ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-THYD4

PROGRESS ON THE APS-U INJECTOR UPGRADE*

J. Calvey, T. Fors, K. Harkay, U. Wienands, ANL, Argonne, IL, USA

Abstract

For the APS-Upgrade, it was decided to leave the present APS injector chain in place and make individual improvements where needed. The main challenges faced by the injectors are delivering a high charge bunch (up to 16 nC in a single shot) to the storage ring, operating the booster synchrotron and storage ring at different rf frequencies, and maintaining good charge stability during APS-U operations. This paper will summarize recent progress on the injector upgrade. Topics include bucket targeting with the new injection/extraction timing system, modeling of high charge longitudinal instability in the PAR, and measurements of charge stability for different modes of operation.

INTRODUCTION

The APS injector complex consists of a linac, particle accumulator ring (PAR), and booster synchrotron. These machines will remain for the APS-Upgrade [1], with several significant changes. The most important of these are a decoupling of the booster and storage ring rf frequencies, the capability of running with much higher charge per bunch, and a stricter standard for efficiency and charge stability. Key parameters for the PAR and booster are given in Table 1.

Table 1: PAR and Booster Parameters for the APS / APS-U

parameter	APS	APS-U	units
PAR			
Revolution time	102	102	ns
Energy	425	up to 475	MeV
Charge	0.5-3	2-20	nC
Booster			
Revolution time	1.22	1.22	μs
Energy	0.4-7	0.4-6	GeV
Charge	0.5-3	2-17	nC
Momentum offset	-0.6	variable	%

This paper discusses recent progress on the injection/extraction timing system, understanding PAR longitudinal instability, and quantifying charge stability. Other important updates include a higher power 12th harmonic amplifier in the PAR [2], and an upgrade of the booster photon diagnostics [3].

INJECTION/EXTRACTION

TIMING SYSTEM

The APS-Upgrade storage ring will run at a slightly higher frequency than the present ring. In order to avoid a costly re-alignment of the booster, it was decided to decouple the booster and storage ring RF frequencies. Bucket targeting will be accomplished by adding a frequency “bump” in the middle of the booster ramp. This will change the amount of time the beam spends in the booster, so that it lines up with the correct storage ring bucket at extraction. We also have the option of adding an overall frequency ramp in the booster, so that both injection efficiency and extracted emittance can be optimized [4].

Figure 1 illustrates the difference between a targeting bump and frequency ramp. Both show the turn-by-turn horizontal beam position at a dispersive BPM. The measured position with no frequency bump or ramp is subtracted off. The left plot shows this measurement for two different targeting bumps. The starting and ending positions are the same, since there is no net change of frequency. Bucket 340 requires a small positive frequency bump, while bucket 320 requires a large negative bump. The latter bump is large enough to cross the cavity resonance, leading to Robinson instability. Of course, this situation should be avoided in regular operation.

For Fig. 1 (right), there is a net frequency ramp between injection and extraction, between –18 and +12 kHz. This is reflected in a horizontal position change at the dispersive location. Some cases seem to show an instability around turn 80,000; this is not presently understood.

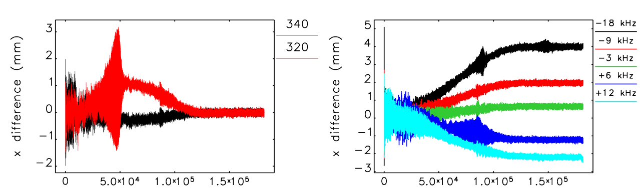

Figure 1: Horizontal position at a dispersive BPM (B1C4P1) in the booster. Left: effect of different targeting bumps. Right: effect of different frequency ramps.

Machine studies of increasing complexity have been done with the prototype system in the present APS ring. As of this writing we have:

- Verified we can control the three rf sources separately.
- Demonstrated bucket targeting in the Booster (bump).
- Tested transfer from the Booster to Storage Ring (SR) at different rf frequencies of both rings at extraction (ramp).
- Verified that we can inject into Booster and transfer to SR, with different rf frequencies at injection.

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

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-THYD4

The last scenario is the most challenging, and we observe larger than expected rf jitter. Work is ongoing to mitigate this issue.

PAR LONGITUDINAL INSTABILITY

Bunch length blowup as a function of charge has been observed in the PAR. It is caused by a combination of potential well distortion and microwave instability [5], and is one of the main factors limiting high charge injection into the booster [6].

This instability has been modeled with the particle tracking code `elegant` [7, 8]. The simulation includes longitudinal impedance and beam loading in the rf cavities. The impedance model was developed by simulating each element in CST Microwave Studio [9].

Fig. 2 compares the measured and simulated bunch length and energy spread vs charge. The bunch length is measured using a photodiode detector [10], and the energy spread is derived from measurements of the horizontal beam size at two synchrotron light monitors (SLMs). There is fairly good agreement between the measured and simulated bunch length, though the simulation is a bit lower. The simulation replicates the mostly linear blowup until very high charge, and the sudden jump around 18–19 nC.

For the energy spread, the agreement is not as good. The measured energy spread vs charge actually dips at two points- ~7 and ~13 nC. Similar features have been observed at NSLS-II [11]. Measurements above 16 nC varied significantly shot-to-shot, though they generally showed a large jump in the energy spread. While the simulation shows an energy spread blowup on the order of the measurement, the details are quite different. Accurately modeling the microwave instability is difficult, since it can depend on the high frequency part of the impedance. Agreement could be improved by repeating the impedance calculations with finer resolution.

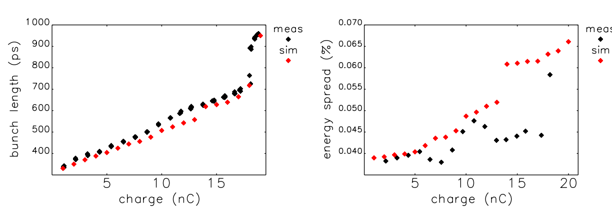

Figure 2: Measured and simulated bunch length (left) and energy spread (right) in the PAR.

We plan on reducing the bunch length at extraction with a high power RF12 amplifier [2] (for bunch compression), and higher beam energy (to reduce instability). According to simulation (Fig. 3), increasing the RF12 voltage from 21 to 30 kV should be very effective at compressing the bunch, though there is a jump in the bunch length at 18 nC. Increasing the PAR energy from 425 to 475 MeV pushes this threshold out to 20 nC. Our goal of a 600 ps bunch length is achieved for 19 nC, and just missed at 20 nC.

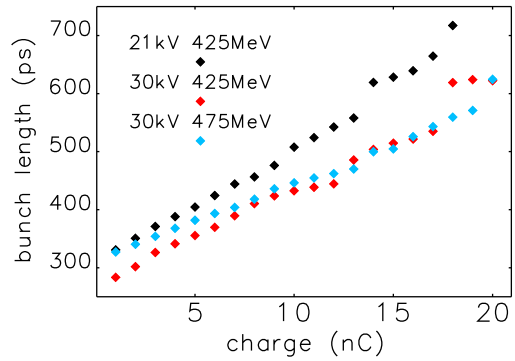

Figure 3: Simulations of the PAR bunch length blowup, comparing the present values of RF12 voltage and PAR energy to the planned APS-U values.

CHARGE STABILITY

In the present APS, charge stability is not really a concern- as long as a reasonable amount of charge makes it through the injector, it can be used to top up. In the APS-U, however, swap-out injection demands a much stricter requirement: ±5% rms. In addition, injection will be much more frequent, with 9–30 seconds between shots (depending on the mode of operation and degree of lattice errors). To help bridge this gap, a series of studies were performed to quantify injector stability over the course of several hours, and identify potential issues. These studies were done in two operating modes: continuous injection (where beam is run continuously through the injector chain), and intermittent injection (in which beam was enabled and disabled in set intervals).

Continuous Injection

In 324 bunch mode, the APS-U will require ~2.3 nC for most bunches, and ~4.6 nC for guard bunches [12]. Table 2 gives a list of continuous injection studies at (approximately) 2, 3, and 4 nC. The table lists the measured charge in the three transfer lines: Linac-to-PAR (LTP), PAR-to-Booster (PTB), and Booster-to-Storage Ring (BTS), as well as the overall efficiency and rms charge stability. For these studies, beam was run continuously through the injector for 5–8 hours. The measured charge for the first 2 nC study is shown in Fig. 4. For most cases, the efficiency is > 95%, and the rms charge stability is < 5%. Note that the current monitors are only accurate to a few percent.

For cases with poor efficiency or stability (e.g. index 2 and 6), the cause of the problem can usually be identified. Process variables (PVs) are monitored at a 2 Hz rate during these studies, which helps with diagnosing the problem. In case 6, for example, it was found that the efficiency was strongly correlated with the injection kicker setpoint (Fig. 5). This setpoint is adjusted by a “controllaw”, which tries to minimize transients at booster injection, and may have improperly set up that day. This controllaw has since been improved [13], and behaves much more consistently.

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-THYD4

Table 2: Continuous Injection Studies

Index	LTP (nC)	PTB (nC)	BTS (nC)	eff (%)	RMS (%)
1	1.99	1.80	1.90 ± 0.05	95	2.6
2	2.02	1.96	2.00 ± 0.15	99	7.5
3	1.99	1.96	1.81 ± 0.08	91	4.4
4	3.07	3.01	3.10 ± 0.08	101	2.6
5	4.17	3.85	4.12 ± 0.15	99	3.6
6	4.08	4.01	3.26 ± 0.23	80	7.1

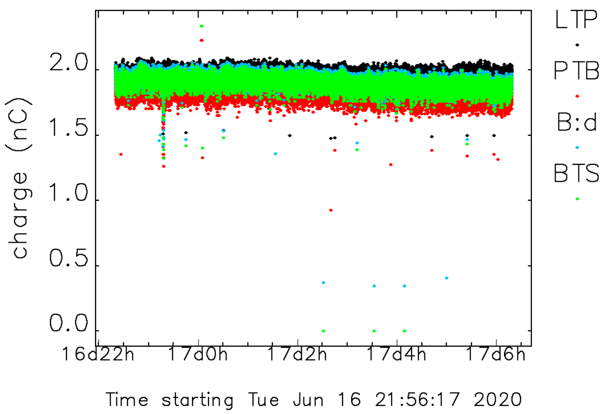

Figure 4: Charge measured by injector current monitors with continuous injection of 2 nC for 8 hours.

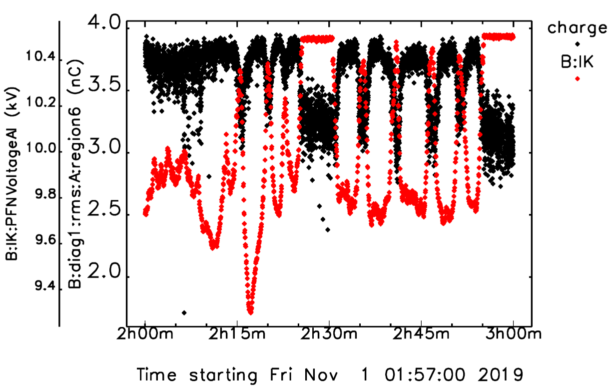

Figure 5: Bad efficiency caused by horizontal injection 'controllaw'.

Intermittent Injection

Because injection in the APS-U will be so frequent, it is important to know how long it takes after beam is enabled to achieve stable beam through the injector. To address this question precisely, special PVs were developed which give current monitor readings for a single bunch as it travels through the injector chain. Thus the efficiency is known on a shot-by-shot basis.

For these studies, beam was enabled for 20 seconds, then disabled for 20 seconds. The synchronized PVs were collected, then the data was separated for each cycle, to give the charge in each transfer line as a function of time after beam was enabled. The results of this calculation are shown in Fig. 6, for 2 and 5 nC. At 2 nC, the LTP charge is stable immediately, and the PTB is stable after 1 shot (0.5 sec). The BTS charge takes about 4 shots to be completely stable.

At 5 nC, the LTP and PTB are stable after 1 shot, but the BTS takes 6-8 shots to stabilize. The most likely culprit here is the booster cavity tuner loops, which take several seconds to adjust after the booster charge is changed. In the APS-U, these tuners will need to be locked in place, at the value required for the expected charge. Preliminary studies at higher charge have shown that the stabilization time can be reduced dramatically if these tuners are locked.

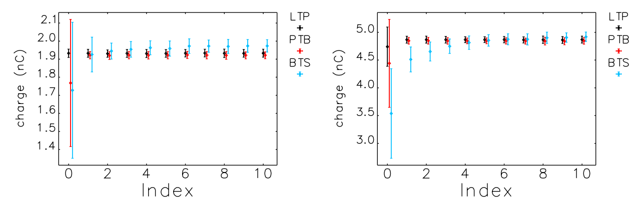

Figure 6: Charge vs shot after beam enable for 2 nC (left) and 5 nC (right). The points show the average of ~100 cycles, while the errors bars give the standard deviation.

CONCLUSION

Work on the APS-U injector complex is ongoing, in a number of important areas. Studies with a prototype of the new timing system have demonstrated bucket targeting and frequency ramps. Both are visible in a dispersive BPM. Modeling of the PAR longitudinal instability agrees reasonably well with measured data. The simulations predict that, with 30 kV RF12 voltage and 475 MeV beam energy, the bunch length can be kept below our 600 ps goal up to 19 nC charge. Injector charge stability has been studied, using both continuous and intermittent injection. Charge stability is generally good up to 5 nC, and causes of poor efficiency can usually be identified.

ACKNOWLEDGMENTS

We thank T. Berenc for help with machine studies, C.-Y. Yao for developing the PAR impedance model, and N. Arnold and S. Veseli for creating the synchronized current monitor PVs.

REFERENCES

[1] R. O. Hettel, "Status of the APS-U Project", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 7–12. doi:10.18429/JACoW-IPAC2021-MOXA02

[2] K. C. Harkay *et al.*, "First Beam Results Using the 10-kW Harmonic Rf Solid-State Amplifier for the APS Particle Accumulator Ring", presented at NAPAC'22, Albuquerque, NM, USA, Aug. 2022, paper TUPA23, this conference.

[3] J. C. Dooling, W. Berg, J. R. Calvey, K. C. Harkay, and K. P. Wootton, "Measurements of Bunch Length in the Advanced Photon Source Booster Synchrotron", presented at

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-THYD4

NAPAC'22, Albuquerque, NM, USA, Aug. 2022, paper TUPA22, this conference.

[4] J. R. Calvey *et al.*, “Plan for Operating the APS-Upgrade Booster with a Frequency Sweep”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 201–204. doi:10.18429/JACoW-IPAC2021-MOPAB046

[5] K. C. Harkay *et al.*, “Circuit Model Analysis for High Charge in the APS Particle Accumulator Ring”, in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 151–154. doi:10.18429/JACoW-NAPAC2019-MOPLM21

[6] J. R. Calvey, J. C. Dooling, K. C. Harkay, K. P. Wootton, and C. Yao, “Measurements and Simulations of High Charge Beam in the APS Booster”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 197–200. doi:10.18429/JACoW-IPAC2021-MOPAB045

[7] M. Borland, “elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation”, Rep. LS-287, APS, Sep. 2000. http://www.aps.anl.gov/Science/Publications/lsnotes/ls287.pdf

[8] Y. Wang and M. Borland, "Pelegant: A Parallel Accelerator Simulation Code for Electron Generation and Tracking", in *"Proc. 12th Advanced Accelerator Concepts Workshop*, vol. 877, p. 241, 2006.

[9] C. Yao, J. Carvelli, K. C. Harkay, D. Hui, L. H. Morrison, and J. S. Wang, “Longitudinal Impedance Modeling of APS Particle Accumulator Ring with CST”, in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 140–143. doi:10.18429/JACoW-NAPAC2019-MOPLM17

[10] J. C. Dooling, J. R. Calvey, K. C. Harkay, B. X. Yang, and C. Yao, “Fast Photodetector Bunch Duration Monitor for the Advanced Photon Source Particle Accumulator Ring”, in *Proc. IPAC'18*, Vancouver, Canada, Apr. 2018, pp. 1819–1822. doi:10.18429/JACoW-IPAC2018-WEPAF006

[11] A. Blednykh, B. Bacha, G. Bassi *et al.*, “New aspects of longitudinal instabilities in electron storage rings”, *Sci Rep* vol. 8, p. 11918, 2018. https://doi.org/10.1038/s41598-018-30306-y

[12] J. Calvey and M. Borland, “Modeling Ion Effects for the Argonne Advanced Photon Source Upgrade”, *Phys. Rev. Accel. Beams*, vol 22, no. 11, p. 114403, 2019. 10.1103/PhysRevAccelBeams.22.114403

[13] C. Yao, J. R. Calvey, G. I. Fystro, A. F. Pietryla, and H. Shang, “APS Booster Injection Horizontal Trajectory Control Upgrade”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 449–450. doi:10.18429/JACoW-IPAC2021-MOPAB124