NSLS-II Fast Orbit Feedback System

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On behalf of FOFB Team

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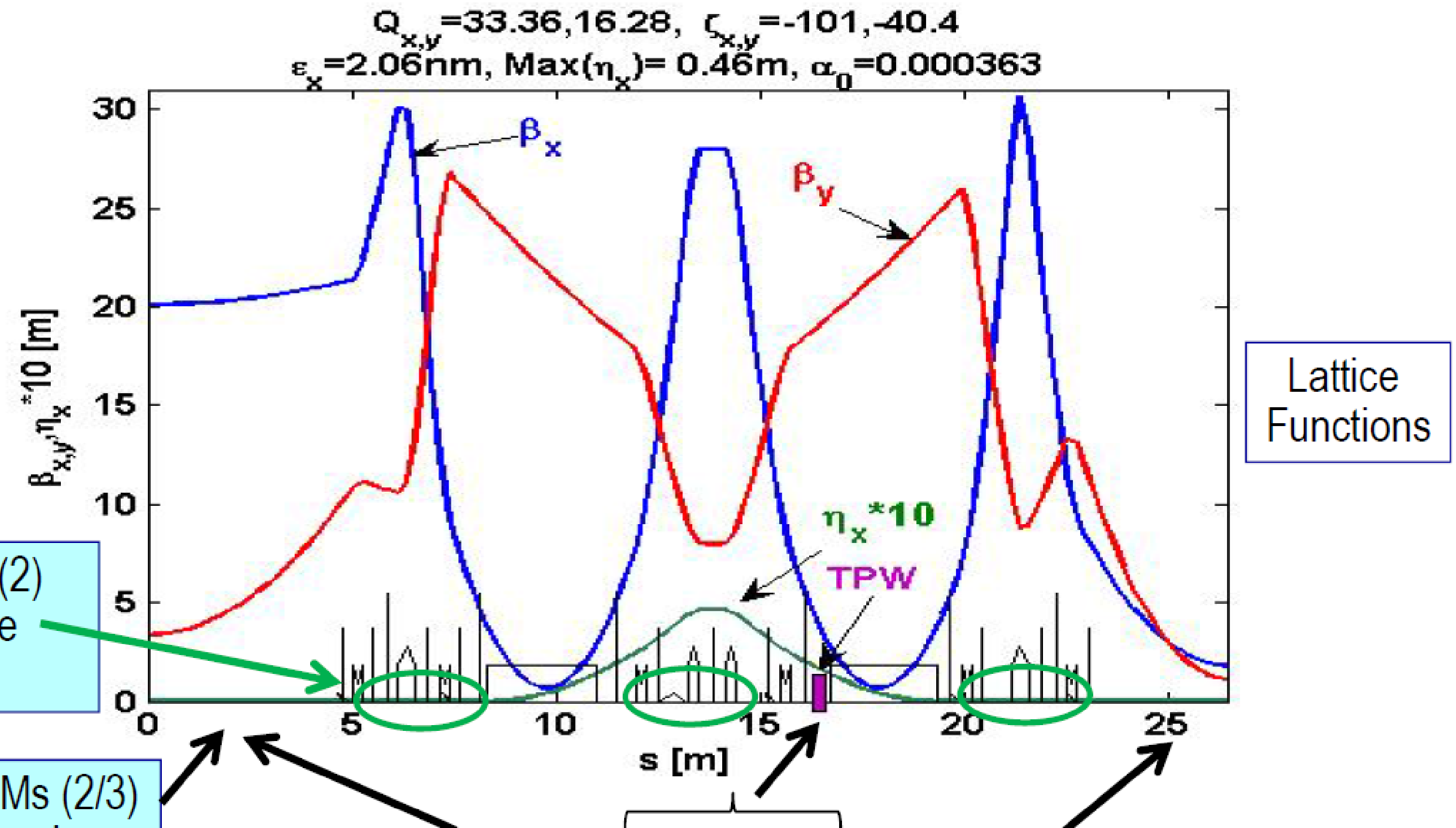
Outline

- NSLS-II fast orbit feedback (FOFB) system
  - Orbit stability requirement
  - System architecture
  - Hardware system
  - Algorithm and implementation
- FOFB system status
  - Short term performance
  - Long term performance
  - Beam stability operation case 1: local bump with FOFB running
  - Beam stability operation case 2: orbit recover after beam dump
  - Beam stability operation case 3: X-Ray stability: photon local feedback
  - Derivative instruments from BPM/FOFB development at NSLS-II
- FOFB system future plan
  - Electron beam stability
  - Photon beam stability
- Summary

NSLS-II Orbit Stability Requirements



Electron Beam Sizes & Divergences

Types of source	Long ID	1-T 3-Pole wiggler	Bend magnet	Short ID
σ_x (μm)	108	175	44.2	29.6
$\sigma_{x'}$ (μrad)	4.6	14	63.1	16.9
σ_y (μm)	4.8	12.4	15.7	3.1
$\sigma_{y'}$ (μrad)	1.7	0.62	0.63	2.6

Most challenging Beam stability Requirements = ~ 0.31 μm

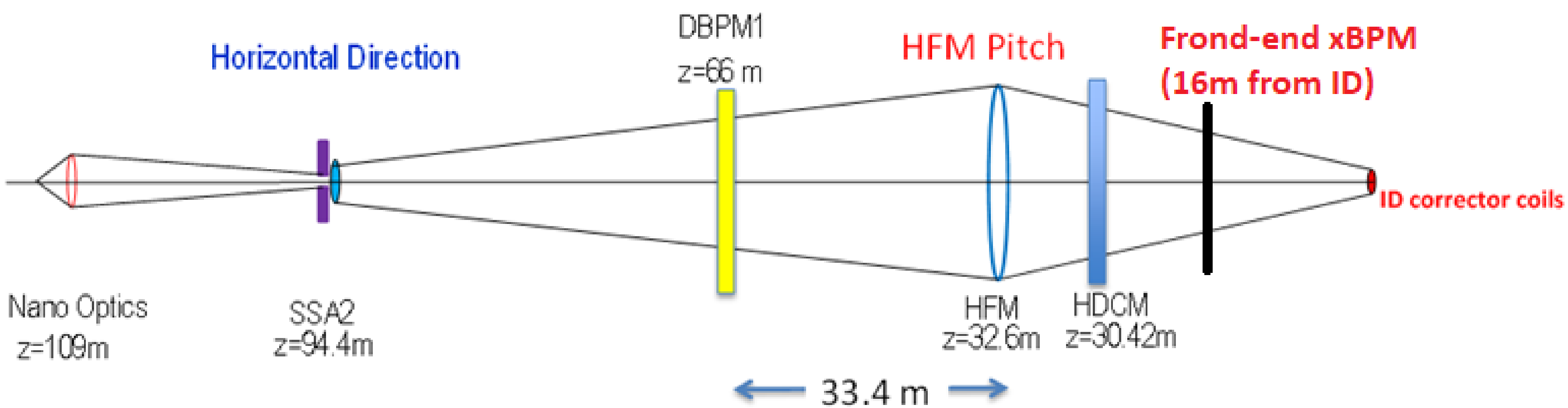
NSLS-II Orbit Stability Requirements In Reality

- **The ultimate goal for light source stability is the photon stability at the user end-station. Sometimes the 10% criterial can't need the user requirement.**

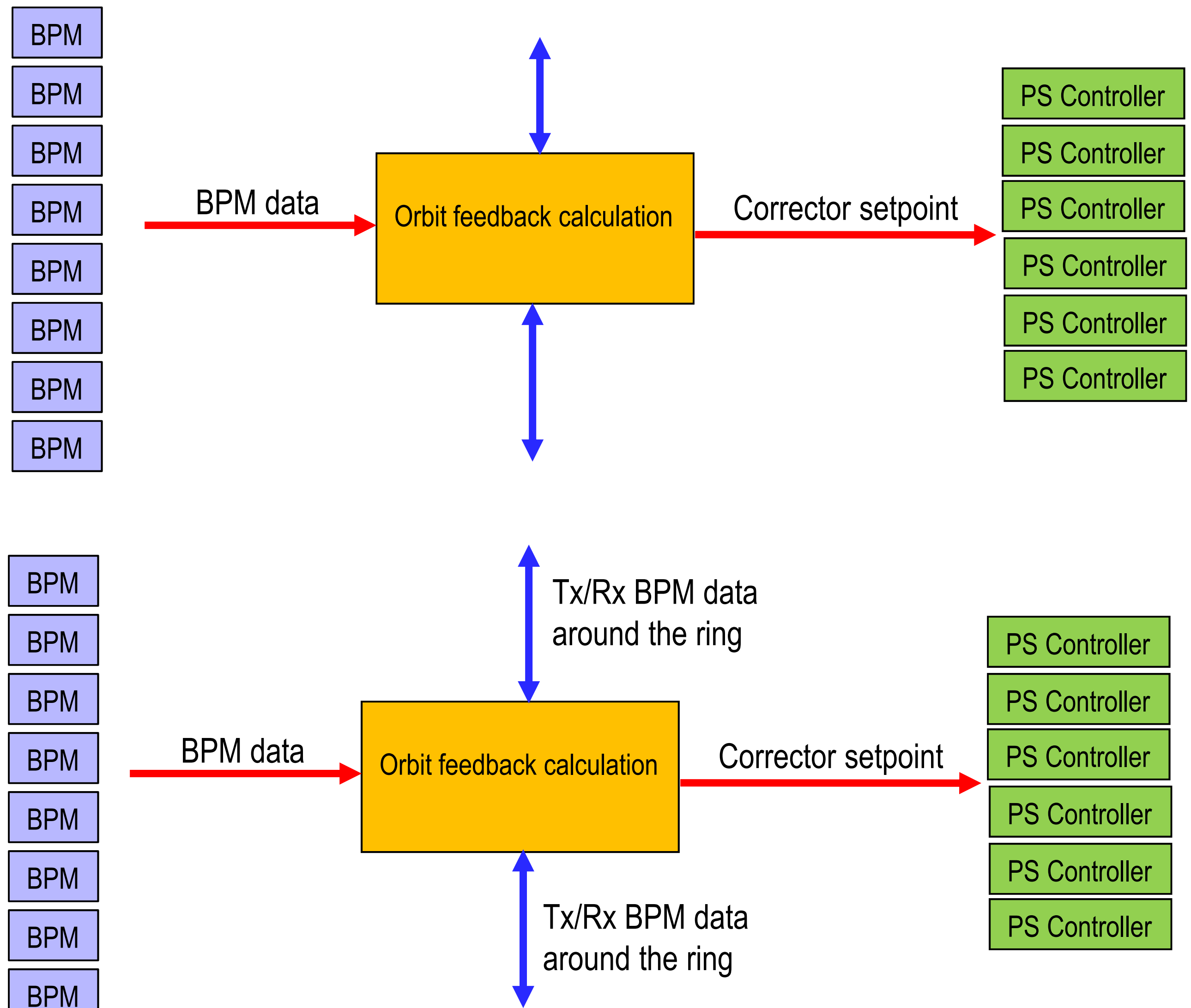
  NSLS-II, HXN (3-ID) beamline:

  Frond-end xBPM (16m away form ID source) long term drift is less than 1um.

  This corresponds to 1/16 urad = 62.5nrad long term ID angle stability. → Beyond the resolution of RF BPMs.



FOFB system architecture: two tier structure



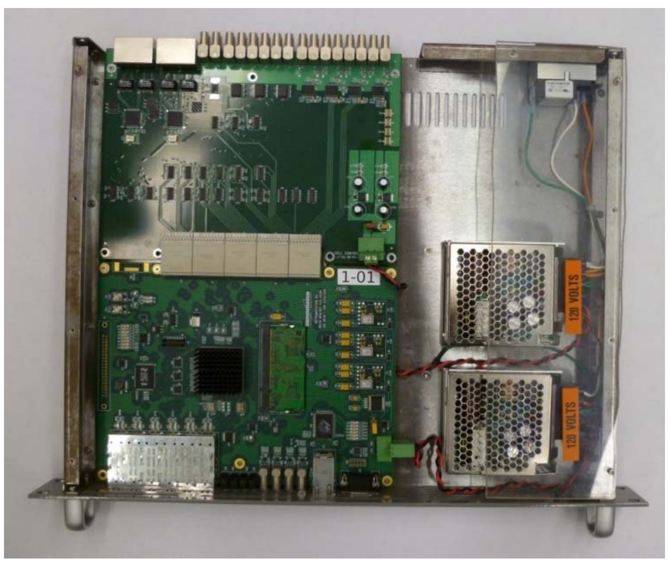
FOFB system architecture

Common tasks for any global fast orbit feedback system:

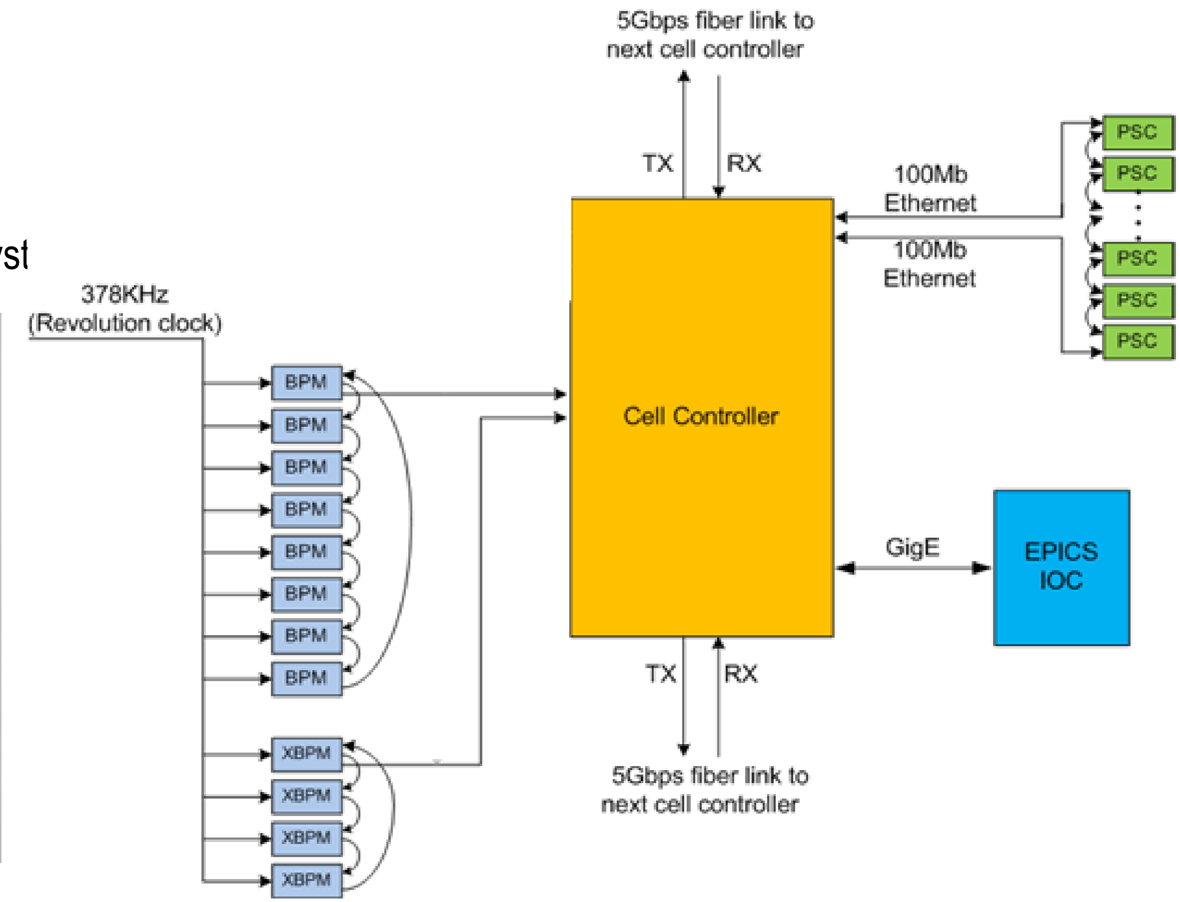
1. Deliver BPM data to feedback calculation unit
2. Performance feedback calculation
3. Deliver corrector setpoint to power supply controller

Cell controller at NSLS-II:

→ Receiver local BPM data
→ Tx/Rx BPM data to/for other cell
→ Carry out FOFB calculation
→ Tx corrector setpoints to PS control syst



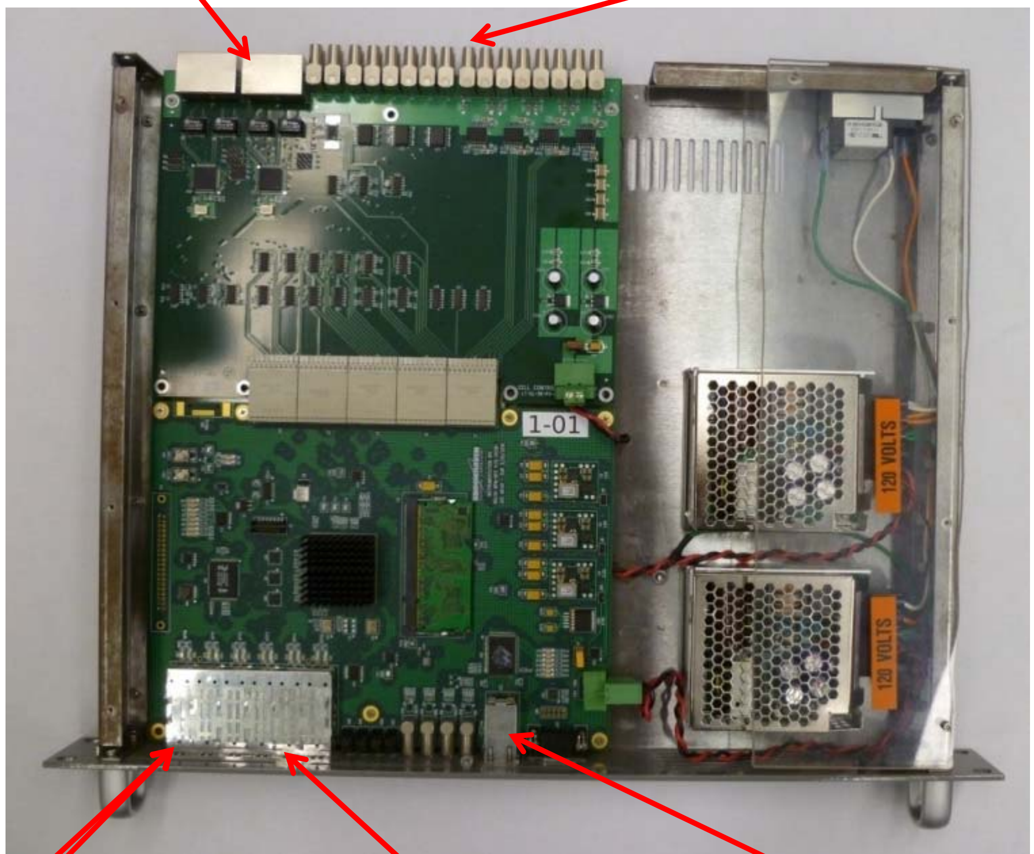
Cell Controller



FOFB system architecture

100 Mbit/s link for corrector setpoints

IO signals (16 inputs, 12 ouptuts, 4 Vout) for fast machine protection

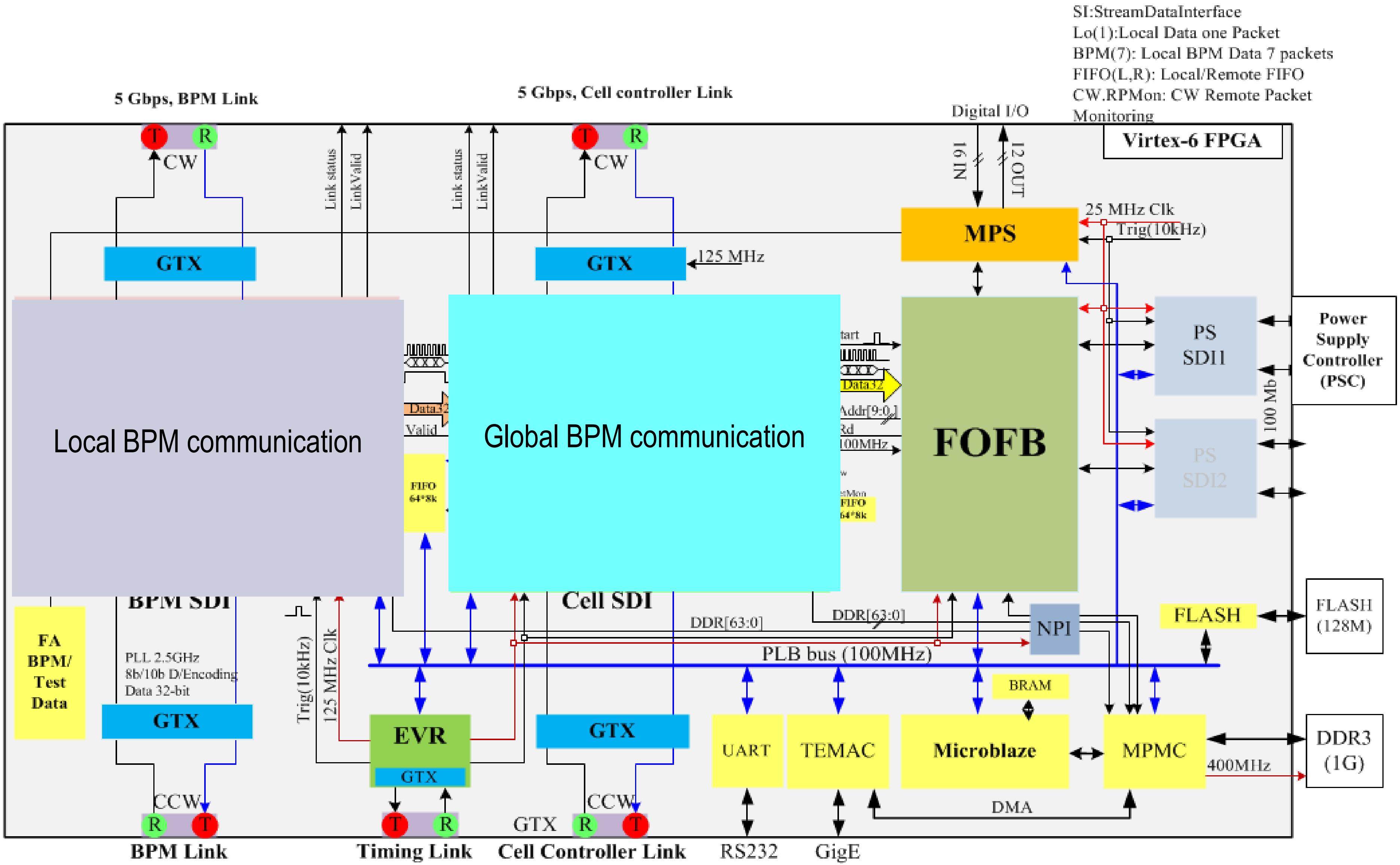


Embedded Event Received

Gigabit Ethernet to EPICS IOC

5 Gigabit/s SDI link for BPM and CC data

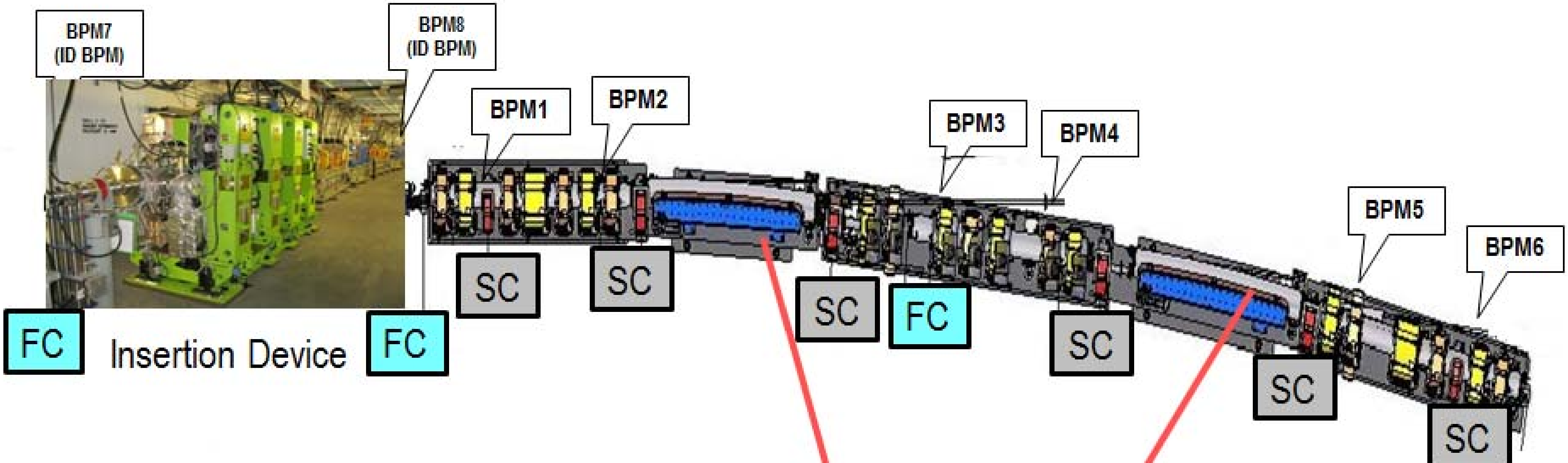
FOFB implementation: FPGA block diagram



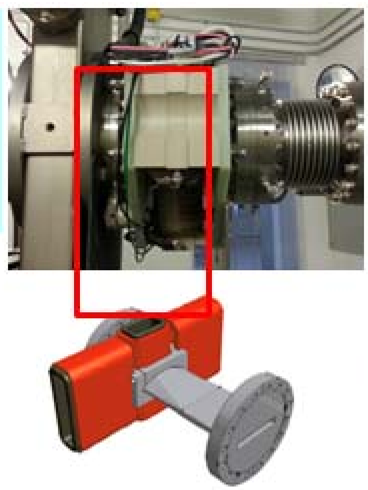
FOFB system architecture: FOFB calculation in FPGA vs CPU/DSP

	Calculation power	Flexibility	Architect simplicity	Stability
CPU, DSP-base FOFB calculation	Limited, due to series calculation nature.	Good. It is C/C++ based.	Need to build interface to other systems (BPM, power supplies) Deterministic depends on real-time OS.	Depends on CPU scheduling, memory and other OS/software related features.
FPGA-based FOFB calculation	Strong due to the parallel DSP resources.	Not good, unless have FPGA expertise.	Seamlessly integrate with other systems. Deterministic at nanosecond, natural of FPGA.	Stable since it runs on FPGA firmware.

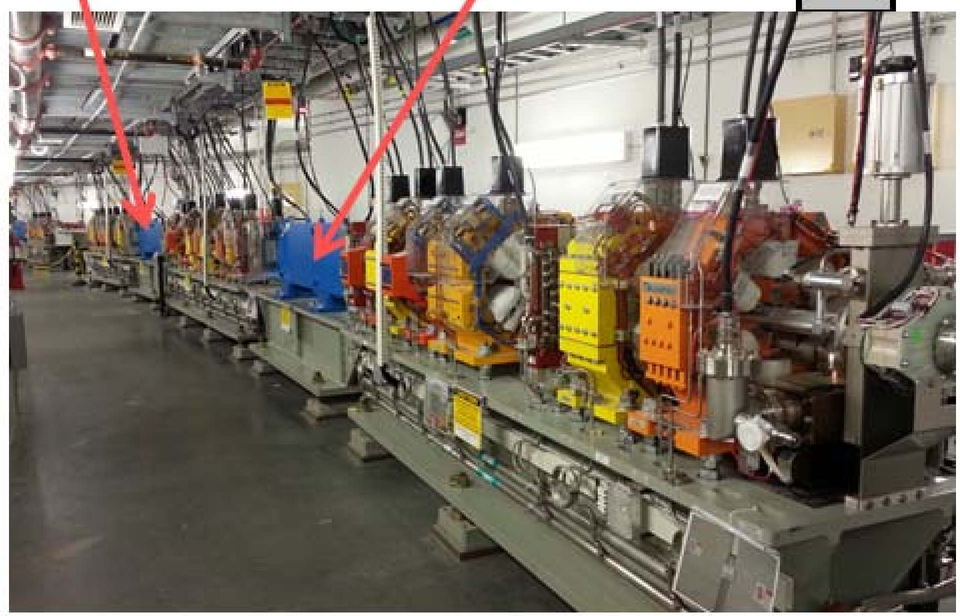
FOFB hardware: correctors



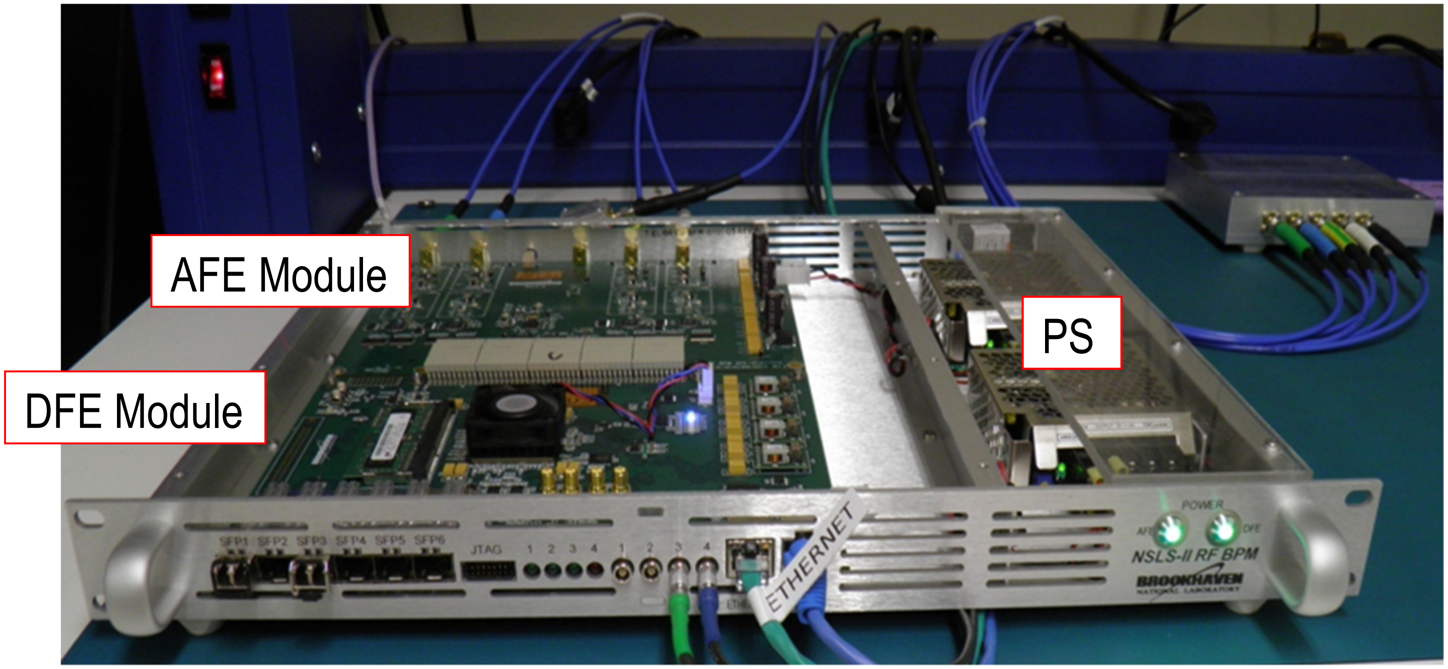
Fast correctors (Qty=3)
- ✓Fast response – 2 kHz
- ✓Weak strength – 15 µrad
- ✓Utilized for – Fast orbit feedback



30 mm fast (air core)

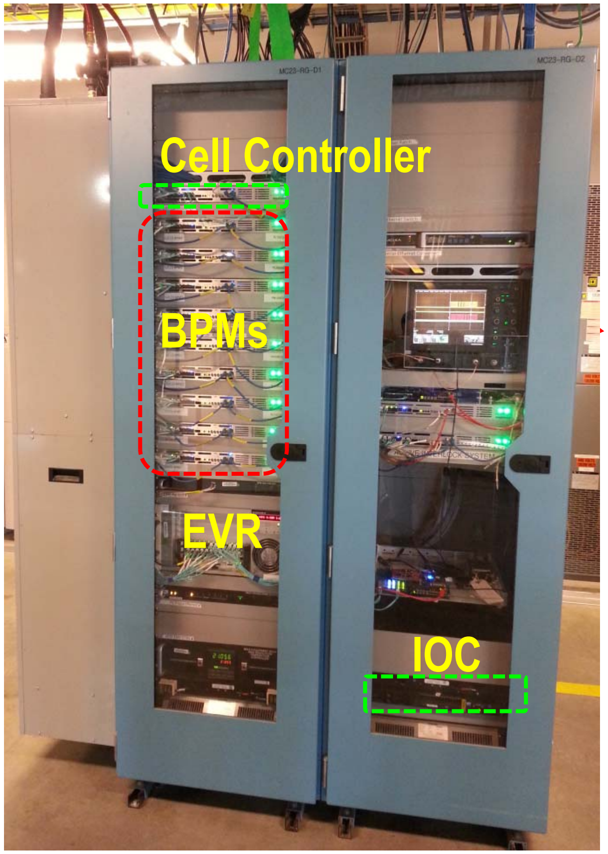


FOFB hardware: BPM



Data Type	Mode	Max Length
ADC Data	On-demand	256Mbytes or 32M samples per channel simultaneously
TBT	On-demand	256Mbytes or 5M samples Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
FOFB 10KHz	**Streaming via SDI Link** and On-demand	Streaming - **X,Y**,SUM ; For On-Demand: 256Mbytes or 5M samples Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
Slow Acquisition 10Hz	Streaming and On-demand	80hr circular buffer Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
System Health	On-demand	80hr circular buffer; AFE temp, DFE temp, FPGA Die temp, PLL lock status, SDI Link status

FOFB hardware in a cell



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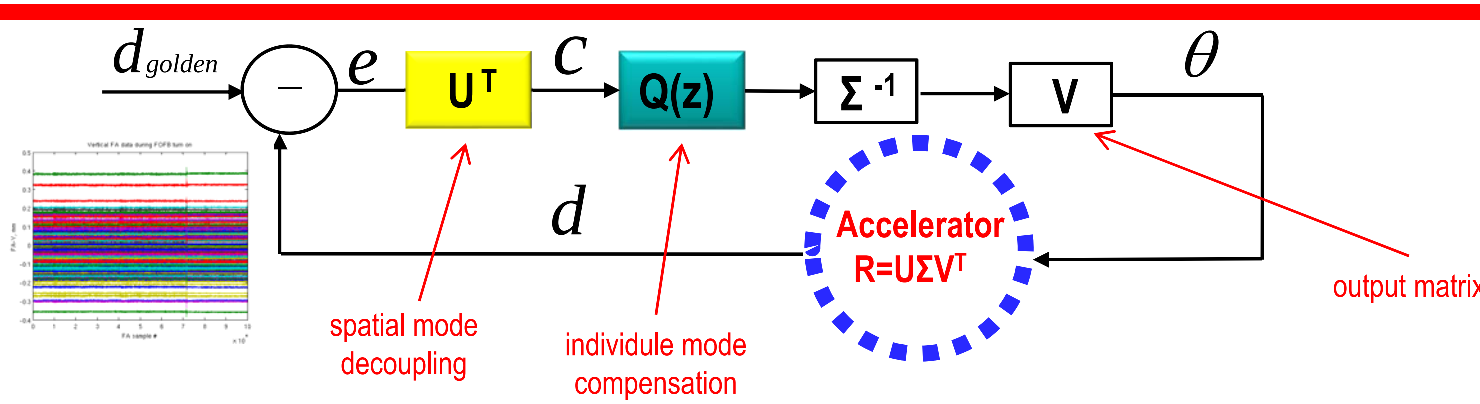
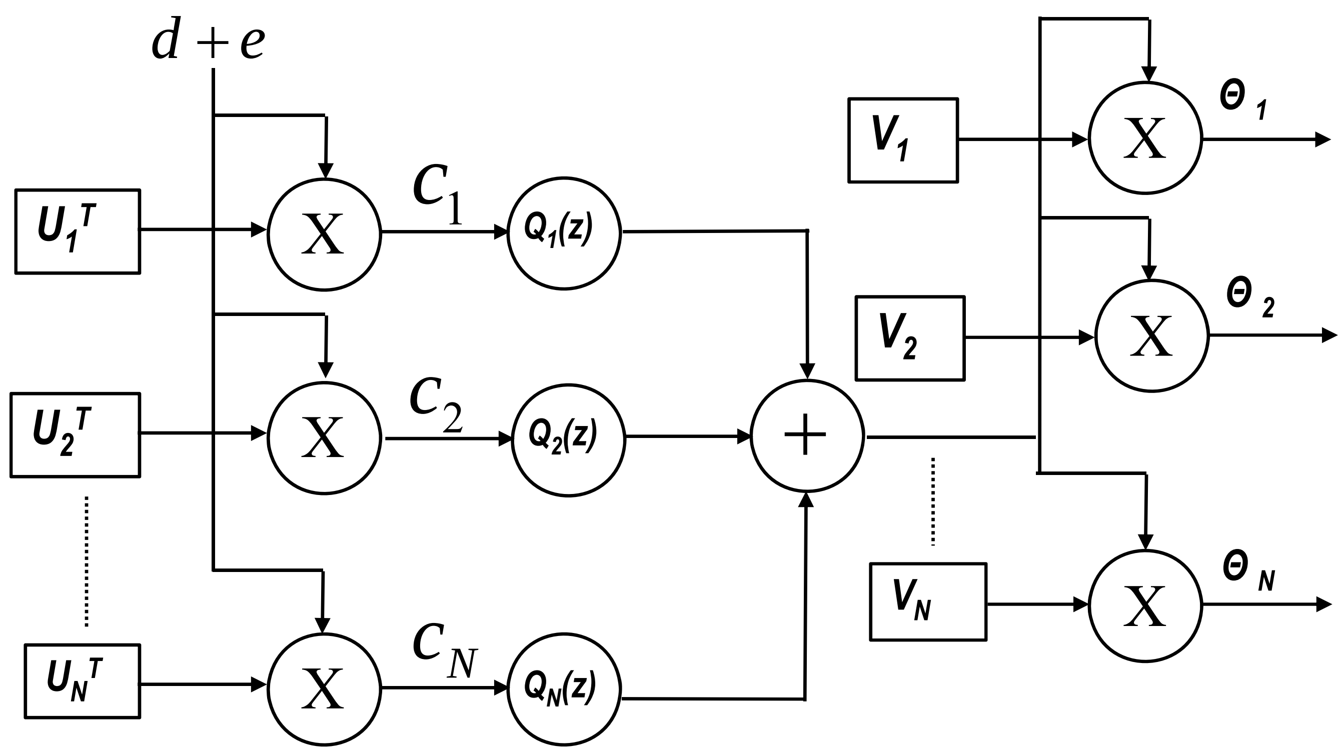
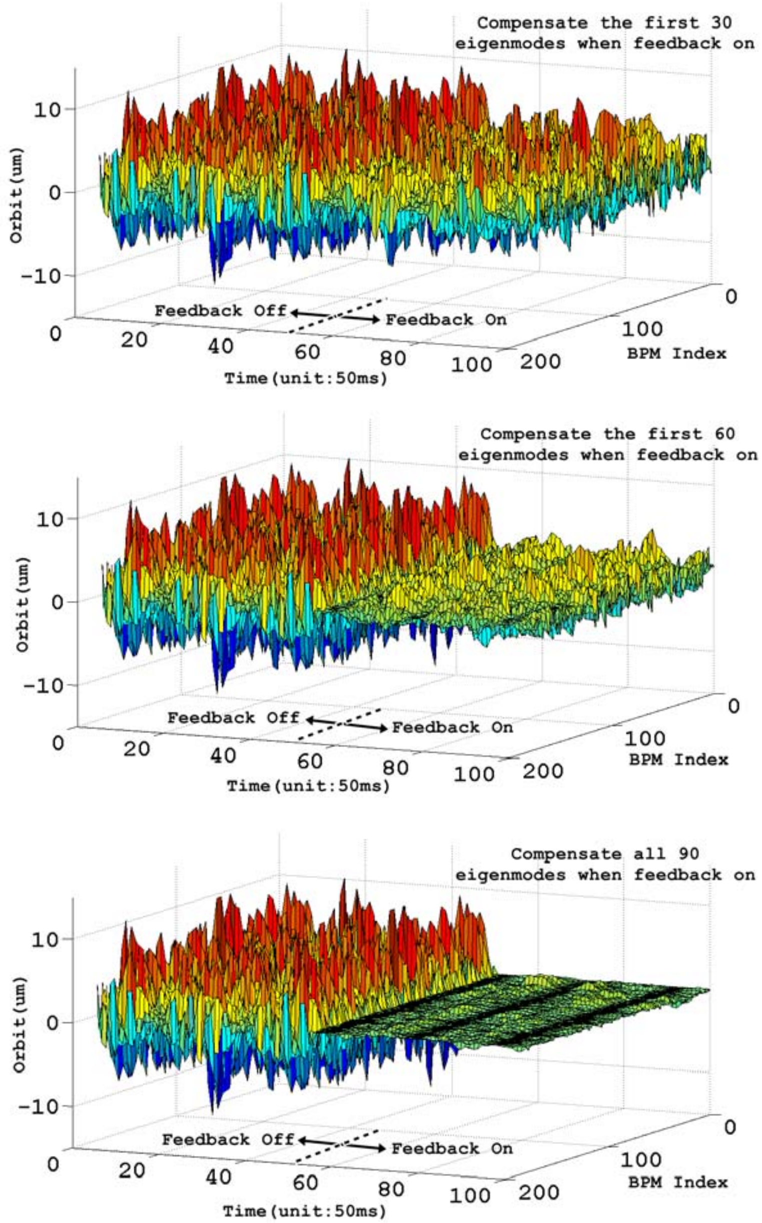
FOFB algorithm: spatial mode decomposition (MIMO problem to SISO problem)



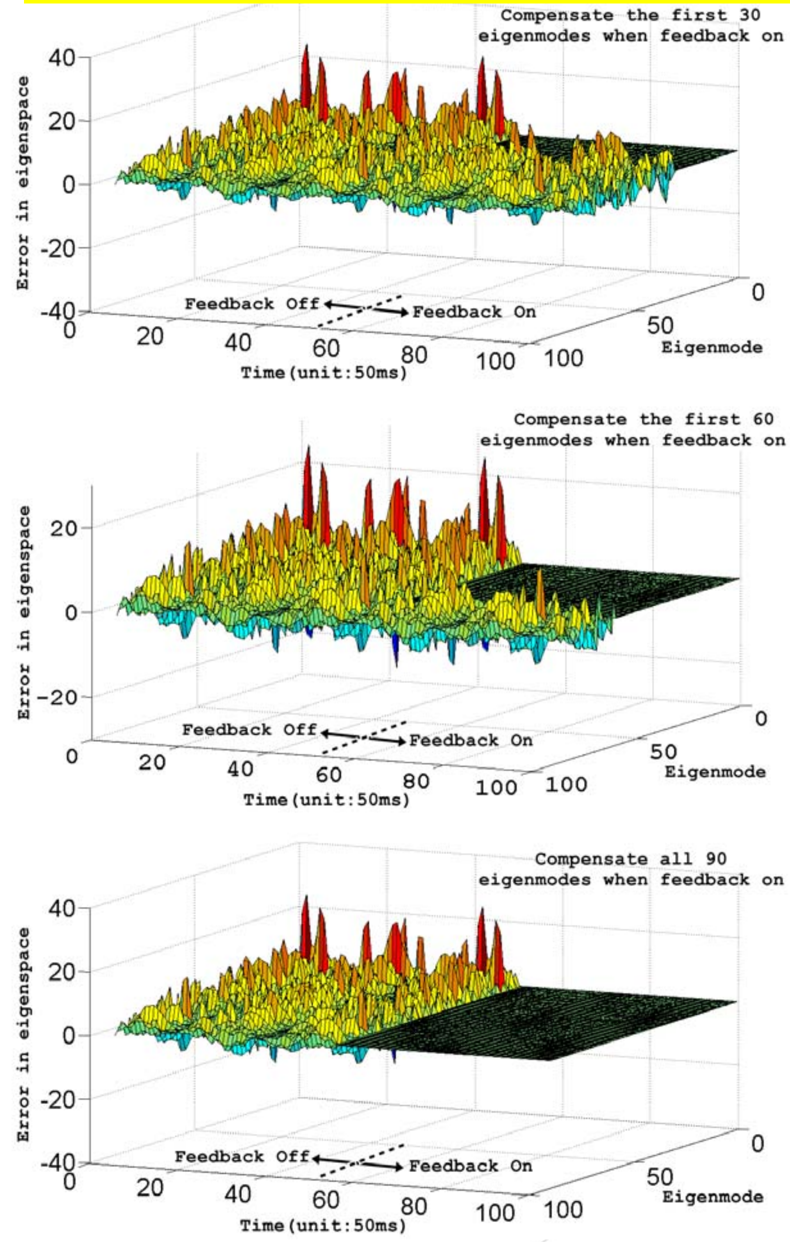


FOFB algorithm: spatial mode decomposition

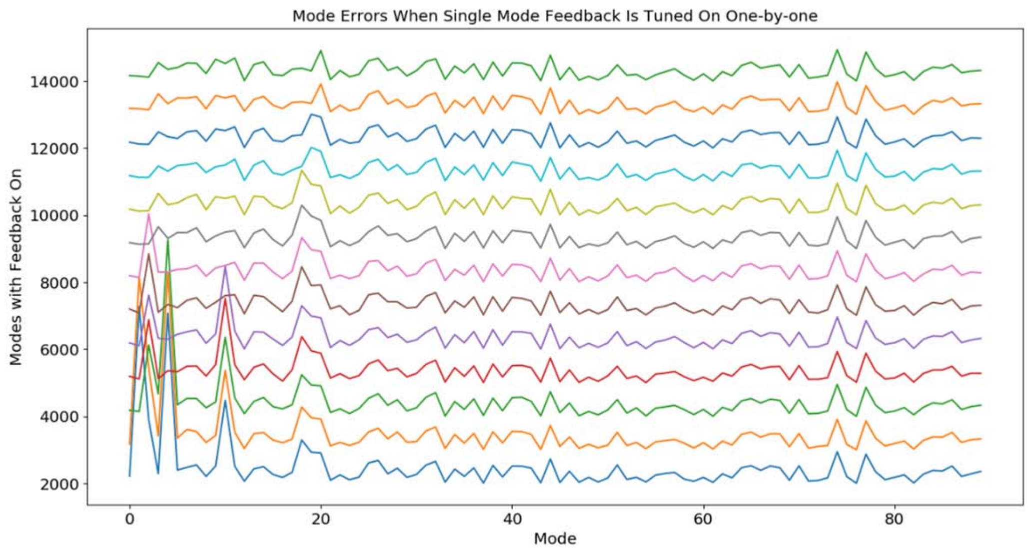
Orbit changes for different compensation



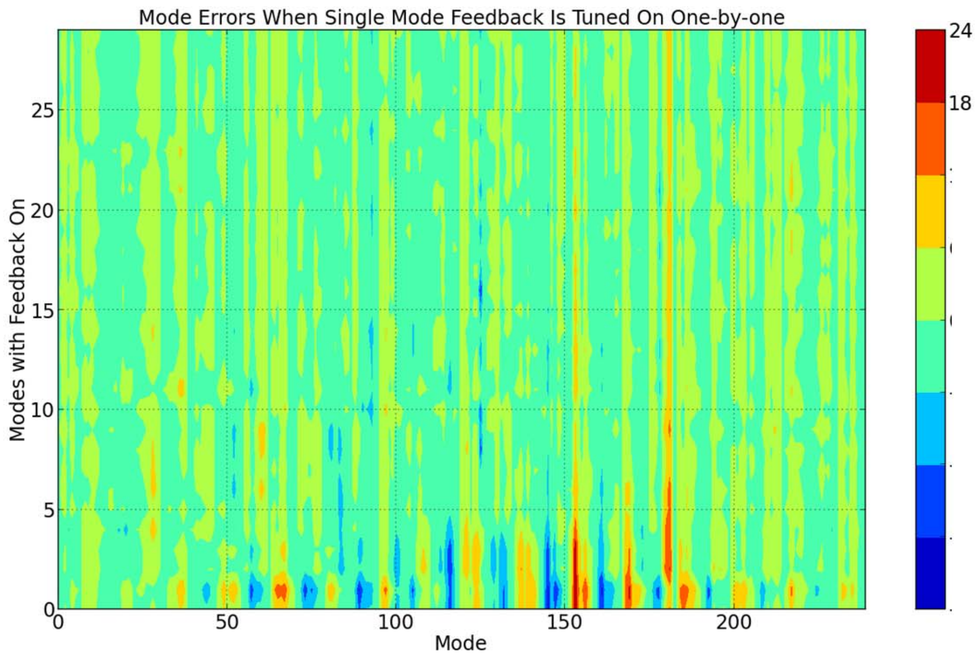
Error in mode space for different compensation



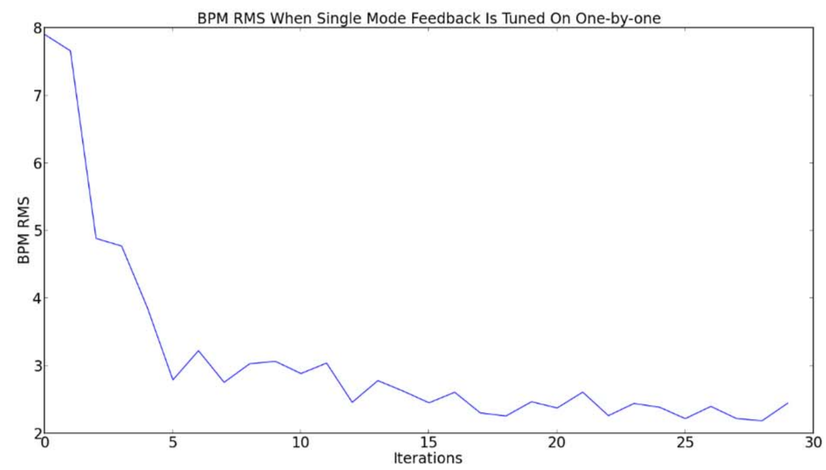
FOFB algorithm: spatial mode decomposition



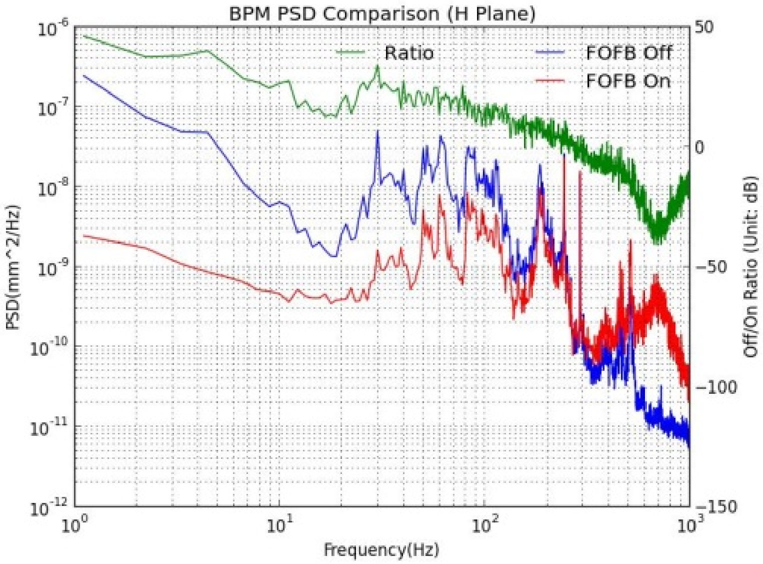
One by one close loop in mode space

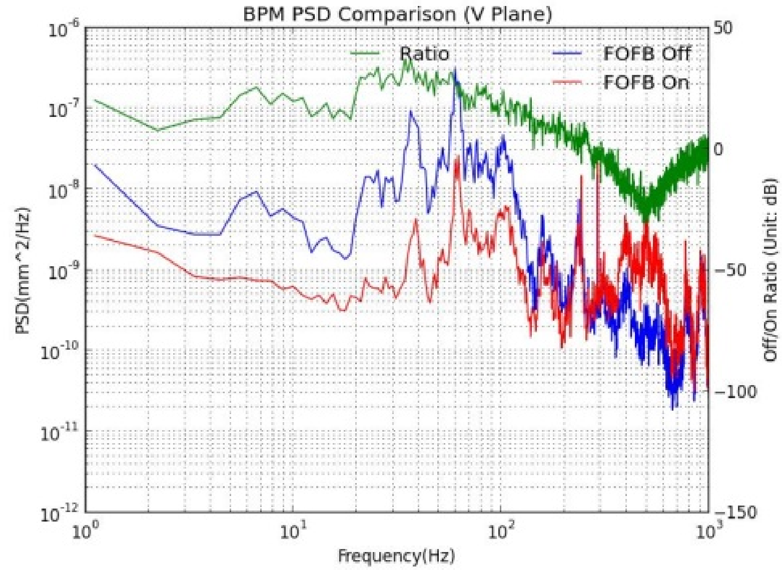


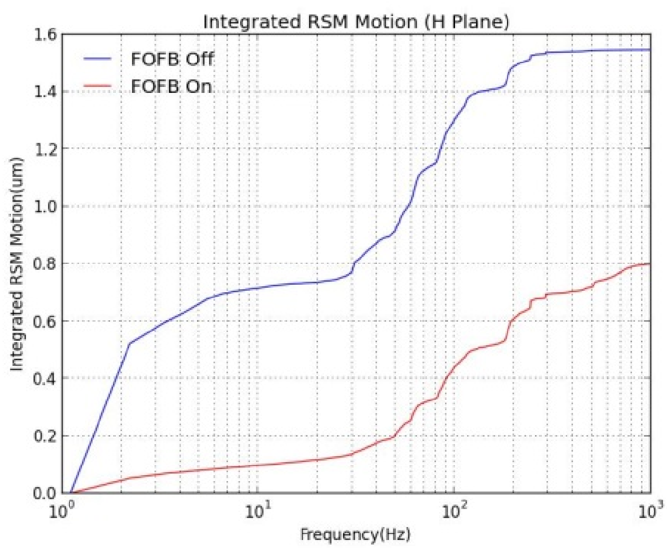
BPM errors when close loop in mode space

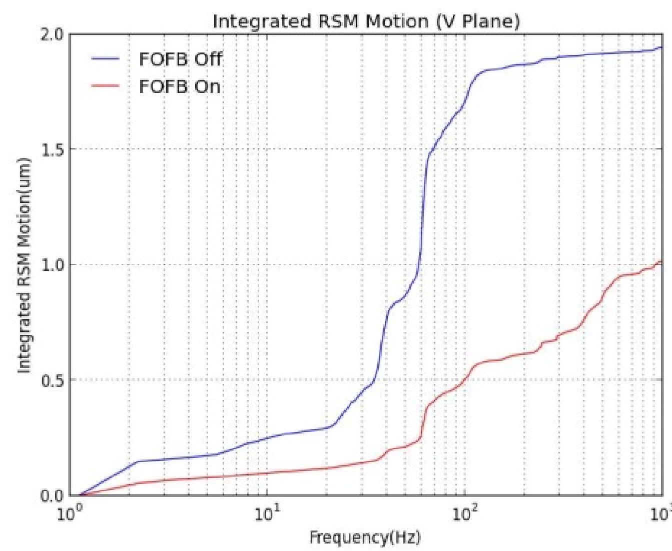


FOFB status: short term performance (power spectrum density)

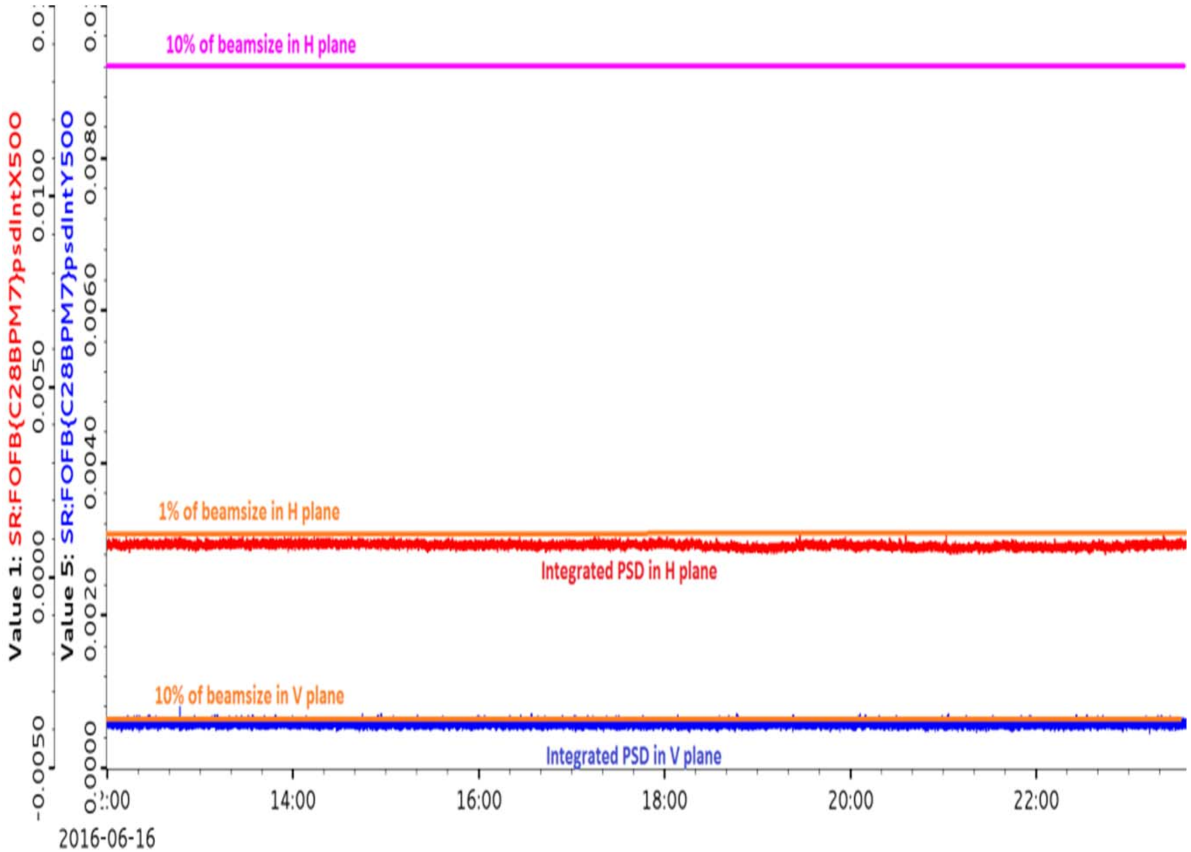


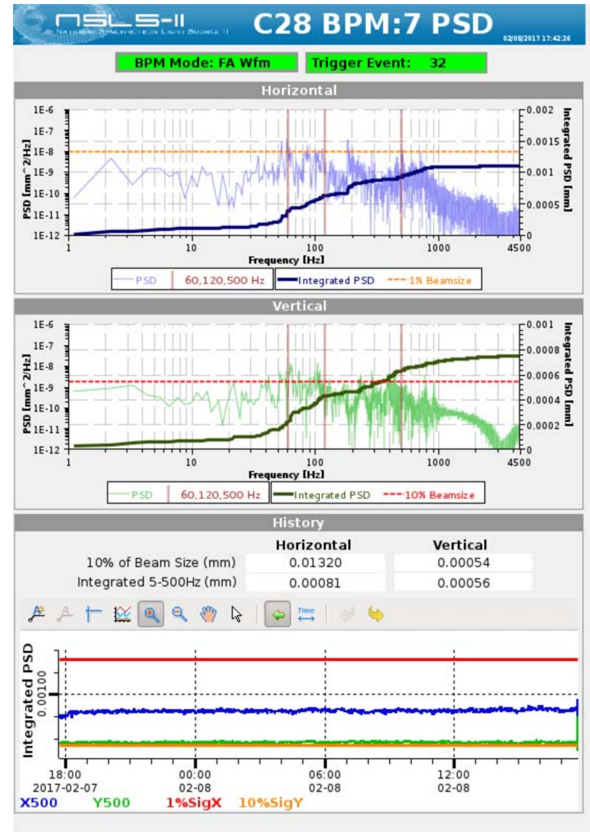






FOFB status: short term performance (power spectrum density)





FOFB short term stability:

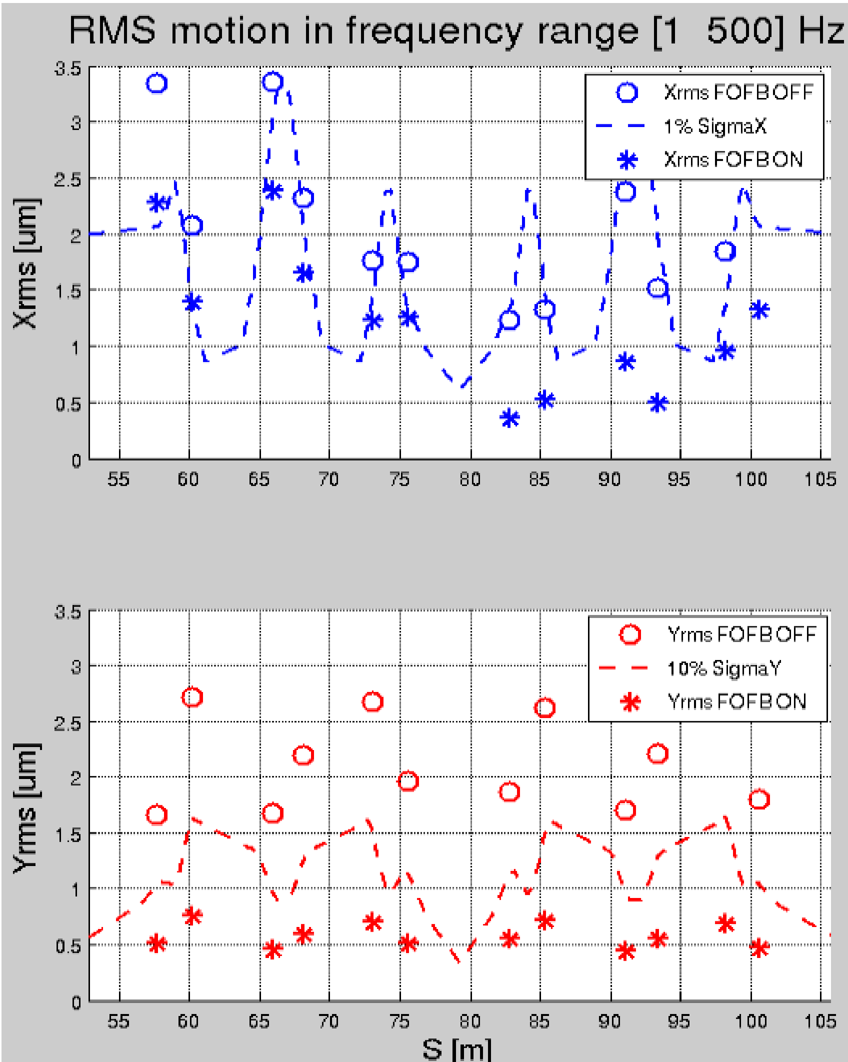
→H and V plane noises suppression up to 200Hz.

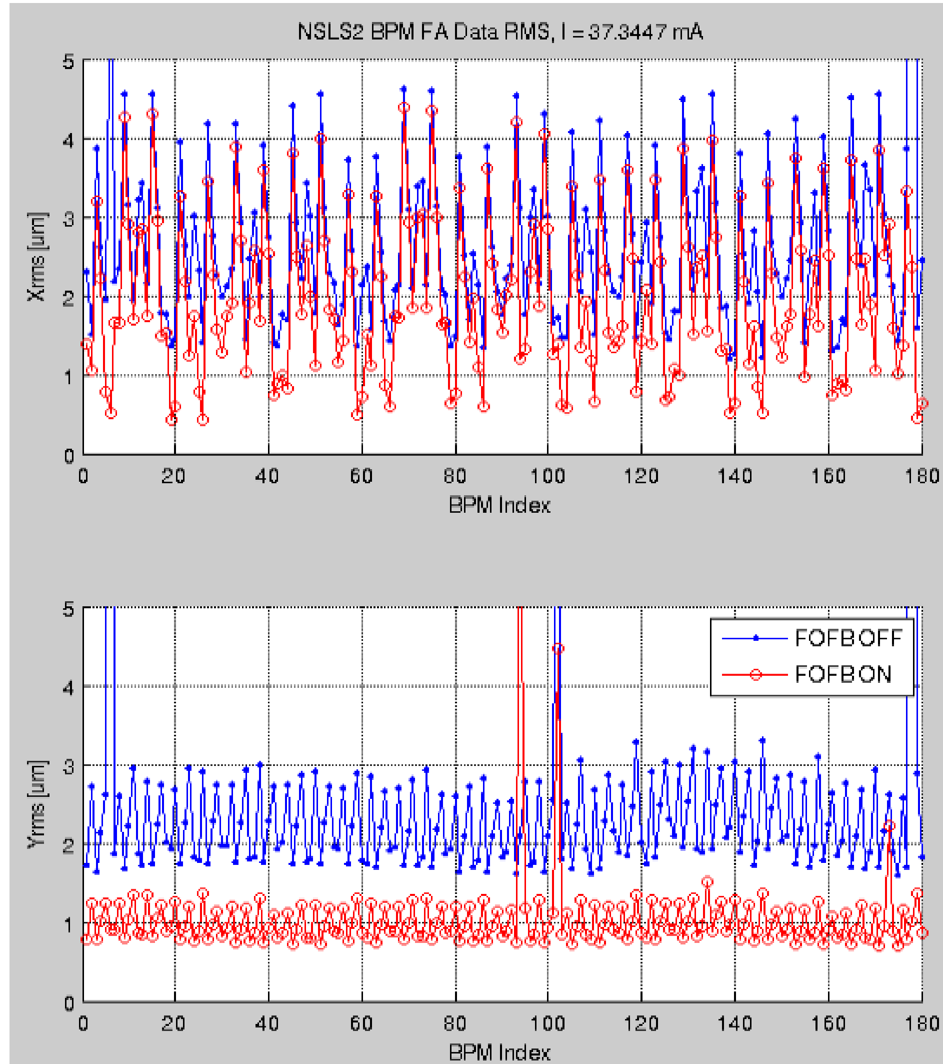
→Integrated PSD (500Hz) in H plane (about 800nm), is within 1% of beamsize

→Integrated PSD (500Hz) in V plane (about 550nm), is within 10% of beamsize

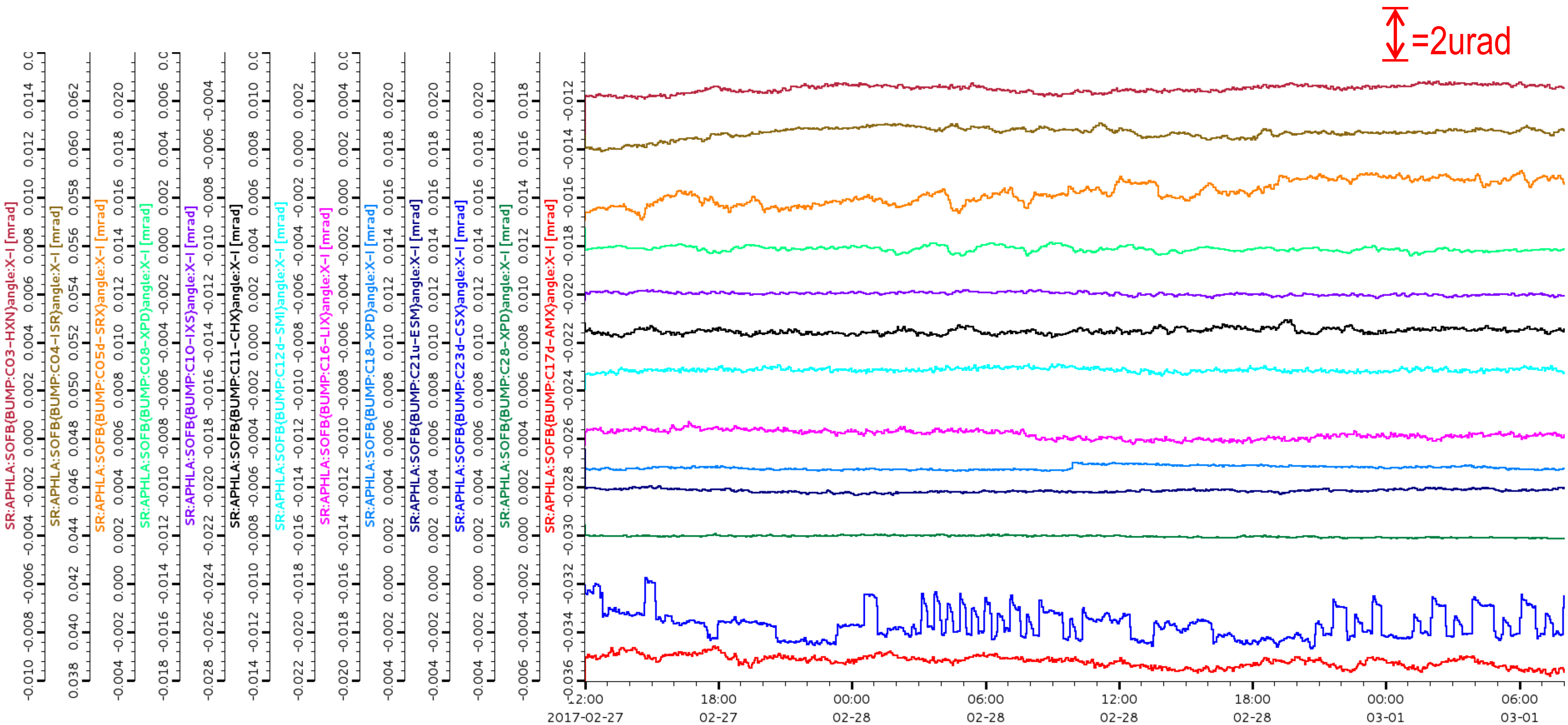
FOFB status: short term performance (power spectrum density)

RMS Motions Along the ring



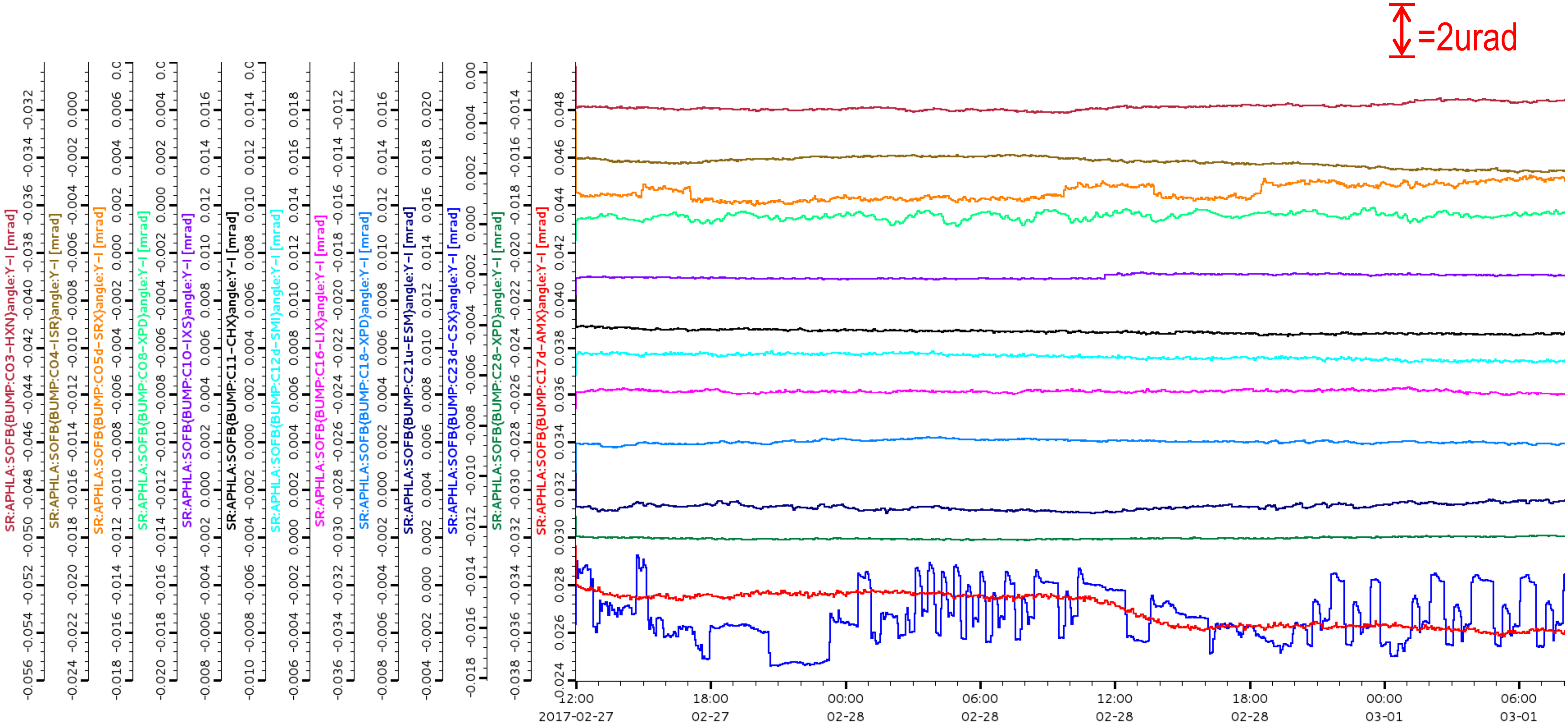


FOFB status: long term performance



H plane ID angles long term drift

FOFB status: long term performance



V plane ID angles long term drift

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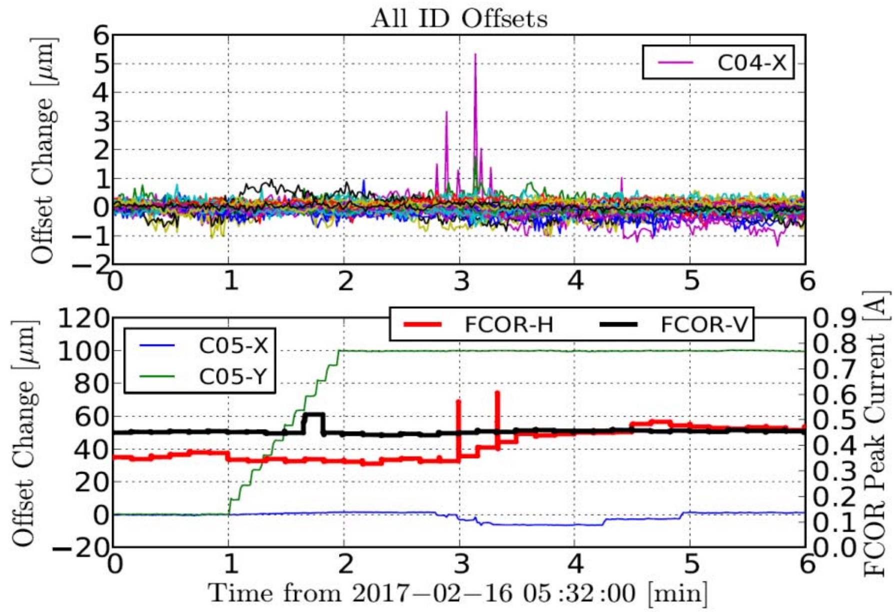
Beam stability operation case 1: local bump with FOFB running

Motivation: during user operations with FOFB running, occasionally some individual beamlines need to adjust the ID angle and offset by large values. FOFB alone can't achieve this since fast correctors are not strong enough. Slow correctors settings need to adjust with local bump program to get large ID angle/offset adjustment. We want to achieve this without turn on/off FOFB and without any disturbances to other beamlines.

Procedure: run local bump program with FOFB running. To prevent fast correctors from saturation, a procedure is developed to shift fast corrector strength to slow correctors with FOFB and local bump program running.

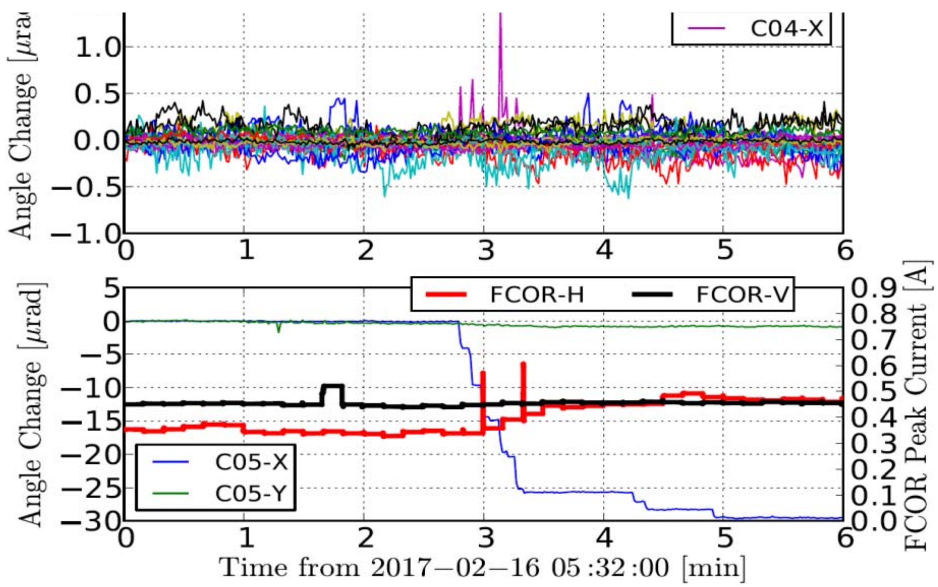
Result: we can run local bump program to adjust the ID angle larger than 10urad and ID offset larger than 10um without stopping FOFB and without global disturbances.

Beam stability operation case 1: local bump with FOFB running



At 1minute, C05 Y needs a 100um offset:

→ Local bump runs
→ During local bump, fast corrector's strength gets larger
→ Shift fast corrector strength to slow corrector (at 1.6 minute)
→ No large disturbance for this large local bump



At 2.8 minute, C05 H needs a 30urad change

→ Local bump runs
→ During local bump, fast corrector's strength gets larger
→ Shift fast corrector strength to slow ones (at 3 & 3.3 minute)
→ No large disturbance for this large local bump

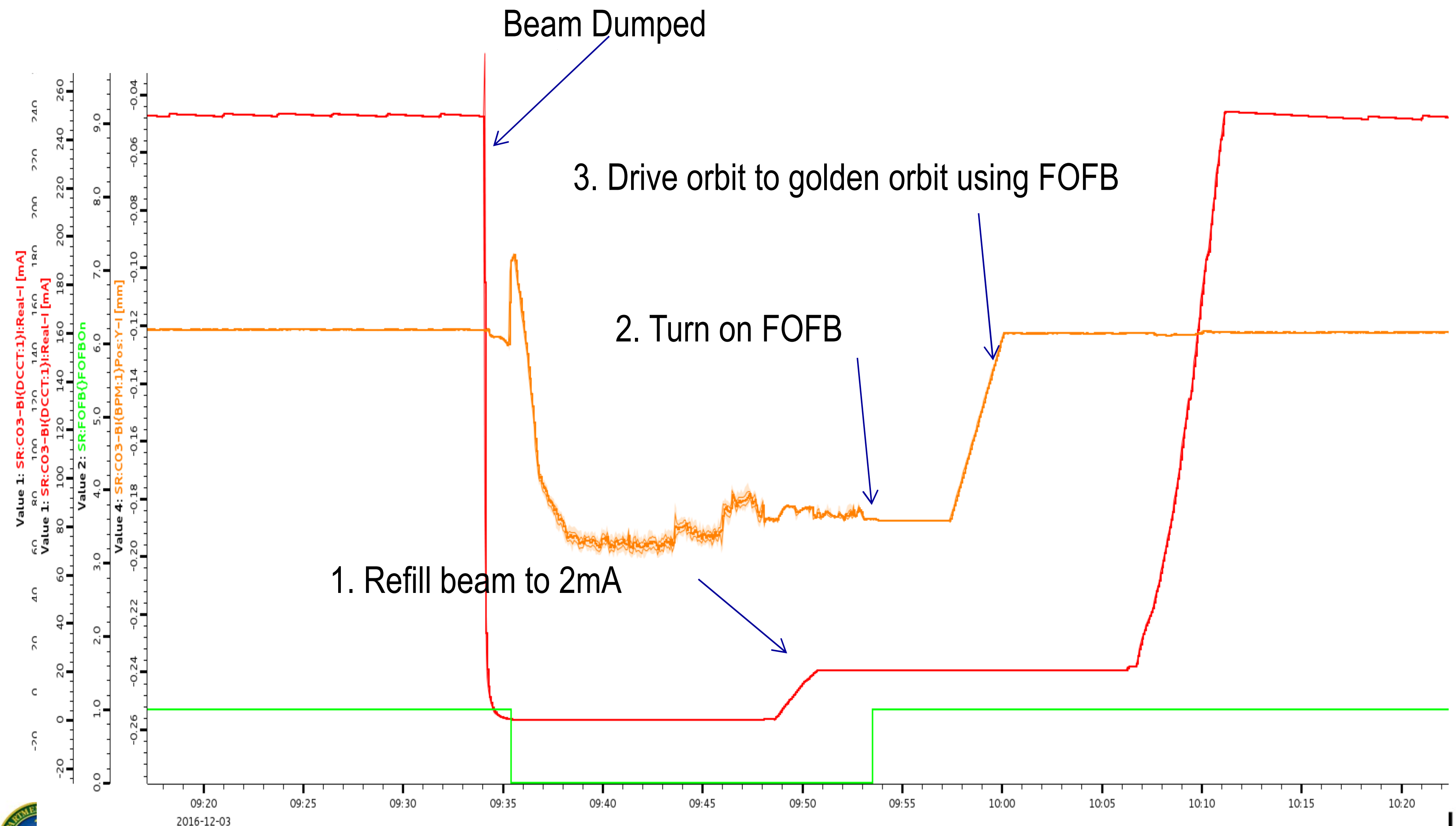
Beam stability operation case 2: orbit recover after beam dump

Motivation: after beam dump, the old procedure is to use orbit correction and local bump to recover the beam orbit. Some beamlines noticed differences before and after beam dump. It is desirable to recovery the orbit with less than 1um error.

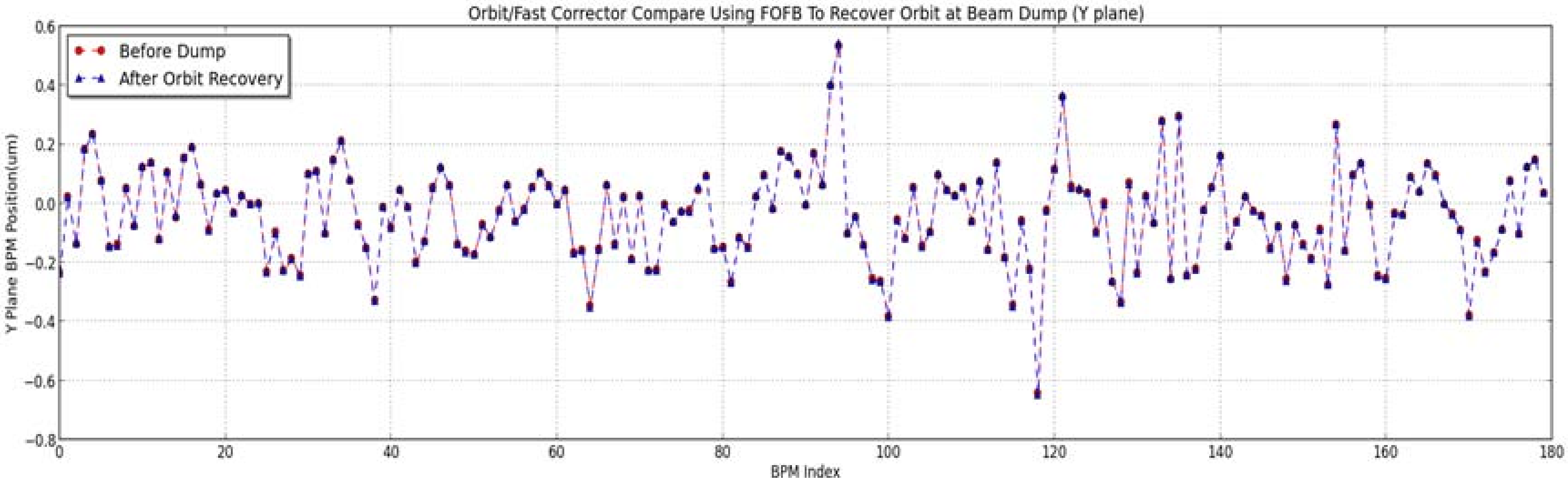
Procedure: for beam dumps not caused by power supply system, after initial refill, turn on FOFB without orbit correction and local bump adjustment. The FOFB will bring the orbit to the previous saved target reference orbit. This procedure recovers the orbit with less then 1um error and reduces the recovery time by eliminate orbit correction and local bump adjustment steps.

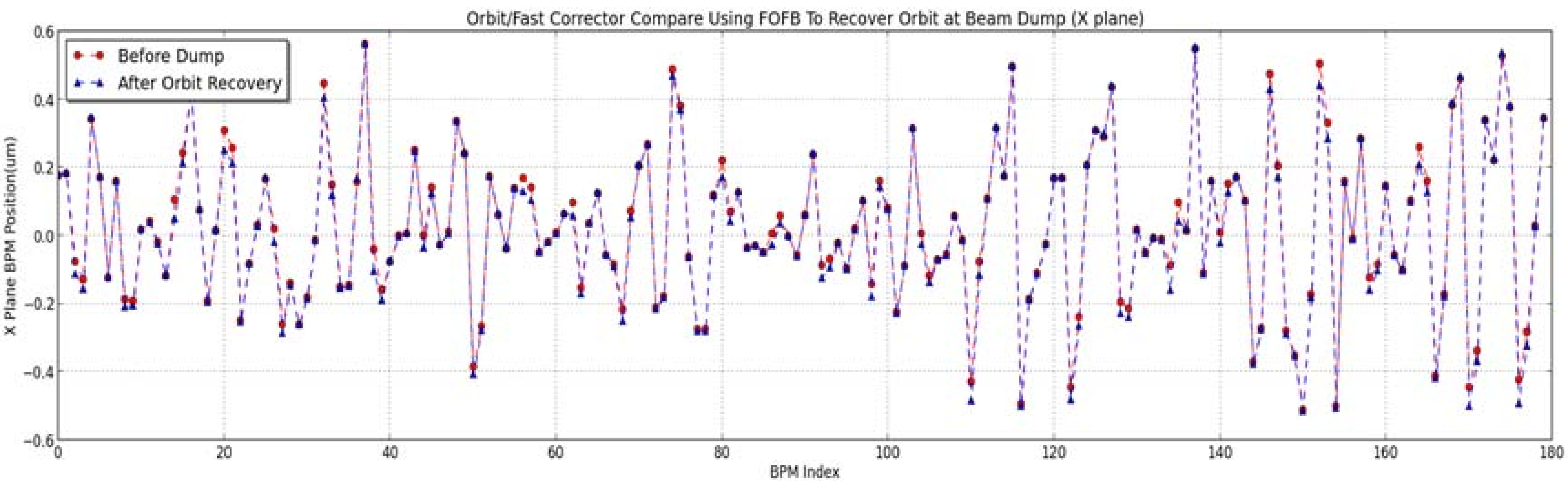
Result: FOFB will recover the orbit with less than 1um error.

Beam stability operation case 2: orbit recover after beam dump



Beam stability operation case 2: orbit recover after beam dump





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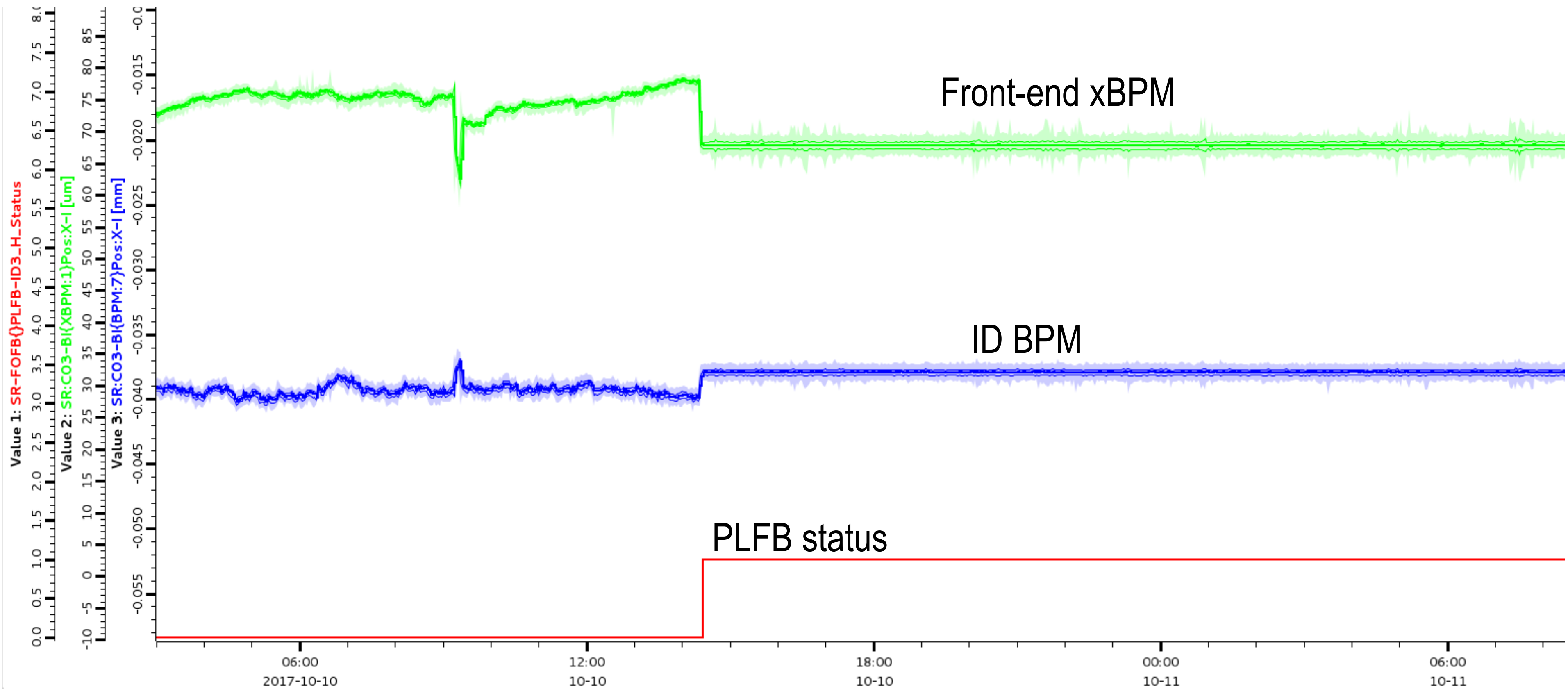
Beam stability operation case 3: photon local feedback

Motivation: some beamlines request much more stringent photon stability (for example, HXN needs ID angle long term stability: 50nrad). This request is beyond the resolution of our RF BPM. We can use the xBPM (front-end xBPM or beamline xBPM) as sensors, and use ID corrector coil as actuators to make photon local feedback to achieve the stringent long term stability requirement.

Procedure: with FOFB running, measure the response between xBPM and the ID corrector coil current. Design a photon feedback system to stable the xBPM readings. The response could be gap dependent.

Result: we have released the photon local feedback system for the four beamlines which have front-end xBPM installed. We have also tried to use beamline xBPM as sensors, but didn't release it because the beamline xBPM reading dependent many factors of beamline settings.

Beam stability operation case 3: photon local feedback *(optical)*



HXN photon stability with photon local feedback (H plane)

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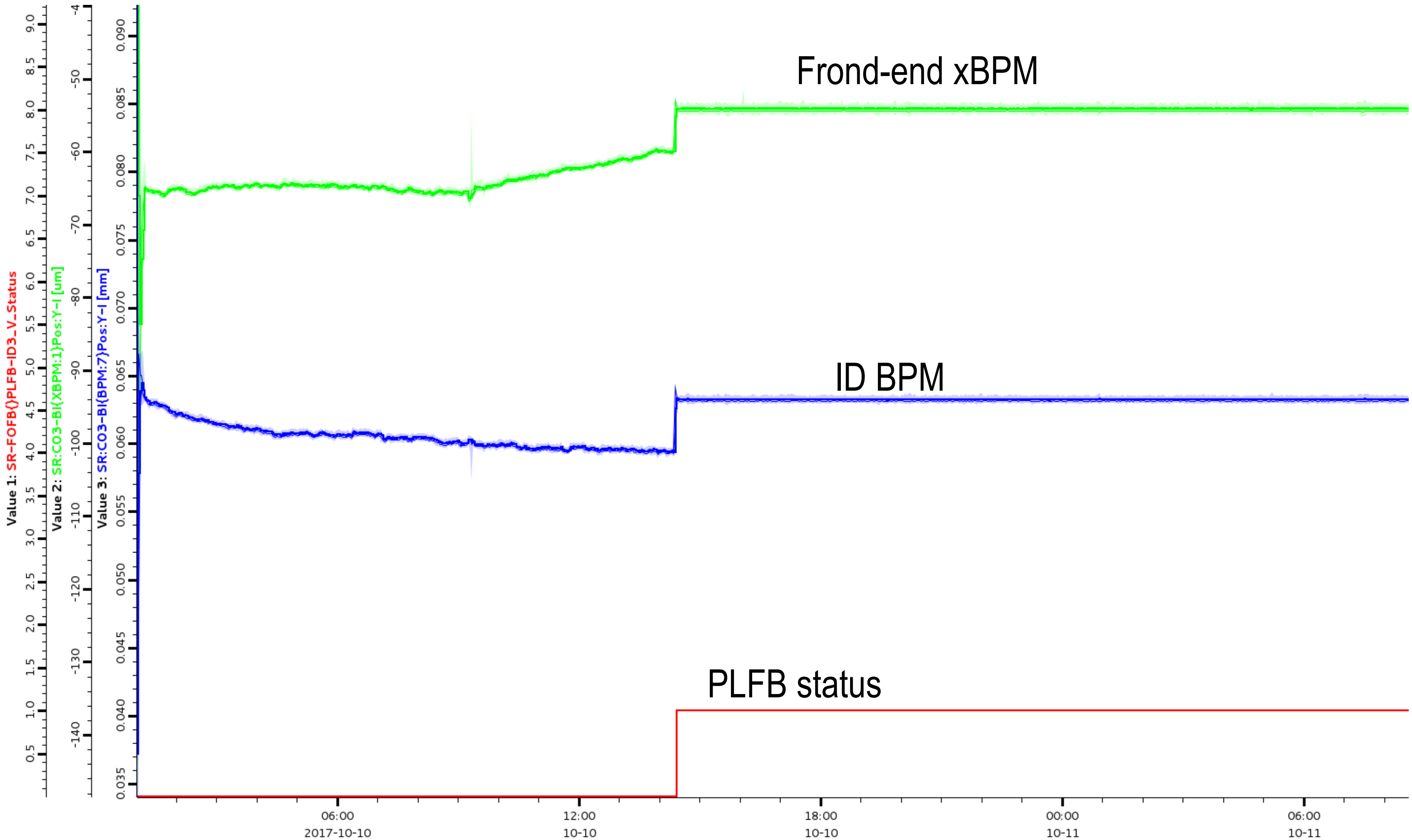
Beam stability operation case 3: photon local feedback



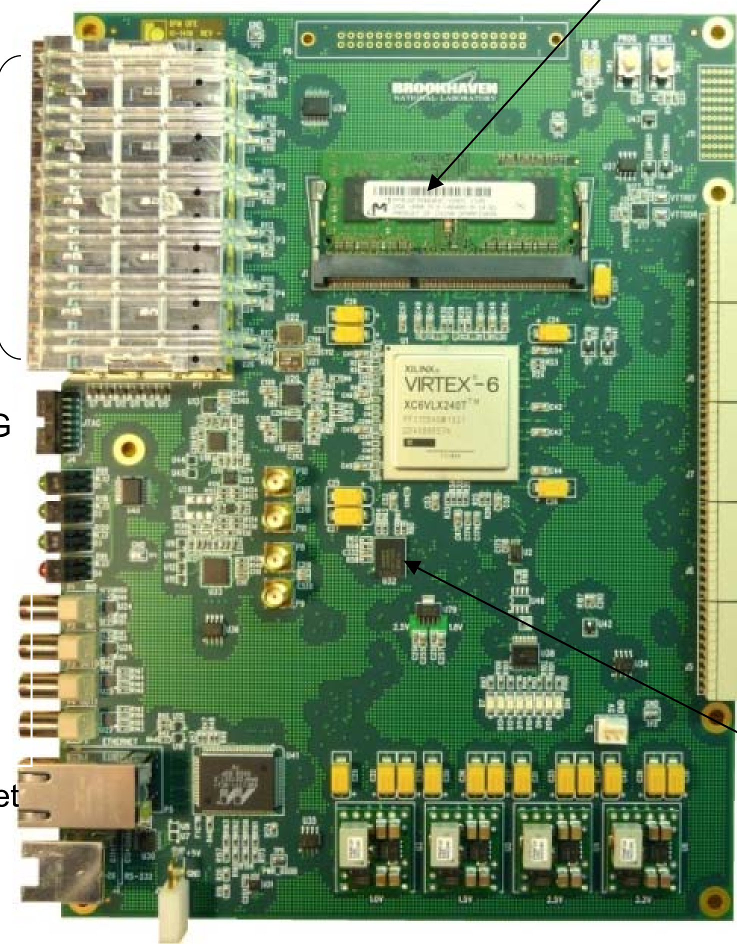
HXN photon stability with photon local feedback (V plane)

Other applications from BPM/FOFB developments

- The BPM/FOFB development at NSLS-II provide a common FPGA-based digital platform with many com useful features:

Features:

- Virtex-6 FPGA (LX240T)
- Embedded MicroBlaze soft core µP
  - Xilkernel OS and lwIP TCP/IP stack
- Gigabit Ethernet
- 2Gbyte DDR3 SO-DIMM
  - Memory throughput = 6.4 GBytes/sec
- Six 6.6Gbps SFP modules
  - Embedded Event Receiver
  - Fast Orbit Feedback
- Fixed Point DSP Engine
- 1Gbit FLASH memory



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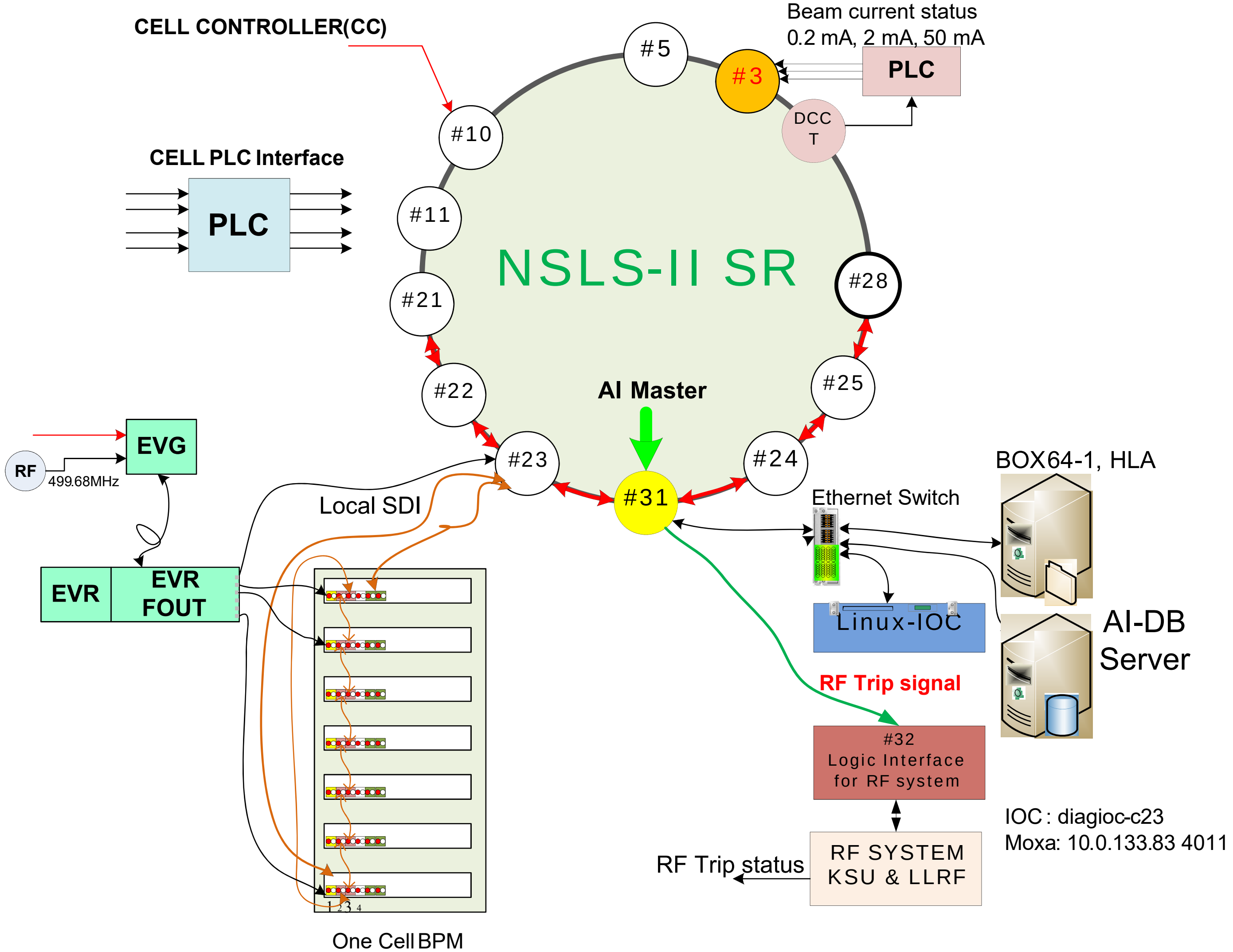
Derivative instruments from BPM/FOFB developments: active interlock master



Cell Controller

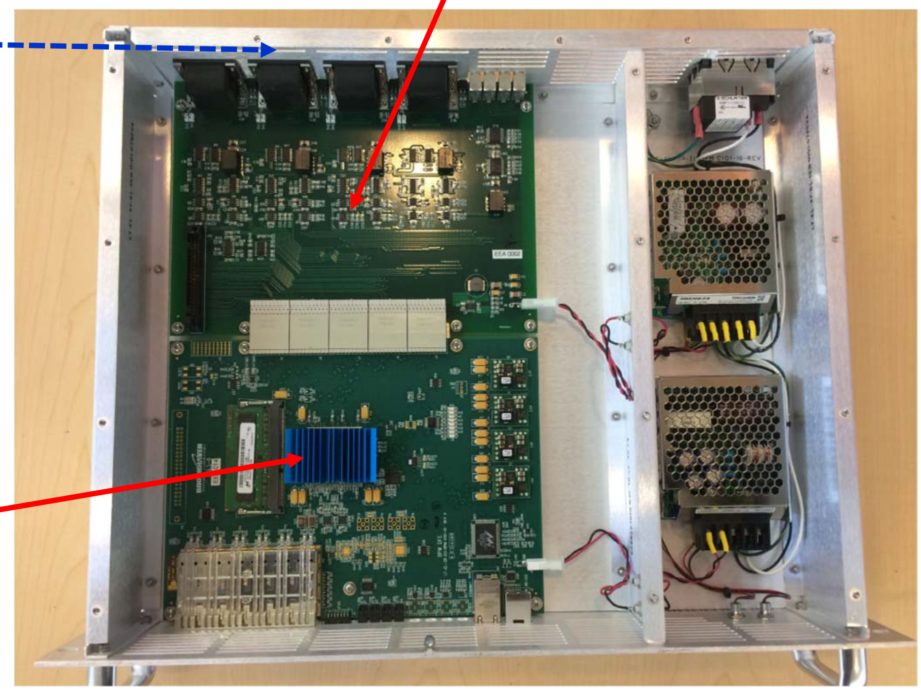
Derivative instruments from BPM/FOFB developments: Encoder timestamp module

Beamline Encoder Timestamp Module: To provide NSLS-II timing system timestamp for beamline encoder signals.

Encoder interface

Encoder interface module

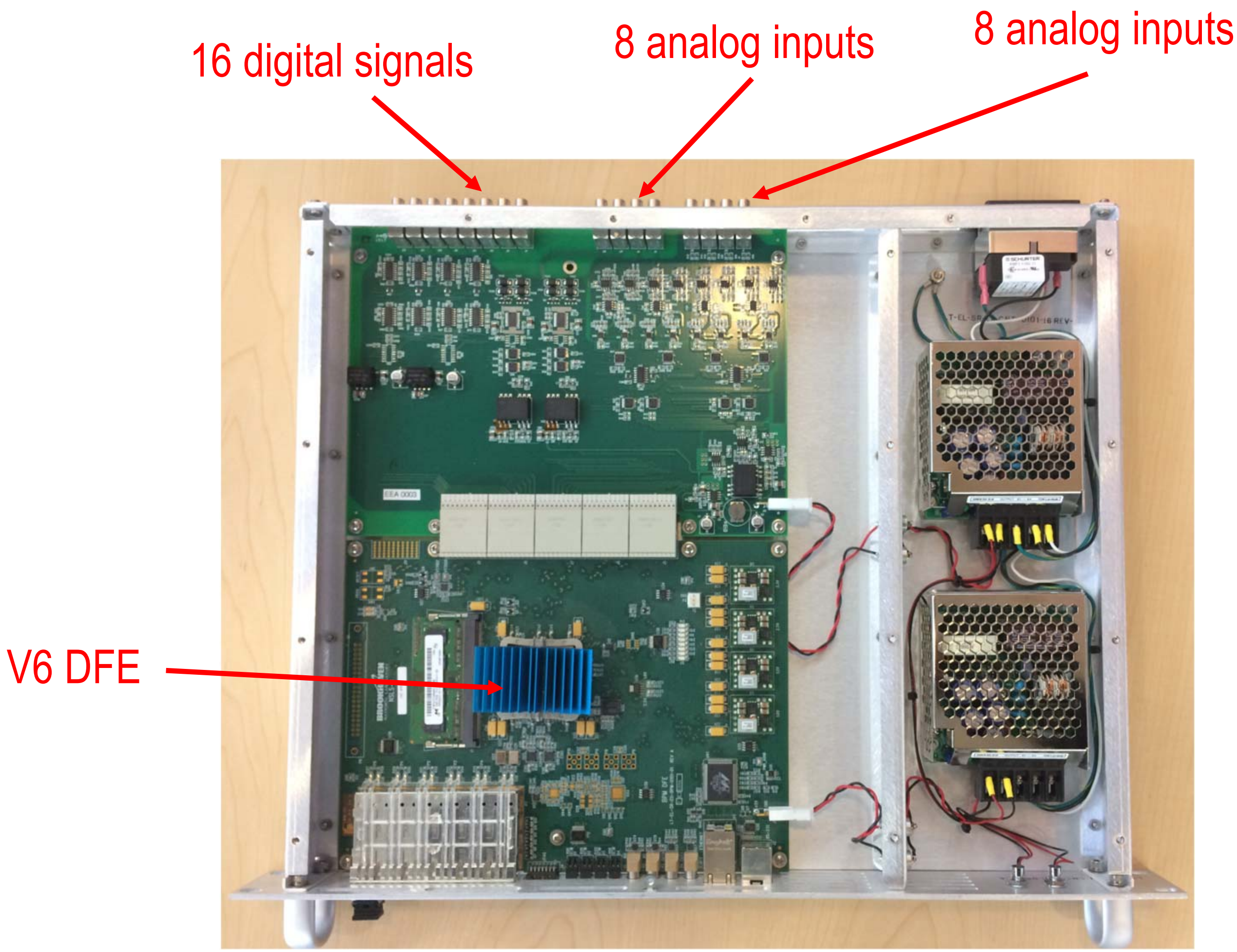
V6 DFE



Beamline Encoder Timestamp Module

Derivative instruments from BPM/FOFB developments: Generic DAQ timestamp module

General DAQ Timestamp Module: To provide NSLS-II timing system timestamp for 8 analog inputs, 8 analog outputs, 16 digital inputs/outputs signals.

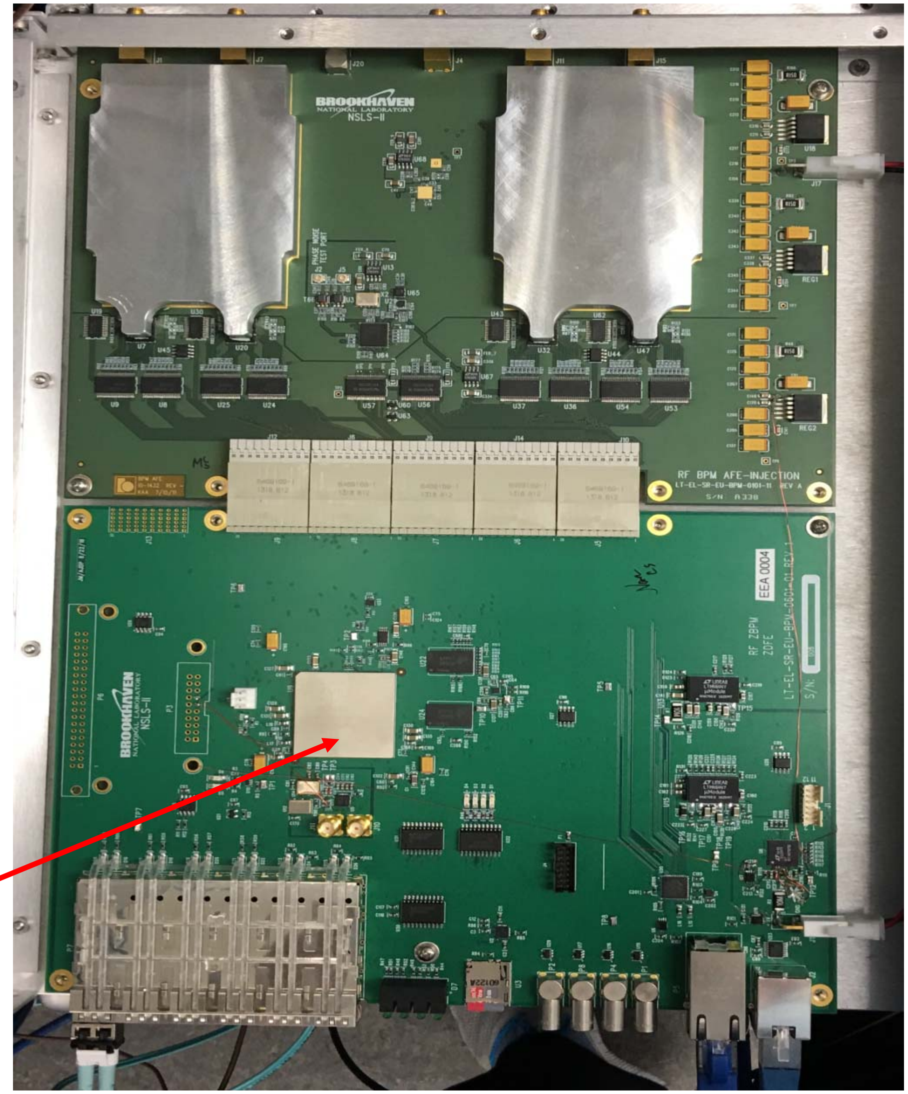


Generic DAQ Timestamp Module

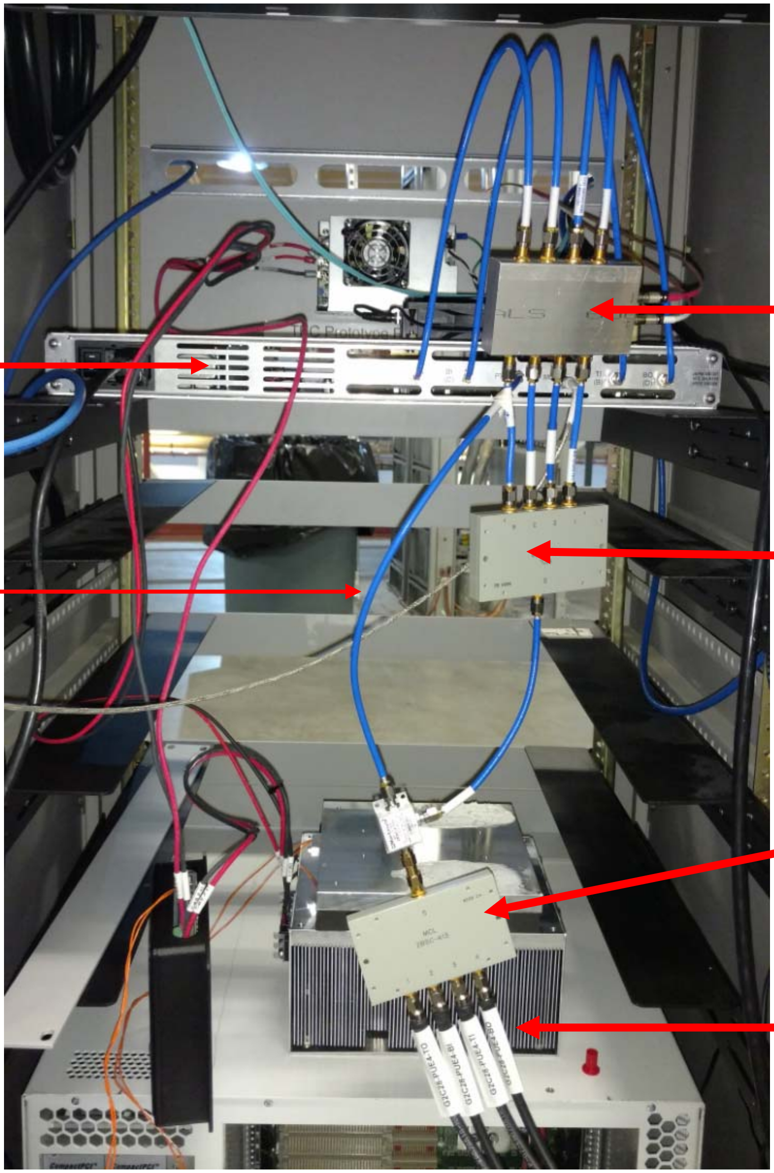
BPM update stage 1: Zynq-based DFE

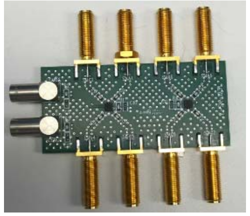
- New Zynq DFE will provide many new features for the overall performance of BPM, cell controller and other derivative instruments.
- The new Zynq DFE's connector is pin-to-pin compatible with the Virtex6 DFE board. All the derivative instruments can be updated without any hardware re-design effort.
- RF switch circuit is tested with new DFE board. It improves BPM stability and removes the dependences of temperature-controlled rack.

Zynq DFE



BPM update stage 1: testing Zynq-based DFE





Existing BPM

PT 500 MHz

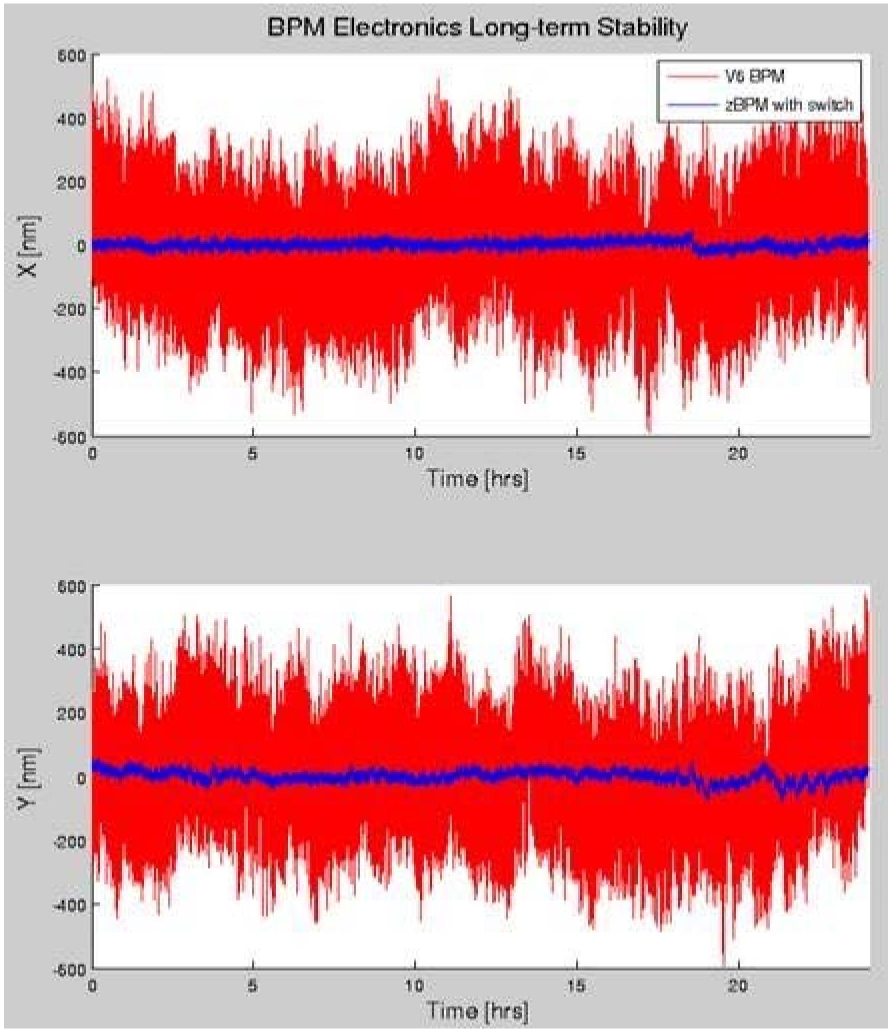
RF SWITCH box

Splitter

Combiner

Beam signal 400 mA

BPM update stage 1: Zynq-based DFE stability



Existing V6 BPM : installed in temperature-controlled rack(+/- 0.1 C): (Red curve)

→ Stability (RMS):130nm (H plane), 126 nm (V plane)

zBPM with RF switch: installed in open rack (+/-0.5 C)
→ Stability (RMS): 11nm (H plane), 20nm(V plane)

Conclusions: RF switch reduce the BPM's temperature dependence.

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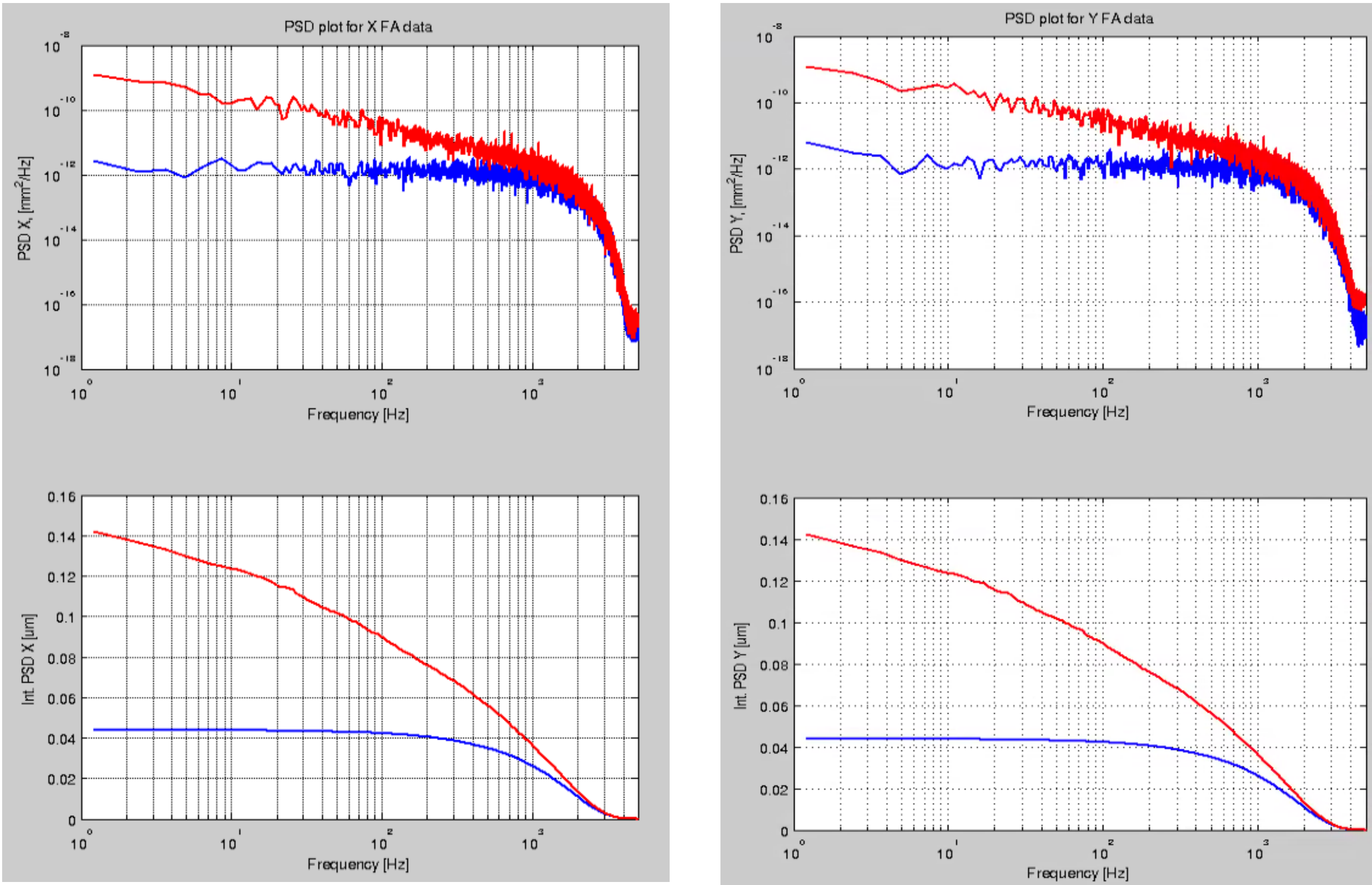
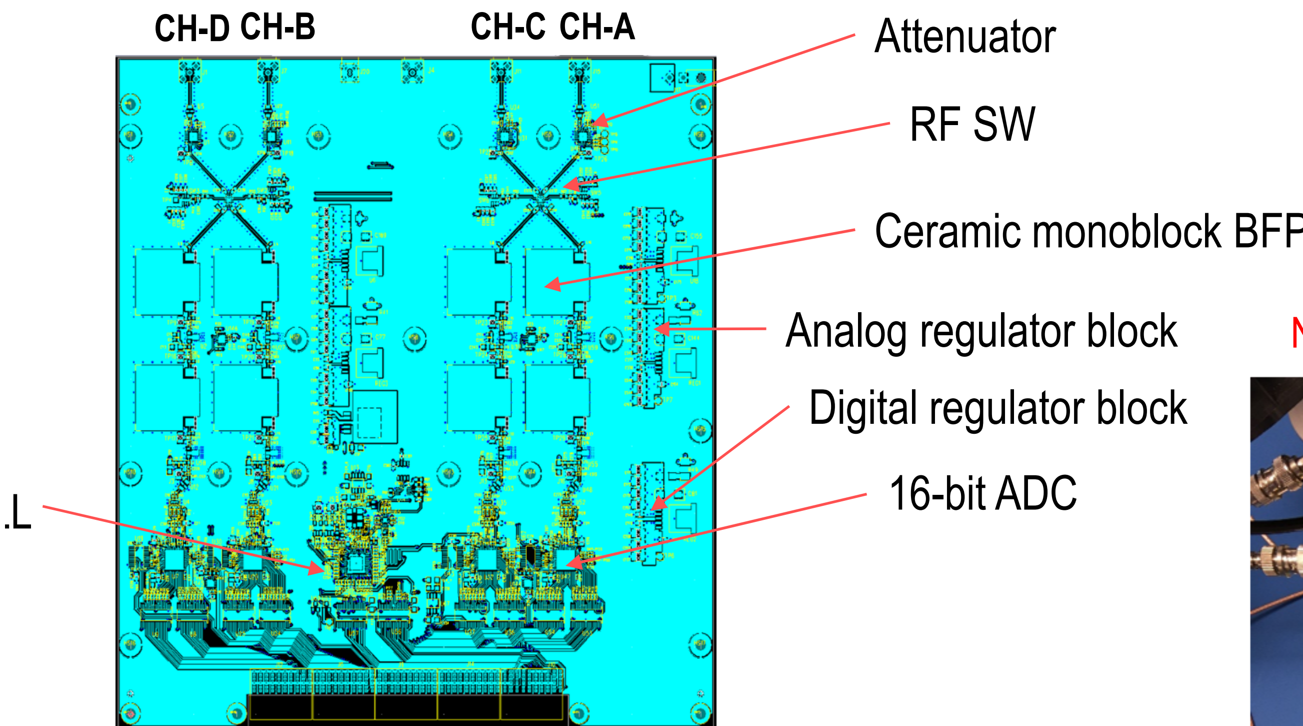
BPM update stage 1: Zynq-based DFE stability



BPM PSD plot
Red: V6 BPM in temperature-controlled rack
Blue zBPM with RF switch in open rack

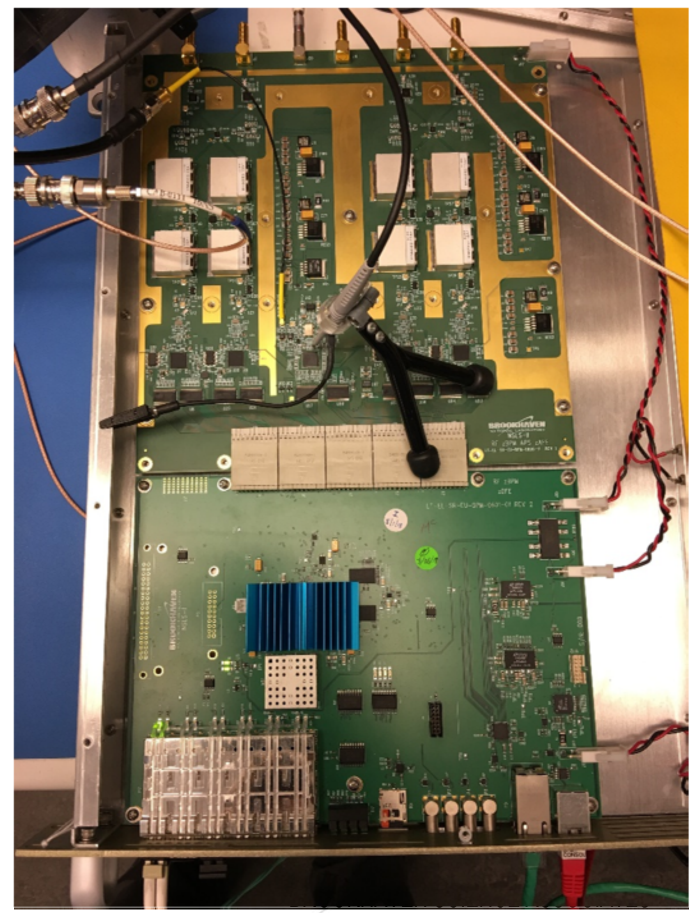
BPM update stage 2: AFE upgrade with RF switch and board temperature control



Key improvements:

- New PCB design.
- Incorporates RF switch circuit.
- New RF shied box.
- Bottom side only has GND copper plane and vias.
- Board temperature is controlled by Peltier cooling plate.
- New type monoblock ceramic BFP.
- Improved voltage regulators.

New BPM under testing (Nov.1, 2018)



FOFB future plan: electron beam orbit stability

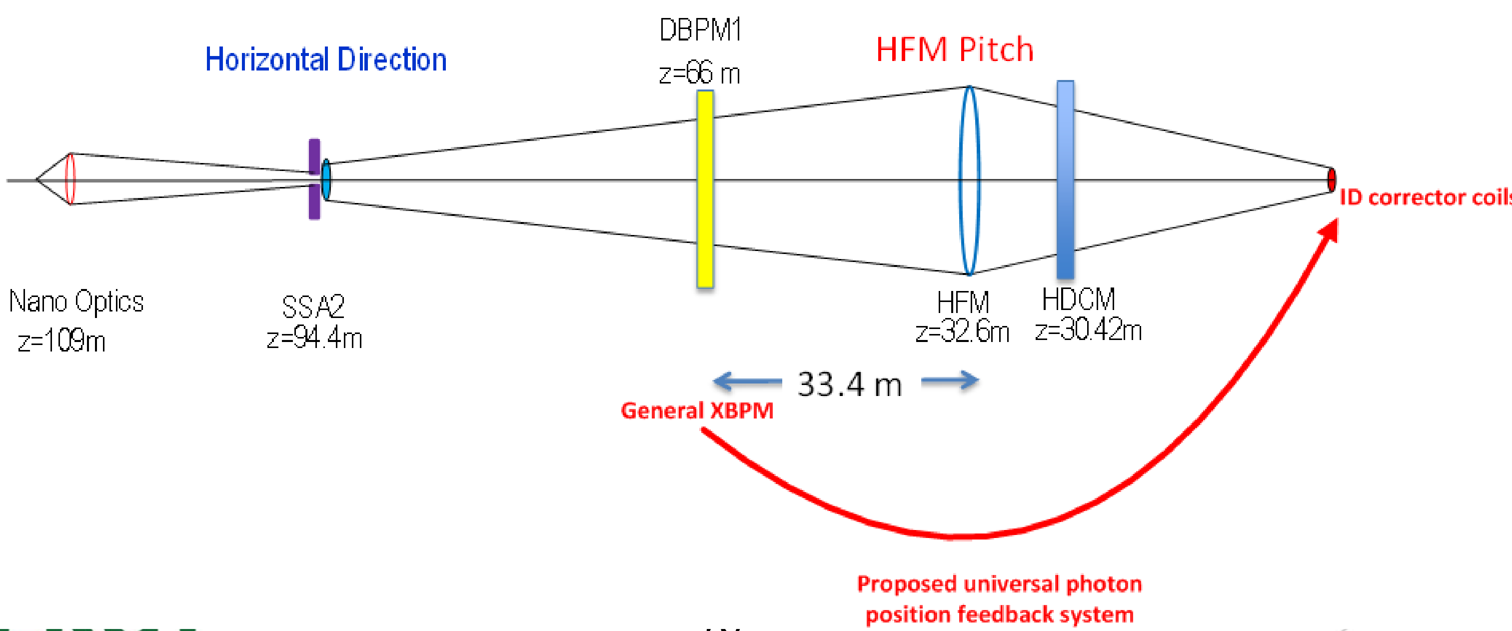
- Based on the existing hardware:
  - We have done PI control in spatial mode. More SISO feedback control algorithm (internal model control etc.) will help to find the optimized noise suppression in each spatial mode.
  - Combine slow orbit feedback system (SOFB) with FOFB. Need to separate in either frequency domain or spatial domain. Since our FOFB has gain in low frequency, we will try to separate the two feedback systems in spatial domain.

- Performance improvement from hardware update:
  - With the improvement of BPM resolution and power supply control system, we should be able to improve the FOFB performance.
  - In the long term, with the updated DFE for BPMs and cell controllers, we can send the BPM data with 10Gbit/second rate. The new DFE also provides much more resource to do different FOFB calculations. With some update of power supply control system, we can increase the feedback sampling rate from 10kHz to 20kHz or higher. The higher sampling rate is helpful to improve the FOFB performance.
  - Study the possibility to include xBPM into the FOFB loop. This needs to enable the xBPM fast data link into the FOFB SDI.
  - Introduce FPGA-based machine learning to make adaptive feedback control.

FOFB future plan: photon beam orbit stability

The photon beam stability is the ultimate goal

- Photon beam stability should include xBPM from beamlines
  - FOFB in accelerator can't suppress the noises from beamline optics
  - Some beamlines might need photon beam stability beyond the limits of RF BPM or fast corrector in accelerator
- Universal hardware platforms for beamline feedback system. Deliver stabile photon beam to the experiment end station.
  - Sensor: xBPM or beamline user signals
  - Actuators: piezoelectric to control mirror (bandwidth limited), fast ID correctors



Summary

- NSLS-II FOFB system meets the design requirements with 240 BPMs and 90 fast correctors.
- The system can be used for orbit controls during user operations for different scenarios.
- Large calculation resources from FPGA enable us to do more complicated FOFB algorithm.
- Some derivative instruments have been developed and used at NSLS-II facility, both in accelerator and beamlines. All these instruments will benefit from the efforts of Zynq DFE development with minimum hard redesign. Hardware design reuse and code sharing have proven working very well at NSLS-II.
- Approach beam stability from feedback systems from both accelerator and beamlines.