

# SIMULATION STUDY OF INJECTION PERFORMANCE FOR THE ADVANCED PHOTON SOURCE UPGRADE\*

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## Abstract

A vertical on-axis injection scheme has been proposed for the hybrid seven-bend-achromat (H7BA) [1] Advanced Photon Source upgrade (APSU) lattice. In order to evaluate the injection performance, various errors, such as injection beam jitter, optical mismatch and errors, and injection element errors have been investigated and their significance has been discovered. Injection efficiency is then simulated under different error levels. Based on these simulation results, specifications and an error-budget for individual systems have been defined.

## INTRODUCTION

A hybrid seven-bend-achromat (H7BA) lattice has been designed for the APSU. It features a 67 pm natural emittance and its brightness exceeds today's APS by two to three orders of magnitude. Strong nonlinear effects associated with the design present a great challenge to the injection design. Based on investigations made for several different injection configurations, an on-axis single sector "swap-out" vertical injection scheme was adopted, and the injection performance was calculated including various machine errors.

The change of Courant-Snyder invariant  $\Delta A_u = A_u - A_{u,0}$  is used to determine quantitatively which injection errors dominate, ( $A_u = \gamma_u u^2 + 2\alpha_u uu' + \beta_u u'^2$ , where  $u$  stands for  $x$  or  $y$ ,  $\gamma_u$ ,  $\alpha_u$  and  $\beta_u$  are corresponding optical function at the injection point,  $A_{u,0}$  is the value in ideal conditions). For an error that causes equivalent emittance increase,  $A_u$  stands for the equivalent emittance with errors; for an error that causes beam centroid motion,  $A_u$  is equivalent to the amplitude of the motion, as  $\Delta u = \sqrt{\Delta A_u \beta_u}$ .

This paper first describes the types of errors that were included in the injection study. It then gives calculated  $\Delta A_u$  under various error levels, which are chosen based on our past operational experience and on assumptions about the new hardware systems. The range of  $\Delta A_u$  is obtained by summarizing contributions from all types of errors, and the significance of each sub-system error is identified. The injection performance is studied by simulating injection efficiency at different  $\Delta A_u$  levels. The specifications and an error-budget for individual systems are given based on the overall injection performance requirement. To validate the obtained specifications, a simulation that includes shot-to-shot variations of various parameters is done, and results are given at the end. The injection efficiency is simulated by 1000-turn tracking a bunch consisting of 2000 particles

with a distribution corresponding to that of the booster. Synchrotron radiation, apertures, rf systems, etc. are included in tracking.

## TYPE OF INJECTION ERRORS

Many imperfections could occur during injection:

### Transverse Optical Function Mismatch

This is a systematic error. Because of the filamentation process after injection, a transversely mismatched injected bunch is equivalent to a matched bunch with emittance ellipse enclosing the entire mismatched bunch ellipse, as seen in Fig. 1. The emittance increase  $\Delta A = A - A_0$  depends on the magnet strength errors in the booster to storage ring (BTS) transport line, and on how well the optical functions can be corrected.

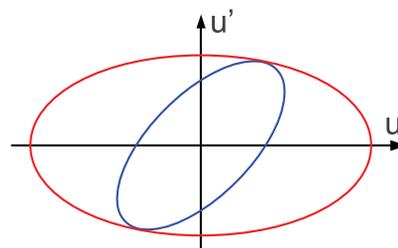


Figure 1: Optical function mismatch at the injection point. Blue - mismatched injected beam emittance  $A_0$ ; red - equivalent injected beam emittance  $A$ .

To evaluate how  $\Delta A$  varies versus the magnet strength error level, the current APS BTS line design, with an arbitrary matrix added at the end to match optical functions at the injection point, is used as the simulation model. Mismatched optical functions and associated  $\Delta A$  are calculated at three magnet strength error levels: 1%, 2%, and 3%. 5000 uniformly distributed random cases are simulated for each error level, and the maximum of  $\Delta A$  for all cases with beta function error of less than 5%, 10%, and 15% are calculated, see Fig. 2. Beta function error is used because this parameter is convenient to measure and correct in practice. From Fig. 2, it is seen that emittance increase depends strongly on the magnet strength error level, in a way that is not strongly reflected in the beta function error at the injection point. Based on our operational experience, three cases are chosen for the injection performance simulation studies: no optical errors; beta error level at 10% and magnet strength error level at 1%, which gives  $\Delta Ax = 20$  nm and  $\Delta Ay = 4$  nm; beta error level at 10% and strength error level at 2%, which gives  $\Delta Ax = 40$  nm and  $\Delta Ay = 8$  nm.

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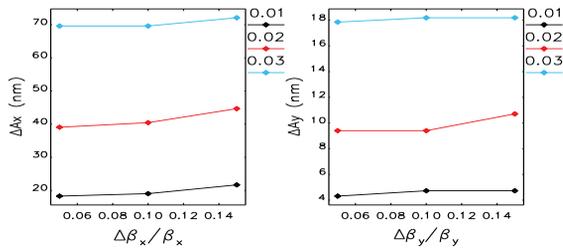


Figure 2: Equivalent emittance increase vs. fractional beta function error level at different fractional magnet strength error levels.

### Longitudinal Mismatch

This is a systematic error with two major causes: collective effects in the booster, and the storage ring high harmonic cavity (HHC), used to lengthen the bunches. The HHC is included in the storage ring lattice used for tracking. The injected bunch is assumed to have 100 ps rms bunch length and 0.12% rms energy spread, which is probably a conservative assumption [2].

### Injected Beam Trajectory Error

Three types of trajectory error exist during injection:

- Injected beam trajectory mismatch at the injection point  $(x, x', y, y')$  — systematic error. This error is equivalent to having non-zero closed orbit at the injection point in the storage ring.
- Injected beam pulse to pulse jitter  $(x, x', y, y')$  — random error. The jitter corresponds to a beam center spreading over  $\Delta A$  in phase space. To simplify the simulation, errors are set in terms of the equivalent trajectory error at the injection point, as  $\Delta u = \sqrt{\Delta A_u \beta_u}$ . The measured BTS jitter value [3] is used, with  $\Delta A_y = 0.3$  nm (corresponding to  $\Delta y \approx 28 \mu\text{m}$ ), and  $\Delta A_x = 5$  nm (corresponding to  $\Delta x \approx 180 \mu\text{m}$ ).
- Bending angle errors of the septum and SR injection kickers — random error. The calculated  $\Delta A$  versus the kicker and septum magnet strength errors is shown in Fig. 3. The main error source is the stripline kicker strength error, which causes the vertical injected beam trajectory error. For  $\Delta A_y = 20$  nm,  $\Delta y \approx 250 \mu\text{m}$ .

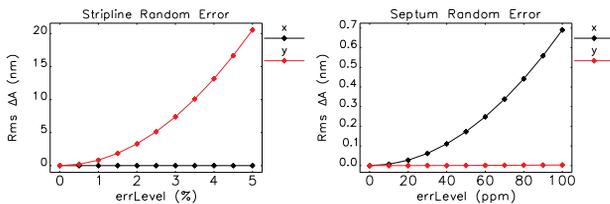


Figure 3: Equivalent injection beam oscillation amplitude (in Courant-Snyder invariant form) vs. stripline (left) and Lambertson magnet (right) error levels.

### Injected Beam Longitudinal Error

Injected beam can have energy mismatch and arrival time errors. These errors can be either systematic or random. In normal operation, the shot-to-shot jitter is small, therefore most of the errors are systematic. In simulation, both errors can be represented as energy errors, see Fig. 4.

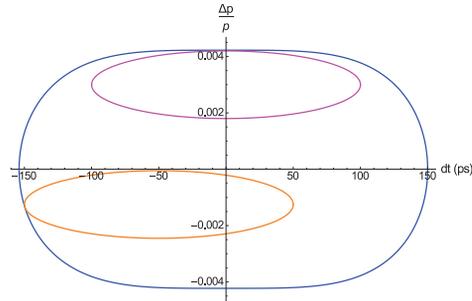


Figure 4: Assumption made for longitudinal mismatch injection simulation. Orange line: mismatched injected beam profile with an arbitrary injection error,  $\sigma_l = 100$  ps and  $\sigma_p = 1.2 \times 10^{-3}$ ; Magenta line: mismatched injected beam profile, injection error equivalents to an energy offset of 0.3%; Blue line: ring's rf bucket.

## INJECTION PERFORMANCE AT DIFFERENT ERROR LEVELS

In the previous section, we discussed possible injection error types and levels. To investigate how injection performance is impacted by different levels of errors, we performed injection simulation for injected beam with emittances of a)  $\epsilon_x = 60$  nm and  $\epsilon_y = 20$  nm (matched beam); b)  $\epsilon_x = 80$  nm and  $\epsilon_y = 24$  nm; and c)  $\epsilon_x = 100$  nm and  $\epsilon_y = 24$  nm. The injected bunch length was 100 ps and  $\frac{\Delta p}{p} = 0.0012$ . These represented various mismatch scenarios. Other errors were simulated as injection offsets of  $\Delta x = 0 \mu\text{m}, 100 \mu\text{m},$  and  $200 \mu\text{m}$ ;  $\Delta y = 0 \mu\text{m}, 150 \mu\text{m}, 250 \mu\text{m}, 350 \mu\text{m},$  and  $450 \mu\text{m}$ ; and  $\frac{\Delta p}{p} = 0, 0.0015, 0.003,$  and  $0.0045$ . 2000 particles had been tracked for 1000 turns for 100 sets of storage ring optical errors [4]. Figure 5 shows the injection loss rate averaged over 100 set of SR optical errors as a function of the orbit error at different energy error levels. The injected beam emittance used in this plot was  $\epsilon_x = 80$  nm and  $\epsilon_y = 20$  nm.

To satisfy the requirement of having the average loss rate is less than 1%, the total error budget is set to  $\Delta x = 200 \mu\text{m}, \Delta y = 250 \mu\text{m},$  and  $\Delta p/p = 0.003$ . This corresponds to the following conditions: injected beam jitter at the level measured in the current BTS line; 5% kicker strength error; 0.3% energy error; BTS magnet strength error of 1%; and beta function errors of 10%. The distribution of loss rate over 100 optical errors at this error level is shown in Fig. 6.

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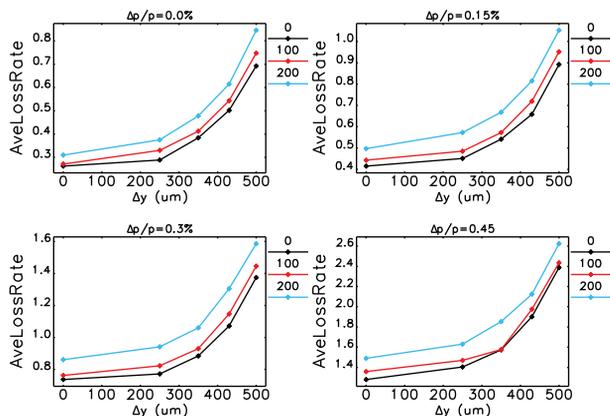


Figure 5: Injected beam loss rate (in %) averaged over 100 optical errors vs.  $\Delta y$ . Legend - x orbit mismatch ( $\Delta x=0,100,200 \mu\text{m}$ ). Simulation condition:  $\varepsilon_x = 80$  and  $\varepsilon_y = 20$  nm.

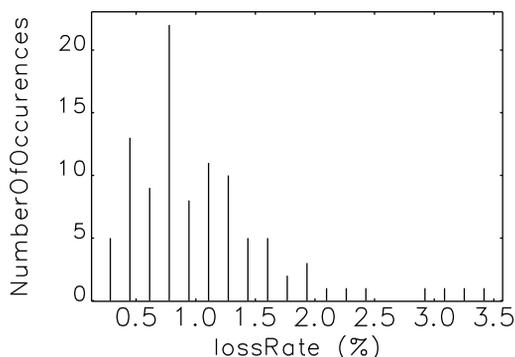


Figure 6: Injection beam loss rate distribution over optical errors (100 seeds). Simulation conditions:  $\Delta x = 200 \mu\text{m}$ ,  $\Delta y = 250 \mu\text{m}$ ,  $\Delta p/p = 0.003$ ,  $\varepsilon_x = 80$  and  $\varepsilon_y = 20$  nm.

## SHOT-TO-SHOT INJECTION PERFORMANCE SIMULATION

In order to determine the error level specification, all errors are assumed to be systematic in the previous section. To simulate shot-to-shot variation of the injection losses, a BTS optical mismatch error was chosen that is equivalent to  $\varepsilon_x = 80$  nm and  $\varepsilon_y = 20$  nm, along with the energy error of  $\Delta p/p = 0.003$ . The storage ring optical error set that gives the maximum loss rate in Fig. 6 was also chosen. This represents one possible case of systematic error. Then, random errors were assigned to the kickers, septum, and injected beam trajectory. The error amplitudes are listed in Table 1. 2000 particles were tracked for 1000 turns for 5000 random cases; the resulting distribution of the loss rate is shown in Fig. 7. Only 6 out of 5000 shots have loss rate greater than 2%.

Table 1: Summary of Various Injection Beam Errors

Source	Type	Level	$\Delta x$ ( $\mu\text{m}$ )	$\Delta y$ ( $\mu\text{m}$ )
Optical Mismatch	Sys.	$\Delta K_1/K_1 \leq 0.01$		
Energy Mismatch	Sys.	$3 \times 10^{-3}$		
Orbit Mismatch <sup>a</sup>	Sys.		100	80
Stripline	Ran.	$\Delta\theta/\theta \leq 0.05$		230
Septum	Ran.	30 ppm	24	
Jitter	Ran.	Operational	180	27

<sup>a</sup> This part is included via the storage ring error ensembles.

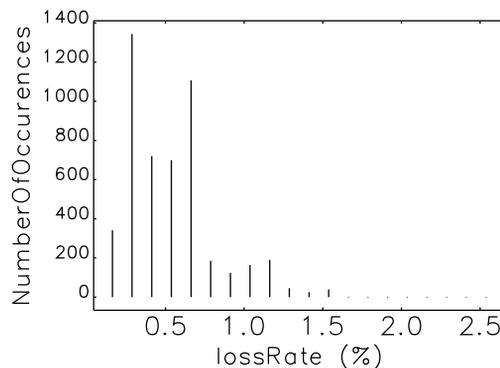


Figure 7: Injection beam loss rate distribution shot-to-shot. Simulation conditions: optical mismatch error that gives equivalent  $\varepsilon_x = 80$  nm and  $\varepsilon_y = 20$  nm, energy error of  $\Delta p/p = 0.003$ , optical error that gives the maximum loss rate in Fig. 6.

## CONCLUSIONS

We have analyzed most of the errors that could happen during the injection into the APS MBA ring. Using the Courant-Snyder invariant, all types of errors can be compared quantitatively and the most significant errors can be identified. The injection performance was studied by calculating average injection efficiency for different error levels, and the error budget established. Choosing one particular systematic error set (which gives the largest average injection loss), the shot-to-shot variation of injection performance was also studied. Simulation results show that less than 2% injection beam loss can be obtained under current error level specifications.

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