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NEW RF BPM ELECTRONICS FOR THE 560 BEAM POSITION MONITORS OF THE APS-U STORAGE RING*

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Abstract

With the upgrade of the APS storage ring to a multi-bend achromat lattice, 560 RF Beam Position Monitors (BPMs) will be required. The projected beam sizes are below 10 microns in both horizontal and vertical planes, putting stringent requirements on the BPM electronics resolution, long-term stability, beam current dependency and instrument reproducibility. For the APS-U project, the Libera Brilliance+ instrument has been upgraded in technology and capabilities, including the addition of independent multi-bunch turn-by-turn processing and an improved algorithm to further reduce artifacts of the crossbar-switch. More than 140 instruments, equipped with 4 BPM electronics modules each, are being delivered to Argonne National Laboratory, consisting the largest scale production for Instrumentation Technologies. In this contribution, the extensive test-conditions to which the instruments were exposed and their results will be presented, as well as the beam-based long-term drift measurements with different fill patterns.

BPM ELECTRONICS REQUIREMENTS

The performance requirements for the BPM electronics of the APS-U machine [1] cover the measurement resolution, beam current dependence (BCD), fill pattern dependence, intermediate-term drift and other functional and safety requirements. The requirements are gathered in Table 1.

Table 1: BPM Electronics Requirements List

Item	Requirement
Position measurement resolution (RMS)	0 dBm to -32 dBm: 1.3 µm -32 dBm to -40 dBm: 2.6 µm ... -60 dBm: 32.5 µm
Beam current dependence (mean change)	0 dBm to -32 dBm: 1 µm -32 dBm to -60 dBm: 2 µm
Fill pattern dependence	< 1 µm at -23 dBm (CW and 90% fill patterns)
Intermediate-term drift	100 nm drift in 4 hours under stable temperature environment

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BPM ELECTRONICS DEVELOPMENT

The present version of the BPM electronics from Instrumentation Technologies (i.e. Libera Brilliance+) did not fulfill the technological and functional requirements of the project. For this reason, a new BPM module has been developed during the first phase of the project, with redefined RF front-end, gain scheme, PCB layout and refreshed components. The RF path has been adapted with proper amplification and attenuation stages, as well as with redefinition of the cross-bar switch matrix and A/D converters. The optimum working point is at 0 dBm input power (CW) but the module can withstand up to +12 dBm without damage. The gain scheme was set up for the most optimum and linear attenuation values (28 dB, 20 dB, 12 dB, 3 dB, 0 dB). The FPGA was upgraded to the latest Xilinx Kintex Ultrascale+ XCKU3P. Compared to the Virtex-5 model used in the previous version of the BPM module, it contains 9x more logical cells and 4x more DSP slices. This provides much more real-time processing capabilities for the beam position calculation. The A/D converters are dual-channel 16-bit LTC2185. The module is built on a 12-layer HDI PCB with controlled impedance on 6 layers and via-pairs 1-2, 2-3, 2-11, 3-10, 10-11 and 11-12. The power consumption of the BPM module is reduced by 25% and totals to about 18 W.

The project included software upgrades that introduced a real-time multi-bunch turn-by-turn position processing, improved cross-bar switch glitch removal and programmable synthetic data generator for easier fast orbit feedback control development. The new software was compiled for the latest (at time of development) Ubuntu 18.04 64-bit Operating System.

The prototype unit was put under test at the existing APS storage ring at the end of February 2020, just a couple of weeks before the COVID-19 outbreak. The first beam tests were used to confirm the assembly of the analog front-end (single-bunch performance, beam current dependence).

PRE-SERIES ACCEPTANCE PROCEDURE

The pre-series, consisting of the first 4 produced units with a total of 16 BPM modules, were available 4 months after the start of the project, and went through a detailed acceptance procedure, planned for April 2020 at Instrumentation Technologies' premises in Solkan, Slovenia. Due to the lockdown and travel restrictions, the acceptance was done over several video conferences, on a

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random unit which was chosen by the APS team. The unit was put on a test bench and underwent the complete test set specified in the Factory Acceptance Test (FAT) procedure. The intermediate-term drift was measured overnight and the results were checked the next day.

All four units passed the factory acceptance successfully and were delivered to APS by May 2020.

SERIES PRODUCTION AND DELIVERY

The production of the large series started after the site acceptance tests were conducted by the APS engineers and results were compliant with requirements.

The production was planned in five batches with deliveries stretching from September 2020 to April 2021 containing 16, 28 or 32 units (4 BPMs per unit).

Typical installation time (firmware, software, FPGA) and standard FAT duration for 1 unit took about 3 hours. The extended FAT included more tests and an overnight drift test. The drift tests were done in a climatic chamber.

The default FAT was done on each unit. The extended FAT was done on every 10th unit and included an intermediate-term drift test. Tests revealed some BPM modules not meeting the narrow requirements on the off-centered beam current dependence performance. These modules did not show an obvious discrepancy but were just on the side of the Gauss curve, and were later accepted as compliant.

In total, 616 BPM modules were produced. Out of 616 pieces, 22 were found non-compliant immediately after production. A summary of the production quantities is shown in Table 2.

Table 2: Summary of Module Production

Modules	Quantity
All produced	616
Failed after manufacturing	22
Repaired in production	3
Stock at I-Tech	17
Failed the FAT (performance)	4
Failed the FAT (BCD), but confirmed for delivery	15
Delivered	576

Of the production issues, the most common were with power supplies (7), micro-controller (4), ADCs (3), attenuators (2), RF amplifiers (2), sensors (2) and FPGA (2).There were 3 modules rejected after the FAT (BCD and intermediate-term drift issues).

In scope of the FAT, the turn-by-turn noise performance and beam current dependence (BCD) performance were measured with a signal power range from 0 dBm to -60 dBm for both centered and off-centered conditions (3 dB attenuator on one channel). For off-centered conditions, the position was offset by ~750 µm.

Results are presented in Fig. 1 for all 576 BPM modules, divided in centered & off-centered conditions. Results were similar for horizontal and vertical planes. The scaling factor was 10 mm.

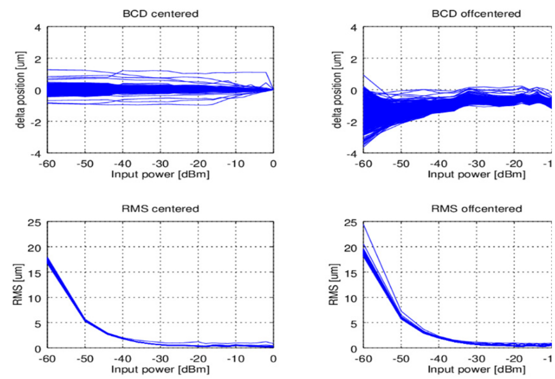

Figure 1: Turn-by-turn RMS and BCD performance measured for 576 BPM modules.

There were just 2 modules that show slightly different performance curve at low input signal power. At input power range from 0 to -35 dBm, the RMS is sub-micron. However, under off-centered conditions, variation through the power range is more visible.

The BCD for centered conditions was < 2 µm throughout the measurement range, with few exceptions. Under off-centered conditions, the dispersion was larger but still < 4 µm.

The shipments were delivered over land-air-land transport means. The third delivery was delayed significantly in December as a consequence of a cyberattack event at the US carrier. The shipment was delivered after approximately 1 month delay, with several carton boxes damaged during transportation, which also affected the measurement performance of 2 BPM modules.

SITE ACCEPTANCE

Site acceptance testing of the delivered units was originally planned to be performed at on off-site testing and storage facility. Several factors, including precautions to mitigate COVID-19 exposure, required site acceptance testing to be performed in existing lab spaces at APS. Two labs were reconfigured to support testing of the received Libera Brilliance+ units. In the APS storage ring, four BPM locations were removed from operations to provide signals for beam testing.

Tests Performed

The first production units were delivered in October 2020, with the final delivery made in April 2021. The site acceptance testing facility allowed for testing of 4 units per day, with the intermediate-term drift test acting as the limiting factor on acceptance testing rate. The short-term tests were performed during the day, with intermediate drift measurements set up to run overnight to allow the operating temperature of the units to stabilize.

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For each production unit delivered, the extended factory acceptance test was repeated at APS. This included measuring channel-to-channel gain differences, turn-by-turn resolution, fill pattern dependence, beam current dependence, channel-to-channel isolation, and intermediate-term drift. Of the 576 delivered BPM modules, two modules failed the intermediate-term drift test, and two additional modules failed the channel isolation measurement. The two channel isolation failures were in units from packing cartons that were damaged during shipping.

In addition to all units repeating the extended FAT, randomly selected units were chosen for additional measurements in the APS storage ring. Several units from each delivery were tested in the storage ring.

Storage Ring Acceptance Testing

To facilitate storage ring testing with beam, a set of four BPMs was removed from operations and dedicated to Brilliance+ acceptance testing. This allowed units to be swapped out without disturbing any operational systems. For resolution and drift measurements, 4-1 combiners were used to combine and split the signals from each BPM location to provide equal signals to each input channel of the BPM modules. Testing in the APS storage ring had two objectives: to verify adequate performance at low signal levels that are anticipated during accelerator commissioning, and to measure long-term drift performance over a one-week period. During dedicated machine studies, the turn-by-turn resolution of each module was measured under conditions simulating accelerator commissioning, including a single bunch of stored beam, and a single pass of charge that was dumped after the first turn. For single pass measurements, the measured position was collected for 1000 injections to find the standard deviation. The resolution requirements and measured values are shown in Table 3.

Table 3: Summary of First Article Single Bunch Measurements in the APS Storage Ring

Measurement	Resolution Requirement	Typical Measured Resolution (Average of First Article Modules)
Single stored bunch (1 mA)	< 16.5 μm	3.3 μm
Single bunch, single pass (1 nC)	< 58 μm	11.7 μm

The second important test using the APS storage ring was the verification of long-term drift. To meet APS-U stability requirements [2], a maximum long-term drift of 400 nm peak-to-peak over a 5-day period is required. Position drift was recorded for tested units during both 24-bunch and 324-bunch symmetrical fill patterns. All of the tested units have met this requirement. One suspected non-conforming module was discovered to be caused by a bad cable connection. Examples of long-term drift stability in the APS storage ring are shown in Figs. 2 and 3.

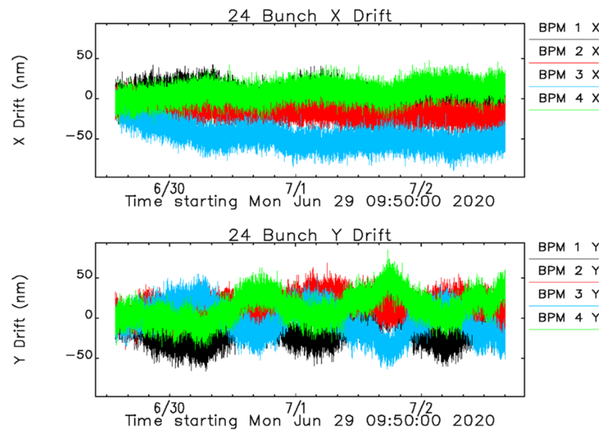

Figure 2: Long-term drift in 24-bunch fill pattern.

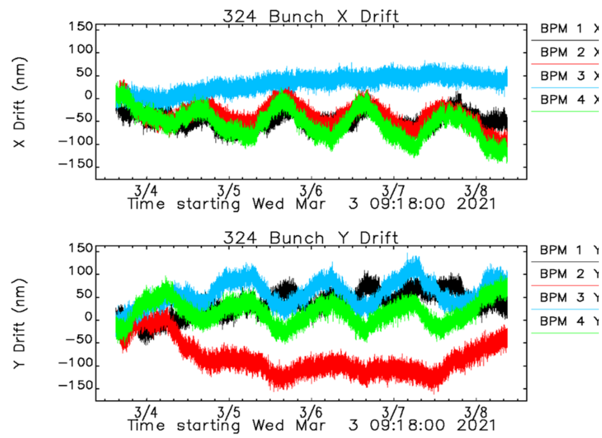

Figure 3: Long-term drift in 324-bunch fill pattern.

CONCLUSION

A new BPM system was developed and produced for the APS-U. The project was prepared and run by the APS and Instrumentation Technologies' groups and was completed in the projected timeline with no delays. This was the largest delivery project for Instrumentation Technologies so far. Out of 576 delivered modules, 4 did not pass the site acceptance tests and will be repaired or replaced. The reproducibility in RMS measurement performance of all modules is within 30 – 200 nm RMS. Measurement results at present APS beam showed the long-term drift performance of randomly selected modules fulfill the 400 nm peak-to-peak drift requirement over 5 days. Of the new functionalities, the multi-bunch turn-by-turn feature was able to record trajectories of 4 individual bunches. Electronic components used in the new modules are supported for a minimum of 15 years or are upgradeable (e.g. CPU module, FPGA chips).

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