NSLS-II Fast Orbit Feedback System



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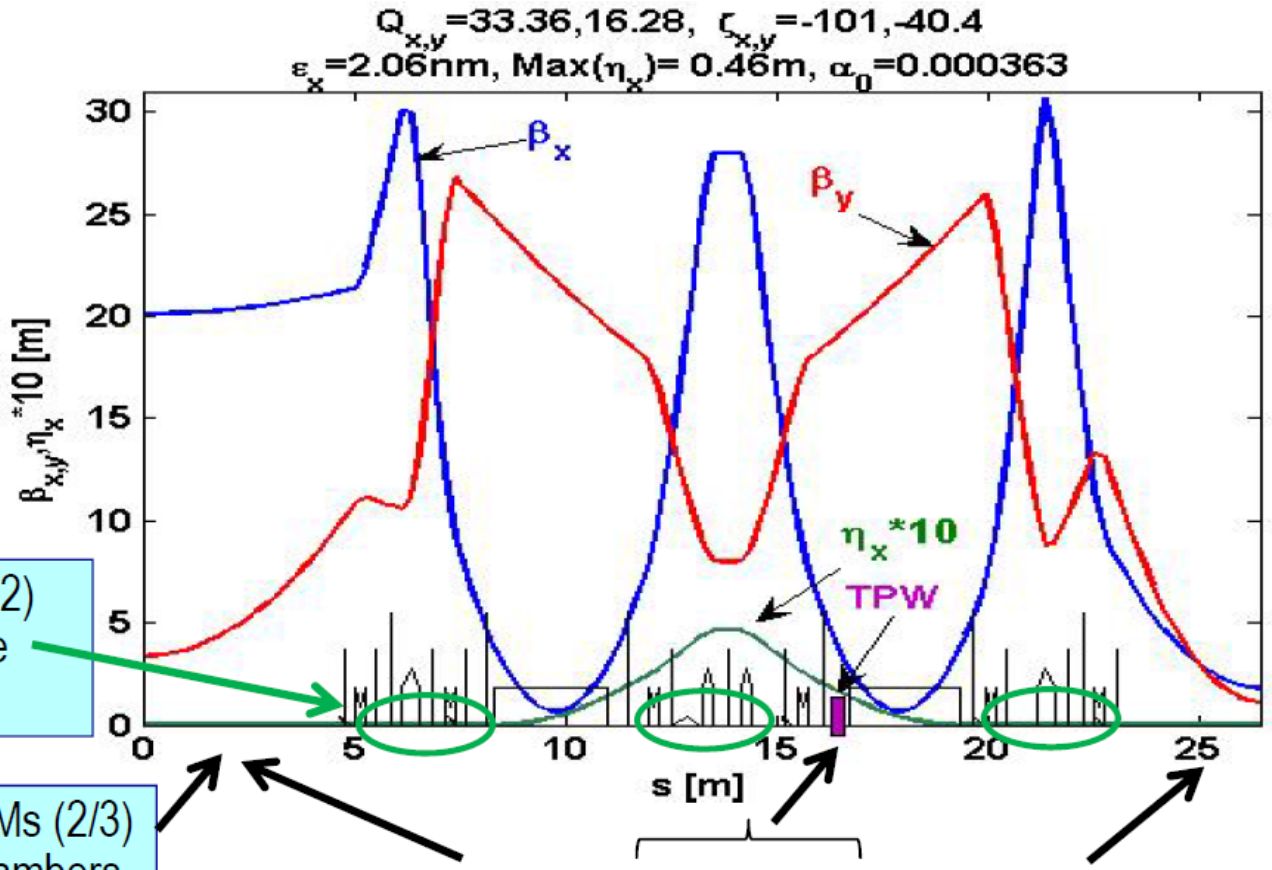
On behalf of FOFB Team

Electron and X-Ray Beam Stability Review, January 2018, BNL

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
  - FOFB application 1: small angle/offset adjustment for individual beamline
  - FOFB application 2: local bump with FOFB running
  - FOFB application 3: orbit recover after beam dump
  - X-Ray stability: photon local feedback
  - Derivative instruments from BPM/FOFB development at NSLS-II
- FOFB system future plan
  - Hardware update
  - Algorithm optimization
- Summary

NSLS-II Orbit Stability Requirements



Lattice Functions

Standard BPMs (2) on each multipole chambers

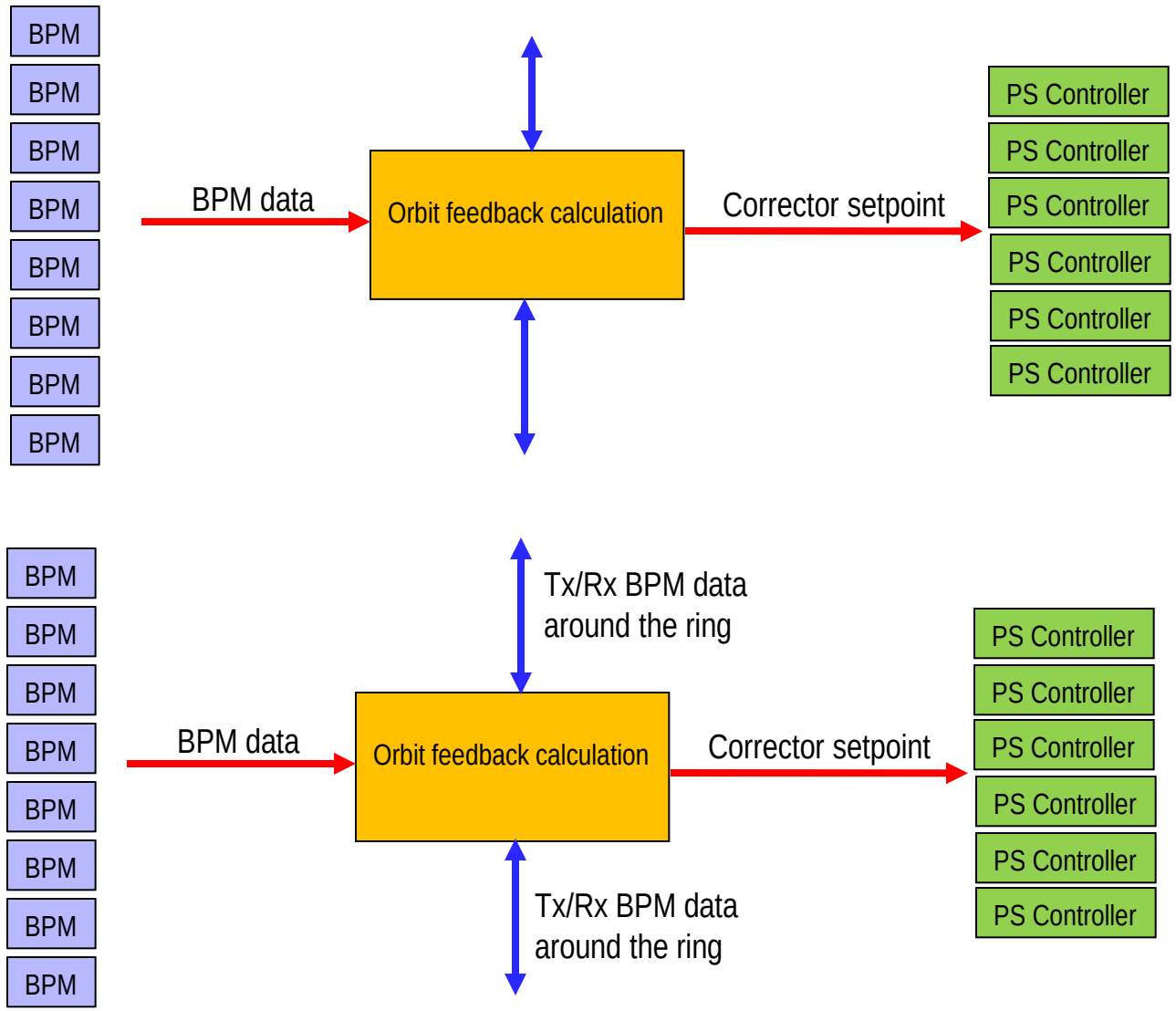
High stability BPMs (2/3) on ID straight chambers

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

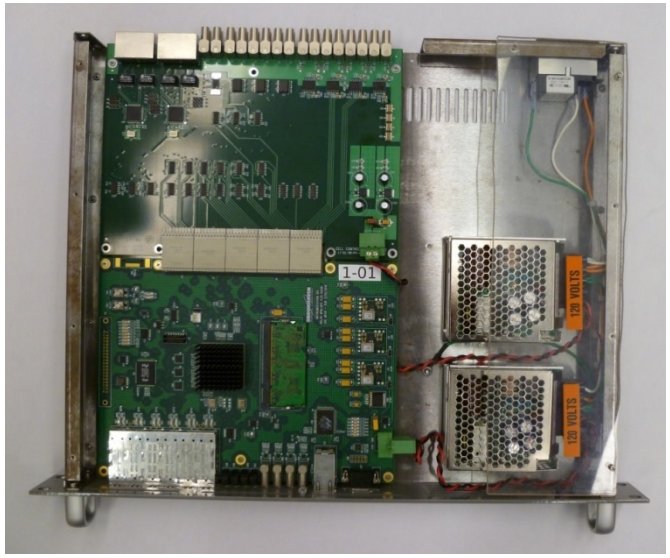
Most challenging Beam stability Requirements = ~ 0.31 μm

FOFB system architecture

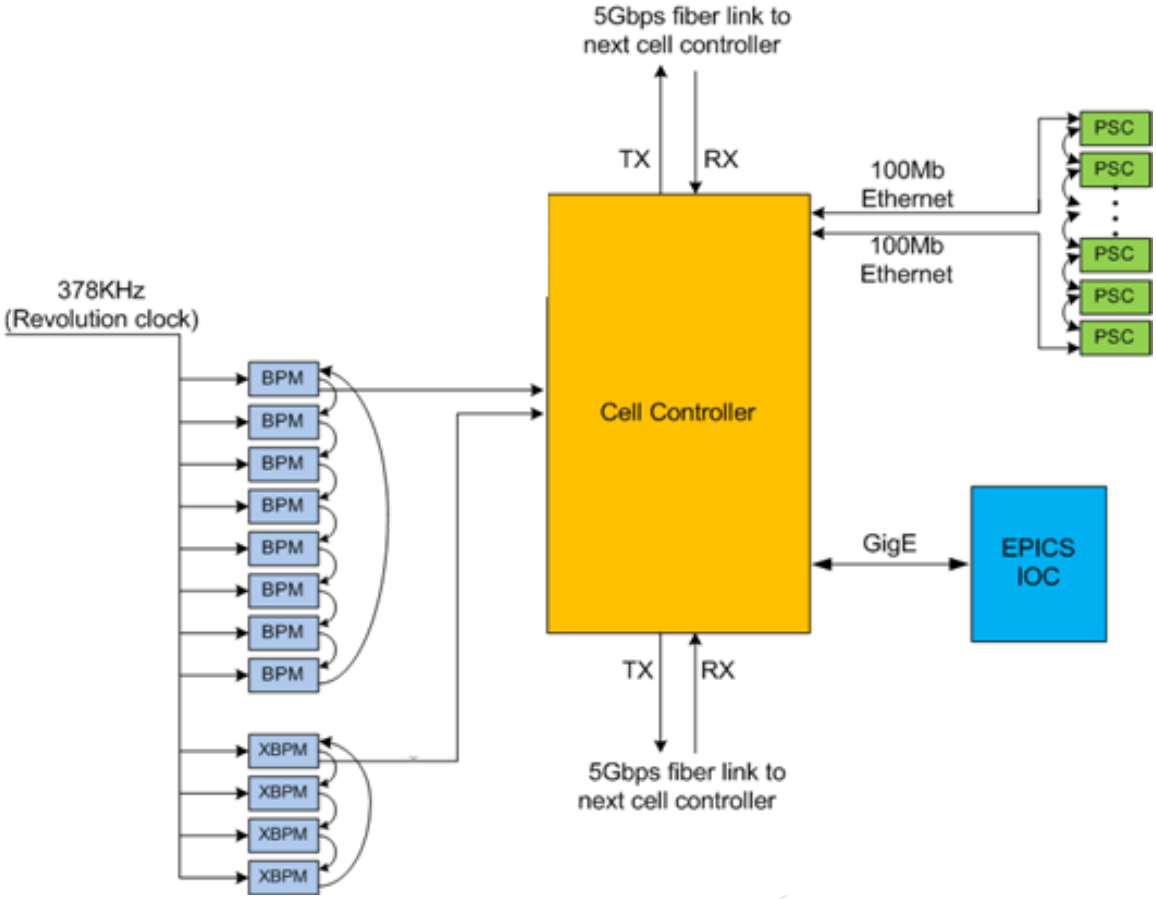


FOFB system architecture

1. Try to deliver BPM data to a place that orbit calculation module have directly access. Don't shove data around too much.
2. Similarly, try to deliver corrector setpoint from a place that orbit calculation module have directly access.
3. Looks we need a place that can:
   - → Receiver local BPM data;
   - → Tx/Rx BPM data to/for other cell;
   - → Carry out FOFB calculation;
   - → Tx corrector setpoints to PS control system.



Cell Controller !



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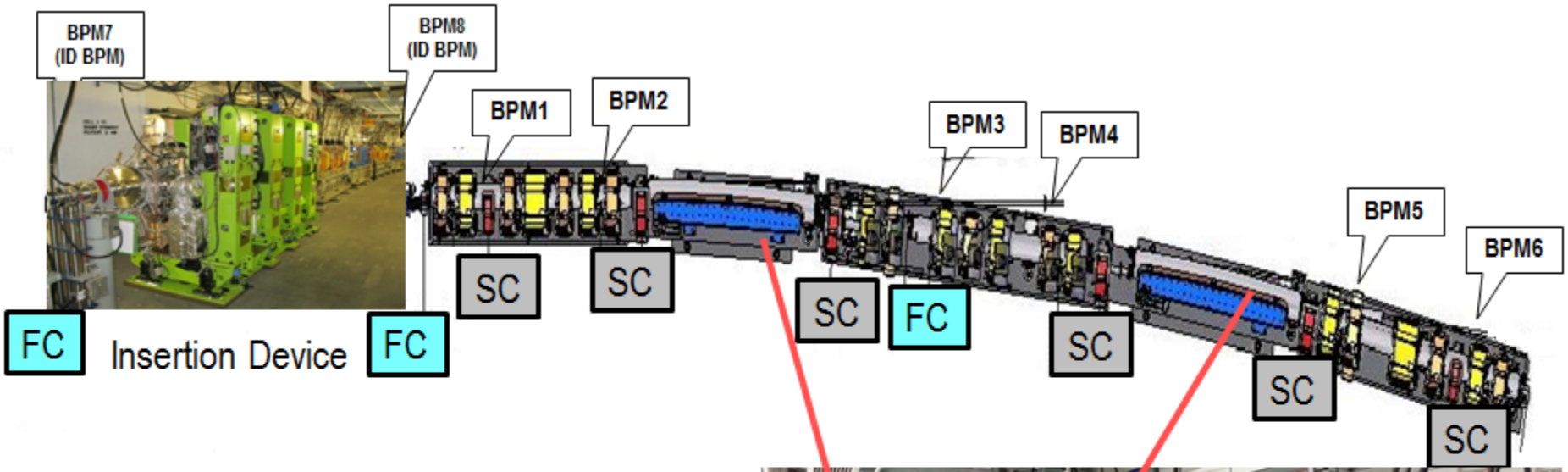
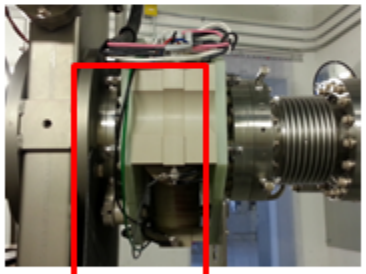
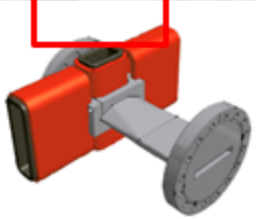
FOFB hardware: correctors

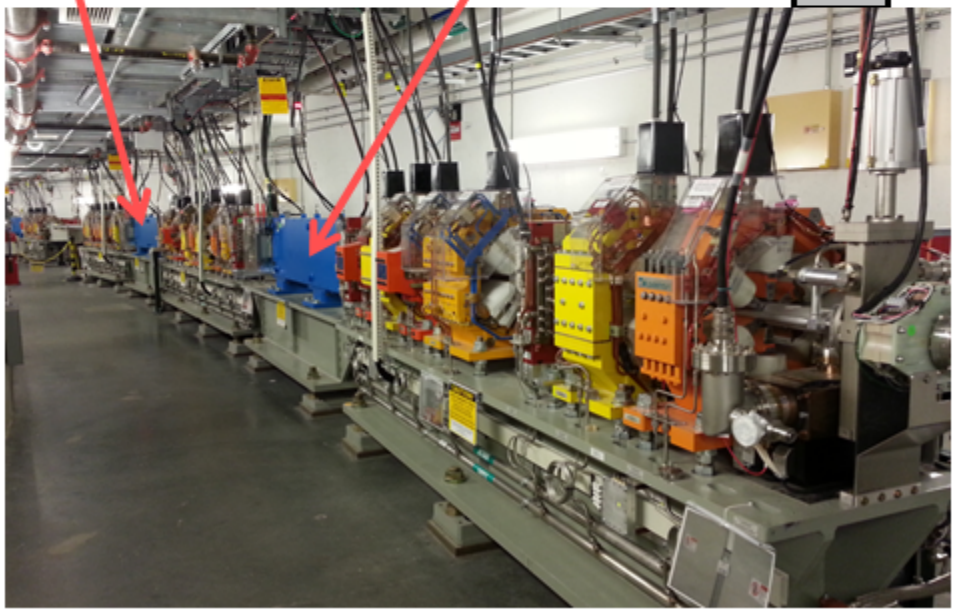


Fast correctors (Qty=3)
- ✓Fast response – 2 kHz
- ✓Weak strength – 15 μrad
- ✓Utilized for – Fast orbit feedback

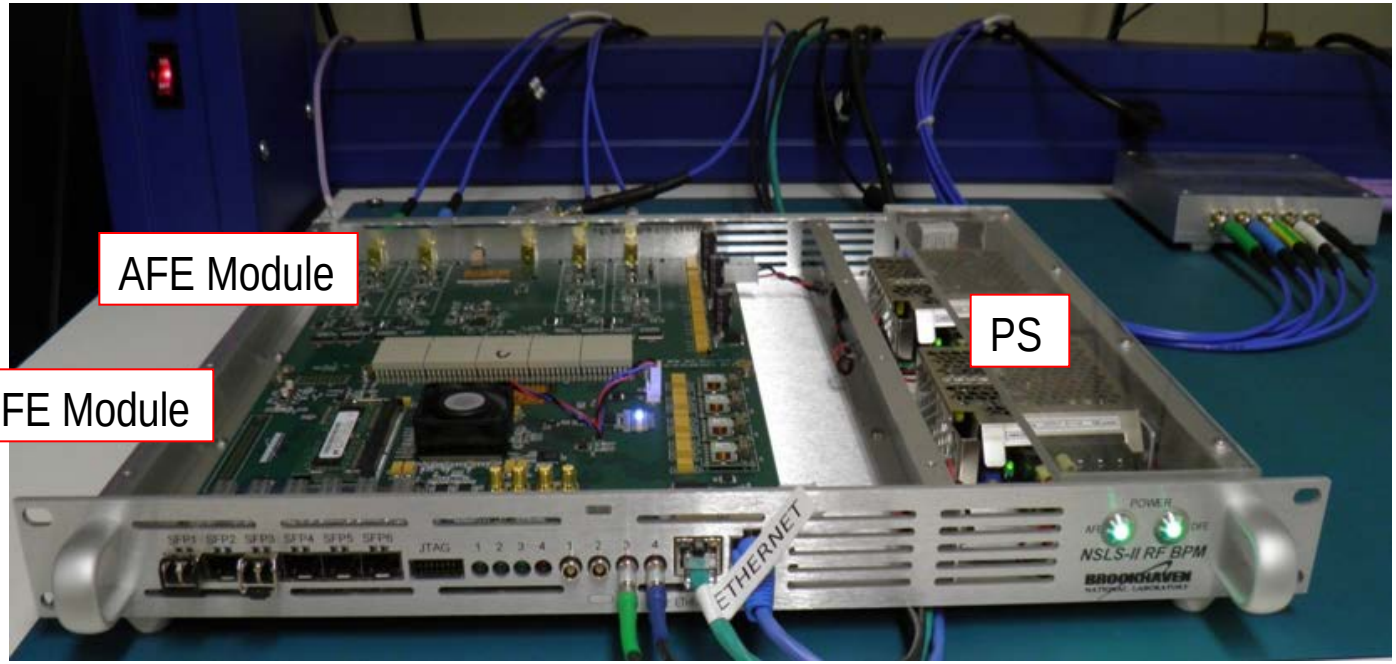




30 mm fast (air core)



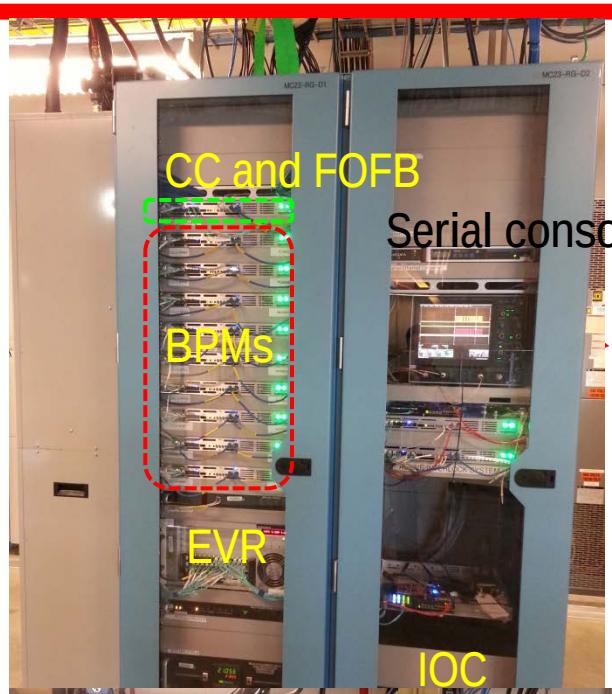
FOFB hardware: BPM





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

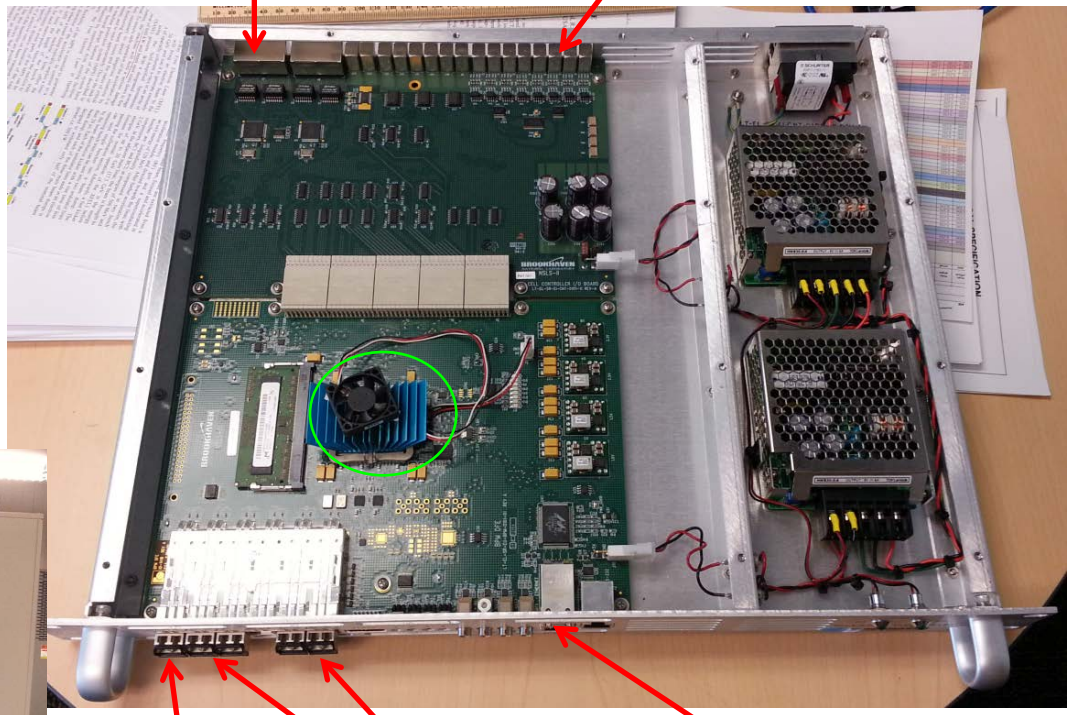
FOFB hardware: cell controller





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

100 Mbit/s link for corrector setpoints



Embedded Event Received

Gigabit Ethernet to EPICS IOC

5 Gigabit/s SDI link for BPM and CC data

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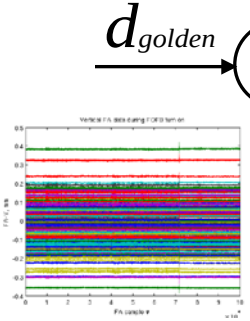
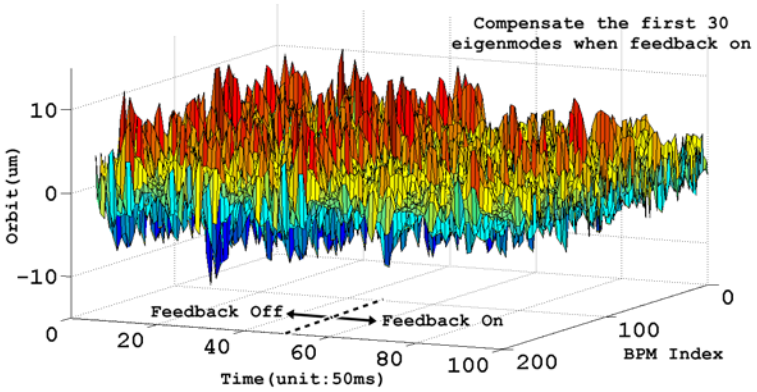
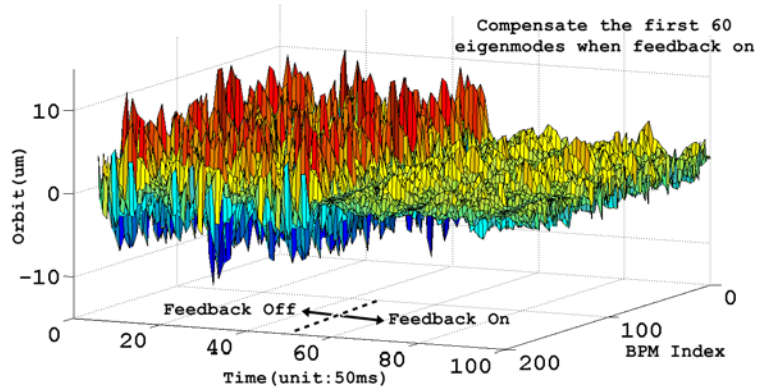
FOFB algorithm: eigenmode decomposition

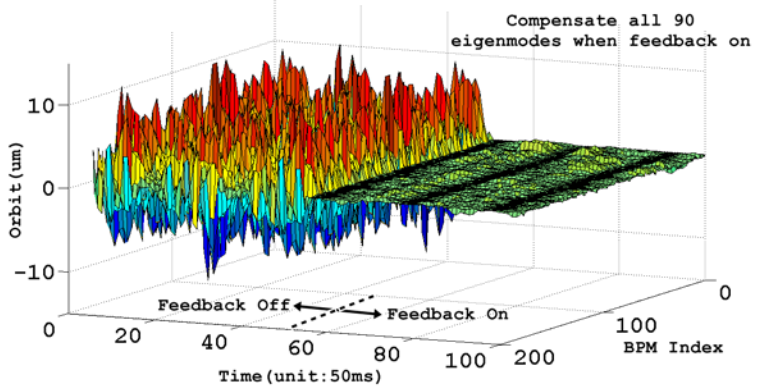


FOFB algorithm: eigenmode decomposition

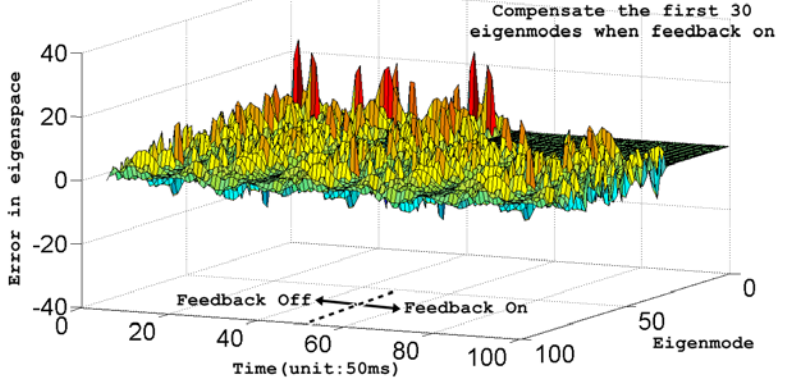
Orbit changes for different compensation

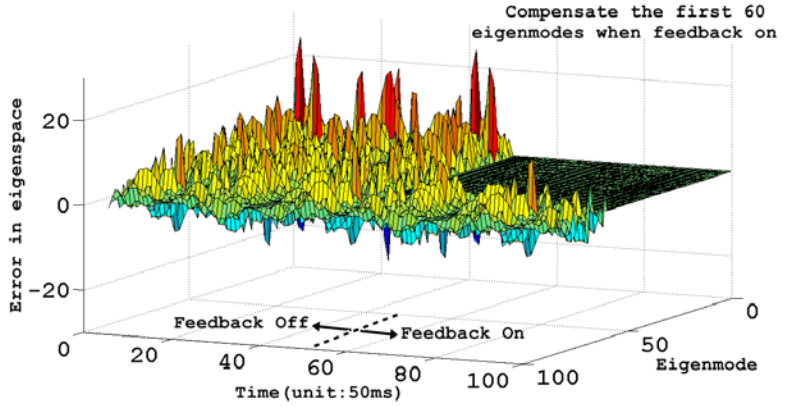


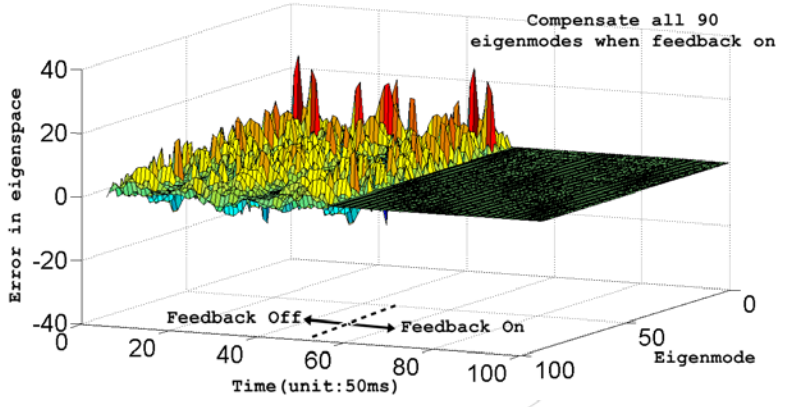




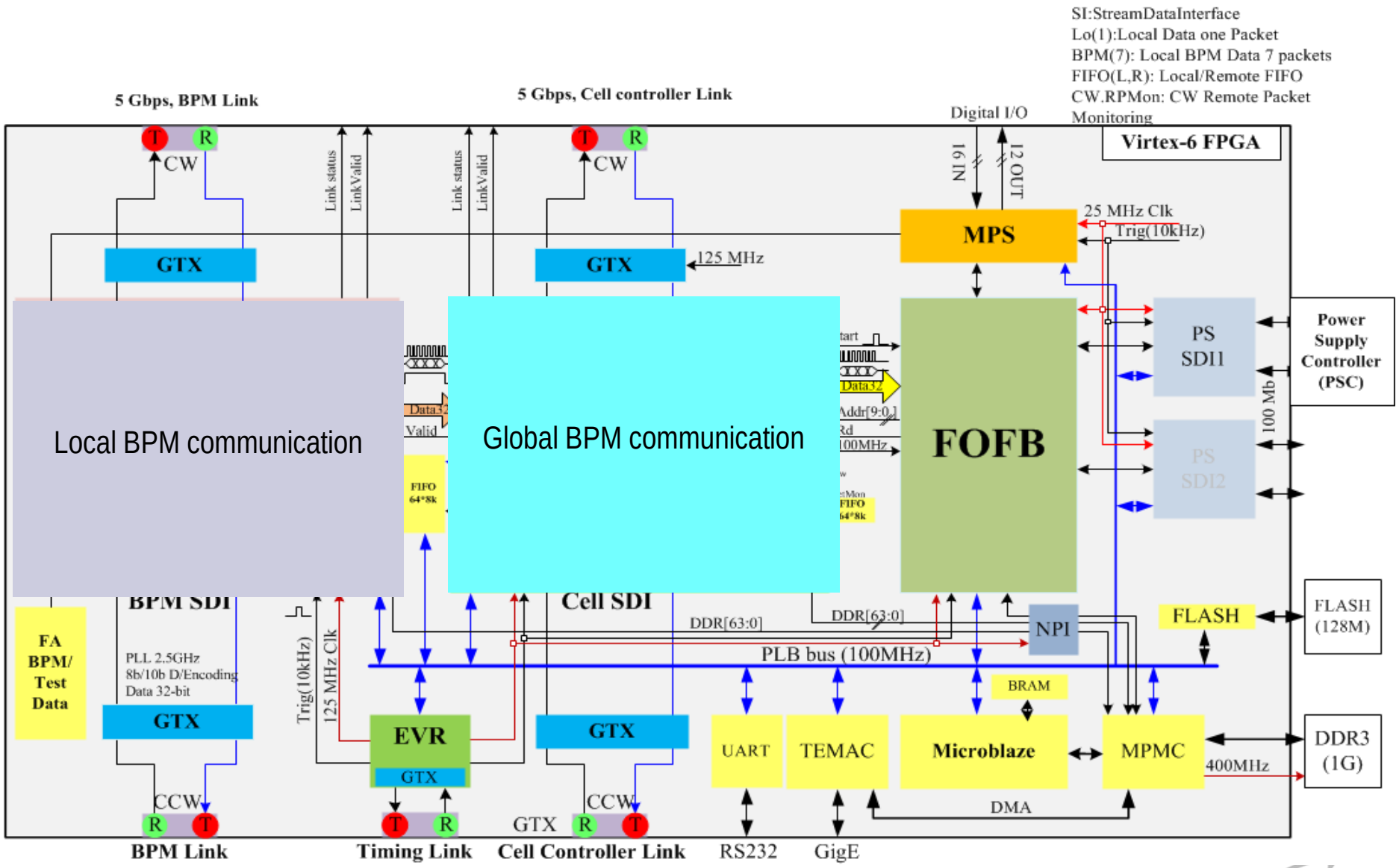
Error in eigenspace for different compensation







FOFB implementation: FPGA block diagram



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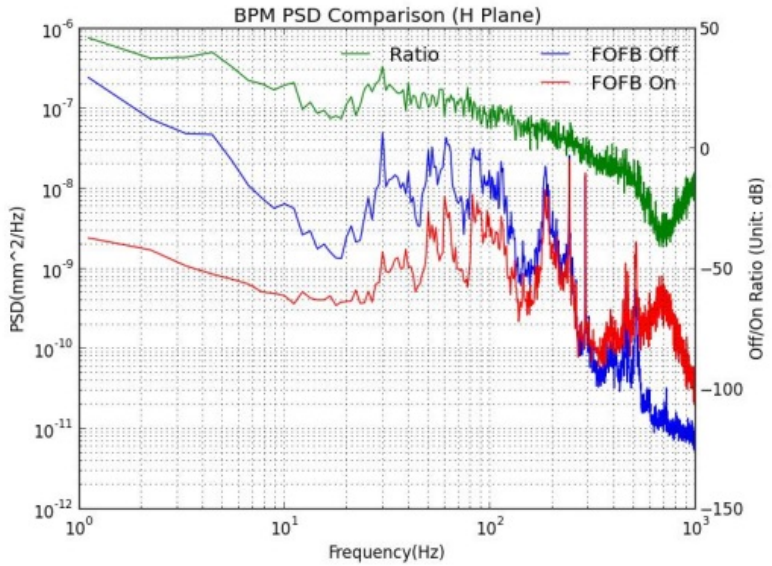
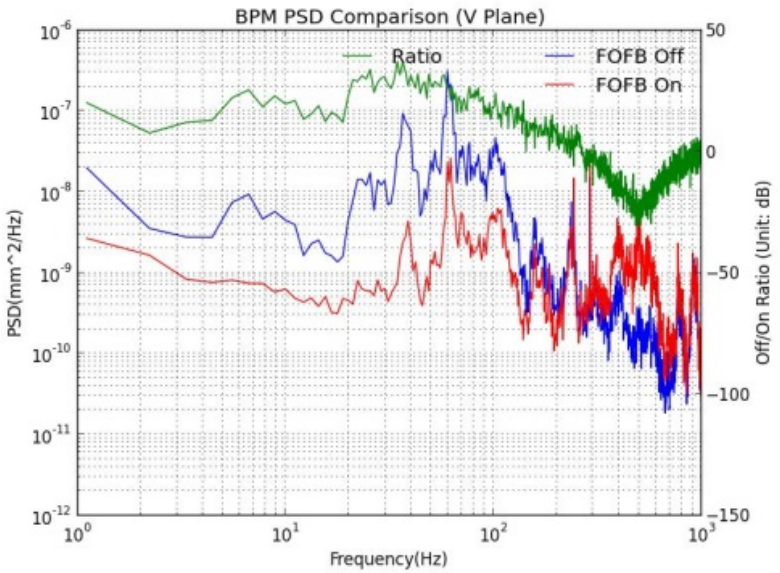
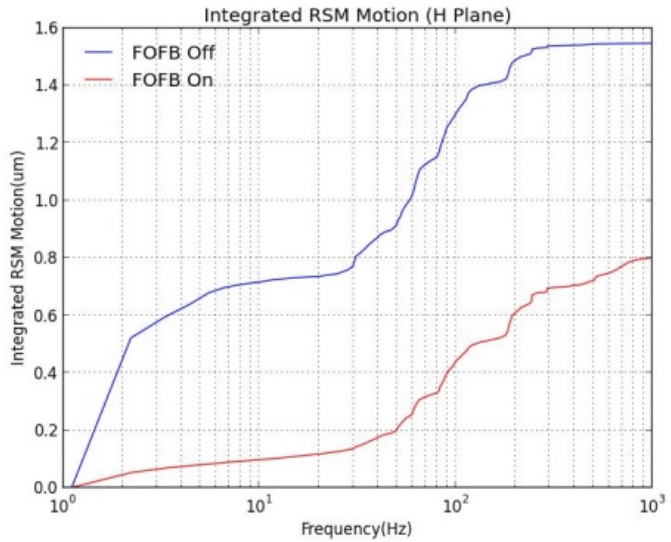
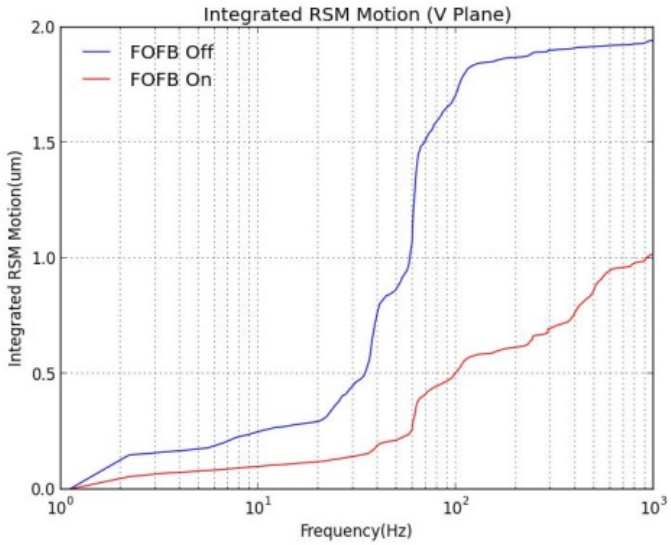
FOFB status: short term performance (power spectrum density)

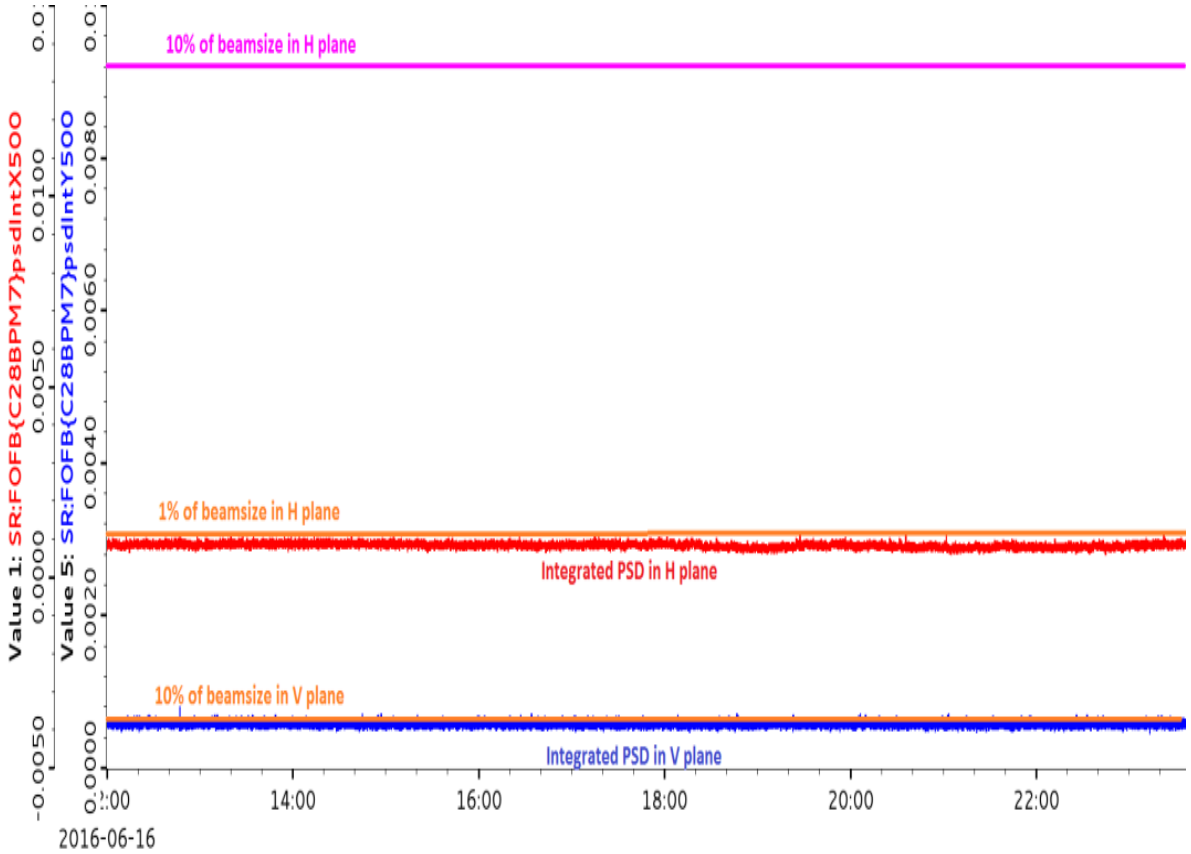


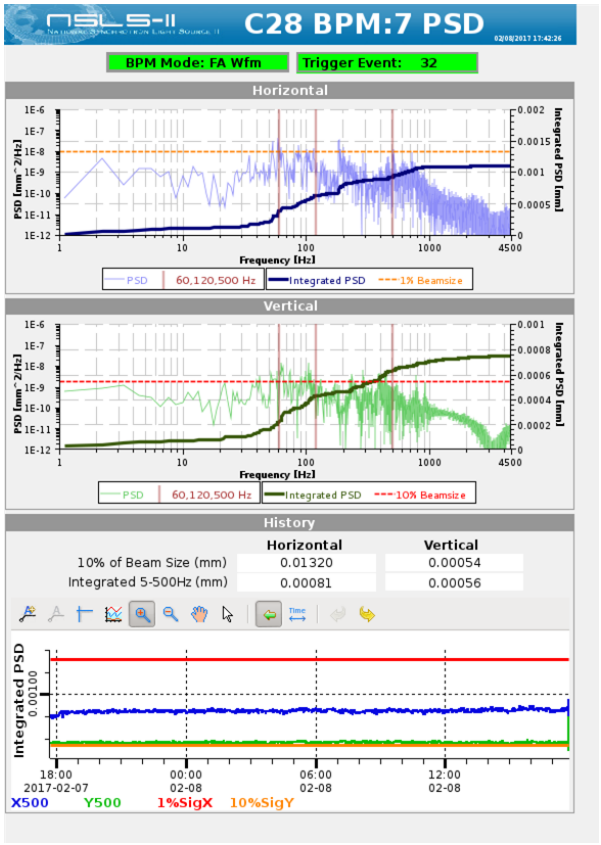






FOFB status: short term performance (power spectrum density)





FOFB short term stability:

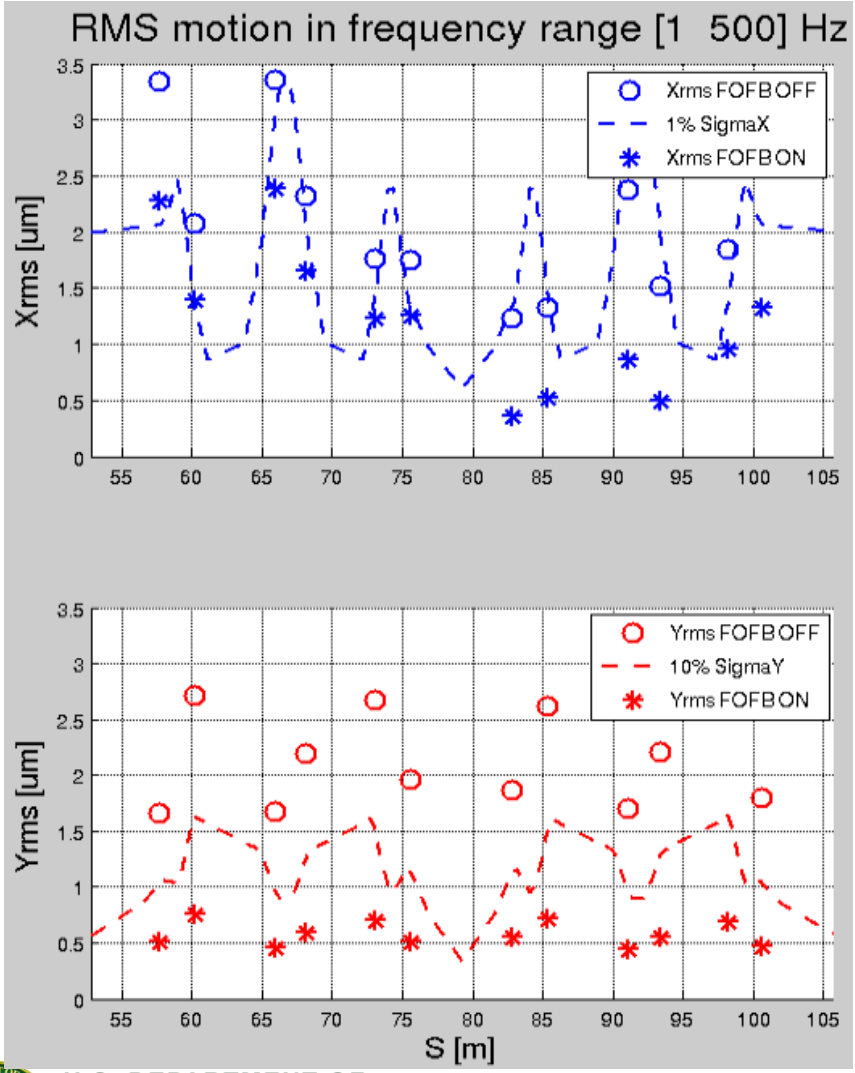
→H and V plane noises suppression up to 250Hz.

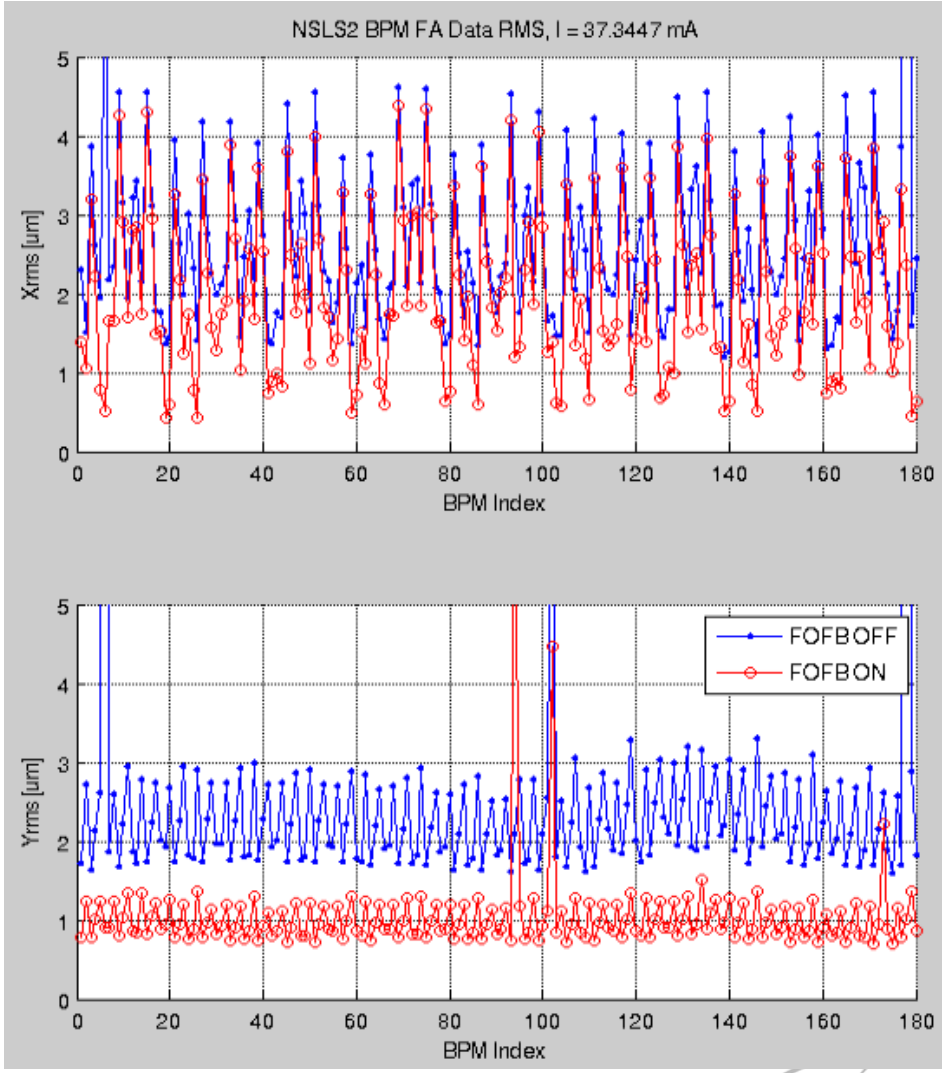
→Integrated PSD in H plane (about 800nm), is within 1% of beamsize

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

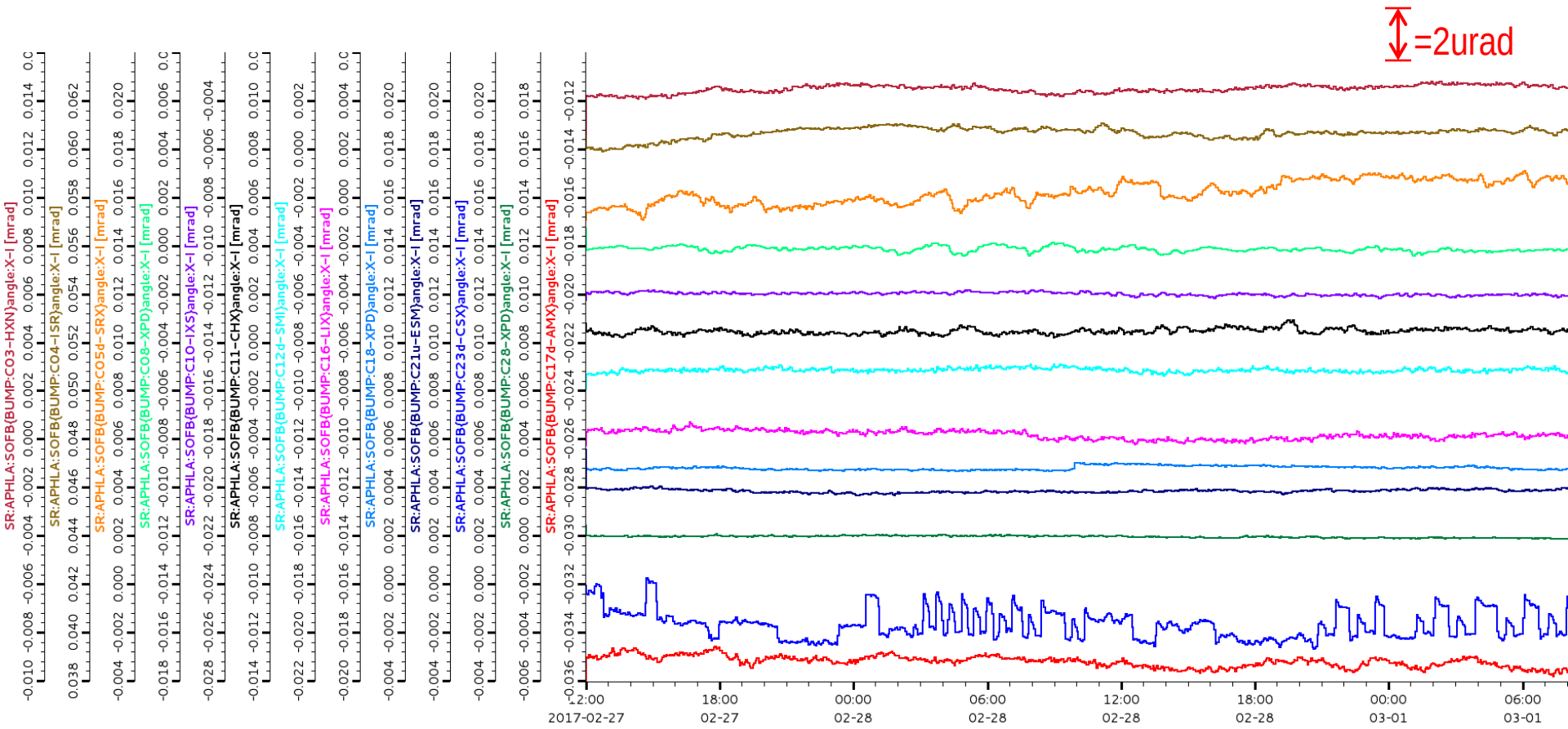
FOFB status: short term performance (power spectrum density)

RMS Motions Along the ring





FOFB status: long term performance



H plane ID angles long term drift

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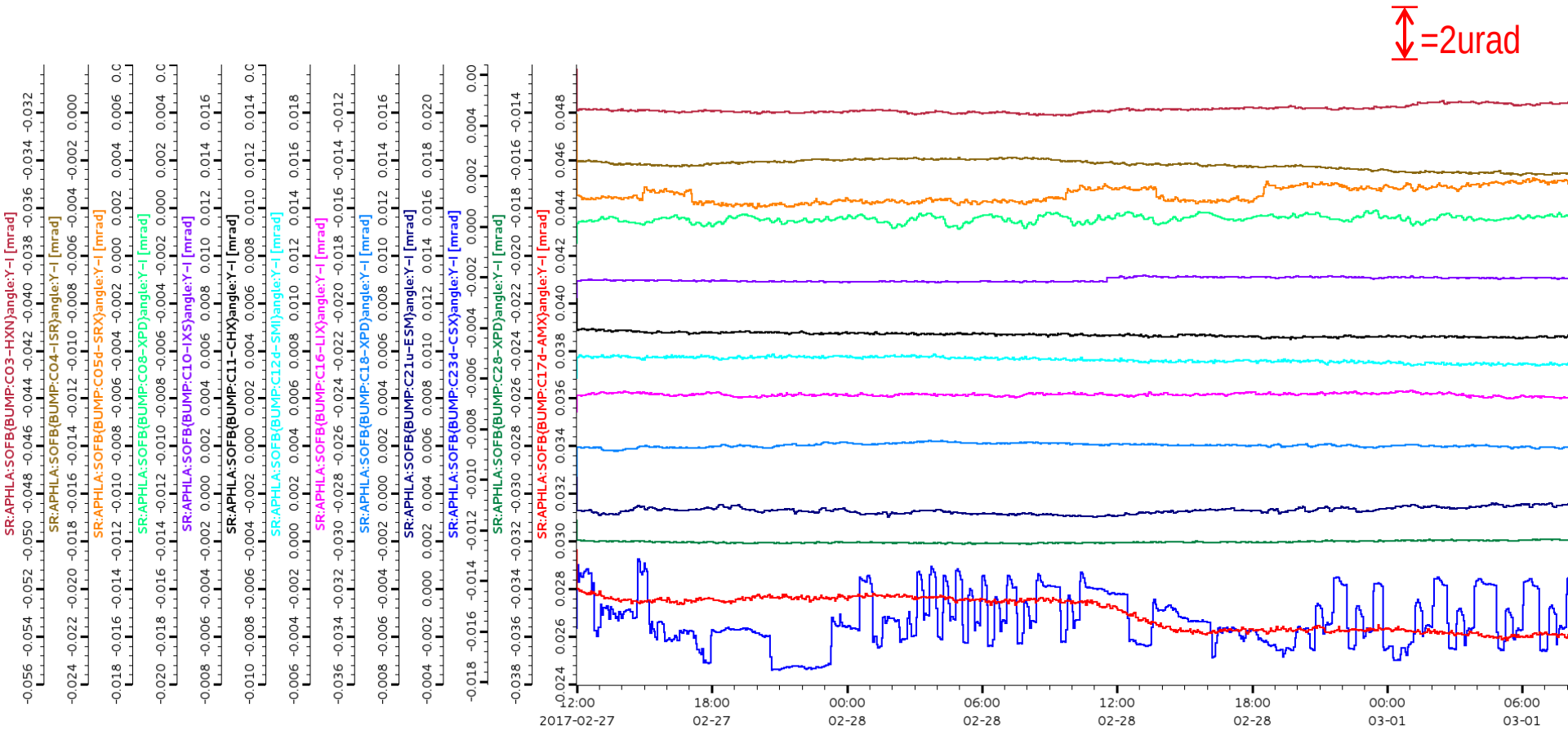
FOFB status: long term performance



V plane ID angles long term drift

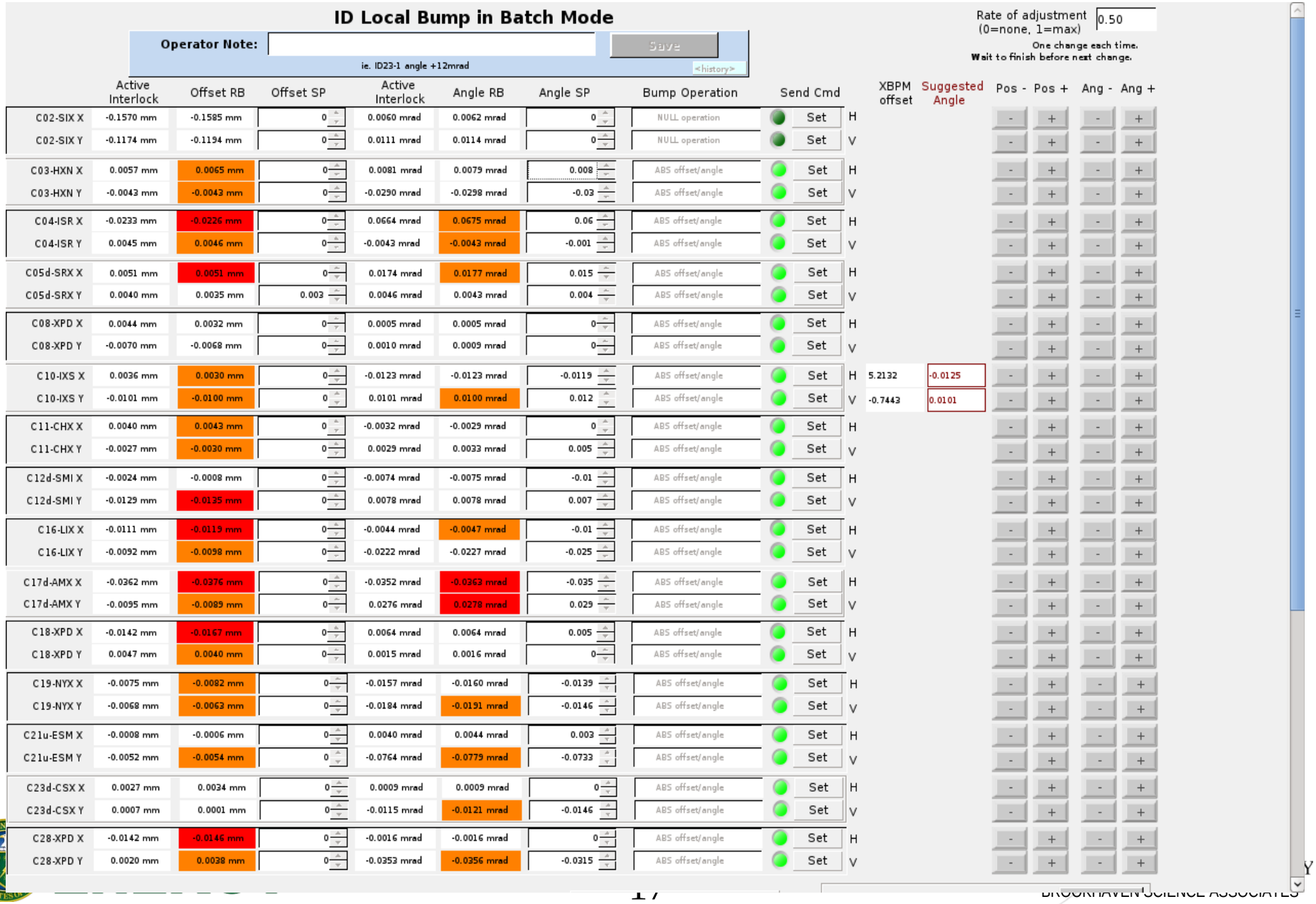
FOFB application 1 : small angle/offset adjustment

Motivation: during user operations with FOFB running, occasionally some individual beamlines need to adjust the ID angle and offset. We want to achieve this without turn on/off FOFB, which can cause some disturbances to other beamlines.

Procedure: since FOFB's function is to keep the electron beam orbit to the reference orbit, we can calculate new reference orbit when a beamline request small angle/offset adjustment. Then, the new reference orbit is downloaded to the cell controllers.

Result: we can adjust the ID angle with 50nrad resolution and the ID offset with 100nm resolution.

FOFB application 1 : small angle/offset adjustment



ID Local Bump in Batch Mode

Operator Note: [ ] Save

ie. ID23-1 angle +12mrad <history>

Rate of adjustment (0=none, 1=max) 0.50

One change each time.
Wait to finish before next change.

	Active Interlock	Offset RB	Offset SP	Active Interlock	Angle RB	Angle SP	Bump Operation	Send Cmd		XBPM offset	Suggested Angle	Pos -	Pos +	Ang -	Ang +
C02-SIX X	-0.1570 mm	-0.1585 mm	0	0.0060 mrad	0.0062 mrad	0	NULL operation	Set	H			-	+	-	+
C02-SIX Y	-0.1174 mm	-0.1194 mm	0	0.0111 mrad	0.0114 mrad	0	NULL operation	Set	V			-	+	-	+
C03-HXN X	0.0057 mm	0.0065 mm	0	0.0081 mrad	0.0079 mrad	0.008	ABS offset/angle	Set	H			-	+	-	+
C03-HXN Y	-0.0043 mm	-0.0043 mm	0	-0.0290 mrad	-0.0298 mrad	-0.03	ABS offset/angle	Set	V			-	+	-	+
C04-ISR X	-0.0233 mm	-0.0226 mm	0	0.0664 mrad	0.0675 mrad	0.06	ABS offset/angle	Set	H			-	+	-	+
C04-ISR Y	0.0045 mm	0.0046 mm	0	-0.0043 mrad	-0.0043 mrad	-0.001	ABS offset/angle	Set	V			-	+	-	+
C05d-SRX X	0.0051 mm	0.0051 mm	0	0.0174 mrad	0.0177 mrad	0.015	ABS offset/angle	Set	H			-	+	-	+
C05d-SRX Y	0.0040 mm	0.0035 mm	0.003	0.0046 mrad	0.0043 mrad	0.004	ABS offset/angle	Set	V			-	+	-	+
C08-XPD X	0.0044 mm	0.0032 mm	0	0.0005 mrad	0.0005 mrad	0	ABS offset/angle	Set	H			-	+	-	+
C08-XPD Y	-0.0070 mm	-0.0068 mm	0	0.0010 mrad	0.0009 mrad	0	ABS offset/angle	Set	V			-	+	-	+
C10-IXS X	0.0036 mm	0.0030 mm	0	-0.0123 mrad	-0.0123 mrad	-0.0119	ABS offset/angle	Set	H	5.2132	-0.0125	-	+	-	+
C10-IXS Y	-0.0101 mm	-0.0100 mm	0	0.0101 mrad	0.0100 mrad	0.012	ABS offset/angle	Set	V	-0.7443	0.0101	-	+	-	+
C11-CHX X	0.0040 mm	0.0043 mm	0	-0.0032 mrad	-0.0029 mrad	0	ABS offset/angle	Set	H			-	+	-	+
C11-CHX Y	-0.0027 mm	-0.0030 mm	0	0.0029 mrad	0.0033 mrad	0.005	ABS offset/angle	Set	V			-	+	-	+
C12d-SMI X	-0.0024 mm	-0.0008 mm	0	-0.0074 mrad	-0.0075 mrad	-0.01	ABS offset/angle	Set	H			-	+	-	+
C12d-SMI Y	-0.0129 mm	-0.0135 mm	0	0.0078 mrad	0.0078 mrad	0.007	ABS offset/angle	Set	V			-	+	-	+
C16-LIX X	-0.0111 mm	-0.0119 mm	0	-0.0044 mrad	-0.0047 mrad	-0.01	ABS offset/angle	Set	H			-	+	-	+
C16-LIX Y	-0.0092 mm	-0.0098 mm	0	-0.0222 mrad	-0.0227 mrad	-0.025	ABS offset/angle	Set	V			-	+	-	+
C17d-AMX X	-0.0362 mm	-0.0376 mm	0	-0.0352 mrad	-0.0363 mrad	-0.035	ABS offset/angle	Set	H			-	+	-	+
C17d-AMX Y	-0.0095 mm	-0.0089 mm	0	0.0276 mrad	0.0278 mrad	0.029	ABS offset/angle	Set	V			-	+	-	+
C18-XPD X	-0.0142 mm	-0.0167 mm	0	0.0064 mrad	0.0064 mrad	0.005	ABS offset/angle	Set	H			-	+	-	+
C18-XPD Y	0.0047 mm	0.0040 mm	0	0.0015 mrad	0.0016 mrad	0	ABS offset/angle	Set	V			-	+	-	+
C19-NYX X	-0.0075 mm	-0.0082 mm	0	-0.0157 mrad	-0.0160 mrad	-0.0139	ABS offset/angle	Set	H			-	+	-	+
C19-NYX Y	-0.0068 mm	-0.0063 mm	0	-0.0184 mrad	-0.0191 mrad	-0.0146	ABS offset/angle	Set	V			-	+	-	+
C21u-ESM X	-0.0008 mm	-0.0006 mm	0	0.0040 mrad	0.0044 mrad	0.003	ABS offset/angle	Set	H			-	+	-	+
C21u-ESM Y	-0.0052 mm	-0.0054 mm	0	-0.0764 mrad	-0.0779 mrad	-0.0733	ABS offset/angle	Set	V			-	+	-	+
C23d-CSX X	0.0027 mm	0.0034 mm	0	0.0009 mrad	0.0009 mrad	0	ABS offset/angle	Set	H			-	+	-	+
C23d-CSX Y	0.0007 mm	0.0001 mm	0	-0.0115 mrad	-0.0121 mrad	-0.0146	ABS offset/angle	Set	V			-	+	-	+
C28-XPD X	-0.0142 mm	-0.0146 mm	0	-0.0016 mrad	-0.0016 mrad	0	ABS offset/angle	Set	H			-	+	-	+
C28-XPD Y	0.0020 mm	0.0038 mm	0	-0.0353 mrad	-0.0356 mrad	-0.0315	ABS offset/angle	Set	V			-	+	-	+

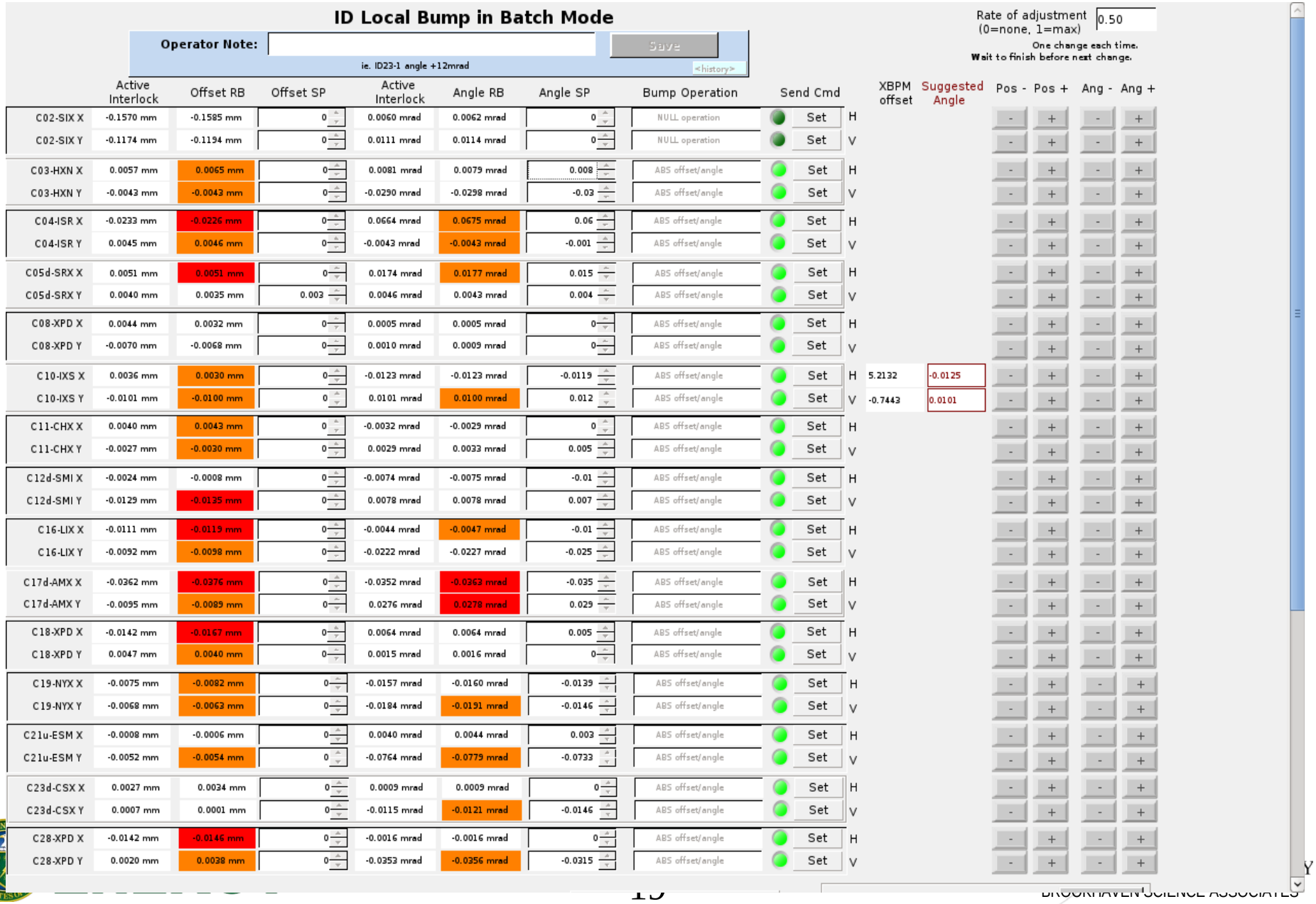
FOFB applications 2: local bump with FOFB running

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.

FOFB applications 2: local bump with FOFB running



ID Local Bump in Batch Mode

Operator Note: [ ] Save

ie. ID23-1 angle +12mrad <history>

Rate of adjustment (0=none, 1=max) 0.50

One change each time.
Wait to finish before next change.

	Active Interlock	Offset RB	Offset SP	Active Interlock	Angle RB	Angle SP	Bump Operation	Send Cmd		XBPM offset	Suggested Angle	Pos -	Pos +	Ang -	Ang +
C02-SIX X	-0.1570 mm	-0.1585 mm	0	0.0060 mrad	0.0062 mrad	0	NULL operation	Set	H			-	+	-	+
C02-SIX Y	-0.1174 mm	-0.1194 mm	0	0.0111 mrad	0.0114 mrad	0	NULL operation	Set	V			-	+	-	+
C03-HXN X	0.0057 mm	0.0065 mm	0	0.0081 mrad	0.0079 mrad	0.008	ABS offset/angle	Set	H			-	+	-	+
C03-HXN Y	-0.0043 mm	-0.0043 mm	0	-0.0290 mrad	-0.0298 mrad	-0.03	ABS offset/angle	Set	V			-	+	-	+
C04-ISR X	-0.0233 mm	-0.0226 mm	0	0.0664 mrad	0.0675 mrad	0.06	ABS offset/angle	Set	H			-	+	-	+
C04-ISR Y	0.0045 mm	0.0046 mm	0	-0.0043 mrad	-0.0043 mrad	-0.001	ABS offset/angle	Set	V			-	+	-	+
C05d-SRX X	0.0051 mm	0.0051 mm	0	0.0174 mrad	0.0177 mrad	0.015	ABS offset/angle	Set	H			-	+	-	+
C05d-SRX Y	0.0040 mm	0.0035 mm	0.003	0.0046 mrad	0.0043 mrad	0.004	ABS offset/angle	Set	V			-	+	-	+
C08-XPD X	0.0044 mm	0.0032 mm	0	0.0005 mrad	0.0005 mrad	0	ABS offset/angle	Set	H			-	+	-	+
C08-XPD Y	-0.0070 mm	-0.0068 mm	0	0.0010 mrad	0.0009 mrad	0	ABS offset/angle	Set	V			-	+	-	+
C10-IXS X	0.0036 mm	0.0030 mm	0	-0.0123 mrad	-0.0123 mrad	-0.0119	ABS offset/angle	Set	H	5.2132	-0.0125	-	+	-	+
C10-IXS Y	-0.0101 mm	-0.0100 mm	0	0.0101 mrad	0.0100 mrad	0.012	ABS offset/angle	Set	V	-0.7443	0.0101	-	+	-	+
C11-CHX X	0.0040 mm	0.0043 mm	0	-0.0032 mrad	-0.0029 mrad	0	ABS offset/angle	Set	H			-	+	-	+
C11-CHX Y	-0.0027 mm	-0.0030 mm	0	0.0029 mrad	0.0033 mrad	0.005	ABS offset/angle	Set	V			-	+	-	+
C12d-SMI X	-0.0024 mm	-0.0008 mm	0	-0.0074 mrad	-0.0075 mrad	-0.01	ABS offset/angle	Set	H			-	+	-	+
C12d-SMI Y	-0.0129 mm	-0.0135 mm	0	0.0078 mrad	0.0078 mrad	0.007	ABS offset/angle	Set	V			-	+	-	+
C16-LIX X	-0.0111 mm	-0.0119 mm	0	-0.0044 mrad	-0.0047 mrad	-0.01	ABS offset/angle	Set	H			-	+	-	+
C16-LIX Y	-0.0092 mm	-0.0098 mm	0	-0.0222 mrad	-0.0227 mrad	-0.025	ABS offset/angle	Set	V			-	+	-	+
C17d-AMX X	-0.0362 mm	-0.0376 mm	0	-0.0352 mrad	-0.0363 mrad	-0.035	ABS offset/angle	Set	H			-	+	-	+
C17d-AMX Y	-0.0095 mm	-0.0089 mm	0	0.0276 mrad	0.0278 mrad	0.029	ABS offset/angle	Set	V			-	+	-	+
C18-XPD X	-0.0142 mm	-0.0167 mm	0	0.0064 mrad	0.0064 mrad	0.005	ABS offset/angle	Set	H			-	+	-	+
C18-XPD Y	0.0047 mm	0.0040 mm	0	0.0015 mrad	0.0016 mrad	0	ABS offset/angle	Set	V			-	+	-	+
C19-NYX X	-0.0075 mm	-0.0082 mm	0	-0.0157 mrad	-0.0160 mrad	-0.0139	ABS offset/angle	Set	H			-	+	-	+
C19-NYX Y	-0.0068 mm	-0.0063 mm	0	-0.0184 mrad	-0.0191 mrad	-0.0146	ABS offset/angle	Set	V			-	+	-	+
C21u-ESM X	-0.0008 mm	-0.0006 mm	0	0.0040 mrad	0.0044 mrad	0.003	ABS offset/angle	Set	H			-	+	-	+
C21u-ESM Y	-0.0052 mm	-0.0054 mm	0	-0.0764 mrad	-0.0779 mrad	-0.0733	ABS offset/angle	Set	V			-	+	-	+
C23d-CSX X	0.0027 mm	0.0034 mm	0	0.0009 mrad	0.0009 mrad	0	ABS offset/angle	Set	H			-	+	-	+
C23d-CSX Y	0.0007 mm	0.0001 mm	0	-0.0115 mrad	-0.0121 mrad	-0.0146	ABS offset/angle	Set	V			-	+	-	+
C28-XPD X	-0.0142 mm	-0.0146 mm	0	-0.0016 mrad	-0.0016 mrad	0	ABS offset/angle	Set	H			-	+	-	+
C28-XPD Y	0.0020 mm	0.0038 mm	0	-0.0353 mrad	-0.0356 mrad	-0.0315	ABS offset/angle	Set	V			-	+	-	+

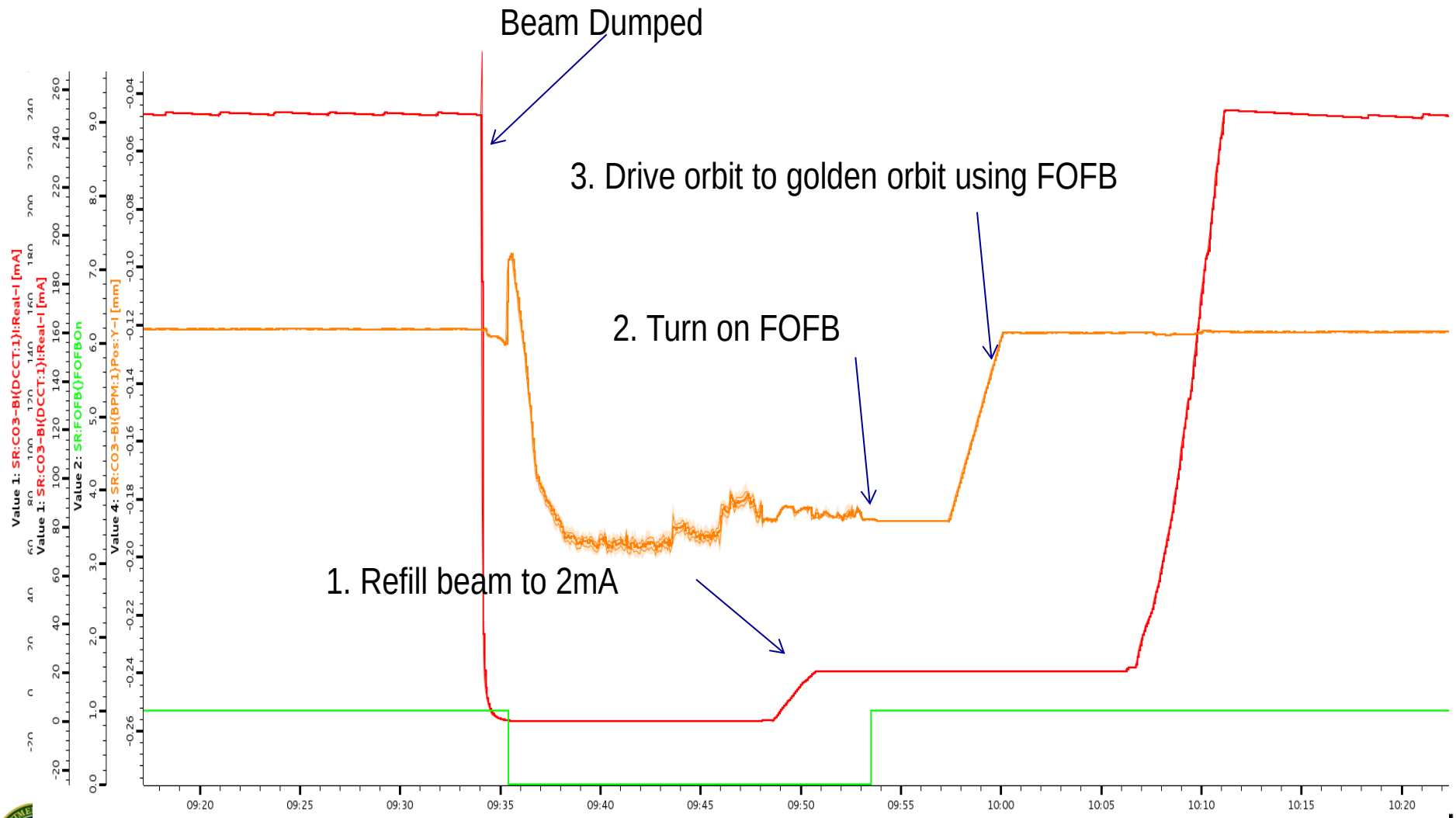
FOFB application 3: orbit recover after beam dump

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.

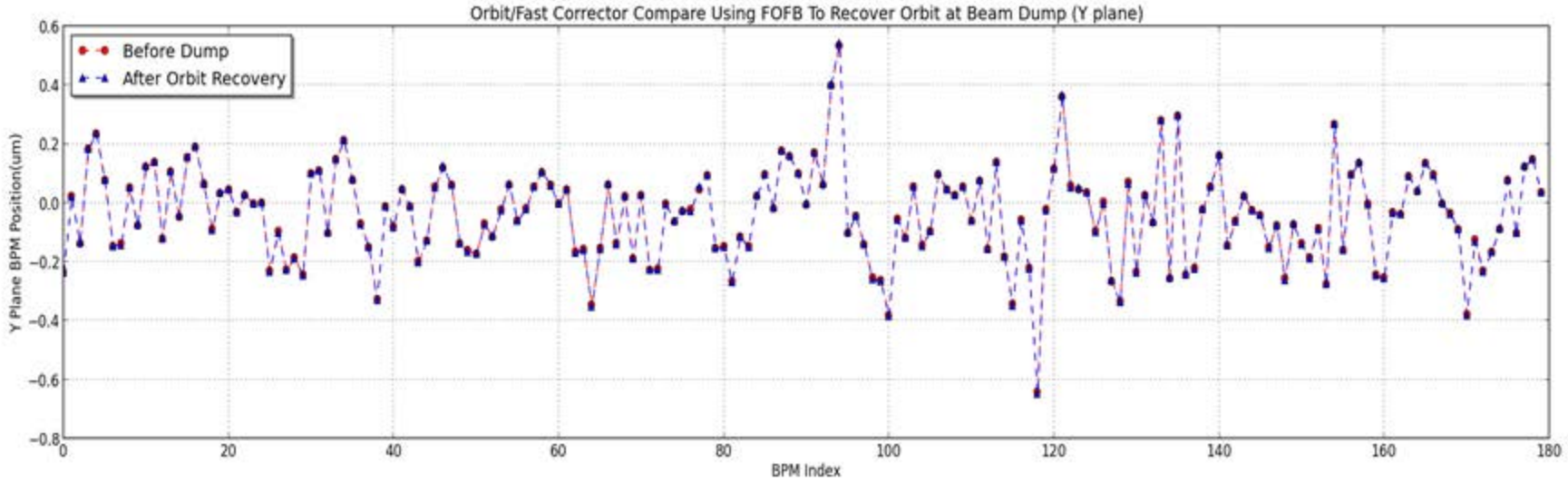
Procedure: for beam dumps not caused by power supply system, after initial refill, turn on FOFB without orbit correction and local bump adjustment. The FOFB will bring the orbit to the previous saved target reference orbit. This procedure recovers the orbit with less then 1um error and reduces the recovery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

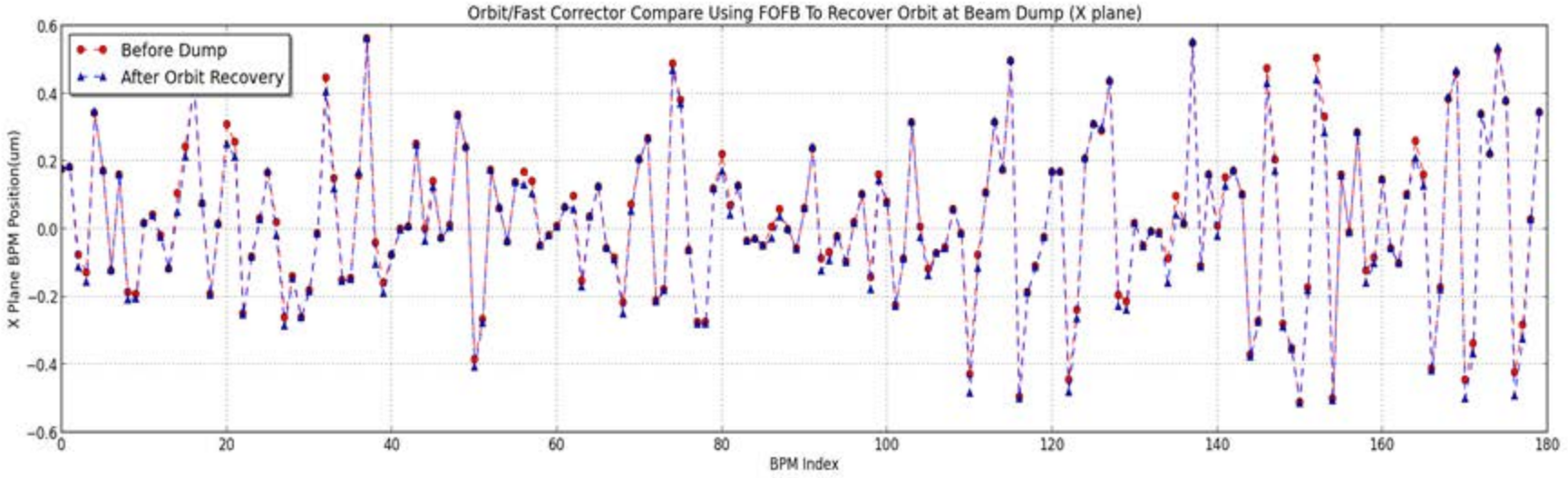
Result: FOFB will recover the orbit with less than 1um error.

FOFB application 3: orbit recover after beam dump



FOFB application 3: orbit recover after beam dump





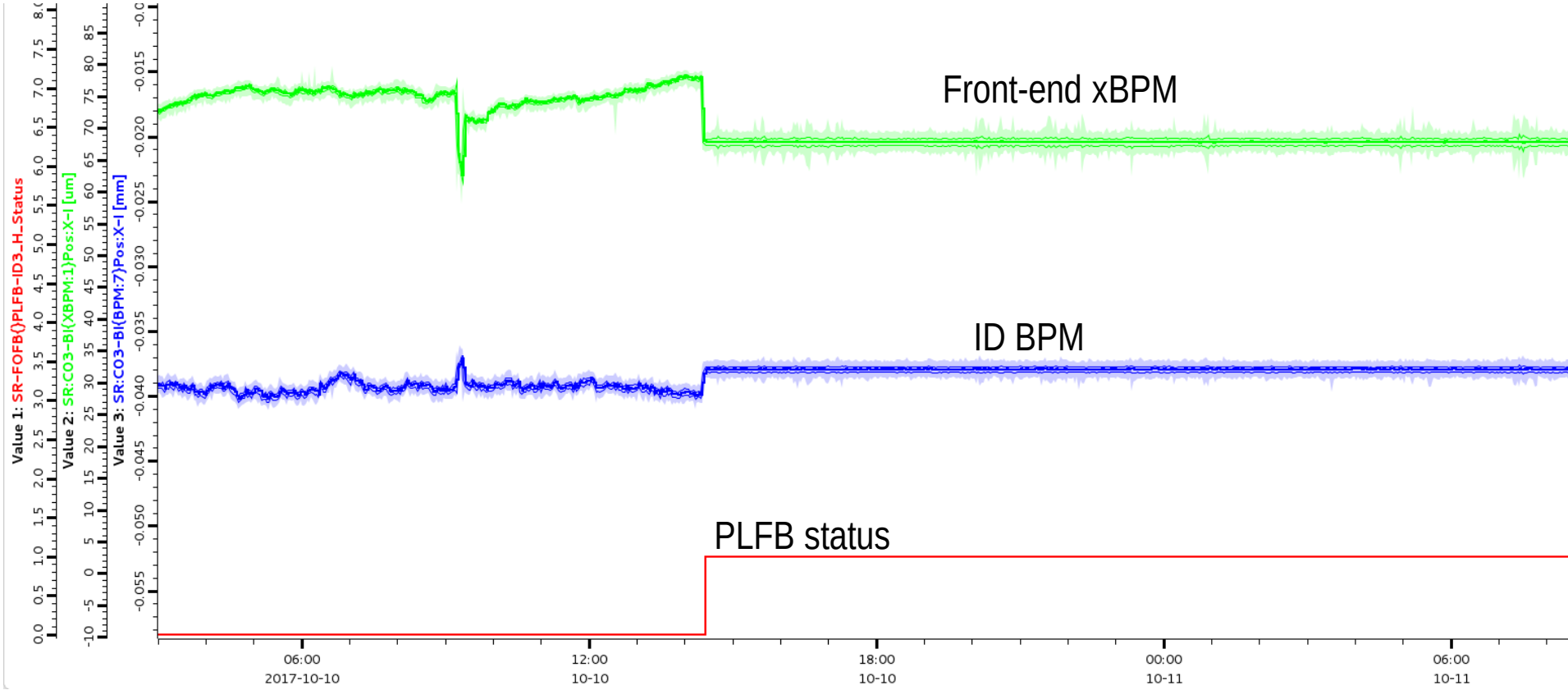
FOFB application 4: photon local feedback

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.

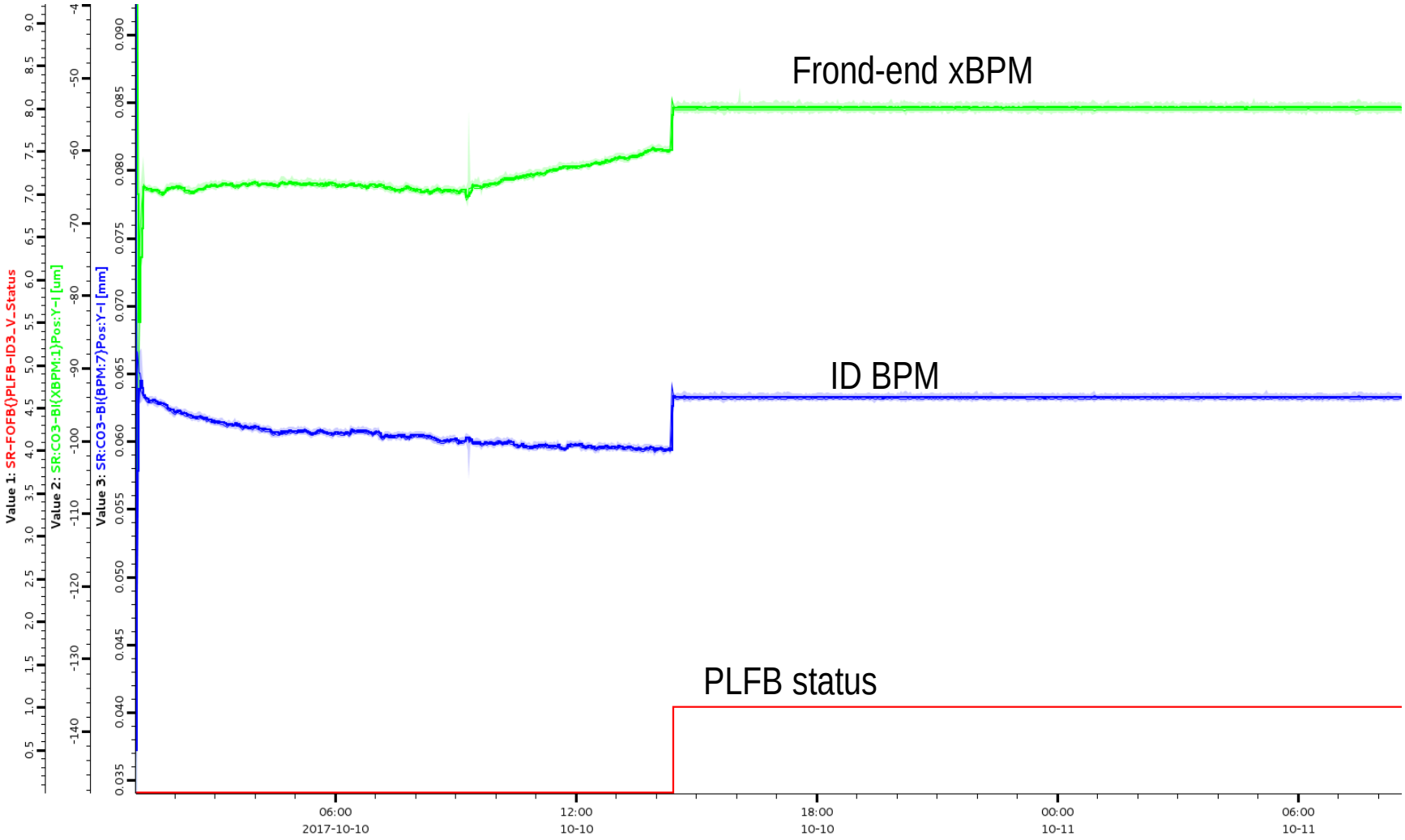
Result: we have released the photon local feedback system for the four beamlines which have front-end xBPM installed. We have also tried to use beamline xBPM as sensors, but didn't release it because the beamline xBPM reading dependent many factors of beamline settings.

FOFB application 4: photon local feedback



HXN photon stability with photon local feedback (H plane)

FOFB application 4: photon local feedback



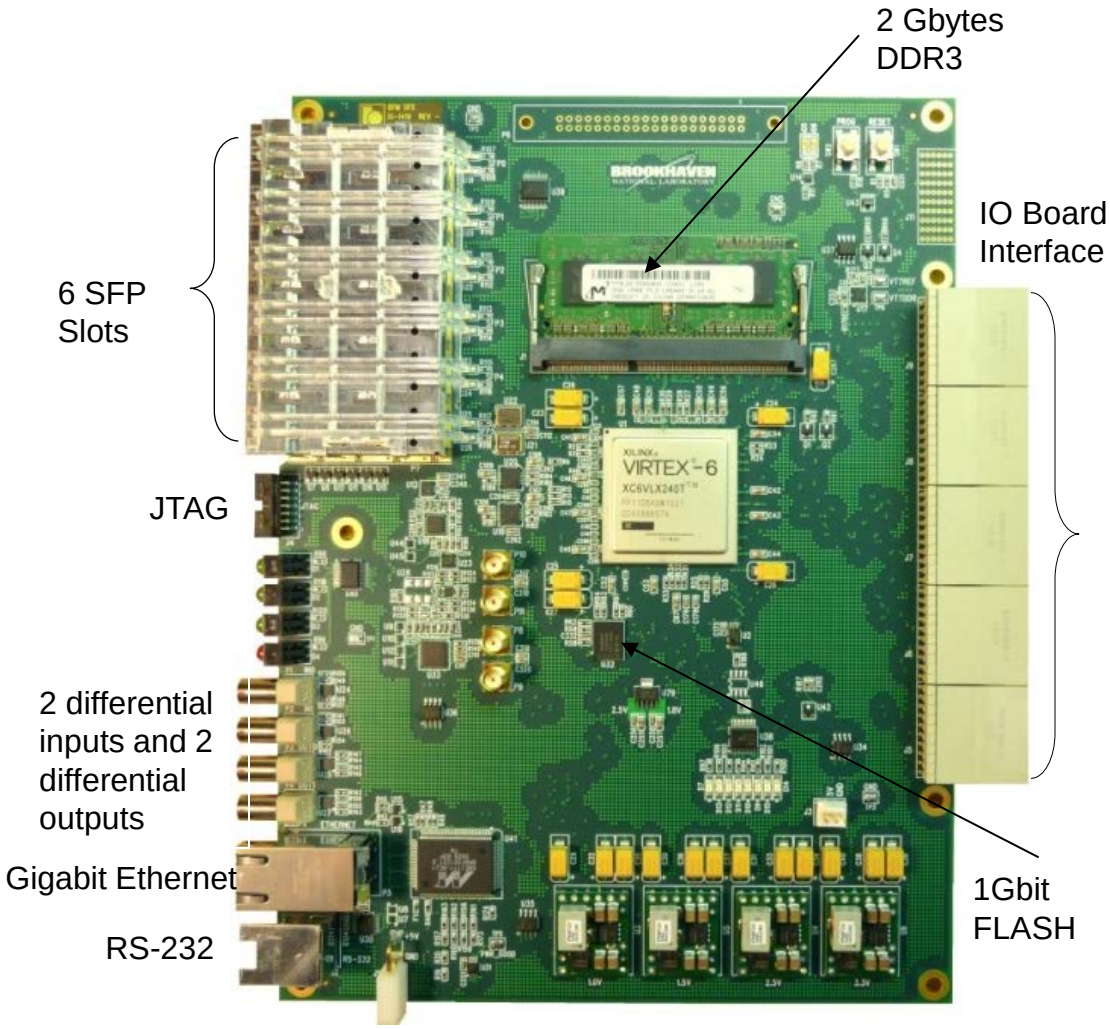
HXN photon stability with photon local feedback (V plane)

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:

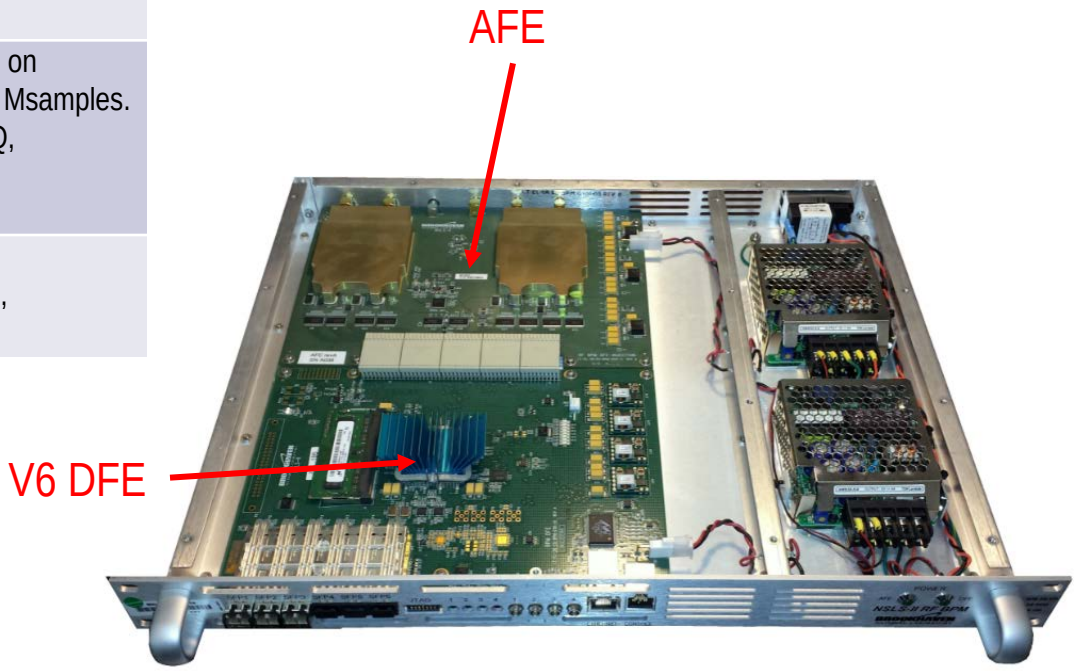
- Virtex-6 FPGA (LX240T)
- Embedded MicroBlaze soft core µP
  - Xilkernel OS and lwIP TCP/IP stack
- Gigabit Ethernet
- 2Gbyte DDR3 SO-DIMM
  - Memory throughput = 6.4 GBytes/sec
- Six 6.6Gbps SFP modules
  - Embedded Event Receiver
  - Fast Orbit Feedback
- Fixed Point DSP Engine
- 1Gbit FLASH memory



Derivative instruments from BPM/FOFB developments: 1-BPM

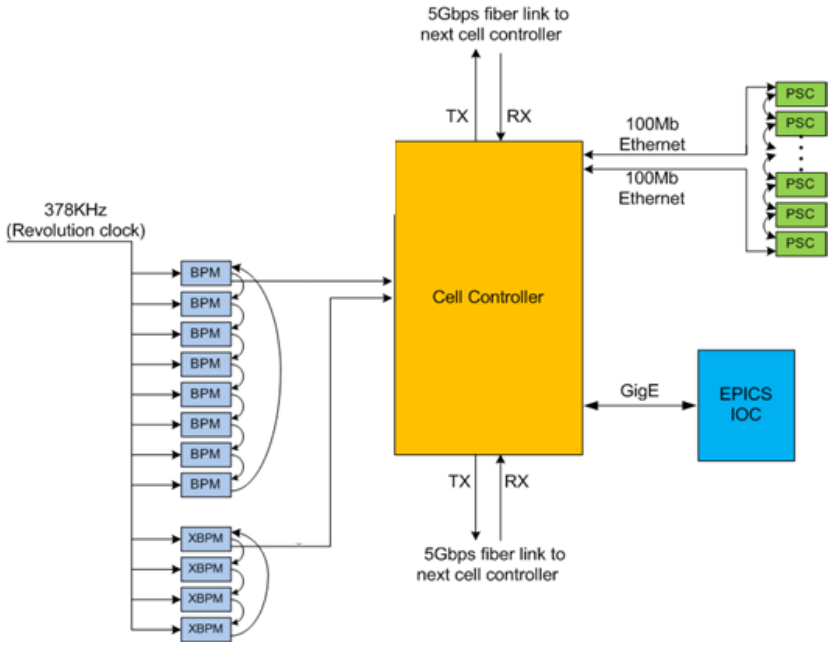
- Benefit from the common platform, we have developed 7 useful instrument at NSLS-II.

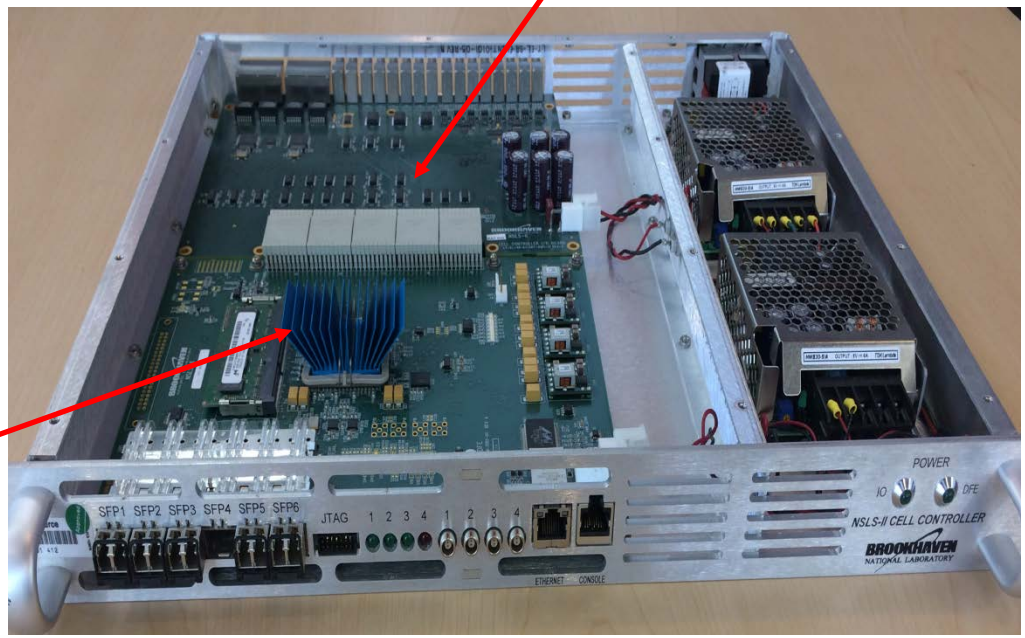
Data Type	Mode	Max Length
ADC Data	On-demand	256Mbytes or 32M samples per channel simultaneously
Turn-by-Turn (TbT), Frev=379 kHz	On-demand	256Mbytes or 5 M samples Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
Fast Acquisition (FA) , 10KHz	Streaming via SDI Link & on demand	Streaming - X,Y,SUM; For on demand: 256 Mbytes or 5 Msamples. Va,Vb,Vc,Vd, X,Y, SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
Slow Acquisition (SA), 10Hz	Streaming and On-demand	80hr circular buffer Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd



BPM

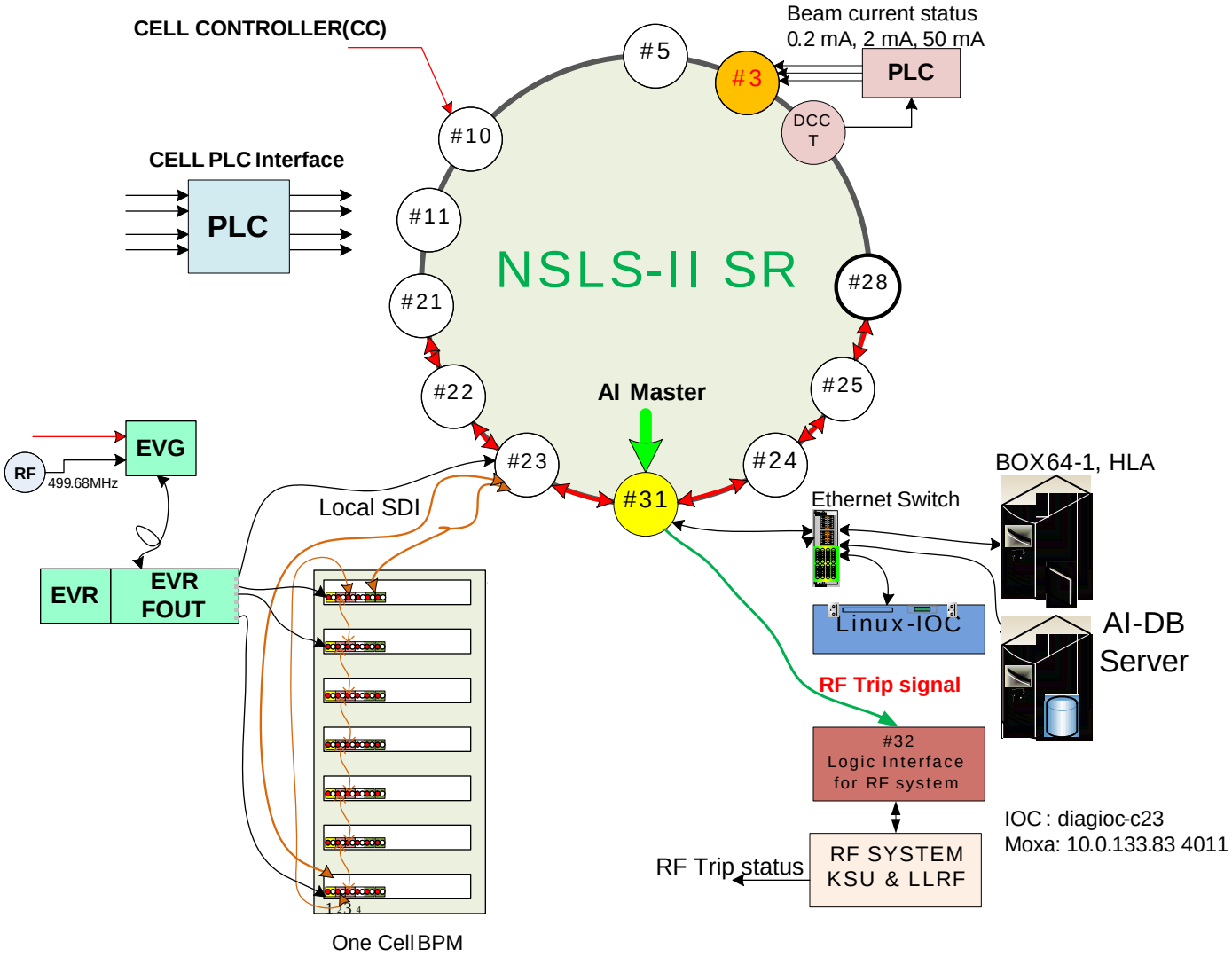
Derivative instruments from BPM/FOFB developments: 2- cell controller for FOFB





Cell Controller

Derivative instruments from BPM/FOFB developments: 3- active interlock master



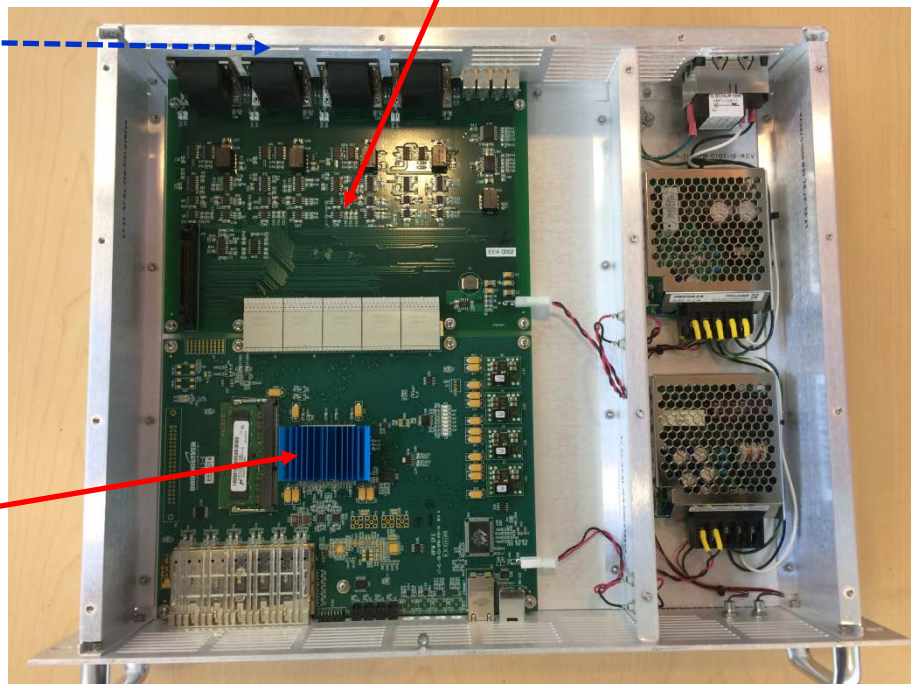
Derivative instruments from BPM/FOFB developments: 4- Encoder timestamp module

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



Encoder interface

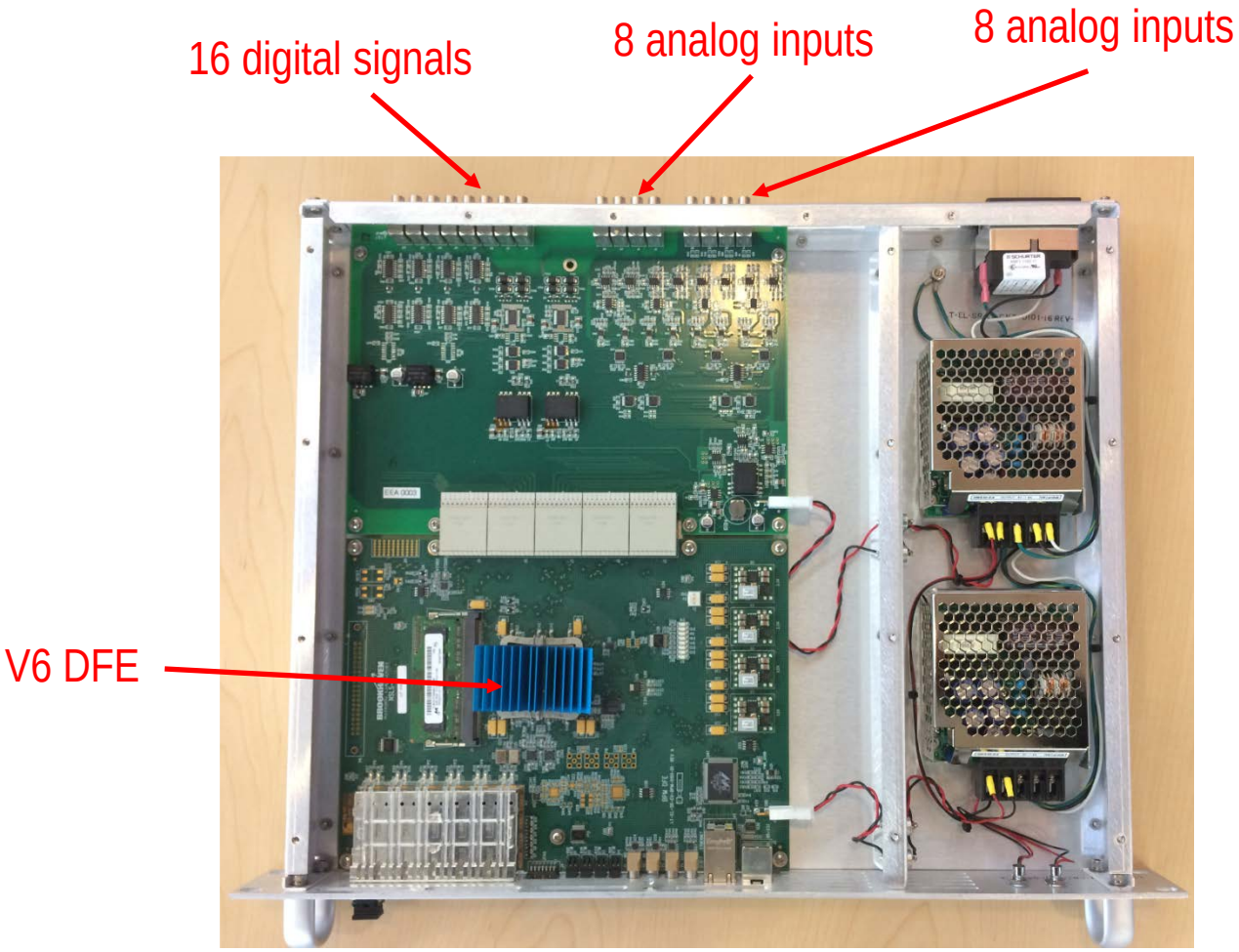
Encoder interface module



Beamline Encoder Timestamp Module

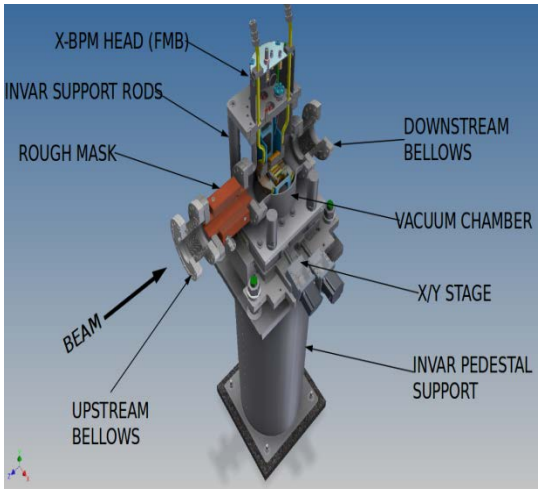
Derivative instruments from BPM/FOFB developments: 5 – Generic DAQ timestamp module

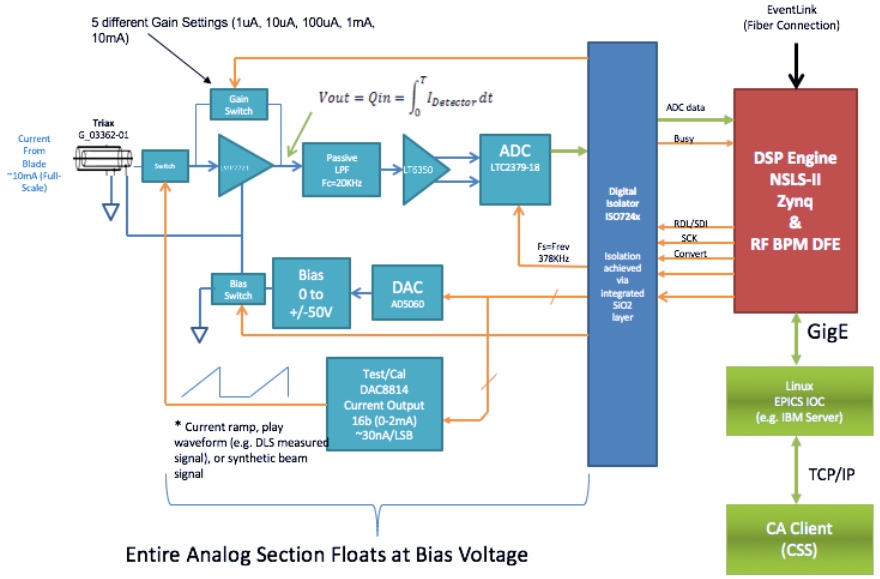
General DAQ Timestamp Module: To provide NSLS-II timing system timestamp for 8 analog inputs, 8 analog outputs, 16 digital inputs/outputs signals.

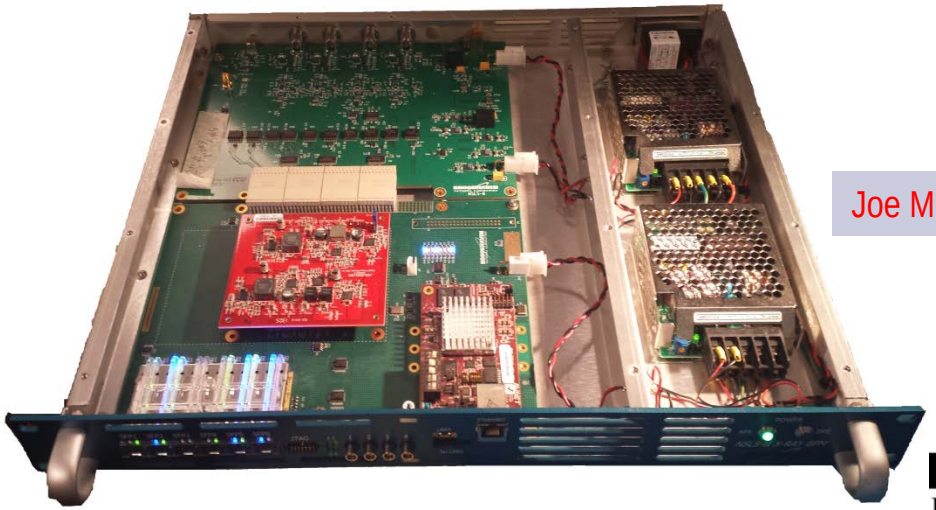


Generic DAQ Timestamp Module

Derivative instruments from BPM/FOFB developments: 6 NSLS-II xBPM







Joe Mead and Kurt Vetter

Derivative instruments from BPM/FOFB developments: 7 Diamond xBPM

DIAMOND BPM OPERATION

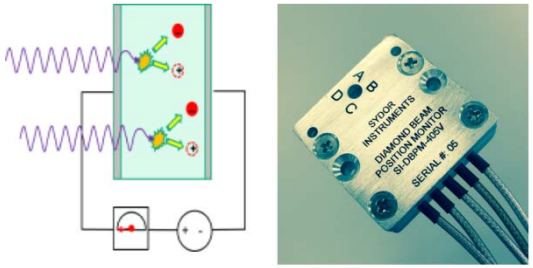
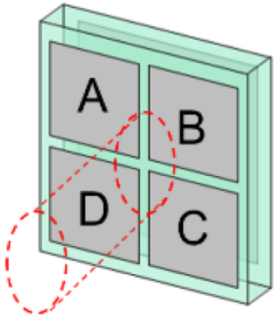


Fig. 1 Electron-hole pair production in CVD diamond (Left). Sydor DBPM (Right).



$$Y = G_y \frac{(A+D)-(B+C)}{A+B+C+D}$$

$$X = G_x \frac{(A+B)-(C+D)}{A+B+C+D}$$

Fig. 2 Quadrant Diamond BPM (Left). The charge collected by each quadrant is utilized to calculate the x-ray beam position via a difference over sum algorithm (Right)

SYDOR INSTRUMENTS

A SYDOR TECHNOLOGIES COMPANY

X-ray Beam Stabilization System Utilizing Diamond Beam Position Monitors

Andrei Fluerasu[a], Lutz Wiegart[a], Jaime Farrington[b]

[a]Brookhaven National Laboratory, Upton, NY 11973, [b]Sydor Instruments LLC, Rochester, NY 14624

Jaime Farrington

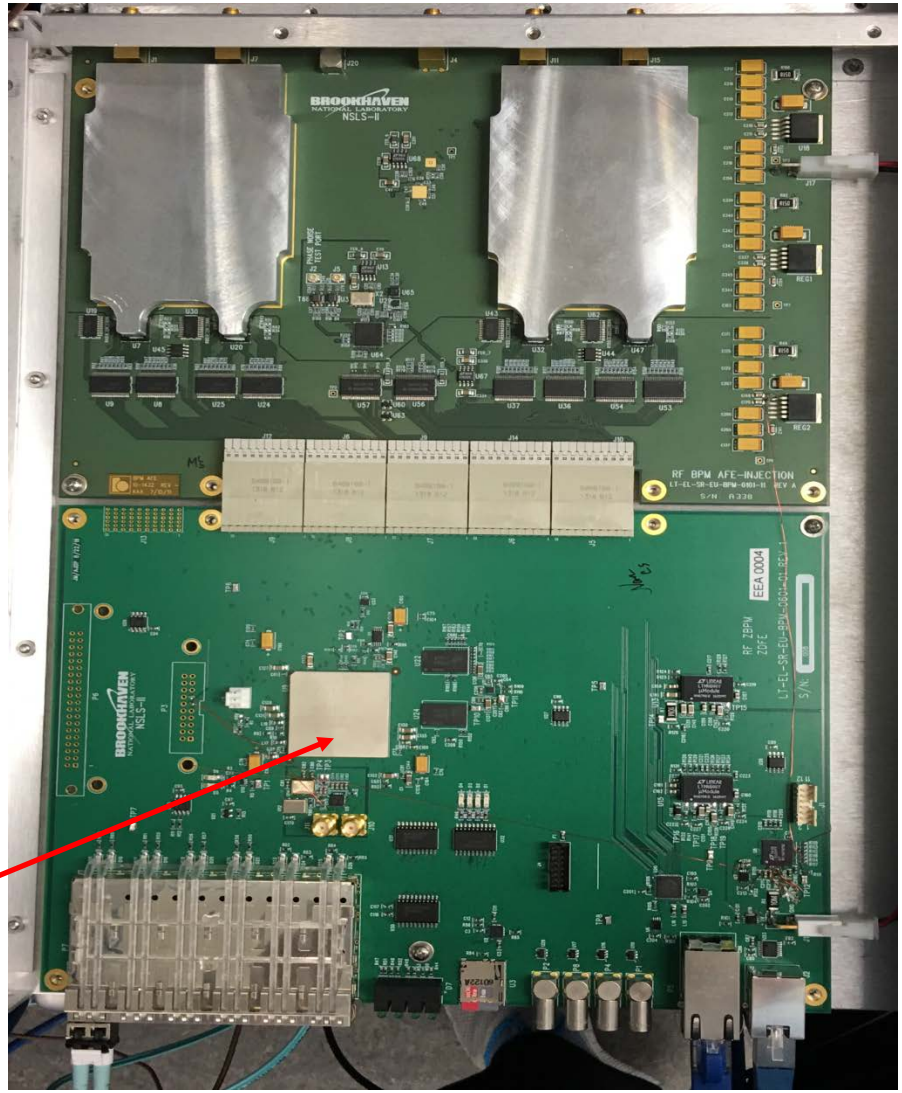


Diamond xBPM from Syndor

Ongoing update of 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.



FOFB future plan: electron beam orbit stability

- Based on the existing hardware:
  - we will investigate new algorithm to improve the FOFB bandwidth and the overall performance.
  - We have not fully use the eignen-space compensations. Detailed study will find the way to optimize the feedback loop for each eigenmode and thus improve the FOFB performance.

- 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. 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.

FOFB future plan: photon beam orbit stability

The photon beam stability is the ultimate goal.

- Continue to check the photon stability requirement from each beamline. Find a way (using FOFB, or build some kind of local feedback system) to meet the stability requirements. For example, find applications of photon local feedback in other beamlines.

- Improve the bandwidth of photon local feedback system using hardware link between the sensor (xBPM) and the actuators (ID corrector coils).

- Collaborate with beamlines to improve the monitoring of photon stability.

Summary

- NSLS-II FOFB system meets the design requirements with 240 BPMs and 90 fast correctors.
- The system can be used for many orbit controls during user operations.
- Many 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.
- Looking forward to finding opportunity to feather improve the performance to provide all the beamlines the best orbit stability.