Status of NSLS II

F. Willeke, BNL
Particle Accelerator Conference 2011, New York City
March 29, 2011
Outline

- Requirements
- Design
- Facility Status
- Injectors
- Critical Subsystems
- Insertion Devices
- Photon Beam Lines
- Construction Status
- Summary
Mission

- NSLS: a very productive light source
  4th decade of operation
  Strong on-going science program

- State of the art of accelerator technology:
  \textbf{Factor 10^4} increase in brightness,
  \textbf{Factor 10} increase in flux

  More than a quantitative step

- 2005: DOE acknowledges mission need
  for a synchrotron radiation facility with
  1 nm spatial resolution
  0.1 meV energy resolution

- Start of NSLS-II Project:
  2005 CD 0
  2007 CD 1
  2008 CD2
  2009 CD3
  2015 CD4
# Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Spectral Brightness</td>
<td>$10^{21} \cdot \text{mm}^{-2} \cdot \text{mrad}^{-2} \cdot \text{s}^{-1} \cdot 0.1% \text{bw}^{-1}$</td>
</tr>
<tr>
<td>Spectral Flux Density</td>
<td>$10^{15} \cdot \text{s}^{-1} \cdot 0.1% \text{bw}^{-1} @ 2 \text{ keV}$</td>
</tr>
</tbody>
</table>

## Accelerator Main Parameters

- **beam energy:** 3 GeV
- **beam intensity:** 500 mA
- **Intensity Stability:** 0.5% ➔ Top-Off Injection mode
- **small beam emittance:**
  - $\varepsilon_x = < 1 \text{ nm rad}$,  
  - $\varepsilon_y = 8 \text{ pm rad}$
- **orbital stability:** $\Delta y < 0.3 \text{ \mu m}$
- **RF Phase Stability:** 0.01 Degree
- **Number of beamlines:** > 60
Low Emittance Lattice Design

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

- **Soft Bending Magnet**: $B = 0.4$ T
  - $\beta_{x\text{-max}} \sim \xi \sim 1/L_{\text{bend}}$
  - Achieve close to theoretical minimum emittance without excessive chromaticity $\varepsilon_x = 2$ nm

- **Soft bend**, low radiation loss Emittance $\sim 1/\rho$
  - low radiation loss, 283 keV/turn/electron
  - Efficient use of **damping wigglers** to reduce emittance by increased betatron damping rate
  - 3 x 2 x 3.5 m wiggler @ 1.8 T: $\varepsilon_x = 1$ nm (baseline)
  - 8 x 2 x 3.5 m wiggler @ 1.8 T: $\varepsilon_x = 0.6$ nm (optional)
Facility Overview

(1) Accelerator Tunnel  3.7m x 3.2 m x 792m
(2) Experimental Floor, width 17m
(3) 200MeV S-Band LINAC
(4) 3GeV Booster Synchrotron C=158m
(5) RF Building, lq. He Plant
(6) Compressor Building
(7) Central Cooling Tower
(8) Service Buildings: HVAC, DI water
(9) Lobby
(10) Laboratory and Office Buildings
(11) Vehicle underpass
(12) Extra long beam line
Facility Overview

Staged Availability Building

1\textsuperscript{st} pentant: Mar 15 '11
RF May 18 '11
Injector Jul 28 '11
2\textsuperscript{nd} Pentant Jun 2 '11
3\textsuperscript{rd} Pentant Sep 27 '11
4\textsuperscript{th} Pentant Nov 28 '11
5\textsuperscript{th} Pentant Feb 9 '12

Storage Ring Tunnel
NSLS-II INJECTOR

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

200 MeV LINAC
- Frequency: S-Band
- Charge: 15nC
- ∆E/E: <1%
- sectors
- Thermionic Gun Sub-harmonic 500MHz Buncher
- Variable bunch patterns, 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
- Charge: 10-15nC @20-30mA

PETRA &-cell 500MHz Cavity
Injector Status

- **Injector Building** Ready July 28, 2011

- **LINAC** Turn Key Contract Award April 2010 (RI)
  
  Design Complete
  
  production of components in progress
  
  Frontend Delivery: June 2011
  
  LINAC Delivery and start Installation August 2011

- **Booster** Semi-turnkey Contract Award: May 2010 (BINP)
  
  Design Finalized, Prototypes of components being produced
  
  Booster Installation: Spring 2012
Critical Subsystems with Novel Features

Magnet Systems
- high field quality,
- micron mechanical reproducibility,
- 30 micron alignment tolerance
- 25 nm mechanical stability

RF
- High Beam loading,
- High RF phase stability
- bunch lengthening

Instrumentation
- Sub-micrometer BPM
- Pico-meter emittance measurements

Controls
- High speed real time deterministic data communication
- Integrated high level controls
- Integrated equipment database

Power Supplies and Electronics
- High reliability

Insertion Devices
- high field quality
- novel materials
Magnet Field Quality

Medium energy (3GeV) + High intensity (500mA) + low emittance (<1nm, 8pm) beam

- Lifetime strongly dominated by Touschek effect

Low emittance lattice with moderate chromaticity and highly optimized sextupole fields

- Dynamic aperture fair: 15 mm x 3 mm @ 2.5% momentum deviation @ \( \tau_{\text{Touschek}} = 3 \) hrs

- Large Dynamic Aperture shrinks for quadrupole and sextupoles with “normal field quality

- small field errors required: systematic errors \( \Delta B/B = 10^{-4} \), nonsystematic \( \Delta B/B 10^{-5} @ 25\text{mm} \)

| Allowed Relative Field Error Quadrupoles @ \( r = 25, x 10^{-4} \) |
|-----------------|------------------|------------------|
| n   | Normal Aperture | Large Aperture |
|     | norm | skew |     | norm | skew |
| Symmetry-allowed |       |      |     |      |      |
| 6    | 3    | 0    | 0.5 | 0    |
| 10   | 3    | 0    | 0.5 | 0    |
| 14   | 3    | 0    | 0.1 | 0    |
| Symmetry-unallowed |     |      |     |      |      |
| 3    | 2    | 2    | 3   | 1.5  |
| 4    | 2    | 1    | 2   | 1    |
| 5    | 1    | 1    | 0.3 | 0.1  |
| 6    | -    | -    | -   | 0.1  |
| 7-9  | 1    | 1    | 0.1 | 0.1  |
| 10   | -    | -    | -   | 0.1  |
| 14   | -    | -    | -   | 0.1  |
| 11-13,15 | 0.5 | 0.5 | 0.1 | 0.1  |

Need 90mm aperture quads in center of achromate
Storage Ring Magnet Systems
based on successful prototypes

Normal Quadrupole
Magnet 120 Units to be built by BINP

Normal Sextupole
169 Units to be built by Danfysik

Wide Quadrupole
120 Units to be built by TESLA Ltd

Wide Sextupole
75 Units to be built by IHEP

Dipoles 54 units 35 mm gap and 6 units with 90mm gap to be built by Buckley

156mm and 100 mm DC dipole correctors (192 units) to be built by Everson Tesla

30 large aperture sextupoles and 60 large aperture quadrupoles
To be built by Buckley Industries
Magnet Production

- 7 Contracts awarded in Fall 2009
- All manufacturers made large effort to meet high and reproducible field quality
- ~ 6-12 months development needed before production could start
- Advanced Production methods provide 10 micron precision of pole structure and 3 micron mechanical reproducibility
- Magnet production is taking off and ~15% of production is completed

Remarkable reproducibility after de-assembly-reassembly

Precision machining
EDM
Fine planking
Magnet acceptance Testing at BNL
Girder, Supports and Integration

- Girder girders have been designed and manufactured for low vibration response \( (f_{res} > 30\text{Hz}) \) and high thermal stability.
- Visco-elastic layers in supports are an important feature.
- A precision alignment procedure based on stretched wire with AC current was developed which allows to measure magnet center with 5 \( \mu \text{m} \) precision.
- Intricate procedure to align the magnet and secure high precision alignment while girders are transported and installed developed.
- Alignment performed in temperature controlled enclosure which mimics tunnel conditions.
- Procedure fully tested.
- First girder equipped with magnets, vacuum components and diagnostic equipment.

Environmental Room \( (\Delta T < 0.1 \text{ C}) \) for 30 \( \mu \text{m} \) Precision Alignment.
First Fully Integrated NSLS-II Magnet Girder
Instrumentation-BPM System

- New improved Button Monitor, Boron-Nitride Heat distribution washers avoid beam heating issues

- In-house development BPM electronics. 500MHz band pass filter, sampling at 117MHz, pilot tone mixed with beam signal for continuous relative calibration of channels

- Beam test at ALS confirm: meet demanding NSLS-II requirements resolution 0.2 µm, stability 0.2µm)

- Detrimental TE (H) modes in keyhole-shaped beam pipe exited by beam

   → RF shield separates beam- from antechamber
Vacuum System

• Vacuum System Based on extruded Aluminum
• Multistage production with final integration in-house
• Status: ~1/3 of chambers ready for installation

• Glidcop masks absorb synchrotron radiation
• New Design Shielded Bellow, Ag+Rh coated sleeves
• First Units being manufactured in-house
Storage Ring RF

Requirements

<table>
<thead>
<tr>
<th></th>
<th>Baseline Capability with 2 RF Cavity Systems Required Voltage 3.3 MV</th>
<th>Fully Build-out Capability with 4 RF Cavity Systems Required Voltage 5 MV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>P(kW)</td>
</tr>
<tr>
<td>Dipole</td>
<td>60</td>
<td>144</td>
</tr>
<tr>
<td>Damping wiggler</td>
<td>3 (21 m)</td>
<td>259</td>
</tr>
<tr>
<td>Cryogenic-PMU</td>
<td>3</td>
<td>76</td>
</tr>
<tr>
<td>E-IVU</td>
<td>2</td>
<td>33</td>
</tr>
<tr>
<td>Additional devices</td>
<td>~7</td>
<td>120</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>529</td>
</tr>
<tr>
<td>Available RF Power</td>
<td></td>
<td>540</td>
</tr>
</tbody>
</table>

RF Stability Requirements

<table>
<thead>
<tr>
<th>Reason</th>
<th>Δφ (deg)</th>
<th>dδ (x10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centroid jitter due to Residual dispersion (ID’s)</td>
<td>0.81</td>
<td>3</td>
</tr>
<tr>
<td>Vertical Divergence (from momentum jitter)</td>
<td>2.4</td>
<td>9</td>
</tr>
<tr>
<td>Dipole, TPW (position stability due to momentum jitter)</td>
<td>0.27</td>
<td>1</td>
</tr>
<tr>
<td>Timing experiments (5% of 15ps bunch @&gt;500Hz)</td>
<td>0.14</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Cavities: Superconducting single cell 500mHz Cavities
Reasons: more economic on the long term, better beam loading performance
RF Power Source: Klystron Amplifiers 310kW
Passive superconducting 3rd harmonic cavity for bunch lengthening
Storage Ring RF System

- Single cell 500 MHz SC Cavity: CESR-B Design
  - Updated design to comply with safety regulations,
  - Input coupler adaption
- 310 kW klystron RF transmitter,
  - Turn-key, in production
- In-house development LLRF Controls
  - FPGA based control module, designed, fabricated,
    tests performed
  - Extensive LLRF modeling,
  - Future option for adaptive feedback for optimized control
RF Systems

Lq He Cryogenic Plant
900W lq. He Plant
Turn-key system in production

3rd Harmonic Cavity
-Bunch lengthening factor 2-3
-Margin for Touschek lifetime
-New design
-Production in collaboration with Industry (SBIR)
-Low power test successful
Insertion Devices

Damping Wiggler 1.8T
6 x 3.5m in production

IVU 20, 21, 22
Design complete

Brightness of NSLS-II radiation devices

- EPU contract award
- 3 Pole Wiggler
  - In production

- Photon Energy
  - U(100) PMU
    - $\lambda_u \approx 100 \text{ mm}$
    - $L = 6 \text{ m (high-}\beta)$
    - $K_{\text{max}} = 9.2$

- IVU20: $\lambda_u = 20 \text{ mm}$, $K_{\text{max}} = 1.83$, $L = 3 \text{ m (low-}\beta)$
- IVU22: $\lambda_u = 22 \text{ mm}$, $K_{\text{max}} = 1.52$, $L = 6 \text{ m (high-}\beta)$
- CPMU17: $\lambda_u = 17 \text{ mm}$, $K_{\text{max}} = 1.67$, $L = 3 \text{ m (low-}\beta)$
- SCU14: $\lambda_u = 14 \text{ mm}$, $K_{\text{max}} = 2.2$, $L = 2 \text{ m (low-}\beta)$

- EPU49 APPLE-II Undulator
  - $\lambda_u \approx 49 \text{ mm}$, $L \approx 4 \text{ m (low-}\beta)$
  - $K_{\text{max,lin}} = 4.34$, $K_{\text{max circ}} = 3.69$

- SCW(60)
  - Supercond. Wiggler
  - $B \approx 3.5 \text{ T}$, $\lambda_u \approx 60 \text{ mm}$
  - $K \approx 19.6$, $\varepsilon_c \approx 21 \text{ keV}$
  - $L \approx 1 \text{ m (low-}\beta)$

- DW100 Damping Wiggler
  - $B \approx 1.85 \text{ T}$, $\lambda_w \approx 100 \text{ mm}$
  - $K_{\text{eff}} \approx 16.5$, $\varepsilon_c \approx 11 \text{ keV}$
  - $L \approx 7 \text{ m (high-}\beta)$

- Bend Magnet
  - $B = 0.4 \text{ T}$, $\varepsilon_c = 2.4 \text{ keV}$

- Three-Pole Wiggler
  - $B = 1.14 \text{ T}$, $\varepsilon_c = 6.8 \text{ keV}$
<table>
<thead>
<tr>
<th>Name</th>
<th>U20</th>
<th>U22 (IXS)</th>
<th>EU49</th>
<th>U21 (SRX)</th>
<th>DW-1.8T</th>
<th>3PW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>IVU</td>
<td>IVU</td>
<td>EPU</td>
<td>IVU</td>
<td>PMW</td>
<td>PMW</td>
</tr>
<tr>
<td><strong>Photon energy range</strong></td>
<td>Hard x-ray (1.9-20keV)</td>
<td>Hard x-ray (9.1keV)</td>
<td>Soft x-ray (250eV-1.7keV)</td>
<td>Hard x-ray (1.9-20keV)</td>
<td>Broad band (&lt;10eV-100keV)</td>
<td>Broad band (&lt;10eV-100keV)</td>
</tr>
<tr>
<td><strong>Type of straight section</strong></td>
<td>Short</td>
<td>Long</td>
<td>Short (canted)</td>
<td>Short (canted)</td>
<td>Long (in-line)</td>
<td>near 2nd Dipole</td>
</tr>
<tr>
<td><strong>Period length (mm)</strong></td>
<td>20</td>
<td>22</td>
<td>49</td>
<td>21</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td><strong>Length (m) &amp; Number of Devices</strong></td>
<td>3.0 x 2</td>
<td>3.0</td>
<td>2.0 x 2</td>
<td>1.5</td>
<td>3.5 x 6</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Number of periods</strong></td>
<td>148</td>
<td>135</td>
<td>36 x 2</td>
<td>69</td>
<td>34 x 2</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Magnetic gap (mm)</strong></td>
<td>5</td>
<td>7.0</td>
<td>11.5</td>
<td>5.5</td>
<td>15.0</td>
<td>28</td>
</tr>
<tr>
<td><strong>Peak magnetic field strength B (T)</strong></td>
<td>1.03</td>
<td>0.78</td>
<td>0.57 (Heli)</td>
<td>0.94 (Lin)</td>
<td>0.72 (vlin)</td>
<td>0.41 (45°)</td>
</tr>
<tr>
<td><strong>Keff</strong></td>
<td>1.81</td>
<td>1.52</td>
<td>2.6 (Heli)</td>
<td>4.3 (Lin)</td>
<td>3.2 (vlin)</td>
<td>1.8 (45°)</td>
</tr>
<tr>
<td>h(\nu) fundamental, eV</td>
<td>1620</td>
<td>1802</td>
<td>230 (Heli)</td>
<td>180 (Lin)</td>
<td>285 (vlin)</td>
<td>400 (45°)</td>
</tr>
<tr>
<td>h(\nu) critical, keV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>64.5</td>
</tr>
<tr>
<td><strong>Total power (kW)</strong></td>
<td>8.0</td>
<td>4.7</td>
<td>8.8</td>
<td>3.6</td>
<td>64.5</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Insertion Devices - New Materials

Successful Tests with **Pr-Fe-B**

Will be operated at Lq N2 temperature,

Fairly flat temperature coefficients

→ Stable operation with enhanced $B_r$

Vacuum bakeout tests in Progress

Magnet test array in production
Control System

EPICS protocol

System Services

Middle Layer Services

LAN Ethernet Channel Access protocol

RF Synchronous Event and Timing line

2GBs Shared Memory Bus (fast orbit feedback, etc)

Front-ends with 2 Tier embedded controllers

(need R&D)

ACC. TUNNEL

CPU

EVR

CEL

BPM IOCs

CPU

EVR

CEL

PS IOCs

BPM

BPM

BPM

BPM

BPM

PS

PS

PS

PS

24
Digital Front End Electronics

BPM Application:

- Calculates beam position from Raw ADC inputs at 117MHz
- Stores 1 million Turn By Turn data points, 10KHz data points and raw ADC measurements
- Provides 10kHz position data for Fast Orbit Feedback

Cell Controller Application:

- Transfers all BPM measurements to all cells in less than 15us over redundant fiber optics
- Computes 90 parallel Eigenvectors in less than 4us for fast orbit feedback
- Responds to beam envelope violations in less than 100us for machine protection

- High speed Serial Communication
- Gigabit Ethernet
- Large Memory
- On board CPU
- Digital Signal Processing
Schedule

Critical Decisions
LINAC
Booster
Transferlines
Injector Installation
Storage Ring
Components
Design and Construction
1st Pentant
Ring Bld Ready (BOD)
Storage Ring Installation
Controls and Safety systems
Insertion Devices
Integrated Testing
Commissioning
The Six Initial NSLS-II Beamlines

- **IXS**: inelastic x-ray scattering
  - 1 meV
  - 0.1 meV
- **HXN**: hard x-ray nanoprobe
  - 100m long
- **XPD**: x-ray powder diffraction
  - coherent soft x-ray scattering/polarization
- **SRX**: sub-\(\mu\)m resolution x-ray spectroscopy
  - coherent hard x-ray scattering
- **CSX**:
- **CHX**:
Conclusion

- NSLS-II is a 3rd generation light source using cutting edge accelerator technology
  - Magnet production
  - Alignment
  - Instrumentation
  - Insertion devices
  - Controls

to meet the desired performance, a brightness of $10^{21}$ 2keV photons per $(\text{mm}^2\text{mrad}^2\text{sec}, 0.1\% \text{bw})$ needed to achieve 1nm spatial resolution and 0.1meV energy resolution

- Most of Accelerator Components are in production
- First Part of Ring Building available for installation
- Installation of components has started
- Linac will be installed and commissioned this year
- Storage Ring Commissioning will start in May 2013
- Project Early completion is envisioned for February 2014
NSLS-II PAC’11 Contributions

Lattice Design: THP189, THP190, THP129,
Accelerator Physics: WEP176, MOP192, WEP217, THP127, THP193, MOP276
Safety Systems: MOP274,
RF: FROBS4, TUP055,
Instrumentation: MOP211, MOP199, MOP198, MOP193, MOP266
Controls: WEODN4, MOP165
Injection systems: TUP211, THP131-135, THP215, WEP282-283
Insertion Devices: THOPS4,
Vacuum: THP216