OPTIMIZATION AND MODELING STUDIES FOR OBTAINING HIGH INJECTION EFFICIENCY AT THE ADVANCED PHOTON SOURCE*

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Abstract

In recent years, the optics of the Advanced Photon Source storage ring has evolved to a lower equilibrium emittance (2.5 nm-rad) at the cost of stronger sextupoles and stronger nonlinearities, which have reduced the injection efficiency from the virtual 100% of the high emittance mode. Over the years we have developed a series of optimizations, measurements, and modeling studies of the injection process, which allows us to obtain or maintain low injection losses. The above will be described along with the injection configuration.

INTRODUCTION

The Advanced Photon Source storage ring (SR) has forty double-bend achromat-style cells whose effective emittance was minimized to a value of 3.1 nm-rad. As a result, the sextupole magnet strengths have increased, reducing the dynamic aperture to the range of 7-10 mm, depending on the optics correction and skew quadrupole field errors, leading to injection losses. Thus it is important to understand and control the injection steering and matching optics, which the paper will cover. The nonlinear aspects are covered elsewhere in these proceedings [1]. We will describe our approach for maximizing the injection efficiency for a given dynamic aperture, then present some modeling of the first-pass trajectory. Also, a correction to the booster-to-storage ring (BTS) transfer line is described.

DESCRIPTION OF INJECTION

The BTS transport line brings the booster beam close to the storage ring beam in an SR 5-m-long straight section in a parallel trajectory. The booster beam is bent horizontally at the end of the beamline by a 1.75-m-long thick-septum magnet of 74 mrad and a 1.05-m-long thin-septum magnet of 33 mrad separated by 0.55 m of drift. The thin septum is attached to the SR vacuum chamber, as shown schematically in Figure 1.

Four ferrite-loaded kickers with separate power supplies are located along the two adjacent sectors. Figure 2 shows the SR magnet locations over several sectors. Arrows point to the location of the four kickers. The magnetic field waveform consists of a rise time of 0.5 μs, a flat-top of about 0.1 μs and an exponentially decaying tail of about 3.5 μs, giving a slightly longer pulse length than the revolution time of 3.68 μs. The kickers are set to produce a bump of about -16 mm (the minus sign refers to inboard injection) in a single turn, the largest kick angle being about 1 mrad. The BTS line launches the beam into the SR at a horizontal offset of about -23 mm. The horizontal booster beam size is about 1.1 mm, about four times larger than the stored beam. The beam separation is designed to be 7 mm. Thus the centroid oscillation for a matched bump is 7 mm. After a few damping times, the betatron oscillation of the injected particles damps down to form a stored beam of equilibrium emittance in the target rf bucket. Due to the extended injected beam distribution, some particles initially oscillate with a larger amplitude of, say, 11 mm and may get lost.

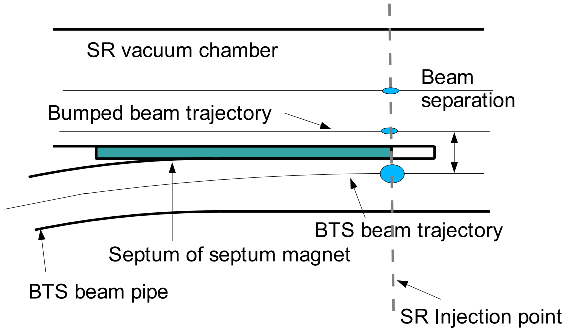

Figure 1: Injection point and vacuum chamber layout showing the thin septum. Injection is from the inboard side of the SR.

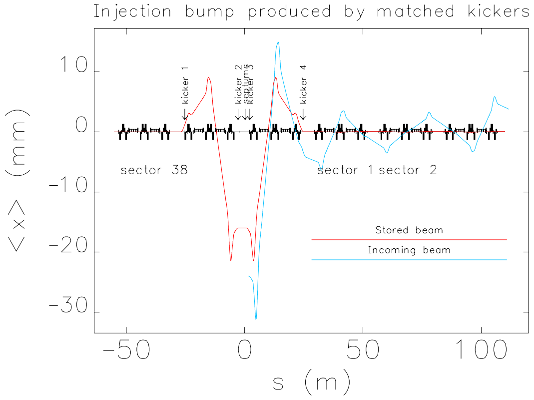

Figure 2: Matched bump for injection.

The available aperture for injection is determined by the physical apertures reduced by the effects of sextupole nonlinearities and skew quadrupole errors, which is described in more detail in [1]. Here we list the critical physical apertures. The vacuum chambers in the arcs have elliptical apertures of ± 42 mm and ± 21 mm in the horizontal and vertical planes, respectively. They are quite large and therefore inconsequential. The straight sections for undulators have the smallest apertures (and acceptance) in the ring in both planes. In the vertical plane the apertures are ± 2.5 mm in two particular straight sections (in only one after May 2005) and ±4.0 mm elsewhere. In the horizontal

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plane the smallest apertures are on the inboard side, with -15 mm for the ± 2.5 mm chambers above, -20 mm for standard chambers, -18 mm for newer standard chambers, and -18 mm for the injection septum.

Figure 3 shows the relative sizes of beams and chamber apertures projected at the injection point. The locations of the centers of the beams are nominal values. It is difficult to measure their positions to, say, 0.1-mm accuracy since we don't have beam position monitors (BPMs) in that region of the SR. Fortunately, knowledge of the actual positions isn't necessary to maximize efficiency. An obvious approach to reduce injection losses is to bring the stored and injected beams as close as possible to each other (i.e., minimize betatron oscillation) at the injection point while not scraping too much charge on the septum wall.

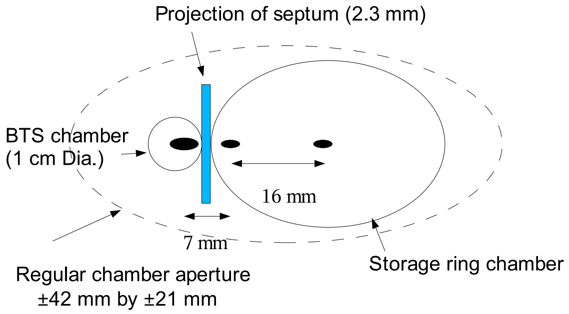

Figure 3: Apertures at the injection point and positions of the kicked and unkicked stored beam and the position of the injected beam. Not to scale.

Note that one doesn't gain that much aperture by making the septum narrower. If one needs to keep four sigmas of the injected and stored beams, then the separation has to be 5.6 mm plus the septum thickness.

Figure 2 shows the stored beam and the injection beam trajectories for an ideal matched bump. The orbit bump is negative because of inboard injection. The injection point is just upstream of the third kicker. For setting up a matched parallel bump, we use the EPICS optimizer `sddsoptimize` from the EPICS SDDS-compliant toolkit [2] to adjust the amplitudes of the kickers until a closed bump is achieved for a given amplitude [3]. The set points of the kickers will depend on the sextupole magnet settings of the two sectors in the bump. Also the stored beam sizes start oscillating as a result of the focusing of the sextupoles by about 22%.

The amplitude of the matched bump is set as large as possible while making sure that the standard 100-mA beam composed of 24 bunches does not suffer significant losses at the septum. When setting up the kicker bump, the orbit on the girders adjacent to the injection straight section is corrected to enforce a parallel bump along the precisely aligned SR vacuum chamber.

Under closed-bump conditions there is excessive injection losses due to insufficient dynamic aperture. The closed-bump condition is therefore only used in tune-up procedures and other analyses. During actual operations we use a mismatched bump condition, which reduces the injection losses by a large factor.

In a mismatched bump where the kick angle of the last two kickers is increased somewhat, the injected beam oscillation amplitude is lowered at the expense of a stored beam oscillation. At large enough mismatch, one gets on-axis injection, which is very good for the injected beam but causes loss for the stored beam. The optimum aperture condition lies between a matched bump and the on-axis condition.

Figure 4 shows the oscillation amplitude equally shared between the stored and injection beam, which maximizes the available aperture for both stored and injection beams. However there are transverse wakefields produced by the oscillating stored bunch that cause particle loss in both injected and stored beam, which has been modeled by Chae [4]. This creates a single-bunch charge limit that is lower than that for a matched bump. In operations we reduce the amount of kicker mismatch from the equally shared case. Thus we have a trade-off between injection efficiency and maximum bunch current. For studies that require high bunch charge, we reduce the mismatch.

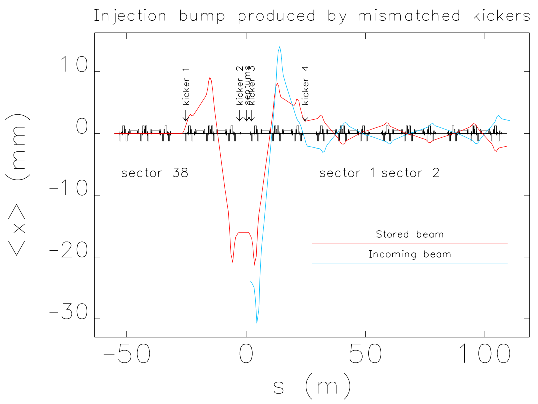

Figure 4: Mismatched bump for injection.

In either a matched or mismatched bump condition, we run a steering optimizer on the BTS transfer line described earlier in [3] involving two horizontal steering magnets and the two septums with the objective to maximize the injection efficiency. Though we don't obtain 100% efficiency after this step, we conclude that at least the beam has cleared the small apertures of the septum beam pipes. To maintain the steering in the BTS line we optionally run a slow BTS trajectory control loop in both planes.

After these steps the injection efficiency is about 85%. When the kickers are configured for a matched bump, the injection efficiency is about 65%.

FIRST-TURN TRAJECTORY

The measurement and modeling of the first-turn trajectory is useful for verifying that the beam isn't being scraped against some of the small apertures in the injection section. The analysis of the first-turn trajectory data provides the initial conditions x, x', and δ at the injection point. In one case the fit of the trajectory model to the measured trajectory using simplex minimization gave the values of x = -24.7 mm, x' = 0.13 mrad, and δ = -0.31%. The ideal coordinates are x = -23 mm, x' = 0 mrad, and δ = 0%. Figure 5 shows the comparison of the optimized trajectory measurement with the ideal model and with the fitted model of the trajectory. The injection oscillation for the matched bump is then about 8.6 mm with δ = -0.3%, a reasonable value but close to the edge of the dynamic aperture. Note that the ideal value of -23 mm for x is almost arbitrary. Referring to Figure 3, the target value for the trajectory is really anywhere inside the BTS tube.

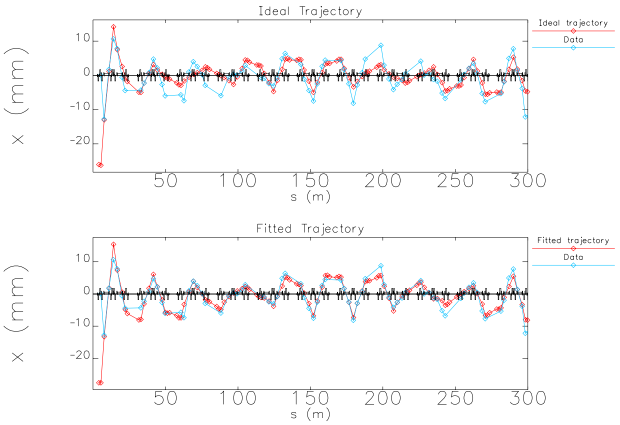

Figure 5: First-turn trajectories for the ideal lattice, and measurements.

The momentum error of -0.3% is confirmed by the analysis of the BPM history over 200 turns (not shown). The BPM history analysis also gives the SR rf bucket phase error. The optics model doesn't fit all parts of the oscillation of Figure 5. We could probably get better agreement if we had used a fitted ring model for optics.

Incidentally, negative δ improves inboard injection when dispersion is present, as it reduces betatron oscillation by $-\delta\eta$, where η is the dispersion at the injection point. A possible injection improvement suggested and attempted by Chae [5] is to make the dispersion in the injection straight section larger, say 0.4 m (a complex change to implement), and then to inject a beam with $\delta = -1\%$. That would reduce the betatron oscillation by 4 mm, a significant amount.

TRANSFER LINE OPTICS

The booster optics was changed a few years ago in order to reduce the equilibrium emittance from 130 nm-rad to 92 nm-rad. Actually the booster is run with a -0.9% momentum error, which reduces the emittance further to 61 nm-rad [6]. This reduction helped injection efficiency somewhat because the BTS beam size at the injection point has reduced from 1.6 mm to 1.1 mm.

The pulsed septum magnets of the booster (and those of the SR) have a 0.15% jitter, measured by the beam-based model-independent analysis reported in [7]. The jitter effectively increased the horizontal beam size by 1.5 mm at the injection point. New power supplies for all pulsed magnets with sufficiently reduced jitter are being built [8].

A betatron and dispersion mismatch in the BTS would decrease the injection efficiency. We made a simple investigation of a dispersion function. The particular dispersion function with initial value of 0 m at the booster extraction kicker is measured by varying the extraction timing of the booster linear ramp and changing nothing else. Note that this dispersion function is not the same one that is matched in the beamline.

Figure 6 shows the comparison between the measured dispersion, the ideal value of the dispersion, and the dispersion for a 2.1% quadrupole adjustment. The measurement agrees with an optics model where the quadrupoles are set 2.1 % above their normal values. Thus there is an apparent 2% calibration error on the quadrupoles, which has since been taken into account. A corrector response measurement would have given the same result, but the dispersion response was easier to do.

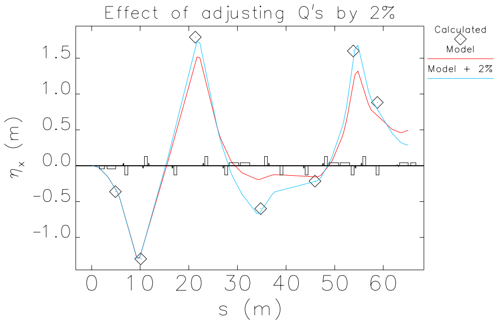

Figure 6: Measured and calculated dispersion in the BTS transfer line, including a model where quadrupoles are set to 2% too strong.

We obtained a good model of the BTS optics. The injection area was upgraded in January 2004 to improve mechanical robustness and diagnostics. A fiducialized YAG crystal has been placed between the two SR septums so that the image of the beam can serve as an additional BPM in addition to providing beam size information. This capability hasn't been used yet.

CONCLUSION

Several procedures and analyses were described for verifying the injection basic configuration. We apply them after every shutdown and whenever some injection problem occurs suddenly.

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