TOP-UP INJECTION SCHEMES FOR HEPS*

Z. Duan†, J. Chen, Y. Jiao, Y. Peng, Q. Wang, G. Xu, and P. Zhang
Key Laboratory of Particle Acceleration Physics and Technology,
Institute of High Energy Physics, Chinese Academy of Sciences,
Beijing, China

Abstract

Top-up injection has become standard mode of operation for most third generation light sources, and has also been succesfully applied in electron-positron circular colliders like KEKB and PEP-II. For next generation ultra-low emittance storage rings approaching the diffraction limit of X-rays, take the High Energy Photon Source (HEPS) for example, top-up injection is a basic requirement but non-trivial to implement. The very small dynamic aperture is insufficient for traditional off-axis injection scheme, instead, a novel on-axis injection scheme was recently proposed for HEPS, based on RF gymnastics of a double-frequency RF system. This paper will describe the physical mechanism of this scheme, related RF issues and the implications for top-up injection.

INTRODUCTION

First implemented in APS [1] and SLS [2] for user exmperiments, top-up injection has become standard mode of operation in most third generation light sources. Frequent beam injection ensures the relative beam current fluctuation within a few 10^{-3}, which significantly improves the photon beam stability and efficiency in user exmperiments. This mode of operation was also realized in electron-positron circular colliders KEKB [3] and PEP-II [4], which greatly enhanced the average luminosity and the almost constant beam current made luminosity tuning much easier.

With these success in existing machines, top-up injection is considered to be a basic requirement in the design of next generation electron (positron) storage rings, but this also brings new challenges. In particular, in the next generation synchrotron light sources with ultra-low emittances approaching the diffraction limit of X-rays, the implementation of top-up injection is somewhat non-trivial.

These diffraction-limit storage rings normally adopt multibend achromat (MBA) cells [5] in the lattice design, and utilize high-gradient quadrupoles to achieve a ultra-low beam natural emittance 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 nominal 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] [6]. Such a small DA is insufficient for traditional off-axis injection schemes, which typically requires a DA on the order of 10 mm. Therefore, we have to seek alternative on-axis injection schemes.

Inspired by various on-axis injection schemes [7–9] suitable for ultra-low emittance storage rings, we proposed a new injection scheme based on RF gymnastics of an active double-frequency RF system [10] and applied it in HEPS. In this paper, the physical mechanism of this injection scheme will be overviewed, followed by the discussion on the control of RF cavities, finally implications for top-up injection will also be presented.

Table 1: HEPS Parameters [6]

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

PHYSICAL MECHANISM OF THE INJECTION SCHEME

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

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

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, e is the electron charge, γ is the relativistic factor, $\eta = \alpha_c - 1/\gamma^2$,

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† duanz@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 nominal tunes.
[2] Insertion devices are not included.

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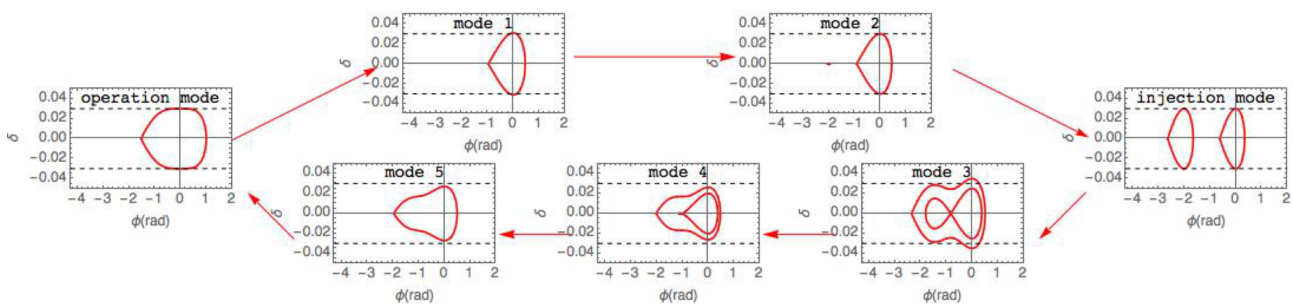

Figure 1: RF gymnastics in a complete injection cycle.

$\beta = \sqrt{1-\gamma^2}$. 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. In fact, from the perspective of low-level RF control, both the voltage and phase of an RF cavity can be varied very fast, with a response time of tens of μs. Therefore, to simplify the treatment, we assume cavities of the same frequency share the same setting, and both the voltages and phases are manipulated in the injection, the Hamiltonian can be simplified as

$$H(\phi,\delta;t) = \frac{h_f\omega_0\eta}{2}\delta^2 + \frac{e\omega_0}{2\pi E_b\beta^2}\Big[N_f V_f\cos(\phi+\phi_f) + \frac{h_f}{h_h}N_h V_h\cos(\frac{h_h}{h_f}*\phi+\phi_h) + \phi\frac{U_0}{e}\Big], \tag{2}$$

where $(V_f, V_h, \phi_f, \phi_h)$ are four free knobs in the design of an injection cycle.

The evolution of RF buckets in a complete injection cycle is illustrated in Fig. 1. The parameters of a nominal design of HEPS [6] are used in this calculation, the double-RF system consists of four 166.6 MHz fundamental RF cavities and two 499.8 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 ramping the four RF knobs between the settings of each two adjacent modes, the evolution of RF parameters is shown in Fig. 2. Note that the bunch length varies a lot, from 32 mm in the operation mode to 2.8 mm in the injection mode, and about 10% increase of beam size is expected due to the intra-beam scattering, which will surely disturb the user experiments. The concrete impact to user experiments is being evaluated and will be presented elsewhere. Moreover, there might be some beam instability issues at the injection

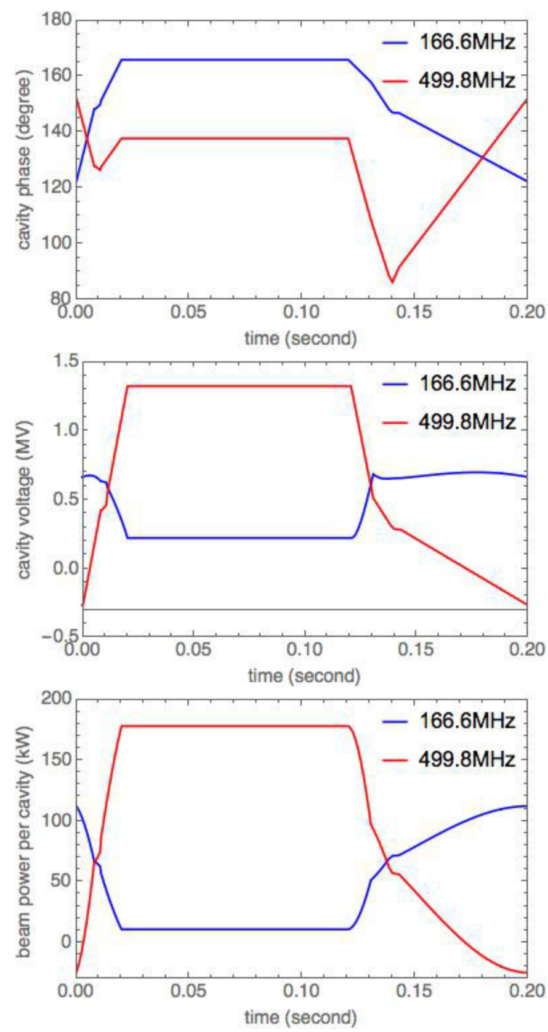

Figure 2: The upper and middle and lower figures show the evolution of RF phases, voltages and beam power per cavity in a complete injection cycle, respectively. Note that beam loading effects and other sources of power consumption are not included in the beam power calculation.

condition due to the very short bunch length, which is also under investigation.

Such an on-axis injection scheme requires the full pulse width of the injection kicker system to be smaller than bunch spacing of the storage ring (6 ns for HEPS), and the kicker pulse fall time to be smaller than the time lag between the injection and circulating bunches in the injection mode (about 2.5 ns for HEPS). These stringent requirements can be realized by stripline kicker systems [11] driven by high voltage fast pulsers [12]. Unfortunately, the readiness of superconducting RF cavities of higher frequencies meets with the technology difficulty in obtaining even faster injection kicker. Therefore, the choice of fundamental RF frequency is a compromise with the choice of injection kicker parameters. Currently, 166.6 MHz superconducting RF cavity and ultra-fast injection kicker are under extensive R&D at IHEP.

RF ISSUES

As illustrated in the previous section, we assumed a complete injection cycle would take 200 ms, and each ramp step would take about 500 µs. Then the question arises that if the low level RF system can cope with such a fast ramping scenario. Table 2 shows the major parameters of the RF cavities. For each cavity, its coupling parameter and tuning angle are chosen so that there is no reflected power when its beam power is at the maximum value.

Table 2: RF Cavity Parameters

Parameter	fundamental RF cavity	harmonic RF cavity
frequency (MHz)	166.6	499.8
number of cavities	4	2
quality factor Q_0	5×10^8	1×10^9
geometric shunt impedance R/Q (Ω)	135.8	93.5
maximum beam power per cavity (kW)	112.2	178.0
cavity voltage at maximum beam power per cavity (MV)	0.66	1.32
coupling parameter β	17293.4	9490.9
loaded quality factor Q_{load}	28912.8	105364
cavity filling time (μs)	55	67
optimal tuning angle ψ(degree)	-32.3	-47.8

The low level RF system controls the frequency, amplitude and phase of cavity fields. The latency in control of amplitude and phase can be controlled within tens of microseconds, similar to the cavity filling times. However, the latency of frequency control depends on the type of tuner. Mechanical tuners with a stepper motor normally provide a tuning range of hundreds of kHz at the expense of a slow response on the level of seconds; fast acting piezoelectric tuners can act very fast (in milliseconds) but have limited dynamic range, for example, only about 6 kHz for the 500 MHz superconducting RF cavities in BEPCII. In a complete injection cycle, keeping an optimal tuning angle requires a frequency control range beyond the reach of piezoelectric tuner. As a result, we assume the frequencies of RF cavities are kept fixed according to the setting in Table 2. Then, the incident and reflected RF power for each cavity can be calculated via

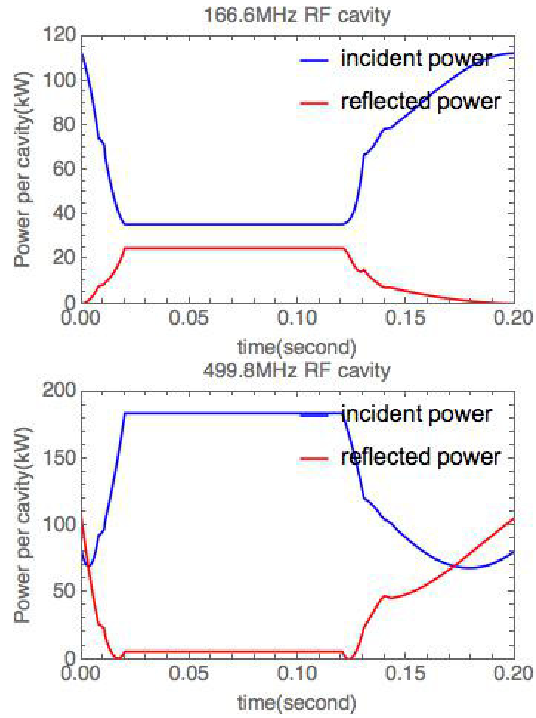

Figure 3: The two plots show incident and reflected RF power of each fundamental and harmonic cavity in a complete injection cycle, respectively.

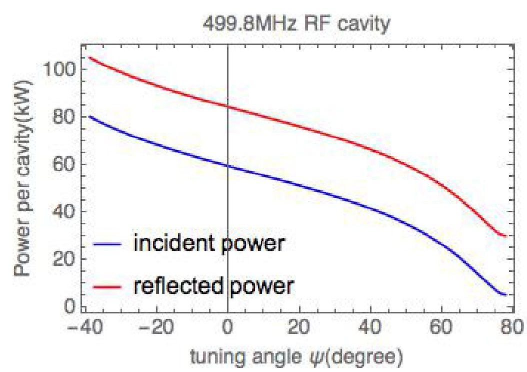

Figure 4: The incident and reflected RF power of a 499.8 MHz cavity versus differnt tuning angles.

$$P_{\pm} = \frac{\beta V_c^2}{8R_s}[(1 \pm \frac{1}{\beta} \pm \frac{2R_s I_0}{\beta V_c} \cos\hat{\phi})^2 + (\tan\psi + \frac{2R_s I_0}{\beta V_c} \sin\hat{\phi})^2], \quad (3)$$

where $P_{\pm}$ denotes the incident and reflected power, respectively, phase $\hat{\phi}$ follows the phasor convention and is related to RF phase in ring dynamics convention via $\cos\hat{\phi} = \sin\phi$. The calculated incident and reflected power of each cavity

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are shown in Fig. 3. The incident and reflected powers of the harmonic cavities are quite large at the operation condition, which can be alleviated by ramping the tuning angles to the optimal value for the operation mode using mechanical tuners, as illustrated in Fig. 4, while keeping the voltage and phase fixed. If mechanical tuners can reach the required 18 kHz frequency shift within a few seconds, then ramping the tuning angle before and after each injection cycle will help reduce the power consumption during operation significantly.

TOP-UP INJECTION FOR HEPS

Different from off-axis injection schemes, the time structure of the high voltage pulser driving the injection kicker has a large impact on the design of the injector chain and the operation mode of top-up injection. A qualified pulser model from FID GmbH [13] runs in a bursting mode. As

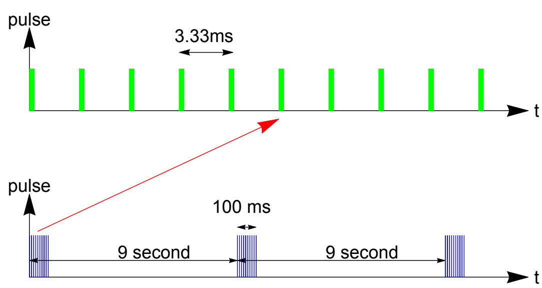

Figure 5: Time structure of the injection kicker pulse.

shown in Fig. 5, a burst pulse has a duration of 100 ms and repeats every 9 s, the spacing between adjacent micro-pulse is 3.33 ms. Therefore, at each injection, a bunch train of no more than 30 bunches following the same time structure can be extracted from the booster and injected into the main ring. To simplify the design, the circumference of the booster is selected to be 1/3 of that of the main ring, and the RF frequency of the booster is 3 times that of the main ring. Since 3.33 ms is much larger than the revolution period, the timing system is capable of selecting a specified bunch to extract from the booster and inject into the corresponding bucket of the main ring. The booster power supply is capable of

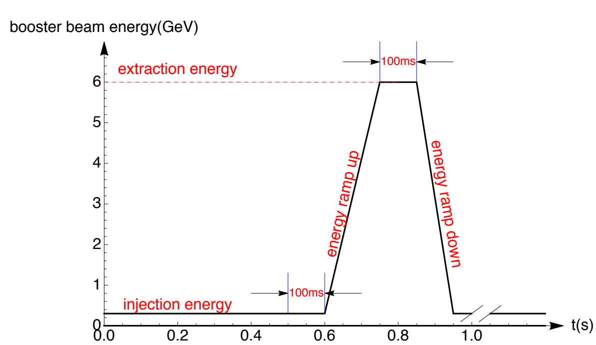

Figure 6: Schematic plot of the booster energy ramp curve.

operating at a repetition rate of 2 Hz. To accord with the time structure of injection kicker and also accommodate the two different filling patterns, the linac is designed to work at the single bunch mode with a repetition rate of 300 Hz, and the booster ramp curve has a flat bottom of 100 ms to store the injected bunches from the linac, and also a flat top of 100 ms to allow extraction of the bunches, a schematic plot of the booster ramp curve is shown in Fig. 6. Moreover, the 30 bunches can be uniformly distributed in the booster with a spacing of 48 ns, as shown in Fig. 7, and the same kicker systems can be applied in the injection and extraction of the booster, which has the same time structure as that of the main ring injection kicker, but with a micro-pulse full width smaller than 96 ns.

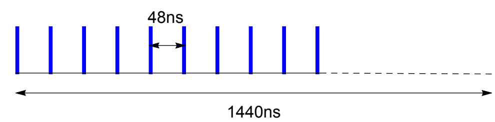

Figure 7: The bunch time structure in the booster.

Top-up injection at HEPS requires a beam current stability of 0.2%. There are two filling patterns under consideration. The first is to uniformly fill 648 bunches, i.e., into 90% of 720 RF buckets, simulations showed the beam lifetime is about 30 hours, and the refill time is about 3.5 min. Since each burst pulse of the injection kicker can inject at most 30 bunches into the main ring, at every refill 120 bunches can be injected with four burst pulses within about 27 s, so that bunch charge uniformity can be ensured. The second is to fill 60 uniform bunches with a bunch charge of about 14 nC while keeping the same average beam current, the beam lifetime can be as short as about 3 hours, and the required refill time is about 20 s. The injection system is capable to refill all the 60 bunches with two burst pulses within about 9 s, which meets the requirements.

OUTLOOK

We reported the recent progress on the study of a novel on-axis injection scheme based on RF gymnastics of a double-frequency RF system for HEPS, and analyzed the RF issues as well as the design of top-up injection for HEPS. More detailed study on injection tolerances as well as possible collective effects are still under way and will be reported in a forthcoming paper.

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REFERENCES

[1] L. Emery, in *Proc. PAC'01*, pp. 2599–2601.

[2] A. Lüdeke and M. Muñoz, in *Proc. EPAC'02*, pp. 721–723.

[3] T. Abe, *et al.*, "Commissioning of KEKB", *Prog. Theor. Exp. Phys.*, p. 03A010, 2013.

[4] J. L. Turner, *et. al.*, in *Proc. of EPAC'04*, pp. 881–883.

[5] D. Einfeld, M. Plesko, and J. Schaper, "First multi-bend achromat lattice consideration", *J. Synchrotron Radiat.*, vol. 21, pp. 856–861, Sep. 2014.

[6] G. Xu, *et al.*, in *Proc. IPAC'16*, pp. 2886–2888.

ISBN 978-3-95450-187-8

[7] L. Emery and M. Borland, in *Proc. PAC'03*, pp. 256–258.

[8] M. Aiba, *et al.*, "Longitudinal injection scheme using short pulse kicker for small aperture electron storage rings", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 020701, Feb. 2015.

[9] 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.

[10] G. Xu, *et al.*, in *Proc. IPAC'2016*, pp. 2032–2035.

[11] B. I. Grishanov, *et al.*, "Very fast kicker with high repetition rate for accelerator applications", *Nucl. Instrum. Meth. A*, vol. 396, pp. 28–34, Sep. 1997.

[12] V. M. Efanov, *et al.*, in *Proc. IPPC'97*, pp. 988–991.

[13] FID GmbH, http://www.fidtechnology.com

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