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ADVANCED PHOTON SOURCE INJECTION RELATED SIMULATION AND MEASUREMENT*

Yipeng Sun†, ANL, Argonne, IL 60439, USA

Abstract

Injection efficiency is one of the key factors in ensuring successful operation of storage ring light sources. In this paper, injection simulation and measurement studies at the Advanced Photon Source will be presented. The tracking simulations and measurements are compared in terms of the dynamic aperture and injection efficiency. Injection efficiency is also measured on the betatron tunes space and on different stored beam orbits.

OVERVIEW

This section introduces the basic concepts for the simulation and measurement studies discussed in the following sections, including: injection scheme, septum position, stored/injected beam separation, smaller measured ID4 physical aperture, definition of measured injection efficiency, etc..

The main ring at the Advanced Photon Source (APS) is a third-generation synchrotron radiation light source research facility. The circumference is 1104 meters and the beam effective emittance is 3.13 nm. The APS accelerator complex is composed of electron guns, linac, transport lines, a particle accumulator ring (PAR), a booster, and a storage ring. The electron beam is accelerated from 450 MeV to 7 GeV in the booster synchrotron over a half second. The electron beam is then injected into the 7 GeV storage ring through a booster-to-storage ring transport line (BTS). The linear optics in one of 40 sectors at APS storage ring is shown in Figure 1. A thick septum, a thin septum and four injection kickers (IK1, IK2, IK3, IK4) are employed in two sectors of the ring as the injection system. Injection efficiency into the storage ring is a key parameter to ensure successful operations of the light source.

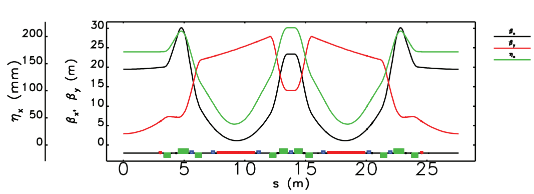

Figure 1: Twiss parameters in one arc section of APS storage ring. Green blocks represent quadrupoles, red blocks represent dipoles, and blue blocks represent sextupoles.

The closed injection bump is shown by the black curve in Fig. 2. The injection kickers are optimized for better injection efficiency and acceptable impact on the stored beam, as a result of which the injection ocsillation is shared between the stored and injected beams. Figure 2 shows trajectories of the stored (red curve) and injected (green curve) bunches using the non-closed bump. Beam separation between injected beam and stored beam closed orbit (without injection bump) at the septum location was set to 22 mm. For closed-bump injection, the stored bunch is not disturbed (black curve), but the oscillation of injected bunch is larger, shown by the blue curve in Fig. 2.

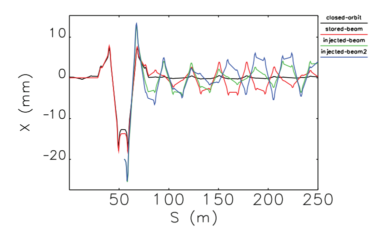

Figure 2: Beam trajectories for injection. Black: stored beam, closed bump. Blue: injected beam, closed bump. Red: stored beam, non-closed bump. Green: injected beam, non-closed bump. The septum magnet is at 56 m.

The position of the septum magnet with respect to the closed orbit of the stored beam was measured and is shown in Fig. 3. In Fig. 3 the electron beam lifetime (in minutes) is plotted in x-y space at the septum. It is observed that the septum is at x=-17 mm. Good agreement is achieved between two measurement methods, which are based on steering correctors, and BPM set points (plus orbit feedback) respectively. The measurement also agrees with the design.

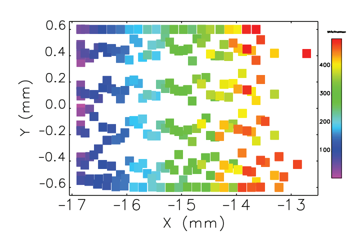

Figure 3: Beam-based measurement of the septum magnet position relative to stored beam. Color map showing the beam lifetime measured in minutes (5 to 500 minutes).

The minimum physical aperture of Advanced Photon Source is at ID4, which was ± 15 mm in x, and ± 2.5 mm in y. In the latest run, a smaller aperture vacuum chamber is installed at ID4. Beam-based physical aperture measurements show that ID4 now has a real aperture of roughly ± 13 mm in x, and ± 1.5 mm in y. Injection efficiency was

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† yisun@aps.anl.gov

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measured while the stored beam orbit was scanned at ID4 using a four-corrector beam orbit bump.

For the injection efficiency measurement, a previously stored single bunch was kicked out while a new bunch was injected at the same time. The bunch charge was measured in BTS line and in the storage ring. The ratio of the beam charge averaged in 10 pulses was defined as the injection efficiency. As shown in Fig. 4, when the stored beam was steered to x = -6 mm, or y = 0.6 mm, the injection efficiency was close to 0. Assuming a maximum residual injection oscillation of 7 mm and 1 mm in x and y, the measurement suggests a smaller ID4 physical aperture than design. This agrees with the beam-based physical aperture measurements at ID4.

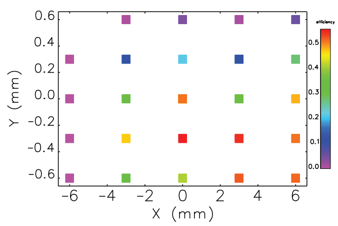

Figure 4: Injection efficiency as a function of stored beam orbit at ID4. Measurements on RHB lattice.

In the following sections, injection-efficiency-related studies are presented for two of three APS operation modes. The detailed measurement and simulation results on these two operation modes will be discussed below.

Table 1: Beam Transmission Simulation on Betatron Tunes

Tune	36.118	36.128	36.138	36.148	36.158
19.232	0.969	0.810	0.997	1	1
19.242	0.995	0.895	0.766	1	1
19.252	0.999	0.967	0.714	0.999	1
19.262	1	0.994	0.852	0.784	1
19.272	1	0.998	0.949	0.565	1

HYBRID OPERATION MODE

The standard operating mode of the APS has a total beam current of 102 mA in 24 single bunches with top-up injection. For the hybrid fill mode, a single bunch above 16 mA is isolated from the remaining 56 bunches by a symmetrical gap of 1.6 ms for some timing mode users. The chromaticity is corrected to +10 in both horizontal and vertical planes, to suppress single bunch instability.

During machine studies to raise single bunch accumulation current limit, it was observed that a lower horizontal betatron tune gives a higher accumulation limit [1]. It was also observed that the injection efficiency followed the opposite trend: 40% at the tweaked tune (36.128, 19.252), compared to 80% at the nominal tune of (36.158, 19.242). To verify the measurement results, simulation studies are performed in ELEGANT [2] using a calibrated lattice model.

To perform simulations of the dynamic aperture measurements with an injection kicker scan, one needs to do a kick aperture simulation in ELEGANT [2]. According to [3], 1 kV of injection kicker translates into 0.105 mrad in beam's angle change (calibration for kickers under 3 kV). In the machine study, the kicker K3 voltage was scanned between 2 kV and 6 kV, which is a kick angle between 0.21 mrad and 0.63 mrad.

The comparison of the simulation and measurement is shown in Fig. 5, where the tweaked lattice ahs larger dynamic aperture. We can see on Fig. 5 for tweaked lattice a small dip around a kick angle of 0.45 mrad, which is then recovered at larger angle. This is probably an indication of a beam hitting some resonances due to transverse amplitude dependent tune shift. It is also observed that the beam loss pattern seems to be a combination of horizontal and vertical physical aperture at different IDs. The differences between measurement and simulation may be due to an imperfectly lattice model in terms of closed orbit (i.e., misalignment and steering correctors are not included in the model), the discrepancy between real and model physical apertures.

A betatron tune scan is performed while recording the beam transmission rate with a fixed 0.45 mrad kick of IK3. The results are shown in Table 1. The beam transmission is sensitive to the fractional betatron tunes. One observes that there is a resonance line (3rd order, $2\nu_x - \nu_y$=N) along the low transmission points. More study is needed to investigate the resonance properties, which is possibly from skew sextupole fields generated by sextupoles and coupling [1].

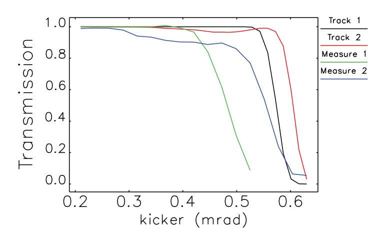

Figure 5: Comparison of kick aperture. Black: simulation of operation lattice; Red: simulation of tweaked lattice; Green: measurement of operation lattice; Blue: measurement of tweaked lattice.

In the simulation for injection efficiency, 19-24 mm beam separation at septum was introduced. The setpoints of IK3 and IK4 are -6.3 kV (-0.6610 mrad) and 10.3 kV (1.0815 mrad). The initial beam condition at the septum is ϵ_x = 100 nm, $\beta_x = \beta_y$ = 12 m, plus a coupling of 10%. A comparison between simulation and measurement is shown in Table 2. It is observed that the injection efficiency is close to 100% up to 24 mm separation. Adding an initial beam angle of 0.2 mrad on top of the 21 mm separation, the simulated injection efficiency is reduced to 80%-90%. It is also observed that the injection efficiency is sensitive on the initial beam angle, which could originate from upstream systems. However, the initial beam angle was found to be very small from one pass trajectory fit in a later measurement [1].

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Table 2: Injection Efficiency for Different Conditions

Lattice	Measurement	19mm-21mm	22-24mm	21mm+0.2mrad	22.5mm+ID4
APS (36.158, 19.242)	80%	100%	100%	85.8%	84%
APS tweaked (36.128, 19.252)	40%	99.9%	99.6%	91.3%	32.1%

The discrepancy between measurement and simulation may be from unstable injected beam condition due to trajectory feedback failure in the transport line when the measurement was performed.

As discussed above, using the measured effective physical aperture of ID4 (± 13 mm in x, and ± 1.5 mm in y) in the simulation, the injection efficiency is shown in Table 2 which has good agreement with measurements. It is concluded that tweaked lattice has larger dynamic acceptance so the single bunch accumulation limit is higher. However, for the injected beam the effective dynamic acceptance is smaller for the tweaked lattice.

REDUCED HORIZONTAL BEAM SIZE (RHB) OPERATION MODE

The so-called Reduced horizontal beam size (RHB) operation mode has a slightly higher effective emittance of 3.4 nm. At one insertion device (ID) the horizontal beam size is significantly reduced to 120 μm. The nominal horizontal beam size at ID is 280 μm. For this lattice, the chromaticity is corrected to +2 in both horizontal and vertical planes.

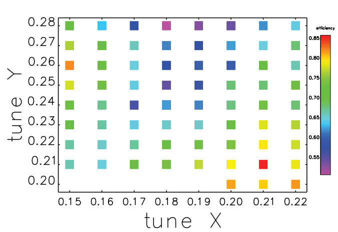

Figure 6: Injection efficiency color map (range from 50% to 85%) on fractional betatron tunes space.

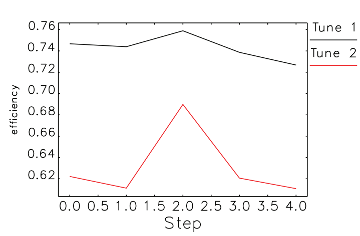

Figure 7: Injection efficiency at tweaked (black) and original tunes (red), repeated for 5 times.

During the latest run of the Advanced Photon Source RHB operation mode, the normal operation was affected by low injection efficiency. Among many possible parameters checked, it was found that the injection efficiency is sensitive to the fractional betatron tunes. Measurements of the injection efficiency as a function of fractional betatron tunes are shown in Fig. 6. Each step represents an average over 10 pulses of injected beam. One observes that the injection efficiency varies between 50% and 85% in the tune range being scanned, which is roughly ± 0.04. The nominal betatron tune is (0.18, 0.24) for the Advanced Photon Source RHB operation mode. Tweaking the horizontal tune up or down by 0.02, the injection efficiency was increased by 15%. The fractional tunes scan result was confirmed by measuring the injection efficiency at two different betatron tunes (repeated for 5 times), as shown in Fig. 7.

Table 3: Injection Efficiency

Tune	Measurement	Simulation
(36.18,19.24)	58%	66%
(36.21,19.24)	75%	79%
(36.18,19.21)	74%	73%

Using a calibrated model, the injection efficiency of RHB lattice was calculated by tracking simulations. Assuming a smaller ID4 physical aperture in the simulation, plus 22.5 mm separation between injected and stored beam orbit, the measurement and numerical simulation results are compared in Table 3. Good agreement is achieved.

CONCLUSION

During the machine studies at the Advanced Photon Source storage ring, it was observed that the injection efficiency was dependent on the fractional betatron tunes. Numerical simulations using the calibrated lattice model confirm that point. It was also observed that the simulated injection efficiency agrees well with the measurement by employing measured physical aperture at ID4. Injection efficiency was measured on the fractional tune map, which provides some guidance on how to tweak tunes when low injection efficiency is encountered during operations.

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