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THE ROLE OF BEAM DIAGNOSTICS DURING APS-U COMMISSIONING*

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Abstract

The Advanced Photon Source Upgrade (APS-U) represents the latest advancement in ultra-low emittance storage ring light sources. Since its commissioning and the commencement of user operations in 2024, APS-U has successfully reached its design beam current of 200 mA and operates reliably for user experiments. The diagnostic systems have been integral to the successful commissioning and operation of the machine. This paper presents the commissioning results for various diagnostic systems in the APS-U storage ring, with a focus on beam position monitors (BPMs). Additionally, we will discuss various beam measurements, including beam current and lifetime, tune, beam stability, and swap-out injection bunch motion.

INTRODUCTION

APS-U is an ultimate low emittance storage ring [1] recently constructed and commissioned at Argonne National Laboratory. The new storage ring is an upgraded of the original Advanced Photon Source (APS) ring; the electron beam energy was reduced from 7 GeV to 6 GeV, and the new lattice features a multi-bend achromat design with horizontal emittance of 42 pm rad. A novel swap-out on-axis injection method has been implemented.

Commissioning of the new storage ring started on April 10, 2024, with beam passing through the Booster to Storage ring (BTS) beamline shortly after. After correcting the polarity of several BTS magnets, beam was injected into the storage ring on April 11. The first turn beam was achieved on April 13, and the beam circulated in the ring for more than 10 turns on April 14, as measured by sum signals from the BPMs at turn-by-turn (TBT) rate. Shielding validation then took place intentionally dumping the injected beam at selected locations. Stored beam was achieved on April 20 with RF systems turned on; the DCCT measured less than 500 μA of stored beam on that day. The injection efficiency and stored beam current were gradually improved in the following days. Swap-out injection was demonstrated later that month, with stored beam DCCT and Bunch Current Monitor (BCM) used to measure the beam currents. As one of the Key Performance Parameter (KPP) thresholds, 25 mA stored beam was achieved in mid-May after fixing a septum issue. Beamline commissioning started in June after achieving 50 mA stored beam.

Diagnostic systems have played a pivotal role in the rapid and successful commissioning of the storage ring. Prior to beam commissioning, major diagnostic systems were carefully tested and integrated with other systems. These pre-beam tests were essential for identifying software bugs, verifying cable connections, and rehearsing data acquisition and analysis procedures. BPM offsets were also measured during the period and have been used for day-1 commissioning [2, 3].

The following sections provide an overview of the APS-U diagnostic systems, pre-beam test and checkout results, and commissioning results for the BPM system, current monitors, and other diagnostics. Machine performance has continued to improve over the past year, with many diagnostic systems brought online and optimized. Some of key improvements that have supported machine operation and development are presented.

APS-U DIAGNOSTICS OVERVIEW

There are 14 RF BPMs installed in a typical APS-U sector, giving a total of 560 BPMs in 40 sectors. Although the BPM feedthroughs share the same design, there are four different types of BPM pickups with different housing dimensions: P0 type, STD type, AP2 type, and BP5 type. The P0 and STD types have circular chambers of 22 mm diameter, and four buttons are symmetrically located at 45-degree angles. The AP2 and BP5 types have photon extraction slots and antechamber; consequently, the button is located at 60-degree angles relative to the horizontal plane. Within a sector, there is one AP2, one BP5, two P0, and ten STD BPMs. The BPM pickup and feedthrough design is described in [4].

Storage ring tunnel side of the BTS transfer line has also been newly constructed, with new button-type BPMs installed. There are 11 such BPMs installed in the new BTS, with the same feedthroughs as the storage ring (SR). The BTS on the booster tunnel side remains the same, so the original stripline-type BPMs are still being used. All the BTS BPMs now use a new type of electronics.

Commercial electronics from Instrumentation Technologies [5] have been selected for the APS-U BPMs, with APS-U specified features. The BTS BPMs are equipped with Spark-EL single-pass electronics, which provide sufficient resolution at 1 nC even with the 8 mm button pickups. External 20 dB attenuators are added for the old stripline BPMs to avoid saturation of the new sensitive electronics at high charge.

The storage ring button BPM signals feed to Libera Brilliance Plus (LB+) electronics via coaxial cables. Each LB+ unit houses four BPM modules, one controller module, one timing module, and one Global Data Transmitter (GDX) module. The BPM modules condition the analog signals, digitize them, and process the data at various bandwidths and precision. The controller module manages the LB+ unit and houses the EPICS IOC; the timing module communicates with the MRF timing

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system [6] so that the BPMs can be PLL-locked to external machine clocks and triggered on different events. The GDX module streams TBT data via fiber links. The streaming TBT data is used for other devices and applications, such as the TBT data acquisition system (TBTDAQ), the beam position limit detection system (BPLD), and the fast orbit feedback system (FOFB).

In addition to the regular LB+ electronics, there are BPMs in the first three sectors after injection straight, equipped with fast RF switches and Spark ERXR electronics. This system allows precise single-bunch measurement for the swap-out injection bunch or for any selected bunch. There are 20 BPMs in the APS-U ring equipped with such electronics and they have been used for injection transient measurements and optimization [7, 8].

Thermocouples (TC), and resistance temperature detector (RTD) sensors are installed in the ring to measure the temperature of various vacuum components, supports, and air. Each BPM pickup has a TC sensor attached to its body to observe potential heating. There are also six RTDs installed for each sector to measure temperature stability of the tunnel air, the BPM supports and plinths supporting the magnets.

In addition to the BPM system and its associated systems, the APS-U ring also has various other diagnostics systems. For example, there are two DC current transformers (DCCTs) which measure the stored beam current. A dedicated bunch current monitor (BCM) is used to measure bunch-to-bunch charges. There are bunch-by-bunch (BxB) feedback systems which suppress coupled bunch instabilities in all three planes. The feedback digitizers also provide extensive diagnostics capabilities using the BxB data. Betatron tunes and synchrotron tunes can be measured with the help of the feedback systems. There are also photon diagnostics tools to measure the photon beam positions or transverse/longitudinal profiles.

PRE-BEAM TEST AND CHECKOUT

Most of the diagnostic systems needed for beam commissioning underwent pre-beam test and checkout after they were installed. The BPM pickups, for example, were measured with a 4-port vector network analyzer (VNA). The measurements confirmed the integrity of the pickups, the jump cables and the patch panels. Electrical offsets of the BPM pickups were also determined from the VNA traces. The installed BPM long-haul cables and electronics in the mezzanine racks were verified using a signal generator and a 1-to-4 switch. The measurement confirmed the correct orientation of cable connections as well as BPM electronics gains of individual channels. The BPM-to-BPM sum signal were also calibrated from this measurement.

Figure 1 plots the statistics of the BPM offsets. The top two subplots show the BPM pickup offsets measured with the 4-port VNA, while the bottom two display the BPM electronics offsets (with cables). These measured offsets were used for beam commissioning and improved the BPM position accuracy which in turn supported successful commissioning.

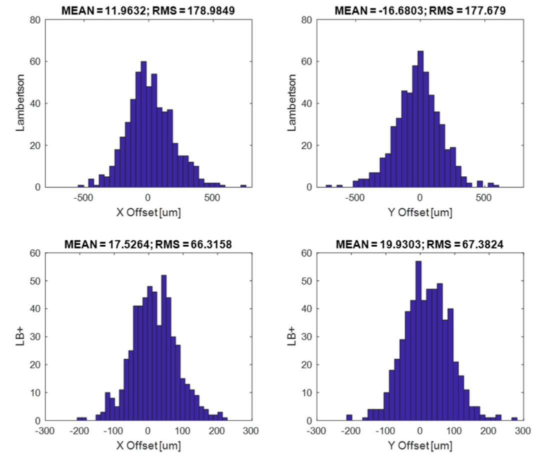

Figure 1: BPM offsets measured using the 4-port VNA (top), and electronics offsets measured using the signal generator and 1-to-4 switch (bottom).

One feature of the LB+ electronics is that each BPM has a synthetic data generator, which was widely used during pre-beam testing. At the time, there was no actual beam data, and the synthetic TBT data was used to test communication with other systems, such as TBTDAQ and BPLD, via fiber links. Up to 4096 turns of arbitrary waveform data can be programmed and streamed out on external triggers. This approach allowed the TBTDAQ and BPLD functionalities, as well as synchronized data acquisition, to be tested with the simulated TBT data.

Other diagnostic systems, like the current monitors, transverse bunch-by-bunch feedback (TFB), longitudinal bunch-by-bunch feedback (LFB), BPLD, temperature monitors, X-ray Beam Position Monitors (XBPM), and others, all underwent pre-beam testing. The DCCT current monitors, for example, were calibrated and prepared for precise stored beam current measurements before commissioning began.

BPM COMMISSIONING RESULTS

Single pass BPM data was used during the initial phase of commissioning. Figure 2 shows the trajectory in the BTS and SR injection area, measured on April 11, 2024. As the BPM sum signals indicate, the injected bunch passed the injection septum and injection kickers, then was lost shortly after the injection area. After further optimization, the injected beam was circulating in the ring for the first turn on April 13, as shown in Fig. 3, where raw ADC data is presented. The horizontal axis shows the 560 BPMs around the ring, starting at the injection point. The vertical axis represents the ADC samples; note that there are 398 ADC samples per turn. The beam signal is represented by the bright strip starting at ADC sample #140. Beam survived the first turn as the strip moved to larger ADC samples following the BPM geographical locations. Some BPMs detected the second-turn signals.

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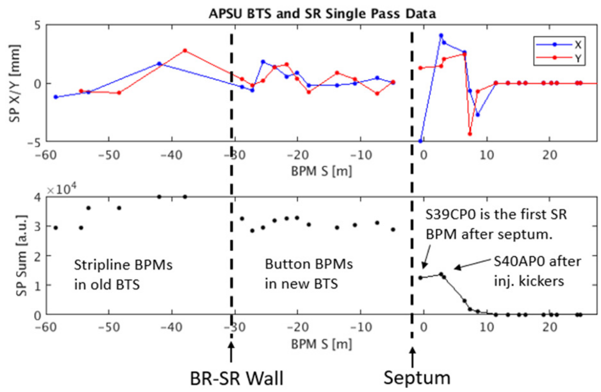

Figure 2: Single pass beam trajectory of BTS and storage ring injection area.

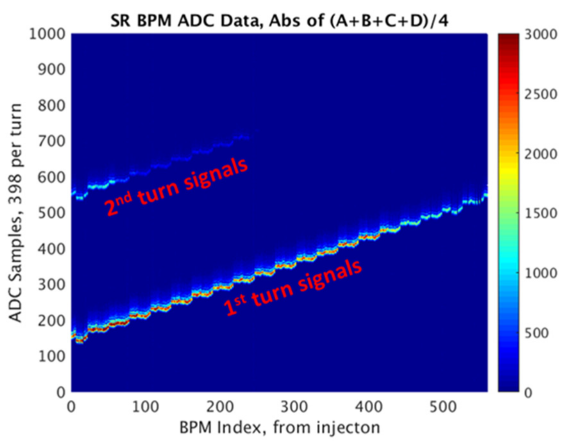

Figure 3: Raw ADC data of the first turn beam circulating in the ring. Beam lost in 2nd turn.

Based on the arrival time of the first-turn beam, as seen in Fig. 3, the BPM signal processing timing was finely adjusted. This way, turn-to-turn signal processing is aligned between BPMs, so they all report the data from the same turn. As the TBT data streams, it can be reliably captured by the TBTDAQ or BPLD system. Figure 4 is a plot of the BPM sum signal of individual turns as detected by the TBTDAQ system. In the plot, the injected beam arrived at turn #3 and survived for more than 10 turns.

Once the beam circulated in the ring, one crucial commissioning task was verifying the shielding. The injected beam was intentionally dumped at selected locations while radiation was measured. Again, the BPM single pass data was used to measure the first turn trajectory and the charge (proportional to BPM sum signals). An example is shown in Fig. 5, where the injecting beam was dumped at the insertion device (ID) straight in S15. In the plot, s = 0 m is the injection point, and negative s values represent BPMs in the BTS line. The ID is between BPM S15BP0 and S16AP0. There was approximately 1 nC charge measured in the BTS, and about 38 % of the charge was captured after the injection. The charge can be estimated benefiting from the calibrated BPM sum signals.

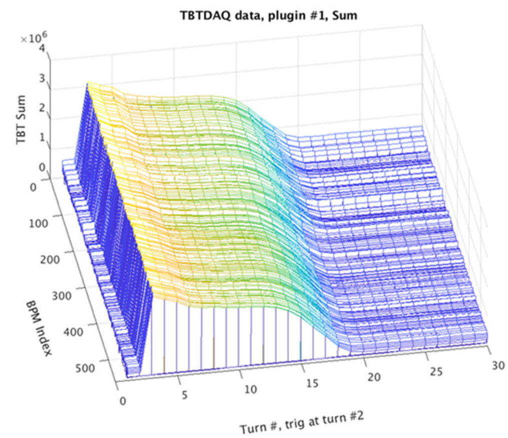

Figure 4: The beam circulates in the ring for ~15 turns. This plot shows the TBT sum signal from TBTDAQ.

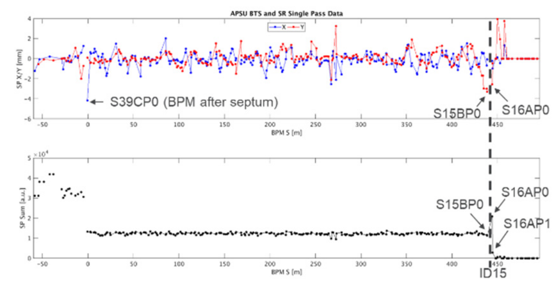

Figure 5: Single-pass trajectory and sum signal from BTS BPMs and the first sectors of the SR. The beam was dumped at ID15 for shielding verification.

Once beam was stored in the ring, the BPM was used to characterize various beam motions, such as the injection transient [8], short-term and long-term orbit stabilities, and post-mortem analysis to help understand causes of beam dumps. Figure 6 is an example of the beam spectrum as of now, averaged from dispersive BPMs AP3 from all sectors. The hump at around 560 Hz was the synchrotron frequency (fs). There were 60 Hz and its harmonics observed, which have been greatly suppressed by the RF noise suppression [9]. Strong 1 Hz motions were also observed in earlier days due to the Booster ramping; that motion has been greatly reduced by tuning the power supplies. In addition to the longitudinal fs motions, the dominant motions are at around 30 Hz horizontally and 60 Hz vertically. These motions will be suppressed with the FOFB system when implemented.

Figure 7 gives another example which utilize BPM TBT data to post-mortem (PM) analyze the beam motions at beam dumps. At each beam dump, a PM trigger event is generated and broadcasted in the MRF timing system; the PM event can then be used to capture TBT data from BPM electronics or TBTDAQ. Other systems, such as RF or power supplies, can also be triggered on the same PM event so that synchronized data can be analyzed. For this example shown in the plot, horizontal position swung negative at ~420 turns before PM trigger, then to positive, which tripped the BPLD/MPS system that issued the beam dump signal. About 40 % of charge lost prior to PM trigger

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and the whole beam was dumped as the RF system was muted after the BPLD/MPS trip. The small ripples in the vertical plane were due to the fanout kicker, which fired after each PM trigger event. The purpose of the fanout kicker is to spread out the power density on the beam dumps/collimators [10].

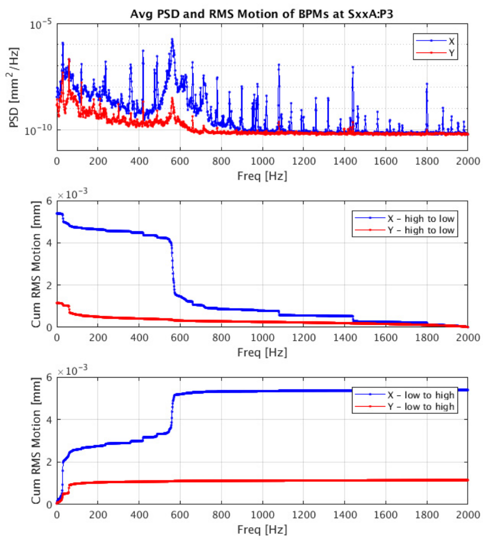

Figure 6: Averaged PSD spectrum and cumulated RMS motions at AP3 BPMs.

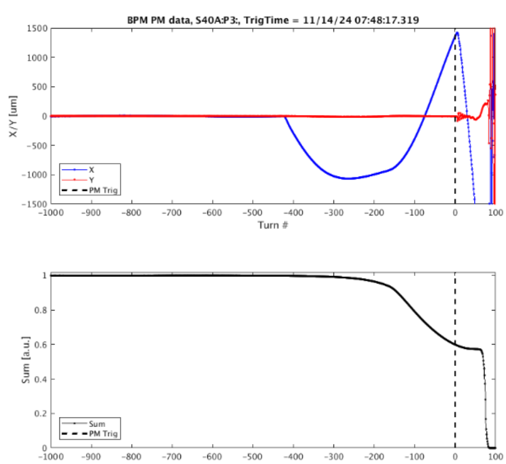

Figure 7: TBT positions and sum signal PM analysis for a BPM at a beam dump.

CURRENT MONITORS

There are two DCCTs installed in the storage ring, both of which were calibrated and fully tested before beam commissioning. When beam was first stored in the ring on April 20, 2024, the two DCCTs both measured a small current of less than 50 µA, and their readings agreed well, see Fig. 8 for the history plot.

The DCCT output voltages are also digitized by a fast digitizer chassis, which streams beam current information to the BPLD/MPS system at TBT rate. The BPLD/MPS system then compares the real time beam current to threshold currents. There are three thresholds: 1) Arm the MPS system whenever there is stored beam, typically set to 0.2 mA; 2) Enable the BPLD to protect vacuum components from ID synchrotron radiation, typically set to 2 mA at those IDs with gap closed; 3) Enable the BPLD to protect vacuum components from bending magnet radiation, typically set to 25 mA (currently using 11 mA as the threshold current to be conservative).

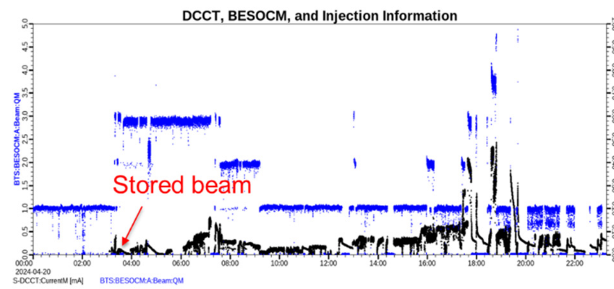

Figure 8: History plot of the SR DCCT measured current (black) and BTS charges, first stored beam in the ring.

A dedicated bunch current monitor (BCM) system measures bunch-to-bunch current from the button BPM sum signal. The system is based on a Radio Frequency System-on-Chip (RFSoC) FPGA chip originally implemented at ALS [11]. For the APS-U storage ring, the BCM digitizer operates with a sampling clock of 3.72 GHz which is 74/7×Frf. This means, effectively, one RF bucket will have 74 samples interleaved from 7 turns. A complete sample loop repeats the 7-turn cycle 4096 times, corresponding to 106 ms. While the interleaved BCM does not allow for turn-to-turn charge measurement of individual bunches, we tested with a high-speed scope as a supplementary tool. The scope has 20 GHz real-time sampling rate, corresponding to approximately 57 real-time samples per RF bucket. Similar to [12], bunch current, centroid (or phase), or even pulse width (bunch length) can be measured using a higher bandwidth scope [13].

OTHER DIAGNOSTICS

As the storage current increased and beamlines were authorized to open the shutters, our first emittance measurement was attempted at the S35 diagnostic beamline in May 2024. The source point at S35 beamline has large dispersion and is not ideal for emittance measurement; the storage ring emittance was later measured at ID beamlines [14]. A dedicated diagnostic beamline is under development, which will provide continuous emittance measurement with high precision.

TFB system was fully tested prior to beam and has been operational since the early commissioning days [15]. The system provides betatron frequency measurement by exciting a single bunch, in addition to its primary function of suppressing transverse instabilities. TFB digitizers have also been used to diagnose the bunch-by-bunch motions,

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such as injection disturbance, fast or slow beam abort, PM analysis of beam dumps, and potential instabilities.

Similar to the TFB system, the LFB is another feedback loop to cure potential coupled bunch instabilities in the longitudinal plane. The LFB system detects the longitudinal motions of individual bunch in two different modes: phase sensing or energy sensing. Phase sensing is similar to a traditional longitudinal feedback system, which measures the bunch arrival time (phase) and corrects it if instabilities are observed. Energy sensing detects the horizontal orbit change at a dispersive BPM. Both phase sensing and energy sensing have been tested, and the performance of the closed loop is being optimized.

Like TFB, the LFB digitizer also provides useful diagnostic capabilities. For example, bunches can be excited at around m×Frev + fs, where m is the mode number, to measure the fs of mode-0 or high order mode. More information can be found in [16, 17]. Figure 9 shows an example of synchrotron frequency measurement as total beam current varies. In the plot, one bunch was excited using LFB and its phase spectrum was measured either using the feedback digitizer or single-bunch BPMs [8]. The plot here is for mode #2, but other high order modes show similar drifting of the synchrotron frequency hump. Synchrotron frequency of mode-0 also drifted at higher current as, but with a smaller slope.

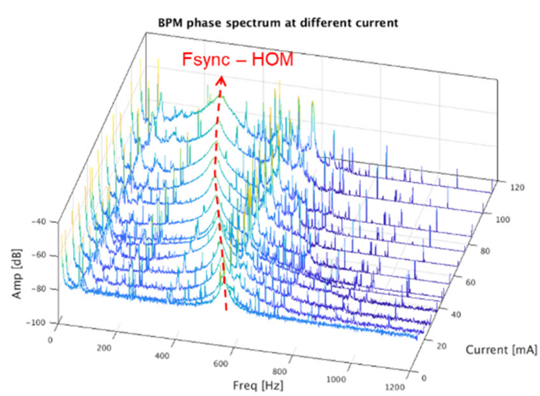

Figure 9: Synchrotron frequency spectrum of one bunch with LFB excitation at around m×Frev + fs, m = 2 for the bunch.

X-ray beam position monitors (XBPM) have also been commissioned as beamlines were brought online. ID beamlines use GridXBPMs [18, 19] and BM beamlines reuse the photo-emission type XBPM from the old APS ring. There are two types of ID beamline front end, namely: high heat load front end (HHLFE) and canted front end (CFE). Accordingly, the GridXBPMs have different designs for the two types of ID beamlines. Most of the XBPMs in HHLFE and BM beamlines have been commissioned and are operational. The sensitivity of the XBPMs was calibrated by steering the electron beam. Additionally, the XBPMs have motion stages that can be used for calibration. The CFE has two ID source points separated by 1 mrad, which complicates the GridXBPM position calculation as synchrotron radiation from the upstream and downstream ID sources both interfere the detector arrays. We are continuing to improve the XBPM performance.

Figure 10 shows an example of an XBPM measured positions and comparison to nearby RF BPMs. The machine was running with 135 mA, 48-bunch for user operation. An M7.3 earthquake from Alaska caused motion detected at around 16:06 on July 16, 2025. The S-wave (second wave) and SS-wave (S-wave reflected) were detected at around 15:53 and 15:57 at RF BPMs due to better resolution.

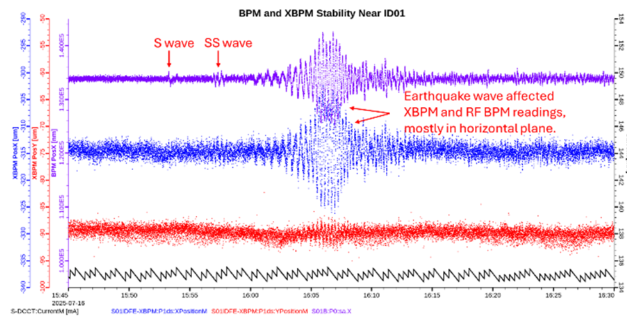

Figure 10: S01 ID XBPM stability and its comparison to a nearby RF BPM.

SUMMARY

APS-U storage ring was commissioned in 2024. The machine has achieved 200 mA swap-out user operation with the designed emittance. A variety of diagnostic tools have proven critical for the successful beam commissioning, operation, and ongoing improvements in machine performance. In particular, the BPM system played a pivotal role in smooth beam commissioning and characterizing beam stability. Most diagnostic systems have seen beam and have been commissioned, including DCCTs, BCM, TFB, LFB, and XBPMs. Performance of some systems continue to improve. A dedicated diagnostics beam is under construction for precise beam emittance measurement, and the team is actively working to bring the FOFB system online.

Many people contributed to the design, construction, testing and commissioning of the APS-U diagnostics systems. The author thanks everyone who has helped throughout this process.

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