ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPG07

APS UPGRADE BOOSTER COMMISSIONING *

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Abstract

After a long shutdown, the Advanced Photon Source (APS) booster synchrotron was recently re-commissioned for the APS Upgrade (APS-U) project. The APS-U requirements for the booster are more demanding than the old APS: much higher bunch charge, reduced beam emittance, and improved charge stability of better than 5% shot to shot. The booster accelerates electron bunches of 1-12 nC from 425 MeV to 6 GeV at a 1 Hz rep rate. While the booster ring hardware was largely kept the same, it is now run on a separate RF source, which is necessary to synchronize the booster with the storage ring because of the latter's reduced size and increased RF frequency. Photon diagnostics have recently been upgraded for reduced thermal drift. This paper will report on the booster re-commissioning process, including checkout of various systems, tests of the new RF source, and tuning for improved performance.

INTRODUCTION

The APS-Upgrade is a 4th generation storage ring (SR) light source at Argonne National Lab [1]. It uses a seven-bend hybrid multibend achromat (MBA) lattice with reverse bending magnets to achieve a 42 pm emittance at 6 GeV beam energy. There are two planned operational modes: 48 and 324 bunches, both with an eventual beam current of 200 mA. Because of the limited dynamic aperture required to achieve such low emittance, the APS-U will use swap-out injection. This means a depleted bunch in the storage ring will be replaced by a full charge bunch from the injector.

The APS injector chain consists of a linear accelerator, particle accumulator ring (PAR), and booster synchrotron. For the APS-U, it was decided to leave the present APS injector chain in place and make individual improvements where needed. The biggest change to the injectors is that the PAR, booster, and storage ring are now operated at different RF frequencies. This was done to avoid realigning the booster to match the new SR frequency, though it has other advantages (discussed below). A comparison of the booster parameters for the old APS and APS-U is shown in Table 1.

The APS ceased operations in late April, 2023. Linac and PAR re-commissioning started in September 2023 [2], and booster re-commissioning in February 2024. Booster re-commissioning was divided into two stages: injection and extraction.

* Work supported by U. S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.
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Table 1: Booster Parameters for APS / APS-U

Parameter	APS	APS-U	Units
Circumference	368	368	m
Revolution time	1.23	1.23	μs
Energy ramp	0.4 - 7	0.4 - 6	GeV
Bunch charge	0.5 - 4	2 - 17	nC
Momentum offset	0.6	variable	%
Repetition rate	2	1	Hz

TIMING SYSTEM

In the APS-U, the PAR, booster, and storage ring are operated at (slightly) different RF frequencies. Operation of the RF in the three machines is coordinated by a new Injection/Extraction Timing and Synchronization system (IETS). Central to the IETS system is the Booster Timing Controller (BTC) module (Fig. 1). The BTC has a separate direct digital synthesizer (DDS) for each of the three rings and provides separate 352 MHz RF references to facilitate synchronization between the machines. In addition it provides the beam-transfer fiducials.

In the booster, we make use of this independent control to vary the rf frequency along the booster energy ramp. This provides two functions (Fig. 2). First, we target the desired storage ring bucket for swap-out injection by using a frequency bump during the energy ramp. This changes the total amount of time the bunch spends in the booster, so it is lined up with the correct storage ring bucket at 6 GeV extraction. In addition, we have the option to use an overall frequency ramp between booster injection and extraction. This allows us to simultaneously optimize booster injection efficiency (which favors on-momentum injection), and extracted beam emittance (which favors off-momentum extraction) [3].

BOOSTER COMMISSIONING

Booster commissioning consisted of the following steps:

1. Power supply testing and RF conditioning
2. Booster extraction fast interlock (BEFI) test
3. Booster injection with IETS
4. Tuning of the booster for good injection efficiency and charge stability
5. Booster extraction to the booster-to-storage ring (BTS) transfer line
6. Testing of the BTS BEam Shutoff Current Monitor (BESOCM)

BEFI and BTS BESOCM are new APS-U radiation safety systems.

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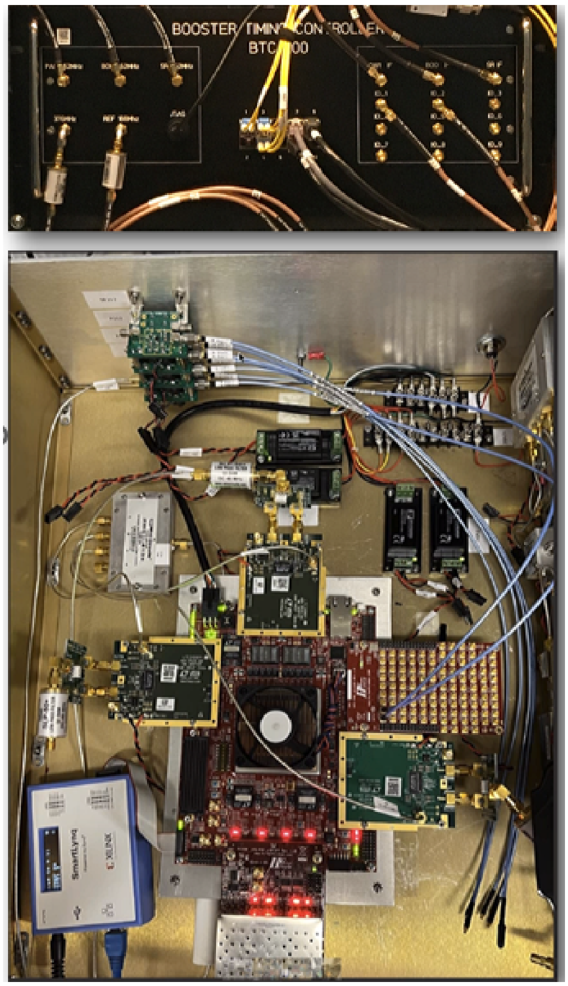

Figure 1: Booster Timing Controller (BTC) module.

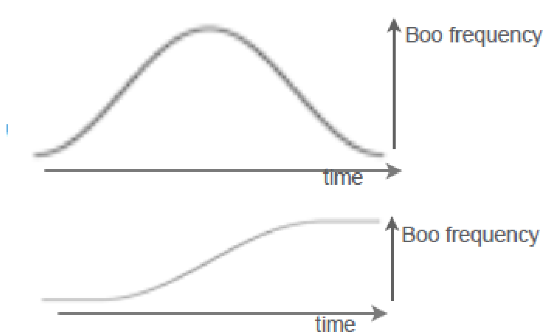

Figure 2: Illustration of a frequency bump for bucket targeting (top), and overall frequency ramp (bottom).

Power Supply Testing and RF Conditioning

The first two steps proceeded relatively smoothly, in spite of the long down time. There were a few minor issues:

- A freewheeling card was replaced in the dipole ramping power supply.
- The high voltage power supply for the injection kicker needed to be replaced.
- Some parameter adjustment was needed for the process that makes corrections to the ramping power supply waveforms.

BEFI Testing

From swap-out safety tracking [4], it was discovered that it was possible (though extremely unlikely) that beam injected into the storage ring could be directed down an X-ray beamline, if the beam extracted from the booster was sufficiently off-energy. To prevent this, a Booster Extraction Fast Interlock (BEFI) system was developed. The BEFI system monitors the booster dipole current, and inhibits booster extraction (by preventing extraction kicker discharge), except when the current is within ±2% of the nominal 6 GeV value. This system was tested and validated as part of booster commissioning.

Booster Injection

Booster injection and acceleration to 6 GeV was tested with and without frequency ramps (Fig. 2). Without frequency ramps, we quickly achieved booster injection. With some additional tuning (including adjustments of injection timing and RF phase, quadrupole ramp parameters, and injection trajectory), we achieved good injection efficiency and charge stability. After several hours of additional work, we recovered our previous high charge record of 12 nC captured in the booster (Fig. 3). The current monitor signal appears wavy, because it is receiving an RF signal from the PAR (for historical reasons), which is no longer synchronized with the booster. The solution is simply to provide a booster RF signal to the current monitor; this has been verified to work but is not yet fully implemented.

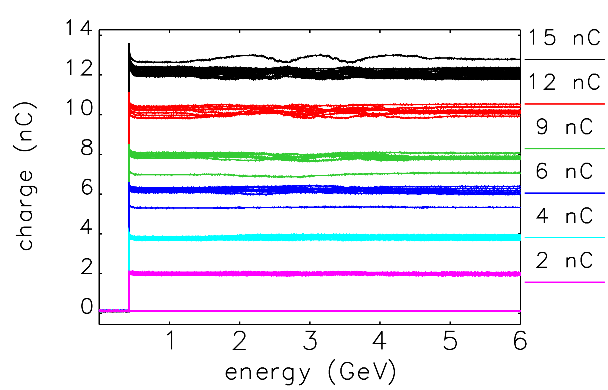

Figure 3: Captured charge in the booster for different injected charge. The incoming charge is indicated in the legend. Each charge level shows 20 shots.

Including a frequency ramp between injection and extraction is more challenging. In this case the booster cavities need to be detuned, so that the frequency ramp does not cross the cavity resonance. The resonance crossing causes substantial beam loss, even at 2 nC. With detuning, we achieved

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good injection efficiency up to 9 nC. The frequency ramp is an additional complication that is not required for storage ring commissioning, so we decided to run without it for now.

Photon Diagnostics

The booster is equipped with three synchrotron light monitors for transverse beam size measurements, and a fast photodiode detector for bunch length measurements. Previous measurements were hindered by heating of the mirrors in the photon transport line, causing the beam image to wander off the detectors. One of the light ports has now been instrumented with a solid polished glidcop mirror, which has much better thermal stability [5]. Quantitative emittance, energy spread, and bunch length measurements will be performed in the near future.

Booster Extraction

Because of additional radiation concerns, booster extraction was treated as a separate step from booster injection. Unlike the booster itself, the booster to storage ring (BTS) transfer line has new power supplies and BPM electronics.

Beam was initially directed to a dump about a quarter of the way through the BTS line. Booster extraction studies included:

- Commissioning new quadrupole power supplies and BPM electronics.
- Setting up the BTS lattice and trajectory.
- Radiological surveys. Additional shielding was installed around penetrations above the BTS line during the dark time. This shielding was demonstrated to effectively reduce radiation dose rates near the penetrations.
- Measuring extraction timing and jitter relative to storage ring rf. The jitter/drift was found to be on the order of 10 ps.
- Commissioning a fiber-optic beam loss monitor along the BTS line [6].
- Setting up timing for SR injection kickers (Fig. 4).

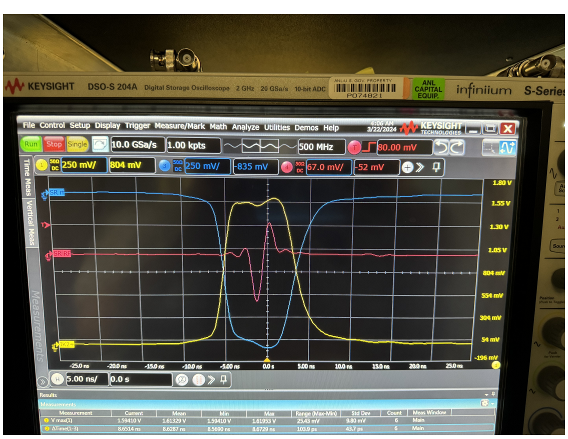

Figure 4: Setting up timing for an injection kicker pulser (blue and yellow) using the signal from a BTS BPM (red). The beam signal provides a timing fiducial for setting the pulser delays.

We first observed beam on a flag inserted at the end to the BTS dump (Fig. 5).

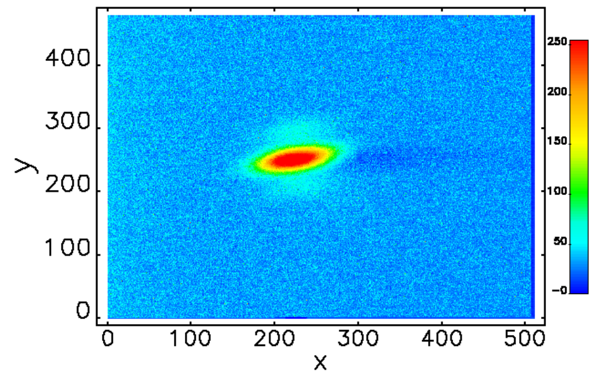

Figure 5: Beam image on a fluorescent screen in the BTS dump.

The beam image had a larger vertical size than expected, which puzzled us for some time. Eventually, it was discovered that the first three quadrupoles in the BTS line had been connected with the wrong polarity. These magnets date from the beginning of APS operation, when it was originally run with positrons. The labeling for these magnets was never updated after the switch to electrons, so the new power supply cables were connected following the positron labels. Once the magnet polarities were fixed, the beam image on the BTS flags matched our expectations.

BESOCM

The BEam Shutoff Current Monitor (BESOCM) is an additional safety system in the BTS. Its purpose is to limit the potential radiation dose around the storage ring in case injected beam is missteered and lost in one location for an hour. It consists of an integrating current transformer (ICT), which monitors the total charge extracted from the booster, integrated over an hour. If this value exceeds 6480 nC (an amount determined by radiation simulations), booster extraction is inhibited and booster RF is taken away. This system was tested and validated during booster extraction studies.

CONCLUSION

After 10 months of downtime, the APS-U booster was recovered and re-commissioned quickly. We demonstrated injection and acceleration to 6 GeV, with good injection efficiency and stability. We also captured 12 nC in the booster (without a frequency ramp). Two new safety systems were validated. Beam extraction was then demonstrated, first to a dump in the transfer line, and then directed to the storage ring. The extracted beam signal was used to set up timing for storage ring injection. The booster and transfer line were then ready to support storage ring commissioning, which began in early April 2024 [7].

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