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SIMULATIONS OF THE INJECTION TRANSIENT INSTABILITIES FOR THE HIGH ENERGY PHOTON SOURCE*

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Abstract

To enable a lattice design with an ultra-low emittance, the swap-out injection [1] has been adopted as the baseline injection scheme for the High Energy Photon Source (HEPS). As requested by the timing experiment users, a special filling pattern of 63 bunches with a high bunch charge of 14.4 nC poses as the major physics challenge of the swap-out injection. In particular, as shown in Ref. [2], a transient beam instability leads to some beam loss during the injection. In this paper, we present similar simulation studies for HEPS, and discuss possible measures to address this issue.

INTRODUCTION

The High Energy Photon Source (HEPS) [3] is a 6 GeV, 1360.4 m, ultra-low emittance storage ring-based light source, to be build in Huairou District, the suburb of Beijing, China. Based on 48 hybrid 7BA lattice cells, it delivers a natural emittance of 34 pm and hard X-rays with an ultra-high brightness. The small dynamic aperture is insufficient for conventional off-axis injection schemes, and the swap-out injection is adopted as the baseline injection scheme. To address the challenges in delivery of the full charge bunches in the injector, in particular to prepare the 14.4 nC high bunch charges as required by the timing experiments, we proposed a scheme to utilize the booster as a full energy accumulator ring [4], to recycle and replenish the used bunch in the storage ring. Injection simulations [5] indicate a promising transmission efficiency in the whole injection process, neglecting the effects of impedance. Nevertheless, injection of a 14.4 nC bunch into the small-acceptance storage ring still poses a threat, as the impedance effects could drive transient beam instabilities and lead to some beam loss, this would in turn raise the bunch charge requirement in the injector, and complicate the collimator design if the injection efficiency is not high enough.

The transient injection instability was simulated for HEPS, the dependence of beam loss on various factors have been studied, and some preliminary discussion on possible measures will also be presented.

SIMULATION SETUP

To study the transient instability during injection, simulations using Pelegant [6, 7] were launched. An updated version of the vertical and longitudinal impedance model [8] of the HEPS were used in the simulation, each represented

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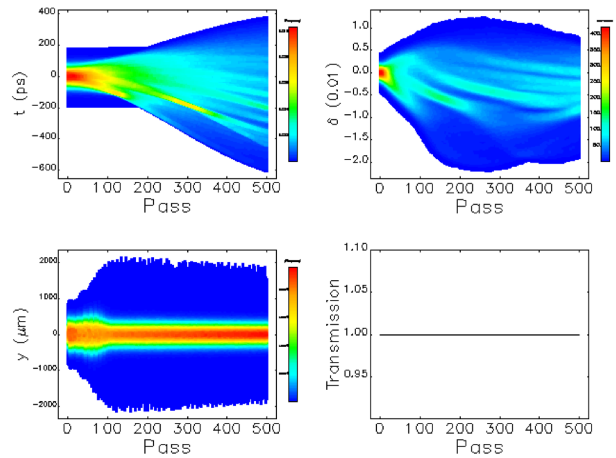

Figure 1: Simulation using a one-turn linear map.

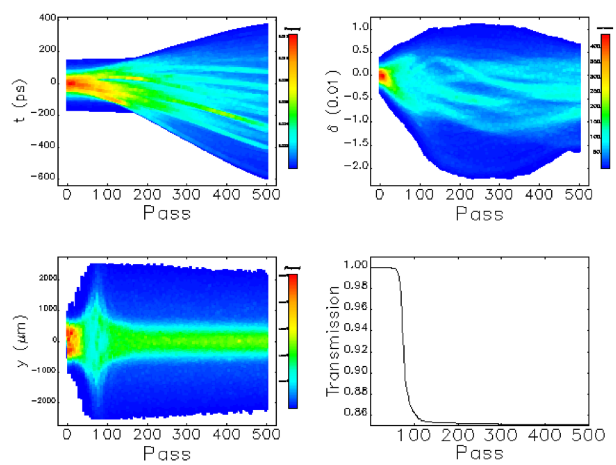

Figure 2: Simulation using an element-by-element tracking.

as an individual lumped element, the behavior in the transverse plane will be studied once the horizontal impedance model is well developed but the instability in the vertical plane is generally regarded as more severe. The injected beam parameters and equilibrium beam parameters in the storage ring are summarized in Table 1. Note that a combination of a 166.6 MHz superconducting RF system [9] and a 499.8 MHz third harmonic superconducting RF system is used in the storage ring, to lengthen the beam and alleviate the short beam lifetime and intra-beam scattering-induced beam emittance growth, meanwhile, the choice of a lower frequency of the fundamental RF system reserves the possibility to test longitudinal injection scheme [10–12] in the future. In contrast, PETRA 5-cell cavities were cho-

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Table 1: Key Parameters of Injected and Stored Beam

Beam Parameters	**Symbol and Unit**	**Injected Beam**	**Stored Beam**
Horizontal emittance	ϵ_x (nm)	40	0.035
Vertical emittance	ϵ_y (nm)	4	0.005
Relative energy spread	σ_δ	1.1×10^{-3}	2.0×10^{-3}
Rms bunch length	σ_t (ps)	40	160
Vertical displacement	δ_y (mm)	0.3	0

sen for the booster RF system, as an engineering decision. As a result, the injected bunch length is much shorter compared to the equilibrium bunch length in the storage ring, the latter also includes the contribution from the longitudinal impedance. A 15 nC injected bunch is tracked with an initial vertically displacement of 300 µm, representing a typical injection error.

Regarding the lattice modeling in the simulation studies, two different scenarios were tested and compared. One used a linear one turn matrix together with lumped RF cavities, a lumped element describing the synchrotron radiation effects, while the other used element-by-element tracking, in both cases a simplified physical aperture of 3 mm and 2.5 mm is included at the tracking point, representing the expected level of dynamic aperture in the presence of lattice imperfections through dedicated lattice calibrations. The comparison between these two scenarios is illustrated in Fig. 1 and Fig. 2, the element-by-element tracking showed about 15% beam loss absent from the other scenario, though the evolution of the beam in longitudinal phase space looks alike for the two scenarios. In fact, the lattice nonlinearity exacerbates the beam blowup, in particular in the tail part of the bunch, this indicates it is necessary to use element-by-element tracking in such an injection transient effect featured by a large initial vertical amplitude and fast beam loss at the physical aperture, in the following simulation studies, element-by-element tracking is always adopted.

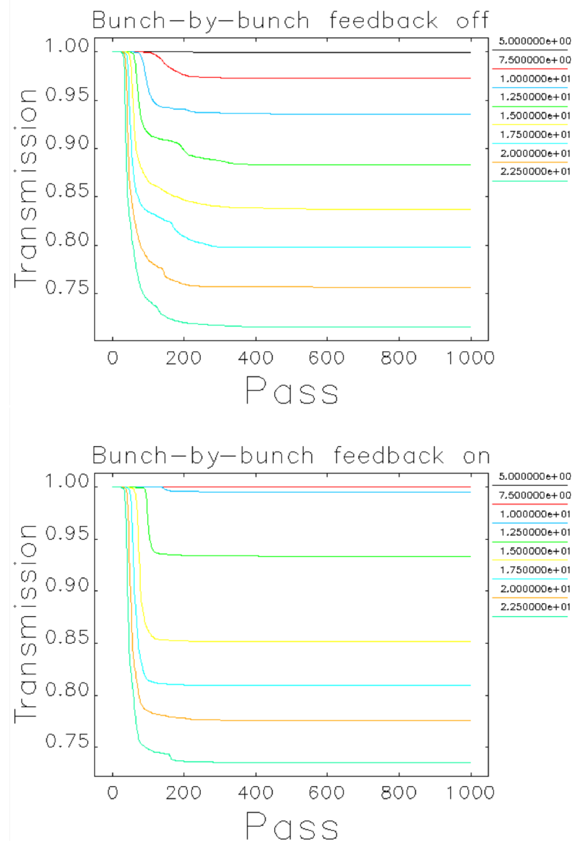

Figure 3: Evolution of transmission efficiency over tracking turns for different injected bunch charges, w/o feedback(upper) and w/ feedback(lower).

POSSIBLE CURES

Feedback

Note that the beam loss occurs primarily when the injected beam circulates for about 100 turns, in contrast to the situation in the case of APS-U [2] where substantial beam blowup occurs after about 400 turns. The fast beam loss could make it more difficult for a bunch-by-bunch feedback system to suppress. To justify this point, a 4-tap digital bunch-by-bunch feedback system was modelled, the maximum amplitude was chosen to be 1.25 µm according to the specification of the feedback system of HEPS [13], and a gain of 0.4 was adopted in the simulation. The simulation results of the injection instability with and without such a feedback system is shown in Fig. 3. For an injected bunch with a smaller charge, within about 10 nC, the feedback system is capable to suppress the beam loss, while for an even larger charge, the effectiveness of the feedback system is not sufficient or even obvious. A closer inspection indicates the feedback system becomes saturated and thus not capable to provide fast enough damping to cope with the very fast amplitude growth for a higher charge injected bunch. Moreover, feedback system with a doubled maximum amplitude is still not sufficient to suppress the beam loss for a 15 nC injected bunch. Actually, a bunch-by-bunch feedback system is more capable to suppress the coherent beam centroid motion, while the observed beam loss primarily occurs in the tail of the bunch, and this could help explain the inefficiency of the feedback system to solve this problem.

Injection Error

The beam loss due to the injection transient instability also depends on the initial vertical beam centroid motion, due

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to injection errors, as shown in Fig. 4. Since the injection errors could be categorized into the static errors and dynamic errors, the contribution of the static errors could be reduced in the injection efficiency optimization, leaving the imperfect injection efficiency dominated by the dynamic errors, mainly due to the errors of pulsed kickers. Ongoing efforts are devoted to better understand the amplitude jitter of the kicker magnets and improve the evaluation of potential jitter in the injection efficiency.

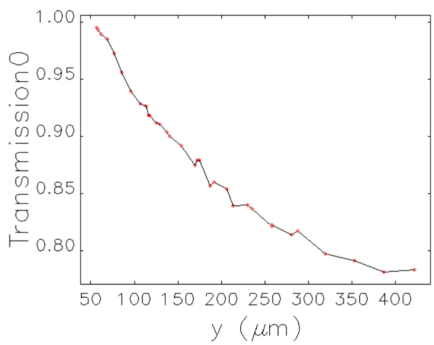

Figure 4: Evolution of transmission efficiency over tracking turns for different initial vertical beam centroid motions.

Bunch Length

Simulation results using different injected bunch lengths are shown in Fig. 5, and indicate a longer injected bunch length is favored to reduce the beam loss. This in turn suggests the very fast beam loss is linked to the very high beam linear density following injection and thus the very strong transverse wakefield. In contrast, in the case of APS-U, the injected bunch length is more comparable to the stored bunch length [2], due to the choice of the same fundamental RF frequency [14], and local high beam linear density regions emerge as a result of synchrotron oscillation, and the beam loss occurs later comparably. To this end, different schemes are under study to lengthen the bunch before extraction from the booster, and this will be reported in a future publication.

Other Issues

In addition, it was also found that an injected beam arriving later compared to the storage ring RF phase suffers from less beam loss during the injection, the different evolution course in the longitudinal phase space of the injected beam could be the cause for this phenomenon, an in-depth investigation is still under way. Meanwhile, since the lattice nonlinearity plays a significant role in leading to the beam loss. We are also trying to compare different lattices to find out the key factors in the lattice behavoir that affect the beam loss, and possibly provide some guidelines for the lattice optimizations.

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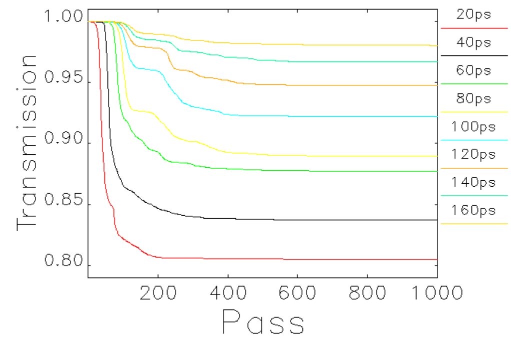

Figure 5: Evolution of transmission efficiency over tracking turns for different injected bunch lengths.

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