ON-AXIS BEAM ACCUMULATION ENABLED BY PHASE ADJUSTMENT OF A DOUBLE-FREQUENCY RF SYSTEM FOR DIFFRACTION-LIMITED STORAGE RINGS*

Gang Xu†, Jinhui Chen, Zhe Duan, Jing Qiu,
Key Laboratory of Particle Acceleration Physics and Technology, Institute of High
Energy Physics, Chinese Academy of Sciences, 100049 Beijing, China

Abstract

Future synchrotron light sources aim to achieve ultra-low emittances on both transverse planes, approaching or even reaching the diffraction limit of X-ray photon energies. These diffraction-limited storage rings (DLSRs) feature very strong lattice nonlinearities and thus very small dynamic aperture, which exclude off-axis injection schemes. In this paper, we propose a longitudinal on-axis injection scheme, which is based on a double-frequency RF system and independently adjustment of the RF phase of each cavity to enable RF gymnastics. Such a scheme looks feasible with the state-of-art technology of fast injection kicker. Comparison with other on-axis injection schemes is also discussed.

Table 1: HEPS Parameters [2]

Parameter	Value
circumference C(m)	1295.616
beam energy E_b(GeV)	6
beam current I_0(mA)	200
natural emittance ϵ_0(pm)	59.4
betatron tunes ν_x/ν_y	116.155/41.172
momentum compaction α_c	3.74×10^{-5}
rms energy spread σ_ϵ	7.97×10^{-4}
harmonic number h_f/h_h	720/2160
SR energy loss U_0(MeV/turn) [2]	1.995
damping times(ms) $\tau_x/\tau_y/\tau_s$	18.97/25.99/15.95

INTRODUCTION

Next generation synchrotron light sources aim to approach the ultimate performance of storage rings, i.e., to generate double-plane diffraction-limited photon beams. These diffraction-limit storage rings normally adopt multi-bend achromat (MBA) cells [1] in the lattice design, and utilize high-gradient quadrupoles to achieve the ultra-low beam emittances of tens of picometers. Therefore, very strong sextupoles are required to compensate for the large natural chromaticities and thus lead to great challenges in optimization of the dynamic aperture (DA) and the momentum aperture (MA). Take the High Energy Photon Source (HEPS, its major parameters are listed in Table 1) for example, a recent lattice design has achieved a natural emittance of 59.4 pm, while an effective DA of 2.5 mm (horizontal) and 3.5 mm (vertical) and an effective MA of 3.0% are obtained with great effort[1] [2]. Such a small DA is not enough for traditional off-axis injection schemes, which typically requires a DA of the order of 10 mm. Dedicated injection sections with large β-functions could be accommodated in the lattice, however, an enlarged DA for off-axis injection could only be achieved at the expense of a reduced MA, therefore, the overall optimization of a lattice for off-axis injection is still a great challenge.

There are several on-axis injection schemes that could possibly meet the need of these DLSRs. The on-axis swap-out injection scheme [3] looks promising and has been adopted by APS-U [7] and ALS-II [8], but a full-charge injector is essential and the proper treatment of the dumped beam needs a serious consideration. Aiba et al. [4] proposed the longitudinal injection with a shifted phase and a little higher energy compared to the circulating beam, which is a clever idea, but requires a large MA and stringent control of phase and energy jitters. Jiang et al. [5] proposed to use an active double-frequency RF system (RF frequency of 250 MHz and 500 MHz, respectively in the case of SSRF-U [6]) to facilitate on-axis beam accumulation. They alter RF voltages to conduct the RF gymnastics, to create empty buckets well separated from the main buckets to enable on-axis injection, and then in reverse process to merge the injected bunches longitudinally to the main RF buckets. This scheme doesn't require a large MA, and it also relaxes the tolerances of phase and energy jitters.

Inspired by these on-axis injection schemes, we proposed a new injection scheme based on phase adjustment of an active double-frequency RF system. In this paper, we'll first describe a complete injection cycle in our scheme with an application in HEPS, then make an comparison with other on-axis injection schemes.

A COMPLETE INJECTION CYCLE

Without synchrotron radiation, a particle's longitudinal motion with a double-RF system is described by the Hamil-

---

* Work supported by NSFC (11475200 and Y4113G005C).

† xug@ihep.ac.cn

[1] The "effective" DA (or MA) means the boundary within which, not only particles survive in the ideal lattice tracking, but also the amplitude-dependent tunes are bounded by the nearest integer and half-integer resonances of the zero-amplitude tunes.

[2] Insertion devices are not included.

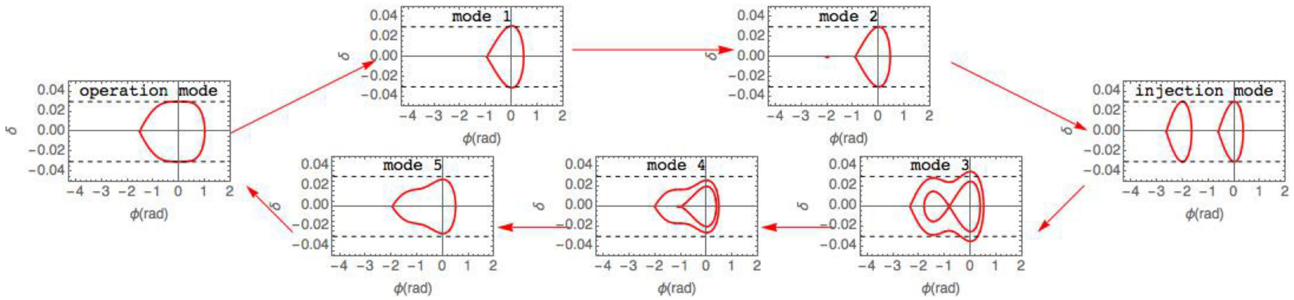

Figure 1: RF gymnastics in a complete injection cycle.

tonian

$$H(\phi,\delta;t) = \frac{h_f\omega_0\eta}{2}\delta^2 + \frac{\omega_0}{\pi E_b \beta^2}\left[\sum_{i=1}^{N_f} V_f^i\cos(\phi+\phi_f^i) + \frac{h_f}{h_h}\sum_{j=1}^{N_h} V_h^j\cos(\frac{h_h}{h_f}*\phi+\phi_h^j) + \phi U_0\right], \qquad (1)$$

where ϕ and δ are a pair of canonical variables with respect to the time variable t, $\omega_0 = 2\pi c/C$ is the angular revolution frequency of the synchronous particle, γ is the relativistic factor, $\eta = \alpha_c - 1/\gamma^2$, $\beta = \sqrt{1-\gamma^2}$. Assume there are N_f fundamental cavities of harmonic number h_f and N_h harmonic cavities of harmonic number h_h, V_f^i and V_h^j are the voltages of i-th fundamental cavity and j-th harmonic cavity, respectively; ϕ_f^i and ϕ_h^j are the phase angles of the synchronous particle relative to i-th fundamental cavity and j-th harmonic cavity, respectively. To simplify the treatment, four equivalent RF parameters $(V_f, V_h, \phi_f, \phi_h)$ can be defined as

$$\begin{aligned} V_f\cos(\phi+\phi_f) &= \sum_{i=1}^{N_f} V_f^i\cos(\phi+\phi_f^i) \\ V_h\cos(\frac{h_h}{h_f}*\phi+\phi_h) &= \sum_{j=1}^{N_h} V_h^j\cos(\frac{h_h}{h_f}*\phi+\phi_h^j), (2) \end{aligned}$$

If we can independently control the phase angle with respect to each cavity, and there are multiple cavities of each frequency, we can then knob the four equivalent RF parameters to do the RF gymnastics. For a specified set of number, height, and width of buckets, as well as the distance between two bucket center, the equivalent RF parameters can be numerically solved, via analysis of the above Hamiltonian.

The evolution of RF buckets within a fundamental RF period in a complete injection cycle is illustrated in Fig. 1. The parameters of a recent HEPS design [2] are used in this calculation, the double-RF system consists of 166.67 MHz fundamental RF cavities and 500 MHz third harmonic cavities. The “operation mode” corresponds to the settings during the routine operation, it is favored to set the parameters of active RF systems such that the electron bunches are optimally lengthened. As a result, the beam lifetime is increased, the IBS effect and some collective instabilities are also alleviated. On the other hand, we need to generate a second RF bucket near each existing bucket in the operation mode for on-axis accumulation. This is called the “injection mode”. Also shown in the figure are 5 intermediate modes, and a complete injection cycle is realized by ramp the cavity phases between the settings of each two adjacent modes.

When an injection cycle starts, the bunch length of the circulating beam shrinks, as the single RF bucket containing circulating beam varies from the operation mode to “mode 1”. Then, another small bucket emerges to the left of the existing bucket as in “mode 2”. After that, the empty bucket becomes larger and more distant from the bucket of circulating beam, and finally the injection mode is set up for on-axis beam accumulation. The phase ramp from the operation mode to the injection mode can be very fast, since the center of a circulating bunch remains fixed in position during this process and no synchrotron oscillation of the beam center is excited, the total time cost is determined by the time constant of the RF phase control loop and RF cavities’ filling time, which is on the order of tens of milliseconds.

At the injection mode, the electron beam pulse from booster is injected on-axis into the storage ring, but possibly with an initial synchrotron oscillation amplitude, it normally takes several damping times for the injected particles to damp down.

After the injection completes, the two separate buckets get closer and closer and finally become connected as in “mode 3”, and then the bucket of injected beam shrinks in size and gradually reach the critical state as in “mode 4”, and then disappears as in “mode 5”. At the meantime, the injected particles gradually escape from the left small bucket and are bounded by the outer bucket. From the injection mode to “mode 5”, it is expected to take several damping times to ensure the injected particles are safely merged to the bucket containing the circulating beam. Then it is favored to stay in “mode 5” for another several damping times such that the large amplitude synchrotron oscillation of injected particles are damped down. When the injected particles are fully merged into the circulating beam, one can launch a fast phase ramp to the operation mode, and this ends an injection cycle.

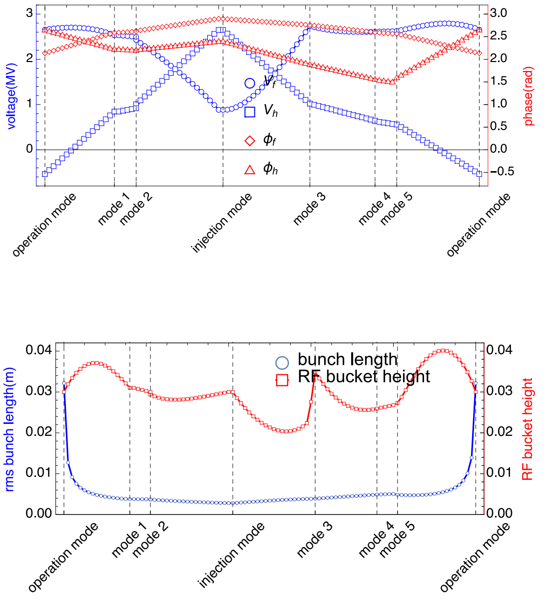

Figure 2: The upper figure shows the evolution of the effective RF parameters, and the lower figure shows the evolution of rms bunch length and RF bucket height of circulating beam, in an injection cycle. Note that the distances between different modes do not reflect the actual time used.

The evolution of effective RF voltages and phases, as well as bunch length and RF bucket height for circulating bunches is shown in Fig. 2. Note that the bunch length shrinks from 32 mm in the operation mode to 2.8 mm in the injection mode, and about 10% increase of emittances is expected due to the intra-beam scattering, which will surely disturb the user experiments. Following the convention of existing light sources, the beamline users can select to gate out the disturbed data collected during injection. Since a whole injection cycle takes only several damping times, and repeats every several minutes, the effect on user experiments is expected to be small. For the same reason, the beam loss due to a reduced beam lifetime in an injection cycle is negligible. Nevertheless, possible beam instability issues with the shortened bunch length are still under study.

COMPARISON WITH OTHER ON-AXIS INJECTION SCHEMES

These on-axis injection schemes all require fast injection kickers, with a pulse full duration and a rise time of a few nanoseconds, these requirements can be fulfilled with a series of stripline injection kickers [9] driven by fast pulse generators [10]. The pulse full duration is specified by the bunch spacing, while a smaller rise time requires more pieces of kickers driven by more pulse generators and hence a higher cost. Figure 3 shows that our scheme allows a longer kicker rise time compared to Aiba's scheme [4], taking into account the 3% MA of the recent HEPS design. Compared to Jiang's injection scheme [5], our scheme features more independent knobs, which enables a more flexible control of the buckets in the longitudinal phase space. In particular, the circulating bunches are centered in fixed positions throughout an injection cycle and the particles neither experience large amplitude synchrotron oscillations, nor even are split during new bunch formation as in Jiang's scheme [5]. In addition, RF voltage adjustment takes seconds [5] while RF phase adjustment takes milliseconds, our scheme costs less injection time comparably.

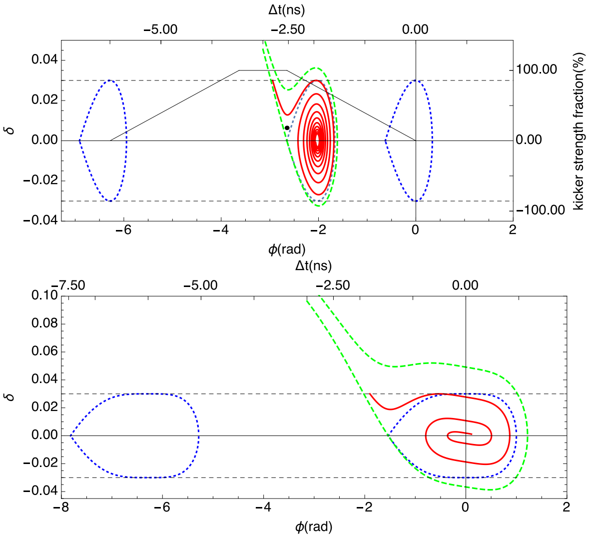

Figure 3: Longitudinal phase space of the injection mode (upper figure) and the operation mode (lower figure). Blue dotted lines are the static buckets while green dashed lines are the buckets in presence of radiation damping [4]. In the presence of radiation damping, a particle trajectory with $\delta_{\max} = 3\%$ is depicted in red. Note that particles with $\delta_{\max}$ larger than the lattice MA will get lost during injection. In the upper figure, the black dot indicates a typical phase space point $(\phi, \delta) = (-2.65, 0.006)$ to inject the beam, and the black lines schematically show an ideal trapezoidal kicker pulse, its full duration is approximately 6 ns, and its rise time (from 0% to 100% of the kicker strength) is about 2.5 ns. In contrast, in the lower figure, the maximum allowed kicker rise time is about 1.8 ns.

CONCLUSION

We proposed a new on-axis injection scheme based on a double-RF system suitable for DLSRs. A complete injection cycle was detailed explained, and comparison with other on-axis injection schemes was discussed. Tolerances of lattice and injection system errors, as well as possible collective effects during injection are still under study, and will be reported in a future publication.

We thank Bocheng Jiang, Yi Jiao, Daheng Ji, Yi Sun, Jianping Dai and Jiyuan Zhai for helpful discussions.

REFERENCES

[1] D. Einfeld, M. Plesko, and J. Schaper, “First multi-bend achromat lattice consideration,” J. Synchrotron Radiat., vol. 21, no. 5, pp. 856–861, Sep. 2014.

[2] G. Xu, et al.,“Recent Design Studies for the High Energy Photon Source”, presented at IPAC’16, Busan, Korea, May 2016, WEPOW026.

[3] L. Emery and M. Borland, Proceedings of PAC’03, Portland, OR, USA, 2003, pp. 256–258.

[4] M. Aiba, et al., “Longitudinal injection scheme using short pulse kicker for small aperture electron storage rings,” Phys. Rev. ST Accel. Beams, vol. 18, no. 2, p. 020701, Feb. 2015.

[5] B. C. Jiang, et al., “Using a double-frequency RF system to facilitate on-axis beam accumulation in a storage ring,” Nucl. Instrum. Meth. A, vol. 814, pp. 1–5, Apr. 2016.

[6] S.Q. Tian, et al., Proceedings of IPAC’2015, Richmond, VA, USA, 2015, pp. 304-306.

[7] M. Borland, et al., “Lattice design challenges for fourth-generation storage-ring light sources,” J Synchrotron Radiat., vol. 21, no. 5, pp. 912–936, Sep. 2014.

[8] H. Tarawneh, et al., “ALS-II, a Potential Soft X-ray, Diffraction Limited Upgrade of the Advanced Light Source,” J. Phys.: Conf. Ser., vol. 493, no. 1, p. 012020, 2014.

[9] B. I. Grishanov, et al., “Very fast kicker with high repetition rate for accelerator applications,” Nucl. Instrum. Meth. A, vol. 396, no. 1–2, pp. 28–34, Sep. 1997.

[10] V. M. Efanov, et al., “Fast ionization dynistor (FID)-a new semiconductor superpower closing switch,” in Proceedings of 11th IEEE International Pulsed Power Conference, Baltimore, USA, 1997, vol. 2, pp. 988–991. For latest FID products, refer to http://www.fidtechnology.com.

ISBN 978-3-95450-147-2