SIMULATION OF THE SINGLE BUNCH INSTABILITIES FOR THE HIGH ENERGY PHOTON SOURCE*

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Abstract

Timing modes pursing a large single bunch charge will be important operation modes for the green-field High Energy Photon Source (HEPS). The single bunch instabilities are simulated with the elegant tracking code, based on the current impedance budget. In particular, a novel on-axis accumulation scheme based on the RF gymnastics of an active double-RF system was proposed as a candidate injection scheme for HEPS, while the zero-current rms bunch length dramatically decreases during the injection, from 32 mm to 3 mm, over a time duration of about 200 ms. The single bunch instabilities are evaluated for both the operation mode with optimal bunch lengthening as well as the injection mode with the very short bunch length, as a first step in understanding the possible beam instability for this injection scheme.

INTRODUCTION

The High Energy Photon Source (HEPS) is a diffraction-limited storage ring to be built in the Beijing area, now under extensive R&D [1]. A nominal lattice design of HEPS features a beam energy of 6 GeV, a natural emittance of 59.4 pm, and a circumference of 1295.6 m [2,3]. The design beam current is 200 mA, and currently two filling patterns are under consideration. One is the high brightness mode with 648 bunches, followed by a 10% gap; the other one is the timing mode, with 60 bunches of equal bunch charges uniformly distributed around the ring, a comprehensive simulation study of the potential single bunch instabilities is required to justify the design of the lattice and impedance components, and in this paper we will focus on this filling pattern with a 14.4 nC single bunch charge. Note that various hybrid filling patterns are also commonplace in high energy synchrotron light sources, these will be carefully evaluated for HEPS in the near future.

On the other hand, we proposed an on-axis accumulation scheme to accommodate the very small dynamic aperture of the HEPS nominal lattice design [4,5]. In this scheme, the voltages and phases of an active double-RF system (including four 166.6 MHz fundamental cavities and two 499.8 MHz harmonic cavities) are manipulated to conduct RF gymnastics. The beam can be optimally lengthened to 32 mm at zero-current during the routine operation (namely the operation mode), while, during injection, empty buckets adjacent to each stored bunch are generated, allowing on-axis accumulation of injected bunches (namely the injection mode), the transition between these two conditions can be achieved by ramping the RF voltages and phases in a pre-set path. However, the zero-current bunch length in the injection mode is only 3 mm, substantially smaller than that in the operation mode, we are yet to understand if there are beam instability issues during the injection.

In this paper, simulations of the potential-well distortion and microwave instability are first presented, followed by the simulation of vertical mode coupling instability with nonzero first order chromaticity, for the injection and the operation modes. The beam stability issues in the on-axis accumulation scheme are also discussed.

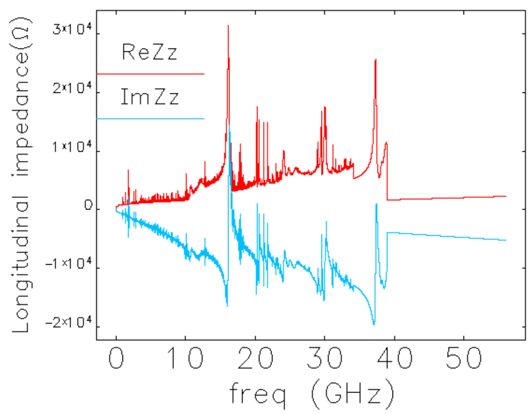

Figure 1: The longitudinal impedance model for HEPS.

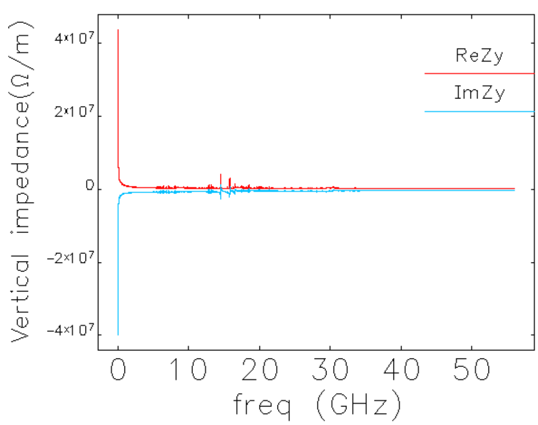

Figure 2: The vertical impedance model for HEPS.

IMPEDANCE MODEL

The longitudinal and transverse impedance models are developed for various components of the HEPS storage ring [6]. The summed longitudinal and vertical impedances are shown in Fig. 1 and Fig. 2, respectively. Note that the geometric impedances were obtained with a 3 mm

* Work supported by NSFC (11605212).
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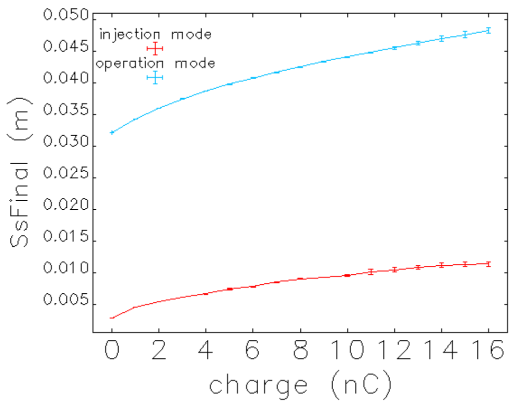
Gaussian bunch via simulations with ABCI [7] and CST [8] codes, however, at the injection mode, the impedance model might miss some high frequency information to properly interact with the micro-structure of the beam. Moreover, estimation of the CSR instability [9] indicates the CSR impedance is also important at the injection mode. We will include the CSR impedance in our simulation in the future, and an upgrade of the impedance model using a 1 mm Gaussian bunch in ABCI and CST simulations is also foreseen.



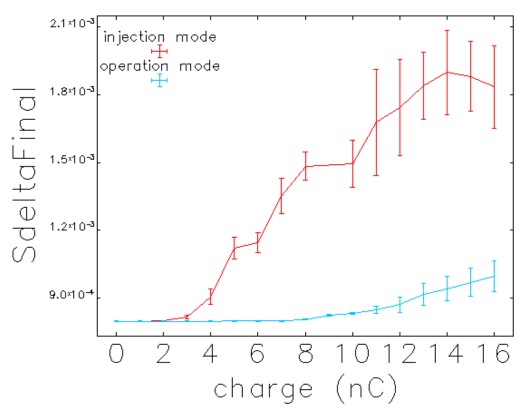


Figure 3: Bunch length (upper plot) and energy spread (lower plot) for the injection mode and the operation mode taking into account of the longitudinal impedances.

LONGITUDINAL INSTABILITY

The elegant [10, 11] code utilizes the impedance rather than the pseudo-Green function wake in the simulation of collective instabilities. To avoid the excessive computing resources required in the element-by-element tracking, a one-turn linear transfer map is used to represent the storage ring, as well as synchrotron radiation and RF cavities. In our simulation for a particular bunch charge, we first evaluate the numerical solution of the Haissinski equation [12] using the Haissinski equation solver in elegant, and obtain the bunch length and the corresponding bandwidth f_0. Then interpolate the impedance model with an equal frequency step size up to about $25f_0$, with typically 4097 bins or 8193 bins, these settings empirically ensure the convergence of the simulated loss factor and kick factor and the time consumption is also acceptable. Then we initialize the longitudinal beam distribution according to the solution of the Haissinski equation and track for 40000 turns. The beam parameters in the final 5000 turns are then analysed to obtain the rms bunch length and energy spread. The simulation results are shown in Fig. 3 for the injection and operation mode, respectively. 250,000 particles and 8193 impedance bins were used in the tracking, and crosscheck with four times more particles and different number of bins showed consistent results.

As the simulation results indicate, the beam is actually substantially lengthened in the injection mode at 14.4 nC compared to the zero-current bunch length, while the microwave instability threshold of the injection mode is much lower than the operation mode, as expected. A much increase in the energy spread is also observed at 14.4 nC in both cases, and the large error bars of the bunch length and energy spread beyond the microwave instability threshold, indicates the turbulent longitudinal coherent motion. Following the experiences of other high energy light sources, it is quite common to operate above the microwave instability threshold and the users are generally insensitive to the turbulent behaviour in the longitudinal phase space. However, we need to carefully evaluate the injection transient effects on user experiments, taking into account the intra-beam scattering effect as well.

TRANSVERSE INSTABILITY

Different from the longitudinal instability that finally reaches an “equilibrium” state with no beam loss, the transverse mode coupling instability (TMCI) leads to beam loss or injection saturation, and could be a severe limitation of the single bunch charge. The TMCI threshold has been estimated with an eigen-mode analysis [9], for a Gaussian longitudinal distribution and zero chromaticity, which is about 0.3 mA (1.3 nC) for the injection mode, and 0.1 mA (0.4 nC) for the operation mode. However, a positive chromaticity helps stabilize the beam and its effect is studies via elegant simulation. The practical longitudinal distribution is also taken into account via introducing the longitudinal impedance. Currently, we are yet to establish an impedance budget for the horizontal plane, since round beam pipes are used in some part of the ring, the horizontal TMCI could also be a severe effect for HEPS, in contrast with 3rd generation light sources. Moreover, currently only the first order vertical chromaticity are taken into account in this study, while studies in APS-U indicated the higher order chromaticities and detuning terms could play an important role for these ultra-low emittance MBA lattice [13]. These effects will be included in the near future.

We studied the most challenging case of 14.4 nC bunch charge, for both the injection and the operation modes. 600000 particles are tracked first with only the longitudinal impedance for 40000 turns, then the final distribution is used in the tracking with both the longitudinal and

ISBN 978-3-95450-182-3

transverse impedances for another 20000 turns, an initial offset of 100 µm is applied to the beam, while no physical aperture was included to show the instability behavior. Fig. 4 shows the evolution of the rms vertical beam sizes for different vertical chromaticity settings. To suppress the transverse instability, a positive vertical chromaticity of unit 3 and 2 are required for the injection mode and the operation mode, respectively.

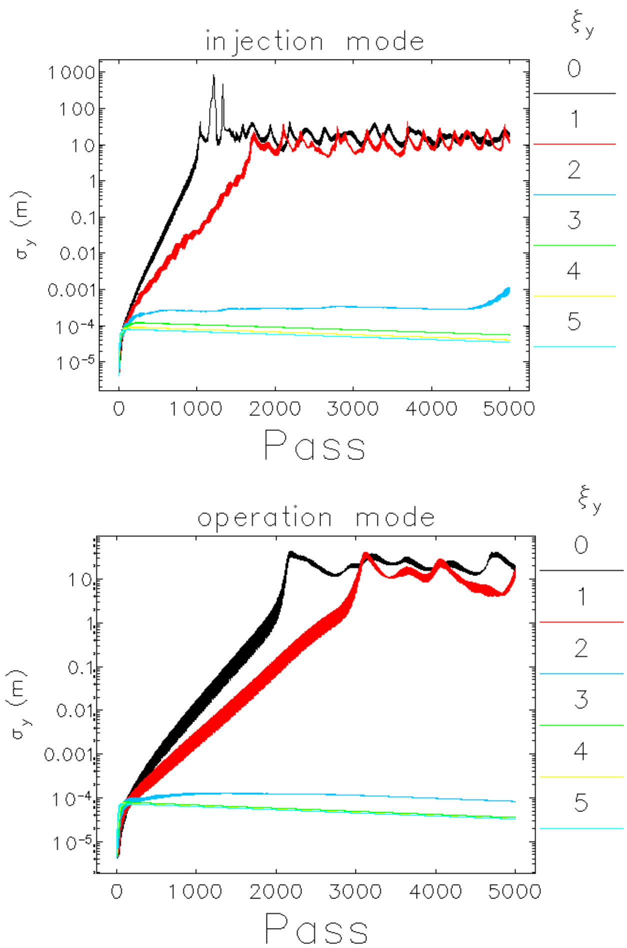


Figure 4: Evolution of the vertical beam size with different vertical chromaticities, for the injection mode (upper plot) and the operation mode (lower plot), respectively.

CONCLUSION

The preliminary simulations of the single bunch instabilities are presented, based on the latest HEPS impedance model. Note that more impedance sources will be studied and included in the impedance model and the simulation results will also be updated to better reflect the expected instability issues in the green-field machine. In addition, the very short bunch length during the injection mode, requires us to include the CSR impedance in the tracking, and a better impedance model will be obtained with a 1 mm Gaussian beam in the ABCI and CST simulations of the geometric impedances.

Current simulations addressed the "static" effects and the current impedance model requires no much different vertical chromaticities to suppress the transverse instability for the injection and operation modes. However, the ramping of RF parameters in this on-axis accumulation scheme leads to a non-adiabatic dynamic evolution of the stored bunches over a course of tens of milliseconds, a start-to-end injection simulation with impedances is underway to check if the beam would be unstable. Meanwhile, crosscheck of the simulation results with the mbtrack code [14] is also underway.

ACKNOWLEDGEMENT

The authors would like to thank M. Borland and R. Lindberg for help with the elegant code, and K. Bane for useful discussions.

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