ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOPLM12

PROGRESS ON THE INJECTION TRANSPORT LINE DESIGN FOR THE APS UPGRADE*

A. Xiao†, M. Borland, ANL, Lemont, IL USA

Abstract

An on-axis vertical injection scheme was adopted for the Advanced Photon Source Upgrade (APS-U) multi-bend achromat lattice. As the design of the injection scheme has become more detailed, the booster to storage ring transport line (BTS) has advanced, including effects such as the septum field map and stray fields of storage ring magnets. Various error effects are simulated for setting specifications and predicting expected performance. The beam diagnostic scheme, including emittance measurement, is incorporated into the beamline design.

INTRODUCTION

The BTS line design for APS-U has advanced as detailed information became available, such as the septum magnet design [1,2]; stray fields from the storage-ring magnets, and beam-based measurement results using the current BTS line. Issues have been identified and addressed in studies.

The injected beam will inevitably pass through some storage ring magnets (Q1 and Q2) as its trajectory merges with the stored beam trajectory, and similarly the stored beam will pass through the septum magnet and stripline kickers. These beams will see different magnetic fields and alignment, as well as different path length. These effects are included in the current BTS line design and results presented here, leading to revised geometry and optical solutions. In addition, a coupling issue was identified and a simple solution was found to minimize the effect.

For beam diagnostics, an emittance measurement station is included in the optical design; the required screen resolution was obtained from simulation results. Simulations of optics measurements and correction were just started. Some beam-based measurements and simulation results for BPM noise, booster extracted beam jitter, quad alignment errors, and dispersion measurement are also presented here.

INJECTION SECTION DESIGN

In the injection section, both stored and injected beam pass through the same elements on different trajectories, i.e. from the upstream end of Q2 magnet to the downstream end of stripline kickers, as shown in Fig. 1. Since we are doing on-axis injection, this section is designed using backward tracking of the the injected beam. From Fig. 1, one can see that the injected beam and stored beam have different path lengths in same elements; even for elements that are the same (for example the three stripline kickers), the path length of injected beam, i.e. the effective length, are slightly different due to different entrance/exit angles. The path length of each element can be calculated analytically, or using a simulation code such as `elegant` [3] to fit the floor coordinates. We use the latter method since it's simple and reduces human errors.

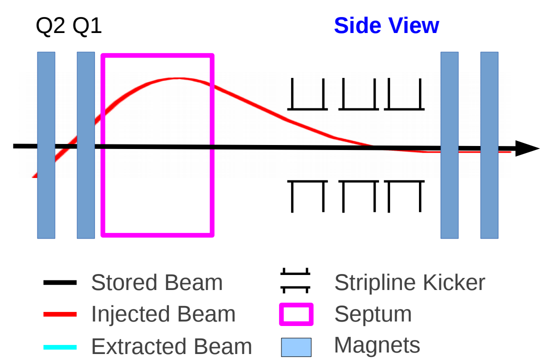

Figure 1: Schematic drawing of injection region.

The septum field map [4] from 3D OPERA simulations is included in the updated BTS line design instead of a hard edge dipole magnet; the details of simulation with the septum field map are described in [5]. The difference in the injected beam trajectory between a hard edge magnet model and the field map is shown in Fig. 2. This difference requires rematching the BTS line geometry.

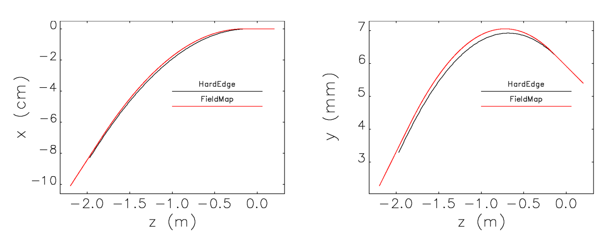

Figure 2: Calculated injected beam orbit from hard edge model (black), and septum magnetic field map (red).

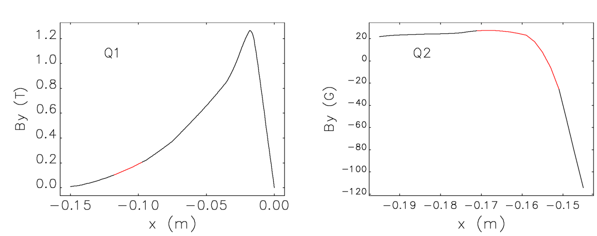

Figure 3: Stray field profile (B_y vs x at $y = 0$ and $z = 0$), red-line shows injected beam centroid range when it goes through the storage ring Q1 and Q2 magnets.

---

* Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

† xiaoam@anl.gov

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOPLM12

The 3D stray field maps of the Q1 and Q2 magnet are given from magnet design calculations [6, 7] with OPERA; Figure 3 shows the mid-plane ($y = 0$) field profile at the magnet center ($z = 0$). The leakage field of Q2 is small and shows a strong non-linear property along the injected beam trajectory, which enters at $x = -0.17$m and exits at $x = -0.15$m; this field is ignored currently in the hope that it can be shielded. The leakage field of Q1 is quite large and provides a bend opposite in sign to the septum, as well as a defocusing quadrupole field to the injected beam (Q1 is a focusing quad to the stored beam). Further, since the injected beam reference frame is tilted here (it will be tilted back using the downstream tilted septum magnet), the injected beam sees a tilted Q1 leakage field while the stored beam sees a normal quad.

COUPLING ISSUES

The effects mentioned in the previous section are accommodated by tracking backwards to the entrance of the Q2 magnet. Optical functions and floor coordinates at the entrance of Q2 are re-matched by adjusting the upstream part of the BTS line. Originally (without Q1 leakage field), the vertical dispersion was corrected to zero at the injection point, and multi-particle tracking showed little $x - y$ coupling effect. The same strategy was used in the new design, but a coupling-related issue was discovered when performing injection simulatoins [8]. First, we tried to correct the coupling with more skew quads, but due to limited space the solution was quite complicated. A better result was obtained through minimization of the cross-plane terms in the sigma matrix (4D match), while allowing non-zero vertical dispersion . Figure 4 shows the phase space at the injection point with and without vertical dispersion correction. It appears that attempting to match the vertical dispersion to zero is harmful because it inadvertently couples the relatively large horizontal emittance into the vertical.

Since explicit correction of vertical dispersion appeared unnecessary, we wondered if correction of cross-plane terms was unneeded, and tried turning off all skew quads; this provided a slightly better result than 4D matching. Figure 5 shows the optical functions without vertical dispersion correction. The injection performance for different correction schemes was modeled with `Pelegant` [9] and is shown in Fig. 6, showing that injection losses are not increased by non-zero vertical dispersion or small residual coupling. The reason is that the vertical injected beam size is much smaller compared with ring's vertical dynamical acceptance, and the contribution from small dispersion plus beam energy error/spread is very small.

DIAGNOSTIC CONSIDERATIONS

Emittance Measurement

Due to limited space, a single quad scan was posited for emittance and single-point beta function measurements; the screen location is indicated in Fig. 5 by the blue arrow. Both horizontal and vertical beam waists can be obtained by independently scanning the two quads upstream of the screen station. The minimum beam sizes are 476-μm(H) and 35-μm(V), assuming ε_y=1-nm. These numbers were given to the diagnostic group for guiding optical system design. Meanwhile, building on earlier work [10], a multi-quadrupole scan method that can determine the 5x5 sigma matrix was developed and will be tested soon.

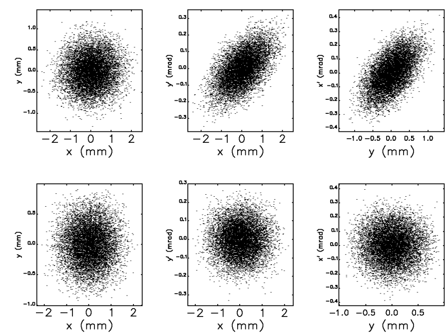

Figure 4: Phase space at the injection point: top/bottom - with/without vertical dispersion correction.

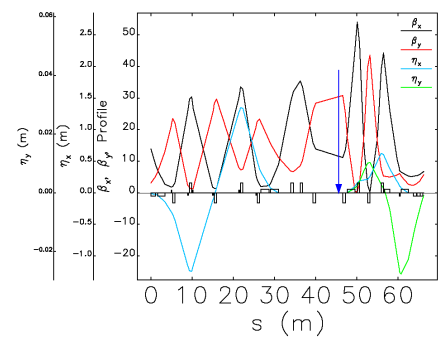

Figure 5: Optical functions for BTS line without vertical dispersion correction.

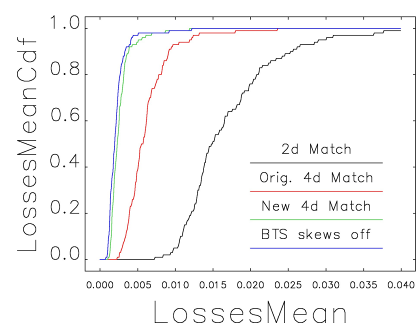

Figure 6: Cumulative distribution of mean simulated injected losses over 30 shots for four different BTS line configurations.

BPM Noise and Injection Jitters

Before performing detailed optics measurements, one needs to know the limitations the BPM noise and injection jitter levels. This was done by taking shot-to-shot BPM data using the current BTS line. SVD was used to decompose the

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOPLM12

collected injection trajectories; the resulting singlar values (SVs) are shown in Fig. 7. The first three (two) SVs in the horizontal (vertical) plane are from booster extraction errors (injection jitters) and the rest are from BPM noise, giving the noise floor [11]. The BPM noise level can be determined by $SV/\sqrt{N}$, where N is the total number of measurements. Actual injection orbits are revealed by removing BPM noise, using the BTS model, allowing one to get $\Delta(x, x', y, y')$ and $\delta = \Delta p/p$ at the entrance of the BTS line. Our multiple measurement results show that the BPM noise level is ~50-μm, and injection jitters are A_x < 5-nm, A_y < 0.1-nm, and $\delta \approx 10^{-4}$, with $A_{u=(x,y)} = \gamma_u u^2 + 2\alpha_u uu' + \beta_u u'^2$.

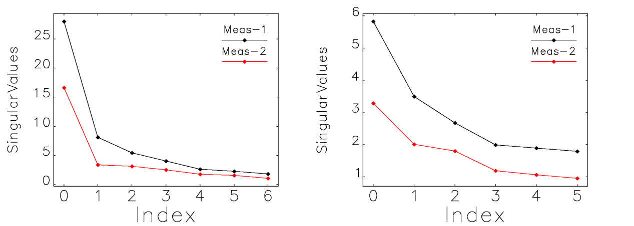

Figure 7: Singular values of BTS jitter measurements: left-Horizontal plane; right-Vertical plane.

Dispersion and Quad Offsets

Simulations are being used to understand optics measurement and correction strategies, starting with dispersion measurement, and including measured BPM noise and injection jitters. There are two common methods for dispersion measurement: (1) Varying the booster rf frequency, in which case the beam position at the extraction point is also changed, and the results should be compared with the "dispersion function" of the BTS line using booster optical functions at the extraction point as input. (2) Varying beam extraction time; the beam position at the extraction point is not changed, so the results should be compared with the "dispersive function", i.e. R_{16} starts from the extraction point. Figure 8 shows that both methods can be used with good accuracy. Due to the fact that for APS, the same rf source is used by SR and booster, varying booster rf will cause stored beam dump, so the method of varying of extraction turns is preferred.

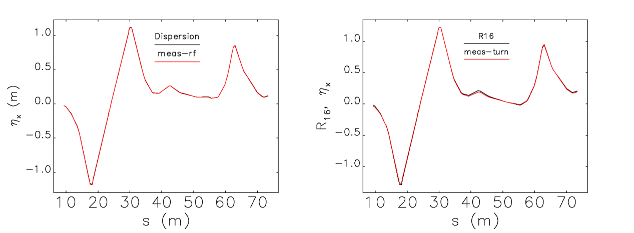

Figure 8: Simulation results on dispersion measurement: left-varying of rf; right-varying of extraction turns.

An investigation was made of the small discrepancy in the second method, leading to discovery of the effect of horizontal trajectory offsets in the quadrupoles, which produce spurious dispersion. Figure 9 shows the simulated measured dispersive function, the R_{16} function from the ideal model, i.e. zero on-momentum orbit through BTS line, and the R_{16} function from a model including orbit error inside the quads. One can see that the measured dispersive function agrees with model that includes quad offsets. This phenomena can be explained by Eq.1,

$$\Delta\theta(\delta) = K_1 L(1+\delta)(x_0 + D\delta) - K_1 L x_0 \qquad (1)$$

i.e. the kick error from a quad for a off-momentum beam is not only from the dispersive trajectory entering the quad, but also from the momentum-dependent variation of the kick from the trajectory offset. The ratio between these two contributions is $\sim \frac{x_0}{D}$. If a quad is at a location of small dispersion, then its offset contribute more to the measurement errors.

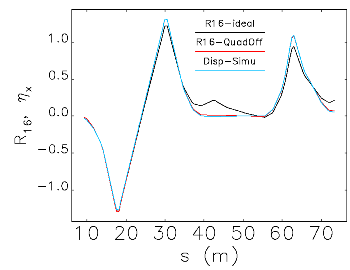

Figure 9: Comparison of simulated dispersive function (blue) and R_{16} from an ideal model (black) and R_{16} from model including quad offset (red).

CONCLUSIONS

As development of engineering designs for the APS-U project proceeds, the BTS line design has been updated with path length adjustment and detailed magnet design results, using data such as the septum field map and storage ring quad stray field maps. The geometry layout and optics were re-matched. Concerned about vertical dispersion in this 3D system, we initially matched the vertical dispersion, but found that a 4D matching approach that emphasizes beam size and reduces coupling terms is much better. However, simply ignoring the issue seems essentially as good; further investigation is needed in future. Required diagnostic systems and correction strategies are under study. An emittance measurement station is included in the design and requirements were specified. BPM noise and incoming beam jitter levels were measured on the existing system as input into further simulations. A simulation study of dispersion measurement methods was performed, revealing an unrecognized impact from quad alignment errors.

ACKNOWLEDGMENTS

Magnet field maps used in this paper are provided by the magnet design group members. Work presented here was inspired by discussions with the APS-U beam physics group. Some simulations used the Bebop and Blues clusters at Argonne National Laboratory.

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOPLM12

REFERENCES

[1] M. Abliz *et al.*, “Septum Magnet Design for APS-U”, in *Proc. North American Particle Accelerator Conf. (NAPAC'16)*, Chicago, IL, USA, Oct. 2016, pp. 1231–1233. doi:10.18429/JACoW-NAPAC2016-THPOA63

[2] M. Abliz *et al.*, “A concept for canceling the leakage field inside the stored beam chamber of a septum magnet,” *Nuclear Instruments and Methods A*, vol. 886, p. 7, 2018.

[3] M. Borland, “elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation,” Tech. Rep. ANL/APS LS-287, Advanced Photon Source, September 2000.

[4] M. Abliz, private communication, 2019.

[5] A.Xiao, M. Borland, and M. Abliz, “Simulation study with Septum field map for the APS upgrade,” presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Aug. 2016, paper MOPLM10, this conference.

[6] M. Jaski, private communication, 2018.

[7] J. Liu, private communication, 2018.

[8] M. Borland, private communication, 2018.

[9] Y. Wang and M. Borland, “Pelegant: A Parallel Accelerator Simulation Code for Electron Generation and Tracking,” *AIP Conf. Proc.*, vol. 877, p. 241, 2006.

[10] M. Borland, *A High-Brightness Thermionic Microwave Electron Gun*. PhD thesis, Stanford University, 1991. SLAC-402.

[11] J. Irwin, C. Wang, Y. Yan, K. Bane, C. Y, F. Decker, M. Minty, G. Stupakov, and F. Zimmermann, “Model-independent beam dynamics analysis,” Tech. Rep. SLAC-PUB-7956, SLAC, 1999.