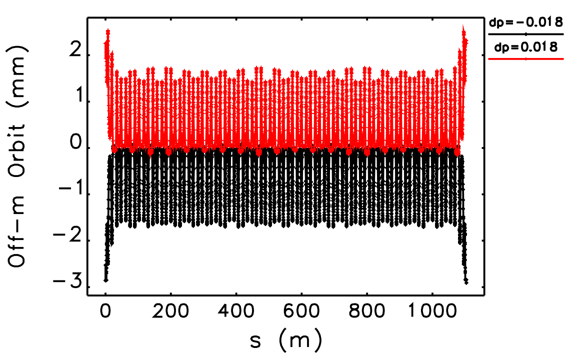

Figure 5: Off-energy closed-orbit of beam with energy offset of ±1.8%. Starting point is injection ID center.

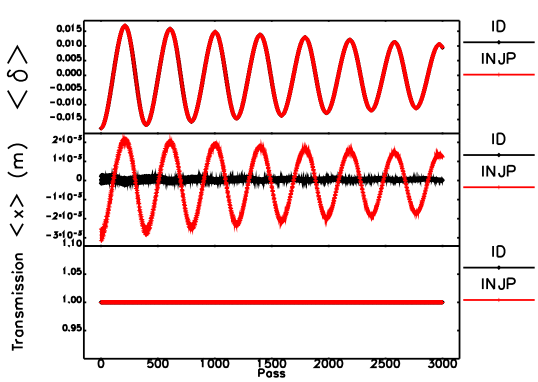

Figure 6: Bunch centroid and transmission parameters. ID: nominal ID; INJP: injection ID (D_x=0.15 m).

The nonlinear optics of the lattice with a special injection straight is still under development. For demonstration of the synchrotron accumulation on off-energy closed-orbit scheme, two families of symmetric sextupoles are employed to correct the chromaticity to 1. The off-energy closed-orbit is shown in Figure 5 for positive and negative energy offsets. Note here second order disperison $D_{x(2)}$ is negative (-1 m) which introduces larger orbit for negative energy offset. The evolution of the injected bunch (with energy offset of -1.8%) is shown in Figure 6. For a pencil beam there is no beam loss. The energy offset and horizontal displacement (initial value of -3 mm, on off-energy closed orbit) of the injected bunch are damped in 3000 turns.

CONCLUSIONS

Schemes for synchrotron accumulation on off-energy closed-orbit were further developed, with possible lattice solutions for APS-U presented in this paper. No fast kickers are needed. The injection section is placed in one special ID straight (with a length of 5.8 m), where the horizontal dispersion is increased to 0.15 m. The effective APS-U ring emittance is increased from 42 pm to 58 pm (at 39 nominal IDs). Off-energy accumulation was illustrated with an energy offset of -1.8%. This lattice solution may work for synchrotron accumulation with either pulsed nonlinear kicker, anti-septum, or original LEP scheme. Applying this lattice solution to storage rings with less number of sectors may introduce relatively larger emittance increasement.

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