MEASUREMENTS AND SIMULATIONS OF HIGH CHARGE BEAM IN THE APS BOOSTER*

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Abstract

For the APS-Upgrade, swap-out injection will require the booster to support up to 17 nC bunch charge, several times what is used in the present APS. Booster injection efficiency drops sharply at high charge, and is the present bottleneck limiting high charge transport through the injectors. Particle tracking simulations have been used to understand what causes are limiting the injection efficiency, and to guide plans for improving it. In particular, bunch length blowup in the injected beam and beam loading in the RF cavities have been identified as the biggest factors. Simulations and measurements have also been done to characterize beam properties along the booster energy ramp. So far, a bunch charge of 12 nC has been successfully extracted from the booster.

INTRODUCTION

The APS-Upgrade [1] storage ring will use swap-out injection, meaning a low charge bunch will be completely replaced by a fresh bunch from the injector. For 48-bunch timing mode, the injector chain will need to supply ~16 nC bunches. Accounting for some injection losses, we have specified a goal of 17 nC extraction from the booster synchrotron. It was decided to mostly keep the present APS injector system the same, and make individual upgrades when needed. The APS-U injector complex will consist of three parts:

- An rf linac, which accelerates electron bunches of ~1 nC charge to 450 - 475 MeV.
- A particle accumulator ring (PAR) which captures a series of 1 nC bunches from the linac, up to the desired charge. The bunches are captured using a 9.8 MHz rf cavity, then compressed with a 12th harmonic (117 MHz) cavity. The 12th harmonic cavity is turned on ~750 ms into the 1 second cycle of the PAR. The bunch compression is needed to transfer the beam into the 352 MHz system in the booster.
- A booster synchrotron, which captures the full-charge beam from the PAR, and accelerates it to 6 GeV.

Basic booster parameters are given in Table 1. Note that the booster is operated off-momentum, which has implications for the injection efficiency and beam parameters. Specific requirements for the extracted booster beam are discussed in another paper in these proceedings [2]. This paper will focus on the present status of high charge booster studies, including measurements and simulations.

Table 1: Booster Parameters

Parameter	Value
Beam energy	0.5 - 6.0 GeV
Bunch charge	2 - 17 nC
Circumference	368 m
Revolution frequency	815 kHz
RF frequency	352 MHz
Ramp time	225 ms
Momentum offset	-0.6%
Horizontal tune	11.75
Vertical tune	9.8
Momentum compaction	9.71×10^{-3}

PAR STATUS

20 nC has been extracted from the PAR, meeting the requirement for APS-U. However, there is a strong bunch length blowup as a function of charge, probably caused by a combination of potential well distortion and microwave instability [3]. At 20 nC, the bunch length is ~725 ps, more than double the low charge value (~325 ps). This leads to a large reduction in the booster injection efficiency.

Mitigating the bunch length blowup in the PAR is a major priority for high charge operation. This will be accomplished with a higher power 12th harmonic amplifier and higher beam energy (up to 475 MeV) from the linac, to help compress and stabilize the bunch [4]. The new amplifier will be installed and tested this August.

BOOSTER STATUS

As of the writing of this paper, we have successfully extracted 12 nC from the booster, or ~70% of our 17 nC goal. Several recent upgrades have helped with booster injection efficiency and stability, including:

- Switching from a “low emittance” lattice to one with zero dispersion in the straight sections [5].
- Orbit correction at multiple points along the ramp.
- Current-controlled sextupole power supplies, which allow for better control of the chromaticity.
- New and re-commissioned diagnostics, including synchrotron light monitors, a bunch duration monitor, and turn-by-turn BPMs.
- Improvements to control of the injection trajectory [6].
- Optimizing the RF cavity voltage at injection as a function of charge.

Radiation surveys were performed for various loss scenarios in the booster to storage ring transfer line [7]. Some

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potential shielding weaknesses have been identified, which need to be addressed before APS-U high charge operation.

Injection Efficiency

The charge captured in the booster for different injected charge values is shown in Fig. 1. Essentially all of the losses occur shortly after injection. The efficiency drops sharply above ~10 nC injected charge; no benefit is gained by injecting more than 15 nC.

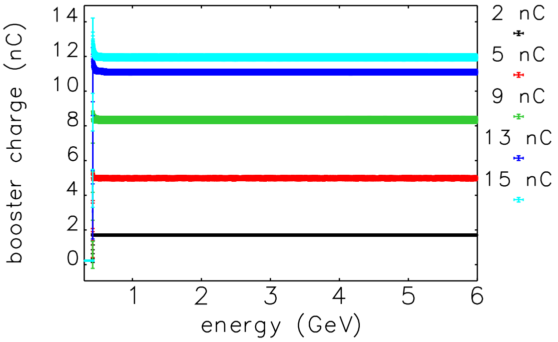

Figure 1: Charge stored in the booster over the ramp, for different injected charge values. 20 traces are shown for each case, which gives some impression of the shot-to-shot charge stability.

Beam Properties along the Ramp

In addition to charge, it is important for the booster to provide a bunch with acceptable transverse emittances and bunch length at extraction. Furthermore, these parameters need to be maintained as much as possible at high charge.

Beam size measurements were taken using a synchrotron light monitor, while the bunch length was measured using a photodiode bunch duration monitor (BDM) [8]. Measurements were taken at multiple points along the booster ramp, and at different charge values. As shown in Fig. 2 (left), the initial beam size blowup in the horizontal beam size damps away about half way through the ramp. After this, the beam size follows the expected increase with energy, with no observable blowup with charge. This is significant, as it indicates no transverse instability up to 11 nC. The vertical beam size also showed no blowup with charge.

Fig. 2 (right) shows the measured bunch length along the booster ramp. Here there is some evidence of blowup in the 11 nC case, though we are not completely confident in the measurement. At high charge, the synchrotron radiation power causes heating of the mirrors in the optics line, which causes the beam image to wander. We plan to install water-cooled mirrors for the booster photon diagnostics, to help stabilize these measurements.

BOOSTER INJECTION SIMULATIONS

As shown in Fig. 1, Booster injection is the present bottleneck limiting high charge transport through the injectors.

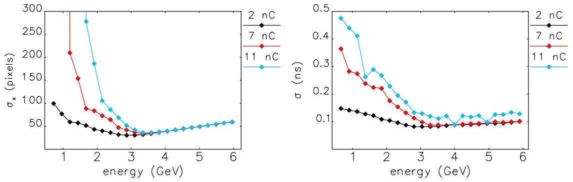

Figure 2: Measured beam parameters along the booster ramp. Left: horizontal beam size. Right: bunch length.

Particle tracking simulations have been used to understand what effects could be limiting the injection efficiency, and to guide plans for improving it. The tracking simulations are done with `elegant` [9]. 50,000 macroparticles are tracked for 3,000 turns (~3.5 ms), which is where most of the losses occur. The tracking is done element-by-element. The simulation includes a model of the transverse and longitudinal impedance, as well as beam loading in the RF cavities (using the `RFMODE` element). The impedance model was developed using the same technique applied to the storage ring [10]. The simulation also includes measured beam parameters (emittances and bunch length) as a function of charge, as well as incoming energy and trajectory errors. The energy error is significant (0.12% rms), and is caused by variations in the booster dipole ramp.

Fig. 3 shows the simulated injection efficiency vs charge, after including all these effects. The results are in good agreement with measurements, except at very high charge. Notably, the simulation also reproduced the low efficiency observed in the “low emittance” lattice [5], which has nonzero dispersion in the straight sections.

Fig. 4 shows a series of longitudinal phase space plots for the 20 nC case. In general, the incoming beam is poorly matched to the booster, because the booster frequency is 3 times the PAR 12th harmonic frequency, and much higher voltage is required in the booster. Combined with the injection energy mismatch, this causes oscillations in the bunch length and beam energy. In this case, there was insufficient voltage at high charge, leading to losses as particles fall out of the RF bucket. However, high RF voltage can also reduce efficiency, as the strong energy oscillations lead to losses on the horizontal aperture at high dispersion locations. Thus the RF voltage needs to be carefully optimized for each injected charge value.

A series of parameter scans were performed to determine which ones have the biggest impact on injection efficiency. For 20 nC injected charge, the incoming bunch length was found to be the most important (Fig. 5). For the nominal -2 kHz cavity detuning, the goal of 85% injection efficiency requires the bunch length to be less than 600 ps. Detuning the cavities to -10 kHz partially mitigates the heavy beam loading, and improves the efficiency. However, detuning the cavities places additional demand on the couplers at extraction [2], which must be carefully considered.

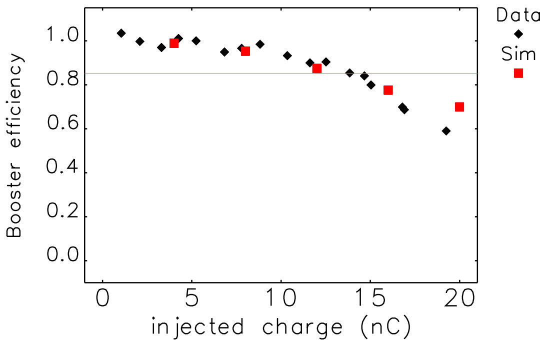

Figure 3: Measured and simulated booster injection efficiency. Our goal is 85%.

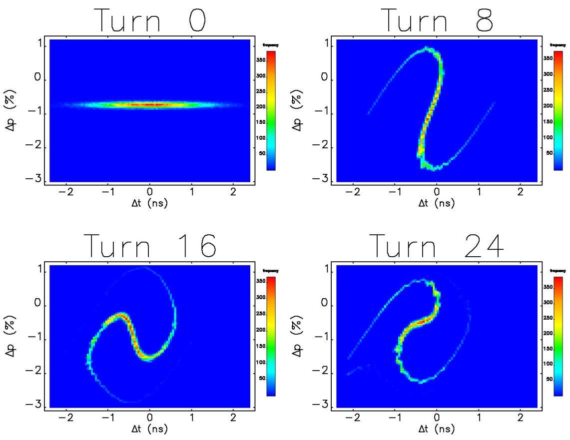

Figure 4: Longitudinal phase space plots: 20 nC. Losses occur around turn 24.

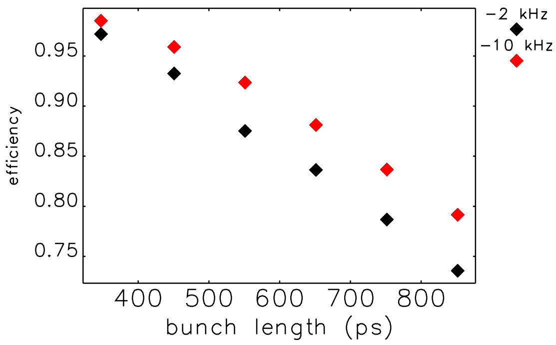

Figure 5: Simulated injection efficiency vs injected bunch length at 20 nC, for different cavity detuning values.

FULL RAMP SIMULATIONS

Simulations of the full booster ramp have also been performed. To keep run times reasonable, the ring is represented by a single `ILMATRIX` element. The beam momentum and synchrotron radiation parameters are ramped using the `RAMPP` element and `modulate_elements` command. The cavity detuning is set to -10 kHz, and the bunch length was limited to 600 ps (effectively assuming the new 12th harmonic amplifier works as planned). With these assumptions, the simulated injection efficiency is > 90% up to 20 nC.

Simulated beam parameters along the ramp for each charge value are shown in Fig. 6. The blowup of the horizontal emittance with charge is damped by 4 GeV. At extraction, the horizontal emittance is 64 nm, identical to the theoretical value. The simulation reproduces the lack of blowup seen in the measurements up to 11 nC, and predicts no transverse instability up to 20 nC.

Similarly, the blowup of the injected bunch length with charge is mostly damped away in the first half of the ramp. There is a small change in the bunch length at extraction, which increases from 96 ps at 4 nC to 99 ps at 20 nC (the theoretical value is 97 ps). Comparing to the measurements (Fig. 2), the simulation does not show the possible instability observed at 11 nC. Further work is needed to understand this discrepancy, though it may simply be measurement error.

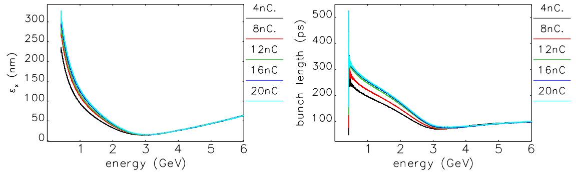

Figure 6: Simulated beam parameters along the booster ramp. Left: horizontal emittance. Right: bunch length.

CONCLUSION

We have successfully extracted 12 nC bunches from the APS booster synchrotron. Particle tracking simulations have identified the two main factors limiting booster injection efficiency: bunch length blowup in the PAR, and beam loading in the booster cavities. The bunch length blowup will be mitigated with a higher power 12th harmonic cavity, and higher beam energy from the linac. Beam loading will be partially mitigated by over-coupling the cavities [2].

Beam properties have been characterized along the booster ramp. Simulations predict no beam size or bunch length blowup at extraction, up to 20 nC. Measurements up to 11 nC show no beam size growth, but some evidence of bunch length blowup at high charge. Further work is needed on this question.

The APS-Upgrade booster will be operated with a frequency ramp between injection and extraction, which further complicates this analysis. This is discussed in another paper in these proceedings [2].

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