NSLS-II
the new synchrotron radiation light source at BNL

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Presentation at ALBA on 13 November 2015

Overview

- NSLS-II Overview
- NSLS-II Timeline
- Commissioning of Injector and Storage Ring
- Commissioning of Insertion Devices, Front-End and Beam-lines
- Achieving of Design Parameters
- NSLS-II Beamlines
- NSLS-II Operations

NSLS-II Performance Goals

The acknowledgement of the NSLS-II mission (CD-0 in 2005) was based on the following expectations:

- **Spatial resolution of 1 nm**
- **Energy Resolution of 0.1 meV**

This translates into very a high brightness requirement of up to

$$B = 10^{22} \text{ photons sec}^{-1} \text{ mm}^{-2} \text{ mrad}^{-2} \text{ (0.1\%BW)}^{-1}$$

Such brightness is achieved with high beam current, small sub-nm beam emittance and in-vacuum insertion devices

$$I_{beam} = 500 \text{ mA}$$

$$\varepsilon_x < 1\, \pi \text{ nm rad}$$

$$\varepsilon_y = 8\, \pi \text{ pm rad}$$

Low Emittance Lattice

- **Large Circumference 792** m
  30 DBA cells $\varepsilon_x \sim N_{cell}^{-3}$
(minimum emittance 1 nm)

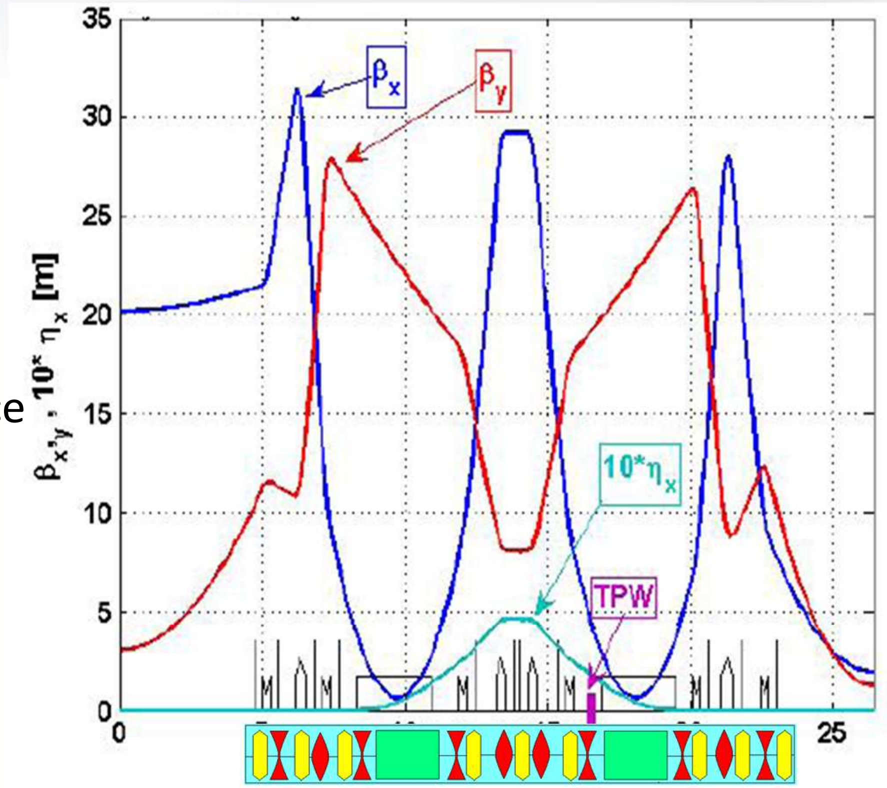
- **Soft (long) Bending Magnet** B= 0.4 T
  $\beta_{x-max} \sim \xi \sim 1 / L_{bend}$

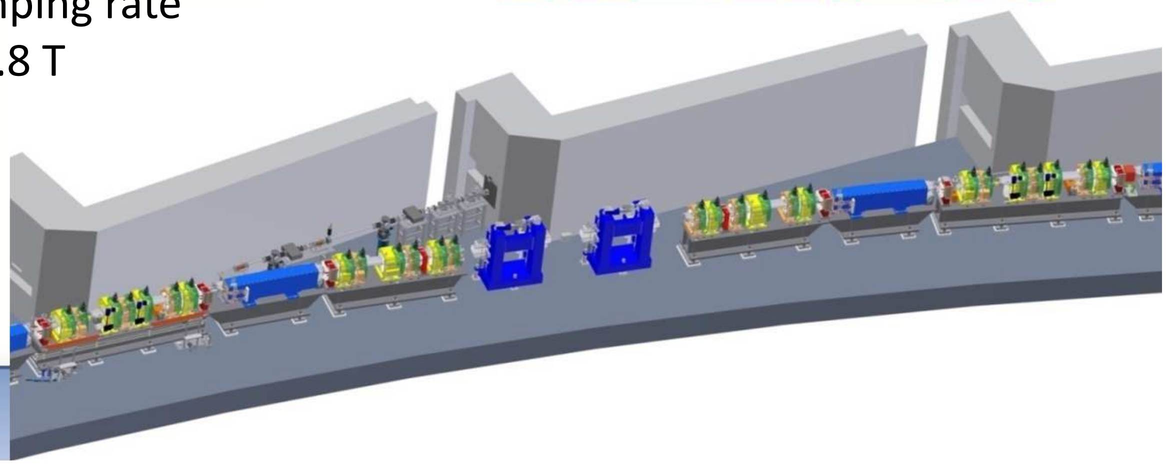
➔ Achieve close to theoretical minimum emittance without excessive chromaticity ε_{xbare}**= 2 nm**

- **Soft Bend**
  ➔ low radiation loss (**287** keV/turn/electron)

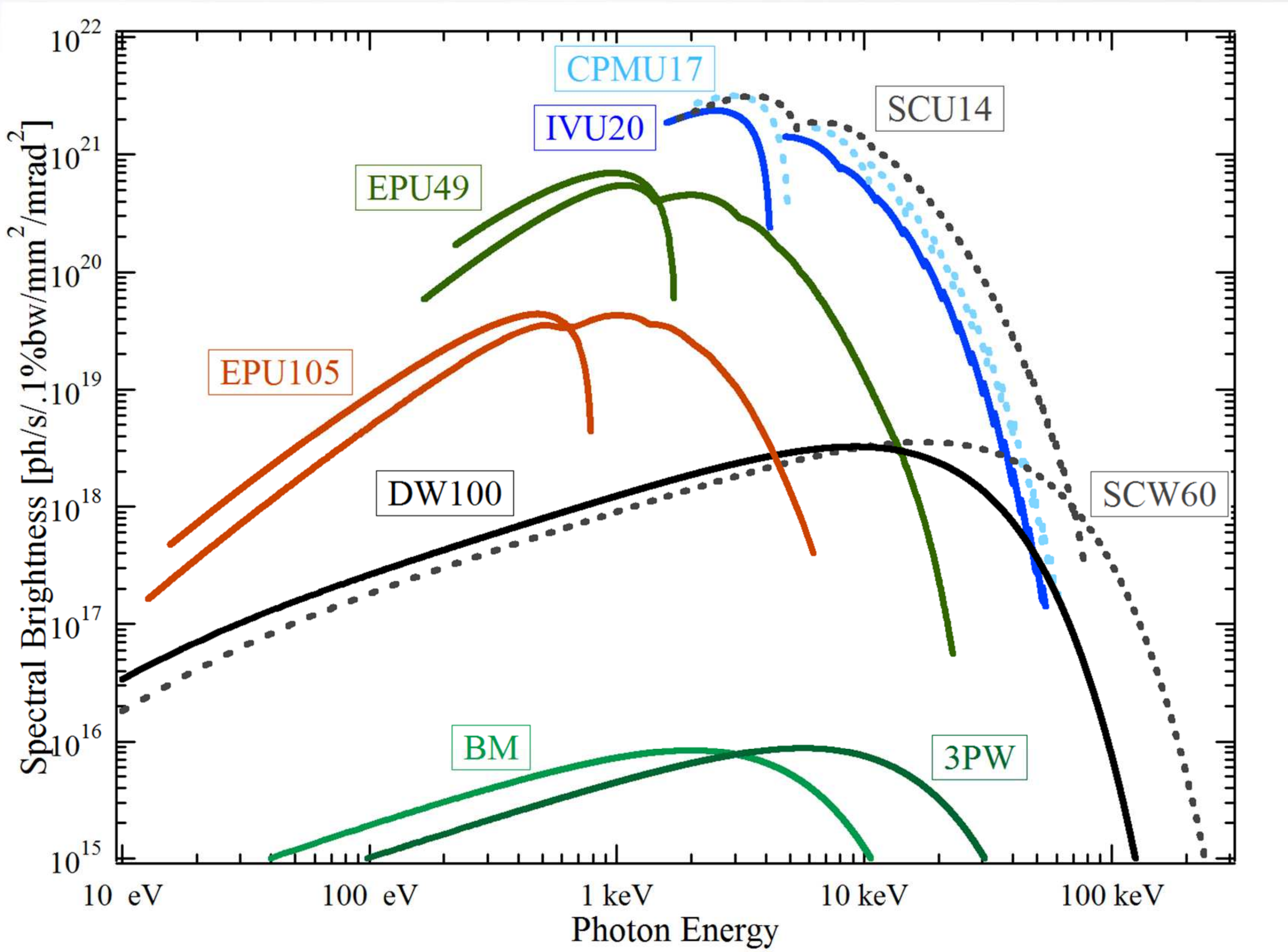
  ➔ efficient use of **damping wigglers** to reduce emittance by increased betatron damping rate
3 x 2 x 3.5 m (B_{max}= 1.85)wiggler @ 1.8 T
$\varepsilon_x = \varepsilon_{xbare} (P_{dipole})^2/(P_{dipole} + P_{wiggler})^2$

$\varepsilon_x < 0.9$ nm

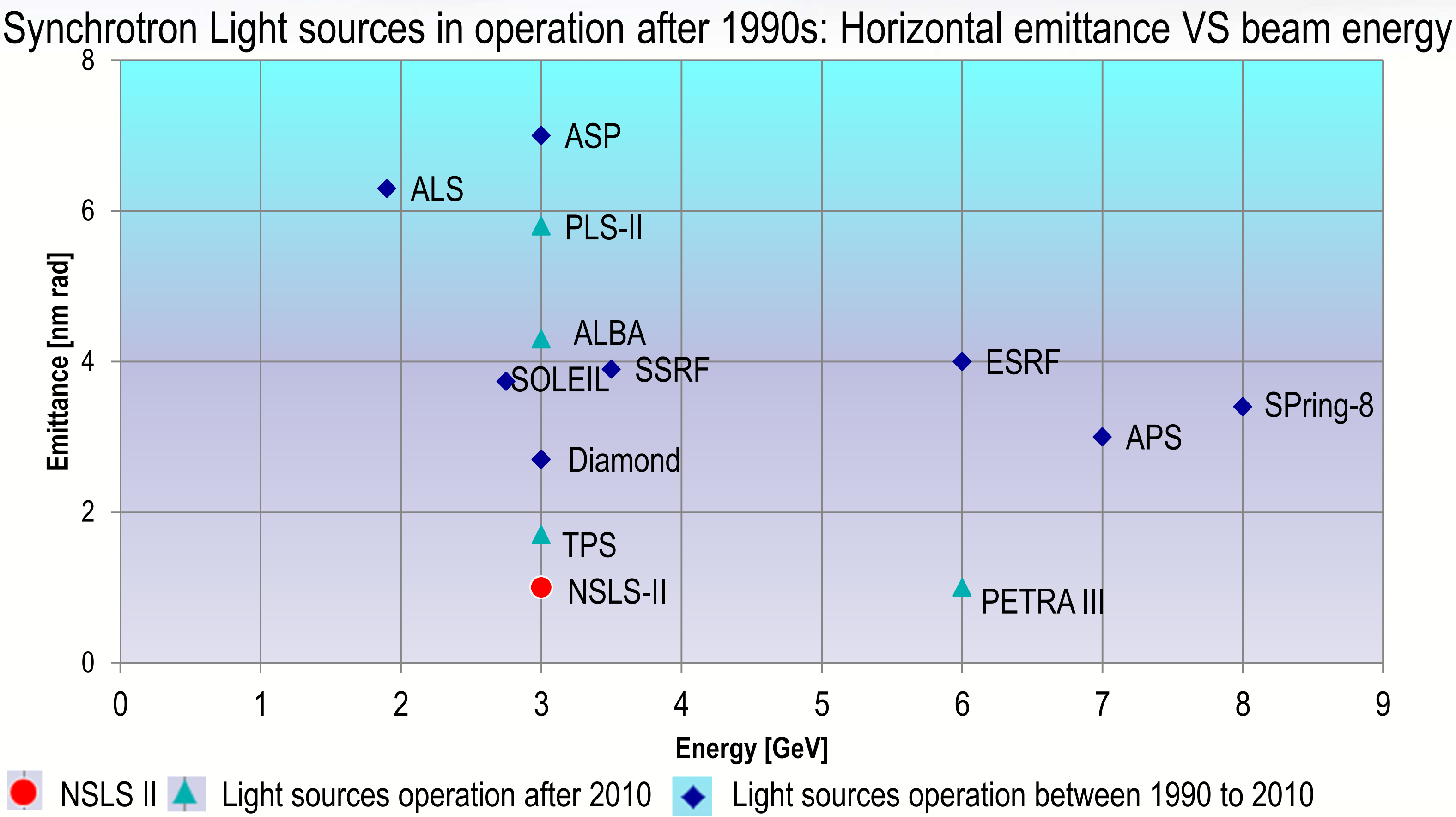




NSLS-II Brightness with Present and Future Undulators



Storage Ring Light Sources: Emittance

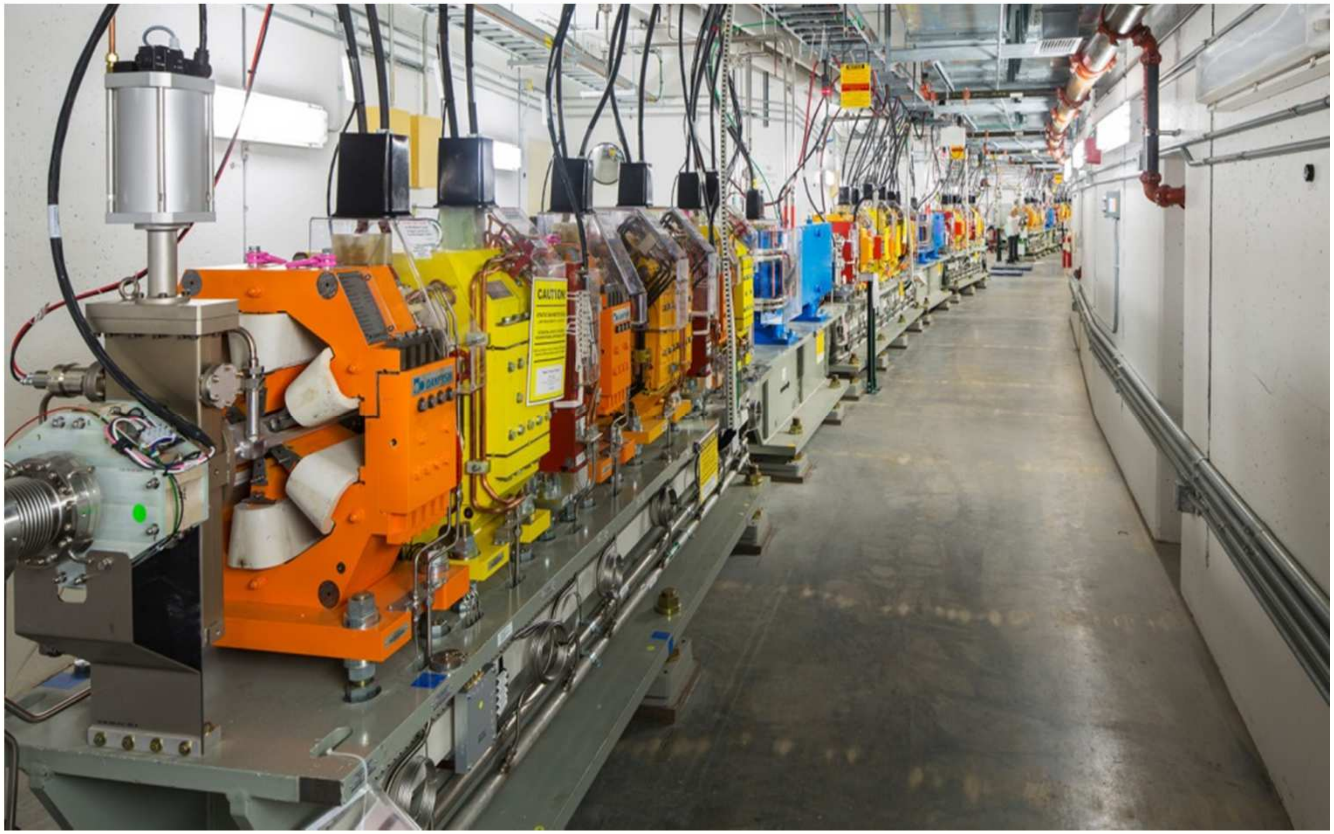


- Small beam emittance in NSLS II produces very high brightness.
- It enables nanoscale resolution for x-ray imaging of structure, elements, strain and chemical states study.
- It enables high-resolution energy spectrum (sub-meV) for low-energy excitations study from nanoscale heterogeneities and disorders.
- It enhances coherent fraction flux for fast dynamics study into sub-millisecond regime.

Accelerator Tunnel

Lattice structure
-30 dba cells
-15 long (9.3m) and -15 short (6.6m) straight sections

27 of which foreseen for insertion devices



Overview Hardware Systems

Magnets: room temperature, electromagnetic

Storage Ring Vacuum: Extruded Al, Integrated NEG (strips) pumping + lumped ion p

Magnet Power Supplies: Switched mode, air cooled, installed in sealed racks

Storage Ring RF: Two (four) 500 MHz, s.c. single cell cavities (CESR-B based design), one 2-cell 1.5GHz passive s.c. 3rd harmonic cavity (in-house/SBIR development), 2(4) klystron RF transmitters, 310kW each,

Booster RF: 1 PETRA 7-cell 500MHz cavity, 90 kW IOT- transmitter

RF Controller: FPGA based digital controller provides 0.1 deg phase stability

Storage Ring Damping Wigglers: 6 x 3.4m , 100mm period Nd-Fe-B with Permadur poles, 1.8Tesla peak field (emittance reduction: 2, used as radiation sources)

Instrumentation: BPM in-house development, band-pass filtered, FPGA V6 based digitizer, pilote tone based continuous relative calibration of the button signals, resolution and stability @ 200 nm

Controls: EPICS, PYTHON based HLA , Deterministic serial loop for real time orbit systems and fast beam interlock

Insertion Devices: IVU, 20mm,21mm,22mm,23mm period length, EPU 49mm, DW 100mm

NSLS-II Systems

Superconducting
500MHz RF

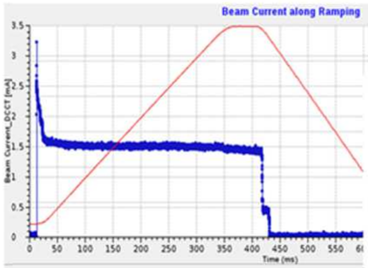
In vacuum
undulators

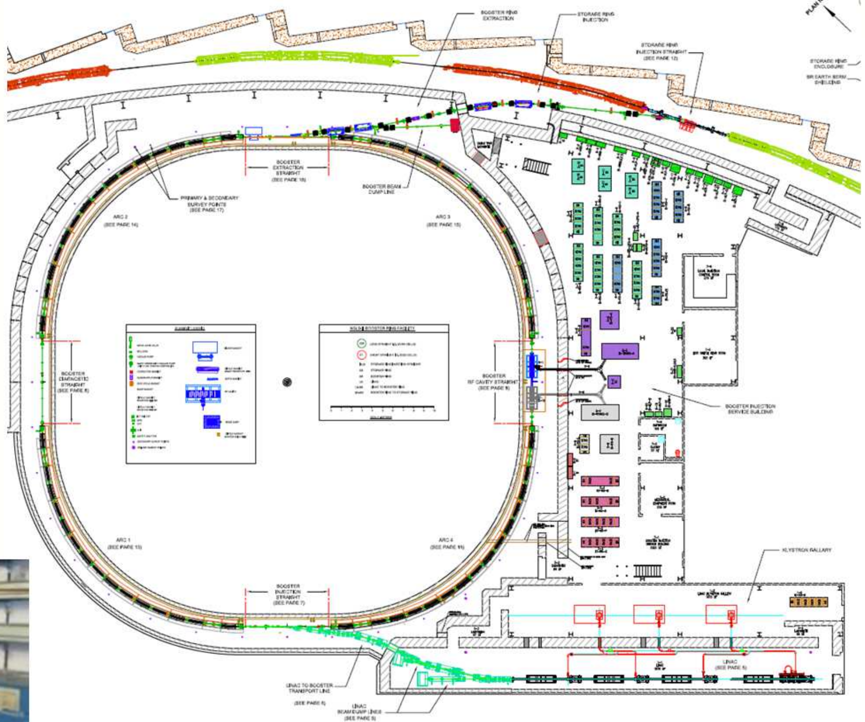
21 m of 1.85 tesla
Damping wigglers

NSLS-II INJECTOR

On-energy top-off injection with 1/min top-off rate

First 3GeV booster
beam Dec 31 2014





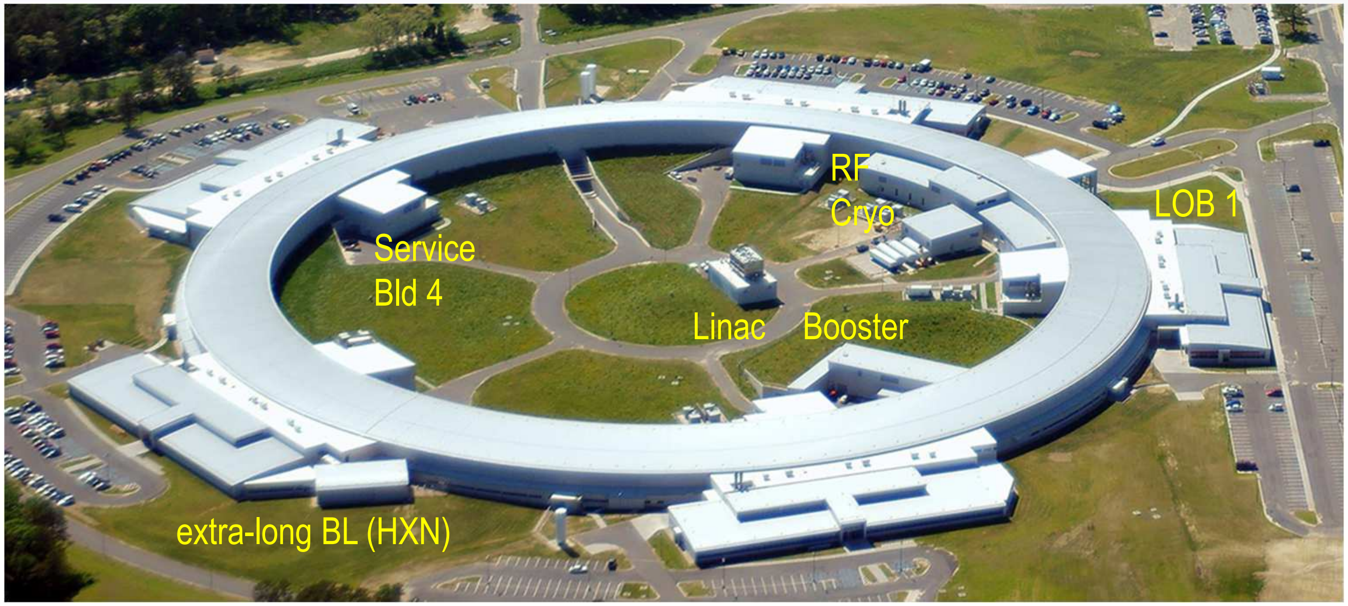
200 MeV LINAC

RF Frequency S-Band
Charge 15nC (nominal)
$\Delta E/E$ <1%
4 sectors
Thermionic Gun Sub-harmonic 500MHz Buncher
Variable bunch patters, single bunch-300ns pulse train
Solid state modulator

3 GeV Booster

Combined Function Lattice	
Circumference	158m
Injection Energy	200MeV
Extraction Energy	3GeV
Cycle Frequency	1Hz (2Hz)
Charge 10-15nC	@20-30mA
Emittance	35 nm rad

NSLS-II Site View



- Accelerator Tunnel 3.7m x 3.2 m x 792m
- Experimental Floor, width 17m
- 200MeV S-Band LINAC
- 3GeV Booster Synchrotron C=158m

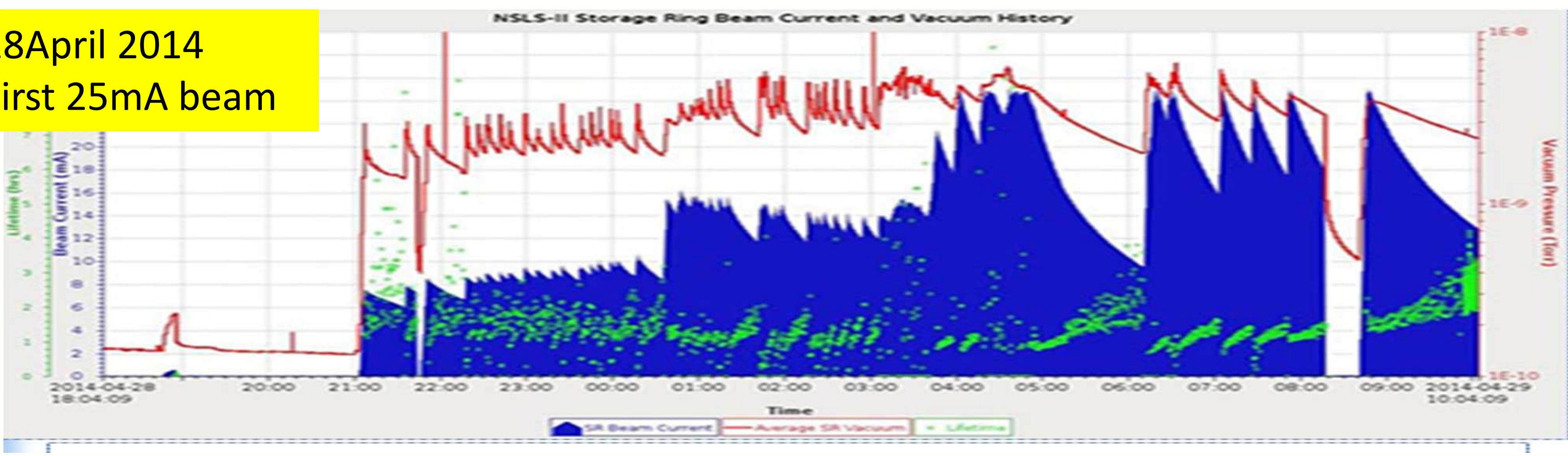
NSLS-II Timeline

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
March2012	Start LINAC Commissioning
December 2013	Booster Commissioning
April 2014	**Storage Ring Commissioning**
Sept 2014	Installation of 8 initial Insertion Device complete
October 2014	**Start of NSLS-II Accelerator Operation**
Fall 2014	Insertion Device and BL Frontend Commissioning
November 2014	First Light observed at CSX-beamline
December 2014	Scope of Accelerator complete (spare s.c. cavity delivered)
March 2015	**CD4** Completion of NSLS-II Project
February 2015	**Science Commissioning of Beam lines started**
March 2015	First synchrotron radiation scientific publication
April 2015	achieve 200 mA, design emittance and beam stability
July 2015	Achieve 300mA , first external user
Fall 2015	Top-off Operations 150-225 mA

Commissioning

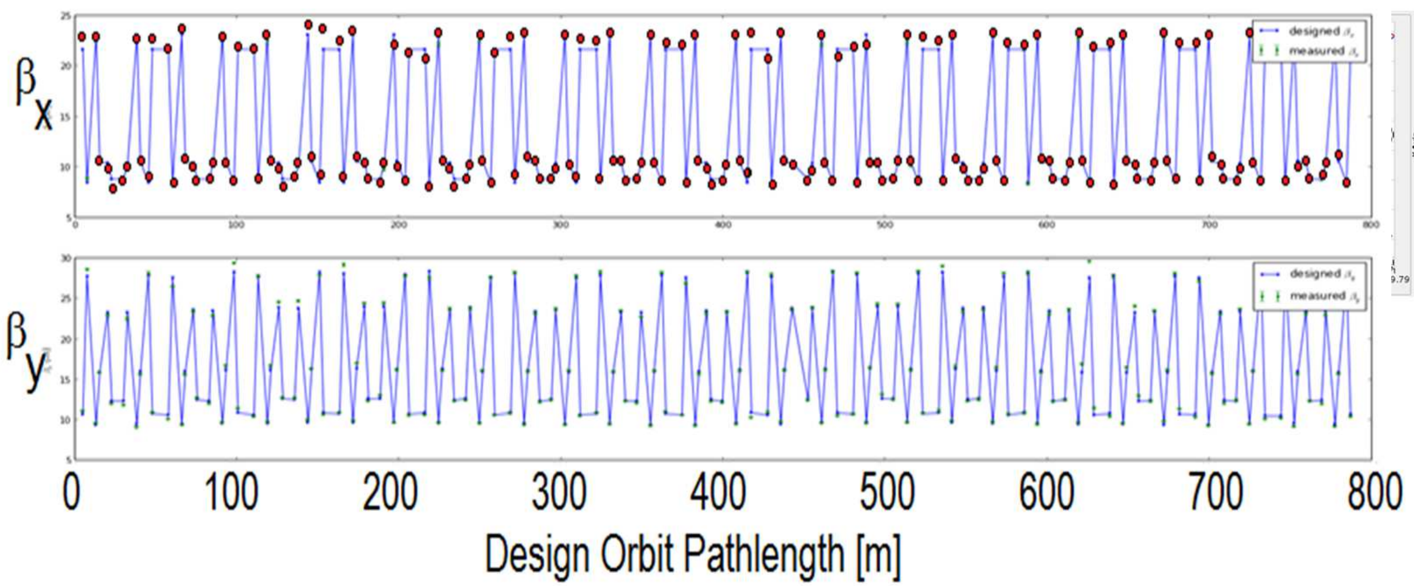
Period	Activity
March - May 2012	Commissioning of the LINAC
4 December’13 – 31 January ’14	Commissioning of the 3 GeV Booster Synchrotron (First acceleration to 3GeV 31Dec’14)
March 26-May 15 2014	Storage Ring Commissioning with a 7-cell Cu RF cavity
April 25	Demonstrate 25 mA of beam current (KPP 25mA)
2-5 July 2015	Commissioning of s.c. RF with beam, demonstrate 50mA
October-December 2014	Commissioning of the 8 initial insertion devices (3 pairs of DW, 4 IVU, 1 EPU) and Frontends
Spring 2015 user run	further optimization during machine studies, reach 200mA

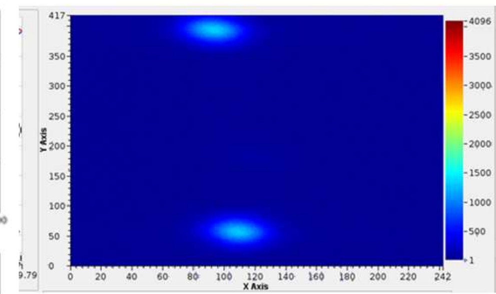
18April 2014
First 25mA beam



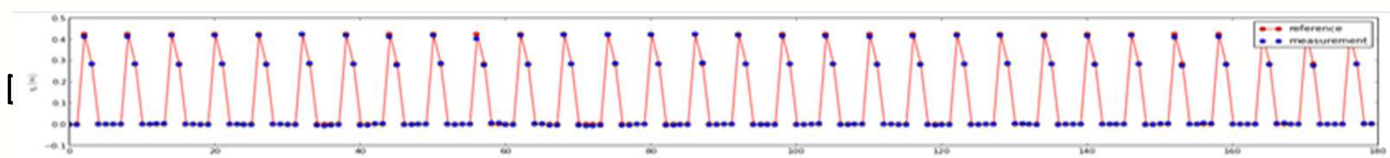
Lattice Commissioning

- Beam Optics sensitive to residual beam orbit
- Use BBA and response matrix measurements and correct iteratively
- ➔ residual orbit 50 μm **beta beat** $\Delta\beta/\beta \leq$ **3% (rms)**



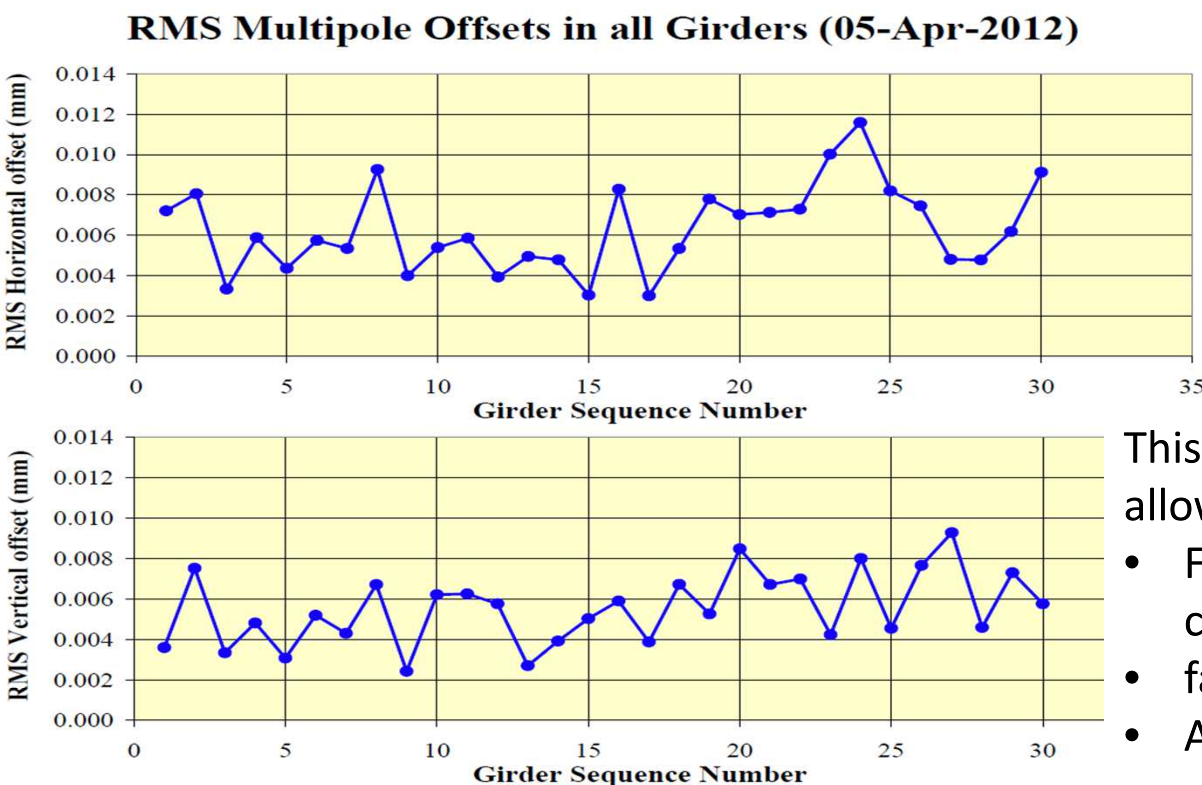


Stable ½ integer resonance crossing (vertical)
Very small errors,
➔ small stopband width

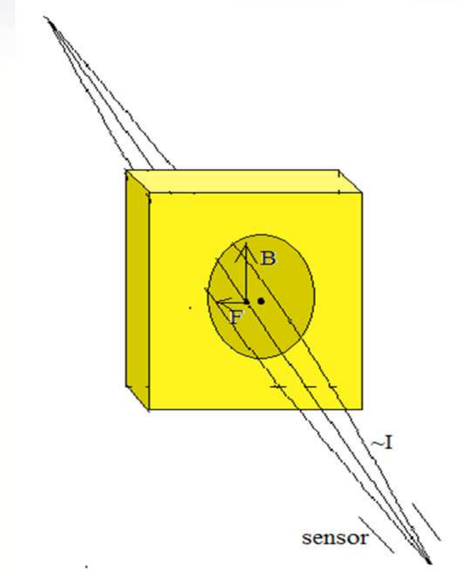


Precision of Magnet Alignment on Girders

Achieved with combination of laser trackers and stretched wire based measurement under strictly controlled conditions



AlignmentSummary_All.xls RMS_Offsets

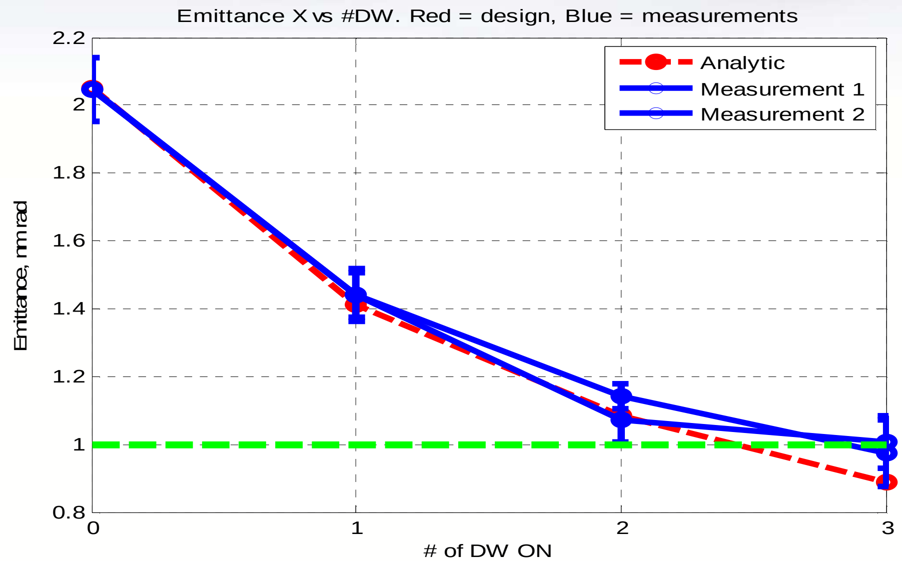


This high precision alignment allowed:

- First few turns without trajectory correction
- fast early commissioning
- Achieve small residual orbit < 50 microns
- Quick convergence BBA measurements and beam optics

Magnet Alignment under Controlled Conditions

Beam Emittance Verification and Optimization



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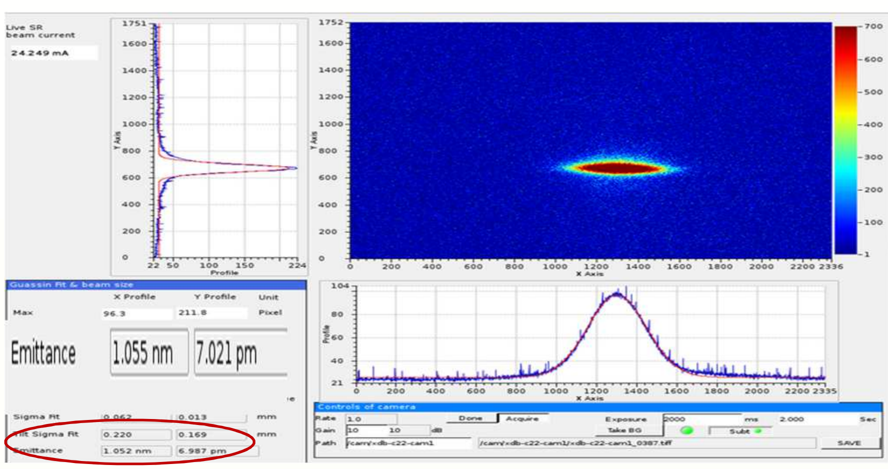
Number of Damping Wigglers

- **Design Emittance Achieved**

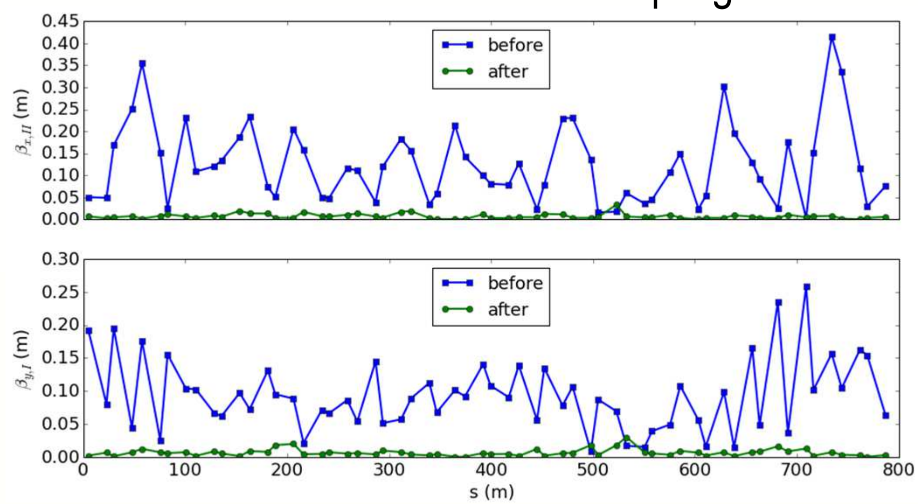
ε_x^{0dw} = 2.05 nm·rad, ε_x^{3dw} = 0.98 nm·rad,

ε_y = 6 pm·rad, exceed diffraction limited value of 8 pm-rad, after

- vertical dispersion correction
- Local coupling correction

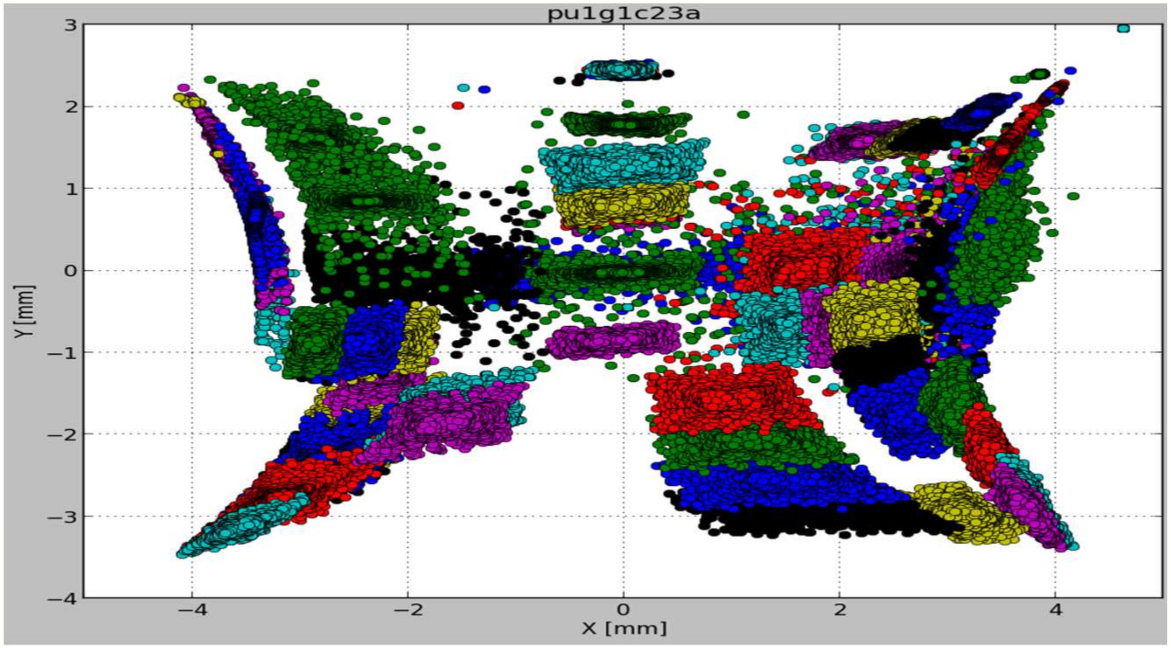


Mode-II beta function after local coupling correction



High Level Control System

- Control System Based on EPICS
- Most Operator Interface based on CSS
- Accelerator Model embedded into EPICS controls
- Python is the HLCS engine, Matlab and Matlab toolkit available
- system middle layer was very important to achieve quick optimization of beam optics, orbit control and beam quality parameters

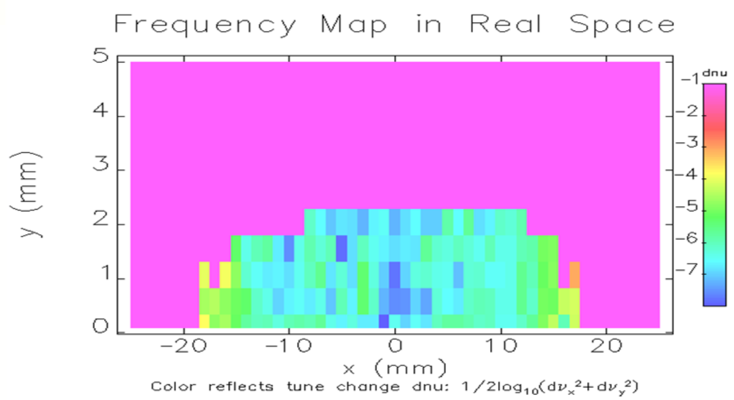


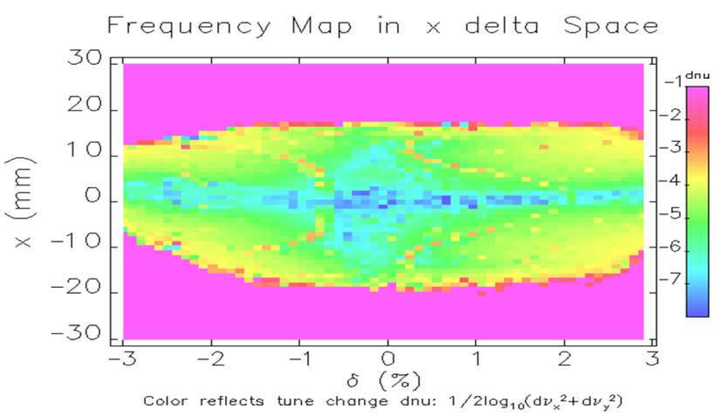
Automated 2-D aperture scan which uses a combination of DC and pulsed magnets

Dynamic Aperture

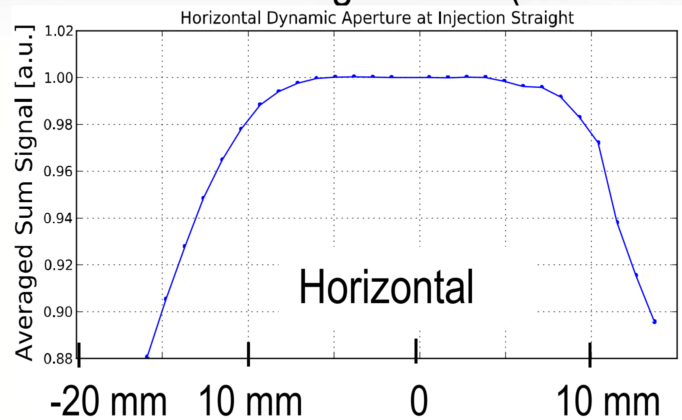
3 chromatic sextupole families, 9 families in total

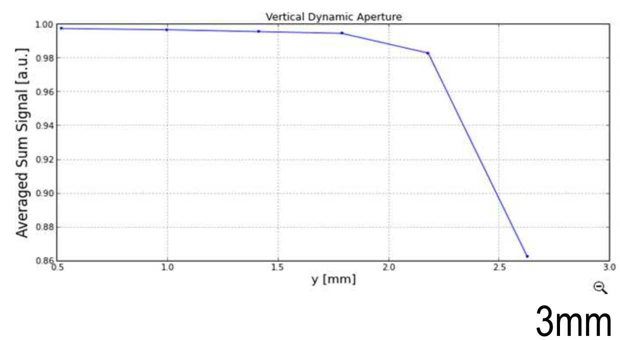
Calculations (frequency maps)

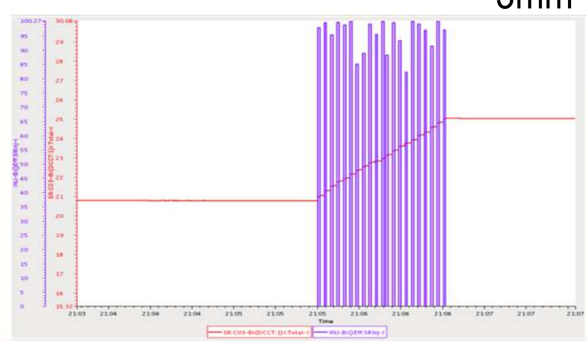




Commissioning Results (bare lattice)







➔ Injection Efficiency of >99%
(with ID gaps closed)

Orbit Stabilization

- **Beam orbit is naturally quite stable** without active stabilization thanks to well designed support system and careful control of all self made sources of vibration
  - Horizontal 2 microns, center of the short straight @ 5% of the beam size
  - Vertical 0.6 microns, center of the short straight @ 20% of the beam size
  (goal is 10% of the beam size)

- **Decentralized, distributed fast orbit feedback 1kHz BW**

- uses fast deterministic data link around the ring
- Algorithm is implemented decentralized in 30 cell controllers (each corrector uses all BPM signals and works with one row of the correction matrix (SVD decomposed)
- Correction has been tested successfully, SVD mode by mode, up to 1 kHz

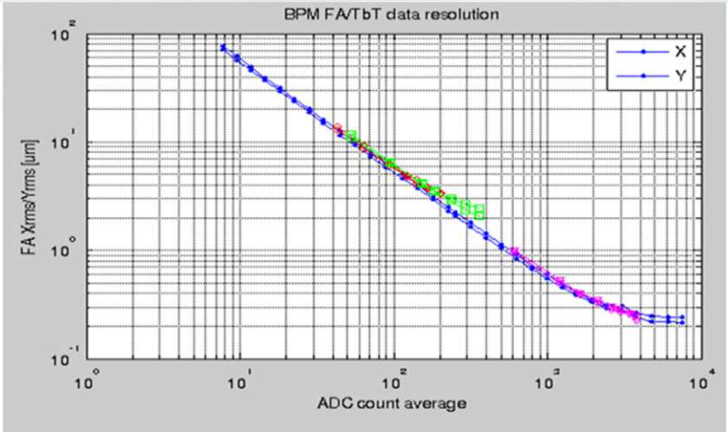
➔ **Beam orbits stabilization to 200 nm level ()**

- **Remaining Effort**

Reproduction of orbits after breaks and shut down (systematic magnet cycling, optimized machine data handling) ➔ work in progress

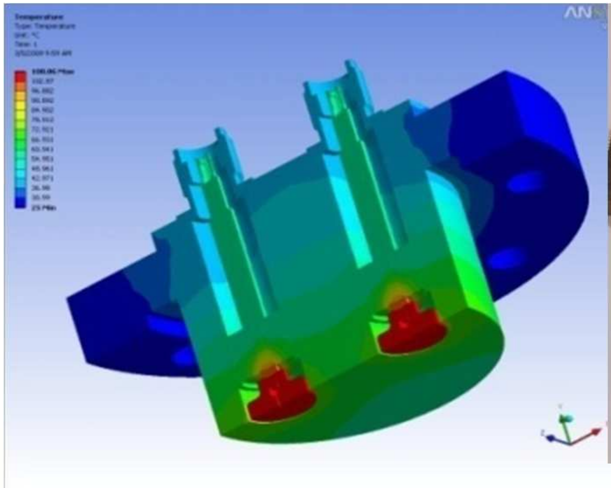
Instrumentation Commissioning

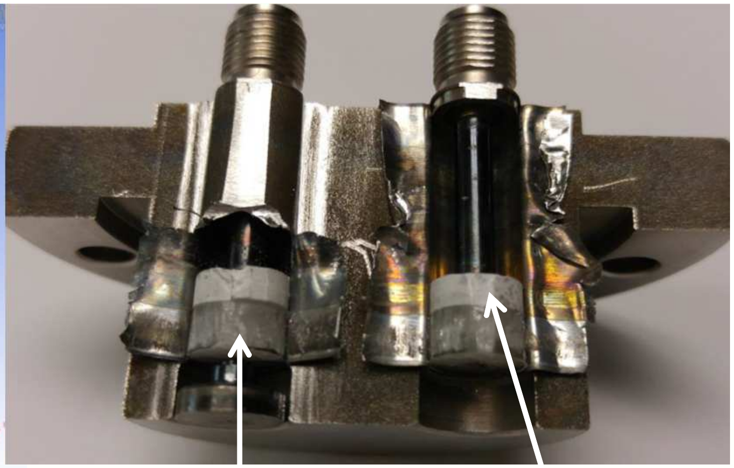
BPM Performance:
200 nm resolution verified with beam
(BPM noise vs resolution of digitalization)



Recent Results
High Intensity Button Test
Test runs 200bunches @ 150mA
Corresponds to
1000 bunches 500mA

➔ Observe some button heating (early design) >100 C
BN insufficient thermal contact with flange?



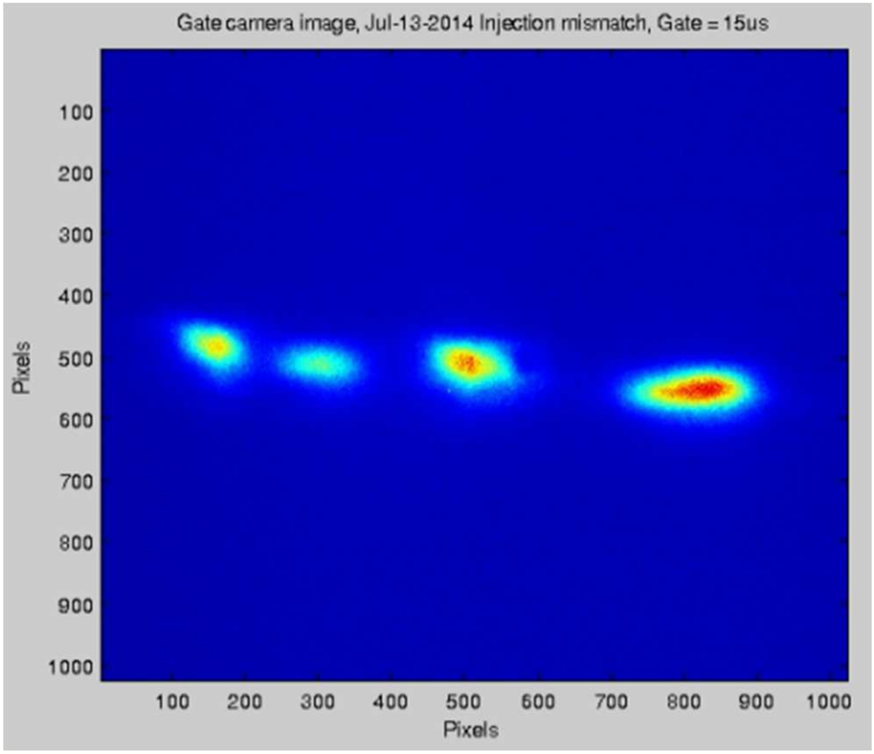


Ceramic Feed through

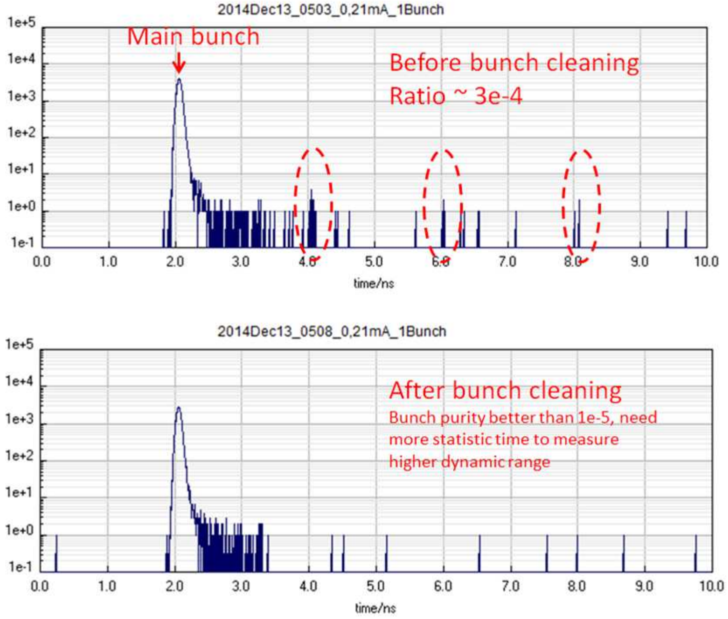
BN Heat Sink

Instrumentation Commissioning

Example: Results with TbT Synchrotron Light Monitor (injected beam on successive turns)

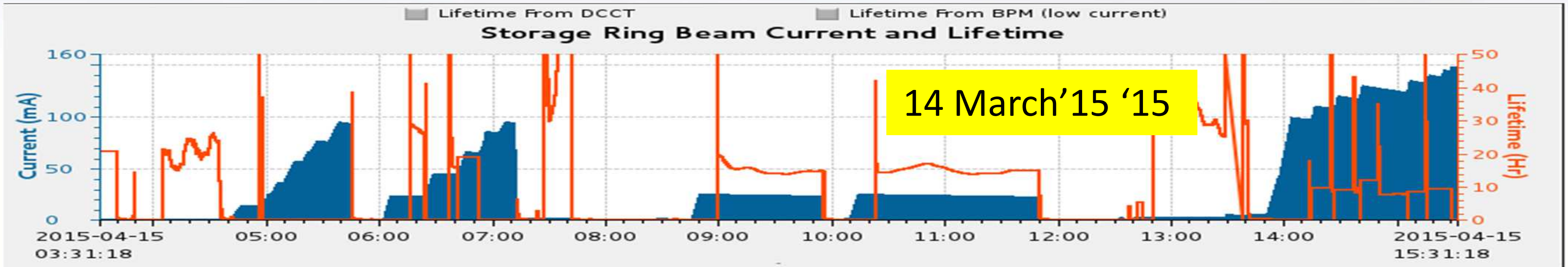


Example: Bunch Cleaning (Injection and Touscheck Effect) using transverse MB-Damper system

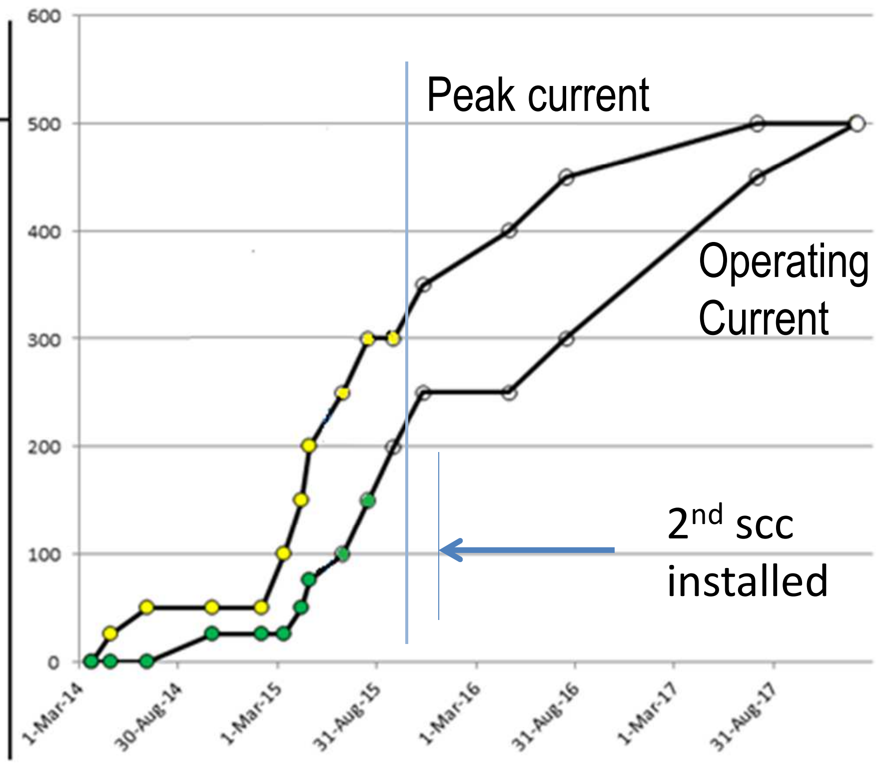


Single bunch purity measured using **Time Correlated Single Photon Counting** method After cleaning, bunch purity was **better than 1e-5**. Bunch purification was realized using BxB feedback system.

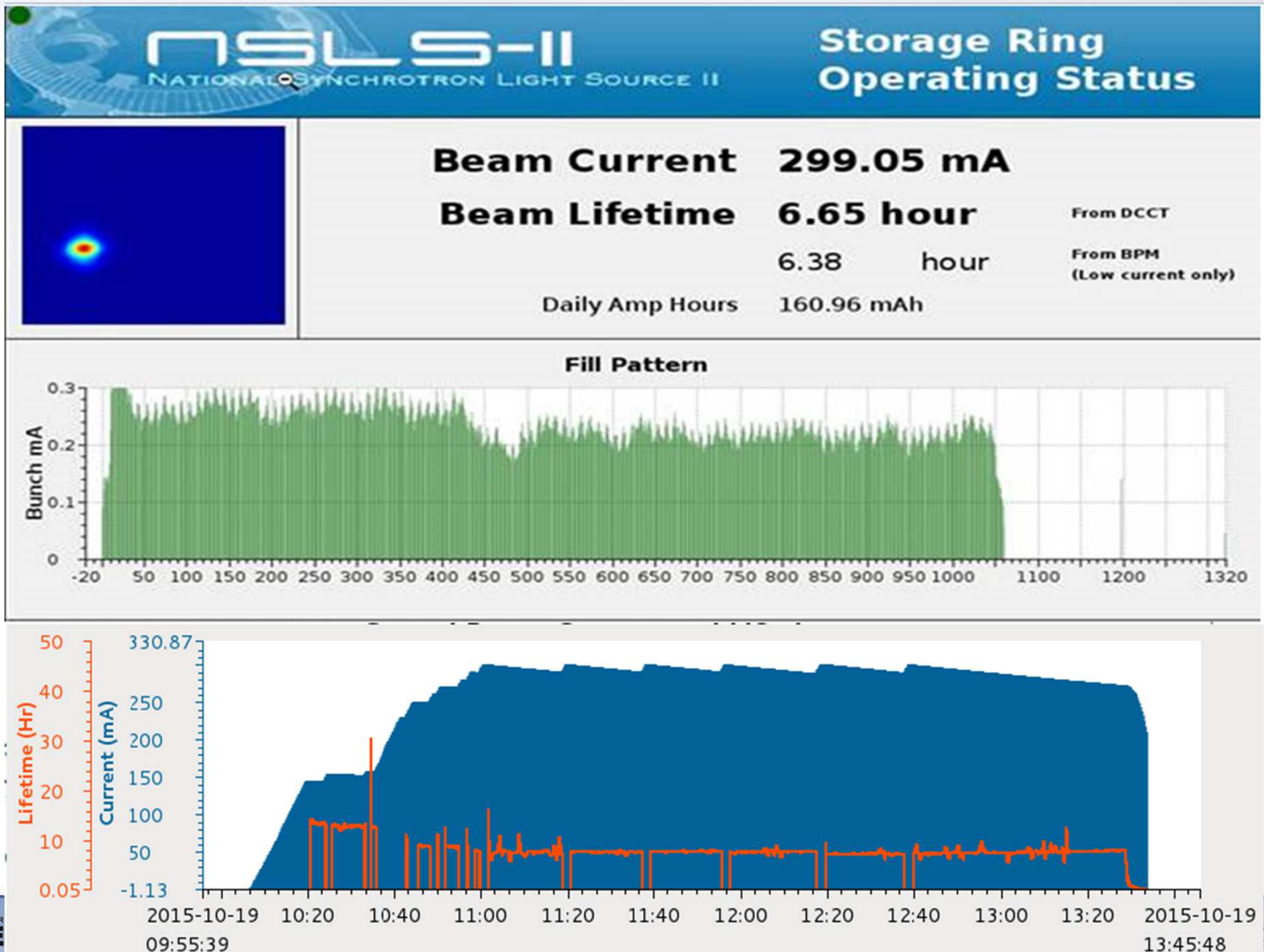
High Beam Intensity



	Peak Current		Operating Current	
26-Mar-14	0	mA	0	mA
29-Apr-14	25	mA	0	mA
5-Jul-14	50	mA	0	mA
1-Nov-14	50	mA	25	mA
1-Feb-15	50	mA	25	mA
15-Mar-15	100	mA	25	mA
14-Apr-15	150	mA	50	mA
30-Apr-15	200	mA	75	mA
30-Jun-15	250	mA	100	mA
15-Aug-15	300	mA	150	mA
1-Oct-15	300	mA	200	mA
25-Nov-15	350	mA	250	mA
1-May-16	400	mA	250	mA
15-Aug-16	450	mA	300	mA
1-Aug-17	500	mA	450	mA
1-Feb-18	500	mA	500	mA



300 mA

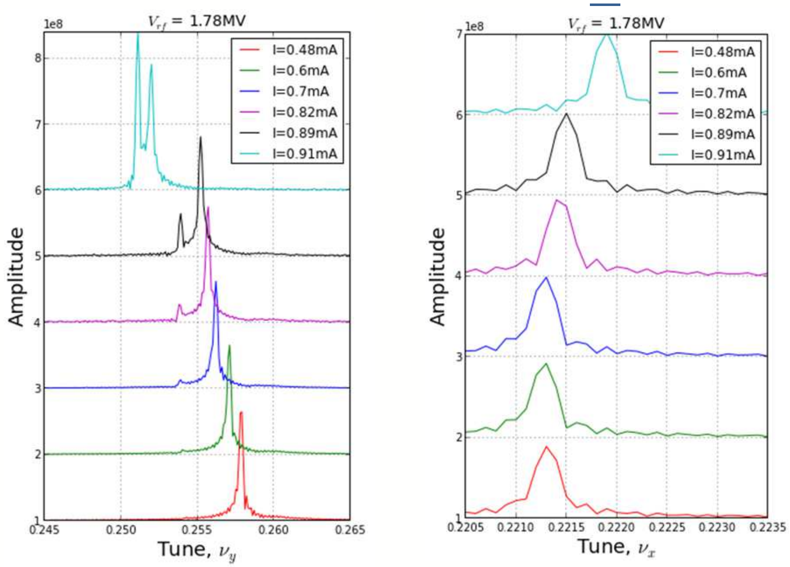


NSLS-II
NATIONAL SYNCHROTRON LIGHT SOURCE II
Storage Ring Operating Status
Beam Current 299.05 mA
Beam Lifetime 6.65 hour
From DCCT
6.38 hour
From BPM (Low current only)
Daily Amp Hours 160.96 mAh
Fill Pattern
Bunch mA
0.3
0.2
0.1
0
-20 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1100 1200 1320
Lifetime (Hr)
Current (mA)
50 40 30 20 10 0.05
330.87 250 200 150 100 50 -1.13
2015-10-19 09:55:39
10:20 10:40 11:00 11:20 11:40 12:00 12:20 12:40 13:00 13:20
2015-10-19 13:45:48

Single-Bunch Instability Threshold

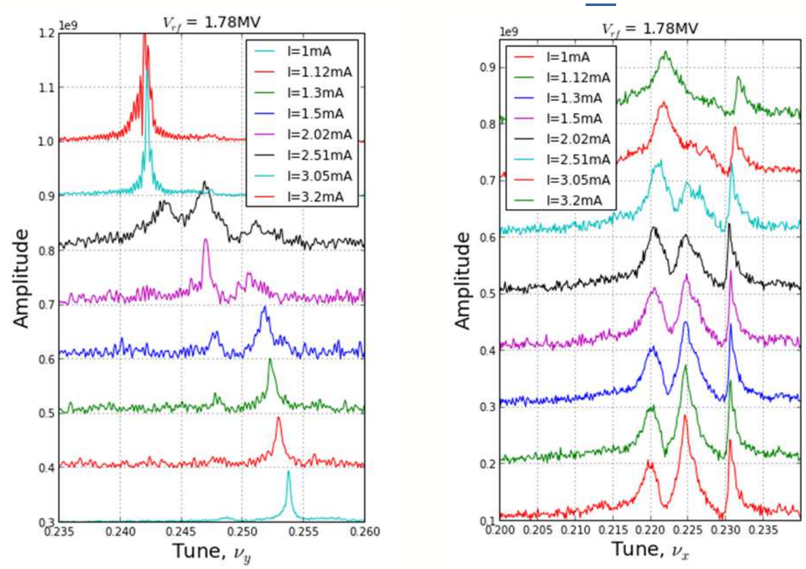
3x2 DW's and 4 IVUs Magnet Gap Closed ($\sigma_s = 6mm$)

Vanishing Chromaticity, I_{th}= 0.95mA



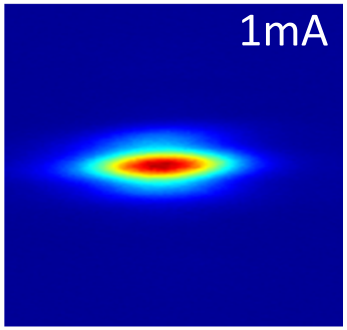
Spectra of BPM 41 vertical and horizontal TbT

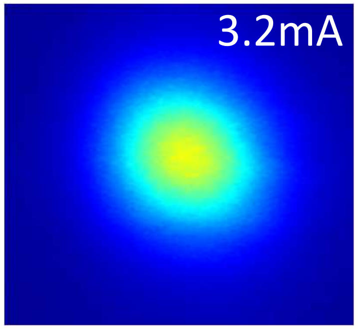
Chromaticity +5/+5, I_{th}= 3.2mA



Spectra of BPM 41 vertical and horizontal TbT

- Single Bunch Intensity Limit due to Transverse Mode Coupling Instability (TMCI)
- Positive Horizontal Tune Shifts Indicates the Dominance of the Quadrupole Impedance
- Stabilizing Effect of Positive Chromaticity, I_{th}=6mA at $\xi_{x/y}$=+7/+7 and I_{th}=3.2 at $\xi_{x/y}$=+5/+5



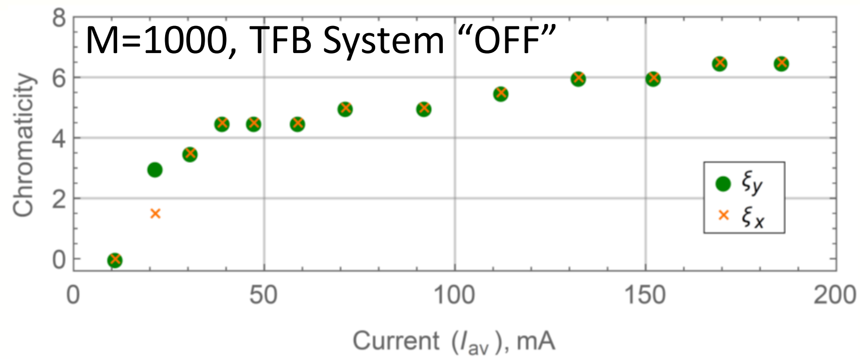


Coupled-Bunch Instability Threshold

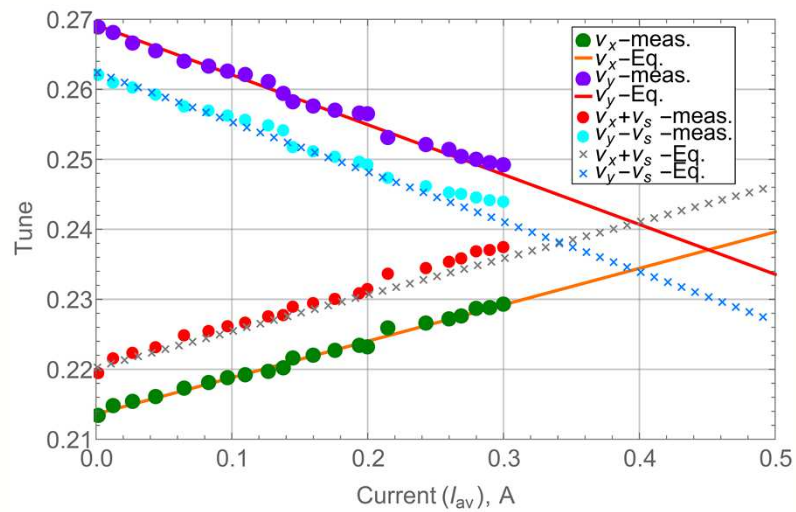
- Coupled-Bunch Instability Threshold is I_{av}=11mA at zero chromaticity. Resistive wall effect.
- Chromaticity +6.5/+6.5 requires to stabilize the beam at I_{av}=200mA for one bunch train. Increasing number of bunch trains helps to reduce chromaticity.
- TFB System Stabilize CB Instability as well.
- Tunes Shifts vs. Average Current due to the Quadrupole Long-Range Wakepotential. Tune Slopes do not depend on Filling-Pattern.

Jul. 8, 2015

3DW's and 7IVU's magnet gaps



Tune Shifts vs. Average Current (Bare Lattice)

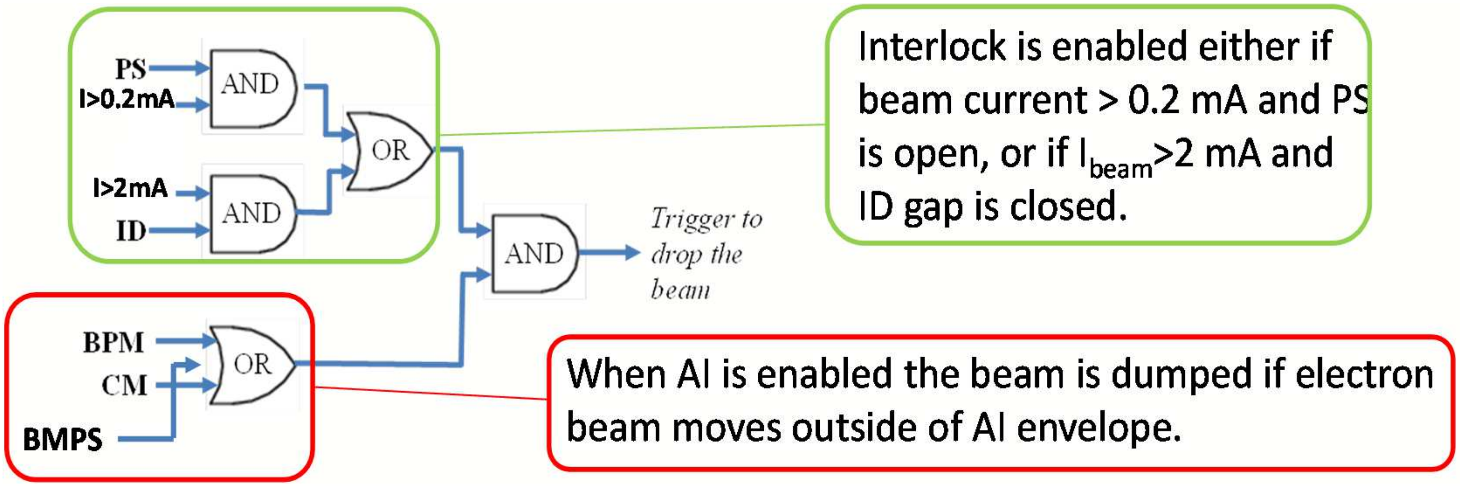


Orbit Interlock System (Active Interlock)

The photon beam position and angle must be kept under tight control when passing through keyhole shaped vacuum chambers and beam line frontend components

→ Tight beam orbit control (**Δx, Δy < 0.5 mm**, **Δx’, Δy’ < 0.25 mrad**) in insertion devices ensured by a fast (0.1 ms) interlock (Active Interlock) as DW beam can damage vacuum components in 10 ms

based on the fast (10kHz) deterministic data link system and FPGA based processors



	0	1
PS	closed	open
I	< 2 mA	>= 2 mA
ID (gap)	gap open	gap closed
BPM (positon/angle)	all within AI limits	some out of AI limits
CM (current)	within range	out of range
BMPS	open	close

Beam Lifetime and Vacuum Performance

- Vacuum improved initially well with photon dose

•Beam Vacuum Conditioning $\eta \propto (\int I_{beam} dt)^{-0.45}$

•Conditioning rate somewhat slower than other recent SR facilities (with exponent of -0.6)

•Present status $\int I_{beam}$ dt ~ 40 Ah

$\Delta P/I < 2.5 \cdot 10^{-11}$ Torr / mA

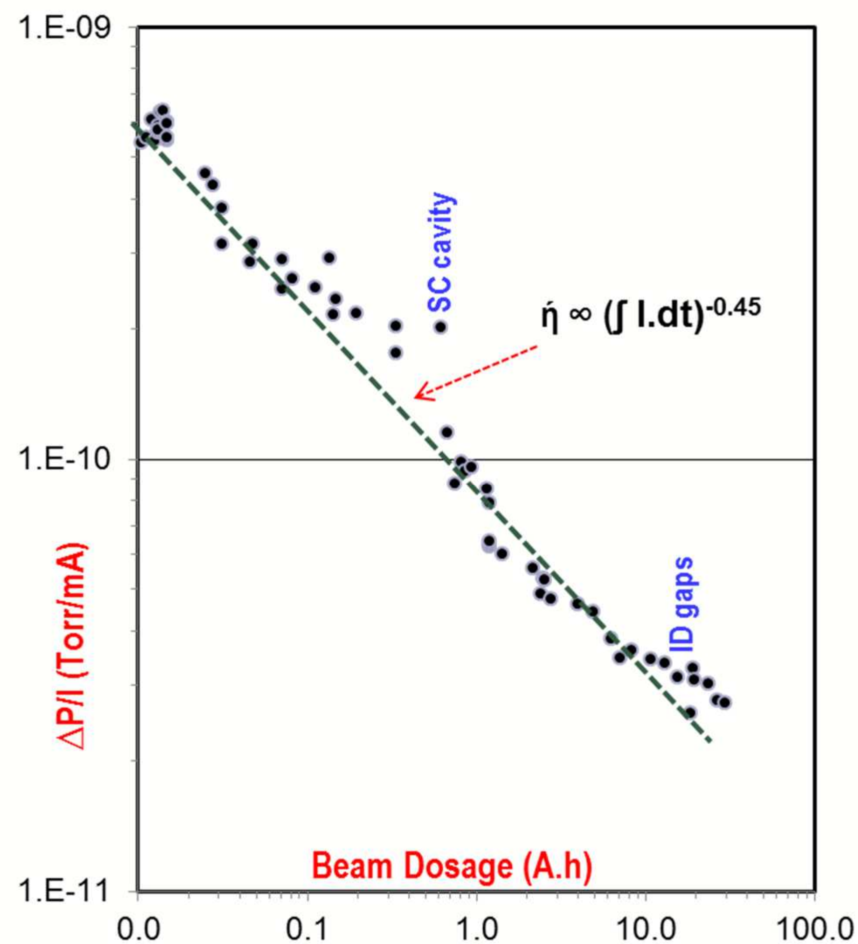
Vacuum lifetime is 48 hours

•~ 10% $\Delta P/I$ increase with all ID gaps closed

➔Will need > 150 Ah to reach < $1 \cdot 10^{-11}$ Torr / mA for operation at 300 mA with τ > 10 h

Dynamic average pressure not improving very well

➔ Plan to improve pumping by NEG coating of a short insufficiently pumped chamber downstream of dipole



Insertion Device Commissioning

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

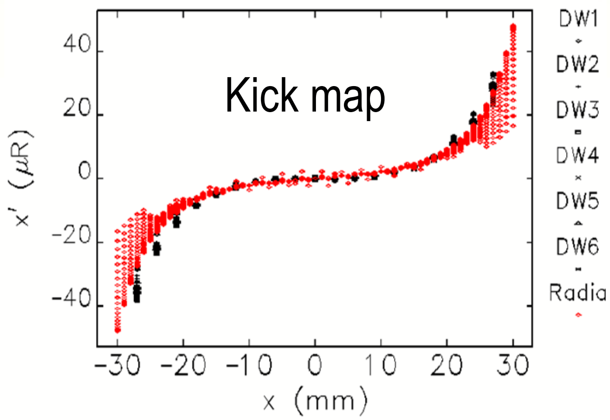
Damping wiggler

IVU22

Insertion Device Commissioning

- Orbit changes only slightly when undulator ID gaps are closed (~10 µm); Tune changes >0.01
  ➔ Feed forward tables converge fast
- DW need local beam optics correction and global tune correction to compensate for ID focusing; can be well corrected and residuals are very small
- Injection efficiency and dynamic aperture found not to be affected by IDs (needs careful vertical orbit adjustments in the small gap (5mm) undulators. Beam life time changes according to smaller emittance values (DW)
- No unpleasant surprises with NSLS-II insertion devices
  Time needed for commissioning an insertion device including beam line frontend is less than a week.

➔ All insertion devices came on line during the Oct-Dec14 commissioning period.



Tune change due to DW gap closing
Measured tunes

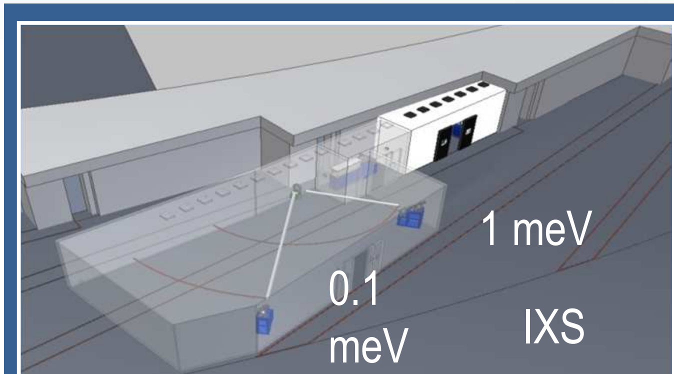
Gap(mm)	Q_x	Q_y
100	.22339	0.24763
50	.22339	0.24974
15	.22339	0.28451

Calculated ΔQ_y = 0.040

NSLS-II Present Performance

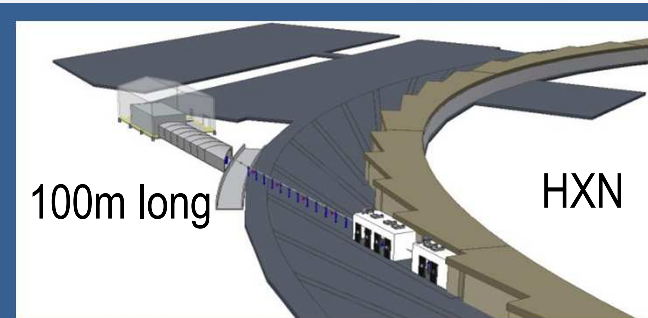
Parameter	unit	Design Value	Actual Value
Circumference	[m]	792	792
Symmetry		3fold	3-fold
Beam Energy	[GeV]	3	3
Beam Current	[mA]	500	300
Single Bunch Current	[mA]	0.5	1
Number of Bunches		1000	1000
Beam Emittance (h)	nm rad	0.9	0.9
Beam Emittance (v)	pm rad	8	6
Number of sc RF Cavities		2	1
RF Voltage	[MV]	4.8	1.8
Orbit Stability h	[$\sigma_{x,y}$]	10%	<5%
Orbit Stability v	[$\sigma_{x,y}$]	10%	10% with feedback
Chromaticity		2-7	2-7
Dynamic Aperture h	[mm]	< 20	16
Dynamic Aperture v	[mm]	< 3	2.6
Bunchlength	[psec]	30-10	30
Nominal Tousheck Lifet	[h]	3	3

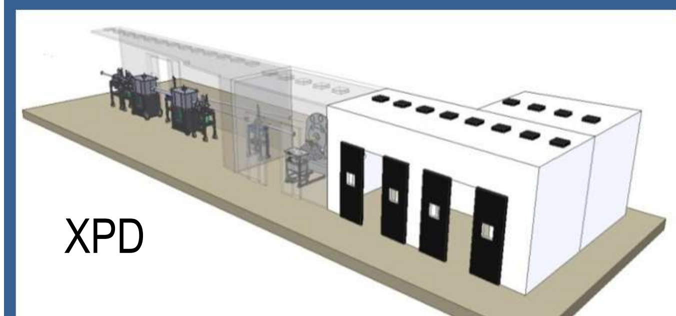
The Six Project NSLS-II Beamlines



inelastic
x-ray scattering
IVU22

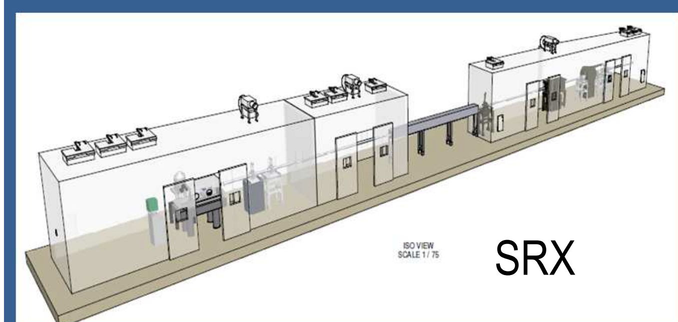
hard x-ray
nanoprobe
IVU20





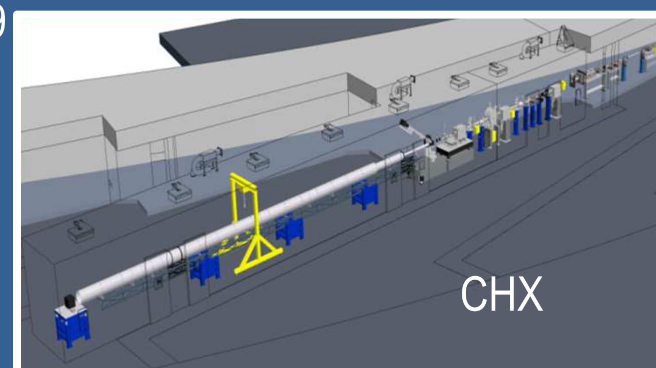
x-ray powder
diffraction
DW

coherent soft x-ray
scattering/polarization
EPU49



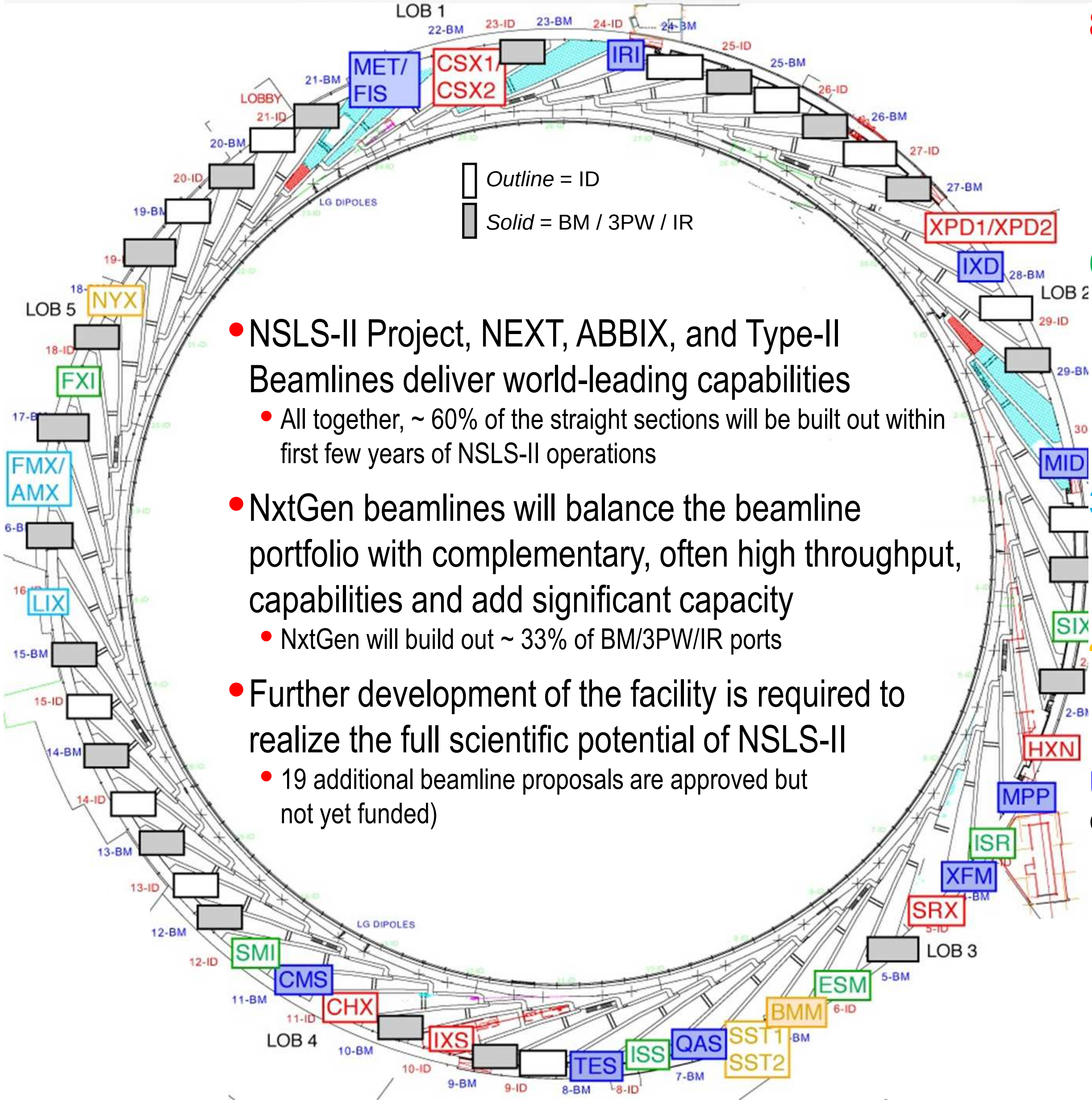
sub-µm resolution
x-ray spectroscopy
IVU21

coherent hard
x-ray scattering
IVU20



FIRST LIGHT CELEBRATION!

Developing the NSLS-II Beamline Portfolio



- NSLS-II Project, NEXT, ABBIX, and Type-II Beamlines deliver world-leading capabilities
  - All together, ~ 60% of the straight sections will be built out within first few years of NSLS-II operations
- NxtGen beamlines will balance the beamline portfolio with complementary, often high throughput, capabilities and add significant capacity
  - NxtGen will build out ~ 33% of BM/3PW/IR ports
- Further development of the facility is required to realize the full scientific potential of NSLS-II
  - 19 additional beamline proposals are approved but not yet funded)

8 NSLS-II Project Beamlines (ops)

Inelastic X-ray Scattering (IXS)
Hard X-ray Nanoprobe (HXN)
Coherent Hard X-ray Scattering (CHX)
Coherent Soft X-ray Scat & Pol (CSX1, CSX2)
Sub-micron Res X-ray Spec (SRX)
X-ray Powder Diffraction (XPD1, XPD2)

6 NEXT MIE Beamlines, start FY17

Photoemission-Microscopy Facility (ESM)
Full-field X-ray Imaging (FXI)
In-Situ & Resonant X-Ray Studies (ISR)
Inner Shell Spectroscopy (ISS)
Soft Inelastic X-ray Scattering (SIX)
Soft Matter Interfaces (SMI)

3 ABBIX Beamlines (complete)

Frontier Macromolecular Cryst (FMX)
Flexible Access Macromolecular Cryst (AMX)
X-ray Scattering for Biology (LIX)

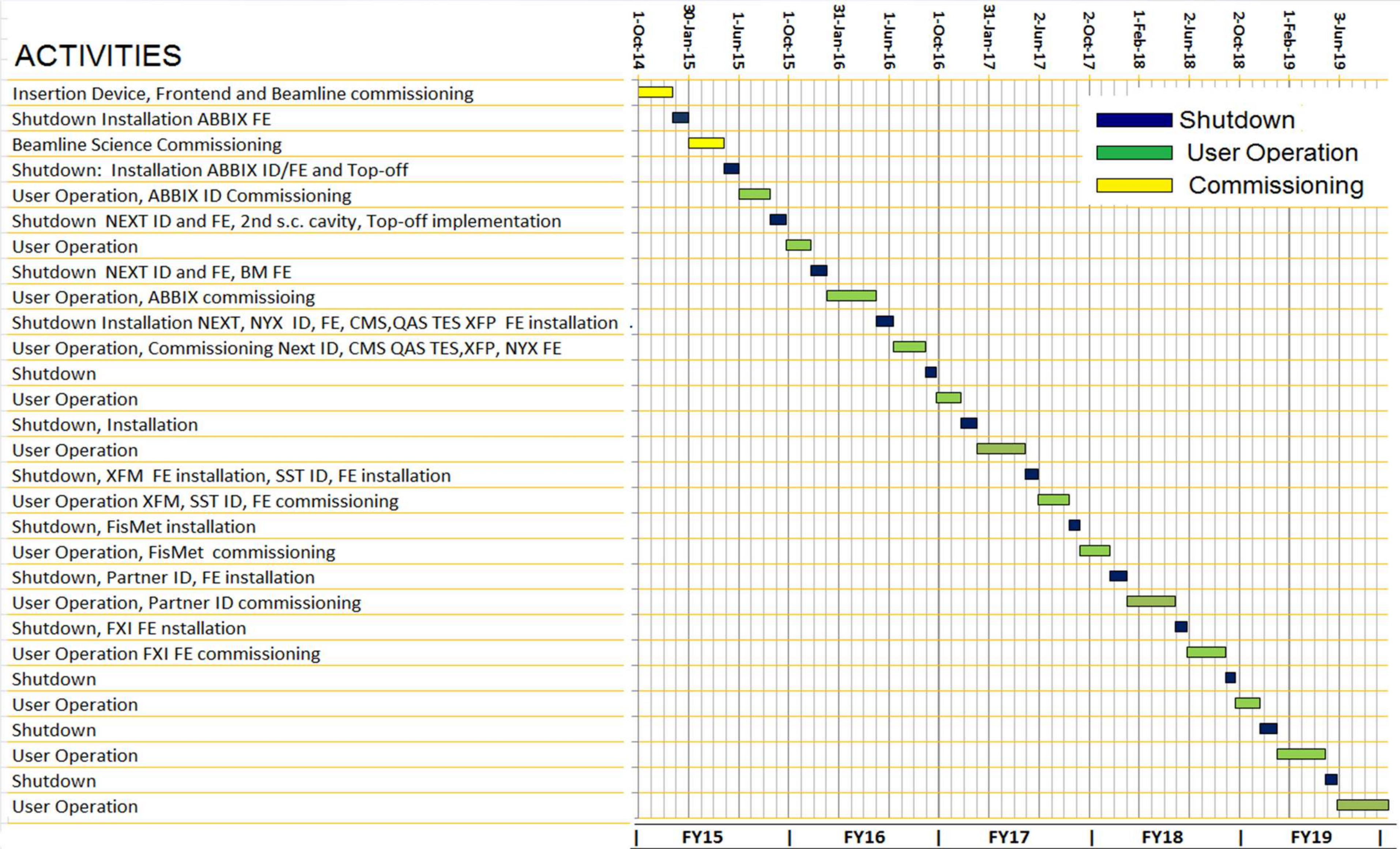
4 Type-II Beamlines (FY18-20)

Spectroscopy Soft and Tender (SST1, SST2)
Beamline for Mater. Measurements (BMM)
Microdiffraction Beamline (NYX), HEX scw

Up to9 NxtGen Beamlines

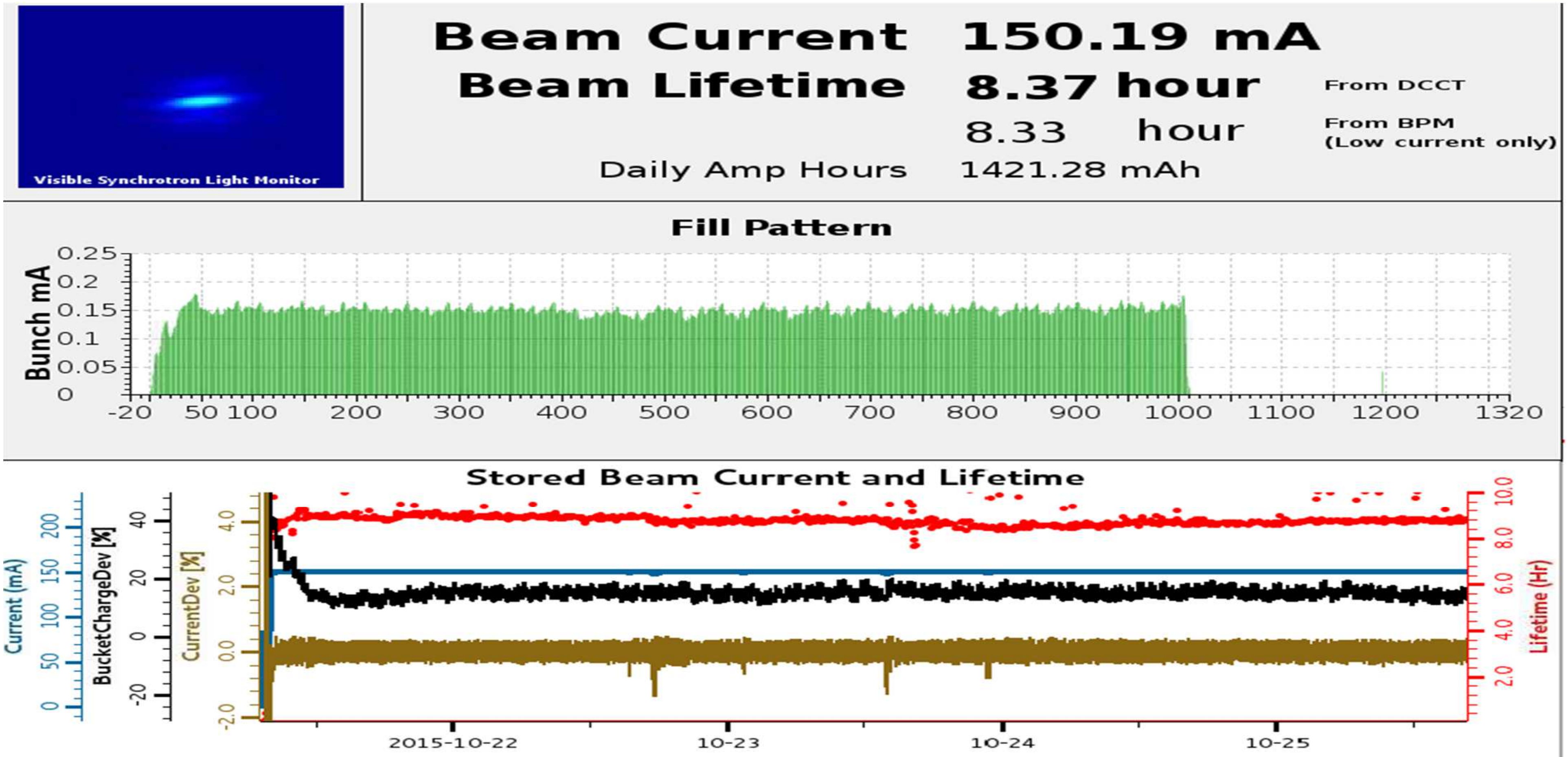
Complex Materials Scattering (CMS)
Magneto, Ellipso, High Pressure IR (MET/FIS)
Metrology & Instrum Development (MID)
Full-Field Infrared Spectroscopic Imaging (IRI)
In-situ X-ray Diffraction Studies (IXD)
Materials Physics & Processing (MPP)
Quick X-ray Absorption Spectroscopy (QAS)
Tender X-ray Absorption Spectroscopy (TES)
X-ray Fluorescence Microscopy (XFM)

Accelerator Operations Schedule FY15-FY19

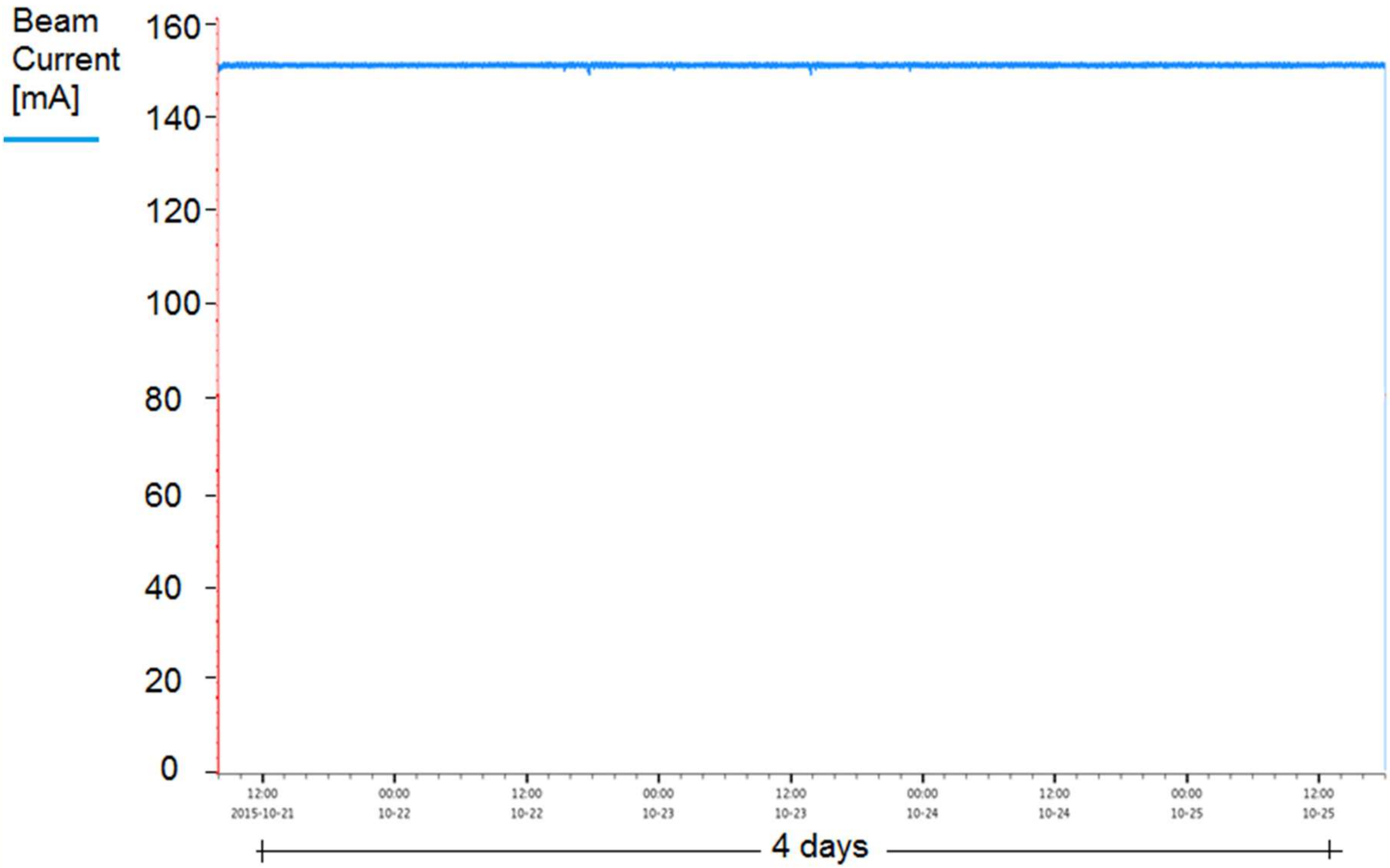


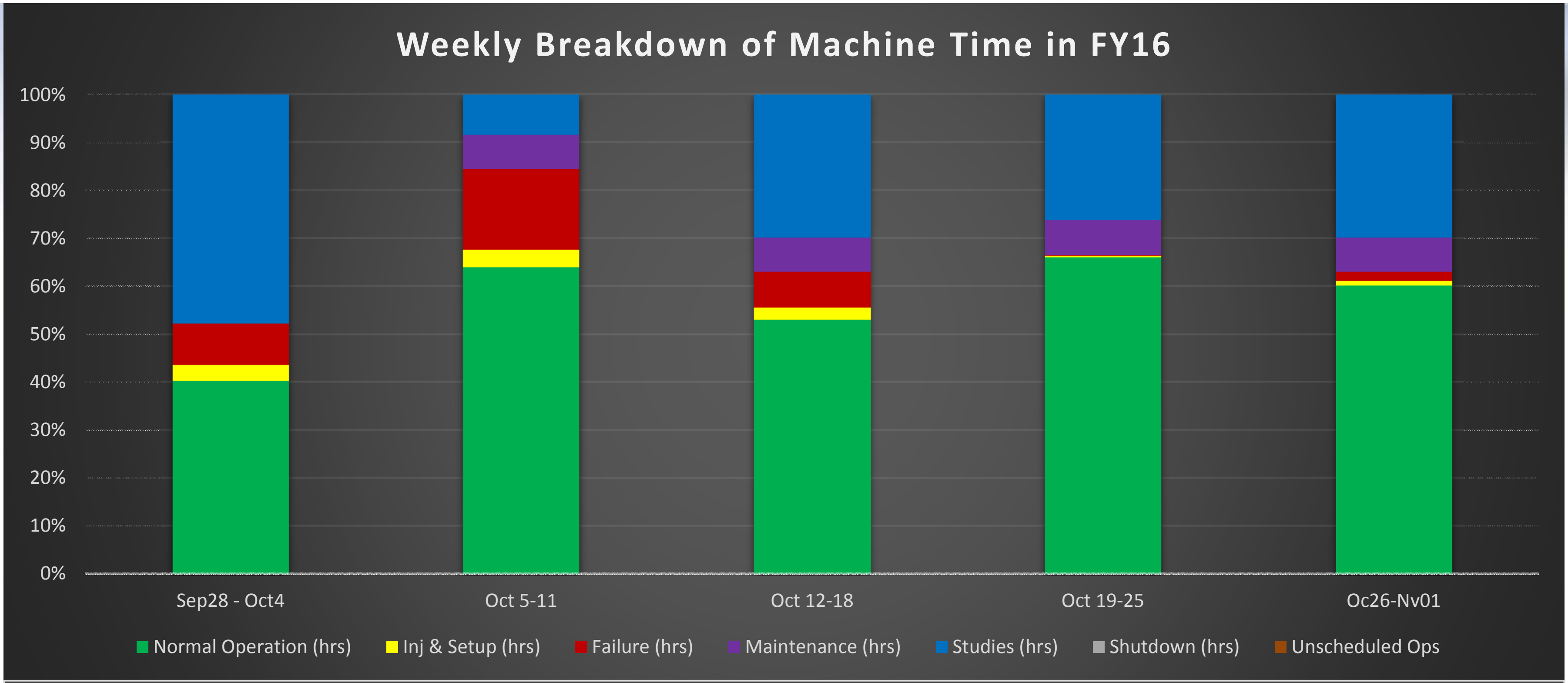
Top off injection operation

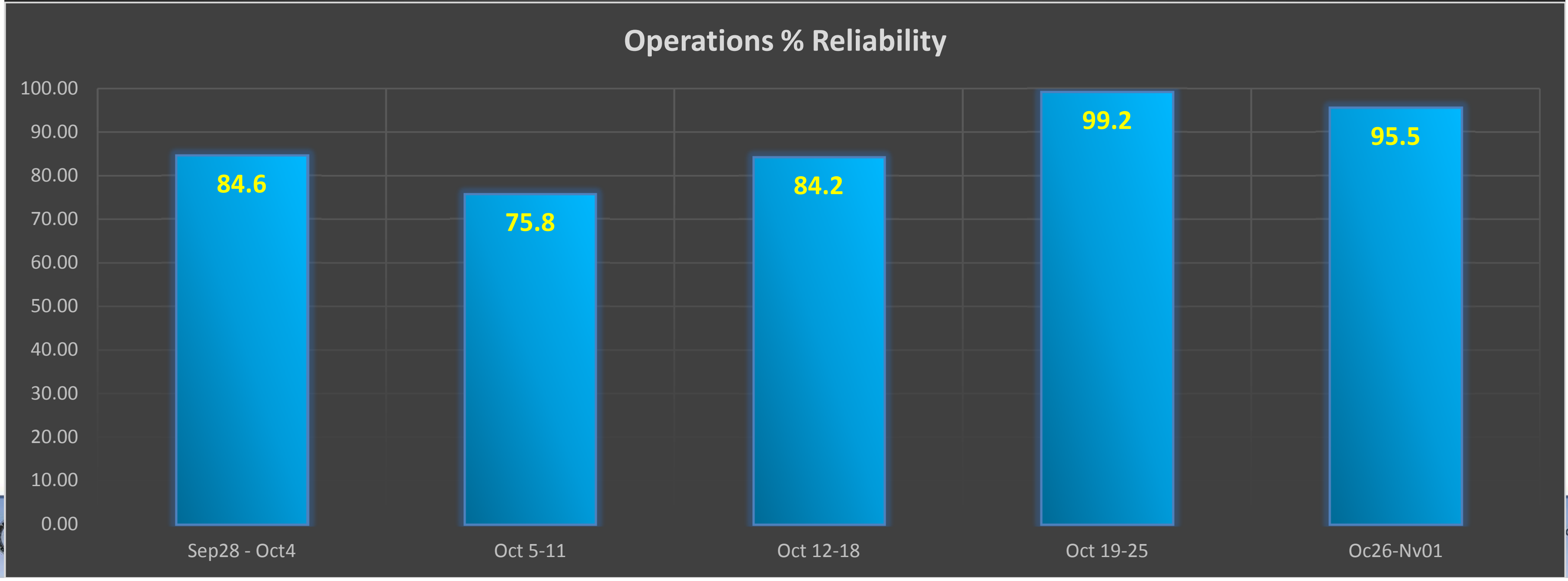
- Top-Off Injection specifications: many bunches in the ring with multi-bunch injection
  - >1 minute between injector cycles for top-off
  - Total Current stability +/- 0.5%, Bunch-to-bunch Q stability 20%
- The injection period depends on beam lifetime, but longer than 1 minute.
- Varying the injected multi-bunch train length to compensate the bucket to bucket charge stability while keeping the beam current stable.



One Week of Top-Off Operations at 150 mA in October 2015



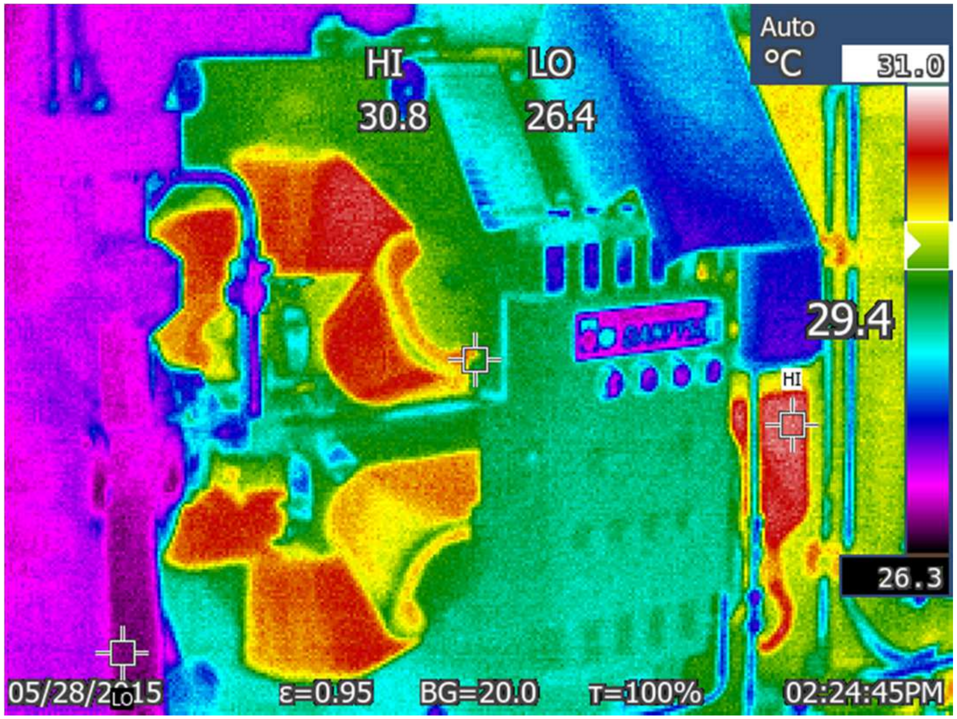

Weekly Breakdown of Machine Time in FY16
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Sep28 - Oct4
Oct 5-11
Oct 12-18
Oct 19-25
Oc26-Nv01
Normal Operation (hrs)
Inj & Setup (hrs)
Failure (hrs)
Maintenance (hrs)
Studies (hrs)
Shutdown (hrs)
Unscheduled Ops


Operations % Reliability
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
84.6
75.8
84.2
99.2
95.5
Sep28 - Oct4
Oct 5-11
Oct 12-18
Oct 19-25
Oc26-Nv01

Preventive Maintenance

Preventive Maintenance is an investment in reliable performance in later years

- **NSLS-II PM process is in development based on SAE standard JA1011**
  - **A systematic maintenance program is under development**
  - **The following factors will be identified for each system/component**
  - Functional requirements
  - Failure modes and effect
  - Proactive tasks and task intervals
  - Default actions (What should be done if a suitable proactive task cannot be found?)



Thermal image of powered sextupole

Outlook

Winter 2015/16

- Installation of 2nd superconducting cavity

Spring 2016

- Installation of 4 more insertion devices (1 x IVU23 2 x EPU57 and EPU105) and 5 more beam line frontends (NEXT Project)
- Include ABBIX beam line into routine operation
- Install first suite of bending magnet frontends
- Establish 300 mA in routine operation
- Demonstrate 400 mA during studies

Summer 2016

- Demonstrate I_{beam} = 450mA
- Commission NEXT ID, Frontends and beam lines

Fall 2016:

Next beam line commissioning

Winter 2016/17

Completion and installation of 3rd harmonic cavity (depending on available funding)

Summary

- NSLS-II is designed as the ultimate 3rd generation Synchrotron Radiation Light source enabling 1 nm spatial resolution and 0.1 meV energy resolution
- The accelerator is designed to provide a photon beam brightness of up to $B=10^{22}\ s^{-1}mm^{-2}mrad^{-2}\ (0.1\%BW)^{-1}$
- The design exploits of state-of-the-art and beyond techniques, it is robust and meets all the requirements
- Commissioning of the NSLS-II Accelerator Complex went much faster as anticipated. All commissioning were achieved.
- Design Beam parameters have been achieved with the exception of total intensity which is at 200mA level.
- The NSLS-II accelerator started operating 5 month before the end of the project
- The NSLS-II project was completed successfully in March FY15 within schedule and budget.
- Accelerator performance is reproducible from the start. Recovery from a shutdown takes only a few hours. This state of maturity is remarkable for a brand-new facility
- Operational Reliability is with presently 90% not yet at the level of a matured facility, however, reliability is exceeding expected values for this phase of operation
- Bright Future in Synchrotron Radiation Based Science at BNL has started

Thank you!