New RF BPM Electronics for the 560 Beam Position Monitors of the APS-U Storage Ring

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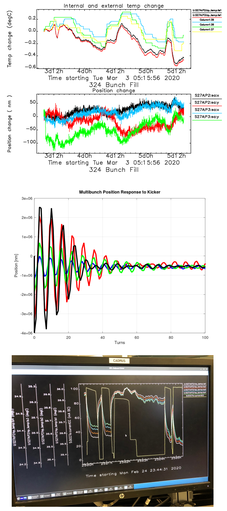
INSTRUMENTATION TECHNOLOGIES

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.

Requirements

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



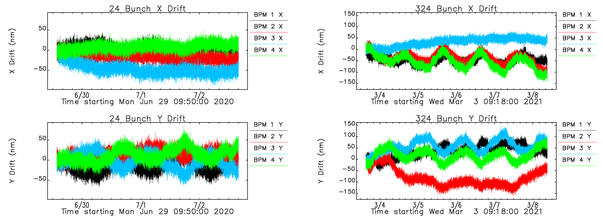
The prototype unit was equipped with two BPM module versions with different gain. Modules were tested at APS starting end of February 2020. Initial results showed stability within 100 nm over several days.

A new multi-bunch turn-by-turn feature was tested with 4 equally-spaced bunches of different charges stored in the APS storage ring. The multibunch window masks were configured to align each bunch within a measurement window. A kicker was used to disturb the beam. The multibunch turn-by-turn position measurements revealed that the amplitude of the beam position oscillation was different for each bunch, verifying that it was functioning as expected.

Prototype tests revealed a hardware bug that was correlated with beam current, high-precision temperature sensors and programmable attenuator's value. The bug was fixed immediately after the prototype tests by a simple component change.

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.

For each 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.



To meet APS-U stability requirements, 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.

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

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.
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.

Contract award — December 2019

Development — December 2019 to February 2020

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. (Figure 1).

The power consumption of the BPM module is reduced by 25% and totals to about 18 W.

The Libera Brilliance+ was refreshed with a new BPM module and with a new computer module (Intel i5 7440EQ).
The Operating System is Ubuntu, 64-bit, which can boot locally from the microSD card, or over the network from the TFTP server.
The timing module supports the MRF protocol and can decode up to 16 different event codes per trigger line.

Prototype tests — February 2020

Pre-series acceptance — May 2020

Due to the lockdown and travel restrictions, the acceptance was done over several video conferences, on a 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.

Testing environment was set up in the laboratory and later improved for time efficiency.
Time needed for firmware, software and FPGA installation, and standard FAT was about 3 hours for 1 unit (4 BPMs).

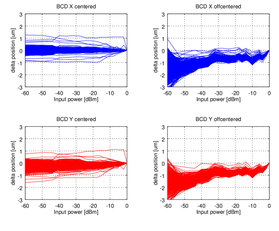
Site acceptance — September 2020 to April 2021

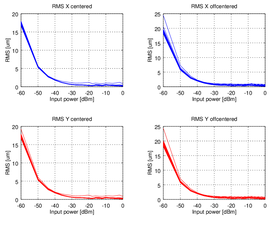
Series production — September 2020 to April 2021

Series production started after the pre-series was confirmed. The first batch of 64 BPMs was shipped in September 2020. Next shipments contained 128 BPMs. The fifth shipment, the delivery was completed in total of 576 BPMs or 144 units.
Production statistics show the hardware design and production was on a high level with few modules discarded and no systematic failure observed.

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

Performance plots below show the beam current dependence and turn-by-turn RMS performance recorded from all 576 BPM modules for centered and off-centered beam conditions.
The reproducibility between the modules is very high which proves the hardware design and high production quality.





APS-U

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.