Status of NSLS-II

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U.S. DEPARTMENT OF ENERGY | Office of Science

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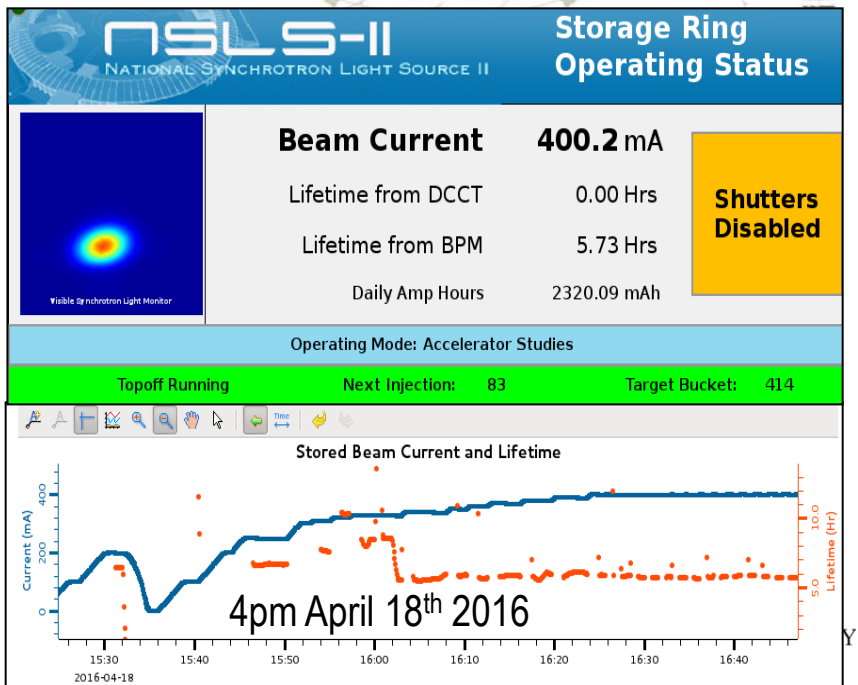
Outline

- NSLS II overview
- Operation status
- Development
- Conclusion and outlook

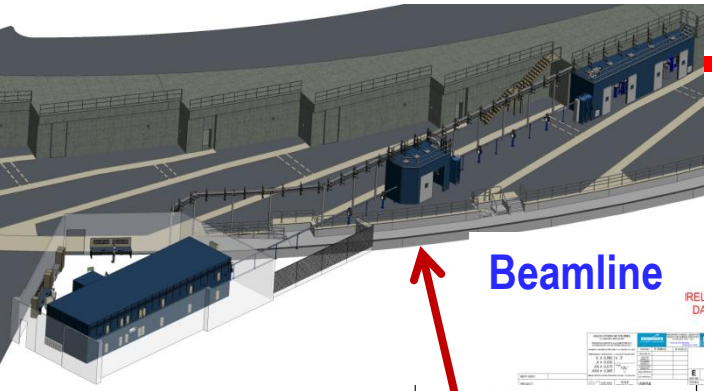
NSLS-II overview

- National Synchrotron Light Source II (NSLS-II) is a new 3 GeV, 500 mA, high-brightness synchrotron light source facility at the Brookhaven National Laboratory, funded U.S. Department of Energy (DOE)
- SR circumference is 792 m with 1 nm-rad horizontal and 8 pm-rad vertical emittance
- Broad spectral range from IR to hard x-rays
- Capacity: >60 beamlines

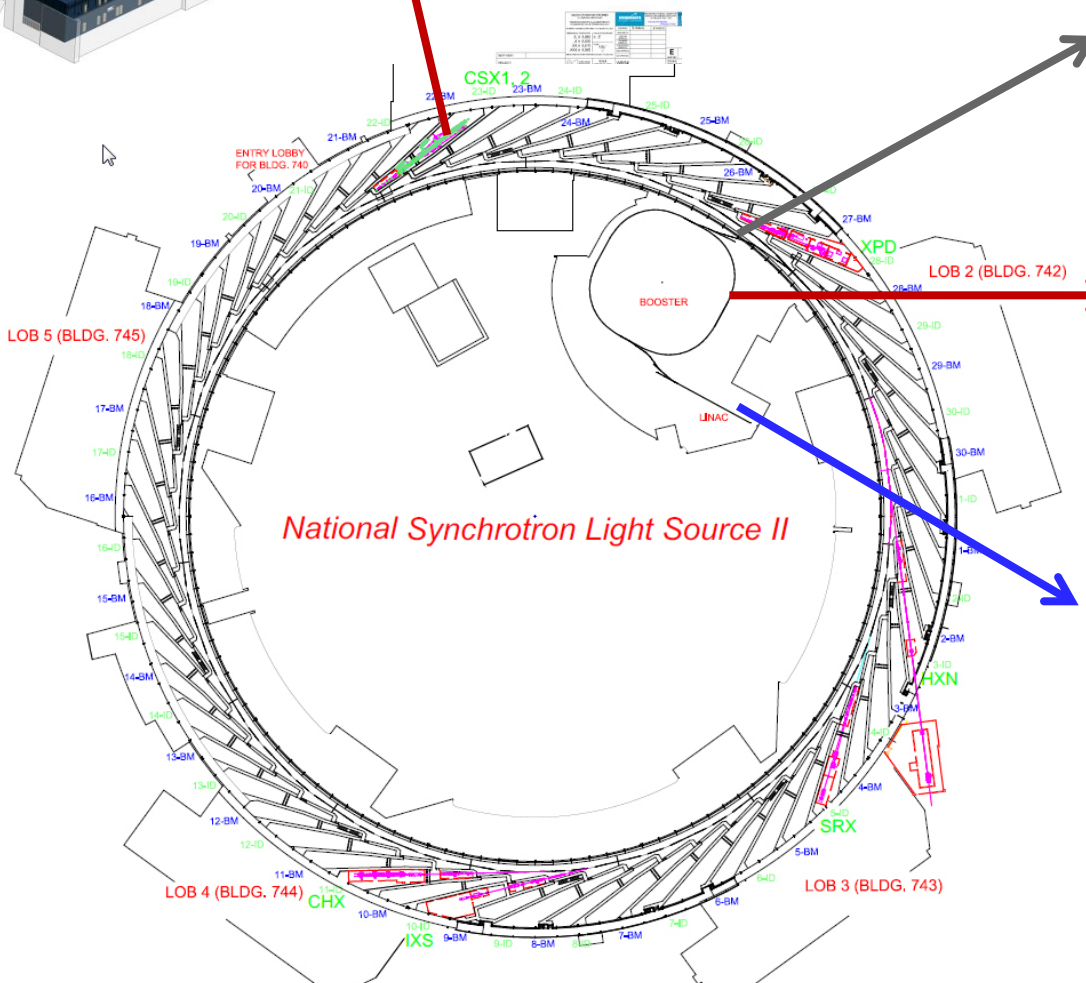
- SR commissioning started in later March 2014
- Six project beamlines operated in Dec. 2014
- Top off operation started in October 2015
- 16 beamlines in top off routine operation at 250 mA
- Stored beam current up to 400 mA

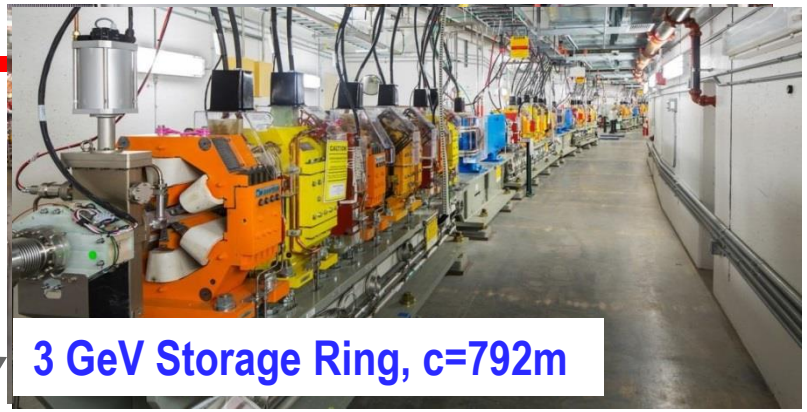


Accelerator and Beamline layout

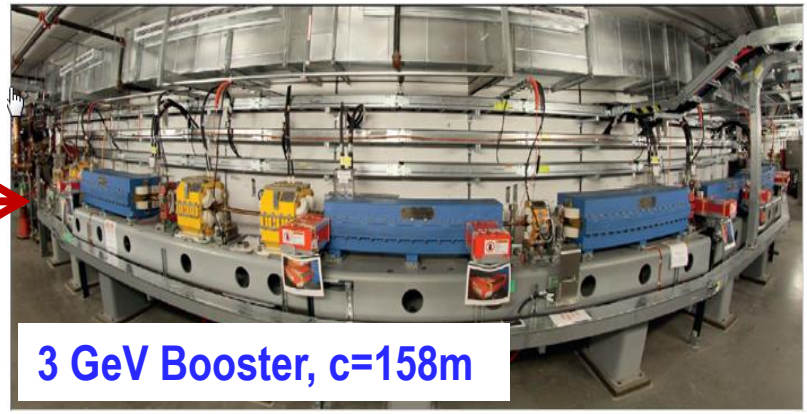


Beamline

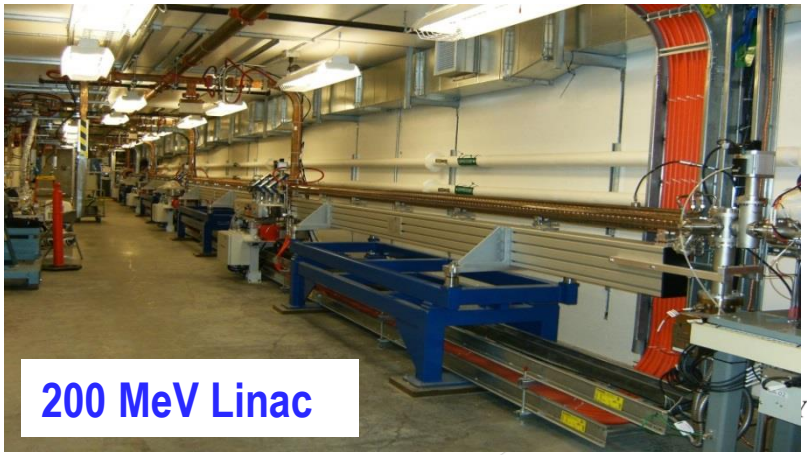




3 GeV Storage Ring, c=792m



3 GeV Booster, c=158m

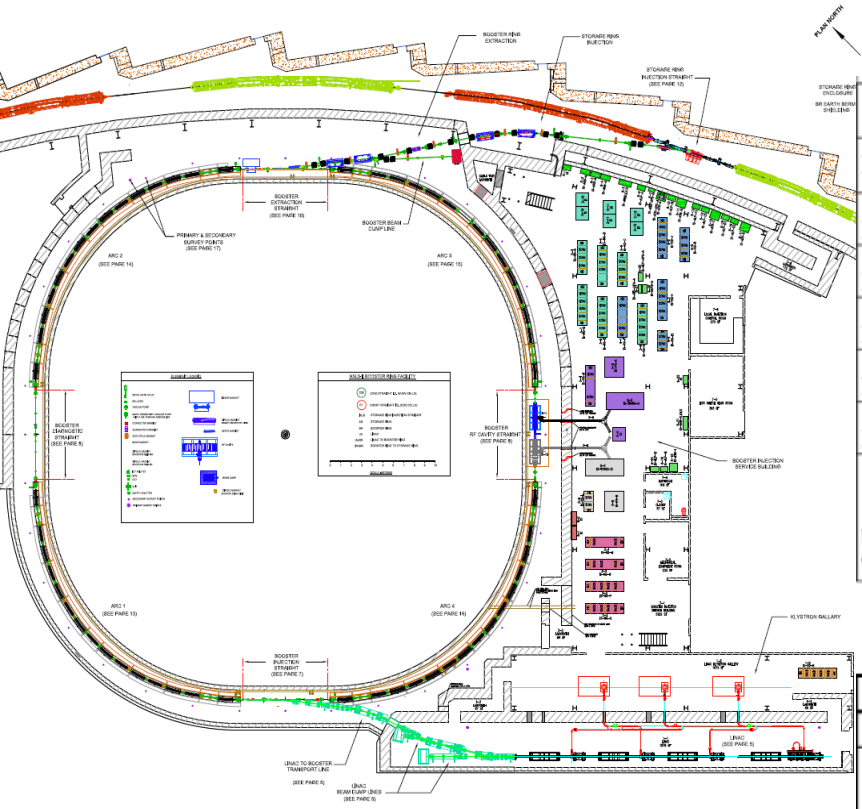


200 MeV Linac

NSLS-II Timeline

- August 2005 **CD-0** Approve Mission Need
- July 2007 **CD-1** Conceptual Design and Cost Range
- January 2008 **CD-2** Performance Baseline established
- January 2009 **CD-3** Approval of Start of Construction
- February 2011 Begin Accelerator Installation
- March 2012 Start LINAC Commissioning
- December 2013 Booster Commissioning
- April 2014 Storage Ring Commissioning
- October 2014 Insertion Device and BL Frontend Commissioning
- December 2014 Scope of Accelerator complete with six project beamlines
- February 2015 **CD-4 c**ompleted and Science Commissioning of six Beamlines started
- April 2015 Achieve goal of beam emittance (1nm-rad) and beam stability at 200 mA
- October 2015 Start top off operation
- January 2016 Start 2nd SRF cavity commissioning
- April 2016 400 mA

Injector

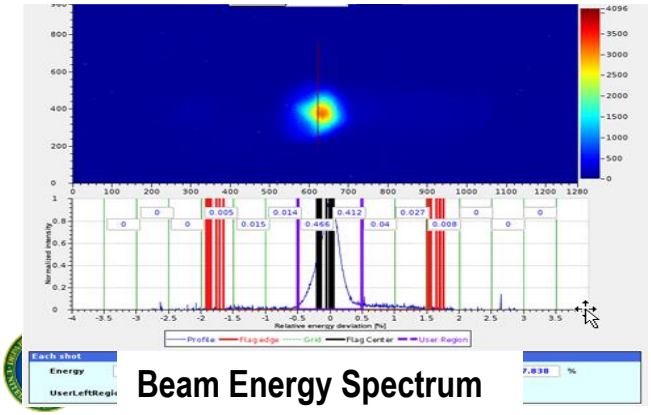


Booster performance

Parameter	Design	Measured
Beam energy	3+/-0.15 GeV	~3 GeV
Bunch charge	0.5…15 nC	0.5…10 nC
Bunch train	1 / 80…160 bunches	1 / 75 bunches
Beam energy spread @3GeV	0.08%	0.10%
Beam emittance X	38 nm rad	33 nm rad
Beam emittance Y	4 nm rad	4…8 nm rad
Charge transport efficiency between ICTs in LB and BSR TL	>75%	~80% as seen between LtB and BsT FCTs

Linac performance

Parameter	Specification	Single Bunch Mode	Multi Bunch Mode
Energy	200 MeV	201 MeV	210 MeV
Charge	>0.5 nC Single Bunch Mode; >15 nC per train Multi Bunch Mode	0.5 nC	16 nC
Bunch Train Length	160 – 300 ns MultiBunch Mode	N/A	160-300 ns demonstrated
Bunch Train Uniformity	<10% MultiBunch Mode	N/A	25%
Energy Spread	<0.5% rms	0.14% FWHM, with 80% of charge within 0.5%	0.41% FWHM, with 72% of charge within 0.5%
Emittance	<38 nm rms - design <70 nm rms - acceptance	X: 58 nm, Y: 63 nm	X: 56 nm, Y: 47 nm

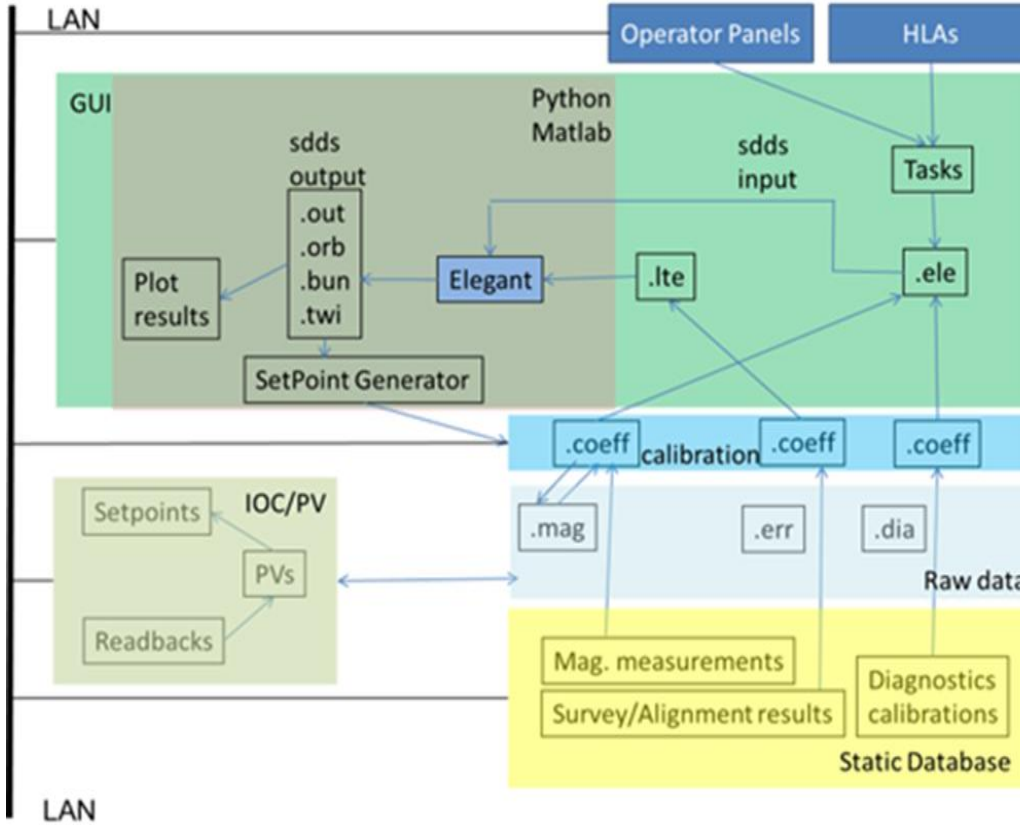


Beam Energy Spectrum

Booster Extended Integration Test

- Extended Integrated Testing was carried out to exercise beam commissioning without beam.
- It provided the environment to test beam commissioning tools and system alarms and interlock signals and trained operators to operate live machine safely.
- The hardware operated as in the actual beam commissioning. The beam signals are simulated and generated by a computer program, ELEGANT, then transported to the same data channel as the real beam signal would travel.

- EIT proved itself to be an efficient way of debugging the controls and the correction systems.
- Many small issues and bugs had already been discovered during the test (BPMs signal coupling, PS ripple).
- During EIT we test also the operations procedures, the shift routines, the use of the logbook and much more and the injector commissioning team built up the operation experience.

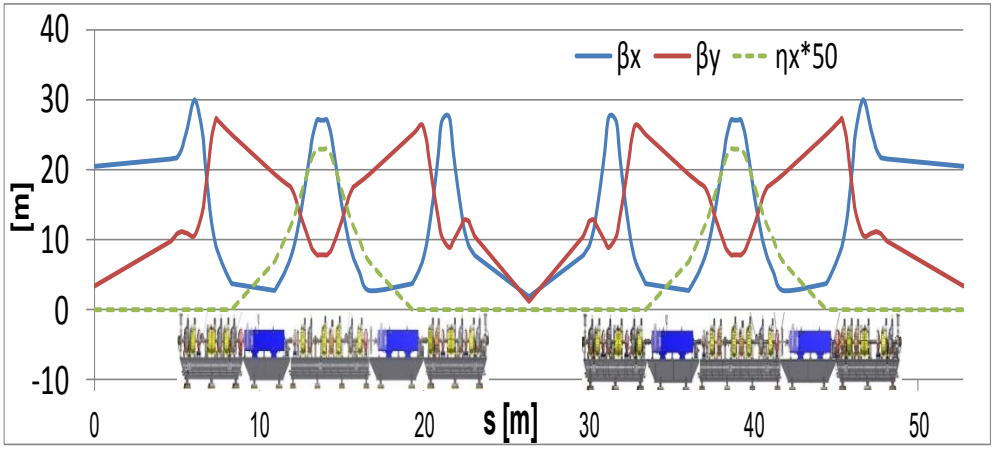


Storage Ring

- 500 mA beam current with 1 nm-rad horizontal and 8 pm-rad vertical emittance
  - Beam sizes at source points are ~100 um/3 um
- 15 long (9.3m) and 15 short (6.6m) straight sections
- High beam stability in position (<10% of rms beam size) and angle (<10% of rms divergence)
- 1080 bunches in 1320 RF buckets, 3 hrs lifetime
- Top off injection for stable intensity (±0.5% variation)
- 16 operation beamlines from diverse radiation sources (DW, EPU, IVU, 3PW, Dipole)

Parameters	Design	Achieved
Beam Energy [GeV]	3	~3
Circumference [m]	792	792
Number of DBA cells	30	30
Number of ID straights	15*6.6, 12*9.3	15*6.6, 12*9.3
Beam Current [mA]	500	400
X/Y Emittance [nm-rad]	1/0.008	~1/0.007
Relative energy Spread	0.1%	~0.1%
RF Voltage [MV]	4.9	3
RF frequency [MHz]	499.68	499.68
Energy loss/Turn [keV]	287/700	287/700

One super-period SR Lattice function



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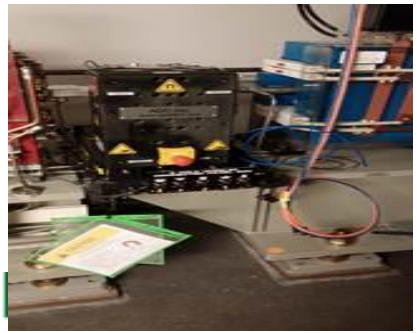
Insertion devices

BL	ID straight type	ID type, incl. period (mm)	Length	K_{max}*	FE type†	FE aperture (h x v, mrad)	# of ID's (base scope)	# FE's	Project	Procurement
CSX	lo-β	EPU49 (PPM) x2	4m (2 x 2m)	4.34	canted (0.16)	0.6 x 0.6	2	1	NSLS-II	Done
IXS	hi-β H	IVU22 (H) (x2)	6m (2 x 3m)	1.52	std	0.5 x 0.3	1	1	NSLS-II	Done
HXN	lo-β	IVU20 (H)	3m	1.83	std	0.5 x 0.3	1	1	NSLS-II	Done
CHX	lo-β	IVU20 (H)	3m	1.83	std	0.5 x 0.3	1	1	NSLS-II	Done
SRX	lo-β	IVU21 (H)	1.5m	1.79	canted (2.0)	0.5 x 0.3	1	1	NSLS-II	Done
XPD	hi-β H	DW100 (H)	6.8m (2 x 3.4m)	~16.5	DW	1.1 x 0.15	0	1	NSLS-II	Done

Damping wiggler

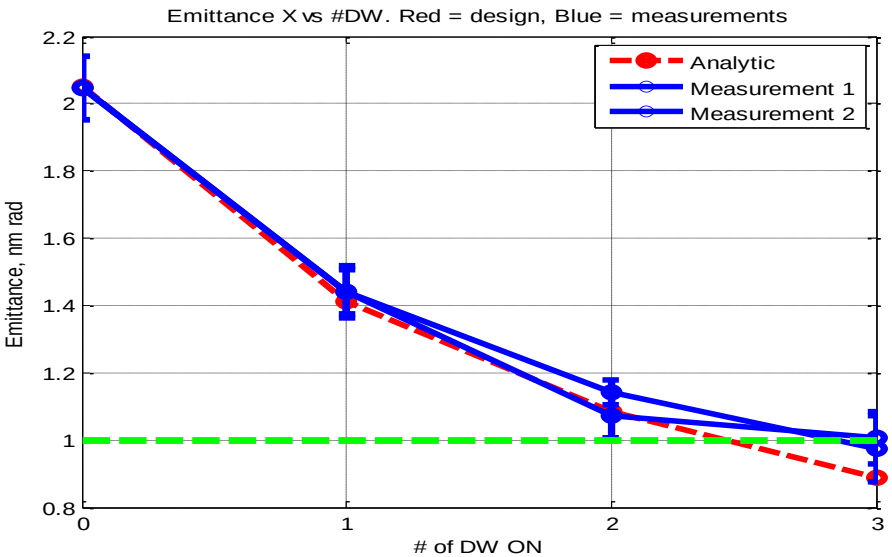
3PW



IVU22

T.Tanabe, C.Kitegi…

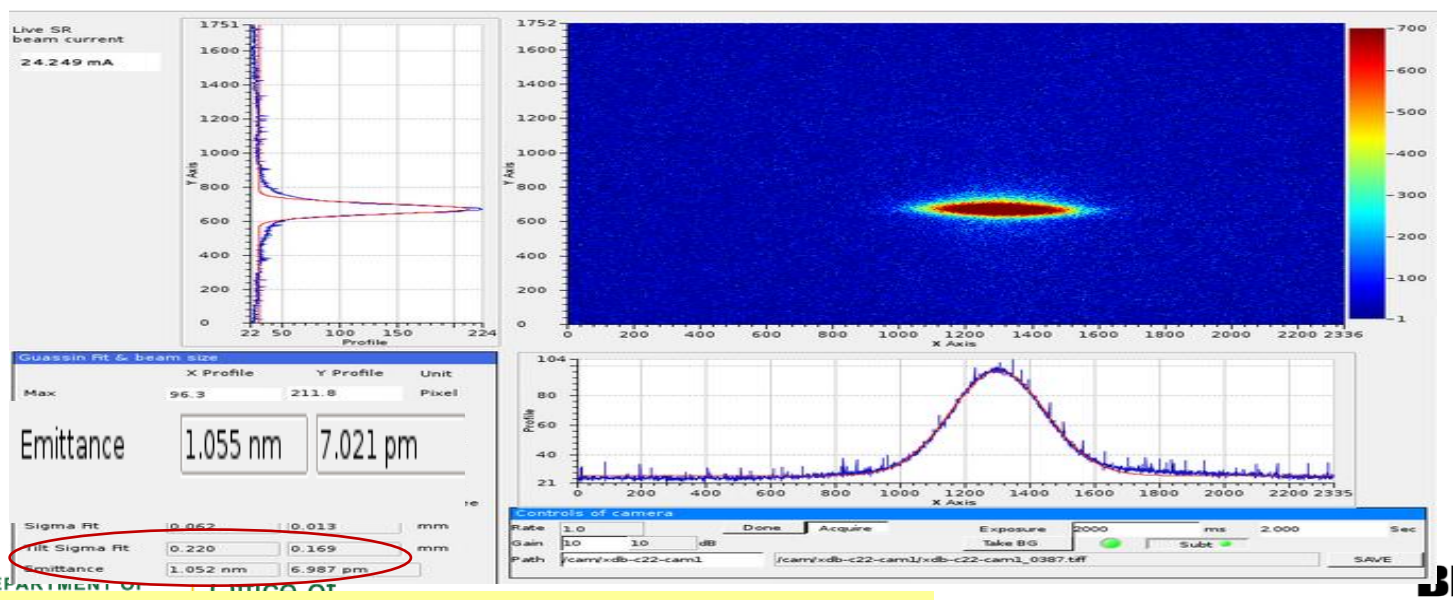
Beam Emittance



- **Design Emittance Achieved**

ε_x^{0dw} = 2.05 nm·rad, ε_x^{3dw} = 1 nm·rad,

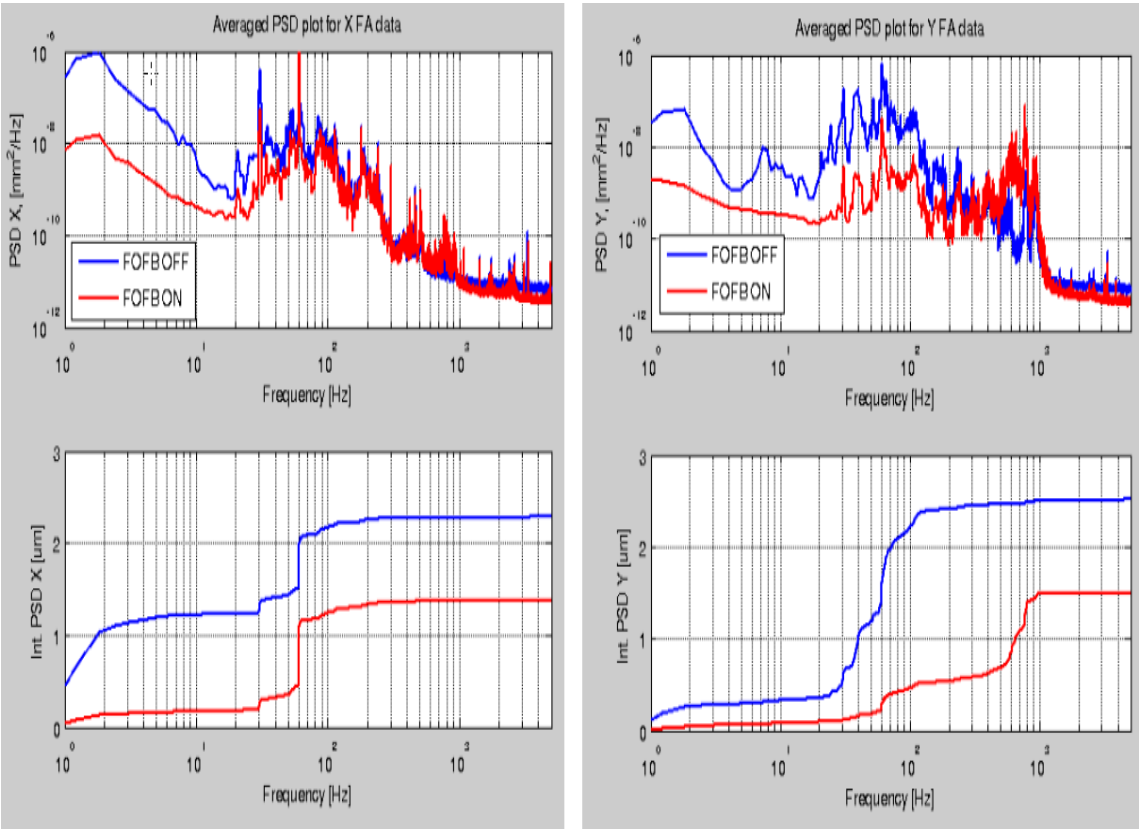
ε_y = 7 pm·rad, exceed diffraction limited value of 8 pm-rad (at 10 keV), which also was verified by HXN x-ray beam image size (change by 33%)



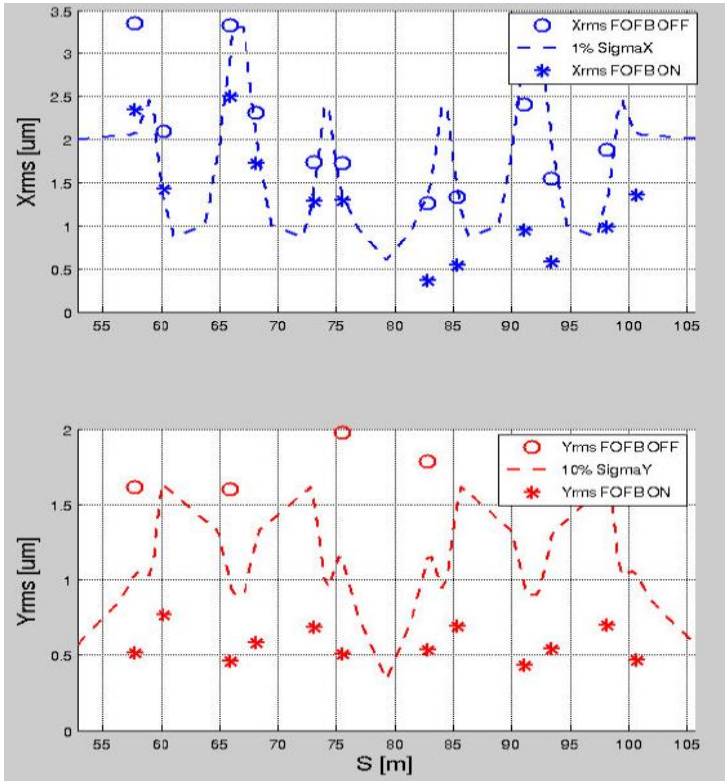
G-M Wang, T. Shaftan et.al, Rev. Sci. Instrum. 87, 033301 (2016)

Orbit Stability

Beam spectrum with FOFB : ON / OFF



RMS motion in frequency range [1 500] Hz

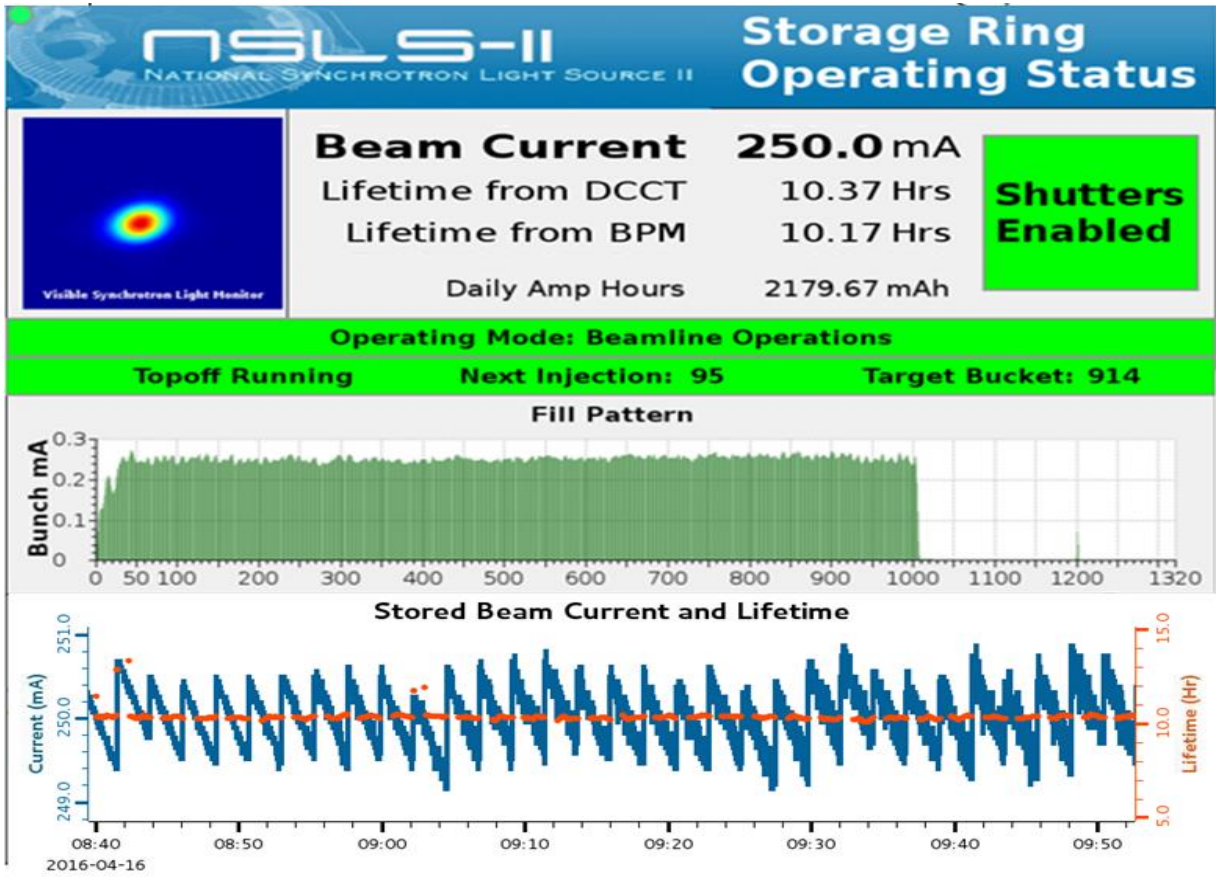


Circle -- FOFB OFF, Star –FOFB ON
Dash line – 1% of H beam size; 10% of V beam size

- Fast Orbit Feed Back (FOFB) suppressed beam motion in frequency band up to 250 Hz.
- The beam orbit stability is specified as 10% of beam size.
- Horizontal orbit stability is well within the requirement, 1% of beam size in [1-500] Hz range.
- Vertical orbit stability is ~ 5% beam size with FOFB.

Y. Tian, L.H. Yu, W. Cheng …

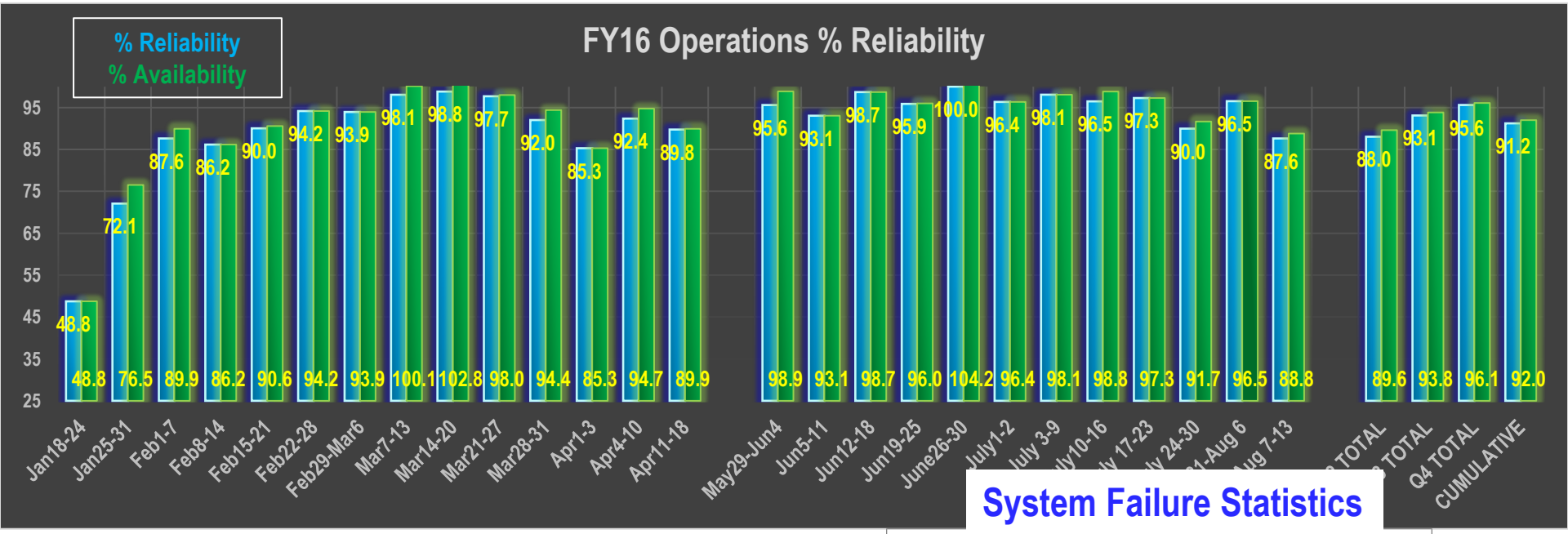
Top Off Injection

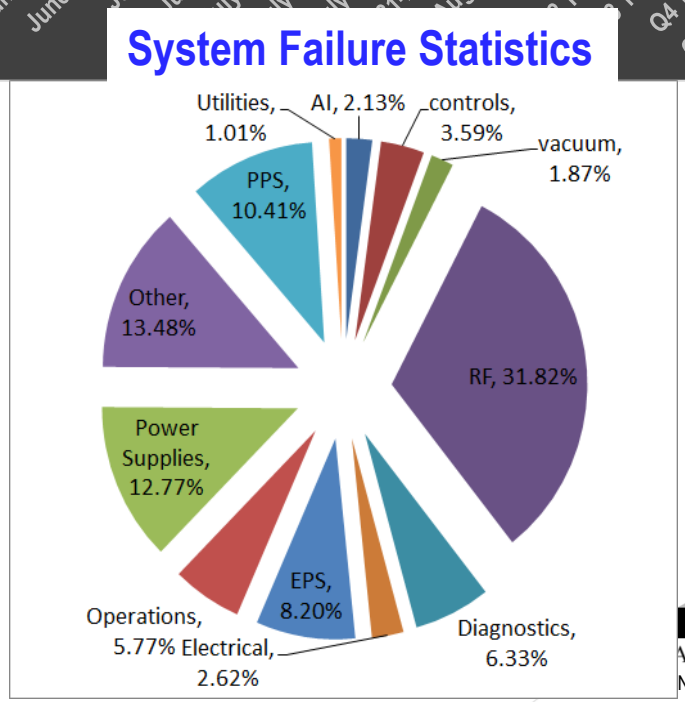


- Top-Off Injection specifications: many bunches in the ring with multi-bunch injection
  - >1 minute between injector cycles for top-off
  - Total Current stability +/- 0.5%, Bunch-to-bunch Q stability 20%
- Top off routine operations started on October 1, 2015 at 150 mA
- Beamlines operation beam current is 250 mA with injection period ~3 mins. Beam current is maintained within 0.5% well and bunch charge deviation ~15%

G-M. Wang, IPAC16

FY16 Machine Operation Status





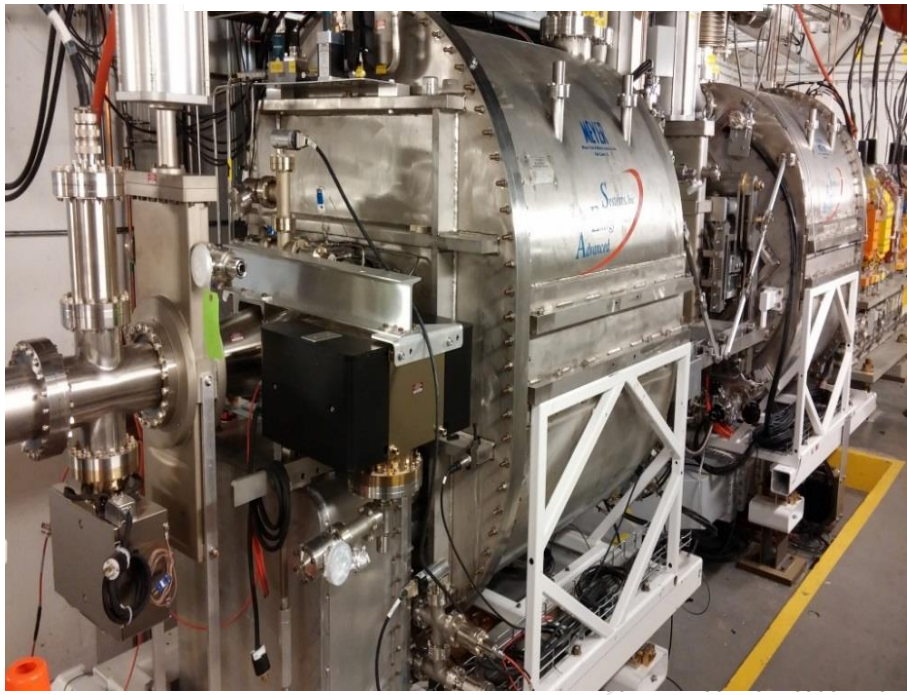
- 3742 hrs operations
- 2nd RF cavity commissioning
- 9 new beamlines into operation
- Yearly reliability 91.4% (goal 90%)
- Host 477 users

Storage Ring SRF status

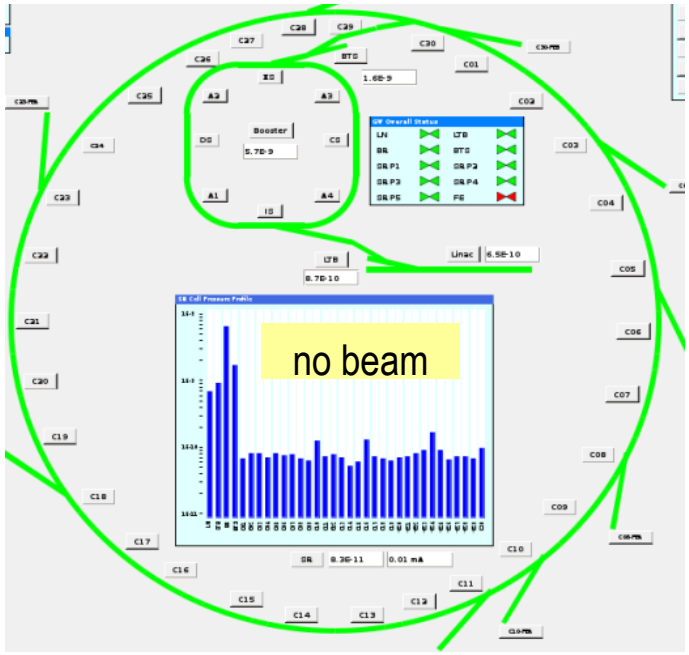
- Two SC 500 MHz RF cavities with 300 kW transmitters have been conditioned to their maximum of 1.8 MV without beam
- Cavity beam vacuum now in 10^{-10} to low 10^{-9} Torr range
- Operating reliably at 1.5 MV each for 250 mA operation with voltage limited by beam lifetime considerations
- Cavity trips have been reduced from an MTBF of ~20 hours to well over one hundred hours and expected to continue to improve

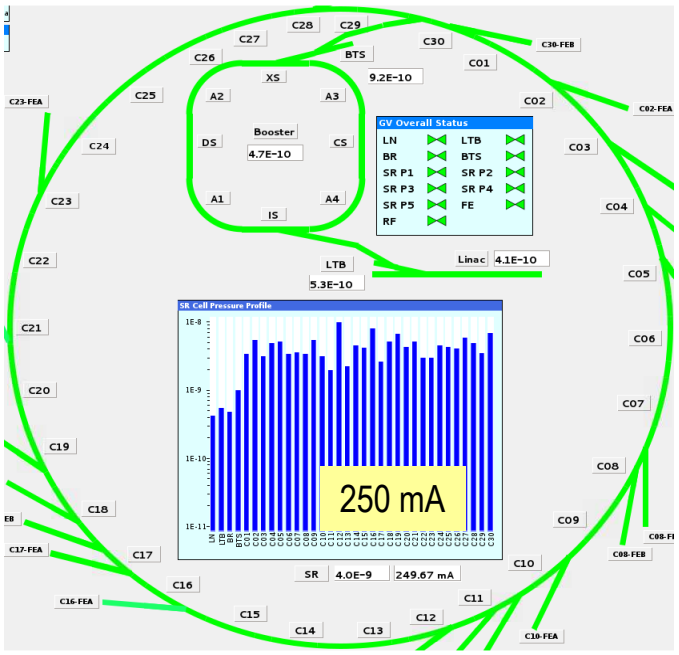
- LLRF controller (developed at NSLS-II) is capable of generating flexible set-point tables and finely control parameters of RF feedback
- With flexible and fast digital LLRF controller we can manipulate with $\varphi(t)$ and $A(t)$ of cavity field within short timescale
- It also enables ramp down function for Equipment Protection System purposes (RF voltage comes down in ~1ms)

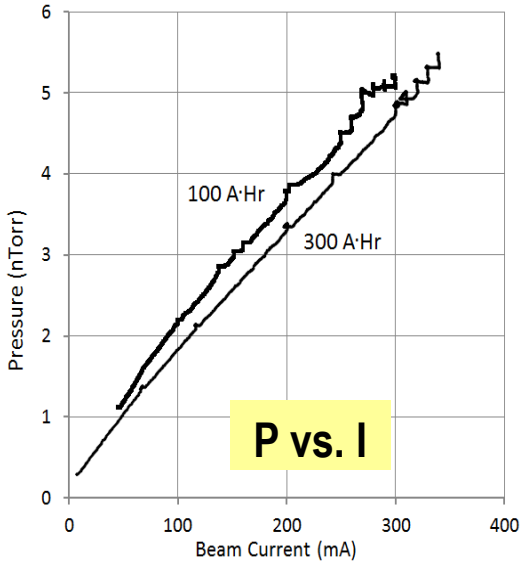
RF cavities in NSLS-II tunnel

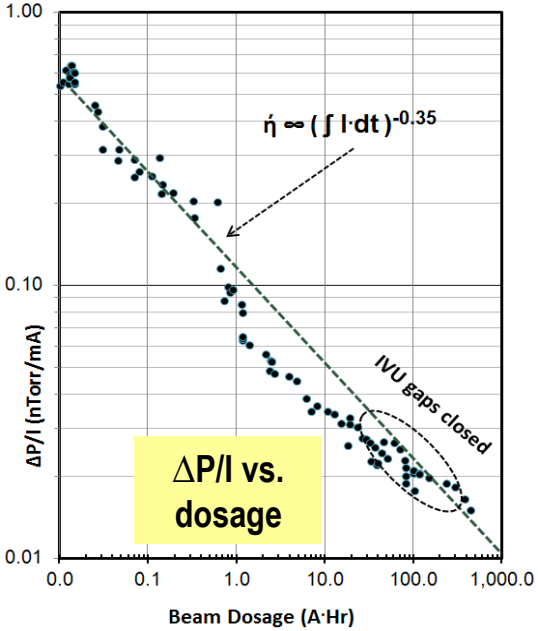


Vacuum condition







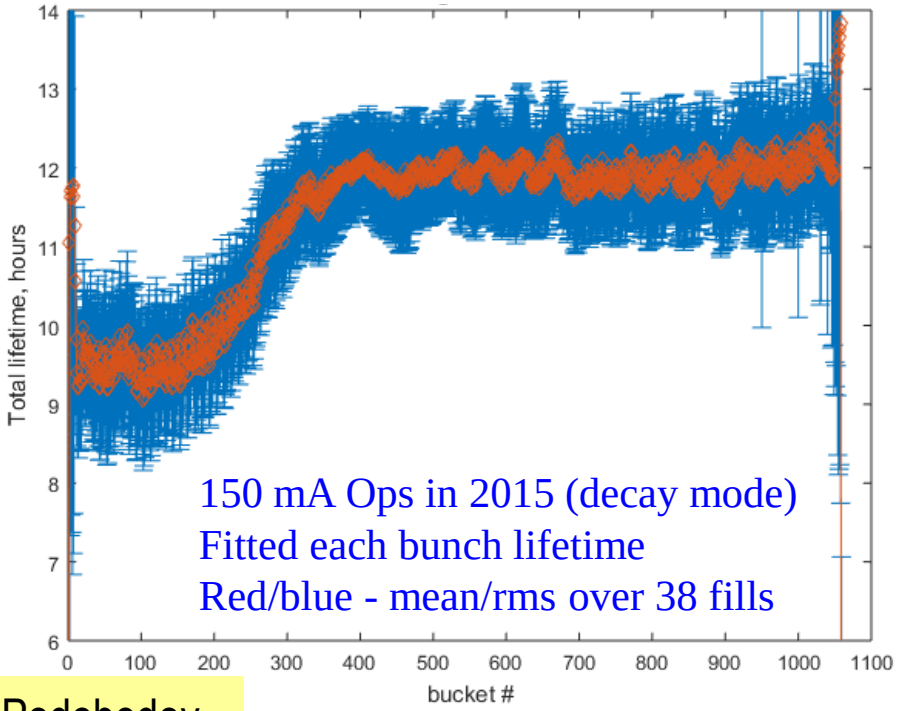


- Pressure increases linearly with current
  < 4×10^{-9} Torr at 250 mA, ~ 6×10^{-9} Torr @ 400 mA
- $\Delta P/I < 1.5\times10^{-11}$ Torr/mA now, @ ~ 1000 A.Hr
- PSD (η) vs. dosage (Γ): $\eta \propto \Gamma^{-0.35}$
  with slower conditioning slope than other SRs
- Goal: $\Delta P/I \sim 1\times10^{-11}$ Torr/mA by late 2017

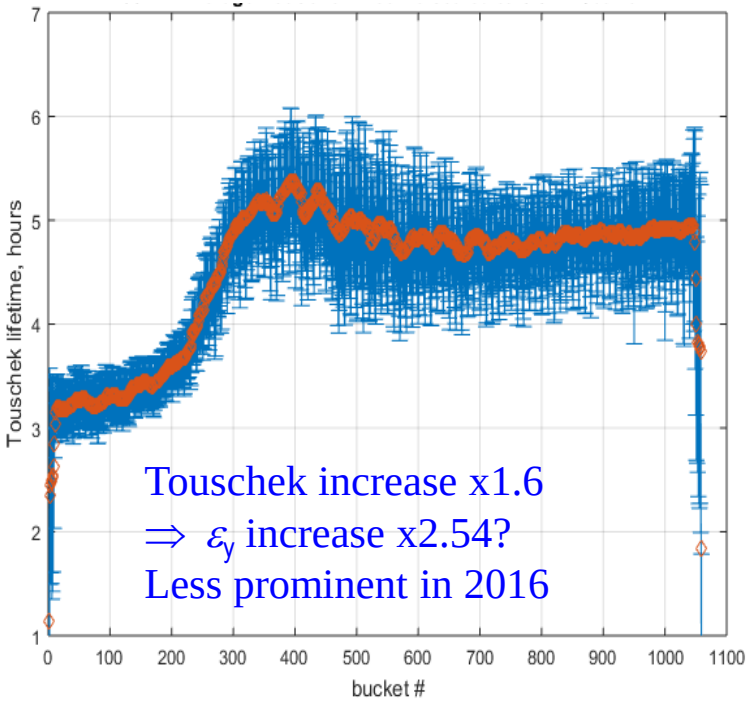
Beam Lifetime at NSLS-II

- Present 250 mA ops lifetime is ~10 hours; gas & Touschek comparable
- Touschek will drop with higher *I* and lower ε_y ; vaccum *P~I*, slowly improving
- Interesting effects have been observed: lifetime increase along a bunch train (fast ion instability)

Total lifetime @ 150 mA

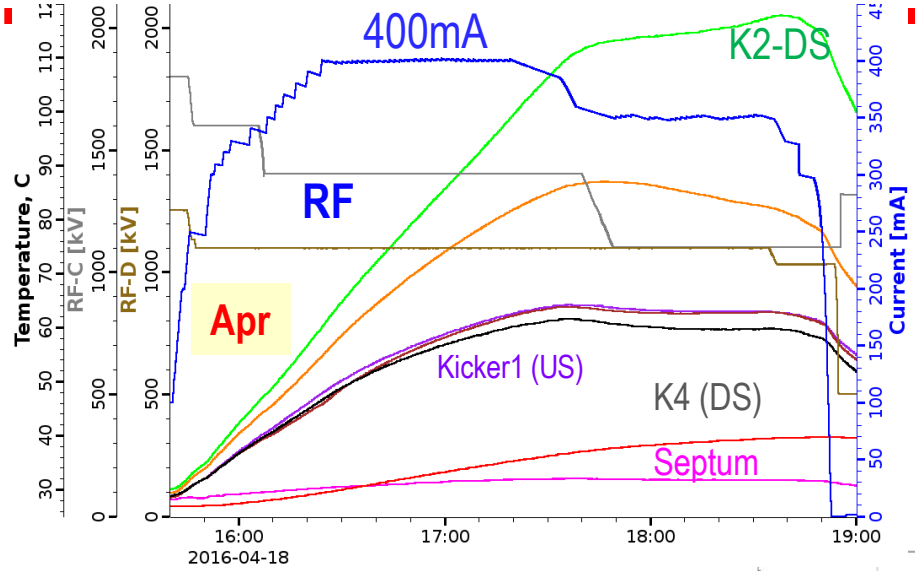


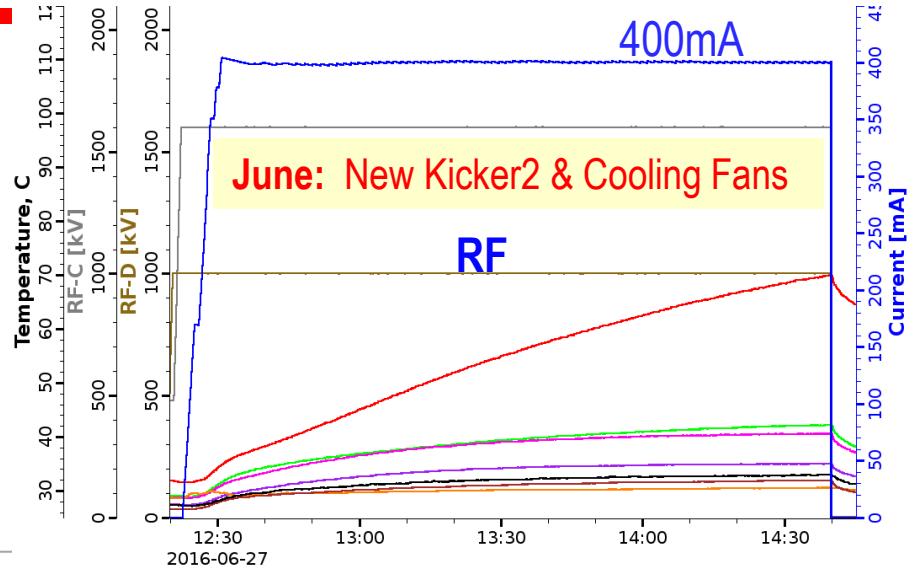
Touschek lifetime scaled to @ 0.5 mA/bunch



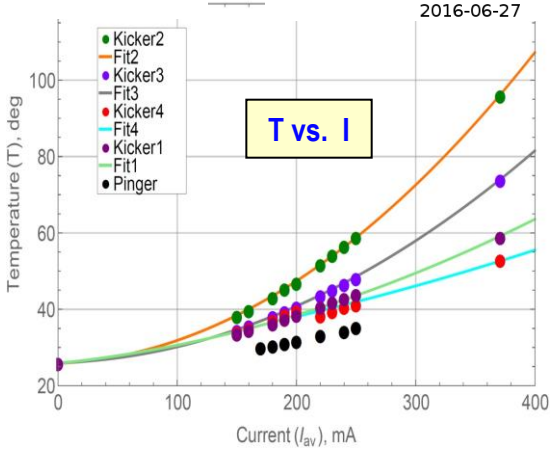
B. Podobedov

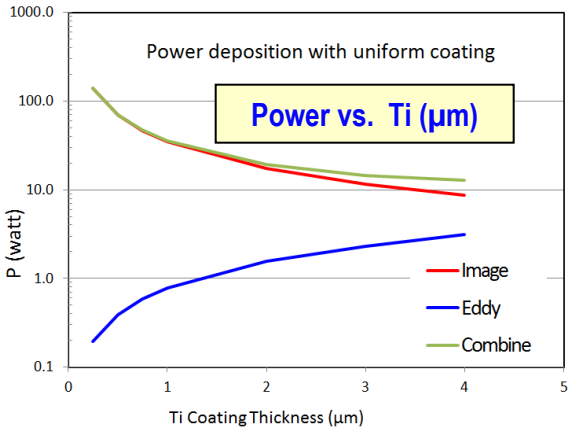
Heating of Kicker Ceramic Chambers



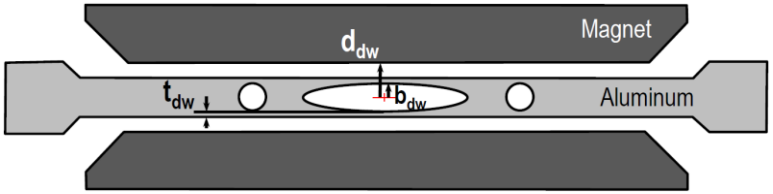


- Chambers coated w only ~ 0.5 μm Ti
- K2 reached > 100ºC @ 400mA
- K2 chamber replaced in May
- Found Ti flaking off, discoloration
- Cooling fans added
- Need good Ti coating up to < 4 μm

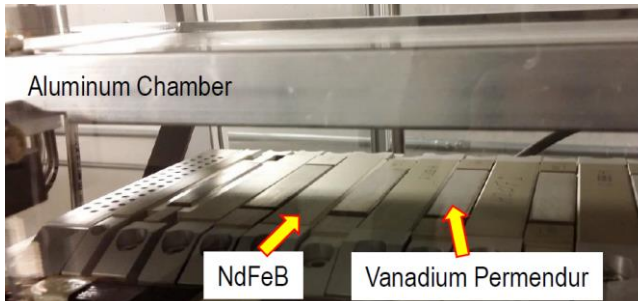




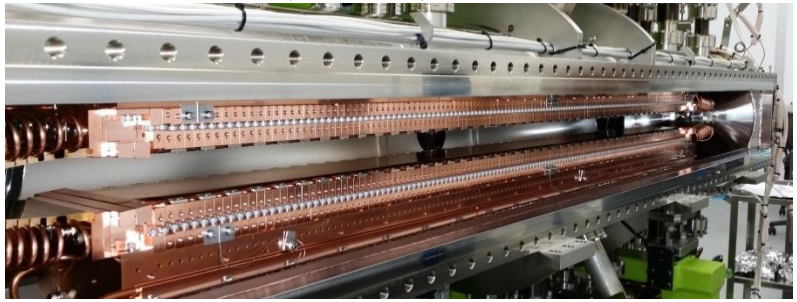
Tune shift with current: quadrupole impedance of IDs



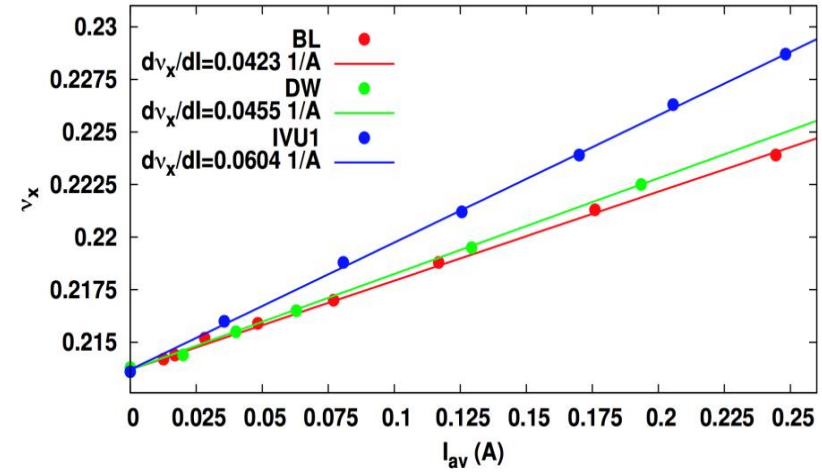
Damping wiggler chamber cross-section with magnetic gap closed, $d_{dw} > t_{dw} + b_{dw}$ and $t_{dw} \ll b_{dw}$

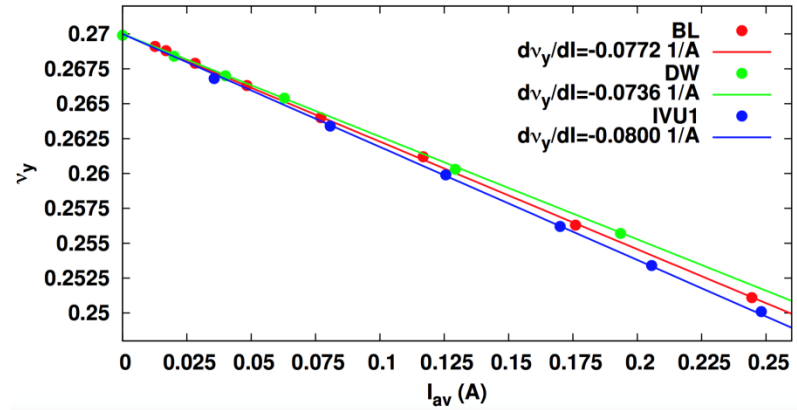


Damping wiggler at open position and the aluminum vacuum chamber (side-view)



IVU





Horizontal (a) and Vertical (b) betatron tune shifts versus average current for lattices with local $\beta_x = 21m$.

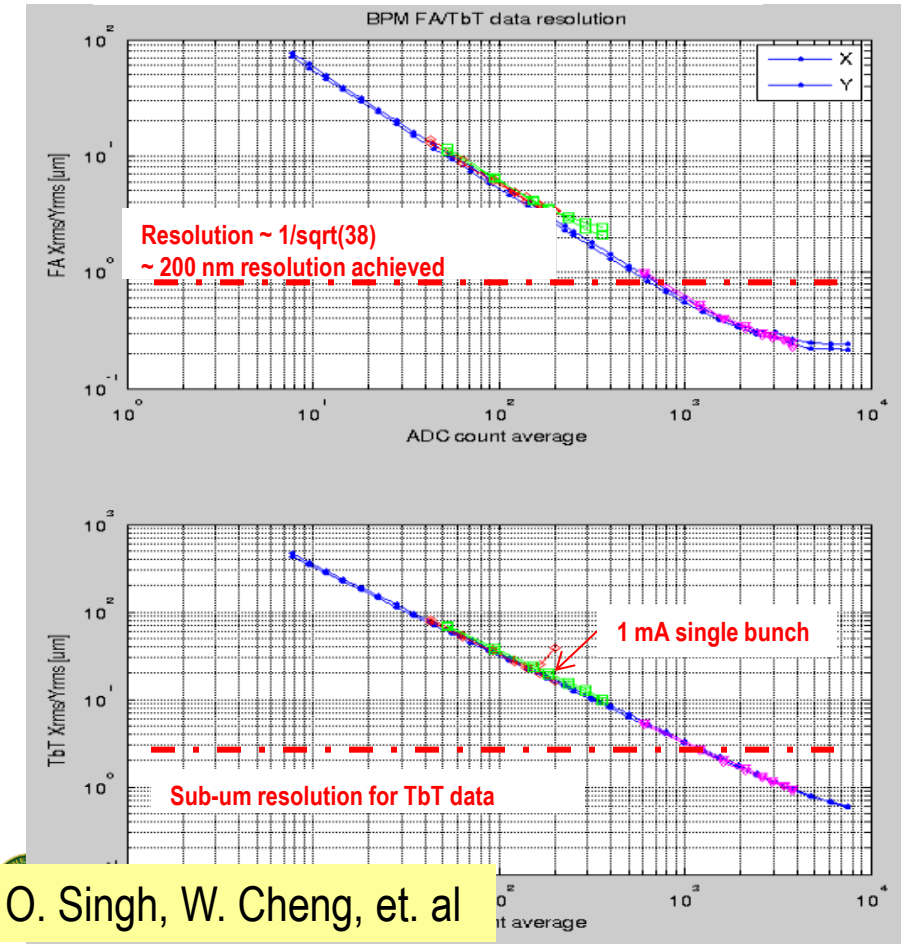
- Measurement results agree with analytic result
- The observed IDs effect on tune slope change in x plane is bigger than y plane, due to high beta function

A. Blednykh, PRAB 2016

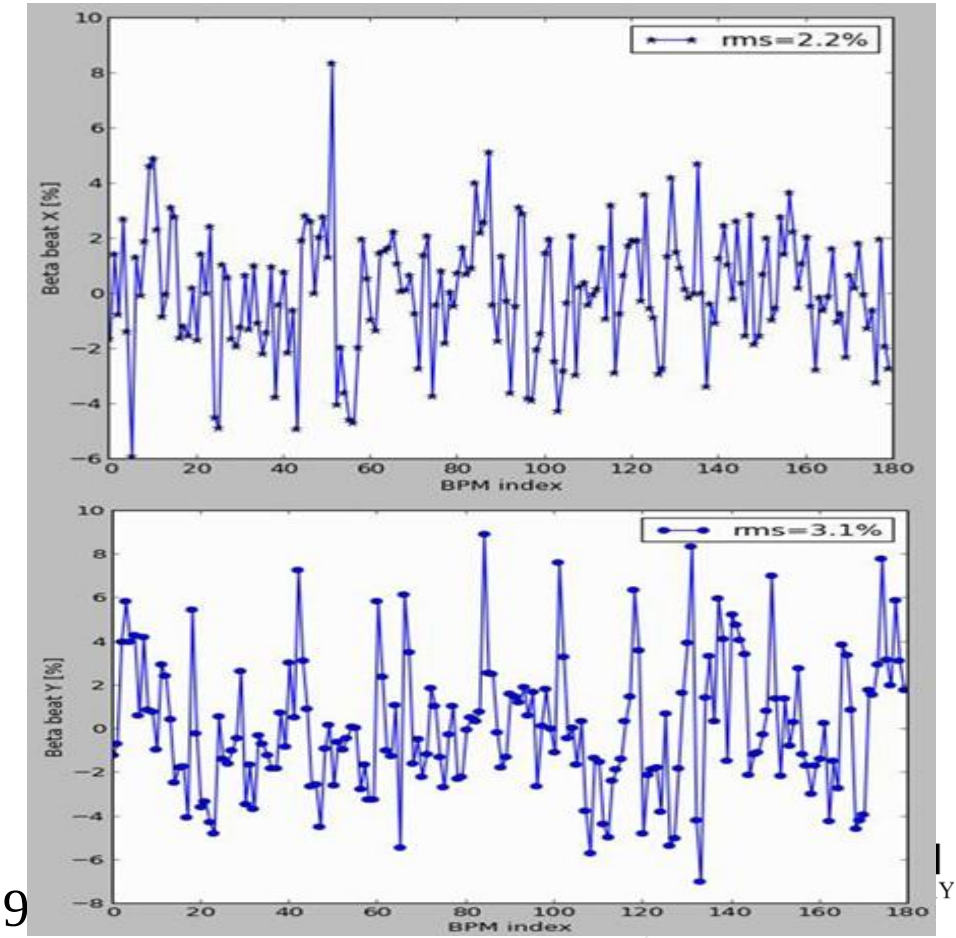
BPM system

- In house development with TBT, 10 kHz and 10 Hz capability
- Resolution verified with beam: 200 nm in 10 kHz, 1 μm in TBT (single bunch fill)
- TBT used for injection & kicked beam studies (routine lattice correction), FA for fast orbit feedback & interlocks, SA for orbit measurements

BPM FA/TBT resolution measurement



BPMs TBT data for lattice correction

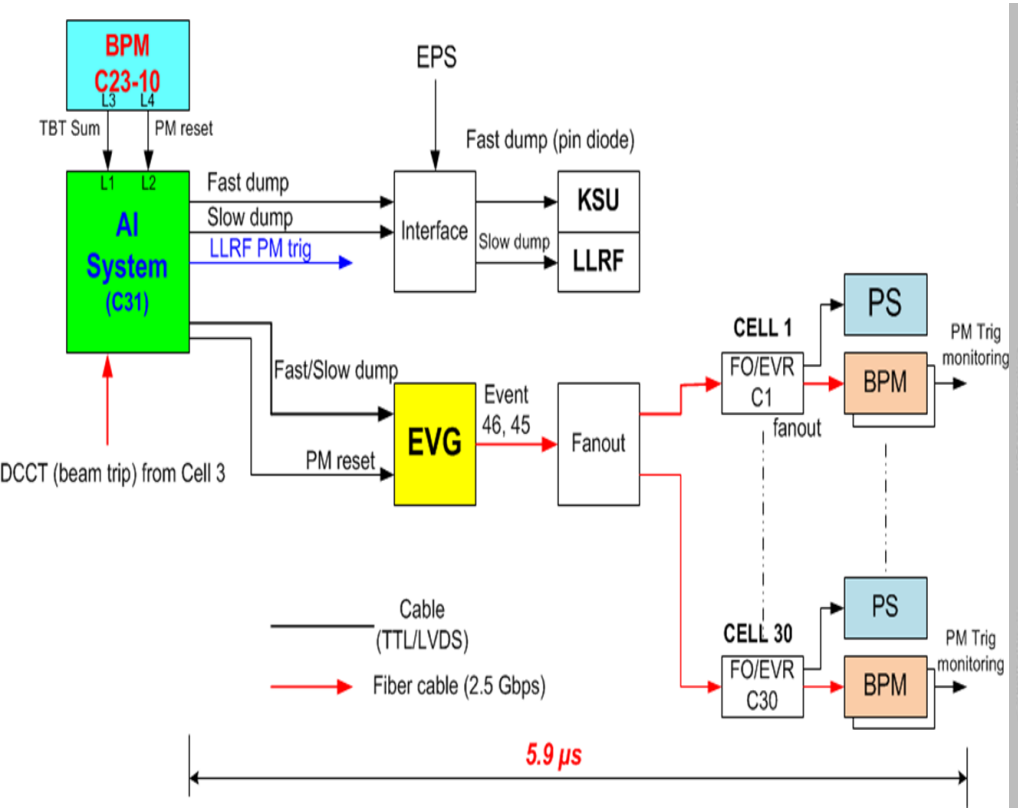


O. Singh, W. Cheng, et. al

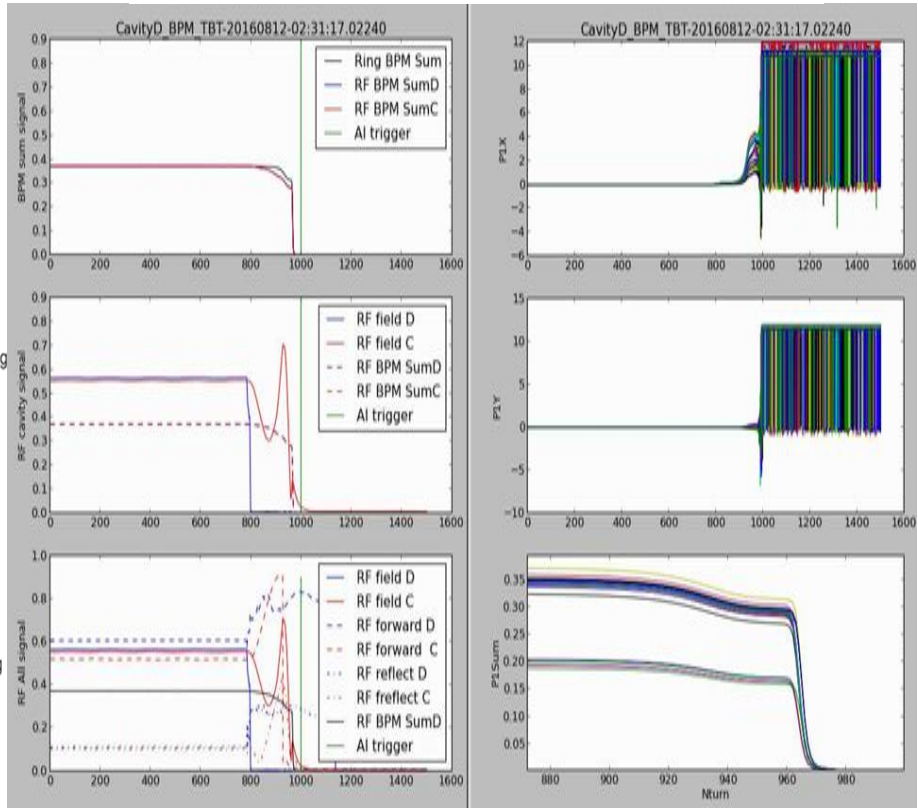
Post mortem function: beam dump analysis

- Various sources (AI protection system or subsystem malfunction) may cause beam dump
- Post mortem function: capture the sub-systems status and beam information during beam dump, including RF system, power supply, BPMs and active interlock system. Data is used to analyze subsystem trip sequence
- Beam dump sources: RF Cavity, PSs, AI, IS kicker, EPS, PPS...

Global PM configuration



Example of beam dump source: RF trip

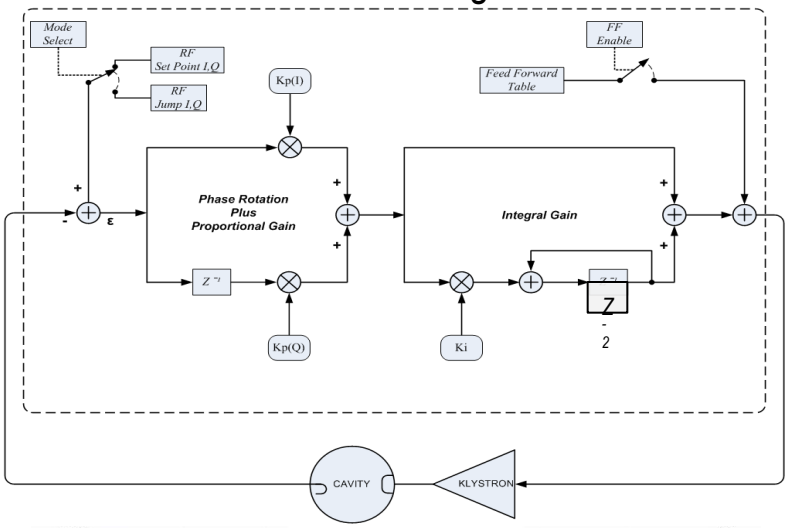


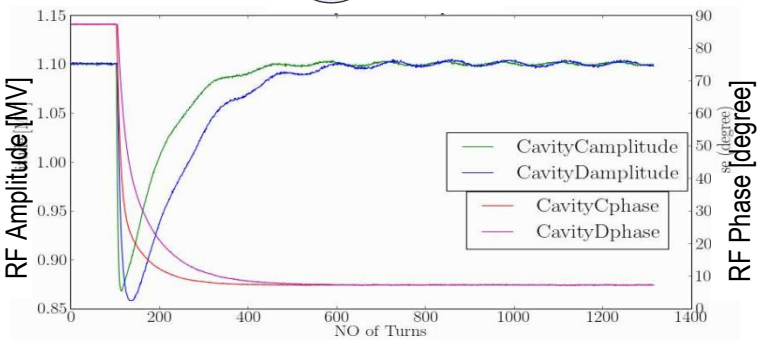
Beam study: RF pinger

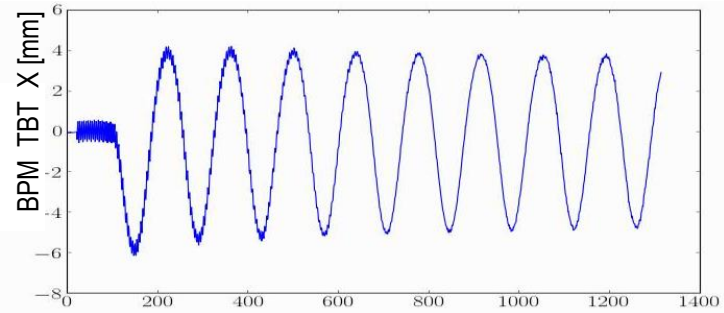
- RF pinger: sudden change of RF cavity phase or voltage, which will induce longitudinal beam oscillations
- RF pinger presents a powerful tool for investigation of beam dynamics
- NSLS-II storage ring RF system is capable of generating flexible set-point tables and finely control parameters of RF feedback
- NSLS-II RF system and SR BPM system are synchronized with precise timing control and high rate data acquisition

- Using RF phase jump, we measured machine momentum aperture
- Studied dynamics of beam crossing ½ resonance with stopband width control

LLRF block diagram







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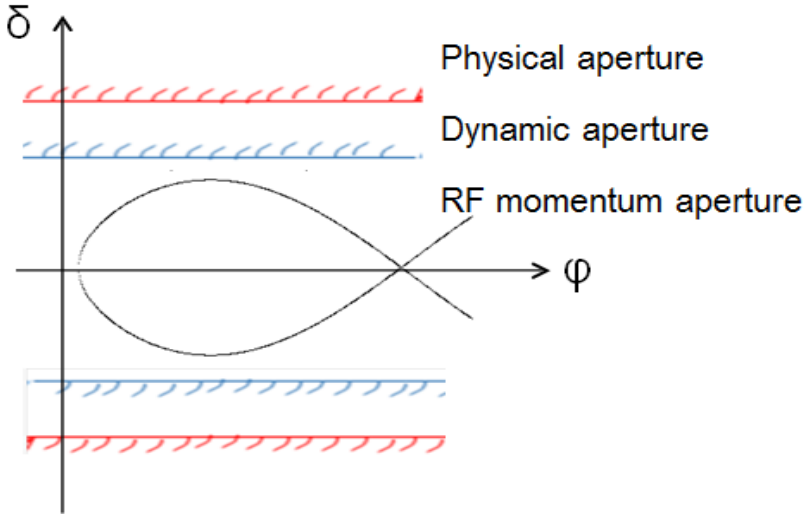
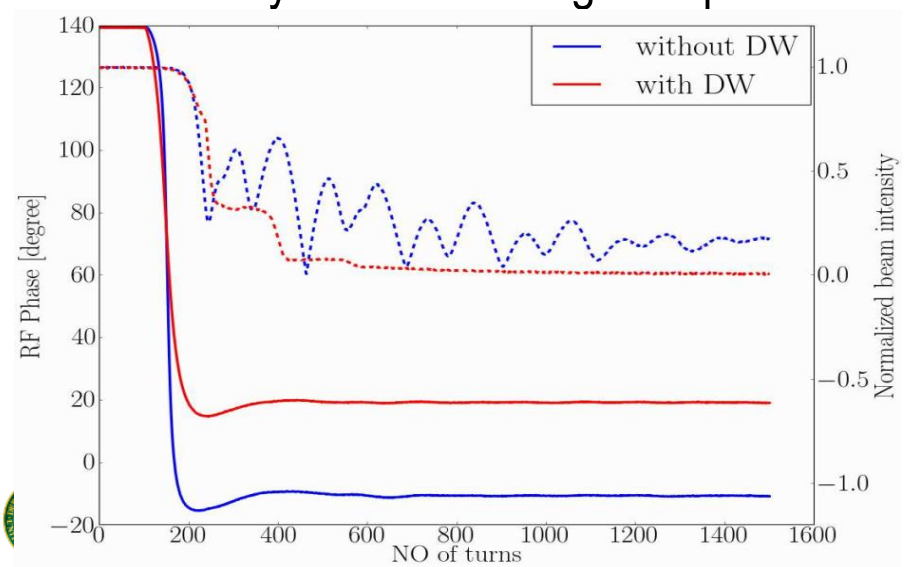
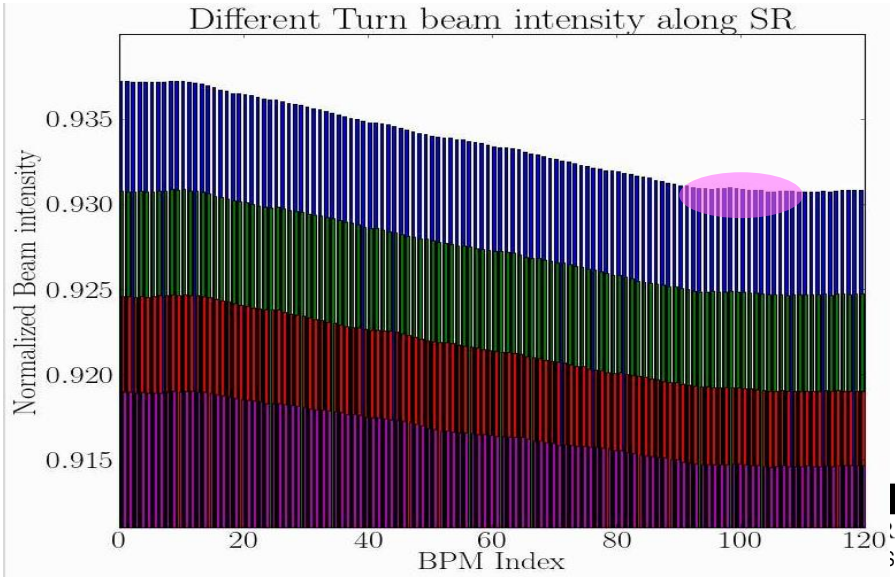
RF pinger applications: momentum aperture measurement

- Momentum aperture studies
  - with and without DWs @ 1.8 MV
  - Localize aperture limit with beam loss
- Retrieval of longitudinal phase space motion
  - TBT X→ δ
  - RF button signal→ ϕ
  - TBT sum signal→ beam loss
- W/O DWs, beam lost with measured δ_{max}@2.4%
- With DWs, beam lost with measured δ_{max}@1.8%
- Conclusion: measured momentum aperture is limited by RF bucket height as predicted

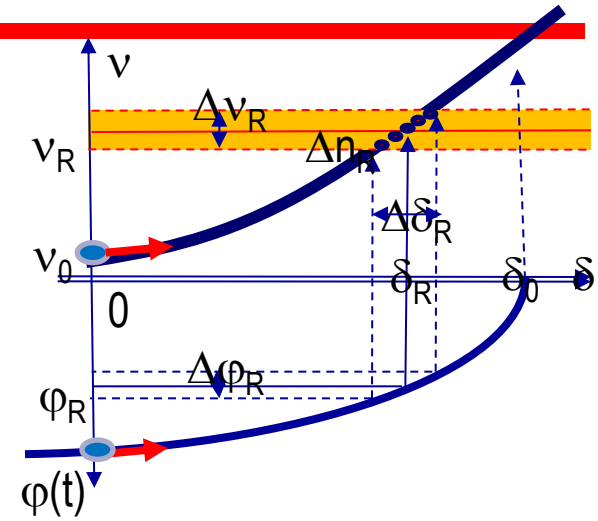


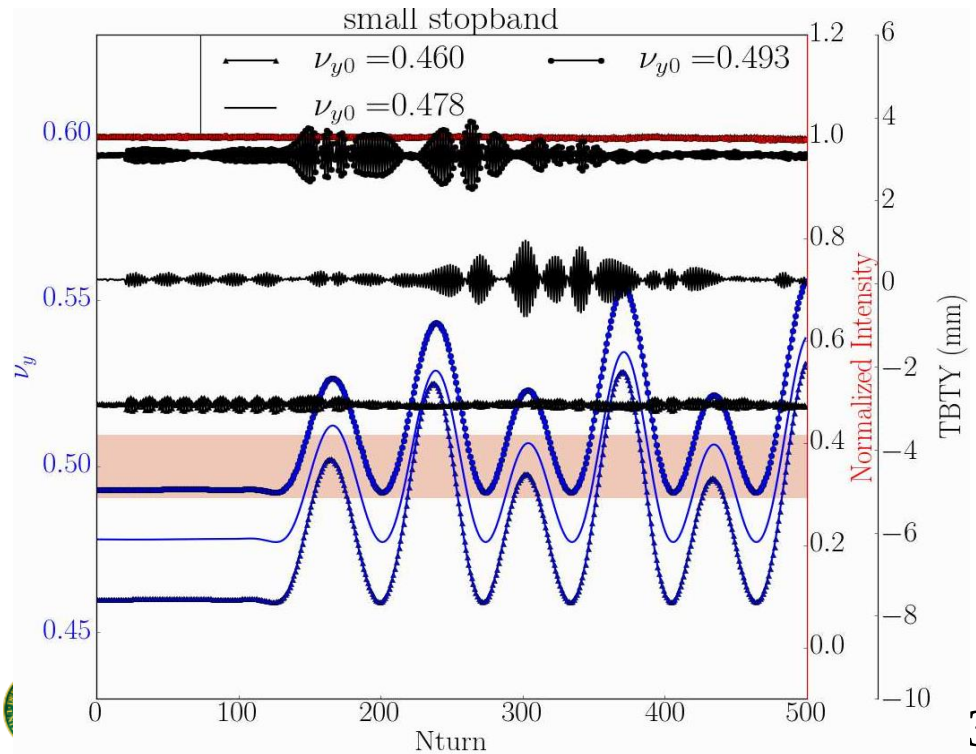


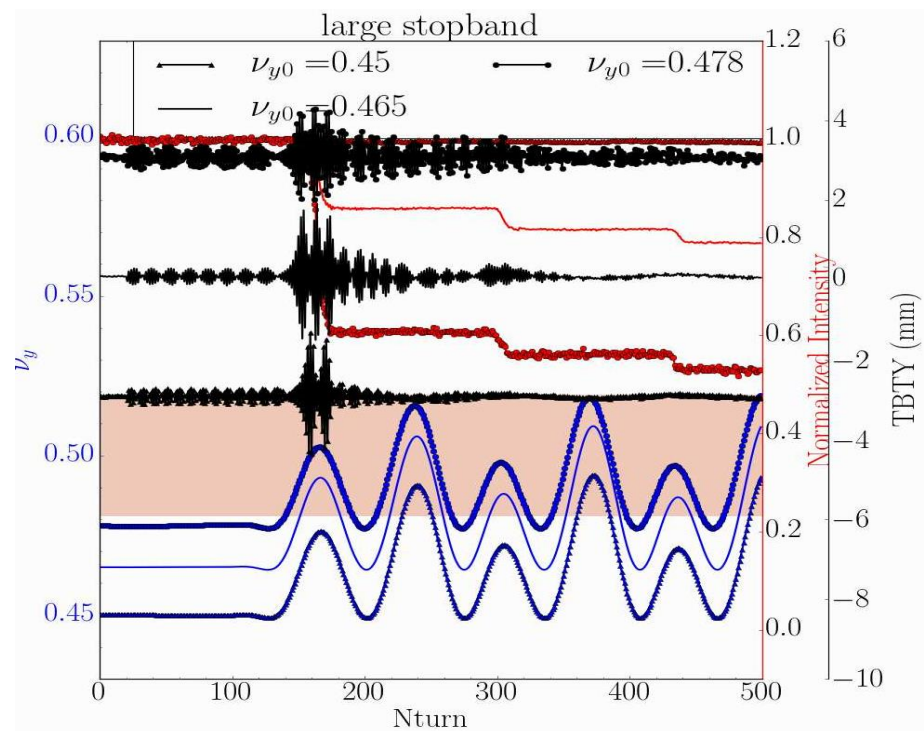


RF pinger applications: Lossless crossing of ½ resonance

- Chromatic tune footprint crosses major resonance (MBA lattice)
- Control resonance stopband with harmonic quads
- Crossing ½ resonance with tune modulation by synchrotron oscillations from RF pinger
- Conclusion: it may be unnecessary to confine the chromatic tune footprint between the resonance stopbands. The storage rings with a large chromatic tune swing can yet successfully reach large momentum aperture







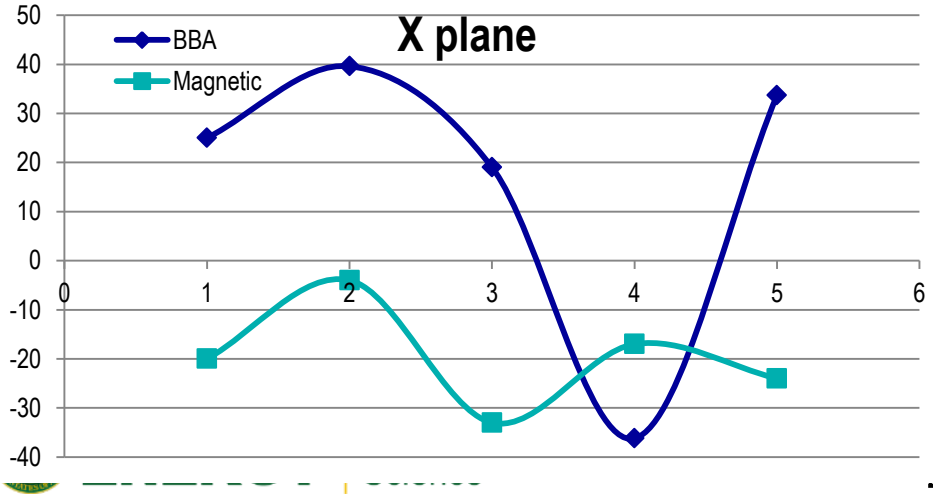
Sextupole alignment

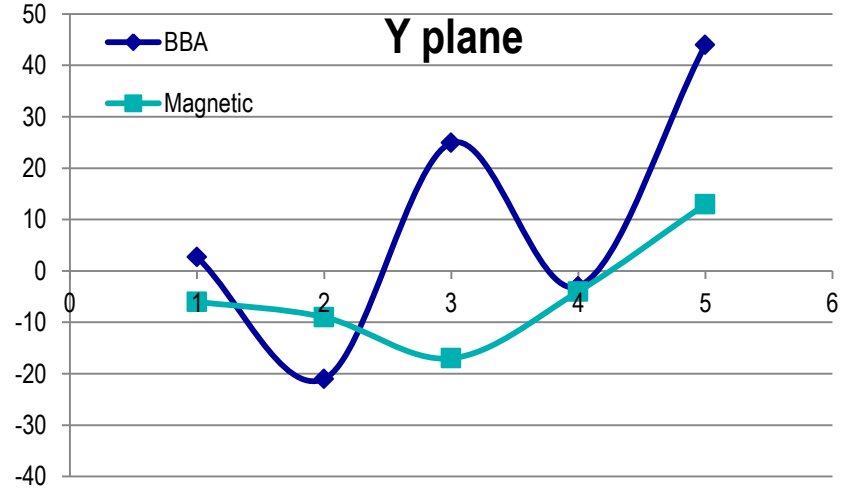
- Sextupole effects: orbit distortion and beta beat
- Specified alignment magnet to magnet 30 um
- Magnetic measurement in the lab: <15 um. Any changes during delivery/installation?
- Method: local bump beam at sextupoles and measure the orbit distortion.

$$\theta_x = \frac{1}{2}k_2L(x^2 - y^2) \qquad \frac{d\theta_x}{k_2Lx_{bump}} = \frac{1}{2}x_{bump} - x_{sext_{offset}} \qquad \left(\frac{1}{2}x_{bump}, \frac{d\theta_x}{k_2Lx_{bump}}\right)$$

$$\theta_y = k_2Lxy \qquad \frac{d\theta_y}{k_2L} = \left(y_{bump} - y_{sext_{offset}}\right)x_{bump} \qquad \left(x_{bump}, \frac{d\theta_y}{k_2L}\right)$$

- Sextupole to Quad alignment error with BBA is within 50 μm (refer to the beam orbit frame).
- Qualitatively, BBA results confirm that sextupole to quad alignment with vibrating wire method are in very high precision.





Conclusion and outlook

- Achieved 250 mA top off routine operation.
- Stored beam current 400 mA with IDs.
- 3700 hrs beamline operation in FY16 with machine reliability >90%.
- Steadily increase of beamline community (16).

- In FY17, provide 4500 hrs operations with 6 new beamlines upto 350 mA.
- Progressing with increasing machine performance and operations reliability.
- Commission new IDs, FEs and beamlines.
- Continue with manufacturing and testing of 3rd RF cavity.
- Advancing simulations operations with 3rd harmonic RF cavity.
- Resolving issue with overheating of kicker ceramic vacuum chambers.
- Developing test bench for experiments with novel undulator concepts.
- Explore low-emittance Storage Ring lattice options.

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