High Precision Beam Position Monitors

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High Brightness Synchrotron Light Source Workshop

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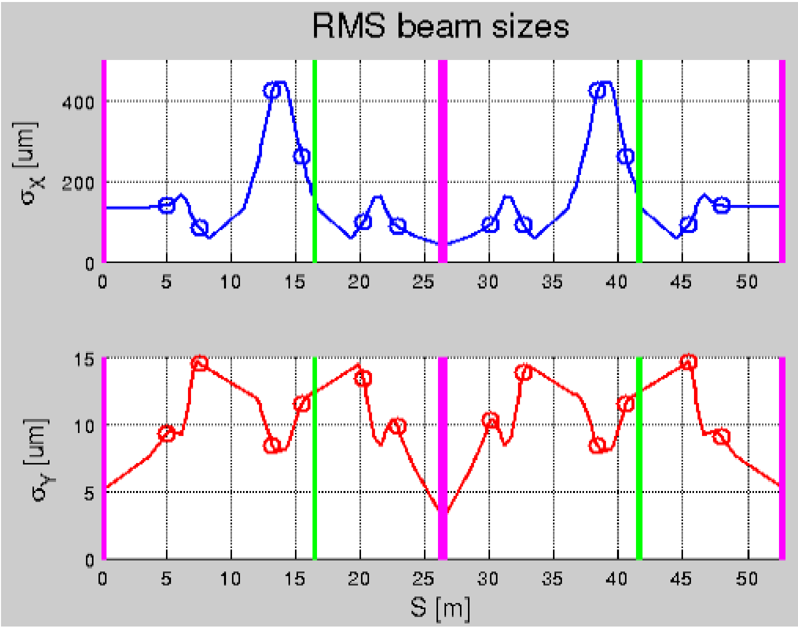
Outline

- Button BPM design
  - Sensitivity
  - Mechanical support
- BPM in-house developed electronics
- BPM performance
  - Resolution
  - RF attenuator dependency and calibration
  - Current and fill pattern dependency
  - Timing alignment for pure turn by turn data
- Beam measurements
  - TbT data applications
  - Orbit stability, short term and long term
  - Compare with xBPM
- Derivative products and future plans
- Summary

NSLS-II storage ring main parameters



Beam sizes in one super period calculated using
ε_x = 0.9 nm.rad, ε_y = 8 pm.rad; $\Delta E/E$ = 0.09%

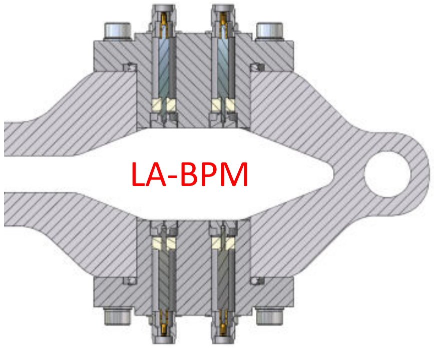
Source point	Long ID	Short ID	3PW	BMB
σ_x [um]	135.0	40.3	153.0	133.1
σ_y [um]	5.2	3.0	12.4	12.5

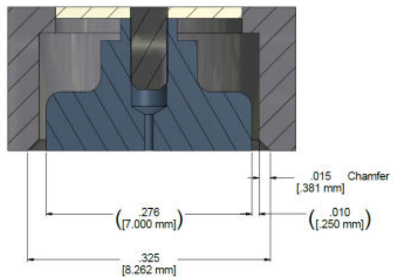
Orbit stability requirements:
< 10% of beam size and divergence

Energy	3.0 GeV
Circumference	792 m
Number of Periods	30 DBA
Length Long Straights	6.6 & 9.3m
Emittance (h,v)	<1nm, 0.008nm
Momentum Compaction	0.00037
Dipole Bend Radius	25m
Energy Loss per Turn	<2MeV
Energy Spread	0.094%
RF Frequency	499.68 MHz
Harmonic Number	1320
RF Bucket Height	>2.5%
RMS Bunch Length	15ps-30ps
Average Current	500mA
Current per Bunch	0.5mA
Charge per Bunch	1.3nC
Touschek Lifetime	>3hrs
Top-Off Injection	1/min

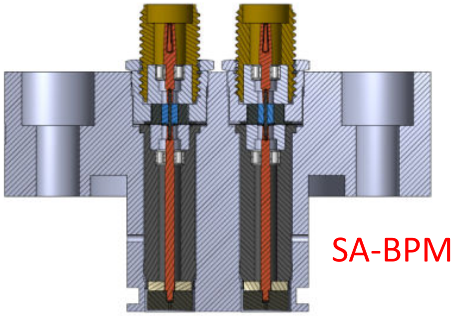
Button BPM pickups

- Types of NSLS2 button BPM:
  - **SR Large Aperture BPM**
  - **SR Large Aperture BPM, 64-deg rotated**
  - **SR Large Aperture BPM, 45-deg rotated**
  - **SR Small Aperture BPM - DW, 60-deg rotated**
  - **SR Small Aperture BPM - EPU, 60-deg rotated**
  - **Special BPMs in injection straight**
  - 5 other types button BPM used in LINAC/LtB/BtS/Booster
- Button BPM sensitivity nonlinearity – 1D fitting
- Button BPM sensitivity nonlinearity – 2D fitting
- BPM SUM signal nonlinearity calculated for machine studies

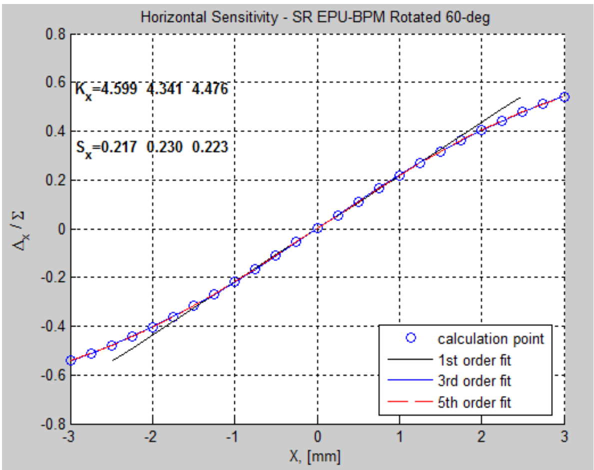


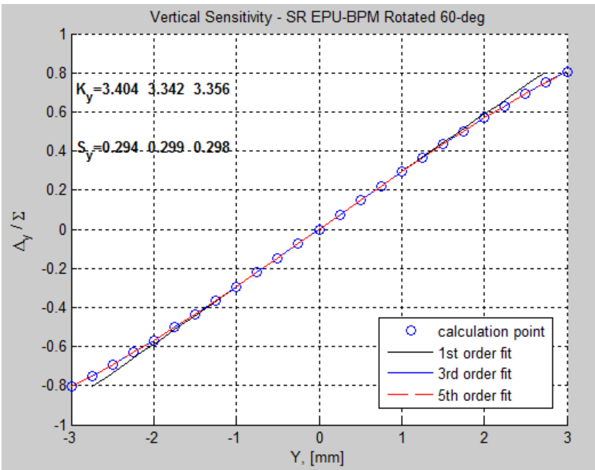


Button diameter – 7mm
Button center distance – 16mm
Gap between button and body – 250µm
Button thickness – 2mm

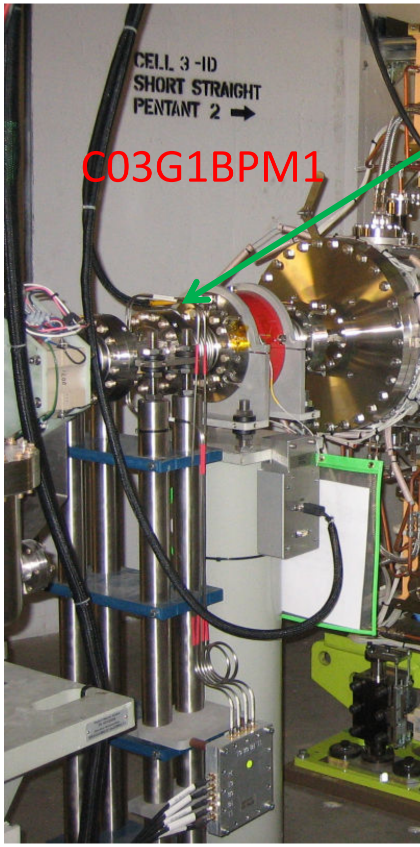


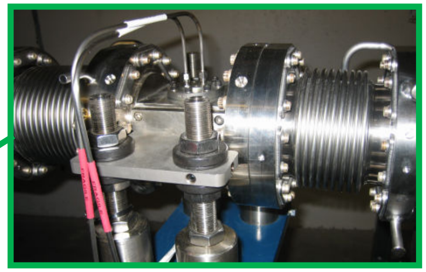
Button diameter = 4.7mm
Button gap = 250µm
Button thickness = 2mm



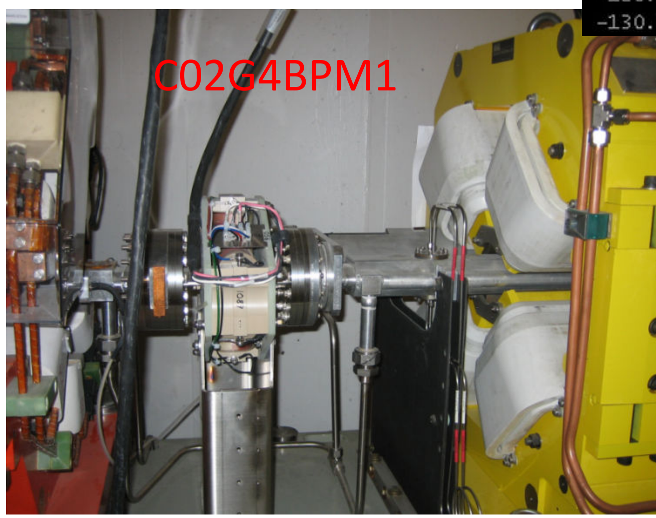


BPM mechanical support and RF shielding

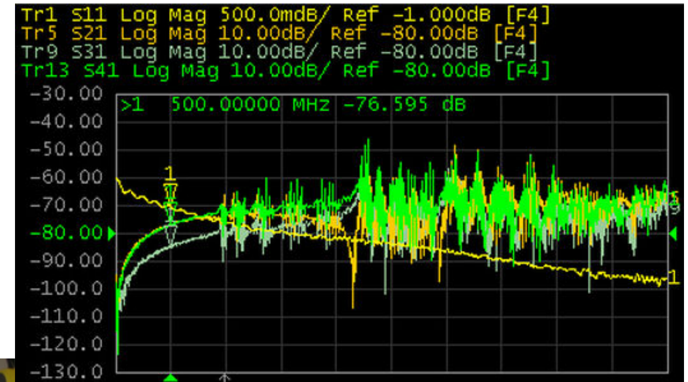




High stability BPM support
(Invar, ground mounting,
isolation bellows)

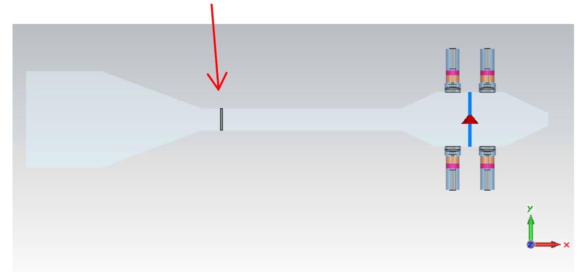


Normal BPM support
(Carbon fiber plate, girder mount)

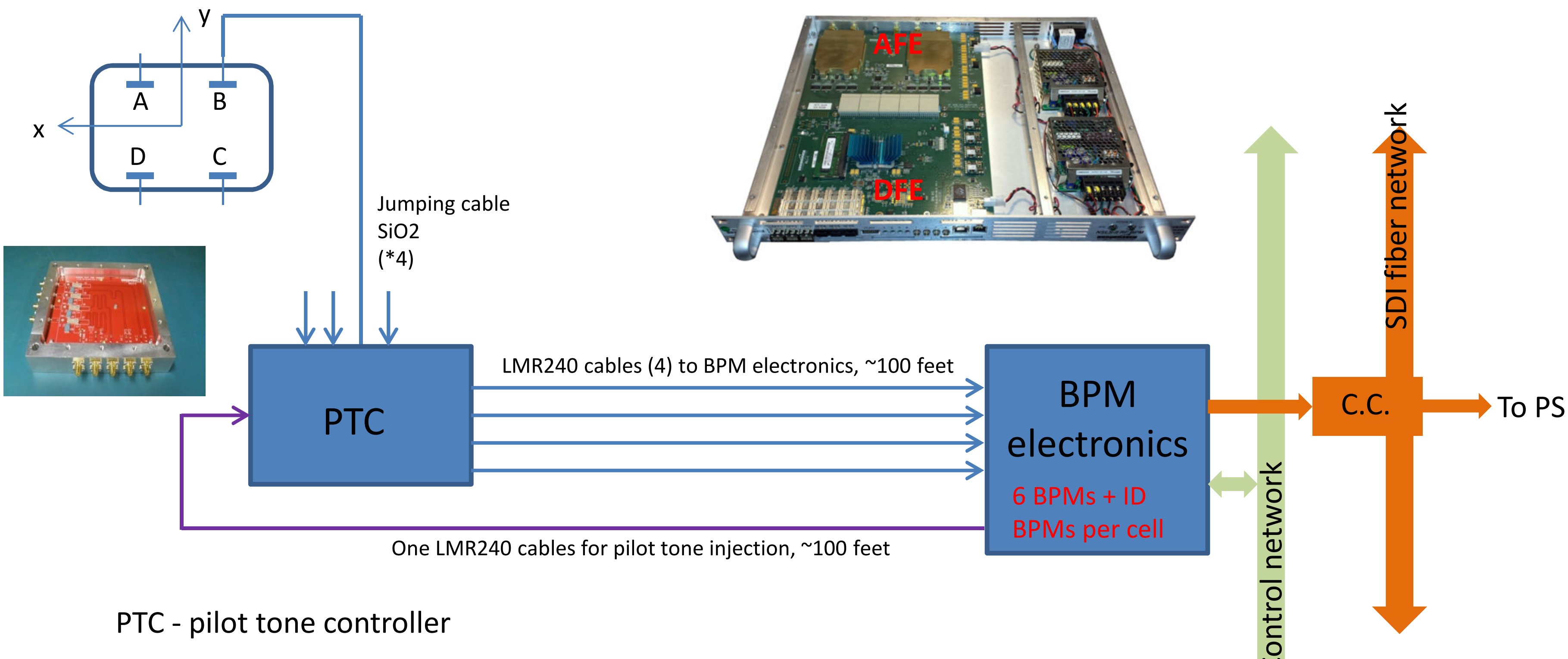


RF shielding to move the cutoff frequency ~900MHz

BeCu shield, 114mm from beam



BPM data acquisition and processing

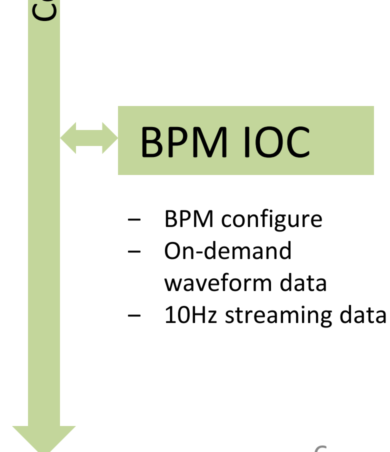


PTC - pilot tone controller

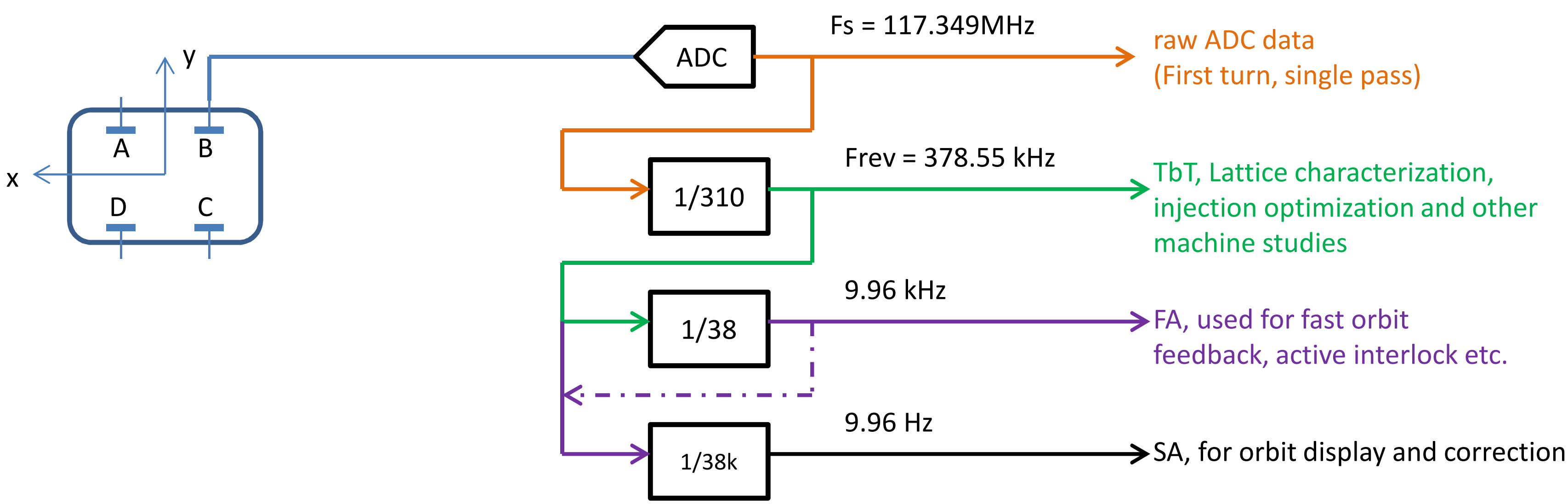
BPM electronics includes AFE + DFE
AFE: BPF + Amplifier + Var. Att + ADC
DFE: Xilinx Virtex 6, integrated uBlaze, SRAM

Local SDI and global SDI network share the 10kHz data around the ring
30 cell controllers for FOFB calculation, corrector settings send to PS
Same SDI 10kHz data is used for Active Interlock

BPM IOC for 10Hz streaming data and on-demand ADC/TbT/FA waveform data



Digital BPM data type (NSLS-II storage ring)

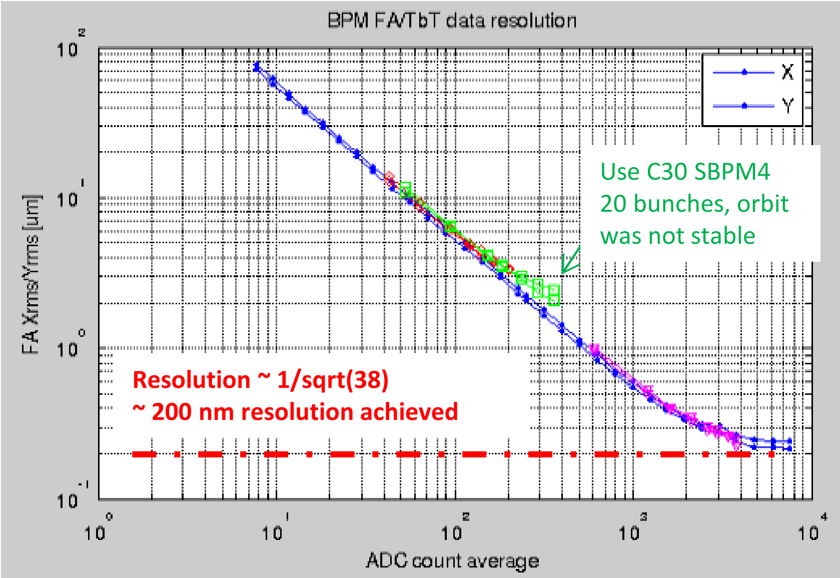


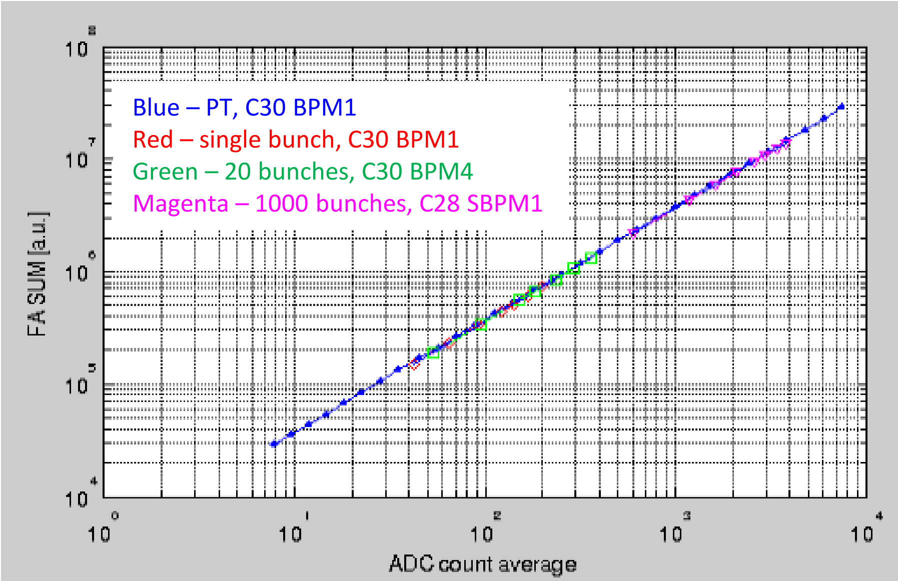
Frf = 499.68 MHz, h = 1320, Frev = 378.55kHz

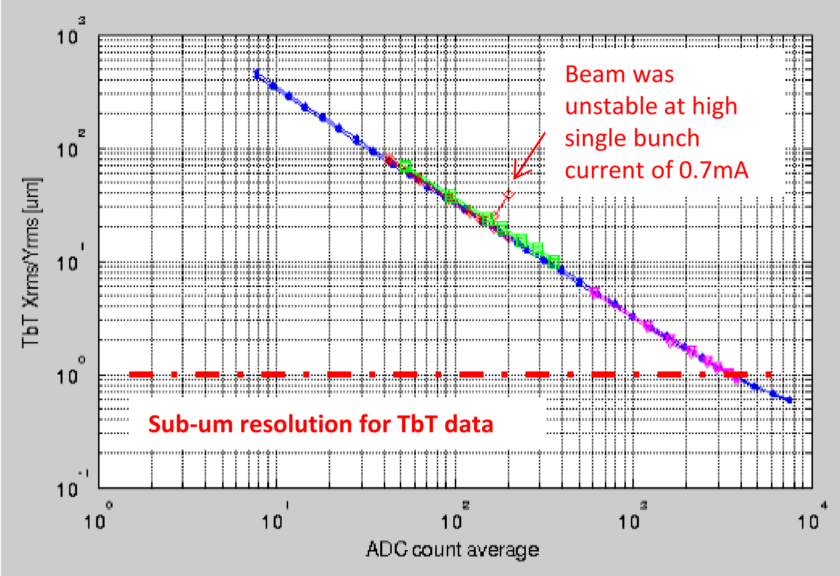
F_adc = 117.349MHz = 310 * Frev

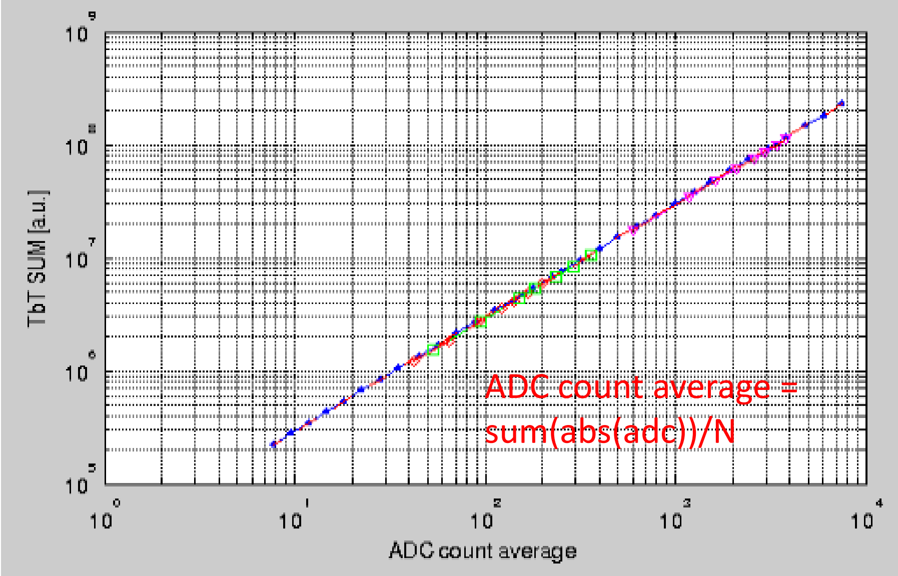
F_if = Frf - 4* F_adc = 1320*Frev - 4*310*Frev = 80* Frev. The 499.68MHz beam signal is in the 9th Nyquist zone with sampling rate of 117.349MHz.

BPM Resolution vs. ADC counts (after BPF)



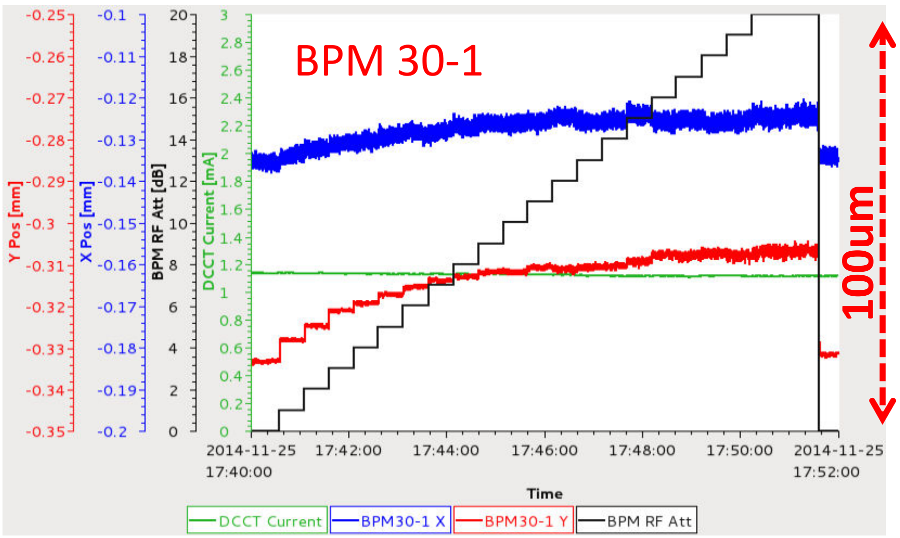


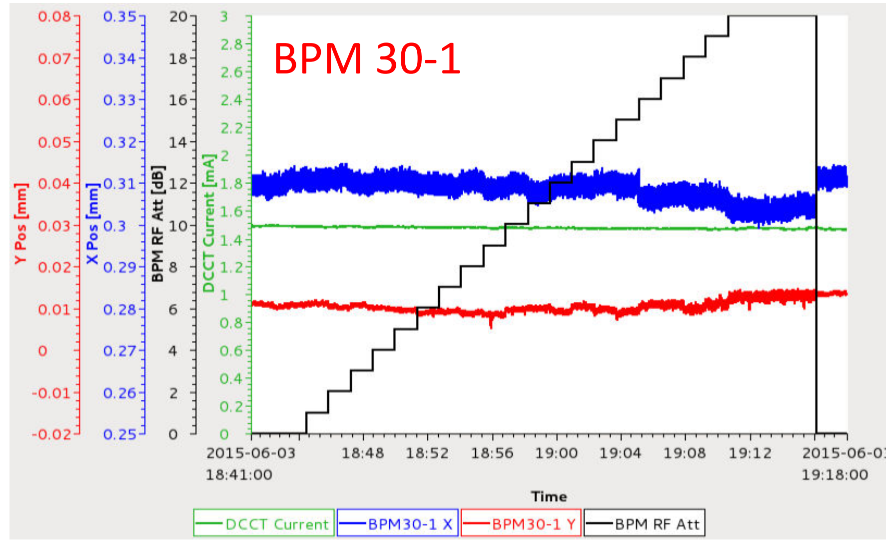


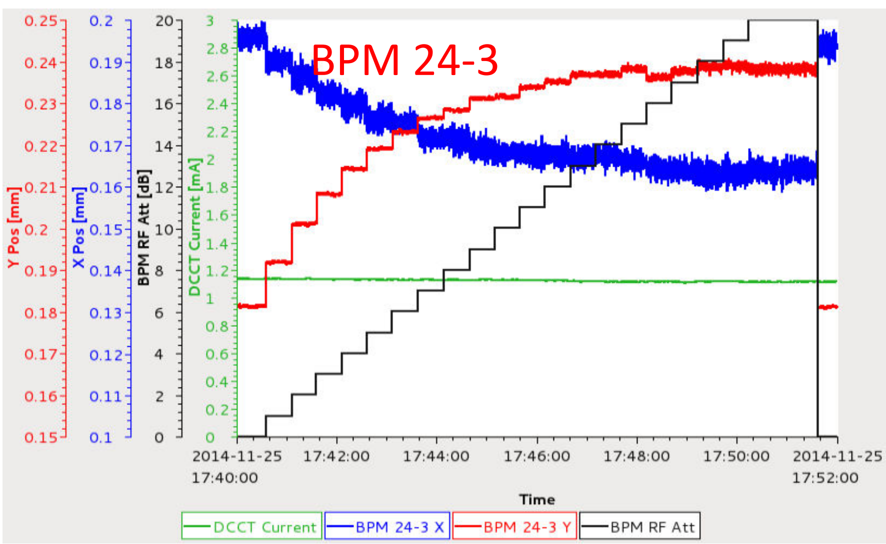


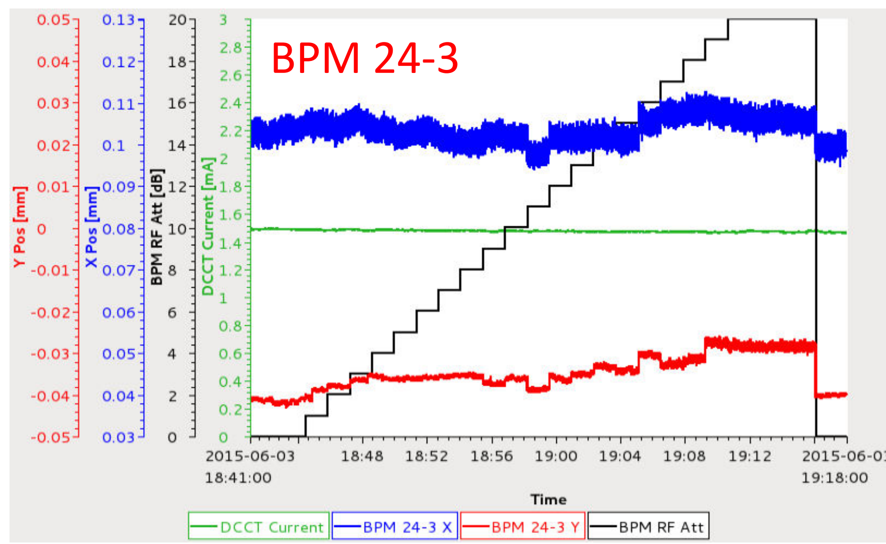
Old LUT

Beam based LUT



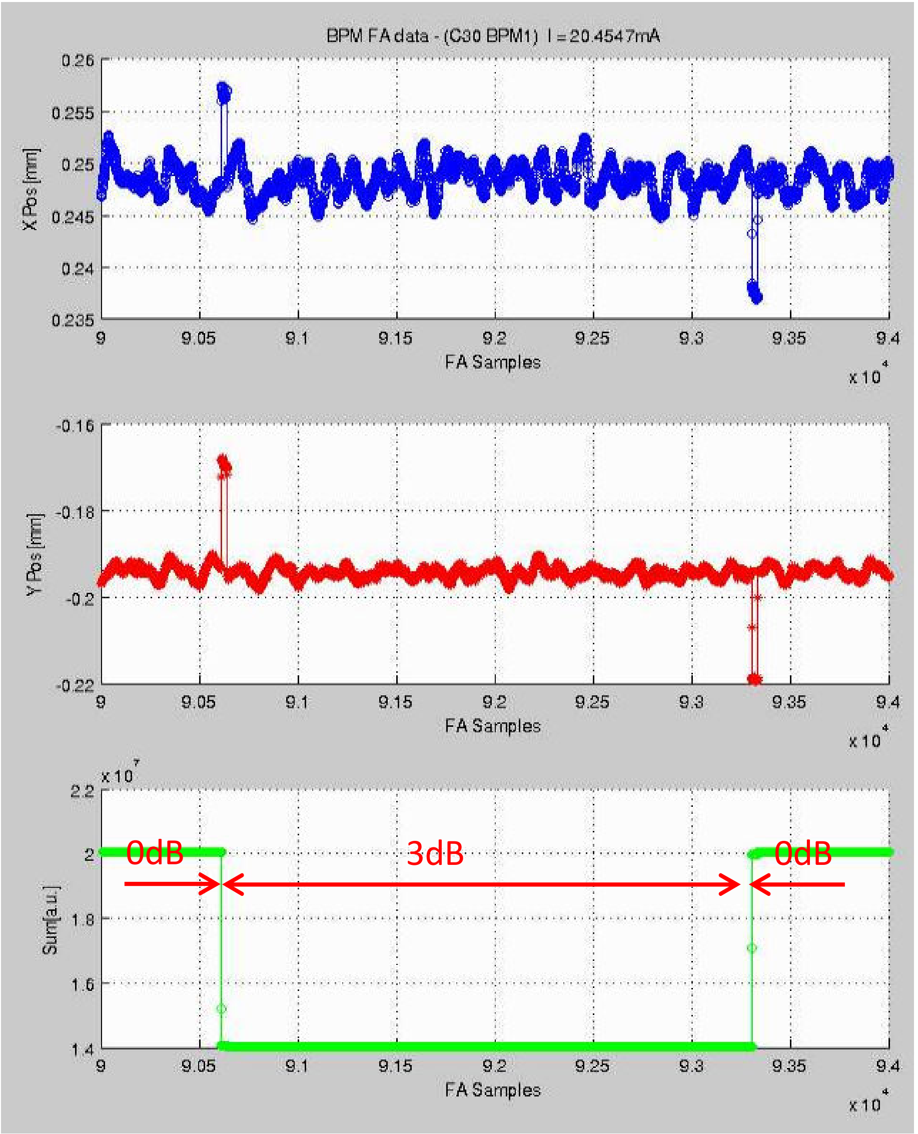






With the new static gain calibration LUT, most of the BPMs has RF attenuator dependency less than 10um, while attenuator varied from 0 to 20dB in 1 dB steps. Note that the LUT was generated in Nov 2014 and it's working fine with different current and fill pattern.

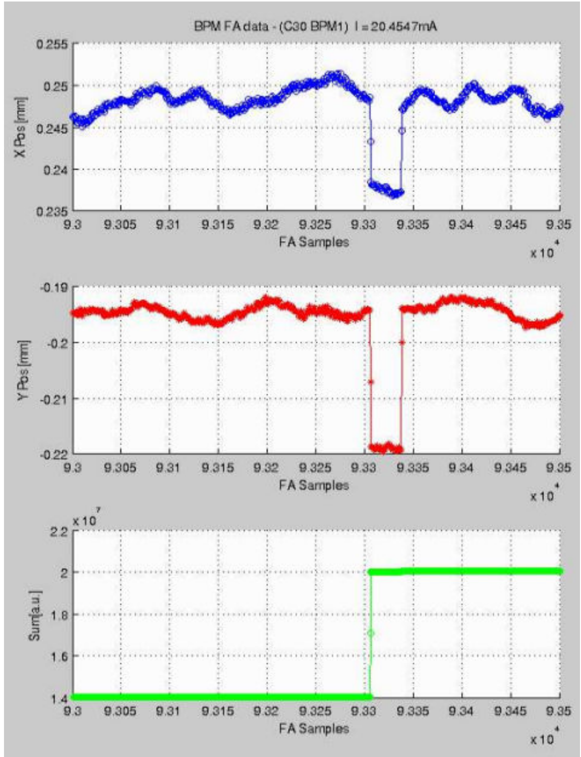
Glitches while change the BPM attenuator settings



Vary Att 0 to 3 dB during the period. It's clear that when Att was changed, there was a glitch on FA position readings. The glitch last for ~32 FA samples.

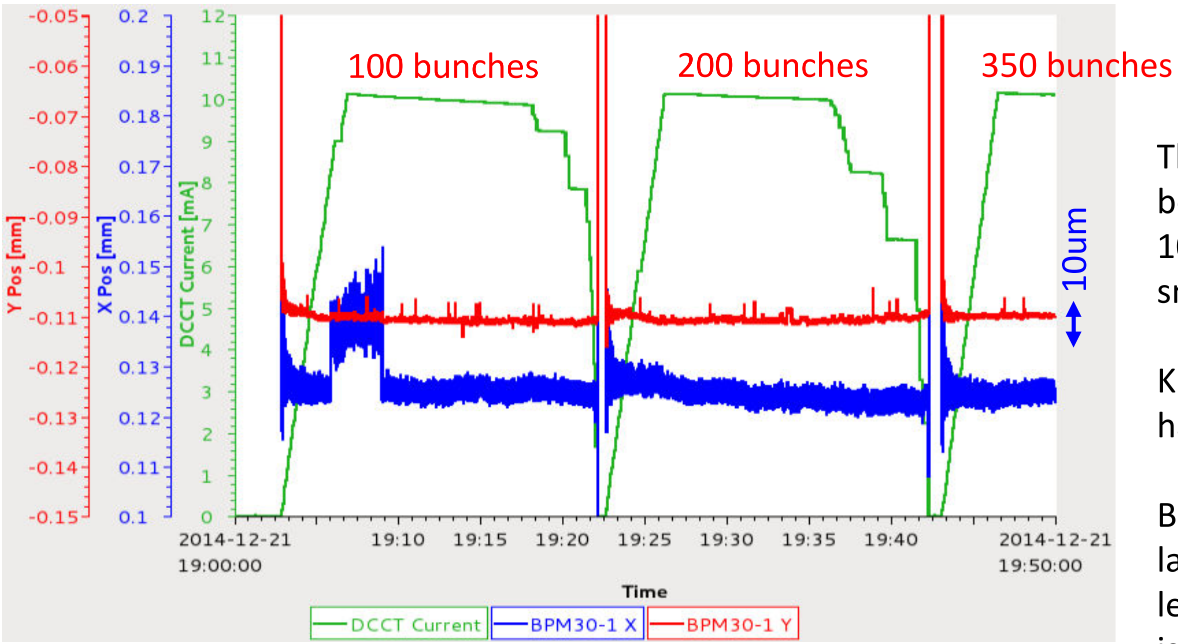
Note the position reading is not changing at 0dB and 3dB, which is because of good RF attenuator calibration.

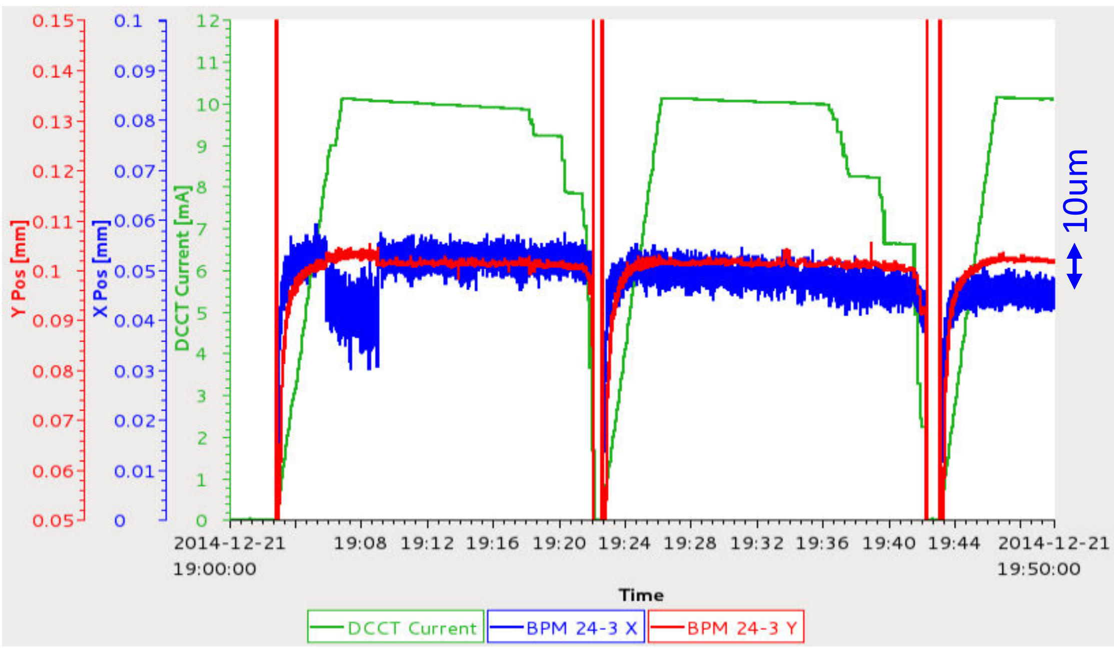
Don't change the BPM attenuator during user operation, especially when FOFB was turned ON



First observed on BPM TbT data, verified with FA data

Current and Fill Pattern Dependency





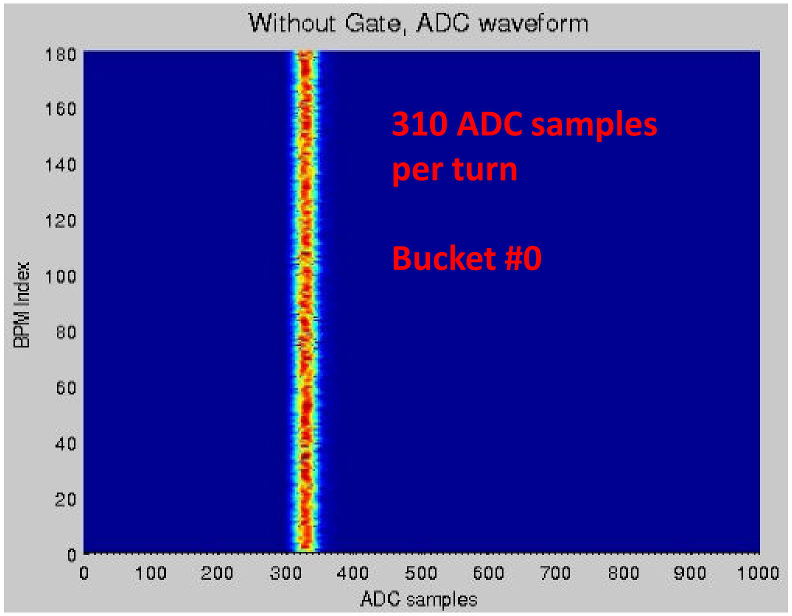
Three different fills to the same total beam current of 10mA distributed in 100, 200 and 350 bunches. Pretty small fill pattern dependency.

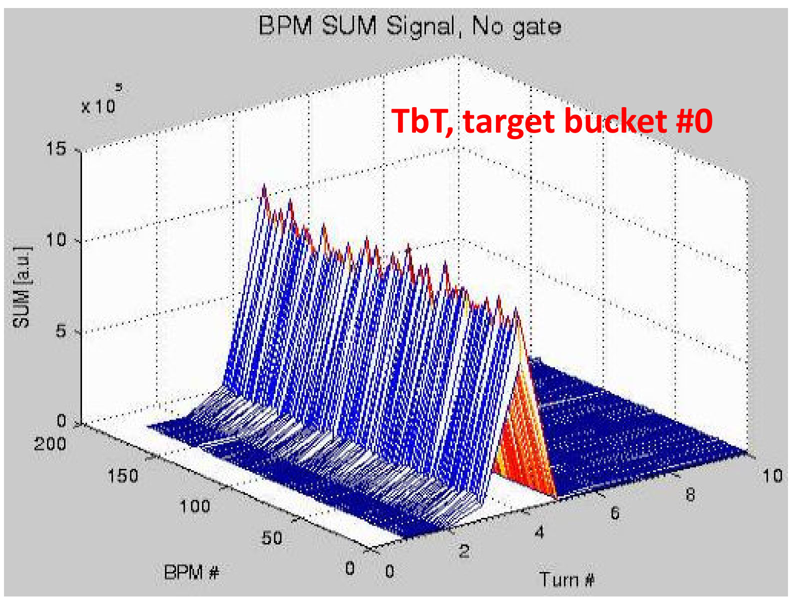
Knock out the bunches in steps to have different fill patterns.

BPMs near RF cavity section see larger current dependency, due to RF leaked signals at 500MHz. The issue is dominant for low current studies (I < 0.2mA). Not a problem when the beam current goes higher.

Recent study with different # of train fills shows small current and fill pattern dependency. < 5um at low current; very small (<1um p-p above 100mA)

Timing alignment

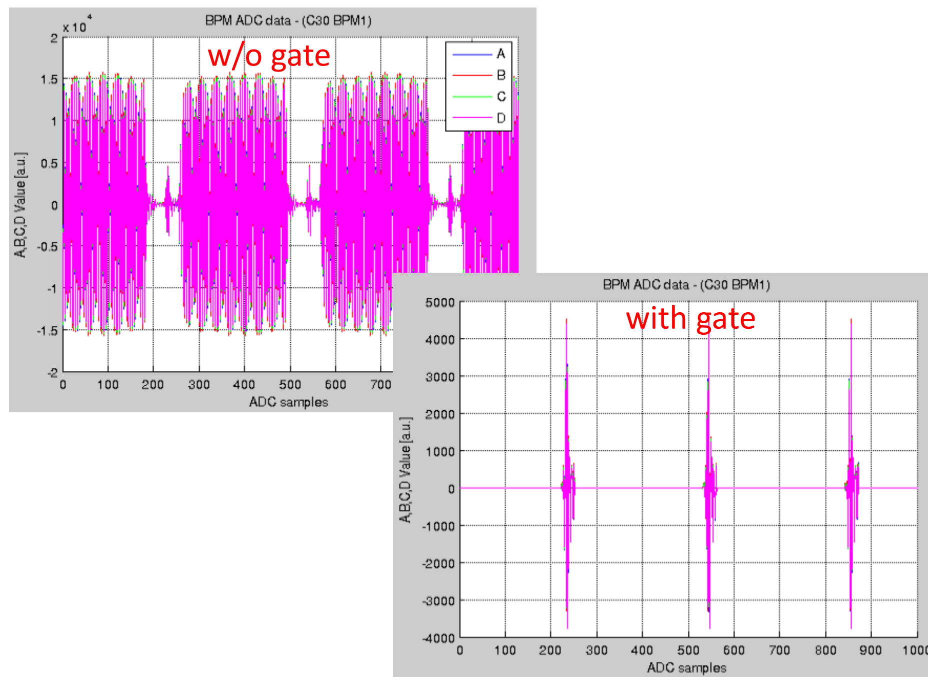




BPM timing has been well aligned since commissioning

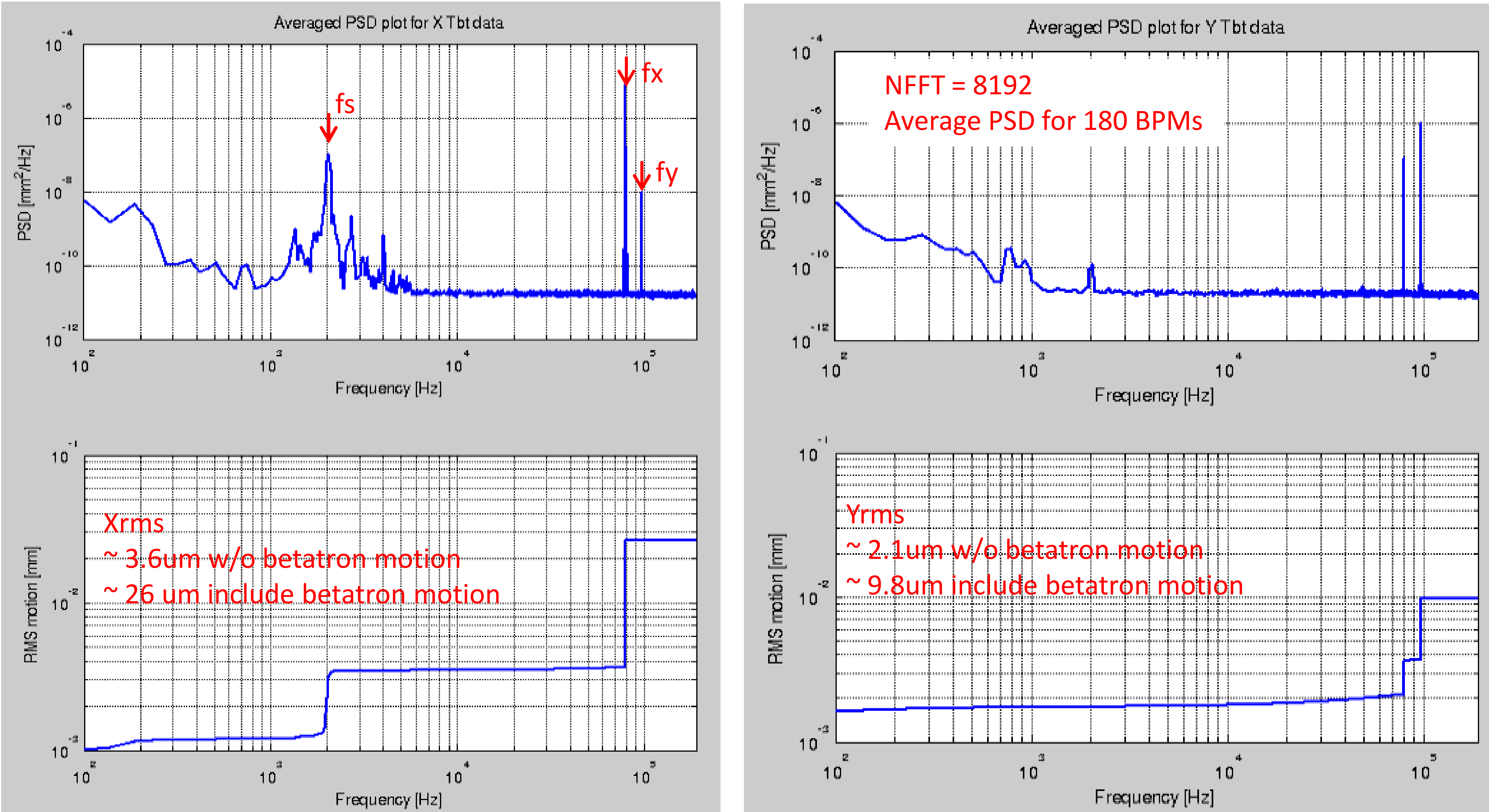
Pure turn by turn data with beam in the bucket #0 - #1000

Recent development of BPM Gated function allows us to measure the beam position from partial bunches. Precisely aligned gated BPM TbT/FA data can be used to “transparent” lattice measurement and collective effect studies.



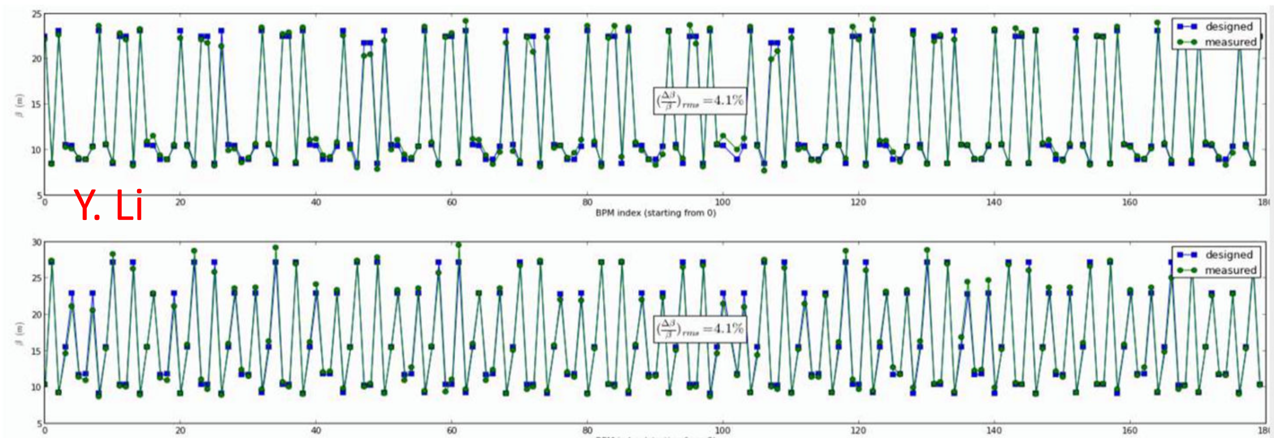
SR BPMs – TbT spectrum

(2015-Jul-11, 17:44:21, 23mA store beam, BxB feedback OFF)



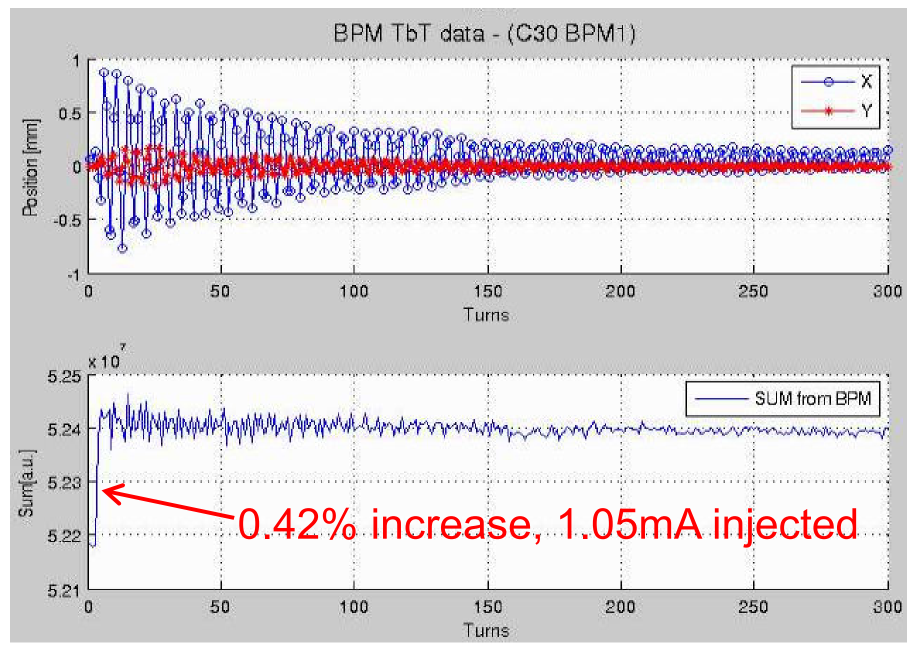
Wide range of applications from synchronized TbT data, including beam instability, lattice, tune measurement, injection optimization, collective effect studies and many more.

BPM TbT applications – more examples

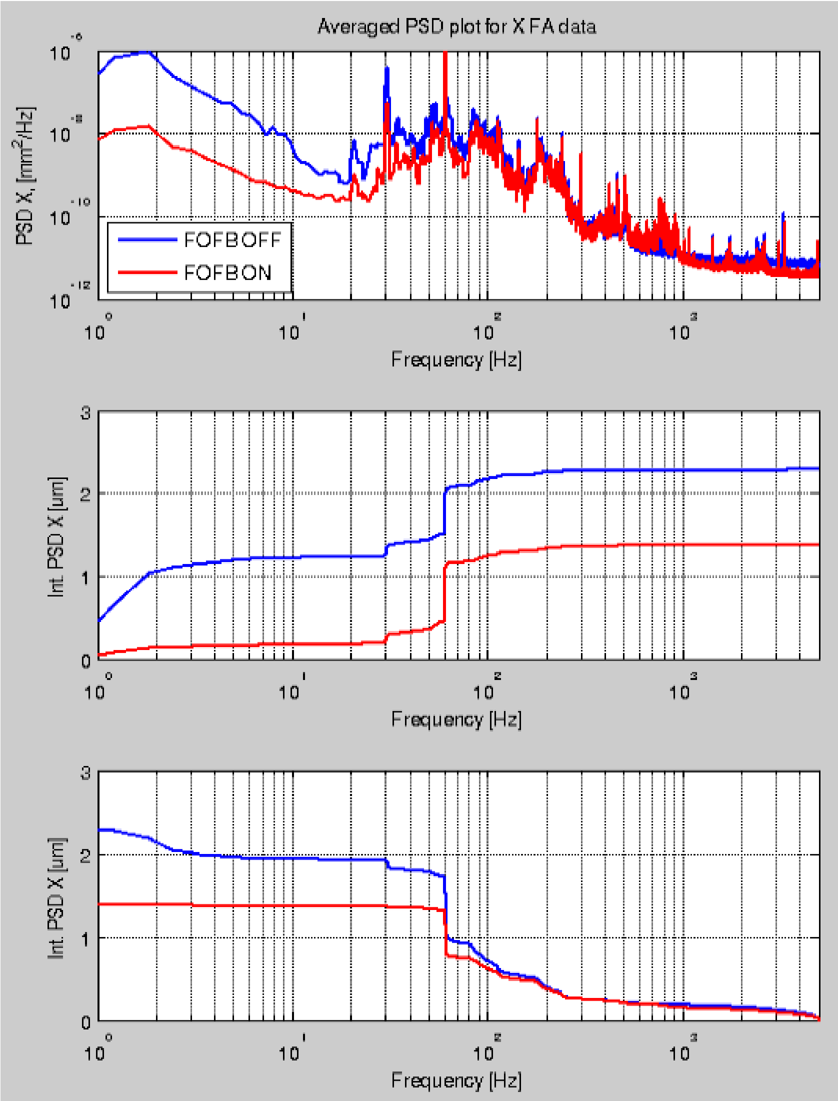


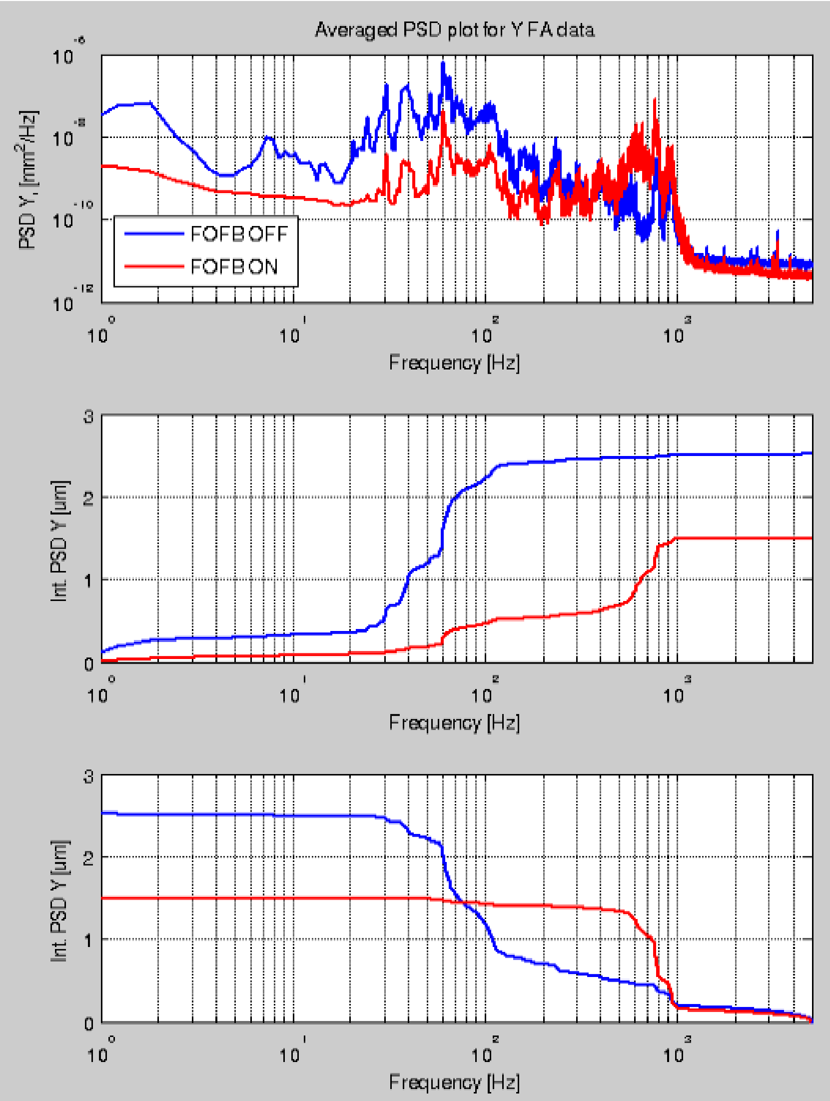
- Beta-beat
- Phase advance
- Coupling etc.

- Injection transient
- TbT SUM signal monitor (beam loss localization)



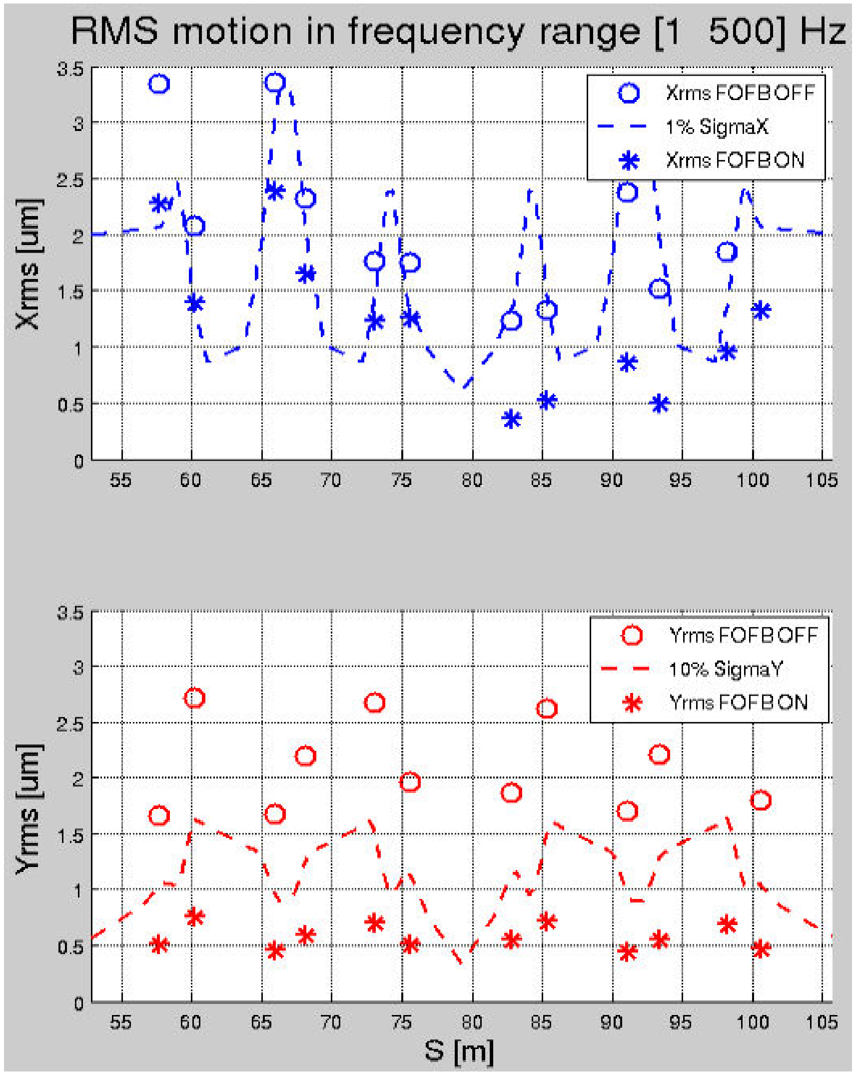
BPM FA Measurement – Short term stability (FOFB ON/OFF)

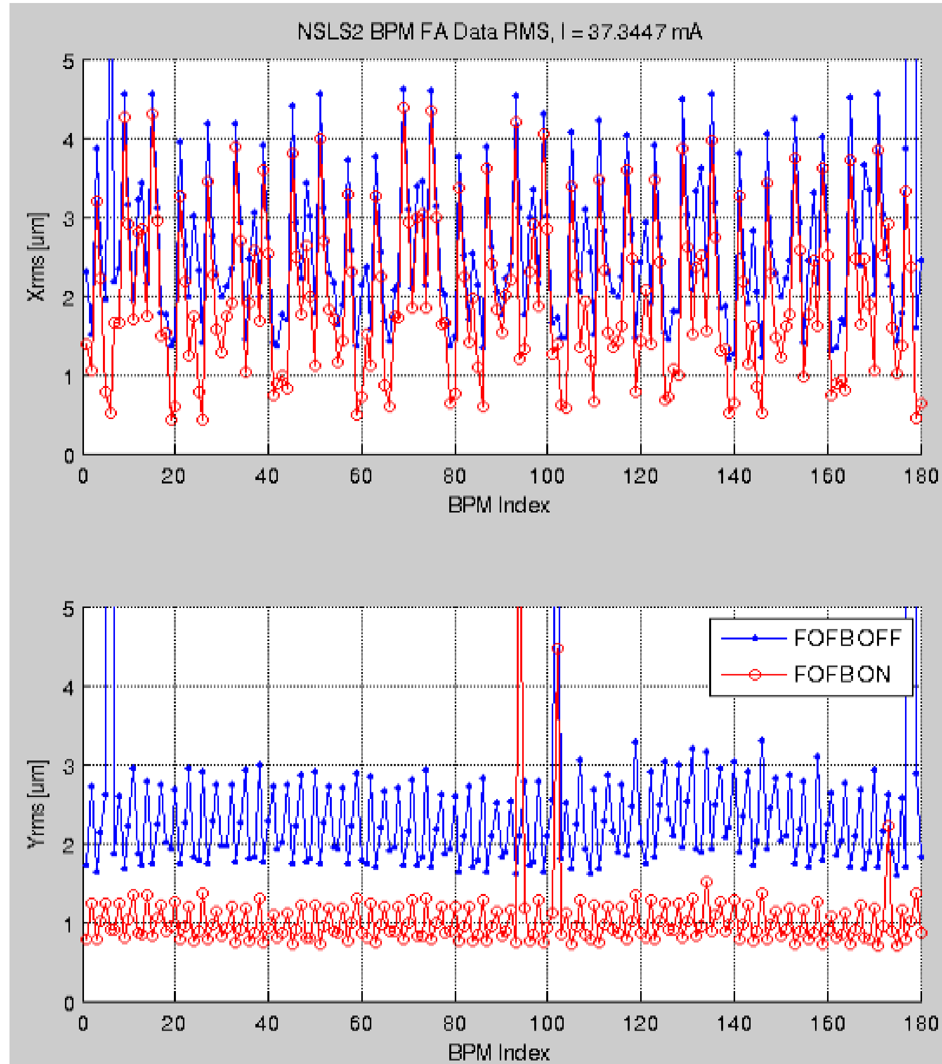




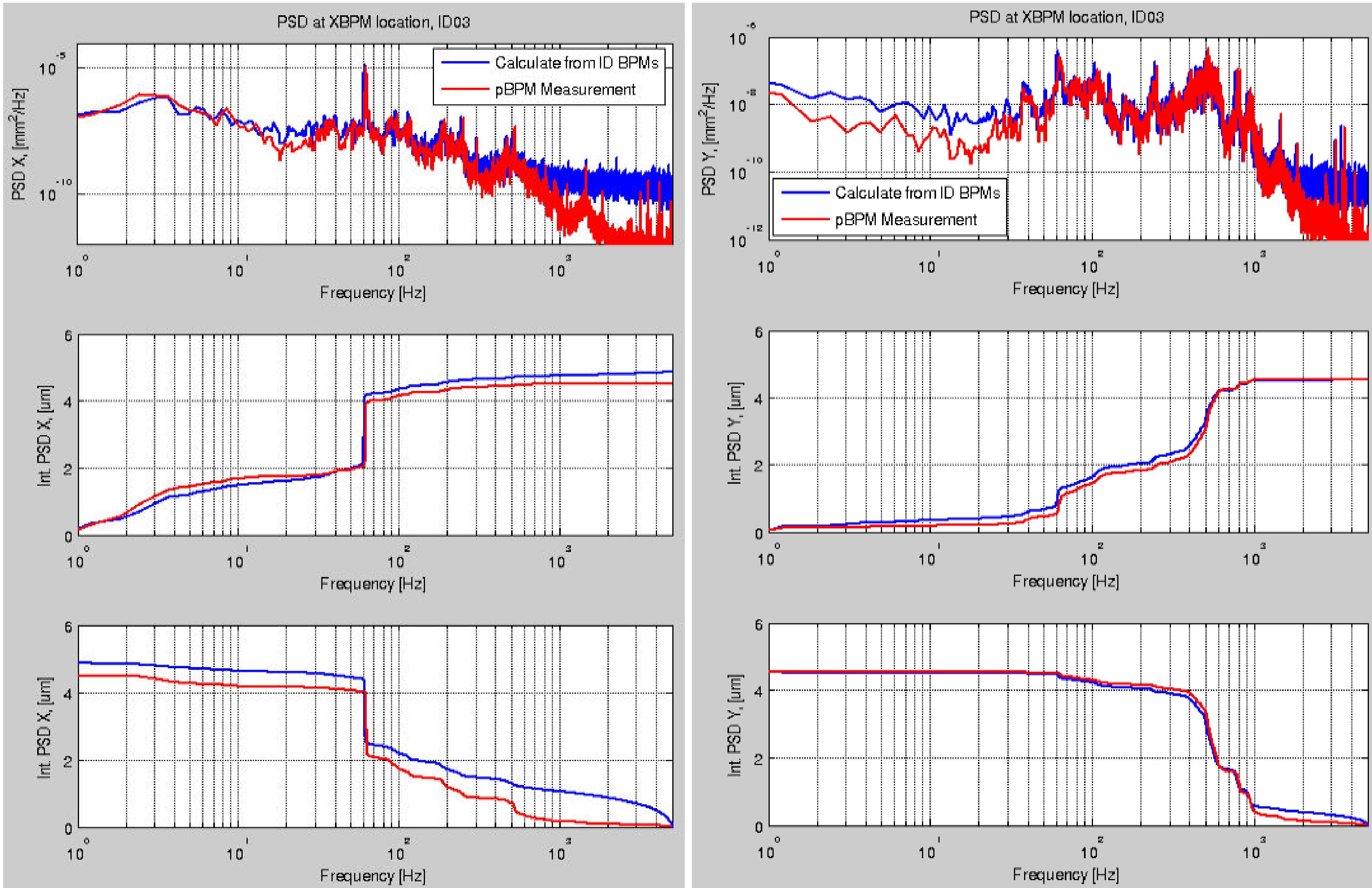
Exclude dispersive BPMs from the averaged spectrum calculation

RMS Motions Along the ring from FA spectrum



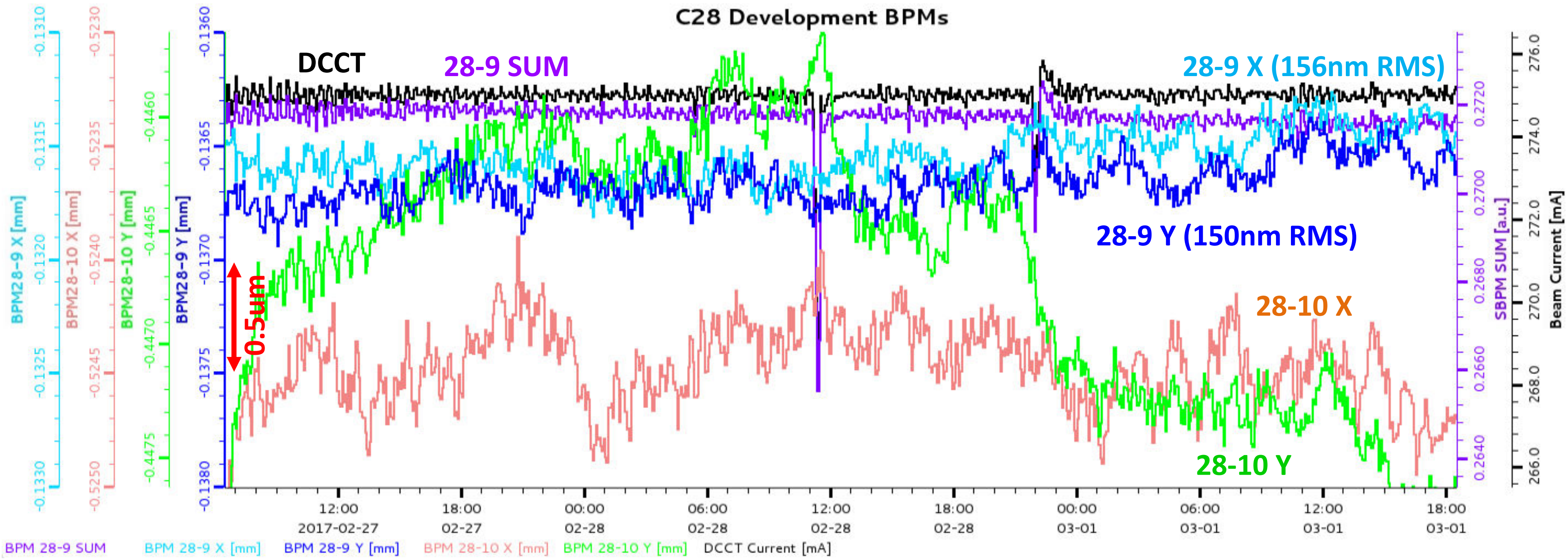


Comparison of PSD spectrum with xBPM



xBPM electronics has less noise, especially for >1kHz range (electrometer bandwidth).

BPM electronics long term stability



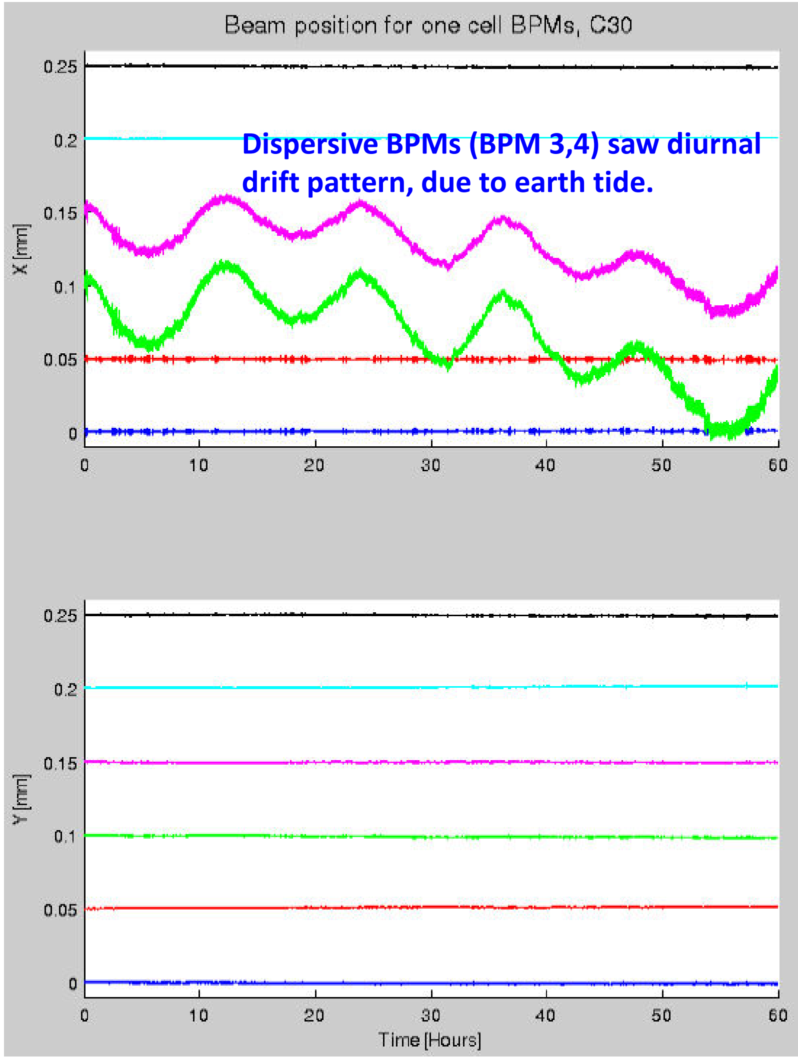
Splitter/combiner of 4-button signal to characterize BPM electronics stability

~**150nm RMS** electronics drift for 60-hours of top-off user beam

Real BPM position stability may be affected by:

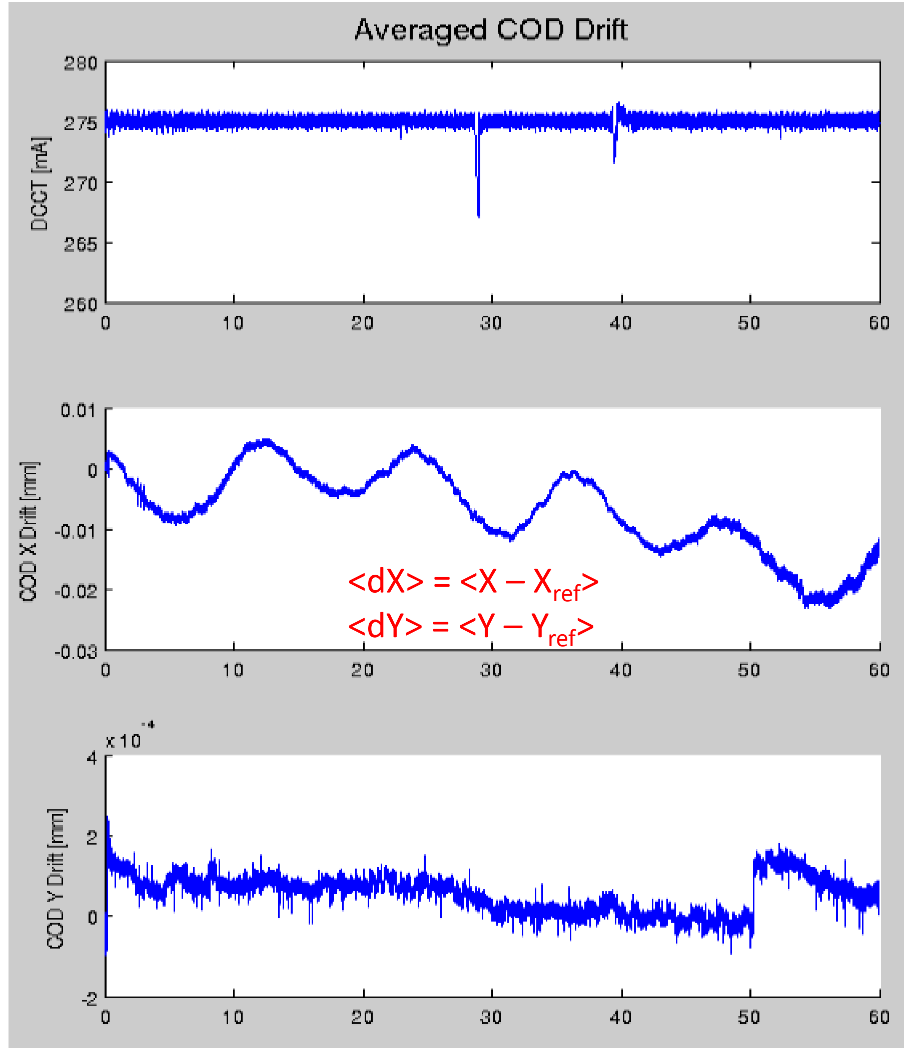
- Mechanical stability of the BPM pickup and supports (temperature, flow rate etc.)
- Beam induced heating
- Earth tide and seasonal effect (mainly at dispersive BPMs)
- Earthquake, nearby traffic, local installation activities etc.

Long term orbit stability (Feb-27-2017, 06:30 – Mar-01-2017, 18:30)



C30 six BPMs X/Y positions. Vertical offset adjusted for better view.

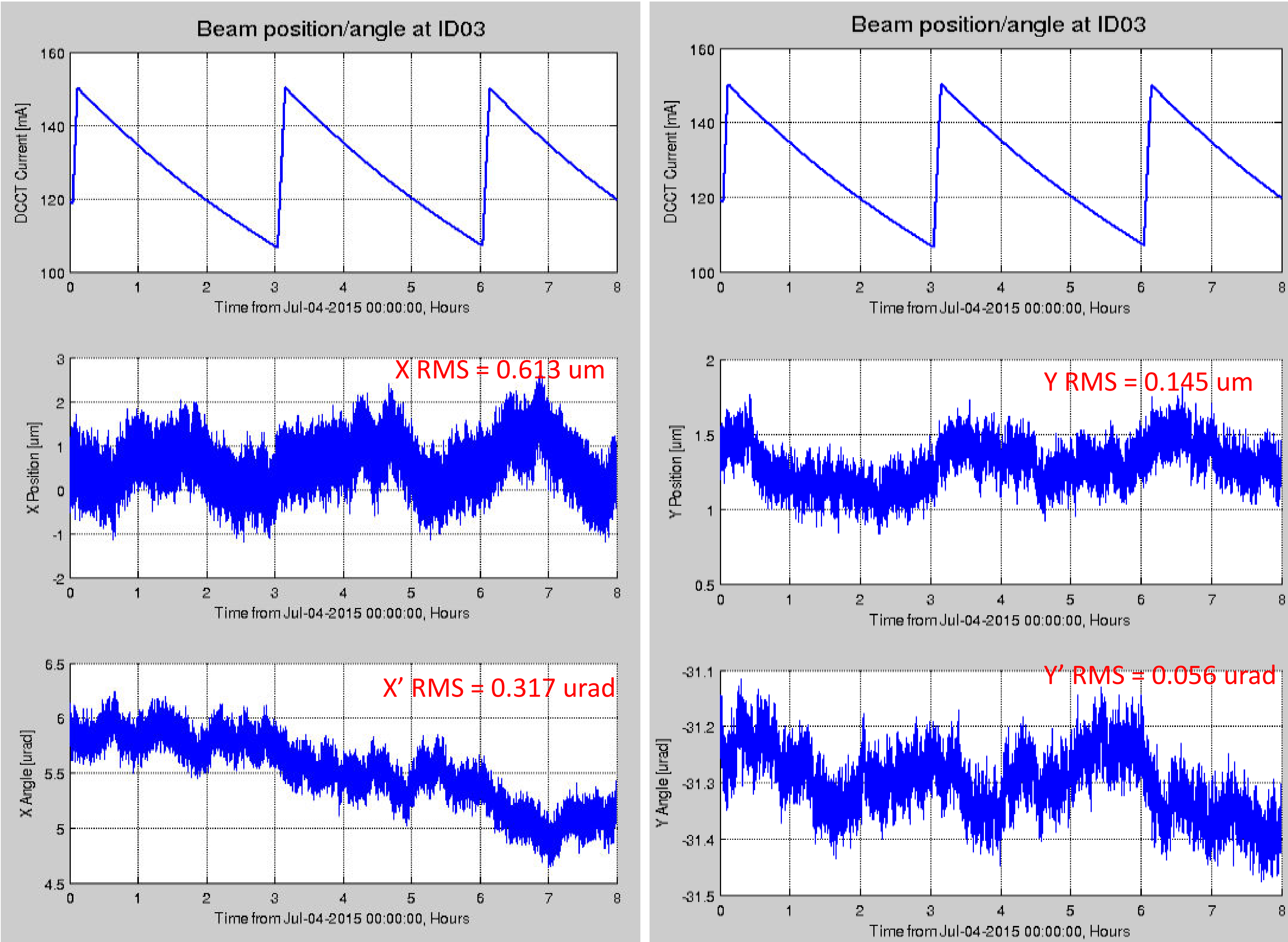
~ 50 um drift at BPM #3 (η_x ~ 0.424m) => $\Delta E/E$ = 1.18e-4 => ΔL = 34 um (ΔFrf = 21 Hz)



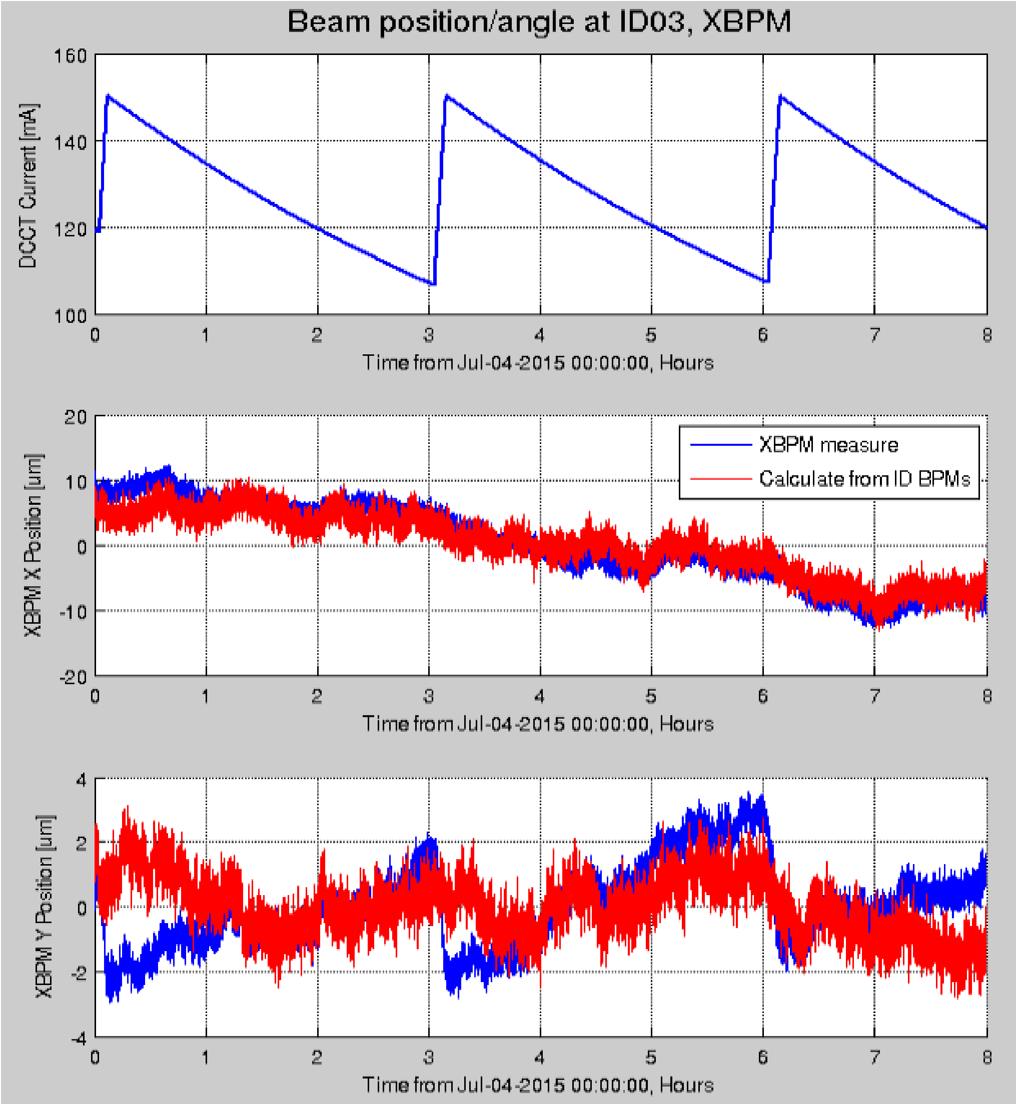
Averaged COD drift, take first COD as reference, check the COD drifting for the period.

X/Y are vectors including all BPMs readings

Long term stability at ID source point



Long term stability @ C03 pBPM

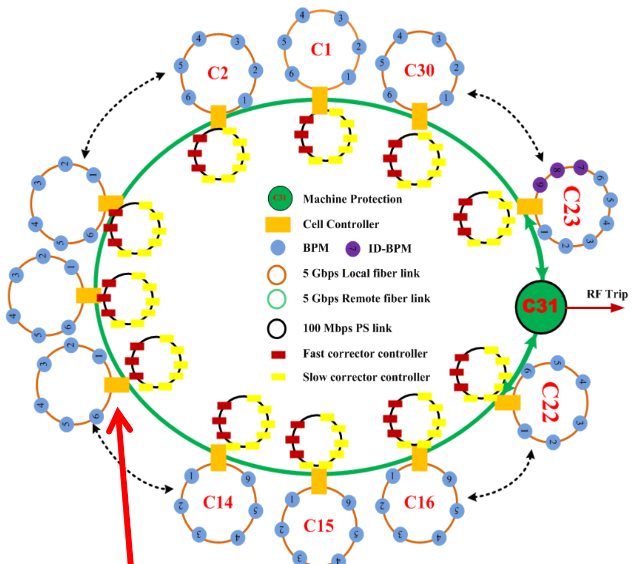


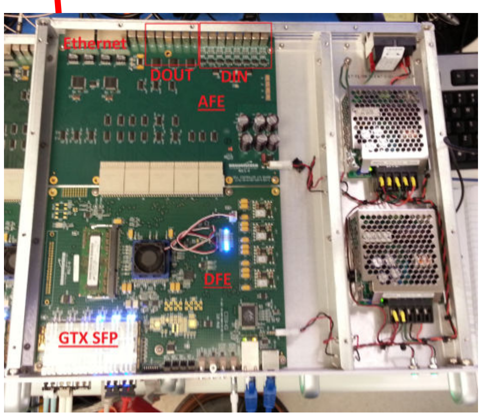
C03 ID gap fixed at 5.92mm

150mA user operation, beam current in 110 – 150mA range. Refill every 3 hours

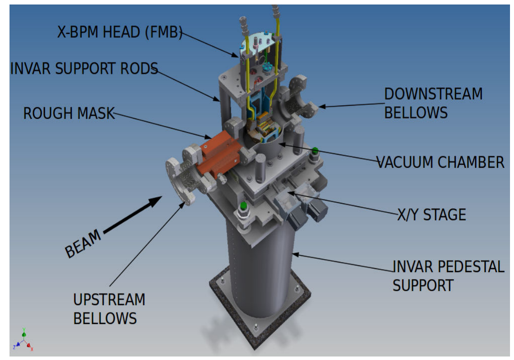
xBPM position can be calculated from two ID BPMs on ends of the IVU, compared to xBPM direct measurement.

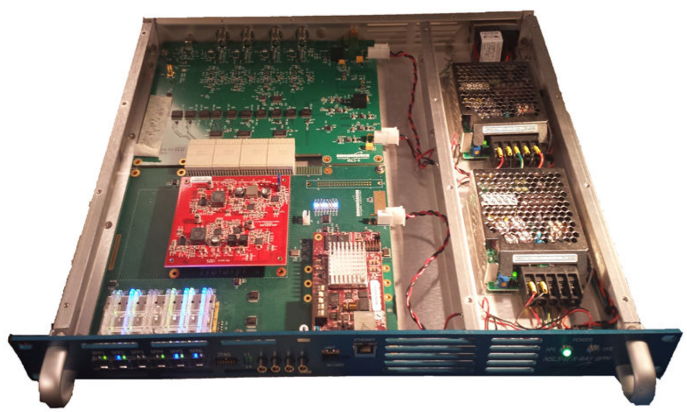
NSLS-II BPM digital receiver derivative instruments





Cell Controller





NSLS-II xBPM

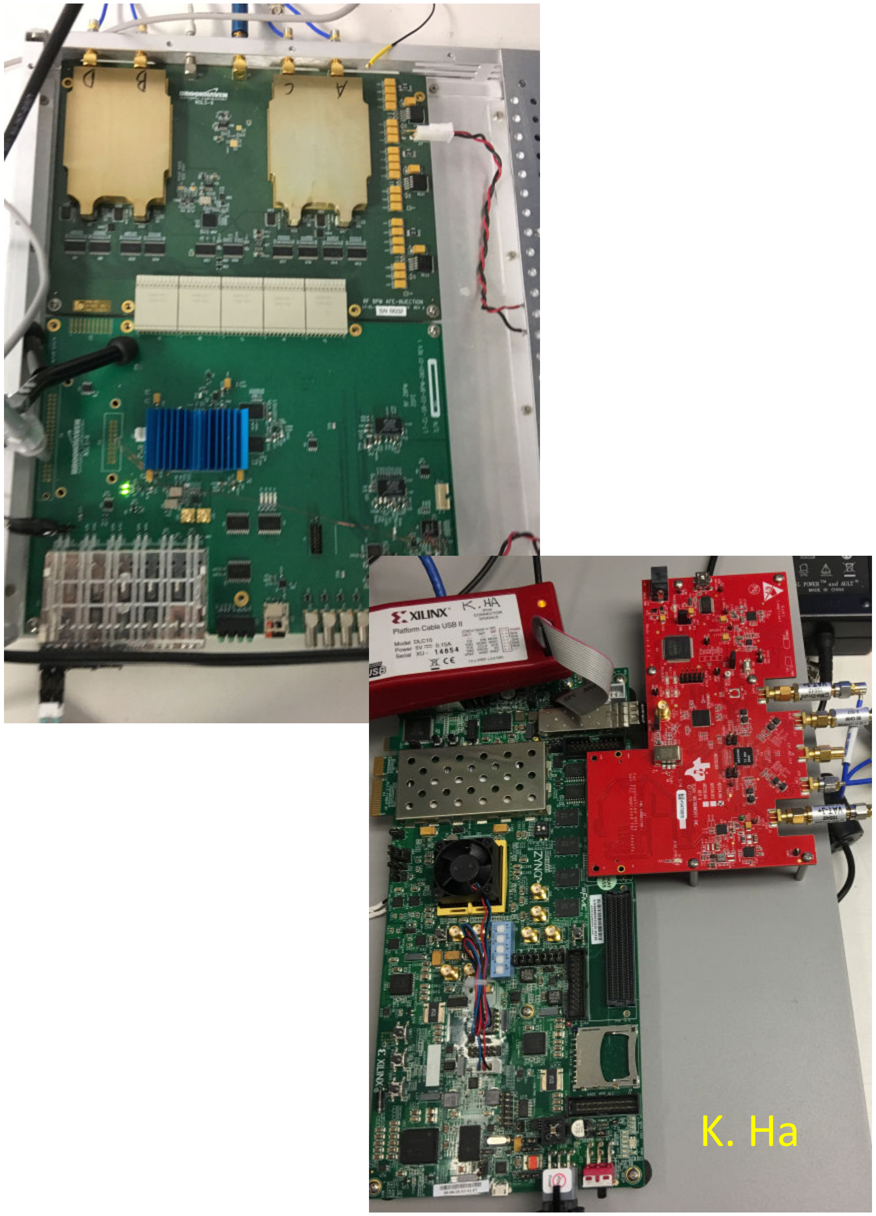
1. Cell Controller
   - FOFB
   - Active Interlock
   - PS AC excitation

2. xBPM electronics
   - Zynq XC7Z045 FPGA
   - ARM A9 processor
   - Linux OS
   - Embedded IOC

3. LBNL BPM
   - Pilot tone calibration

4. Sydor xBPM

Future plans



DFE with Zynq FPGA

- ARM A9 processor
- Linux OS
- Embedded IOC

Improve AFE stability

- Peltier cooling

New AFE electronics with bunch by bunch capability

- 500MHz 14-bit ADC
- External synchronization
- Integrate with new DFE
- Evaluation boards under test

Further improve the BPM/orbit stability

- Mechanical/thermal stability

Advanced beam measurements with expanded capabilities, e.g. BPM gate function.

Summary

- Various types of **BPM button pickups** have been designed, constructed, installed and commissioned, together with the in-house developed electronics.

- The NSLS-II **BPM electronics** has been developed and commissioned in ~5 years (2009-2014). Continuous improvement/development are only possible with experts around.
  - High resolution achieved (200nm@10kHz rate, <1um@TbT rate)
  - Short term orbit stability (~1% beam size horizontally; ~5% vertically)
  - Long term BPM electronics stability < 200nm RMS
  - Derivative instruments have been developed
    - Cell Controller (FOFB and Active Interlock)
    - X-ray BPM electronics (xBPM), Sydor xBPM
    - LBNL EBPM

- New DFE and other developments underway to continuously improve the overall system performance.

Acknowledgements:
Original BPM electronics team (**K. Vetter**, A. Dellapenna, K. Ha, M. Maggipinto, J. Mead, Y. Tian etc.)

NSLS-II BPM related paper/presentation:

- K. Vetter *et. al.*, "NSLS-II RF Beam Position Monitor", PAC11, New York, USA, (2011).
- K. Vetter *et. al.*, "NSLS-II RF Beam Position Monitor Update", BIW12, Newport News, Virginia, USA, (2012).
- O. Singh *et. al.*, "NSLS-II BPM and Fast Orbit Feedback System", IBIC13, Oxford, UK, (2013).
- W. Cheng *et. al.*, "NSLS2 Diagnostic Systems Commissioning and Measurements", IBIC2014, Monterey, CA, USA, (2014).
- J. Mead *et. al.*, "NSLS-II RF Beam Position Monitor Commissioning Update", IBIC'2014, Monterey, CA, USA, (2014).
- W. Cheng *et. al.*, "Characterization of NSLS2 Storage Ring Beam Orbit Stability", IBIC'2015, Melbourne, Australia, (2015)
- K. Vetter, "The BNL EBPM Electronics - High Performance for Next Generation Light Sources", NAPAC'2016, Chicago, IL, USA, (2016)
- W. Cheng, *et. al.*, "Beam Stability during Top-off Operation at NSLS-II Storage Ring", NAPAC'2016, Chicago, IL, USA, (2016)

- B. Kosciuk, et. al., "Development of High Stability Supports for NSLS-II RF BPMs", PAC'09, Vancouver, Canada, (2009)
- A. Blednykh, et. al., "NSLS-II BPM System Protection from Rogue Mode Coupling", PAC'11, New York, USA, (2011)
- W. Cheng, et. al., "NSLS2 Beam Position Monitor Calibration", BIW'12, Newport News, Virginia, USA (2012)
- W. Cheng, et. al., "Performance of NSLS2 Button BPMs", IBIC'2013, Oxford, UK, (2013).