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PARTICLE ACCUMULATOR RING RESTART AND READINESS FOR ADVANCED PHOTON SOURCE UPGRADE COMMISSIONING*

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Abstract

At the Argonne (ANL) Advanced Photon Source (APS), a 425-MeV Particle Accumulator Ring (PAR) is used to stack 1-nC electron pulses from the linac and inject a single bunch into the booster at a 1-Hz repetition rate. All the APS injectors, including PAR, were shut down in April 2023 at the start of the APS Upgrade Dark Time. In this paper, we report on PAR restart activities starting in Oct. 2023. The PAR vacuum pressure was unexpectedly high when first powering the fundamental and harmonic radiofrequency (rf) systems, as well as when first injecting the beam, which initially limited both the beam charge and rf gap voltage. These limits were overcome through many weeks of systematic rf and vacuum conditioning. Additional restart activities include commissioning two new kicker chambers with a special low-impedance, eddy-current-suppressing coating, commissioning of the digital low level rf system, and tests with the Injection Extraction Timing and Synchronization (IETS) system. We demonstrated initial APS-U commissioning performance goals: a stable, 5-nC injected bunch charge with a bunch length short enough for injection into the booster.

INTRODUCTION

The basic layout of the APS-U injectors was described in [1]. APS-U uses on-axis swap-out injection, where the injectors produce enough single-bunch charge to perform complete bunch replacement [2]. The APS-U injector performance goals are summarized in Table 1. The initial goals support APS-U commissioning, with up to 5 nC injected bunch charge and 25 mA total current, as well as User operation in the first year. The initial charge goals make allowances for anticipated injection efficiency into booster and the storage ring (SR). The final goals correspond to the APS-U timing mode, or 200 mA in 48 bunches.

Table 1: APS-U Injector Performance Goals

	APS	Initial	Final
PAR charge	2-4 *nC*	12 *nC*	20 *nC*
Booster charge	2-4 *nC*	10 *nC*	17 *nC*
SR charge (injected)	Accum.	9 *nC*	16 *nC*
Charge stab. (rms)	n/a	5%	5%

PAR IMPROVEMENTS

Several PAR improvements were developed in 2021-2023 to improve reliability and APS-U readiness. These improvements were implemented before or during the Dark Time and include demonstrating 1-Hz top-up operation in preparation for swap-out, developing a digital low-level radiofrequency (LLRF) system for both the fundamental (9.77 MHz) and harmonic (117 MHz) rf systems, and replacing the ceramic kicker chambers. Restart activities prioritized commissioning these improvements.

1-Hz Operation

The PAR cycle time was reduced from 2 Hz to 1 Hz primarily to increase the accumulation time for stacking 1-nC pulses from the linac. Operation at 1 Hz had been used regularly for high-charge PAR studies, but the first long-term test was demonstrated in APS User Top-Up operation from Feb.-Apr. 2023. No injector issues were found, and a benefit was observed for the PAR harmonic rf system, shown in Fig. 1. The cavity and tuner temperatures are lower at 1 Hz. This caused a mismatch, shown by the increased reflected power, that was corrected by tuning the harmonic cavity closer to resonance. This is a benefit, as it allows more harmonic cavity detuning range for high charge.

For a one-week period prior to the Dark Time, the new IETS system was tested with PAR charge up to 14 nC and booster up to 10 nC. Bucket targeting was successfully demonstrated in the APS storage ring. During PAR and booster restart, IETS was successfully checked out prior to APS-U commissioning. More details are found in [3].

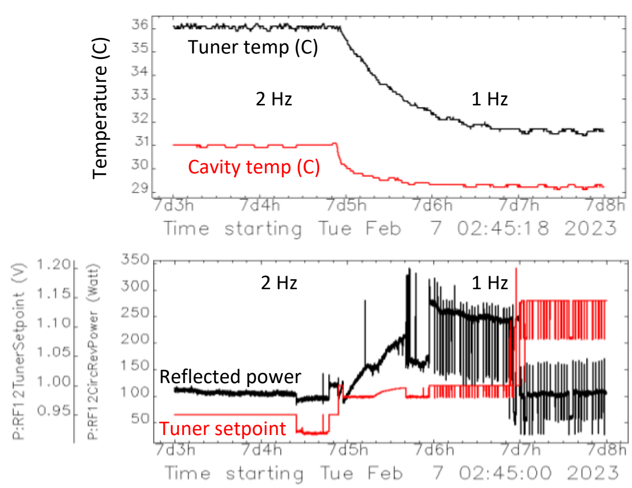

Figure 1: PAR harmonic rf cavity comparison for 2 Hz vs. 1 Hz operation.

Digital Low Level RF System (DLLRF)

The DLLRF system is based upon a MicroTCA platform utilizing hardware from Vadatech Inc., including custom FPGA Mezzanine Cards jointly designed by ANL and Vadatech. The EPICS IOC and Data Acquisition (DAQ) software was provided by ANL. The Linux kernel driver was

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provided by Oak Ridge National Laboratory (ORNL). The FPGA code was jointly developed by ANL and Eric Breeding from both ORNL and DesignLinx Hardware Solutions.

Both DLLRF systems were tested with beam prior to the Dark Time as well as during PAR restart activities. An example data capture of rf amplitude and phase for both the fundamental and harmonic systems during accumulation of two linac pulses is shown in Fig. 2. The beam-loading transients from injection of the two linac pulses are clearly seen at the beginning of the cycle, especially on the harmonic phase, during low harmonic gap voltage. The transient in the harmonic phase during the harmonic voltage ramp is due to the way in which the harmonic cavity tuner is ramped. The transient at the end of the harmonic flattop is due to beam extraction.

A fundamental difference between the analog system and the new DLLRF is that the latter operates on in-phase and quadrature components, as opposed to amplitude and phase. This allows for harmonic voltage setpoints down to zero at the beginning of the cycle. The analog system cannot do this because the phase becomes undefined.

Besides offering better precision control of the rf systems, the DLLRF offers much greater insight into operation of the systems via real-time streaming data which aids system tuning with beam. Final transition to operations is in process.

Kicker Chambers

Three kicker magnets operate in PAR. The vacuum chambers are made of alumina ceramics with a thin-film conducting coating. The surface resistance of the chambers was found to be higher than the design value of 40-50 Ω/sq [4], which contributes to the longitudinal impedance and high-charge bunch length blowup. Replacing the chambers for reliability provided an opportunity to improve the coating and reduce the surface resistance.

Uniform resistive coatings limit how low the surface resistance can be. A thicker coating reduces the surface resistance. But if the coating is too thick, the eddy currents induced by the kicker pulse can cause heating and/or unacceptably distort the field.

Patterned coatings had been developed elsewhere [5] to suppress eddy currents and, thereby, allow thinner coatings. Following this idea, we developed a patterned coating design with 2-3 Ω/sq and low field attenuation. The impedance and field attenuation were analyzed using CST Studio [6]. We partnered with Kyocera to fabricate four patterned chambers, shown in Fig. 3. The dark areas are Ti-coated to carry the image current. The light areas are uncoated and serve to mitigate the eddy current effects. A special four-point probe was developed, shown in Fig. 4, to directly measure the surface resistance, using $R_s[\Omega] = 4.526\, V[mV]/I\,[mV]$. Acceptance testing showed that the chambers gave 3-4 Ω/sq, which is close to the design.

The first chamber was installed in Jan 2023 and performed satisfactorily for three months of operation. The second and third chambers were installed at the beginning of the Dark Time. The final performance was verified after vacuum conditioning, described in the next section.

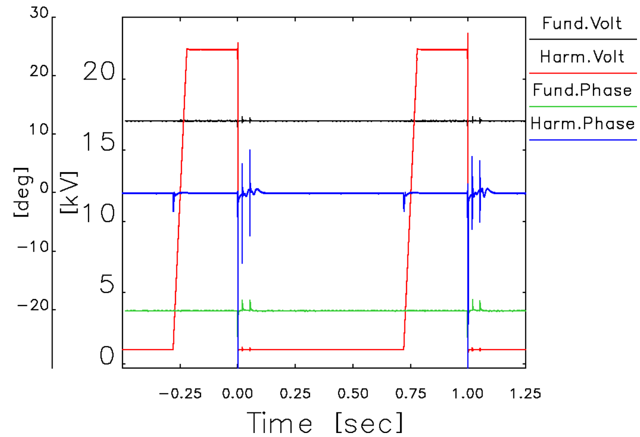

Figure 2: LLRF data during an injection of 2 linac pulses.

Figure 3: PAR kicker chamber with patterned Ti coating.

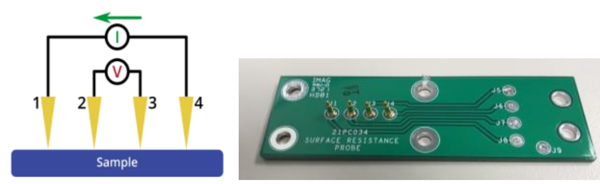

Figure 4: Schematic diagram and printed circuit board for the four-point probe.

VACUUM CONDITIONING

The APS injectors were powered off at the start of the Dark Time in Apr. 2023. Linac and PAR were restarted in Sep.-Oct. 2023, and the booster in Feb. 2024 [3].

The biggest early issues for PAR were poor vacuum and poor injection efficiency. The poor vacuum was related to unintended contamination during installation of the kicker chambers. Poor vacuum also affected rf conditioning, with multipacting suspected in the fundamental cavity. The vacuum issue greatly extended the time required to condition to the nominal fundamental rf gap voltage without and with beam. Figure 5 shows noise spikes on the fundamental field probe after about one month of conditioning. The noise amplitude and frequency vary with beam charge (nC), shown at the top of each plot. Curiously, the signal was often less noisy during higher vacuum activity. Both the vacuum activity and spikes were reduced over the course of conditioning.

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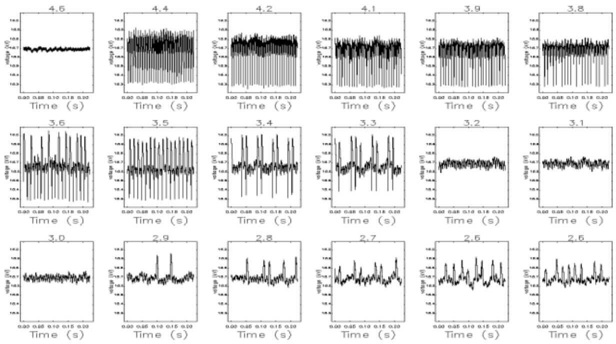

Figure 5: Rf digital data acquisition system showing fundamental gap voltage waveform as the beam decays.

Another issue was poor initial injection efficiency into PAR, which was mostly due to the poor vacuum, but also affected by Linac tuning. The Linac had also undergone improvements and it took time to commission all the new hardware and controls and achieve stable operation. After we were able to inject, beam scrubbing was undertaken to condition the vacuum chamber. Beam scrubbing consists of storing between 2 nC and 8 nC and either topping up, or allowing the beam to decay to 1 nC before refilling. Constant charge best conditions the vacuum surfaces, and decaying charge conditions the rf through any charge-dependent multipacting resonances. The injection efficiency was recovered to 100% over several months. As the vacuum pressure improved, we were able to increase the fundamental and harmonic gap voltages to the nominal values of 20 kV and 22 kV, respectively.

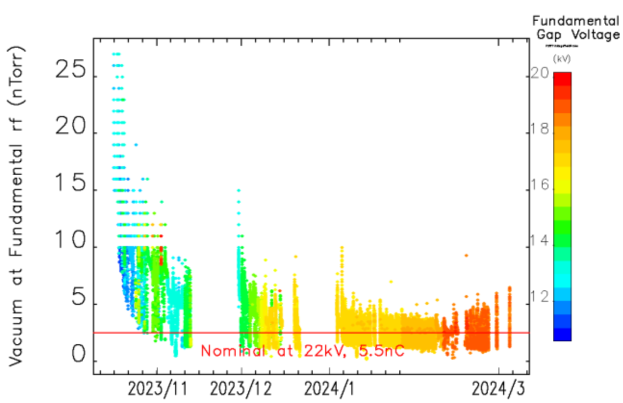

Figure 6: Summary of rf and vacuum conditioning from Oct 2023 to Mar 2024. The PAR charge is 2-10 nC.

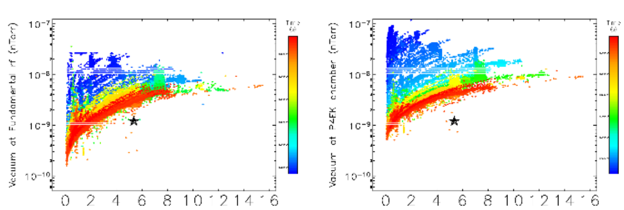

Figure 7: Vacuum history over time vs PAR charge at the fundamental cavity (left) and P4EK kicker chamber (right).

Figure 6 shows the vacuum pressure history at the location of the fundamental rf cavity. The colors show the fundamental gap voltage. Early on, the gap voltage had to be very low, in the 12-13 kV range, otherwise the pressure ran away. Over many weeks of beam scrubbing, the gap voltage could be raised to the nominal 20 kV. Figure 7 shows the same history as a function of PAR charge, both at the fundamental rf cavity and at the P4EK kicker chamber, which is adjacent to the cavity and showed the highest initial pressure. The colors show time, with red being the latest, and the symbols show the well-conditioned vacuum pressures at these locations. Vacuum recovery is within a factor of 2-3 of the historical values and is no longer a concern. Up to 15 nC was extracted from PAR, which is more than enough for initial goals. Vacuum and rf conditioning were completed by the start of APS-U commissioning.

The measured bunch length up to 12 nC was confirmed to be short enough (600 ps rms) for injection into booster (Fig. 8). These measurements were made with low fundamental voltage (15 kV) and nominal harmonic voltage (22 kV); this may partially explain why the bunch length was higher compared to before the new kicker chambers were installed. These measurements will be repeated now that the fundamental cavity is fully conditioned to 20 kV.

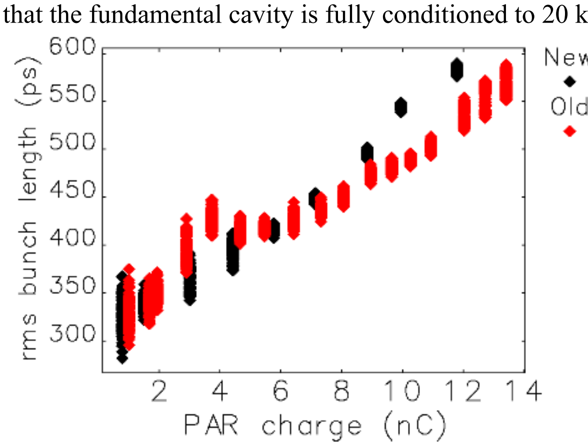

Figure 8: PAR bunch length vs. charge, before (Old) and after (New) installation of three new kicker chambers.

CONCLUSION

PAR was successfully restarted after six months of Dark Time. Several improvements were commissioned after extended vacuum and rf conditioning, and initial APS-U readiness was demonstrated with up to 15 nC PAR charge.

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