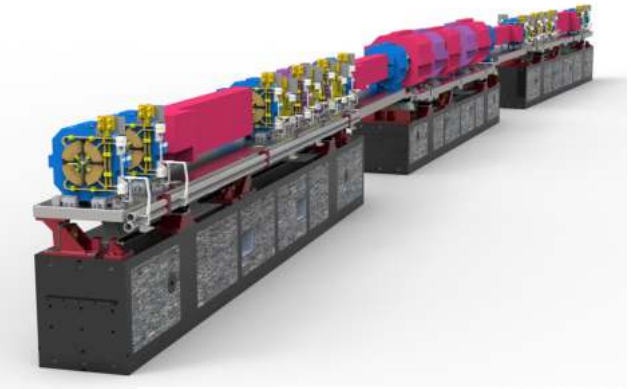
# Upgraded Libera Brilliance+ instruments for the 560 beam position monitors of the APS Upgrade storage ring



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APS Upgrade
Argonne National Laboratory **June 10th, 2021**

**Libera Workshop 2021**

# Acknowledgements

This project is the result of valuable contributions from many people, including but but certainly not limited to:

- Argonne: Ron Blake, Adam Brill, Hanh Bui, Weixing Cheng, Nick Manos, Tony Pietryla, Nick Sereno, Patricia Weghorn
- I-Tech: Uros Dragonja, Peter Leben, Peter Paglovich, Marco Praznik

# Outline

- The APS Upgrade project
- Bpm electronics specifications
- Bpm electronics project timeline
- Some lessons learnt
- Acceptance test results

# APS-U rf bpm electronics performance requirements

- Spec on long-term beam position drift: 1 um rms over 1 week

**Estimated peak voltages and turn-by-turn resolution requirements**

| Num. bunches (rep. rate) | Stored beam current | Charge /bunch | Gaussian bunch length | $V_{peak}$ at BPM electronics | Required TBT resolution |
|---|---|---|---|---|---|
| 48 (13 MHz) | 25~200 mA | 1.92~15.3 nC | 22.0~100.5 ps | 9.52~17.7 V | <1.3 μm |
| 48 (13 MHz) | 25~200 mA | 1.92~15.3 nC | 20.0~38.0 ps | 10.11~49.9 V | N/A |
| 324 (88 MHz) | 25~200 mA | 0.28~2.3 nC | 16.9~83.6 ps | 1.69~3.3 V | <1.3 μm |
| Singlet (271 kHz) | 1 mA | 3.7 nC | 100.5 ps* | 4.2 V | <16.5 μm |
| Single-pass injection (1 Hz) | Multi-turn, non-stored | 1 nC | ~100 ps | 1.2 V | <58 μm |

* Expected actual bunch length is ~30 ps

# APS-U Project Scope

**All existing beamlines incorporated in plans to come back online at conclusion of APS-U**

**New Storage Ring**
- 6 GeV MBA lattice
- **42 pm-rad emittance @ 200 mA current**
- Improved electron/photon stability

**New Insertion Devices**
- Incorporate **SCUs** on selected beamlines

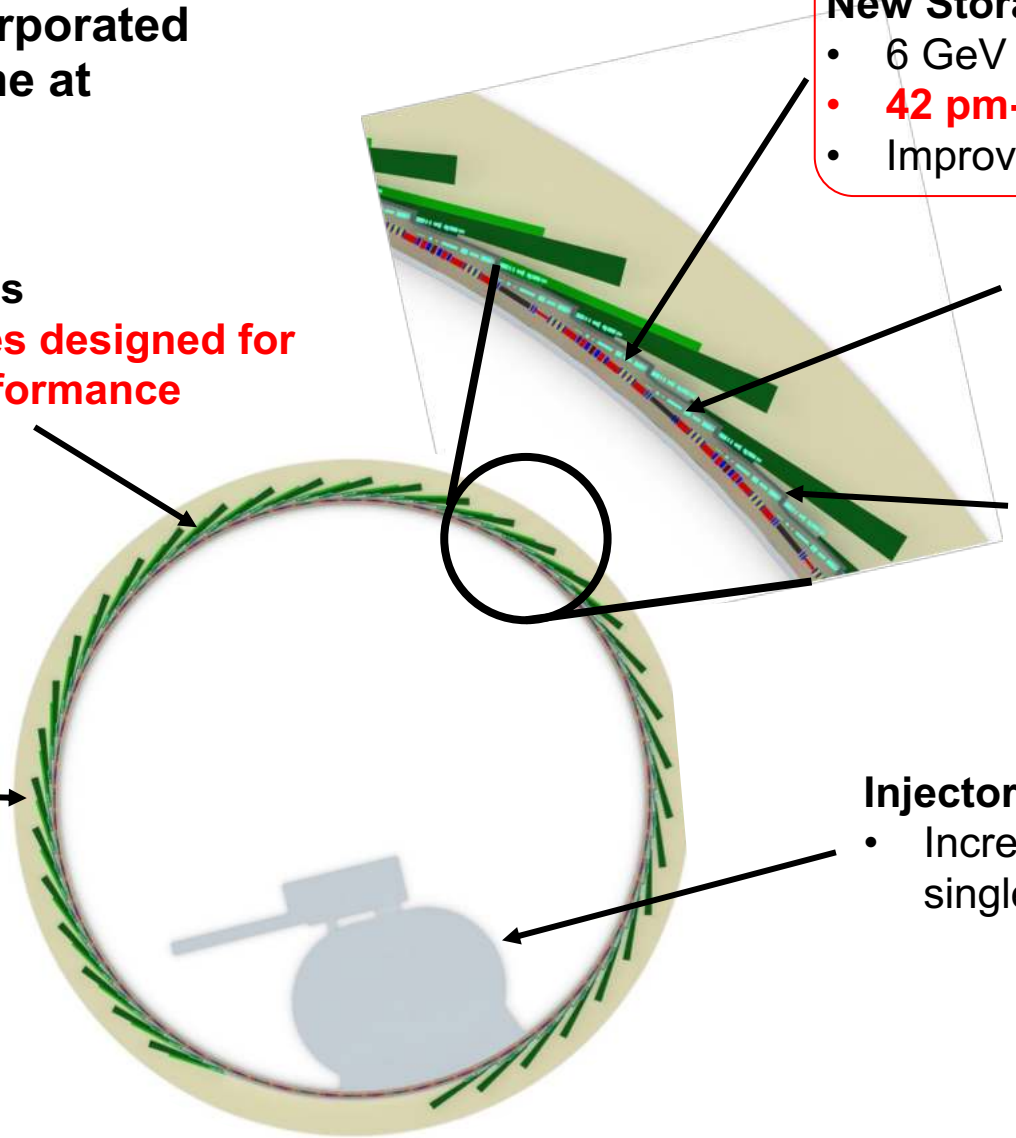
**New/upgraded Front-ends**
- Common design for maximum flexibility
- Integrated hard x-ray beam position monitors

**Injector improvements**
- Increased performance (high single-bunch charge)

**Feature beamlines**
**Suite of beamlines designed for best-in-class performance**

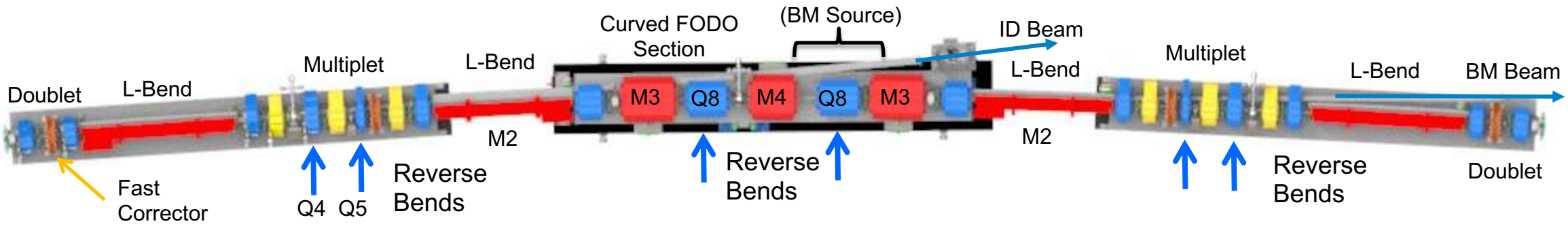
**Beamline Enhancements:**
**improvements to make beamlines "Upgrade Ready"**

**"Do no harm"**



Project is on track for starting the dark-time in April 2023

# APS-U Lattice




- Storage ring consists of 40 Sectors. Each with 33 arc magnets; 27.6 meters / sector
- Each sector is a hybrid 7BA with four longitudinal-gradient dipole bends, three transverse-gradient dipoles, and six reverse bends.
- Diagnostics include 14 rf bpms per sector (560 bpms total) and two GRID xray bpms at each of 35 insertion device front-ends.

# APS-U Libera Brilliance+ requirements

(Reference point: 2016 Libera Brilliance+)

- **Hardware specific**
  - FPGA should be latest-generation (Xilinx Ultrascale+)
  - Three separate turn-by-turn output data streams (fast orbit feedback, beam position interlock, and turn-by-turn DAQ)
  - No obsolete or near-end-of-life components

- **Functionality**
  - Pin-cushion linearization block for all turn-by-turn data streams
  - Single-bunch single-pass capability for measuring first turn(s) during commissioning
  - ADC gating feature with four separate ADC masks - primarily of interest for physics studies *
  - Improved cross-bar switch glitch-removal algorithm
  - Synthetic data generator to support validation of beam position interlocks without beam
  - Tagging of synthesized data samples

- **Computing environment**
  - Use standard currently supported Linux OS and EPICS release
  - Remote firmware updates
  - Booting IOC over the network

* Cheng et al , MethodsX, Volume 5, 2018, pp 626-634

# APS-U Libera Brilliance+ Project timeline

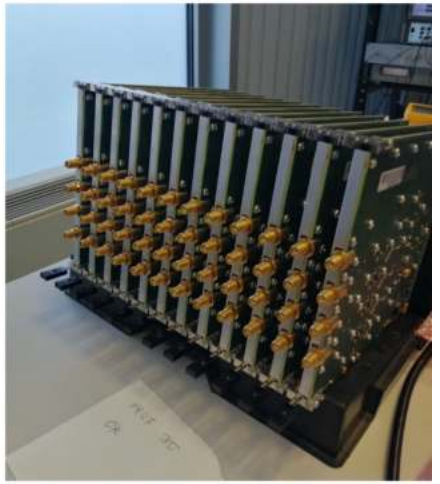
- Contract kick-off meeting: January 20, 2020
- First articles (remote) factory acceptance tests: April 20, 2020
- First-articles shipped: May 22, 2020
- ANL acceptance of first articles: July 20, 2020
- 140 production units in five shipments
  - First production batch shipped: Oct 2, 2020
  - Fifth production batch shipped: April 7, 2021 (exactly on schedule)
- Site acceptance completed: May 7, 2021

New bpm module

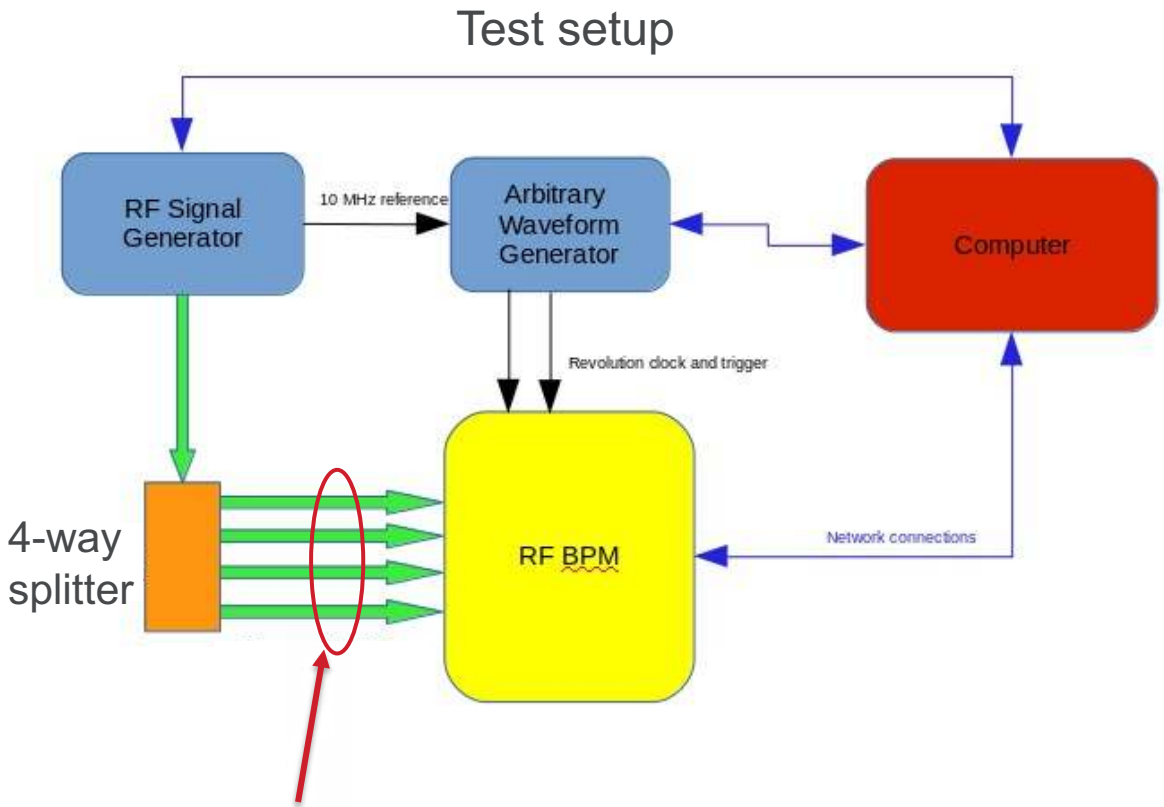

Last units received and accepted


Acceptance testing at ANL


First production units at ANL


Production RF modules at I-Tech

# Acceptance test criteria




**Tests repeated under two test conditions**

1. Phase-matched cables, no attenuators (simulates centered-beam)
2. Phase-matched cables + attenuators to lower Button A by 3dB (simulates off-center beam)

| Test | Test signal | Specification |
|---|---|---|
| Resolution | 0 > -32 dBm | 1.3 um rms |
| | -36 > -40 dBm | 2.6 um rms |
| | -44 dBm | 5.2 um rms |
| Beam current dependence | 0 > -32 dBm<br>-36 > -60 dBm | 1 um rms deviation<br>2 um rms deviation |
| Fill-pattern dependence | -23 dBm @ 100% fill | <1 um rms difference in offsets |
| | -23 dBm @ 90% fill | |
| Intermediate-term drift (4 hrs) | -23 dBm<br>Delta-T: +/-2 deg-C | <100 nm<br>peak-to-peak drift |

| Test | Test signal | Specification |
|---|---|---|
| Channel-channel isolation | 20V, 1 ns pulse with other inputs terminated | >50 dB |
| Uncompensated gain variation | -41 dBm, attenuators at 0 dB | <5% within bpm module<br>< 3% module to module |

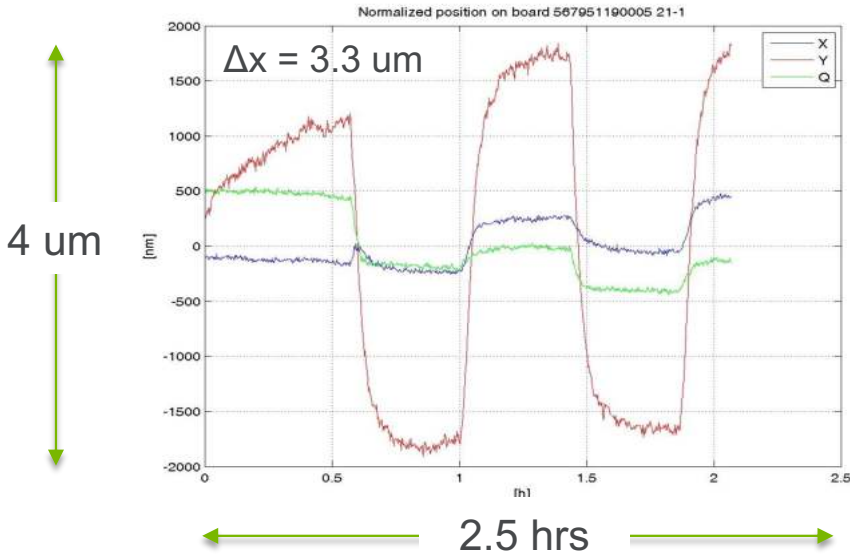
# BPM module hardware

## *"No obsolete or near-end-of-life components"*

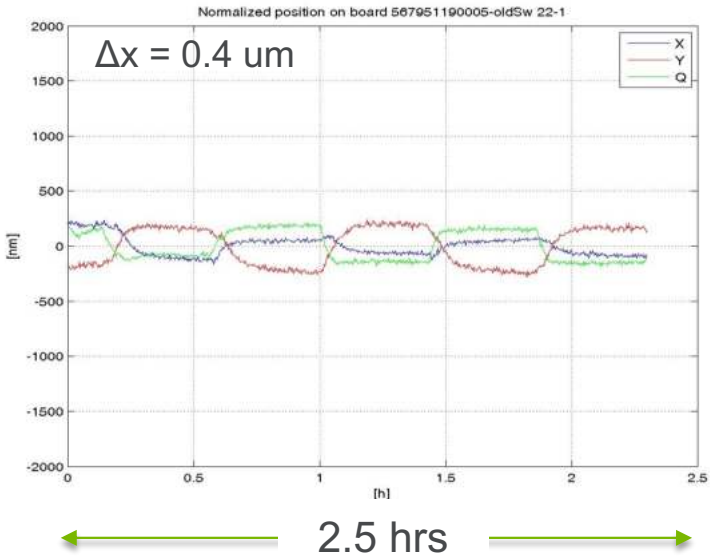
- Original crossbar rf switch device designed by Hittite is now obsolete (HMC427LP3)
- New bpm module used the drop-in replacement from Analog Devices (HMC427ALP3), but resulted in poor temperature dependence of the modules

**Position deviations for 5 deg-C temperature steps (same bpm module)**

***with HMC427ALP3 (new)***




***with HMC427LP3 (original)***




**Cause:**
A key (undocumented) performance parameter was degraded during a redesign of the device for a different manufacturing process (temperature stability of the s-parameters).

**Resolution for APS-U:**
To use the original (obsolete) devices, with I-Tech retaining sufficient stock to address any long-term support needs.

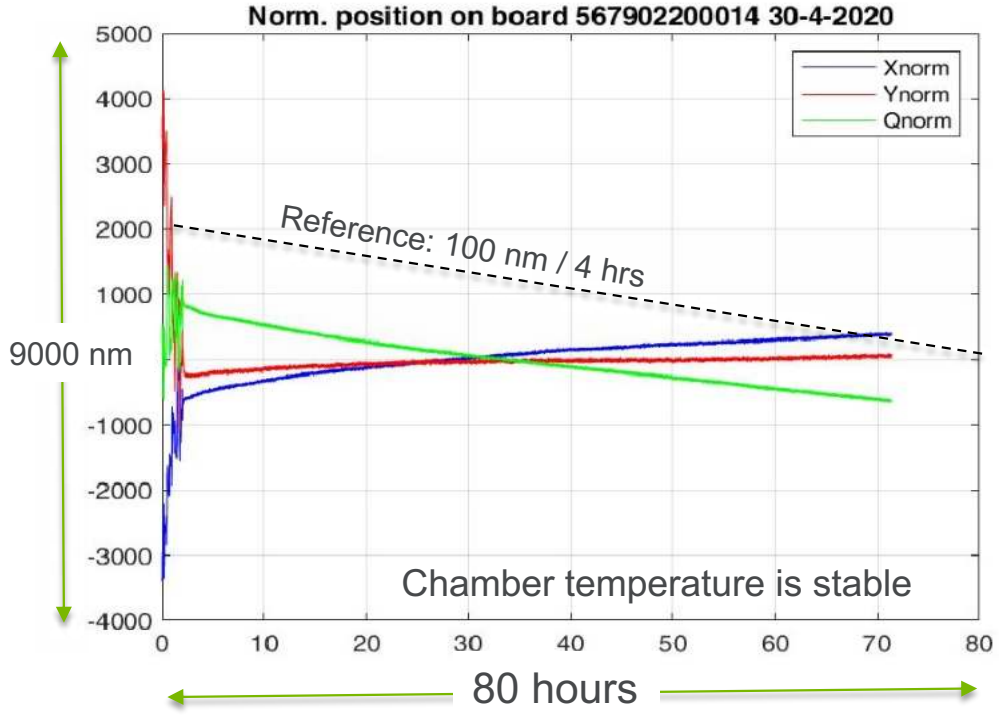
# Long-term drift – challenges

## Specification: <100nm drift over 4 hours and +/-2 deg-C

**Initial setup for FAT**

- Temperature chamber #1: Libera Brilliance+
- Temperature chamber #2: RF & clock generators

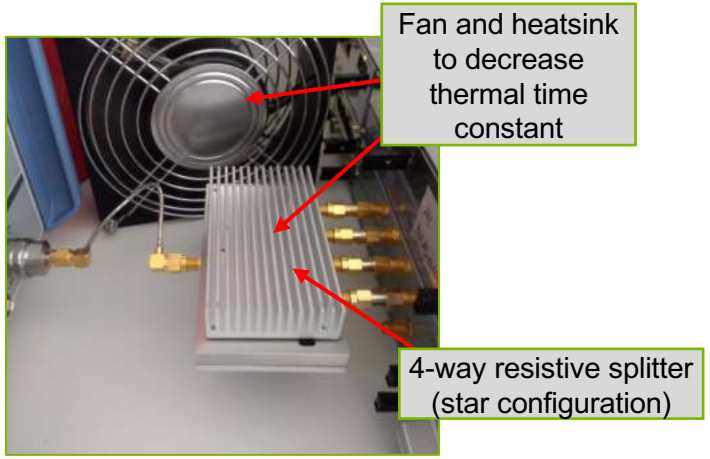
**Initial results showed a continuous small drift with stable chamber temperature**




**A lot of effort was spent trying to narrow down the cause of the drift**

- Temperature gradients on the board
- Cable issues with temperature or humidity
- RF signal drift
- RF splitters configurations and stability
- LB+ Digital Signal Conditioning function
- Parallel investigations at ANL

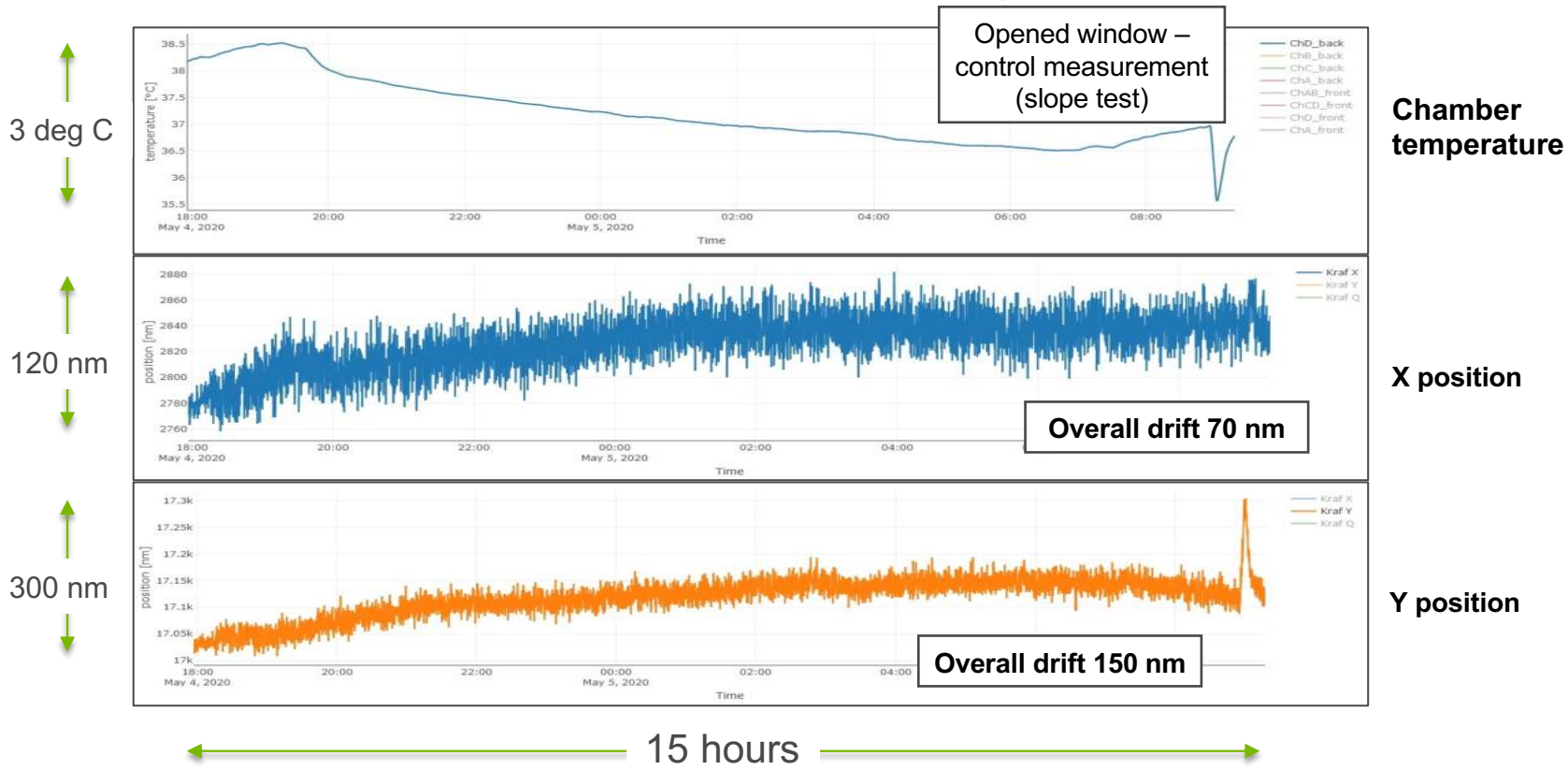
**Alternate setup to evaluate thermal effects on rf splitter**



# Long-term drift – final test configuration

- LMR cables were replaced with semi-rigid cables (better temperature stability)
- Test setup was fixed on a plate and was used for all units tested in the extended FAT
- Under same testing conditions, all results were within specification

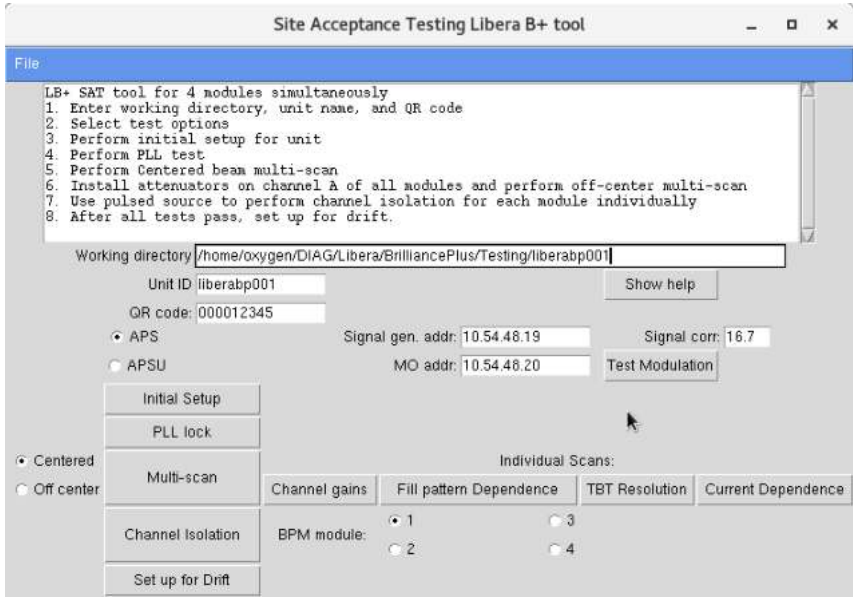
## Measured drift in final test configuration



# Site acceptance tests

- Bench acceptance tests on 100% of the units
- In-ring long-term stability test on 25 units (limited by APS Operations)

- Step-by-step inspection and acceptance of each unit was captured in an electronic traveler system in the APS-U Components Database
- Automated testing using python and Tcl/Tk to perform LB+ configuration, instrument setup, data collection and analysis and archive data in the APS-U Components Database (CDB).
- Tests were performed over range of power levels and for centered and off-center beam: channel gain uniformity, turn-by-turn resolution, beam current dependence, and fill pattern dependence
- Intermediate-term drift tests were run overnight on four units simultaneously (16 bpm modules)
- Channel isolation test performed by applying pulsed input to each channel individually
- 556 of the 560 production modules passed site acceptance tests
  - Two units failed intermediate drift specs
  - Two units failed channel isolation spec (likely damaged in shipping)

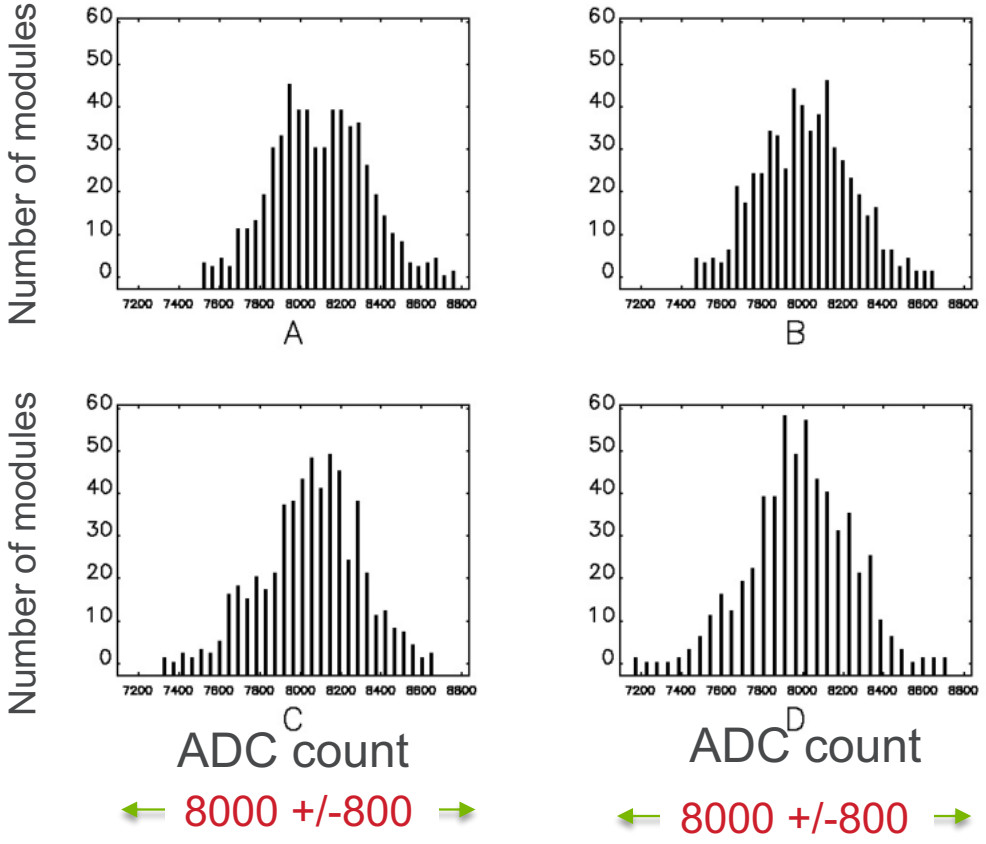



Setup for bench tests

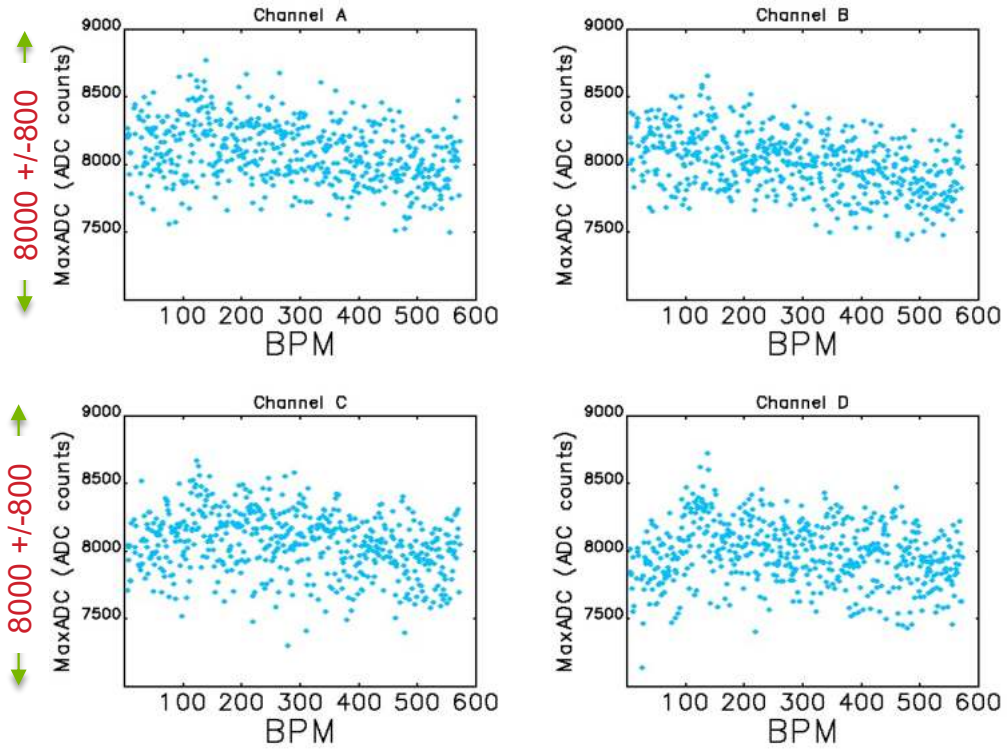
Setup for in-ring test

# Ensemble statistics: uniformity of channel gain

rms ADC counts by channel at
-41 dBm input (as histogram)

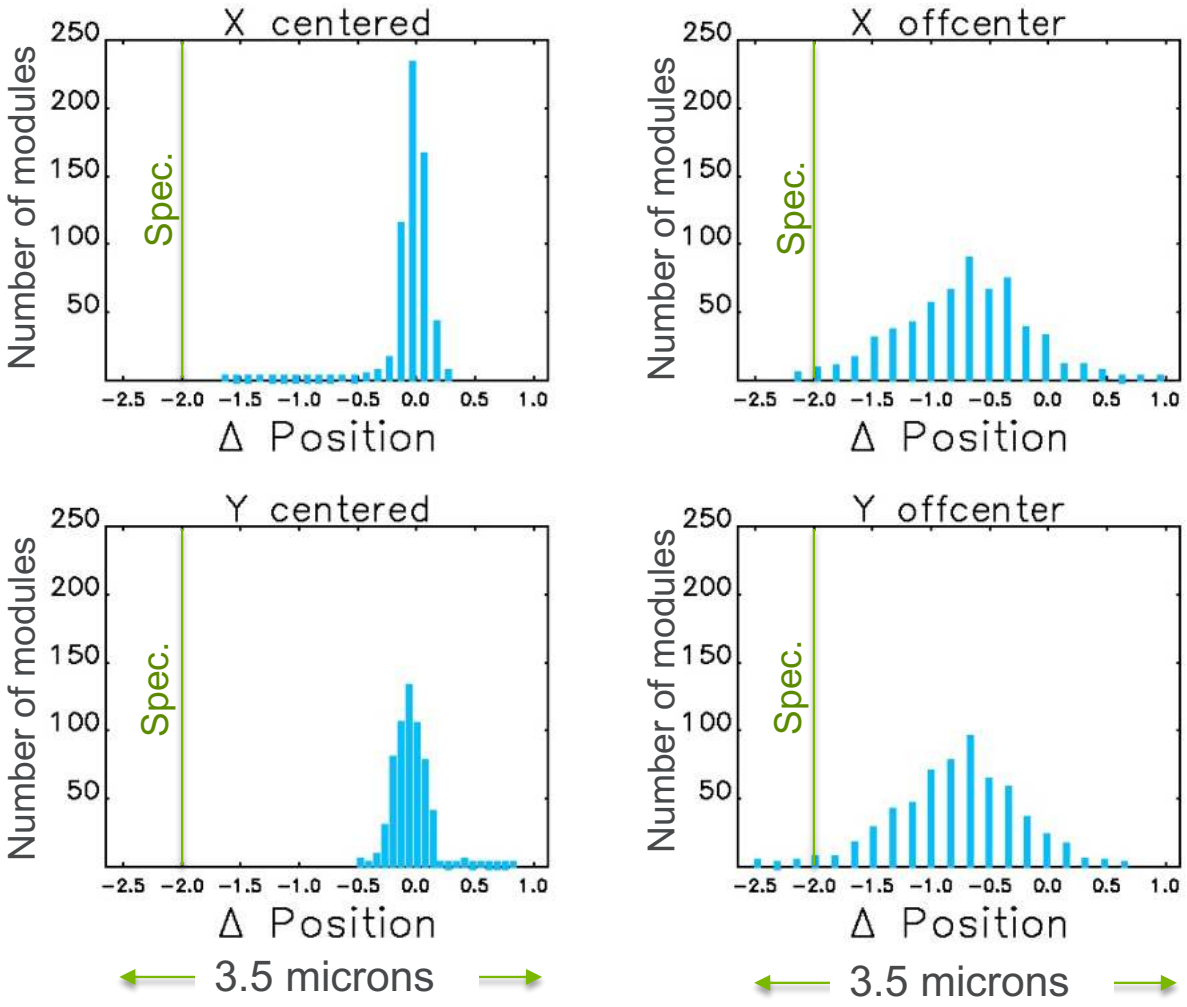



rms ADC counts by channel at
-41 dBm input (by bpm module number)




Equivalently, represents performance
from start to end of the production run

# Ensemble statistics: beam current dependence (-60 dBm)




**Histogram of change in position over input range of 0 dBm to -60 dBm**

Centered beam condition:
< 0.5 um rms over 560 modules

Off-center beam condition:
< 1.5 um rms over 560 modules

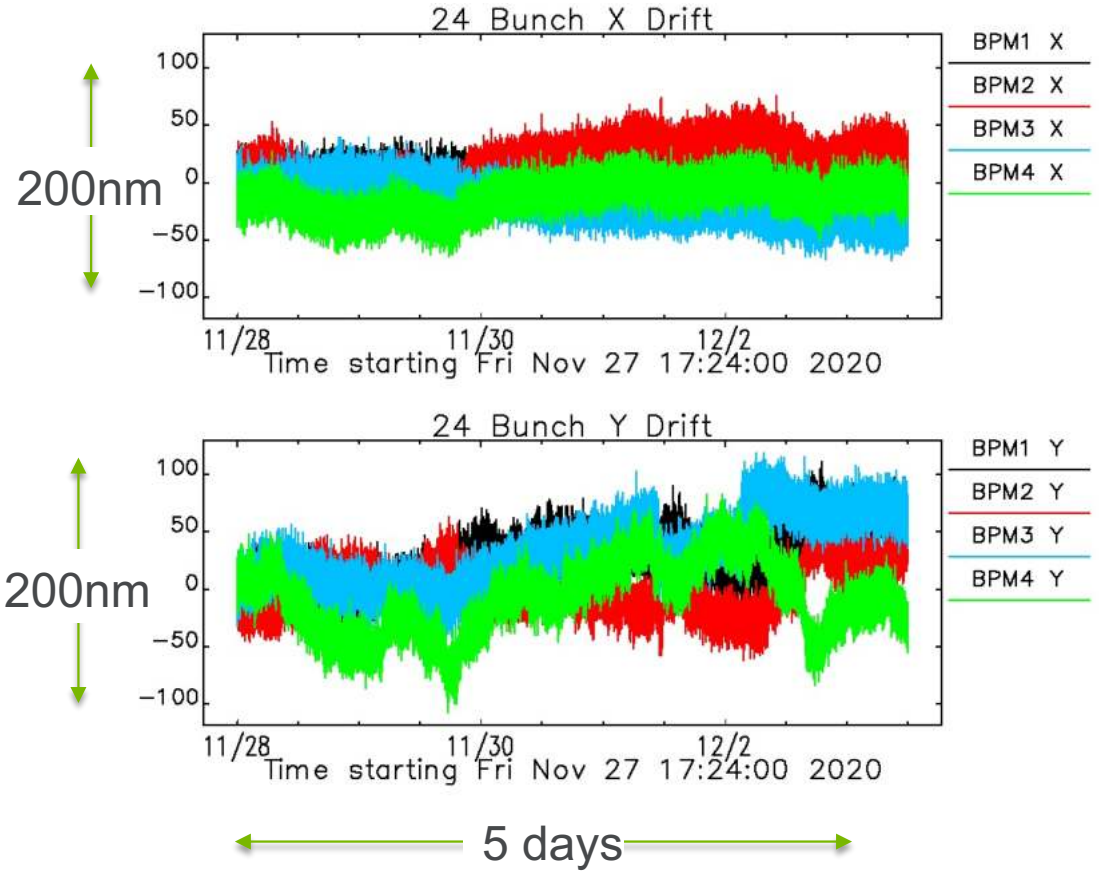
Some percentage of the modules did not meet the off-center spec of +/-2 um at -60dBm

We accepted modules with offsets less than 2.5 microns.

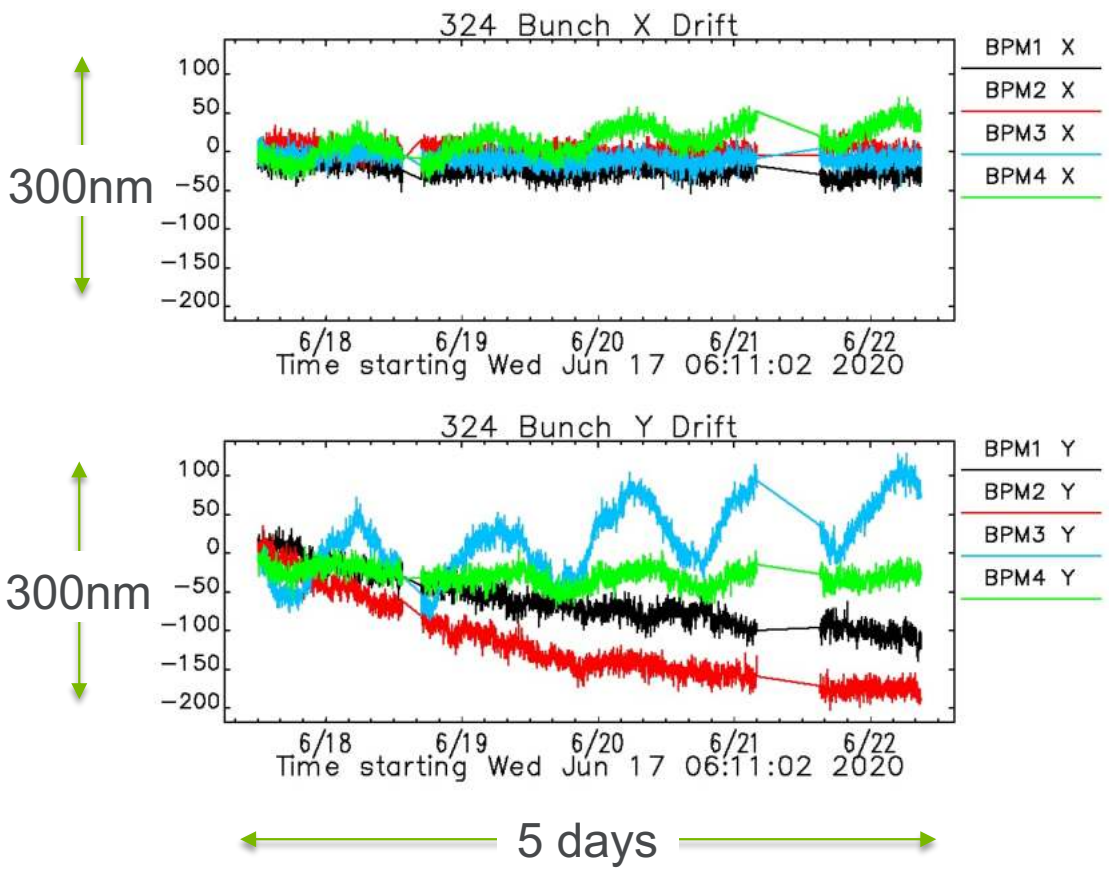
# Representative long-term drift in APS storage ring

## (Spec is 400nm peak-peak over 7 days)

24 bunches, 100mA, topup
Unit 013




324 bunches, 100mA, non-topup
Unit 058



# Summary

- In January 2020, Argonne contracted with I-Tech for 560 newly-developed Libera Brilliance+ rf bpm modules for the APS Upgrade accelerator.
- Despite the global pandemic, I-Tech kept to their promised schedule. Within 16 months, they completed the development of the new Brilliance+ and delivered 560 production bpm modules in 140 production units to Argonne.
- Site-acceptance pass rate was high at 99.2% (4 failures out of 560).
- Stringent APS-U functional and performance requirements have been met.