The Commissioning of the NSLS-II

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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
- Further Near Term Developments
- Outlook

NSLS-II Design 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

$$\mathbf{B > 10^{21}\ photons\ sec^{-1}\ mm^{-2}\ mrad^{-2}\ (0.1\%BW)^{-1}}$$

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

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

$$\varepsilon_x < 1\ \pi\ nm\ rad$$

$$\varepsilon_y = 8\ \pi\ pm\ rad$$

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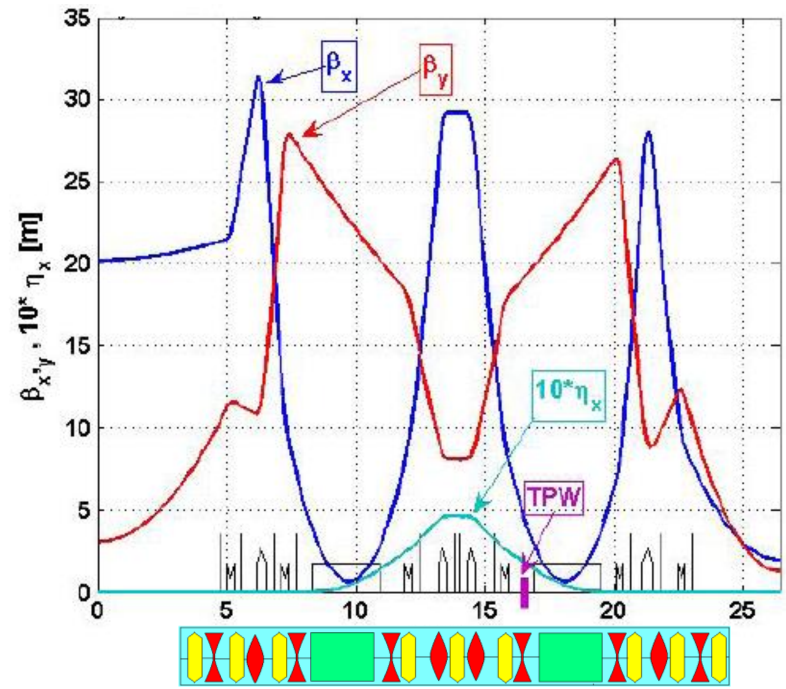
Low Emittance Lattice

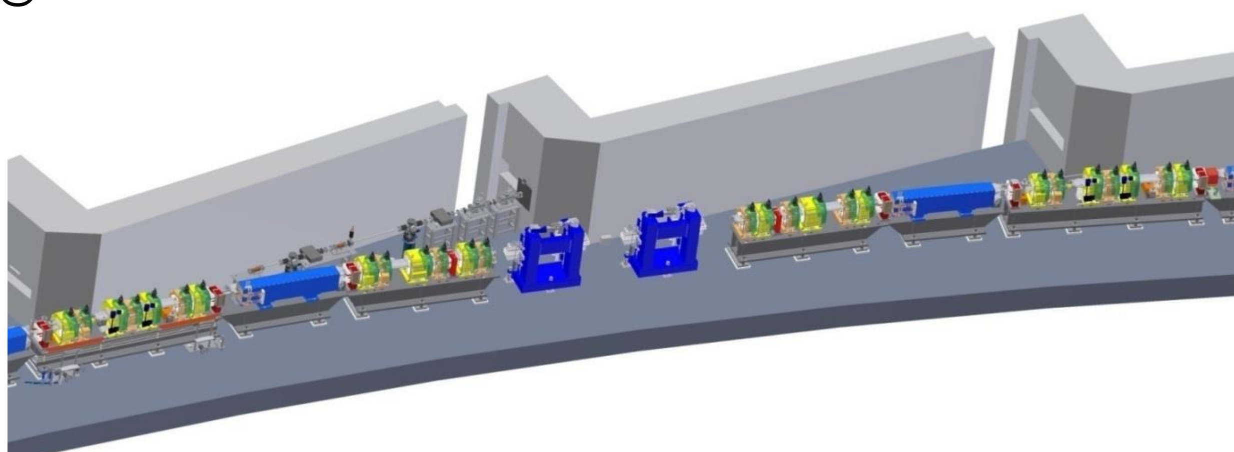
- **Large Circumference 792** m
  30 DBA cells $\varepsilon_x \sim N_{cell}^{-3}$

- **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_x= 2 nm**

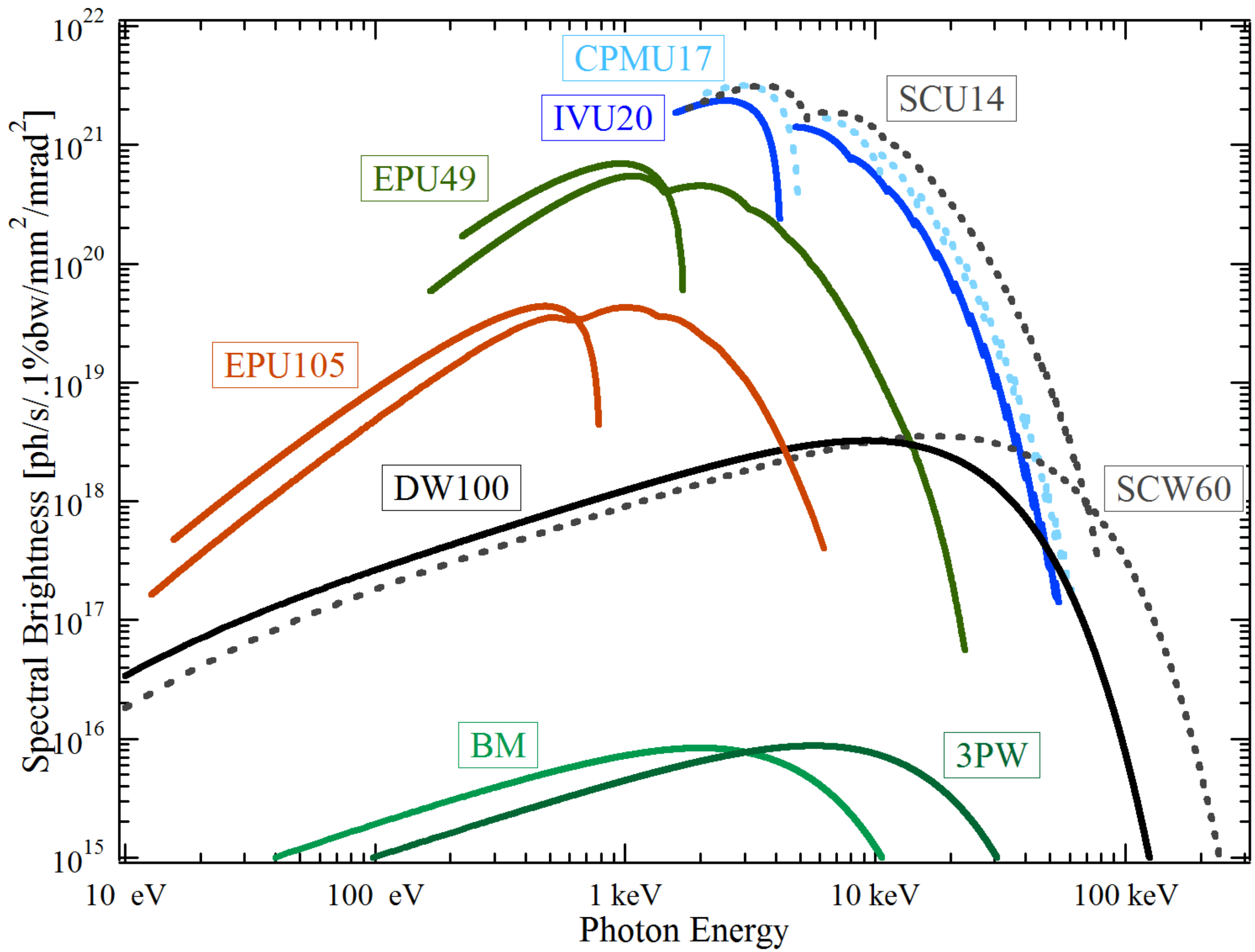
- **Soft Bend**
  ➔ low radiation loss (**287** keV/turn/electron)
  ➔ efficient use of **damping wigglers** to reduce emittance by increased betatron damping rate
  3 x 2 x 3.5 m (B_{max}= 1.85)wiggler @ 1.8 T



ε_x < 0.9 nm



NSLS-II Brightness with Present and Future Undulators



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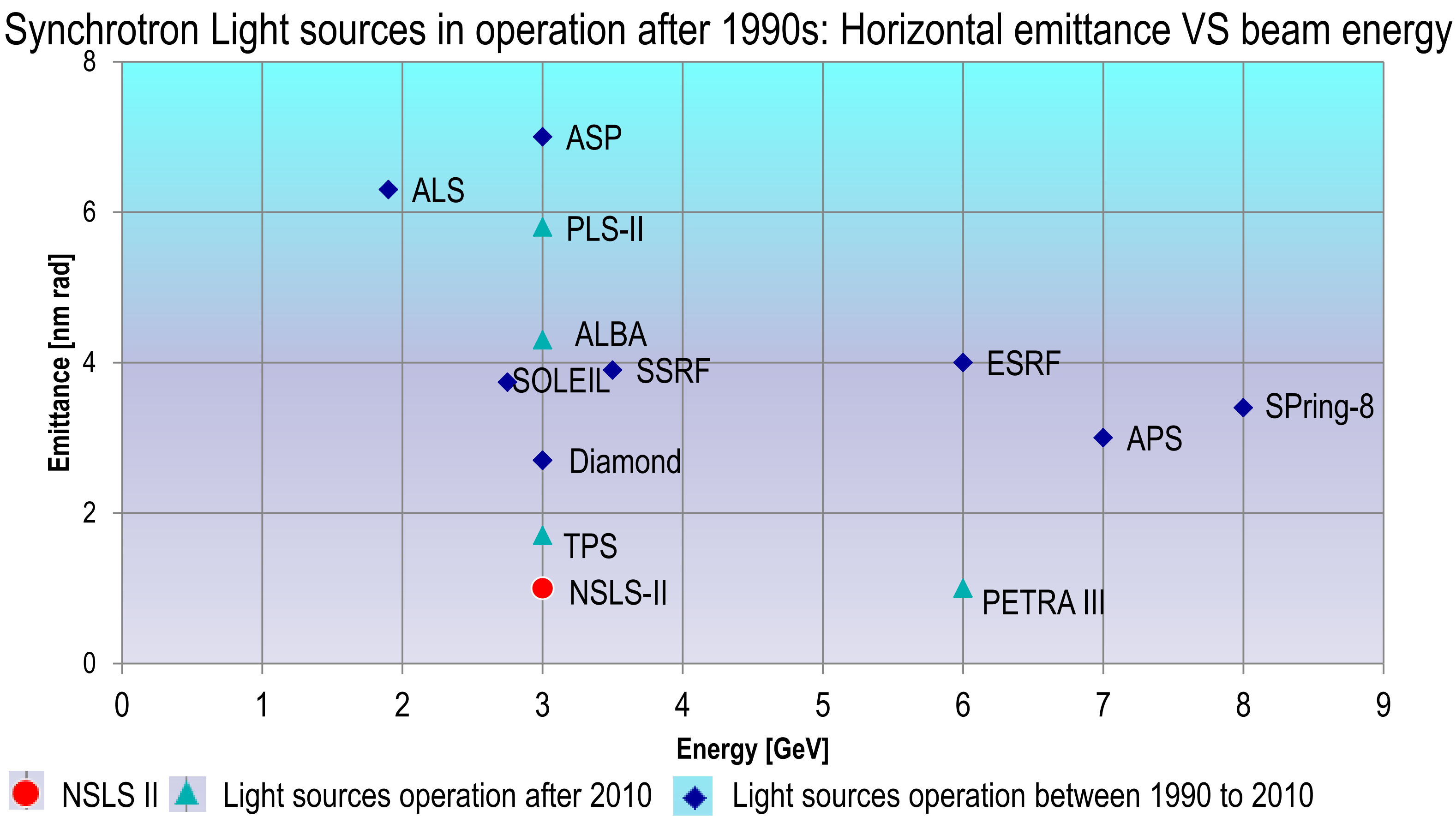
Storage Ring Light Sources: Emittance



- 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

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 RF (500MHz, single cell, 2 cavities)
- High resolution and stability (200 nm) BPM system, in-house design,
- In vacuum undulators in straights (alternating between 6.6m and 9.3 m)
- Switched mode PS with ,10ppm resolution and stability, all 300 quadrupoles individually powered
- Sealed, air-cooled electronic equipment enclosures with high thermal stability (0.1 deg C)

  ➔ stable electronics, high reliability PS

Superconducting 500MHz RF

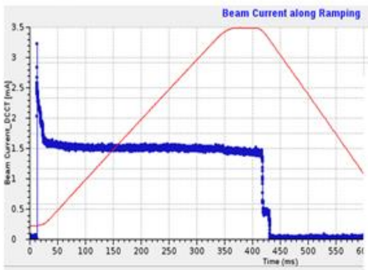
21 m of 1.85 tesla Damping wigglers

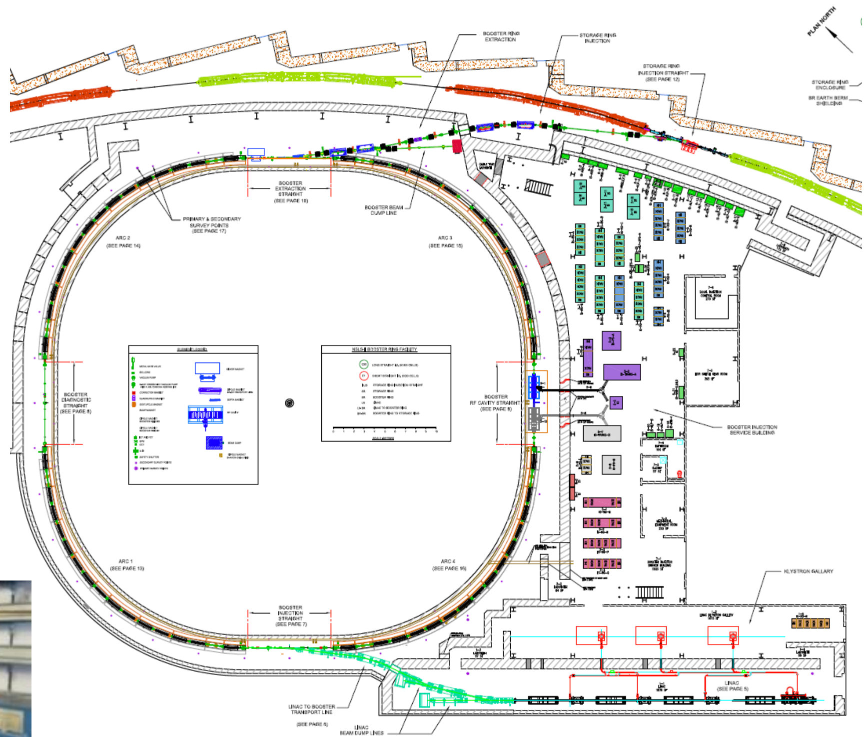
In vacuum undulators

NSLS-II INJECTOR

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

First 3GeV booster beam Dec 31 2014





200 MeV LINAC

Frequency	S-Band
Charge	15nC (nominal)
∆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

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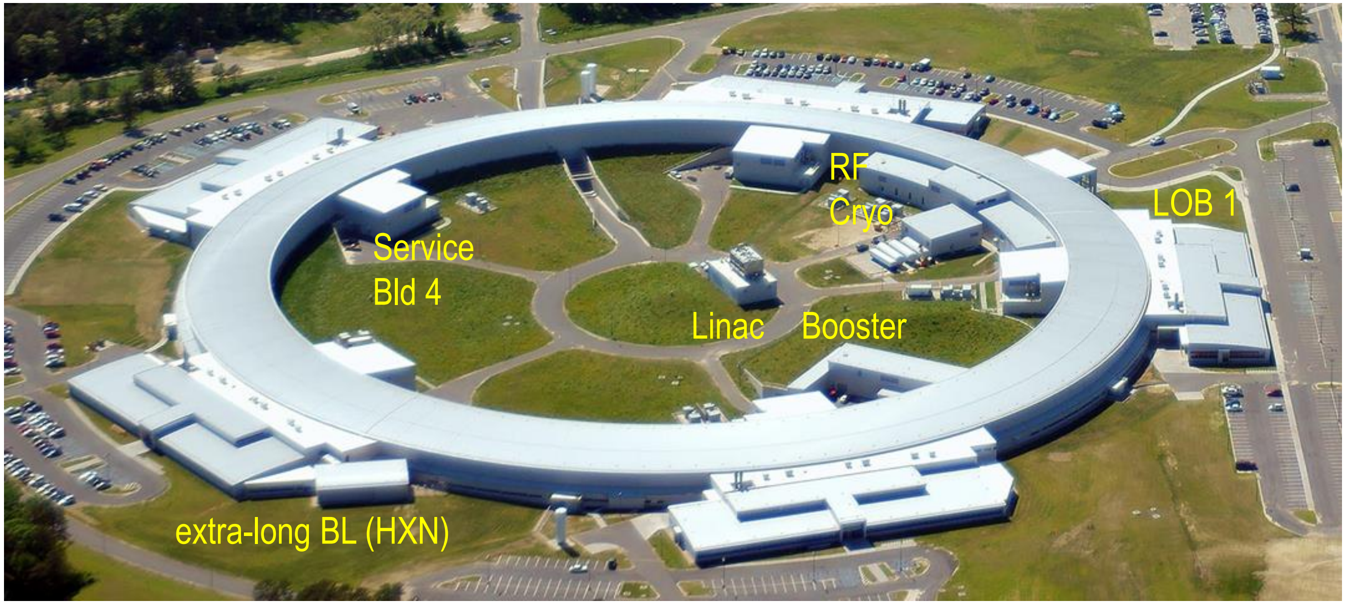
NSLS-II Site View



- 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
CD-4	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

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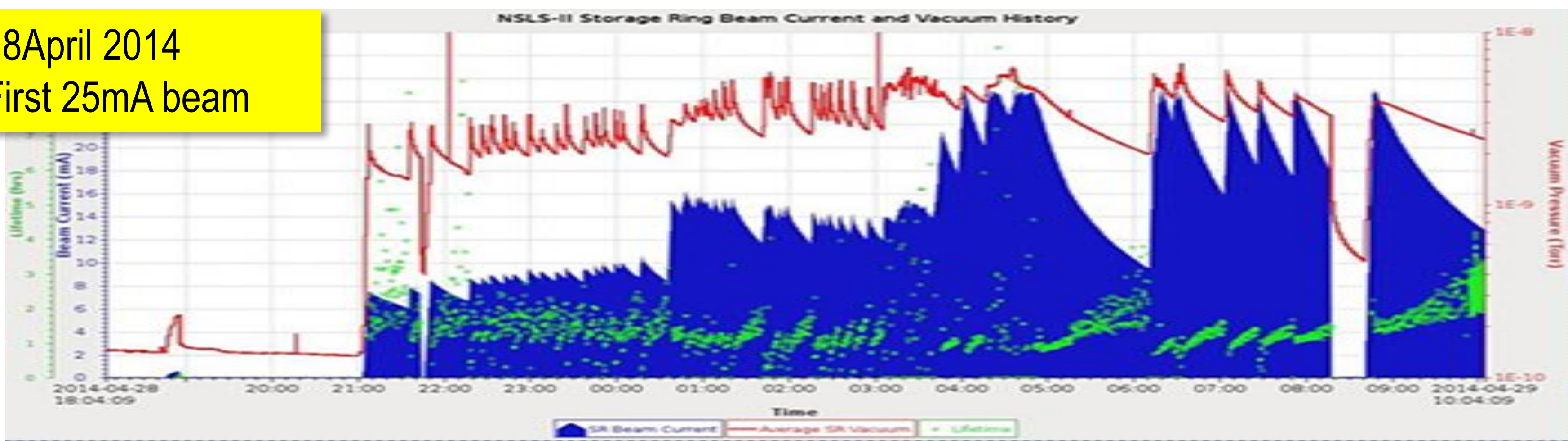
Commissioning

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



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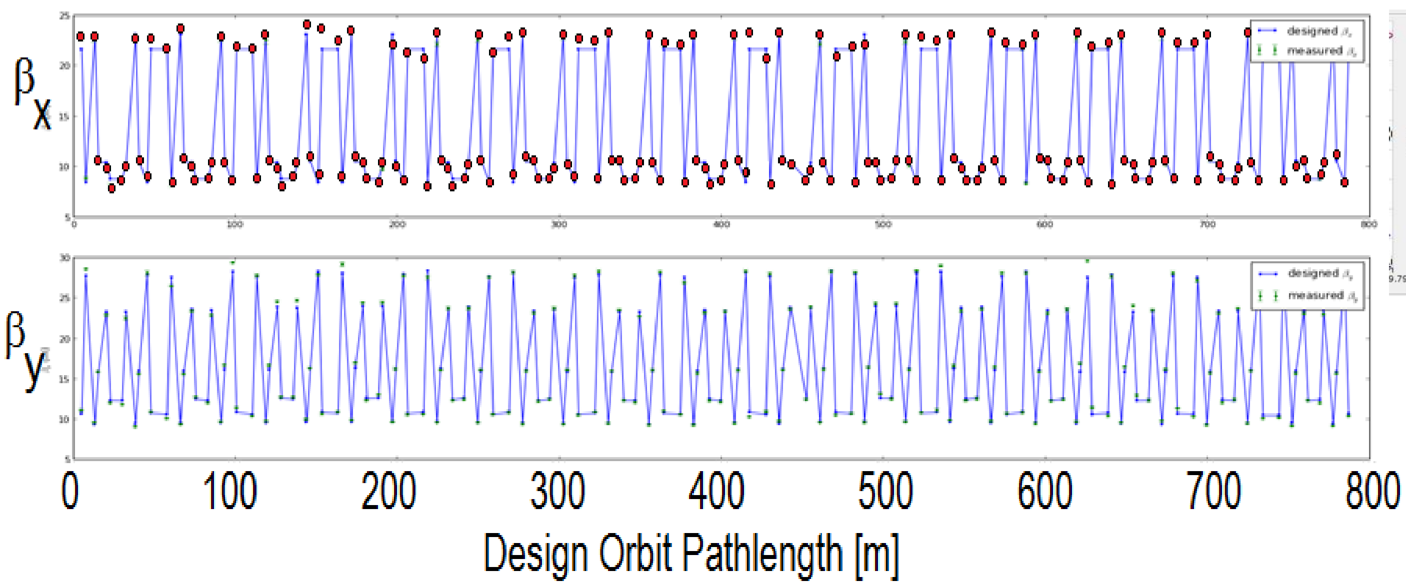
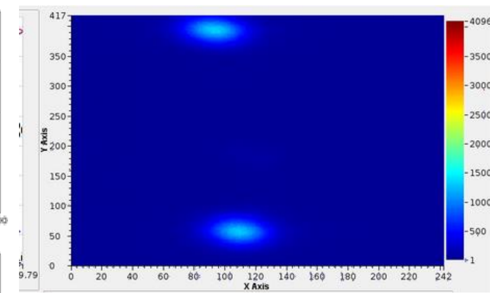
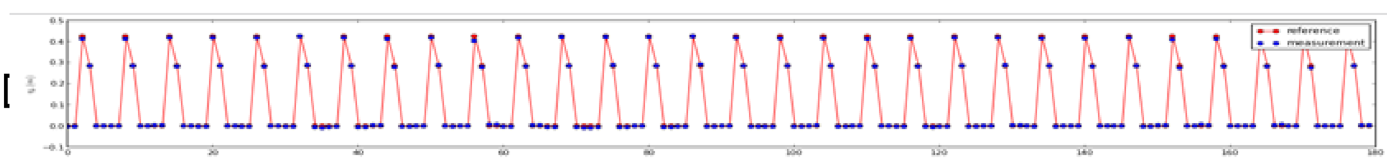
Lattice Commissioning

- 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)**



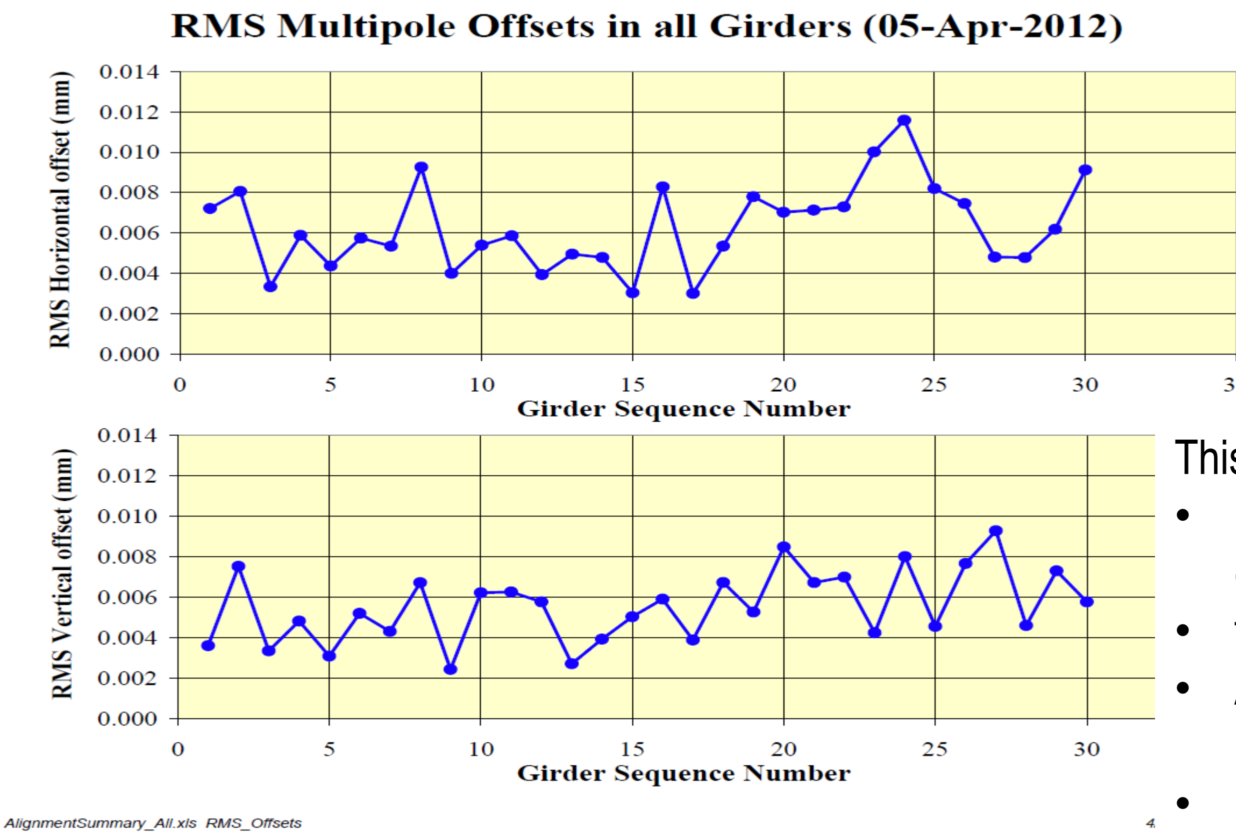


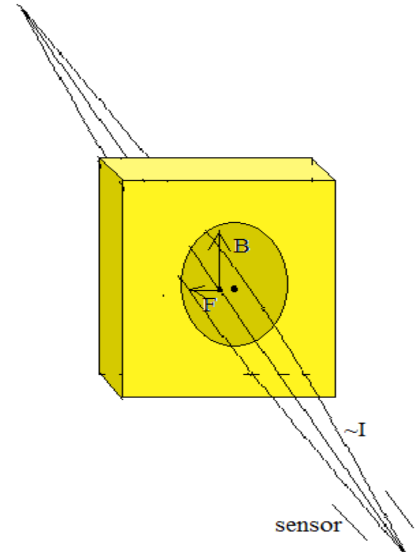
Stable ½ integer resonance crossing (vertical)
Very small errors,
➔ small stopband width



Precision of Magnet Alignment on Girders

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

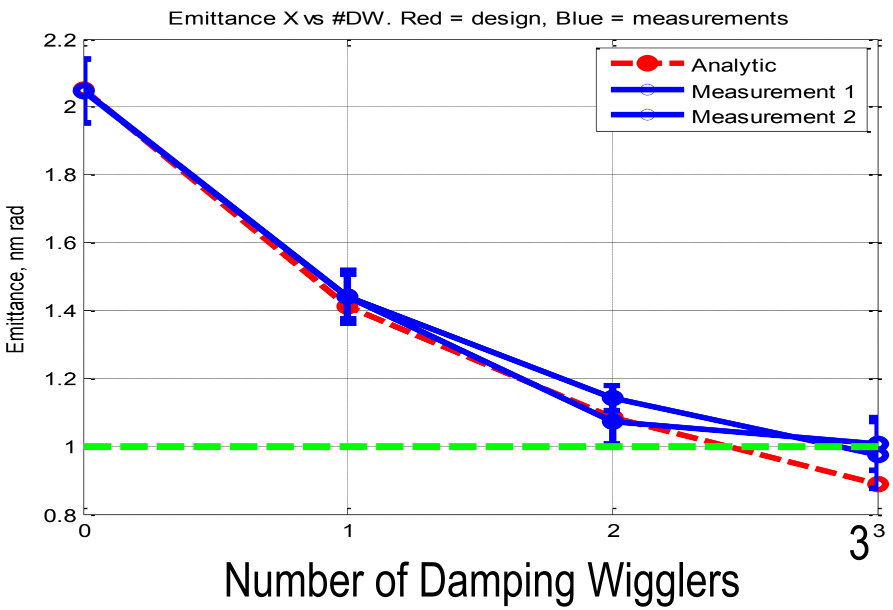




This high precision alignment allowed:

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

Beam Emittance Verification and Optimization

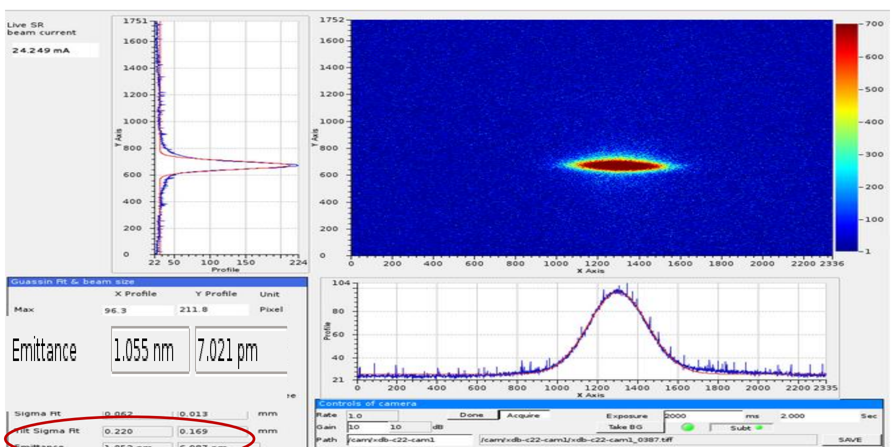


- **Design Emittance Achieved**

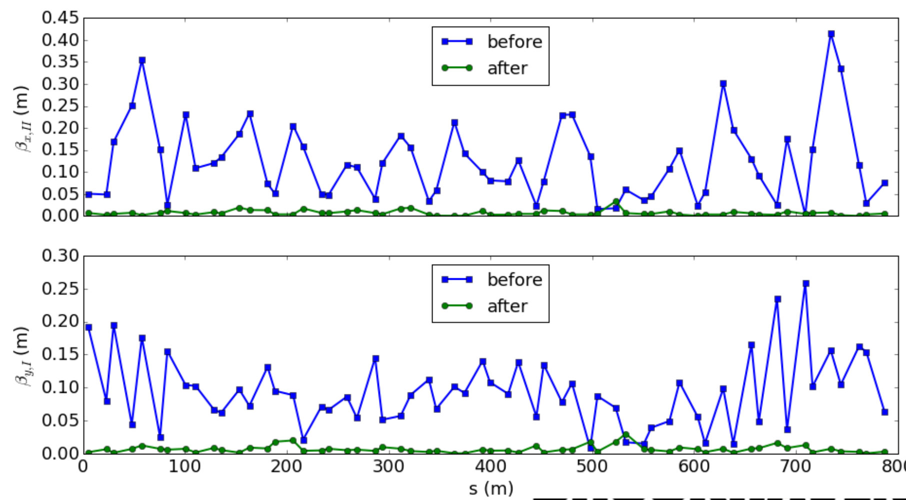
ε_x^{0dw} = 2.05 nm·rad, ε_x^{3dw} = 0.98 nm·rad,

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

- vertical dispersion correction
- Local coupling correction

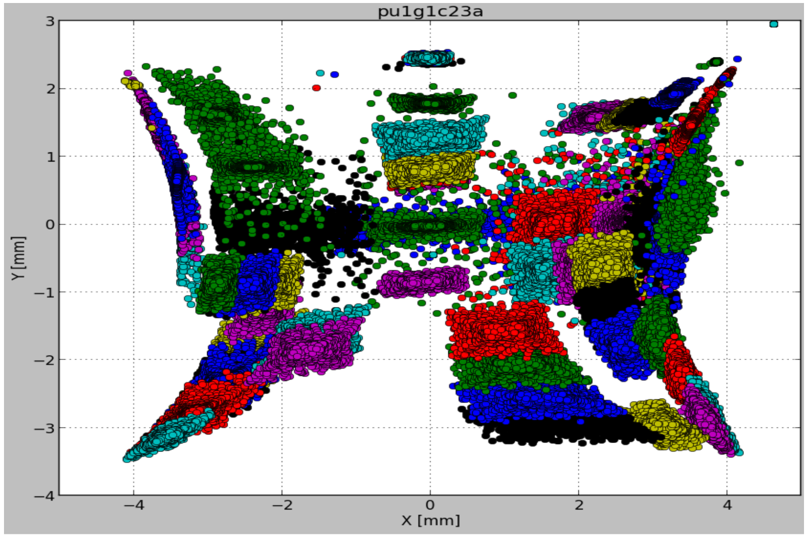


Mode-II beta function after local coupling correction



High Level Control System

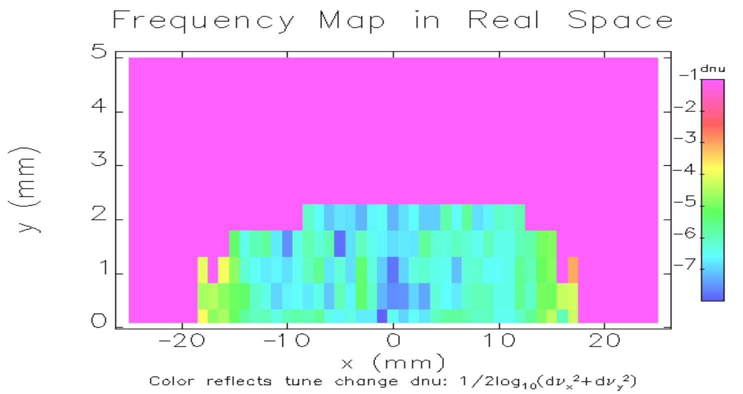
- **Sophisticated High Accelerator Modeling Software imbedded in the control system middle layer was very important to achieve quick optimization of beam optics, orbit control and beam quality parameters**

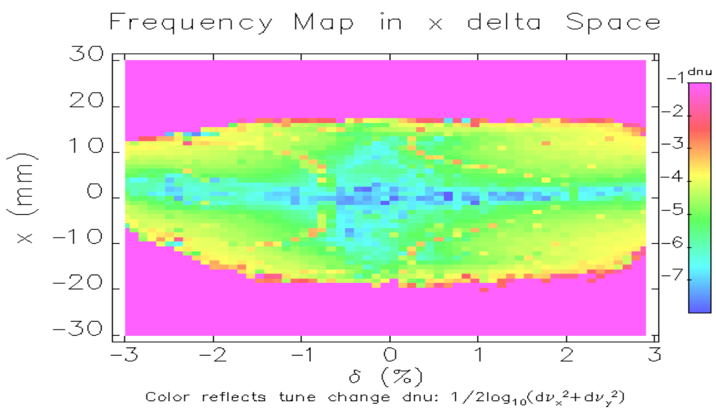


Automated 2-D aperture scan which uses a combination of DC and pulsed magnets

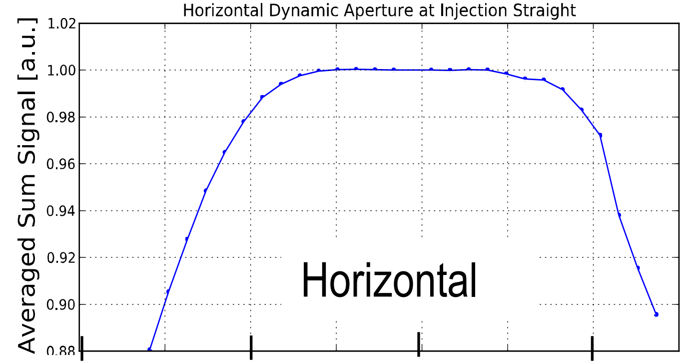
Dynamic Aperture

Calculations (frequency maps)

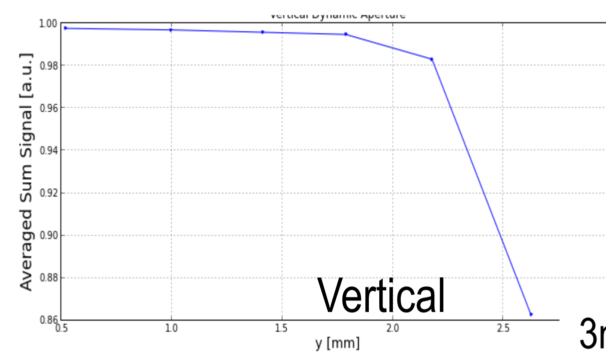




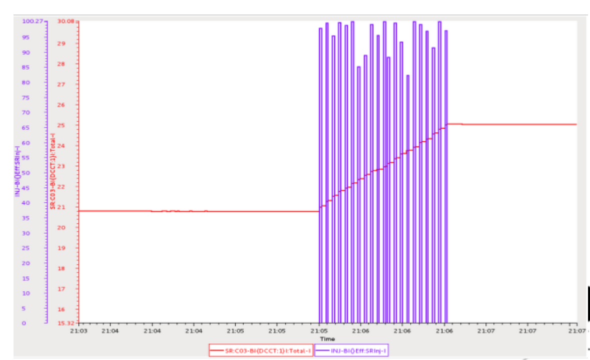
Commissioning Results (bare lattice)



-20 mm 10 mm 0 10 mm



3mm



➔ 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 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

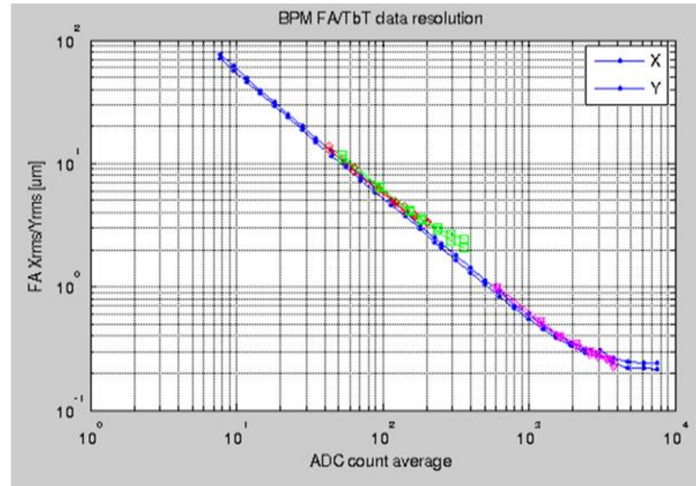
➔ **Beam orbits stabilization to 200 nm level ()**

- **Remaining Effort**

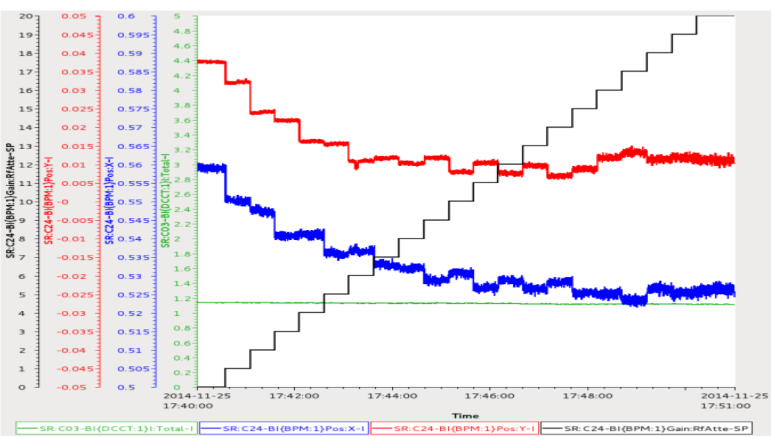
Reproduction of orbits after breaks and shut down (systematic magnet cycling, optimized machine data handling) ➔ work in progress

Instrumentation Commissioning

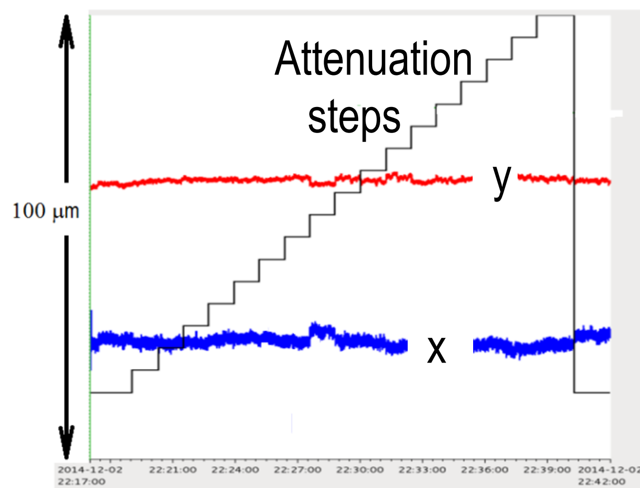
BPM Performance:
200 nm resolution verified with beam
(BPM noise vs resolution of digitalization)



Typical Issue: Uneven attenuation of the four channels leads to false orbit changes if beam intensity varies

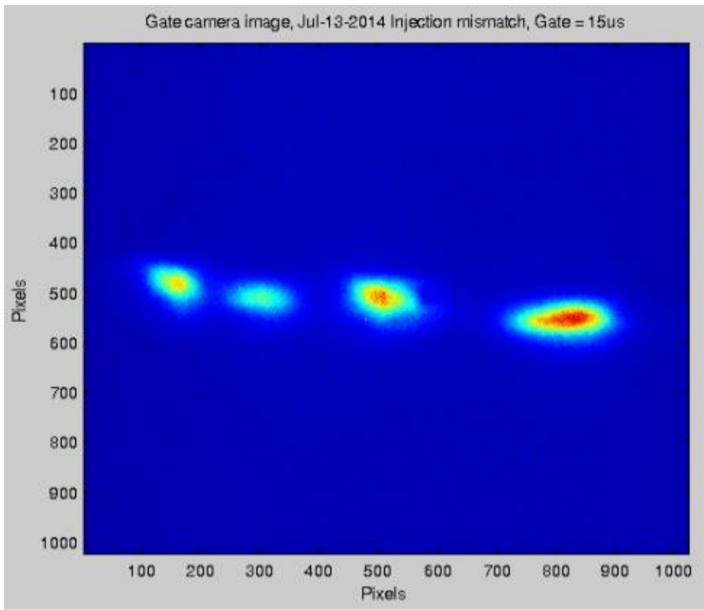


Resolved by improved lookup table

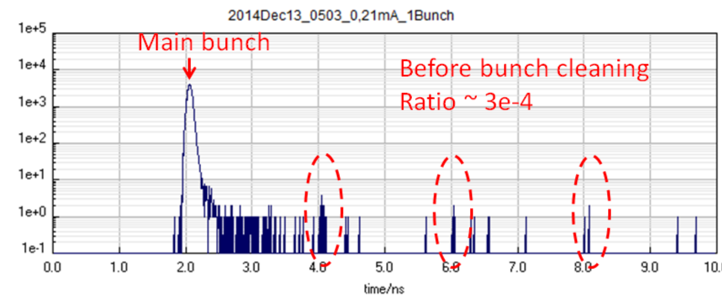


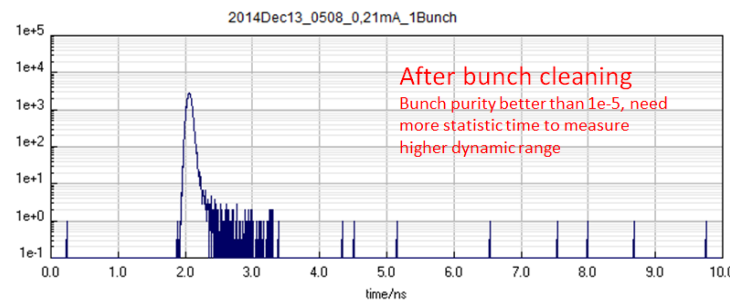
Instrumentation Commissioning

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



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



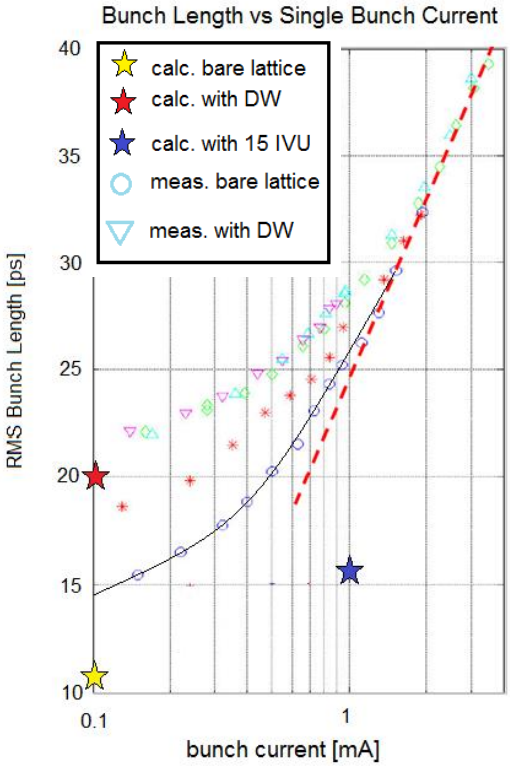


Single bunch purity measured using **Time Correlated Single Photon Counting** method
After cleaning, bunch purity was **better than 1e-5**. Bunch purification was realized using BxB feedback system.

High Intensity Commissioning

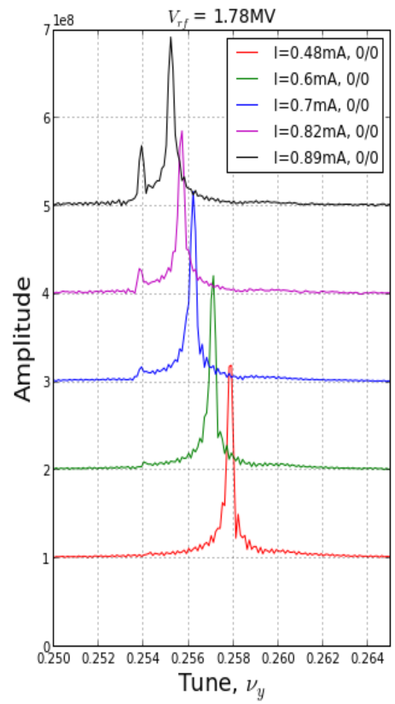
Single bunch observations

longitudinal



V_{rf}=1.9 MV

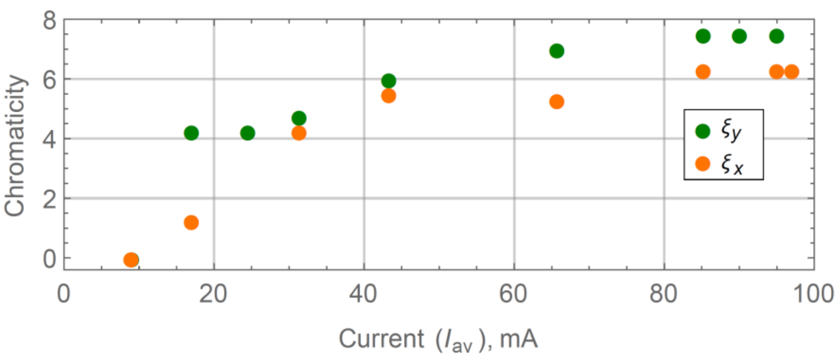
transverse



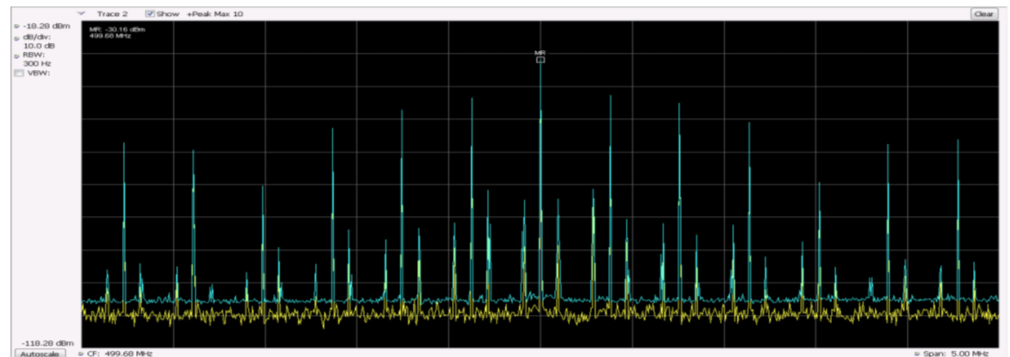
- Significant bunch lengthening vs bunch current (increased energy spread when DW are on) larger than predicted: under study
- Calc. μbI "threshold" ~ 10mA (all IDs incl.) Verified: I_{bunch} < 5 mA
- Significant tune shift with bunch current bunch gets unstable if $\Delta Q_y \sim 0.5\ Q_s$ (signature of TMCI)
- Expected with 20 IVU (60m) 5mm gap $\beta = 3$m 1.5 mA
- Measured: 0.95 mA @ ξ=0 (3 mA @ ξ=5) under study
- Nominal bunch current 0.5mA no issue

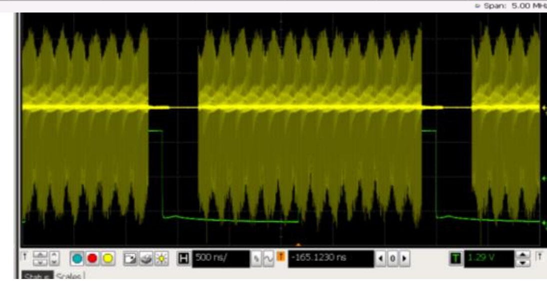
Multiple Bunch Effects

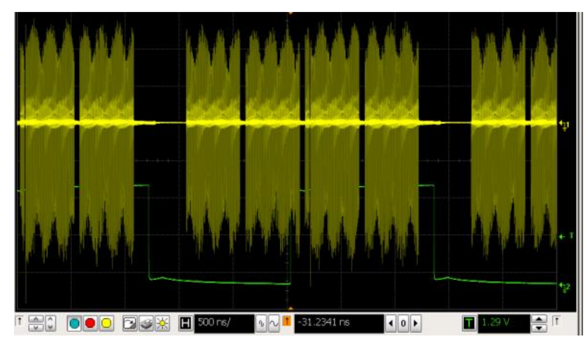
MBI treshold vs chromaticity



MB Modes cluster around m= 0

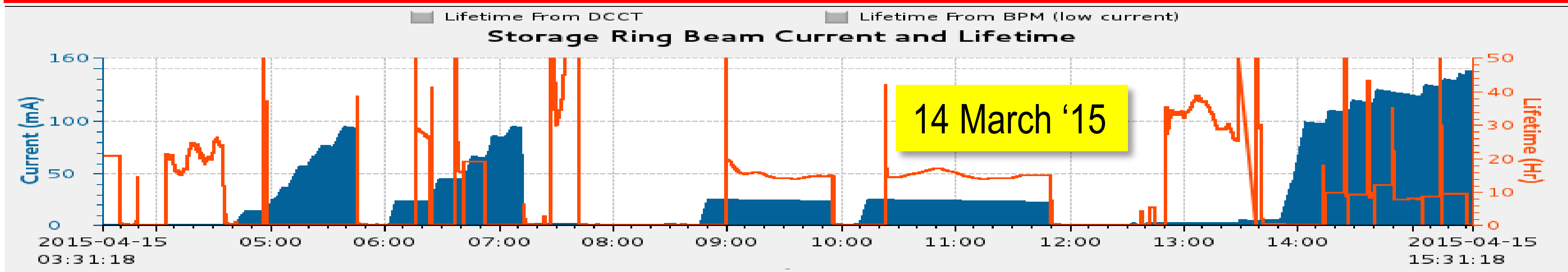




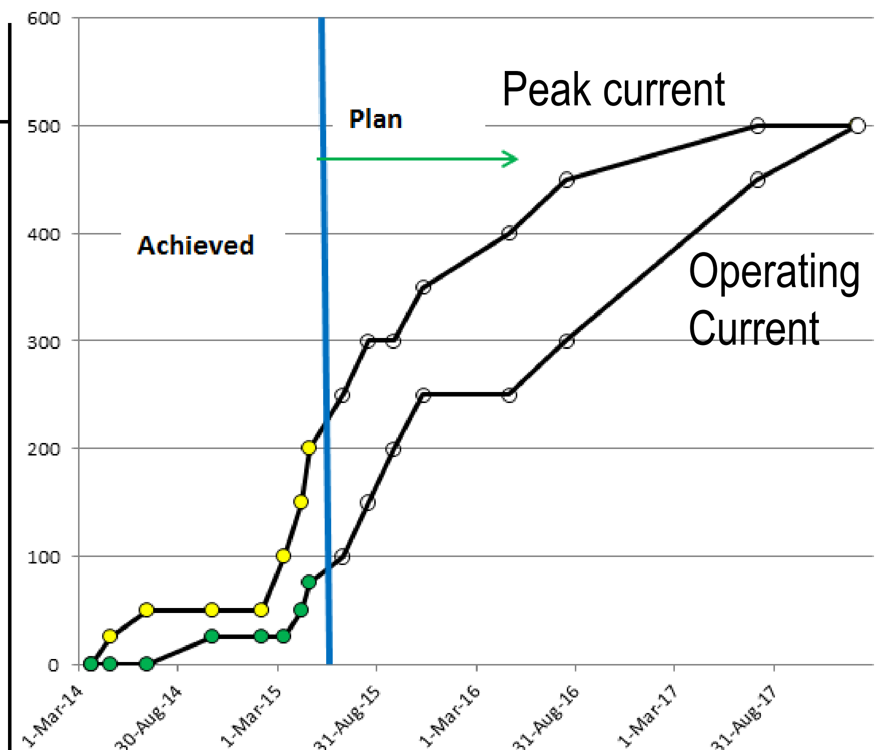


- At nominal chromaticity ξ_{xy}=+2, above 20 mA of beam current, transverse instability observed ξ=0, I > 10 mA unstable)
- Mode spectrum peaks at low mode numbers
- Resistive wall instability should have higher threshold value
- Growth rates seem to vary with number of ion gaps: assume it is an fast ion instability component
  six trains seem near optimum
- Broad band damper system has sufficient power for growth rate extrapolated linearly with beam current

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



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

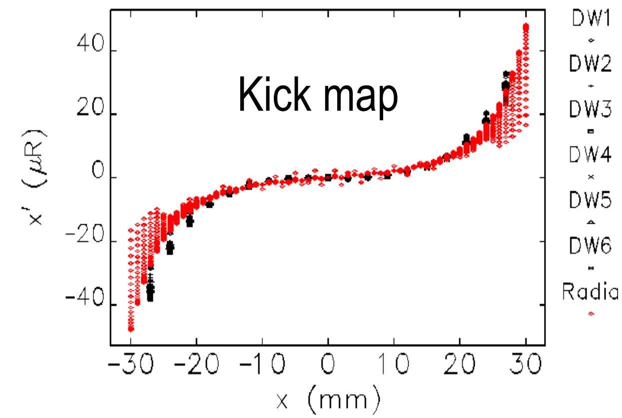
Damping wiggler

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

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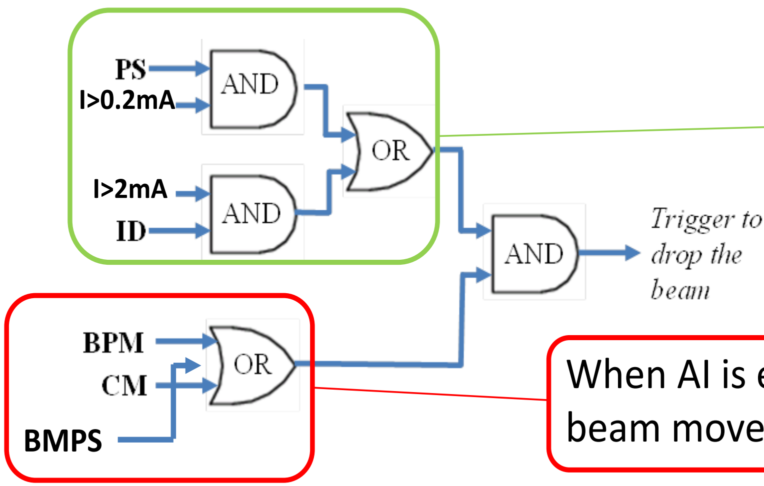
Orbit Interlock System (Active Interlock)

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**, **$\Delta x'$, $\Delta y'$ < 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



Interlock is enabled either if beam current > 0.2 mA and PS is open, or if I_{beam}>2 mA and ID gap is closed.

When AI is enabled the beam is dumped if electron beam moves outside of AI envelope.

	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 improves 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)

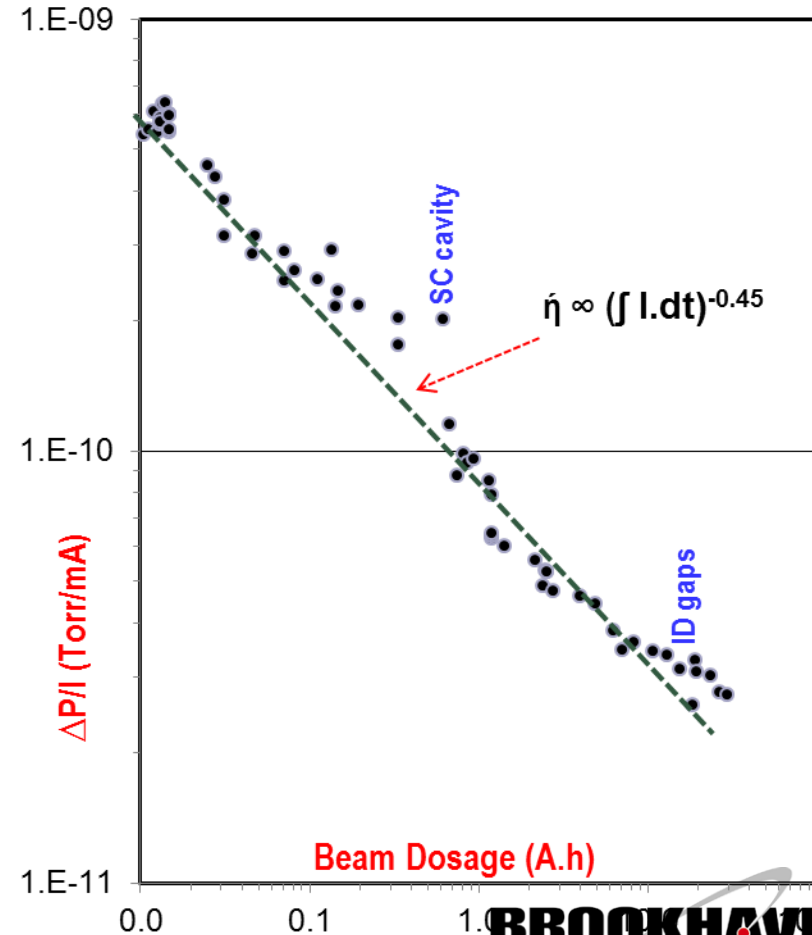
•Present status $\int I_{beam}\, dt \sim 40$ Ah

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

Vacuum lifetime is 48 hours

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

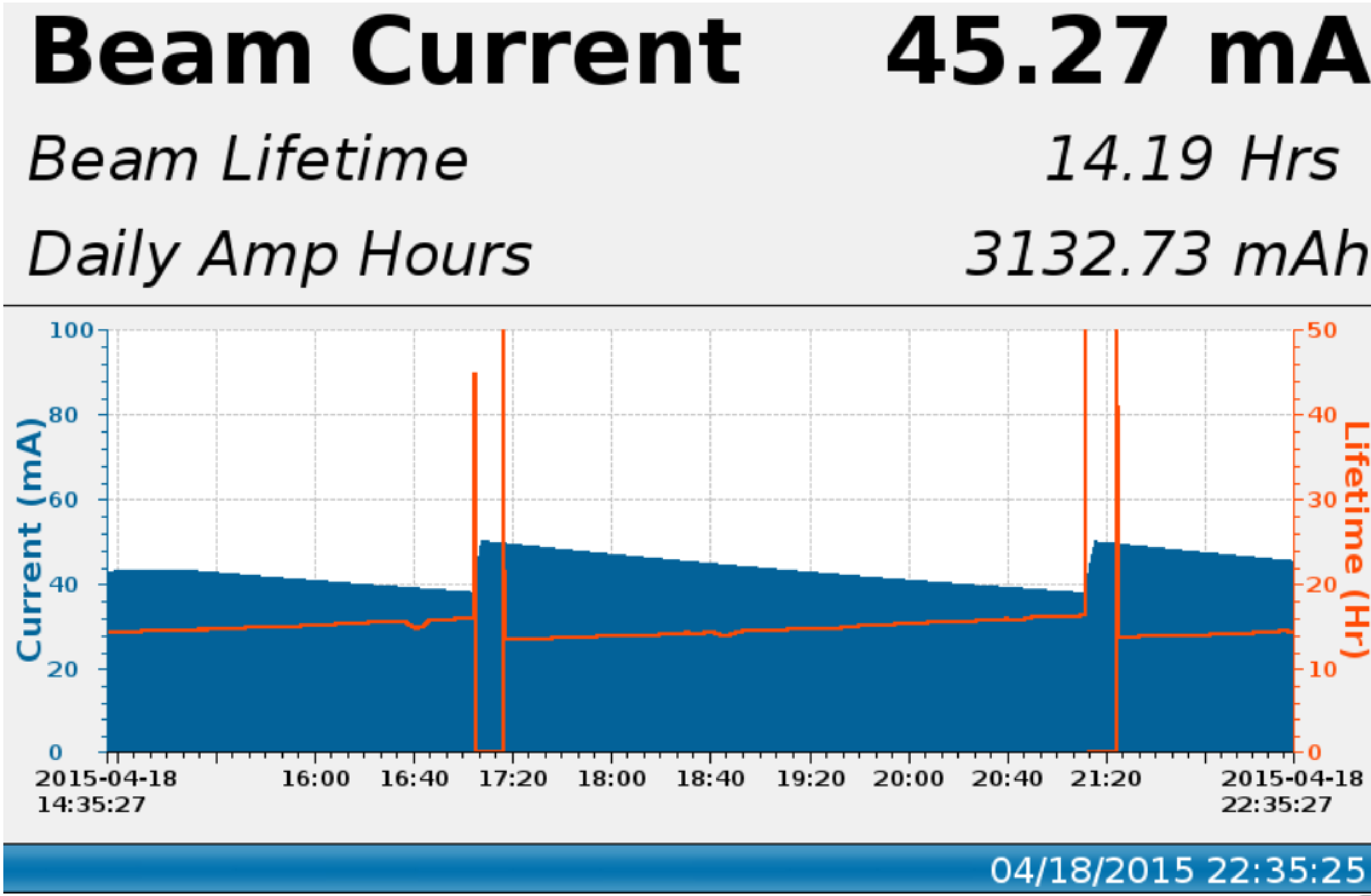
➔Will need > 150 Ah to reach < $1 \cdot 10^{-11}$ Torr / mA for operation at 300 mA with τ > 10 h



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	150
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 RFCavities		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

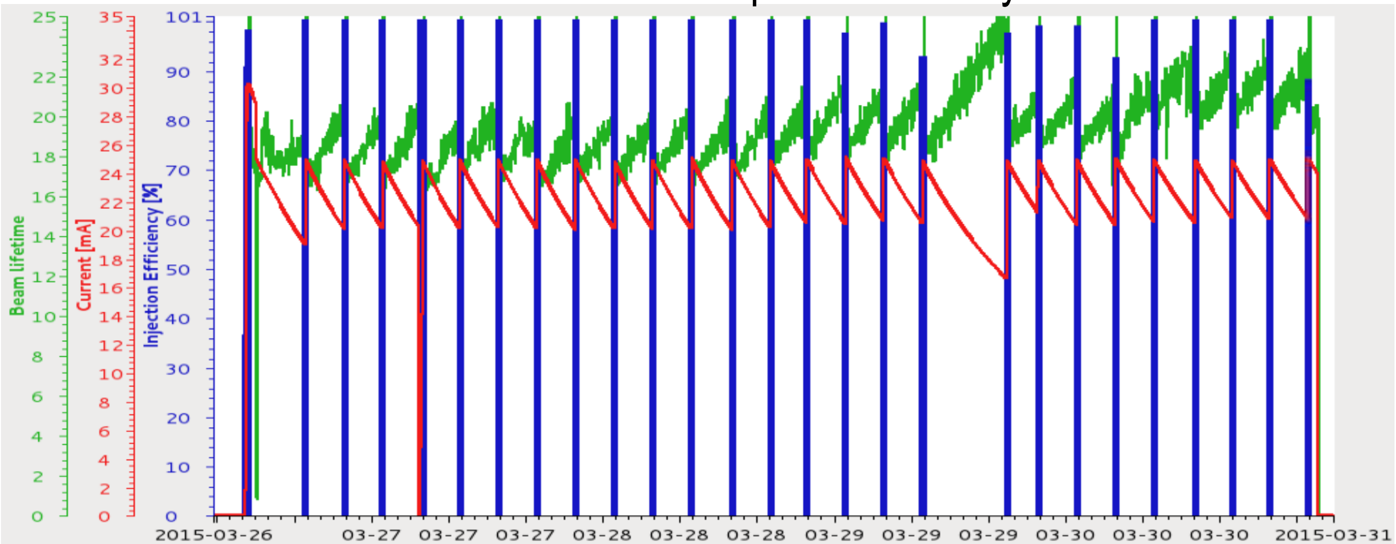
50mA Operation

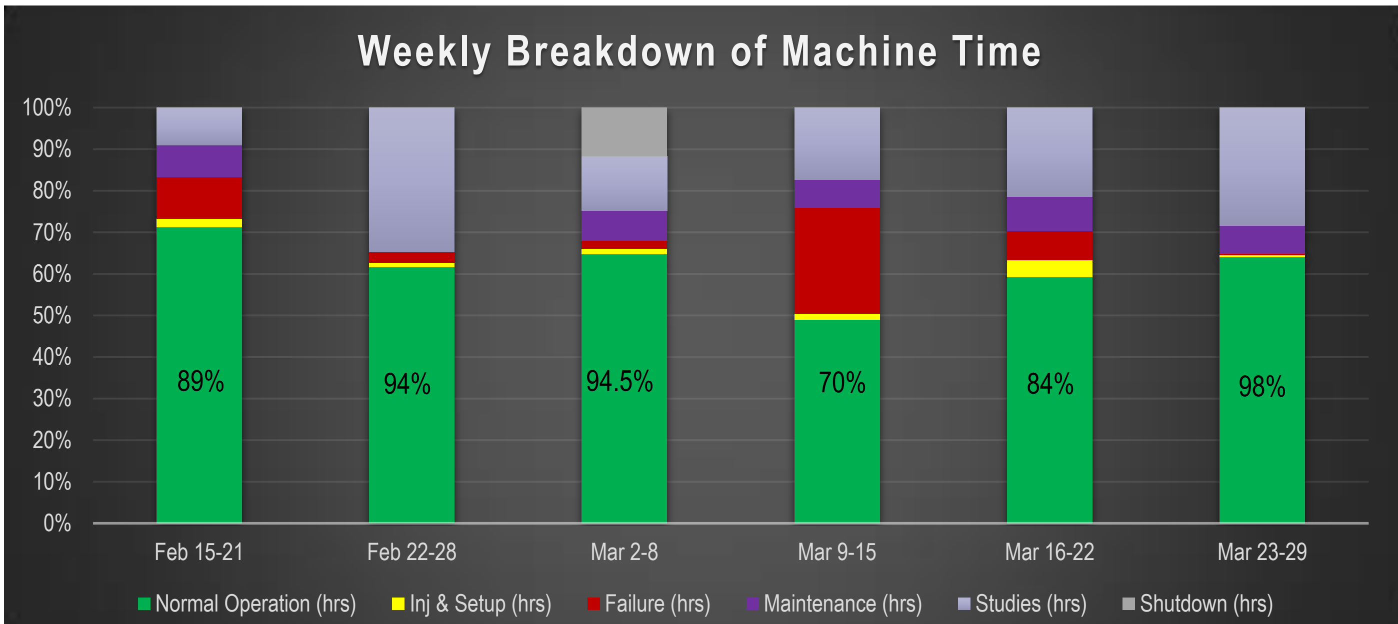


Machine reliability

- 25 mA user operation.
- Beam lifetime is ~ 20 hrs, as expected.
- Machine is stable to keep injection efficiency >90%.
- Machine normal operation time is around ~90%.

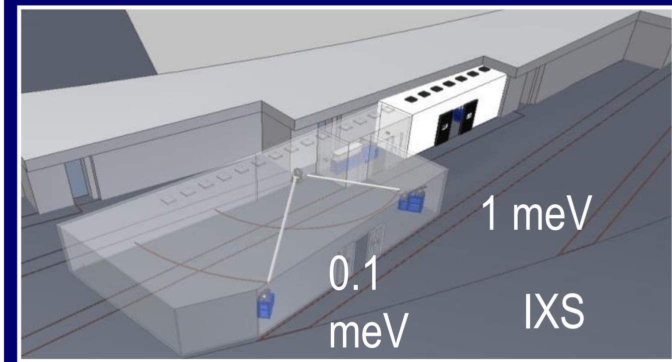
One week beam operation history





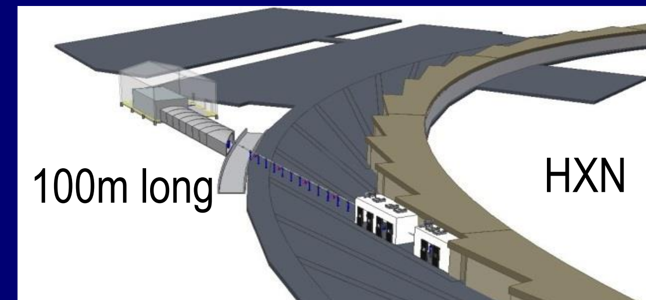
U.S. DEPARTMENT OF ENERGY

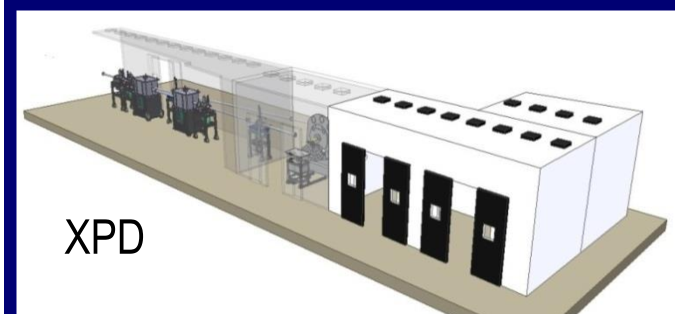
The Six Project NSLS-II Beamlines



inelastic
x-ray scattering

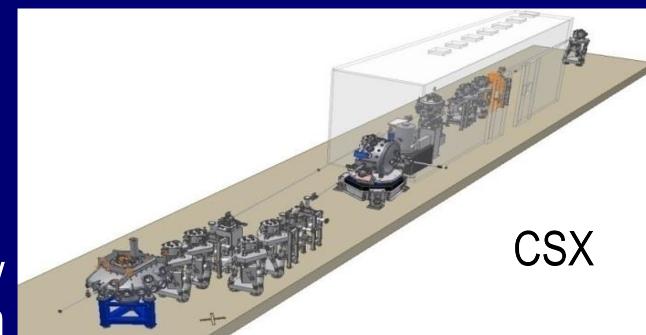
hard x-ray
nanoprobe

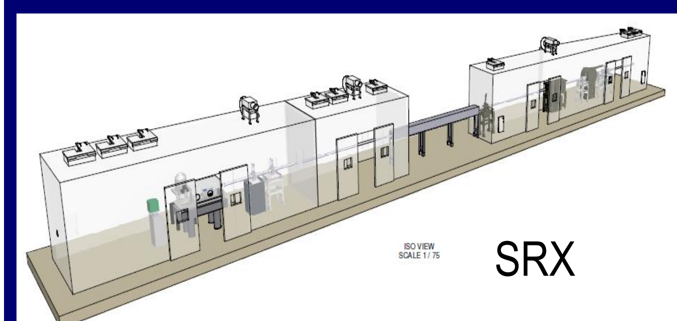




x-ray powder
diffraction

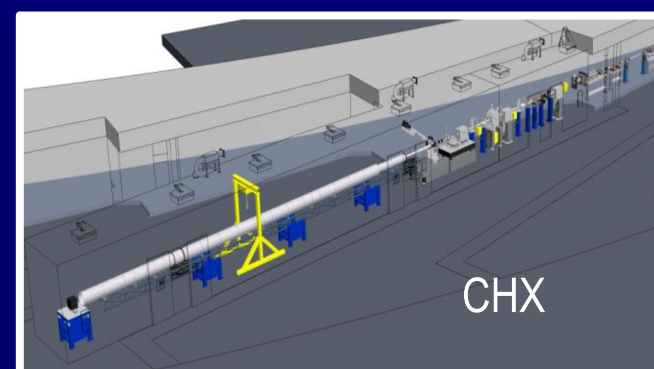
coherent soft x-ray
scattering/polarization





sub-μm resolution
x-ray spectroscopy

coherent hard
x-ray scattering



FIRST LIGHT CELEBRATION!

Outlook

Summer of 2015:

- Demonstration of 300 mA beam current
- Commissioning of 3 more ID (2x IVU21, IVU23), FE and beam lines (ABBIX)
- Installation of 2nd superconducting cavity

Fall 2015

- **Top-Off** operation (injection with open photon shutters)

Spring 2016

- Installation of 4 more insertion devices (2 x IVU23 EPU57 and EPU105) and 5 more beam line frontends (NEXT Project)
- Include ABBIX beam line into routine operation
- Completion and installation of 3rd harmonic cavity
- Install first suite of bending magnet frontends
- Establish 300 mA in routine operation

Summer 2016

- Demonstrate $I_{beam} > 400$mA
- Commission NEXT ID, Frontends and beamlines

Summary

- NSLS-II is designed as the ultimate 3rd generation Synchrotron Radiation Lightsource enabling 1 nm spatial resolution and 0.1 meV energy resolution
- The accelerator is designed to provide a photon beam brightness of 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
- The NSLS-II project was completed successfully in FY15 within schedule and budget.
- The NSLS-II accelerator started operating 5 month before the end of the project
- 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.
- 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!

Further contributions from NSLS-II to this conference

MOPMN024
MOPMN025
MOPJE053
MOPTY038

TUAB2
TUPJ0E37
TUPHA004
TUPHA005
TUPHA006
TUPHA007
TUPHA008
TUPHA009
TUPHA010
TUPMA050
TUPMA052

TUPMA053
TUPMA054
TUPMA055
TUPMA056
TUPMA057

WEPWI052
WEPWI55
WEPWI058