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BEAM DIAGNOSTICS FOR THE APS MBA UPGRADE*

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Abstract

The Advanced Photon Source (APS) is currently in the preliminary design phase for a multi-bend acromat (MBA) lattice upgrade. Beam stability is critical where the requirements are driven by beam size which is expected to approach 4 µm vertically at the insertion device (ID) source points. AC rms beam stability requirements are defined as 10 % the minimum source size at the ID in the band 0.01-1000 Hz. The vertical plane stability goal is the most ambitious requiring a stability of 0.4 µm at the ID source point. In addition, long term drift defined as motion over a seven day period can be no more than 1 µm. In order to achieve these demanding beam stability requirements, a suite of beam diagnostics will be required including rf BPMs, X-ray BPMs, a mechanical motion measurement system (MMS), beam size monitors and a real time orbit feedback system. In addition, a tune measurement system, transverse multi-bunch feedback system and current monitors are planned for the upgrade. We report on the beam diagnostics design and APS storage ring R&D results used to inform the design.

INTRODUCTION

Beam diagnostics requirements for the APS MBA are driven largely by the small electron beam size. The two bunch patterns used in the MBA ring are uniform 48 and 324 bunch fills. All diagnostics must function from low beam currents expected during commissioning up to the full 200 mA design swap-out current. Beam stability requirements are listed in Table 1. Instrumentation for the MBA ring include new commercial Libera Brilliance+ (LB+) bpm processing electronics from Instrumentation Technologies (ITech), Grazing Incidence Insertion Device GRID-XBPM [1,2], new feedback processing electronics [3] and the MMS system [4,5]. The GRID-XBPM results we report are for the prototype we have installed in sector 27 in 2015. Further development of the GRID is required for use in the MBA ring due to the different bending magnet background in the new machine. We present the key design features of these systems and report on beam stability R&D in sector 27 of the APS storage ring.

Table 1: Beam Stability Requirements at ID Source Points

Plane	AC rms Motion (0.01-1000 Hz)	Long Term Drift (100s – 7 days)
Horizontal	1.3 µm 0.25 µrad	1.0 µm 0.6 µrad
Vertical	0.4 µm 0.17 µrad	1.0 µm 0.5 µrad

RF BPM ELECTRONICS AND BUTTONS

The LB+ electronics consists of four channels of bpms, switching to suppress long-term drift and slow (SA) and fast (FA) data streams and two different processing modes. For our R&D program, we had the FA data for orbit feedback increased to 22.6 kHz or one twelfth that of the turn-by-turn (TBT) rate. Testing at APS of the LB+ electronics itself for AC noise using FA data from 0.01 to 1000 Hz and long term drift using the 10 Hz SA data indicated < 0.05 µm rms and < 0.01 µm rms respectively for the APS most used 24 uniform bunch (similar charge to the 48 uniform bunch pattern for the MBA ring) and 324 bunch patterns. These measurements are much less than the rms AC and long term drift specs listed in Table 1. In addition single-shot noise at 0.5 nC was measured to be < 51 µm rms which for commissioning before there is stored beam is ~10 % the expected rms mechanical displacement of the bpms.

An MBA pickup electrode design has been developed which is based on a scaled version of that for existing APS BPMs. We had various button prototype button assemblies constructed and simulated as part of our R&D program. We then fully assembled the buttons developed as part of the R&D into a vacuum chamber assembly with two rf-shielded bellows, as planned for APS-U, shown in Fig. 1.

Figure 1: MBA integrated BPM / rf-lined bellows from vendor B.

Key parts of the design include use of an alternative bellows rf liner scheme, which uses leaf springs to maintain contact between the flexible and rigid portions of the bellows liner. A heat sink is also incorporated near the buttons to remove heat generated by wakefields and synchrotron radiation. Mounting of the bpm assembly will be off the ID vacuum chamber on an Invar stand to minimize mechanical movement due to vacuum chamber heating. Design goals for button pickup electrodes are high sensitivity, high charge induced voltage on the button to maximize signal-to-noise ratio, and minimize wakefield impedance. Sensitivity and power loss of the

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buttons were extensively simulated for both MBA ring bunch patterns and bench tested validating this design [6].

NEXT GENERATION X-RAY BPMS

We have developed for the MBA ring new GRID-XBPMs based on x-ray fluorescence photons from grazing-incidence off of GlidCop absorbers. This novel device located in the front ends is able to handle power for undulators up to 22 kW. The GRID-XBPM is challenging in several ways: (1) The instrument operates in a strong background of bend magnet (BM) radiation. At the APS, the users use the undulator with its field parameter as low as K~0.4. At this level, the total undulator power is roughly equivalent to the main dipole radiation power within 1.5 mrad. (2) Since the most powerful part of the undulator radiation is reserved for the beamline users, the XBPM can only intercept fringe areas outside of the central cone, which further reduces the undulator signals at small K and enhances BM background. (3) The part intercepting the beam needs to handle the full undulator beam in case of mis-steering at the maximum power.

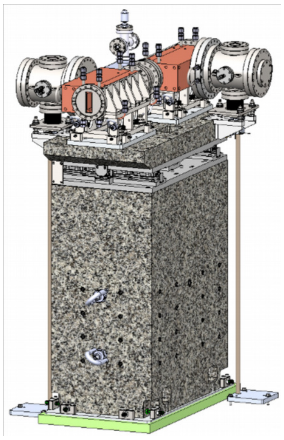

Figure 2: Solid model of the APS GRID-XBPM.

Figure 2 shows the GRID-XBPM design: A grazing-incidence absorber is placed on each side of the beam axis at 18.6 m from the nominal source point. A gap of 1.6 mm is kept between the absorbers. A granite block supports the XBPM to improve mechanical stability and to increase thermal mass for damping temperature fluctuations. When undulator gaps are closed, each absorber may absorb up to 1/3 of the undulator power and heats up the support bracket, rising in 10's of µm in height. The detectors and their optics, supported independently from the granite table top using Invar rod, ensure that the reading is not affected.

The horizontal beam position is calculated from the ratio of difference over sum of the detector signals from the two absorbers. The GRID uses the pinhole optics to read out the vertical position of the beam on the absorber (each absorber gives redundant vertical information). For each GRID absorber it can be shown that the Δ/Σ ratio is proportional to the vertical center of mass of the beam footprint. Figure 3 shows that the GRID-XBPM demonstrated a 30-fold improvement in undulator signal to BM background ratio above that of the photoemission XBPMs presently used at APS. A prototype GRID was installed in sector 27 and used for the past two years in orbit feedback during user operations. During each 7 day user run period both AC and long-term drift specifications (extrapolated out to 18.1 m from the angular specifications shown in Table 1.) were achieved giving confidence in the design for the APS upgrade.

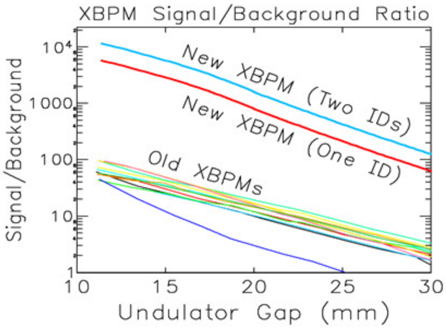

Figure 3: Ratio of the XBPM sum signals to the BM background in the APS Storage Ring.

MMS DEVELOPMENT

In order to investigate long-term beam stability, a MMS has been developed. The need for this development started in early 2010 when periodic 15-minute duration beam motion was reported on many ID locations during user operations. It was determined that the periodic beam position motion was correlated to the cooling water cycle of the vacuum chamber resulting in BPM movement.

The MMS was developed to measure the movement of rf and GRID bpms relative to the floor and measure the floor tilt. For movement relative to the concrete floor, capacitive sensors were mounted on invar rods from the rf bpms upstream and downstream of the ID as well as on the GRID in APS sector 27. Commercial high-resolution non-contact capacitive detectors by Micro-Epsilon were chosen as part of their CapaNCDT 6200, which is a multi-channel measuring system that is entirely modular and can support up to four synchronized channels with integrated ethernet interface. The capacitive sensors operate by measuring the change in voltage of the capacitor formed from the bpm vacuum chamber to an electrode when driven by an AC current. The range of measurement is 500 µm with a resolution of 10 nm.

To measure floor tilt, a Hydrostatic Level System (HLS) was developed. In the HLS three cans connected by pipes were filled with water and located on the concrete floor at each ID rf bpm and the GRID. Capacitive detection is also employed between the water surface in each can and an electrode. The fundamental principle of the HLS is based on the communicating vessels principle where water seeks the same level relative to an external reference point for connected vessels containing a fluid. The baseline design uses Fermi Lab Budker design sensors [7]. Argonne has worked with

Micro-Epsilon to combine their expertise in capacitive detection with the Budker HLS design concept and has developed and built prototypes used in this R&D program. Differences in position at each can give a measure of the floor tilt over time. We demonstrated how to use both sets of sensors to correct for long term mechanical motion over seven days resulting in rms residual motion of 1.4 µm at the GRID-XBPM (reduced from 7 µm before correction).

INTEGRATED BEAM STABILITY TESTS

Figure 4 shows a schematic layout of the MBA diagnostics installed in sector 27 and 28 of the APS storage ring for R&D and testing. Shown in the figure are capacitive and capacitive/hydrostatic sensors at the ID S27B:P0 and S28A:P0 (P0) rf bpms, and the GRID-XBPM. A second special GRID-XBPM created out of the front end exit mask is shown but not installed for these experiments. We instrumented sixteen rf bpms with LB+ electronics including the ID P0 bpms. We used existing electronics for the GRID-XBPM as the commercial electronics was not available for testing. Tying this all together is a new prototype feedback controller (FBC) first tested in 2016.

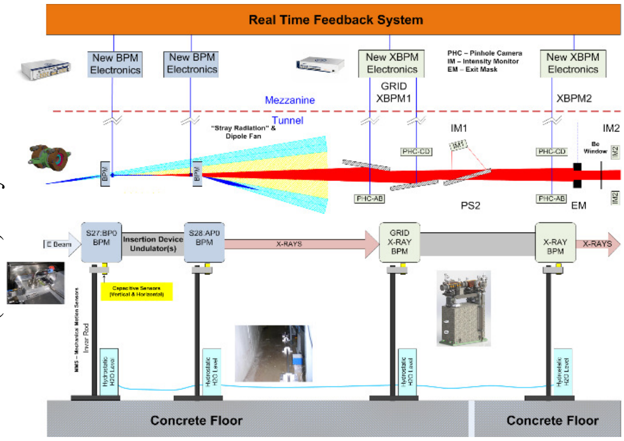

Figure 4: Layout of MBA diagnostics in the insertion device part of sector 27 in the APS storage ring for R&D.

The orbit feedback experiments used four existing fast and four slow correctors in each plane. The fast corrector power supplies used were prototypes for the MBA ring with 10 kHz small signal bandwidth. The FBC used a PID controller and only integral control was used for all the experiments. The micro-TCA based FBC chosen for the R&D program is a CommAgility AMC-V7-2C6678 board that uses a combination FPGA and fast DSP for communication and processing. The FPGA was used for data transmission from the rf bpms, to the DSP and transmission of corrector setpoints calculated by the DSP to fast and slow correctors. The DSP applied the feedback algorithm including an inverse response matrix, PID regulator using C code reused from the existing fast orbit feedback system. The rf bpms filter and send the data at the TBT rate to the FBC where it is decimated to 22.6 kHz. This rate is a 15 fold increase in feedback system rate over the present APS orbit feedback system.

A special data acquisition system (DAQ) is under development at APS and was used to collect bpm and corrector data from the FBC at 22.6 kHz rate. Further developments planned for the DAQ will increase this to the full TBT rate of 271 kHz. In the MBA ring, each FBC will will have access to a "double sector" of bpms and be able to control all correctors in the two sectors. BPM data will be transmitted to adjacent double sector FBCs eventually updating all FBCs with the orbit vector.

A primary goal for algorithm development for the MBA RTFB system is to unify both slow and fast corrector control in a seamless way so that the combined system is stable and achieves the AC and long-term orbit stability requirements listed in Table 1. At APS we have developed and tested this algorithm in this work and also using the APS operational orbit feedback system [8]. The essential idea consists of setting up the fast correctors with a subset of BPMs to correct down to DC using the standard machine inverse response matrix. The slow corrector response matrix is then measured while fast correctors are correcting down to DC. The inverse of this slow response matrix is then used for controlling slow correctors. The resulting slow corrector response matrix quantifies what the fast correctors cannot correct at low frequencies. This special slow corrector response matrix is calculable from an appropriately partitioned machine response matrix.

We demonstrated stable unified feedback operation at 22.6 kHz in both planes for two configurations of correctors and bpms: the first used a "square" response matrix of four fast correctors and ID P0 LB+ bpms and a slow corrector response matrix using four slow correctors and all sixteen LB+ bpms; the second used 16x4 fast and slow response matrices. In both cases we demonstrated stability nearly at the level specified in Table 1. Achieved at the ID P0 bpms was 1.5 µm and 0.46 µm in horizontal and vertical planes respectively for the first configuration and 1.4 µm and 0.45 µm in horizontal and vertical planes respectively for the second. In addition we demonstrated a closed loop bandwidth of approximately 700 Hz in the horizontal plane and 800 Hz in the vertical plane limited by the existing fast correctors and vacuum chamber installed in the APS ring. Simulation of these results with addition of realistic latencies and state space controller continue to be an active topic of R&D.

CONCLUSION

We have described the primary diagnostics for the APS upgrade used to achieve demanding beam stability requirements for the MBA ring. The main results of the R&D effort reported show that the systems described will be able to be used to achieve the demanding beam stability requirements for the MBA ring.

ACKNOWLEDGMENT

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