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FIRST BEAM RESULTS USING THE 10-kW HARMONIC RF SOLID-STATE AMPLIFIER FOR THE APS PARTICLE ACCUMULATOR RING*

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Abstract

The Advanced Photon Source (APS) particle accumulator ring (PAR) was designed to accumulate linac pulses into a single bunch using a fundamental radio frequency (rf) system, and longitudinally compress the beam using a harmonic rf system prior to injection into the booster. For APS Upgrade, the injectors will need to supply full-current bunch replacement with high single-bunch charge for swap-out injection in the new storage ring. Significant bunch lengthening is observed in PAR at high charge, which negatively affects beam capture in the booster. Predictions showed that the bunch length could be compressed to better match the booster acceptance using a combination of higher beam energy and higher harmonic gap voltage. A new 10-kW harmonic rf solid-state amplifier (SSA) was installed in 2021 to raise the gap voltage and improve bunch compression. The SSA has been operating reliably. Initial results show that the charge-dependent bunch lengthening in PAR with higher gap voltage agrees qualitatively with predictions. A tool was written to automate bunch length data acquisition. Future plans to increase the beam energy, which makes the SSA more effective, will also be summarized.

INTRODUCTION

The APS Upgrade (APS-U) is being designed for on-axis injection, where the injectors produce enough single-bunch charge to perform complete bunch replacement, also known as "swap-out" [1-3]. For the design APS-U bunch modes, the injected bunch charge goal is 5-17 nC. By comparison, the typical APS injected bunch charge is 2-4 nC.

The basic layout of the APS injectors for APS-U is shown in Fig. 1. The linac provides 1-nC pulses at a 30-Hz rate. Up to 20 pulses are accumulated and damped in the particle accumulator ring (PAR) [4] at the fundamental rf frequency. In the final 230 ms of the 1-s cycle, the single bunch is captured in a 12th harmonic rf system and the bunch length is further compressed. The bunch is injected into the booster where it is ramped to full energy and extracted into a transport line that was redesigned for matching into the APS-U storage ring (SR) [5].

One of the bottlenecks in achieving high charge in the injectors is significant bunch lengthening observed in PAR, which is due to both potential well distortion (PWD) and microwave instability [6]. The typical zero-charge PAR bunch length is 320 ps. Booster acceptance becomes an issue when the PAR bunch length becomes > 600 ps [7].

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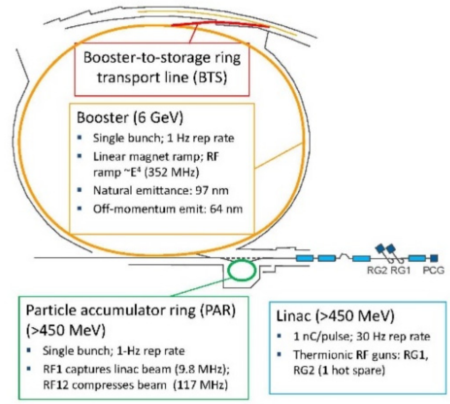

Figure 1: APS-U injector complex.

Mitigation of the PAR bunch lengthening follows two approaches [6]. The first is to increase bunch length compression in the harmonic rf system by raising the gap voltage. The second is to increase the beam energy to raise the instability threshold.

This paper discusses results for the first approach. A 10-kW 117-MHz SSA was installed to replace the 3-kW tube amplifier for the harmonic rf system. The higher rf power enabled raising the gap voltage from 21 kV to over 30 kV, which was the design goal. Increased bunch length compression was observed for bunch charge up to ~13 nC with 28 kV harmonic gap voltage, close to predictions.

HARMONIC RF AMPLIFIER

Tube Amplifier

The limitation of the present harmonic tube amplifier is illustrated in Fig. 2. The forward power saturates at < 3 kW at high charge. The result is that the gap voltage, nominally 21 kV, droops significantly above ~10 nC and bunch compression is compromised.

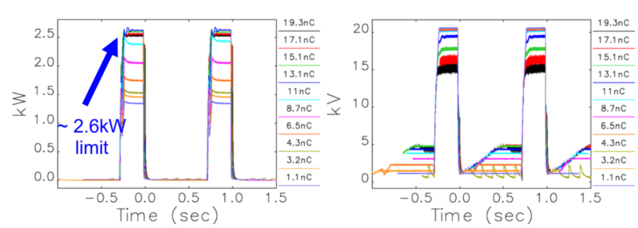

Figure 2: PAR harmonic tube amplifier forward power (left) and gap voltage (right) as a function of bunch charge (2.5 cycles are shown).

APS-U Requirements

Given harmonic rf cavity parameters (R/Q)a ≈ 215.7 Ω and Q (external) = 1900, it takes 3.6 kW of power to merely

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cancel 20-nC beam loading at zero harmonic cavity voltage, which is representative of the PAR injection phase. During the compression phase, at 30 kV and assuming zero fundamental phase error, the estimated harmonic amplifier power requirement is ~5.5 kW. Accounting for 10-deg. phase errors, the power requirement is < 8 kW.

SS Amplifier

PAR employs two 3-kW, 117-MHz rf amplifiers for operations, with one amplifier used as a backup. The output of both amplifiers first goes to a high-power rf switch, then to a circulator, and finally into the PAR enclosure to the harmonic cavity. The new 10-kW SS amplifier (shown in Fig. 3) replaced one of the 3-kW tube amplifiers and has served in operations for a year without major issues.

Figure 3: PAR harmonic rf amplifiers: new 10-kW SSA is shown on the left and 3-kW tube amplifier is on the right.

Several components were upgraded to accommodate the new SS amplifier. Pre-installation work included installation of the following: 10-kW transmission line, new circulator and high-power rf switch, new rf input coupler, new field probes and fast interlock, and water station upgrade. The SSA was initially commissioned with a 3-kW limiter. It was later modified with a 5-kW limiter, which enabled a gap voltage of 34 kV without beam and 26 kV with high-charge beam. The SSA was next modified with an 8-kW limiter, which enabled maintaining a gap voltage of 28 kW at high charge.

BEAM RESULTS

As expected, the SSA performs well at high charge, shown in Fig. 4. These data were acquired with the 8-kW limiter. There is virtually no droop in the gap voltage at higher charge. The forward power is 6.3 kW for 15 nC bunch charge and 28 kV gap voltage. This is consistent with calculations to determine the APS-U requirements.

The cavity vacuum and voltage transients at beam extraction were monitored as the gap voltage, bunch charge, and SSA power limit were increased. The highest vacuum pressure was ~1e-8 Torr, which was acceptable. The voltage transients at extraction can be controlled with harmonic rf tuner feedforward and are not a concern at the higher gap voltage.

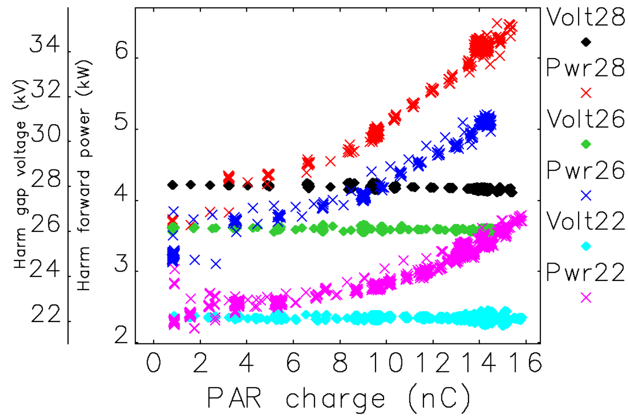

Figure 4: PAR harmonic SSA amplifier forward power and gap voltage (22 kV, 26 kV, and 28 kV) as a function of bunch charge.

The bunch length was measured using a fast photodetector on a synchrotron light monitor port [8]. The photodiode signal is acquired using a digital scope and post-processed using deconvolution with a short-pulse laser response. The bunch waveforms are fit to a Gaussian and the rms bunch length is averaged over 128 turns (one turn is 102 ns). A graphical user interface was written to facilitate data acquisition and post-processing. This diagnostic is known the bunch duration monitor (BDM).

Charge-dependent bunch length measurements using the tube amplifier at 21 kV gap voltage and SSA up to 28 kV were compared (Fig. 5). Above 10 nC, the bunch length for 21 kV was shorter with the SSA. This is because the gap voltage with the tube amplifier drooped to 19.5 kV, resulting in a longer bunch length. At 13.2 nC, the bunch length decreases from 640 ps (tube, 21 kV) to 488 ps (SSA, 28 kV). This is a good result, given that the beam is microwave unstable above ~10 nC. There is a small bunch length blow-up between 3-5 nC that was not observed using the tube amplifier and is not understood.

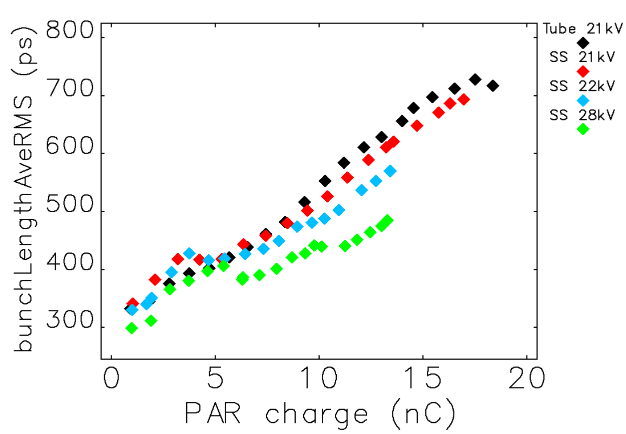

Figure 5: Measured PAR bunch length vs gap voltage for tube and SS rf amplifiers (425 MeV).

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The measured bunch length was compared to theory. The bunch length for 425 MeV was predicted using Haissinski equilibrium bunch density distributions [9] in a dual rf system and assuming a circuit model for the impedance. A fundamental rf gap voltage of 21.6 kV and harmonic gap voltage of 22 kV and 28 kV were used. In prior work, a circuit model reactance Z/n = 25 Ω and resistance R = 1300 Ω gave the best fit to the BDM data [6]. In principle, this analysis is only valid in the linear potential well distortion regime (below ~10 nC in PAR), but prior work shows that it is still useful not too far above the microwave instability threshold. Figure 6 shows the results. Given the limitations of the linear analysis in the presence of microwave instability, the details in the BDM data are not reproduced. However, the overall bunch length comparison is quite reasonable.

Simulations of the bunch length, using the numerically computed impedance, are also in progress [10,11].

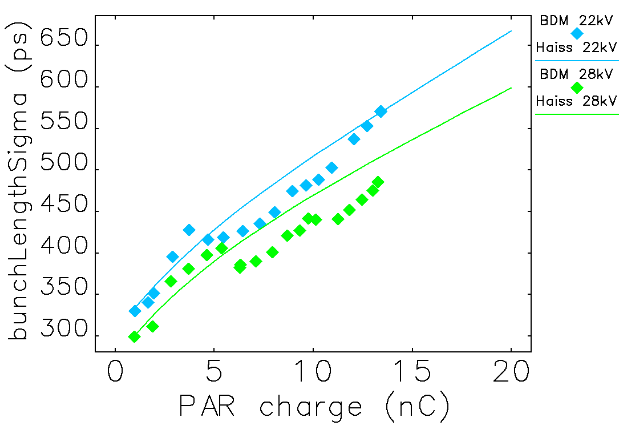

Figure 6: Comparison of BDM data with predicted bunch lengths using Haissinski distributions (425 MeV).

FUTURE PLANS

First measurements with the new harmonic rf SSA have been presented but there is more work remaining. The next task is to optimize the harmonic rf system and beam injection to tune the PAR bunch charge up to 20 nC. In addition to BDM data, time-dependent rf data (as shown in Fig. 1) and synchrotron tune spectra will be analyzed to characterize beam loading and beam instabilities as a function of bunch charge. After PAR is optimized, we will measure injection efficiency in booster to compare with prior studies and predictions [7]. Long term, we have plans to upgrade the linac beam energy to 500 MeV, which will enable future PAR operation at 475 MeV for APS-U. Higher beam energy raises the microwave instability threshold, which is expected to further improve the effectiveness of the SSA to compress the bunch length. Linac upgrade plans are expected to be completed in the next two years.

CONCLUSION

A 10-kW harmonic rf solid-state amplifier (SSA) was installed in PAR to increase bunch length compression at higher bunch charge. The SSA performed as expected and bunch length compression largely agrees with theoretical predictions up to ~13 nC. More work remains to tune the PAR charge up to 20 nC with the SSA. Measurements of booster injection efficiency with higher PAR harmonic gap voltage are also planned. The expectation is that shorter bunch lengths at higher bunch charge better accommodate the booster longitudinal acceptance.

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