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ON-AXIS BEAM ACCUMULATION BASED ON A TRIPLE-FREQUENCY RF SYSTEM FOR DIFFRACTION-LIMITED STORAGE RINGS

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Abstract

Since the multi-bend achromats have been applied to lattice design in the future light source to achieve ultralow emittance, strong sextupoles and concomitant nonlinearities restrict its performance to a certain extent. The empirical understanding is the exclusion of conventional off-axis injection scheme on these light sources. In this paper, we will present a new on-axis beam accumulation scheme, which is based on the triple-frequency RF system. By means of delicate superposition of RF voltage with fundamental and two other harmonic frequencies, a commodious and steady main bucket is able to be formed. The electron bunch from the injector will be kicked into the main bucket on-axis with a reasonable time offset to the circular bunch, and this process may make the minimal disturbance to the experiment users while operating on the top-up mode. The application of this scheme to the High Energy Photon Source (HEPS) [1] will be discussed in the paper, corresponding simulation results are also presented.

INTRODUCTION

The design method to the lattice of the light source has been obtained a significant progress in recent years, which aims to minimize natural emittance, and ultimately achieves diffraction limit at a certain energy range. Upgrade to the injection scheme need to be done along with the development of these lattice design methods, where the one may have to sacrifice dynamic aperture of the main ring to beat this 'ultra-low' target. The empirical understanding is the exclusion of conventional off-axis injection scheme on next generation light sources by virtue of their teeny dynamic aperture. This value to the bare lattice of the High Energy Photon Source (HEPS) is only around 5 mm, far away from the essential requirement of conventional off-axis injection scheme, which is usually larger than 10 mm. Thus the design to the injection scheme has to be prudent on modern light sources.

On-axis injection scheme as a feasible choice has been proposed and designed in several new projects. Upgraded light source APS-U [2] and ALS-II [3] choose to adopt on-axis swap-out injection scheme, which requires a full-charge injector, and how to deal with the dumped beam is an additional problem. Aiba et al. proposed a on-axis scheme with a phase offset and higher energy compared to the circular beam [4], the larger momentum acceptance of the main ring is necessary. B.C Jiang et al. proposed on-axis beam accumulation [5] using a double-frequency RF system. By alternating the cavity voltage to conduct RF gymnastics, an empty bucket can be created away from the main bucket longitudinally, which will accommodate the injected beam. And fusing it with the main bucket by reverse process. Gang Xu et at. proposed a similar injection scheme [6], which is based on the phase adjustment of an active double-frequency RF system.

Enlightened by these inventive on-axis injection schemes, we proposed a new on-axis injection based on the triple-frequency RF system. In this paper, we will describe the requirement of the HEPS injection scheme firstly, and int roduce the construction of a elaborate triple-frequency RF system theoretically, then relevant simulation results will be presented in the following sections.

THE REQUIREMENT OF HEPS INJECTION SCHEME

High Energy Photon Source is a newly designed light source which is about to be constructed at the end of this year, with a 1360.4 m perimeter and designed natural emittance is less than 60 pm·rad. The major parameters are listed in Table 1. Noted that extra energy loss per turn (U_0) by IDs is included.

Table 1: Major Parameters of HEPS

Parameters	Symbols	Values and Units
Circumference	C	1360.4 m
Beam Energy	E_0	6 GeV
Beam Current	I_0	200 mA
Natural Emittance	ϵ_0	34.2 pm·rad
Betatron Tunes	ν_x/ν_y	114.14/106.23
Momentum Compaction	α_c	1.28e-5
Natural Energy Spread	δ_p/p	1.14e-3
Energy Loss per Turn	U_0	4.38 MeV
Harmonic Number	h_0	756

On the basis of the above preliminary parameters of HEPS, where harmonic number with 166.6 MHz fundamental cavity is 756, corresponding minimum time interval between the electron bunch is 6 ns. Restricted by the practical hardware parameter of the ultra-fast dipole kicker, it costs around 4 ns on rise time and fall time of the pulse in total. Overall consideration, a rigorous confine is that the beam from the injector need to be kicked at the longitudinal direction 2 ns

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away from the circular bunch, then the beam can be kicked on-axis directly into the main ring without disturbance to the circular bunch.

CONSTRUCTION OF THE TRIPLE-FREQUENCY RF SYSTEM

The longitudinal motion of the particles without the synchrotron radiation can be expressed as:

$$H(\phi,\delta) = \frac{h_f \omega_0 \eta}{2}\delta^2 + \frac{\omega_0}{\pi E_0 \beta^2}[V_f cos(\phi+\phi_f) + nV_h cos(n\phi+\phi_h) + \phi U_0] \quad (1)$$

Where ϕ and δ are the canonical variables, h_f is the harmonic number, n is the harmonics. ω_0 is the angular revolution frequency of the synchrotron particles, γ is the relativistic factor, and $\eta = \alpha_c - 1/\gamma^2$,$\beta = \sqrt{1-\gamma^2}$. U_0 is the energy loss per turn, V_f, V_h, ϕ_f, ϕ_h are the cavity voltage and phase of the fundamental and harmonic cavity respectively.

To satisfy the requirement of injection, the function of potential energy need to be restricted with several conditions:

$$\begin{cases} P(\phi_s) = 0 \\ P'(\phi_s) = 0 \\ P(\phi_b) = P_{max} \\ P'(\phi_b) = 0 \\ \phi_s - \phi_b > 2ns \end{cases} \quad (2)$$

Where ϕ_b is a stable point with a local maximum potential energy.

To satisfy the optimal bunch lengthening condition, there is another limitation:

$$P''(\phi_s) = 0 \quad (3)$$

Through these conditions, we can reduce the number of independent variables from 7 to 3. Theoretically one just search the region of these variables, and filtrate all the reasonable RF parameters. As a matter of fact, there are abundant solutions in the domain of the definition. Table 2 show that one set of our solutions to the aforementioned HEPS main ring lattice. Figure 1 present the main bucket conducted by the triple-frequency RF system, corresponding time interval between the outermost injection point and the circular bunch is larger than 2 ns, which meets our aforementioned requirement of the HEPS injection scheme.

Table 2: One Set of Triple-frequency RF System Parameters

Parameters	Funda.	2nd Harm.	3rd Harm.
Frequency	166.6 MHz	333.2 MHz	499.8 MHz
Voltage	−7.16 MV	−3.59 MV	0.90 MV
Phase	2.41 rad	3.21 rad	0.82 rad
Beam Power	957.88 kW	50.10 kW	−131.71 kW

Compared to the aforementioned on-axis injection scheme utilizing an active double-frequency RF system, the most conspicuous preponderance of this scheme is all the RF parameters can remain unchanged, no matter in the injection period or the operation period. Figure 2 present the voltage seen by the bunch generated by the triple-frequency RF system. However extra 2nd harmonic cavities are needed, and the construction cost of these extra RF cavities. Meanwhile, more cavities mean more straight sections to install them, this could be a problem in modern light source design, in which only around 5 m for a normal straight section. Besides the scheme also introduce into more impedance elements, corresponding beam collective instabilities need to be studied and simulated more prudent.

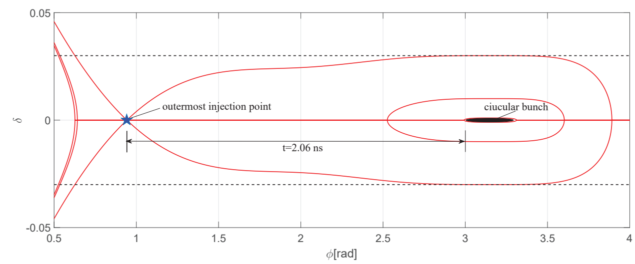

Figure 1: The main bucket formed by the triple-frequency RF system. Blue star points present the outermost injection point, balck filled ellipse present the circular bunch in the main ring.

SIMULATION OF DOUBLE-FREQUENCY RF SYSTEM

We do the simulation of a double-frequency RF system on HEPS at first, so as to generalize to the triple-frequency RF system. Modern light source usually utilize the harmonic cavity to lengthen the beam, which aims to ease the emittance growth by IBS effect and improve beam lifetime.

Relevant simulations are done by `ELEGANT` [7]. We utilized the element `RFMODE` to simulate the beam cavity interaction and `ILMATRIX` as one turn map simulation. Moreover direct feedback system to compensate the beam loading effect have been studied on the `ELEGANT`, corresponding feedback filters for the APS-U project are designed well [8], and we utilized these original filter parameters as a preliminary study. At such parameters of the feedback filters, resultant phase and voltage of the fundamental cavity can be maintained well. In Figure 3 we do the scan of the bunch length along with the detuning frequency of the harmonic cavity, and final bunch distributions are presented too.

SIMULATION OF THE TRIPLE-FREQUENCY RF SYSTEM

Since our ultimate purpose is to establish the triple-frequency RF system with the beam cavity interaction at 200 mA. At first `RFCA` element in the `ELEGANT` is utilized to testify the results of the aforementioned calculation. Figure 4 present a simple injection process, the initial beam is injected at dt=-2ns away from the circular bunch, and move to

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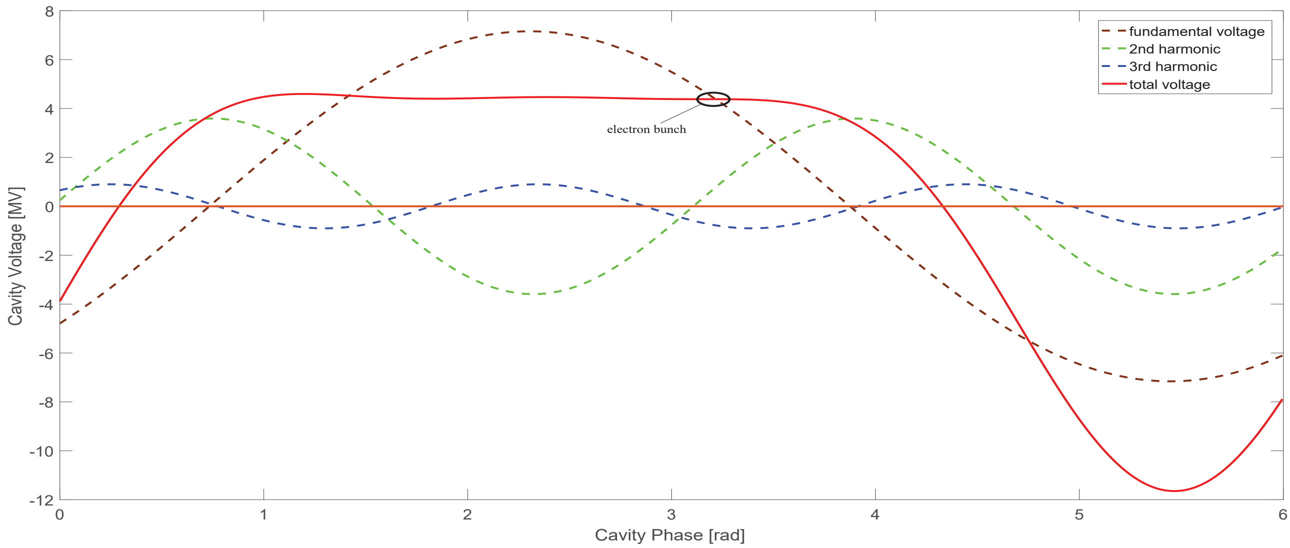

Figure 2: RF voltage seen by the bunch for the triple-frequency RF system.

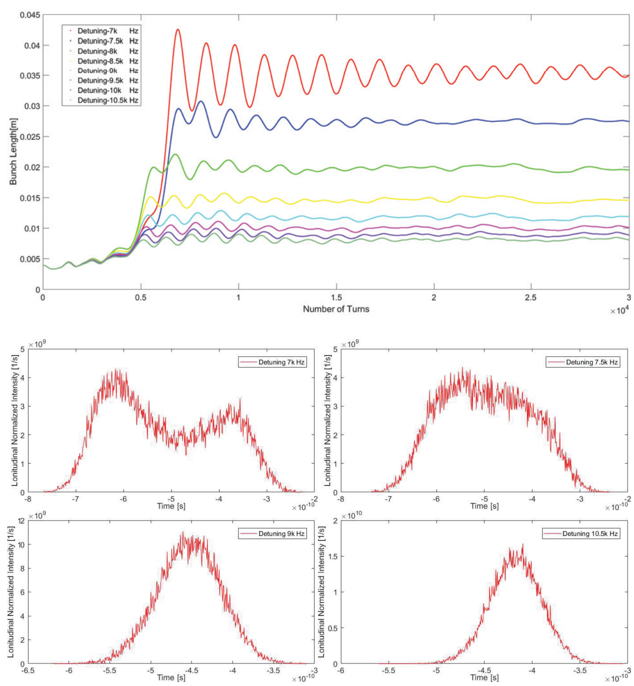

Figure 3: Bunch length and corresponding final distributions varied with detuning frequency.

the centre of the main bucket through longitudinal motion including synchrotron radiation.

Then we do the similar simulation utilizing RFMODE including beam cavity interaction at 200 mA. Supposing two SC active cavities work at 166.6 MHz [9] and 333.2 MHz respectively, the other one works on the passive mode at 499.8 MHz. Recent results show that the feedback system with aforementioned filter parameters doesn't work very well. The cavity phase of the fundamental and 2nd harmonic cavity shifted away from the initial setpoint in the RFMODE as the beam accumulated. Further work need to be done to

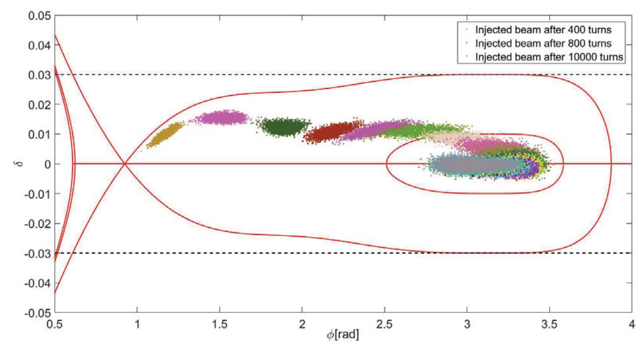

Figure 4: Beam injected at dt=-2ns away from the circular bunch and passed through over 10000 turns.

affirm the optimized filter parameters to meet the requirement of such triple-frequency RF system. Moreover relevant instabilities have been studied on HEPS project, MWI and TMCI including the harmonic cavity need to be treated under such a complex RF system. Robinson instabilities in double-frequency RF system have been studied by R.A.Bosch et al., [10], corresponding effects at triple-frequency RF system need to be researched.

CONCLUSION

In this paper, we carried out the preliminary design on the on-axis beam accumulation based on a triple-frequency RF system. A commodious main bucket is formed through such delicate method, in which the injected beam and circular beam can stay together without disturbing each other. Optimal bunch lengthening condition is utilized to obtain a ideal-flat potential curve, and shorter bunch length can be achieved by shift the cavity voltage or phase away from such severe condition. Future work on the simulation of beam cavity interaction including triple-frequency RF system and relevant instabilities are still under studying.

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REFERENCES

[1] G.Xu *et al.*, "Recent Design Studies for the High Energy Photon Source", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, WEPOW26.

[2] M.Borland *et al.*, "Lattice design challenges for fourth generation stroage-ring light sources", *J Synchrotron Radiat.*, Vol 21, No.5, pp.912-936, Sep.2014.

[3] H.Tarawneh *et al.*, "ALS-II, a Potential Soft X-ray, Diffraction Limited Upgrad of the Advanced Light Source", *Journal of Physics: Conference Series*, Vol 493, No.1, p.012020, 2014.

[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 faciliate on-axis beam accumulation in a storage ring", *Nuclear Instruments and Methods in Physics Research* A Vol.814, pp.1-5, April 2016.

[6] G.Xu *et al.*, "On-axis Beam accumulation Enabled by Phase Adjustment of a Double-Frequency RF System for Diffraction Limited Storage Rings", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, WEOAA02.

[7] M.Borland, "Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation", Advanced Photon Source LS-287, Septumber 2000.

[8] T.Berenc, "Modeling RF Feedback in Elegant for Bunch Lengthening Studies for the Advanced Photon Source Upgrade", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, MOPMA006.

[9] P.Zhang *et al.*,"A 166.6 MHz Superconducting RF System for the HEPS Storage Ring", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, MOPVA079.

[10] R.A.Bosch *et al.*,"Robinson instabilities with a higher-harmonic cavity", *Phys.Rev,St Accel.Beams*, Vol 4, p.074401, 2001.