The APS Booster Synchrotron: Commissioning and Operational Experience*

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Abstract

The Advanced Photon Source (APS) at Argonne National Laboratory (ANL) was constructed to provide a large user community with intense and high brightness synchrotron radiation at x-ray wavelengths. A 7-GeV positron beam is used to generate this light. Acceleration of the beam from 450 MeV to 7 GeV is accomplished at a 2-Hz repetition rate by the booster synchrotron. Commissioning of the booster began in the second quarter of 1994 and continued on into early 1995. The booster is now routinely used to provide beam for the commissioning of the APS storage ring. Reported here are our commissioning and operational experiences with the booster synchrotron.

I. INTRODUCTION

1.1 The APS

The APS is a synchrotron radiation laboratory built to provide an extremely bright x-ray source for a large user community. Construction and installation of all primary accelerator components is complete. We are now in the process of commissioning the accelerator complex.

There are four accelerators at the APS: the linac, the positron accumulator ring (PAR), the booster synchrotron, and the storage ring. The linac is designed to accelerate an electron beam up to 200 MeV, direct the beam at a tungsten target, and produce positrons. The captured positrons are accelerated in the second stage of the linac up to the nominal energy of 450 MeV, and are then transferred to the PAR. This process is repeated at 60 Hz. The PAR captures the 30-ns bunch train of the linac and damps it down both longitudinally and transversely. After 24 linac pulses are accumulated another 96 ms are allowed to pass before the damped bunch is transferred to the booster for further acceleration. The APS booster synchrotron (booster) raises the energy of a 450-MeV positron or electron beam up to 7 GeV in approximately 230 ms. It is designed to do this at a 2-Hz rate. The 7-GeV beam is then transferred to the storage ring where the light is generated and transported to the users.

This paper is entirely about the commissioning and operational experiences with the booster.

1.2 Description of the Booster

The booster employs a classical FODO lattice structure with four "missing dipole" cells for dispersion suppression in the rf straights. There are two mirror symmetry axes and thus four quadrants. Beam enters the machine nominally at 450 MeV and is ramped up to the full 7-GeV extraction energy in just under 230 ms. Currently this process is repeated at a 1-Hz rate; however, we will be moving to 2-Hz in the very near future.

There are 68 dipoles, 80 quadrupoles, 64 sextupoles, 80 correctors, and 5 pulsed magnets in the booster. The dipoles are all connected in series and are powered by two 12-phase power supplies operating in a master/slave configuration. The quadrupoles and sextupoles are each separated into two families of equal numbers with each family powered by a separate 12-phase power supply. The correctors are powered with separate bipolar DC/DC convertors. Each pulsed magnet is individually controlled. They are used for injection and extraction of the beam.

The lattice functions for one quadrant of the machine are shown in Figure 1, while the main parameters of the booster are listed in Table 1.

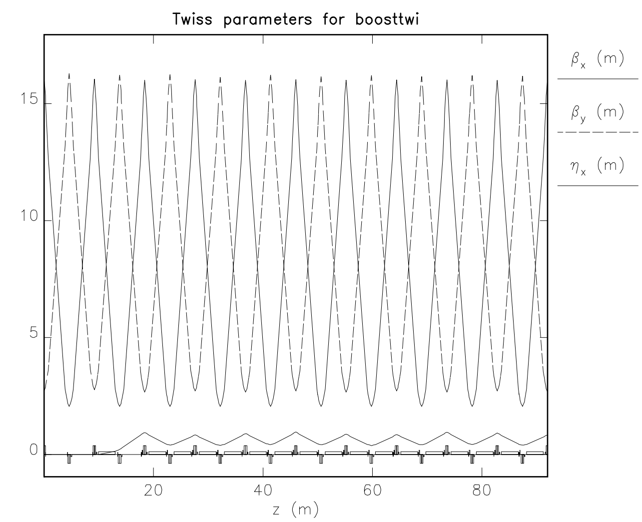

Figure 1: The booster machine Twiss parameters for a quadrant

Table 1: The APS Booster Parameters

Circumference		368	m
Nominal Injection Energy		450	MeV
Design Extraction Energy		7.0	GeV
Maximum Attainable Energy		7.7	GeV
Ramp Repetition Rate		2	Hz
Acceleration Time		230	ms
Tunes:	Q_h	11.75	
	Q_v	9.80	
Nominal Charge per Ramp Cycle		5.8	nC
Injection Emittance (from PAR)		0.36	mm-mrad
Natural Emittance at 7.0 GeV)		0.13	mm-mrad
Energy Loss/Turn at 7 GeV		6.33	MeV/turn
Energy Spread σ_E/E, at 7 GeV		0.001	
RF Frequency		351.9	MHz
RF Gap Voltage at 7 GeV		8.3	MV
Synchrotron Tune at 7 GeV		0.026	

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1.3 Ramp Cycle

With the exception of the correctors, a typical magnet current ramp cycle is shown in Figure 2. Injection is on-axis into a single bunch and occurs on-the-fly between 10 - 15 ms after the start of the ramp. The current, and thus energy, continues upward linearly. Single-turn extraction occurs approximately 230 ms after injection and is also done on-the-fly.

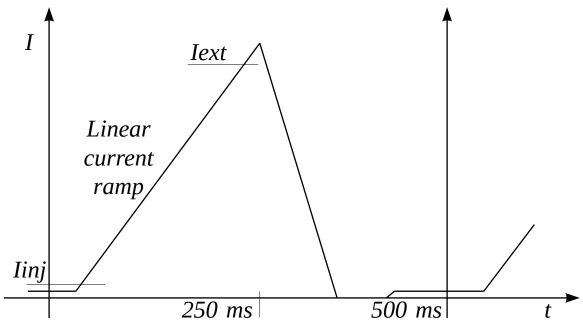

Figure 2: A typical current ramp cycle in the booster.

II. COMMISSIONING AND OPERATIONS

2.1 Chronology

Commissioning of the booster physically began on the 21st of April, 1994, with the first introduction of beam; however, operations were limited to basic systems checks. It was not until August that we attempted acceleration, and then, due to a power supply problem, we were limited to 4 GeV. During the latter part of October the 4 GeV was extracted from the booster and sent to the storage ring for a two-sector test. Preliminary modifications were made to the booster power supplies during the planned down time in the months of November and December. These modifications allowed us to tune the current ramps up to the 7-GeV level. After being off for 2 1/2 months and with modified power supplies, we made the first attempt to accelerate to 7 GeV in the third week of January. Successful acceleration from 400 MeV to 7 GeV was obtained for the first time on the 22nd of January, '95. After some preliminary measurements were finalized, the 7-GeV beam was delivered to the storage ring on the 20th of February. We have had consistent running since then.

2.2 Ramping Power Supplies

A large amount of effort has gone into getting the ramping power supplies to track together with the dipole. Descriptions of their performance and the ramp tuning methods used to achieve the desired tracking tolerances can be found elsewhere [1, 2]. Only a brief description will be provided here.

The power supply currents must all track one another to within tight tolerance; otherwise the beam encounters destructive resonances and is lost before extraction time. The specification is

$$\frac{\Delta I_{q,d}}{I_{q,d}} \leq \pm 0.14\% \ .$$

This is the maximum allowable fractional current deviation of either the dipole or the two quadrupole supplies from the desired programmed currents. Unfortunately, we were not able to achieve the tolerances we required with the original regulator, timing-phase firing card, and ramp function generators. Extensive modifications were done to the ramping control and power supply monitoring systems. We now run the supplies in hardware voltage-control mode with a slower software current control loop. As can be seen in Figure 3, control is now quite good. Injection occurs at the time location of the arrow. A similar level of control has been achieved for both the focusing quadrupole supply and the dipole.

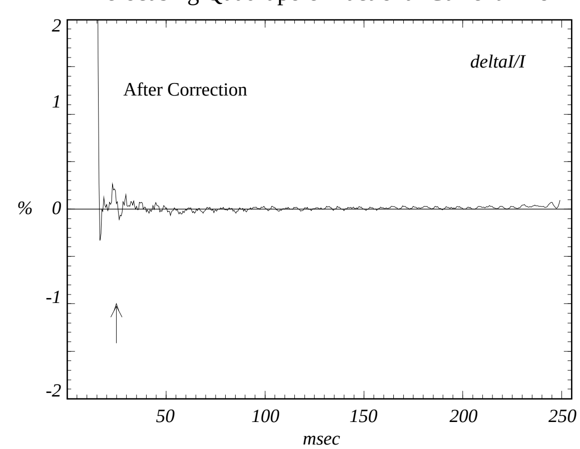

Figure 3: The fractional current error in the quadrupole.

2.3 RF System

There are two sets of two 5-cell 351.9-MHz rf cavities placed symmetrically in the machine. These are driven by a single 1-MW klystron.

The gap voltage varies significanlyt over the course of the energy ramp. At injection the compressed bunch from the PAR takes up a significant portion of the booster rf bucket. During this period the gap voltage is kept as low as required to achieve good capture efficiency. The gap voltage is increased as the energy rises in order to account for the E^4 rise in the synchrotron radiation loses. This is accomplished by varying the drive amplifier amplitude. A typical rf voltage ramp for 7-GeV operation is shown in Figure 4.

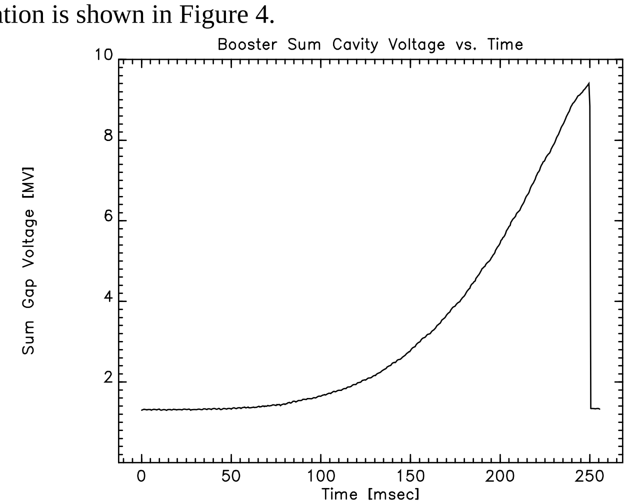

Figure 4: The total sum rf gap voltage in the booster as a function of time during the energy ramp.

2.4 Diagnostics

The primary diagnostics in the booster are the fluorescent screens, integrating current monitor, tune measurement system, and beam position monitoring system. Other secondary diagnostics are the synchrotron light monitor, the beam loss monitor, and the scrapers.

The fluorescent screens are useful only for 1st turn tuning but are quite sensitive (> 20 pC/ pulse visible) and so proved invaluable as an initial injection tuning aid.

We continually monitor the current monitor signal on a scope in the control room. An example of the output is shown in Figure 5. Any losses during the ramp cycle are immediately visible to the operator, providing nearly instantaneous feedback for tuning. The initial drop in the signal is real and is due to some of the PAR charge being lost out of the smaller rf bucket in the booster. The remaining fluctuations are noise.

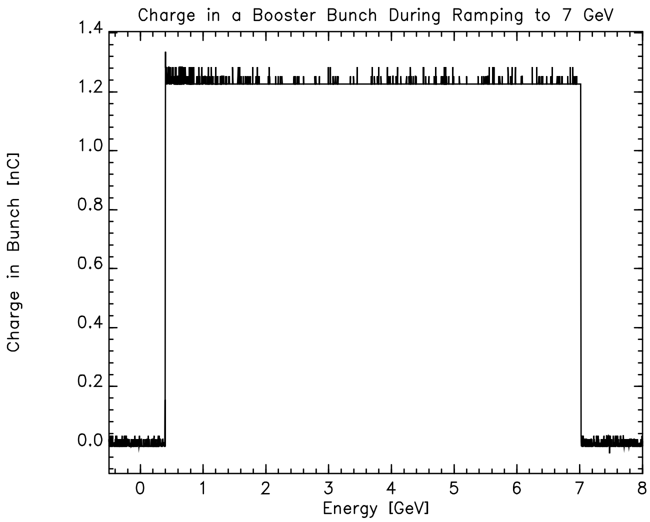

Figure 5: The booster current monitor output as a function of beam energy in the booster.

Measurement of the transverse tunes at injection time and during the ramp cycle also proved extremely valuable in tuning up the machine. The tune measurement system was constructed from stripline beam position monitors and an HP89440 Vector Signal Analyzer (VSA). The VSA came complete with an Ethernet connection and Xwindow software making it useful almost immediately upon hookup. This eliminated the usual troubleshooting delays which are typically found in systems that are designed and built in-house.

Among the many features of the VSA, one came in particularly handy during commissioning: the capture buffer. The VSA has the capability to capture the stripline signal over the course of an entire ramp cycle. This can then be viewed later at ones leisure.

The beam position monitor system (BPM) is nearly identical to that of the APS storage ring. It is capable of measuring the beam position on a single pass. A boxcar averager is used to increase the accuracy, and a timing module and beam history module allow for the possibility of measuring the orbit at any time during the ramp cycle as well as measuring the orbit over a large fraction of a single ramp.

The primary use of the BPM system to date has been to measure the orbit for subsequent processing and application of orbit correction algorithms. Figure 6 shows the measured horizontal and vertical closed orbits before and after correction immediately after injection. It should be noted, however, that we routinely run without correctors on. This is in testimony to the accuracy of the survey and the quality of the magnets and magnet sort.

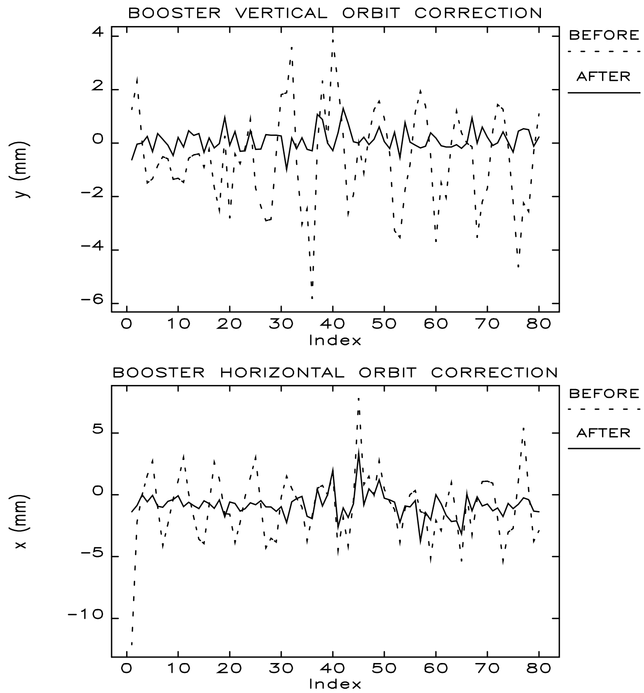

Figure 6: Corrected and uncorrected closed orbits.

III. SUMMARY

The booster has been running reliably since January ‘95, routinely providing 7-GeV beam upon demand for the storage ring. All systems have now been checked out and tested under actual operational conditions. We are now in the process of finalizing the various systems. The commissioning team fully expects to turn the machine over to the Operations Group within this year.

IV. ACKNOWLEDGEMENTS

As with any project of this nature, many people are responsible for its success; however, special thanks go to the core members of the APS accelerator commissioning team, M. Borland, J. Carwardine, G. Decker, L. Emery, and N. Sereno, for their tremendous support during the commissioning of the booster. A special thanks goes to J. Carwardine for his tenacity in making the ramping supplies work. J. Galayda is also acknowledged for his guidance throughout commissioning and his seemingly endless depth of accelerator expertise.

V. REFERENCES

[1] J.A. Carwardine, S.V. Milton, and D.G. McGhee, “Performance of the Ramping Power Supplies for the APS Booster Synchrotron,” these proceedings.

[2] S.V. Milton, “Ramp Tuning of the APS Booster Synchrotron Magnet Power Supplies,” these proceedings.