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THE SWAP-OUT INJECTION SCHEME FOR THE HIGH ENERGY PHOTON SOURCE*

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Abstract

The on-axis swap-out scheme is a promising injection scheme for diffraction-limited storage rings, since it only requires a rather small dynamic aperture and thus potentially allows a higher brightness compared to traditional off-axis injection schemes. However, a full charge injector is necessary for this scheme and its design can be nontrivial, in particular to satisfy the large single bunch charge requirements in special filling patterns for timing experiments. In the High Energy Photon Source, we propose using the booster also as a high energy accumulator ring to recapture the spent bunches extracted from the storage ring, so as to relax the challenges in generation and acceleration of bunches with a high charge, and as a cost-effective solution compared to building a dedicated full energy accumulator ring. In this paper, the beam dynamics issues of this scheme will be presented, trade-offs between the storage ring and booster beam parameters and hardware specifications will also be discussed.

INTRODUCTION

The successful commissioning and operation of MAX-IV has unfolded the curtain of a new era of storage ring-based light sources, so-called diffration-limited storage rings. The on-axis swap-out injection [1] scheme is a very promising injection scheme for these diffraction-limited storage rings, since it requires a rather small dynamic aperture, compared to conventional off-axis injection schemes, and potentially allows pushing towards lattice design with an even higher brightness, in addition, the injection can be transparent to users since only a small fraction of bunches are perturbed during injection, and it is also compatible with round beam operation and insertion devices with small horizontal gaps. It is the baseline injection scheme for ALS-U [2] and APS-U [3], and recently, has been selected as the baseline injection scheme for the High Energy Photon Source (HEPS).

The latest baseline lattice design of HEPS employes a 48-period hybrid 7BA lattice with a circumference of 1360.4 m, the natural emittance is 34 pm for the bare lattice at 6 GeV [4], while the dynamic aperture is only about 3 mm horizontally and 2 mm vertically in relatively worse seeds of imperfect lattice after correction [5], small for off-axis injection but sufficient for swap-out injection. On the other hand, two filling patterns are currently considered for HEPS, aiming at an average beam current of 200 mA, the high brightness mode employs 756 bunches with a single bunch charge of 1.33 nC, and the high bunch charge mode employs 63 uniformly distributed bunches with a 14.4 nC bunch charge. Obviously, a signficant challenge for the swap-out injection scheme is to provide the required full charge bunches and ensure a high efficiency top-up injection.

The injector of HEPS consists of a 500 MeV linac and a 500 MeV to 6 GeV booster, and associated transfer lines [6]. A natural idea is to enhance the capability of the electron source and linac to supply a high charge bunch of about 20 nC, inject into the booster and accelerate all the way up to 6 GeV. Alternatively, to relax the pressure of the electron source and linac, multiple linac bunches of smaller bunch charges can be inject into the same booster bucket using transverse beam stacking [7]. However, simulation studies indicate there is a single bunch instability at the booster injection energy [8], limiting the booster to accept a bunch charge only up to a few nC, which is a signficant challenge for this idea, the intrinsically very short linac bunch leads to a high charge density and enhances the instability.

As a contrast, in the injector chain of APS-U [3], the existing PAR ring is employed as a low energy accumulator ring, that accumulate linac bunches to generate a full charge, but very long bunch to be injected into the booster, the single bunch instability at booster injection is not a limitation due to the relatively low beam density. Nevertheless, significant efforts have been devoted to tackle other high-charge related beam dynamics issues in the PAR and booster [9]. In addition, a dedicated full energy accumulator ring between the booster and the storage ring is another viable option to provide the full charge bunch [2].

For the green-field HEPS, building a dedicated accumulator ring, requires extra budget and man power and is therefore not favored. Instead, we propose a different scheme, utilizing the booster as a 6 GeV accumulator ring to satisfy the full charge requirement of the storage ring. In the following sections, we'll first introduce the basic idea of this scheme, and then describe the related design issues.

THE "HIGH ENERGY ACCUMULATION SCHEME"

To enable the booster as a high energy accumulator ring, two separate transport lines are required to exchange beam between the booster and the storage ring. The whole injection process is illustrated in Fig. 1, a small charge bunch is first injected into the booster, and accelerated to the top energy, at the booster flat-top, a stored bunch is extracted from the storage ring and transported to the booster, off-axis injected and merged with the accelerated small charge bunch,

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then after a few damping times, the full charge bunch is extracted from the booster and injected into the empty bucket left by the original extracted bunch. An injection cycle ends when the booster is empty and ramped down to the injection energy. As a result, only a moderate bunch charge is required to be generated in the linac and accelerated in the booster, and at 6 GeV flat-top energy, the beam instability is generally weaker than at the injection energy with the help of a strong radiation damping.

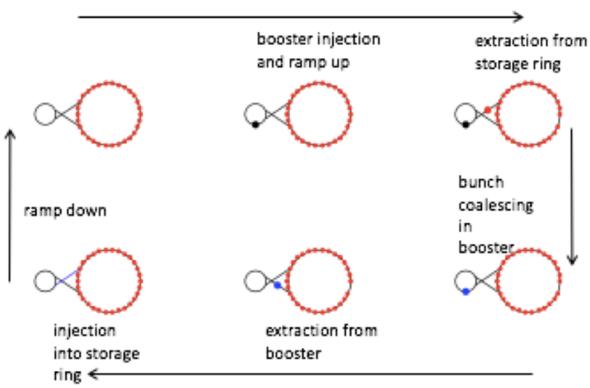

Figure 1: A complete injection cycle.

To enable the on-axis injection in the storage ring, state of art fast kickers are necessary, since various flexible filling patterns are foreseen, injection and extraction kickers are designed to have a very short rise, flat-top and fall times, in contrast with the kicker design with a long flat-top to enable bunch train injection and extraction in ALS-U [2], note that the minimum bunch spacing is 6 ns in the high brightness mode, eight 300 mm-long stripline kickers are employed in both injection and the extraction regions, the associated two high voltage pulsers of each kicker provides a very short Gaussian-like pulse with a FWHM of about 4.5 ns. R&D efforts of the stripline kickers and pulsers are reported in Ref. [10], new designs to satisfy the updated requirements will be reported in a future publication. The 6 m straight section is not sufficient to include both the injection and extraction septum magnets as well as a single set of kickers for both injection and extraction, implementation of the septum magnets in the adjacent arc region requires nontrivial modification of the lattice design and is not favored, therefore, two separate straight sections and thus two sets of kickers are employed for injection and extraction, respectively. To simplify the design, the parameters of kickers and Lambertson magnets are the same for both injection and extraction, the Lambertson magnets are tilted in yaw, roll and pitch, to provide a large horizontal and a small vertical deflection, and to better compensate for the leakage field [11]. the layout of the extraction and injection region is shown in Fig. 2.

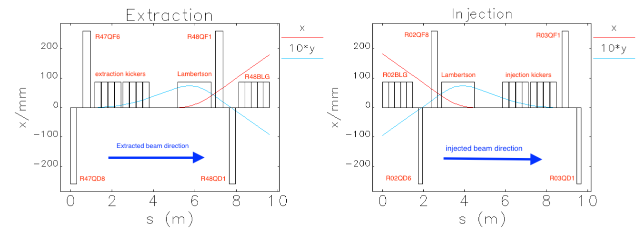

Figure 2: The layout of the extraction and injection regions of the storage ring.

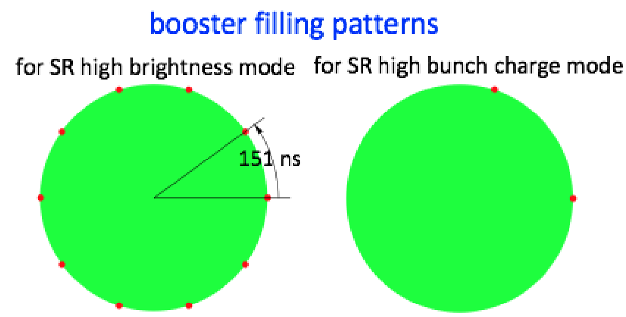

Figure 3: Typically filling patterns in the booster.

BOOSTER MULTIPLE BUNCH OPERATION

To reduce the amount of time required for injection from zero to the 200 mA operation beam current, as well as the refill interval in top-up operation, multiple bunch operation of the booster is also considered. Note that in this injection scheme, the beam injection and extraction do not take place simultaneously in the storage ring, the booster injection and extraction kickers are also required to deflect one bunch at a time. In principle, many bunches can be stored in the booster provided fast kickers with very short rise and fall times are implemented, however, operation with a high average beam current in the booster, would introduce additional complexities, and it is economically favored to utilize conventional kickers with a moderate rise and fall time. Therefore, it is planned to store up to 10 bunches in the booster to work with the storage ring high brightness mode, and 2 bunches to work with the high bunch charge mode, the filling patterns are illustrated in Fig. 3. The booster injection and extraction kickers are designed to provide a half-sine wave with a full width of 300 ns, so that only one bunch is deflected at a time, while this also means there is a minimum bunch spacing of 150 ns in the booster filling and this introduces complexities in the selection of bunches for injection during top-up operation. To enable the transfer of up to 10 bunches between the booster and the storage ring in each injection cycle, the booster ramp curve must have a flat-bottom and a flat-top, since the booster is designed to operate at 1 Hz repetition rate, the electron guns and all injection and extraction kickers work at a 50 Hz repetition rate, the duration of the flat-top and the flat-bottom are both chosen to be 200 ms. The status of HEPS booster lattice design is reported in Ref. [12], and

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the injection and extraction region of the booster is reported in Ref. [13].

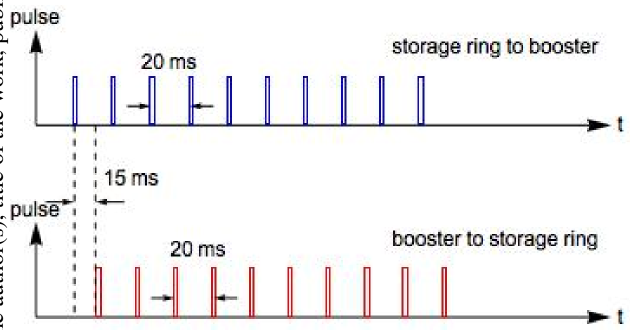

Figure 4: The time structure of bunches in the two transport lines.

In fact, the bunches are extracted from the storage ring at an interval of about 20 ms, while a merged bunch stays in the booster for about 15 ms before being extracted and re-injected into the storage ring, as illustrated in Fig. 4. Consequently, during the transfer of the multiple bunches, there is always only one bunch in the booster with the full charge in the injection cycle, and the maximum average beam current is then kept less than 15 mm. On the other hand, there is always only one missing bunch in the storage ring, and the beam brightness drop in the high brightness mode is negligible, while in the high bunch charge mode, with the missing bunch, the transient beam loading effect is expected to shift the centroids of other bunches, and the disturbance to user experiments requires further study.

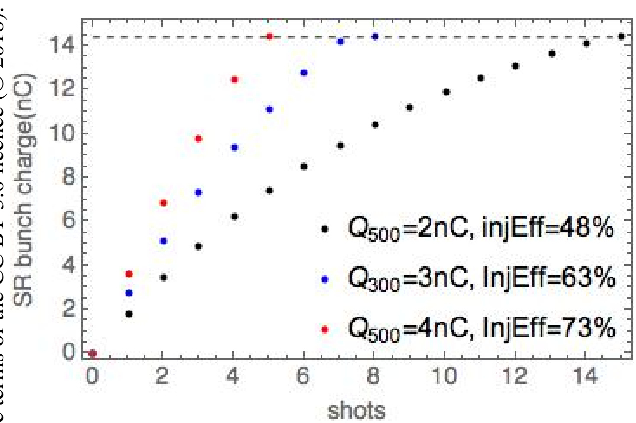

Figure 5: The evolution of storage ring stored bunch charge during fresh injection. Q_{500} represents the bunch charge at the booster injection energy, injEff denotes the total injection efficiency considering the total loss in the fresh injection process.

TRANSMISSION EFFICIENCY ISSUES

In this injection scheme, the bunch with a high charge is transferred twice, the accelerated small charge must compensate the charge loss during the transfer process, in addition to the charge loss of the stored bunch between two adjacent injection, therefore, it is essential to maintain a high transmission efficiency in the whole injection cycle. Assume the transmission efficiencies during the booster ramping, transport from booster to the storage ring, as well as transport from the storage ring to the booster are all 95%, and not dependent on the bunch charge. It is found that the bunch charge at the booster injection energy must be larger than 1.6 nC in order to inject up to the required 14.4 nC bunch charge in the storage ring. As shown in Fig. 5, for increasing bunch charges at the booster injection energy, the number of shots to fill each storage ring bunch decreases and is favored for a shorter fresh injection duration, moreover, the total charge loss during the injection is also smaller and is favored to relax the requirement of radiation shielding. On the other hand, in top-up operation, the available accelerated bunch charge and the transmission efficiency during the bunch transfer, is related to the top-up regulation, the trade-off is illustrated in Fig. 6 assuming a beam current stability of 0.2% and two bunches are filled in the booster. Nevertheless, the transmission efficiency requirement is much relaxed in the high brightness mode, in fact, the high energy accumulation is not necessary for the fresh injection since the required single bunch charge can be easily met with a single accelerated bunch of the booster.

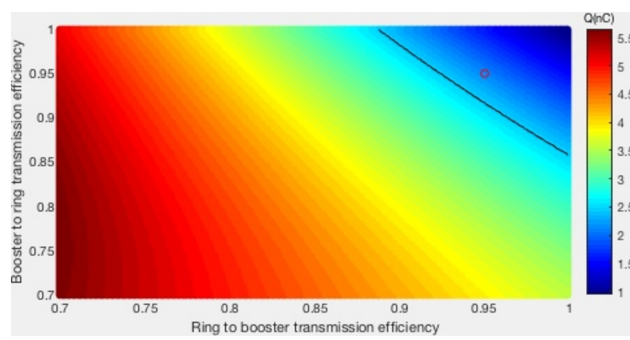

Figure 6: The required accelerated bunch charge at 6 GeV in the booster, for different transmission efficiencies, to achieve the beam current stability of 0.2%. The solid line indicates a bunch charge of 2.5 nC, and the empty circle denotes a transmission efficiency of 95% in both directions.

CONCLUSION

A "high energy accumulation" swap-out injection scheme is proposed as the baseline injection scheme for HEPS, to address the high bunch charge requirements for timing experiments. This scheme relaxes the challenges in generation from scratch and acceleration of high charge bunches in the injector, while it is essential to ensure a very high transmission efficiency. A start-to-end simulation of the whole injection process is underway, in particular, simulations indicate there is a beam instability during injection for a high bunch charge [14], which might lead to a reduction of the transmission efficiency, investigation of these bunch-charge dependent effects is also underway for HEPS. These aspects will be reported in a future publication.

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