NSLS-II Insertion Device Development

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NSLS - II

Second Mini-Workshop on Magnet Simulations for Particle Accelerators in PAC07
2007/06/26-27
Outline

1) NSLS-II Project
2) Lattice Magnets (W. Meng & R. Gupta)
3) Permanent Magnet Damping Wiggler
4) Elliptically Polarized Undulator (EPU)
5) 3 Pole Wiggler
6) Cryo-Permanent Magnet Undulator (CPMU)
   - New Magnet / Pole Materials
7) Superconducting Insertion Devices
   - SCU, SCW and SEPU
   - High Temperature Superconductor (HTS)
A highly optimized x-ray synchrotron delivering:
- extremely high brightness and flux;
- exceptional beam stability; and
- a suite of advanced instruments, optics, and detectors that capitalize on these special capabilities.

Together, these enable:
- ~ 1 nm spatial resolution,
- ~ 0.1 meV energy resolution, and
- single atom sensitivity.
NSLS-II Accelerators

NSLS-II Machine Concept
- New 3 GeV Electron Storage Ring
- Large Circumference (791.5 m), H = 1320
- “Compact” (~158m, H=264) booster
- Large Current (500 mA)
- Superconducting RF
- Top-Off Operation
- DBA30 Lattice
- 15 short and 15 long straights
- Ultra-Low Emittance (<1 nm)
- Damping Wigglers (21 – 56 m)
- Large Dipole Bend Radius (25 m)
- Provision for IR Source
- Three-pole wiggler x-ray sources

Selected Technical Challenges
- Lattice Design: dynamic aperture, energy acceptance
- Source Stability: vibrations, thermal issues, PS and RF noise, feedback
- Impedance Budget: Small gap (5 mm) ID tapers, etc
- Insertion Device: CPMUs, EPUs, SCUs(?)
Storage Ring Functionalities

- 3 GeV, 500 mA ± 1%
  - Upgradeable to 3.6 GeV or 700 mA
- Estimated beam life-time: 2 – 3 hours
- Top-off injection to achieve better than 1% beam current variation for the heat load stability

- Ultra-small emittance ($\varepsilon_x, \varepsilon_y$):
  - Bare Lattice: ~2 nmrad Horizontal & ~0.01 nmrad vertical
  - Baseline: ~1 nmrad horizontal & ~0.008 nmrad vertical
  - Fully built-out: ~1/2 nmrad horizontal, ~0.008 nmrad vertical
- High level of reliability and stability of operation

- Magnet Inventory:
  - 60 dipoles: 2.5 m long, 54 with 35 mm gap, 6 with 93 mm gap
  - 330 quadrupole magnets:
  - 390 sextupoles magnets.
  - 210 corrector magnets
3D Simulation Codes

- **Radia** (v.4.1 can be obtained from www.esrf.eu, v.4.117 from soleil ?)
  - Mathematica’s mathlink program using boundary integral method
  - No need to mesh free space & infinity → no truncation error for field integral
  - Field inside magnetization volume is not accurate due to discontinuity
  - Importing BH curve file of a material is not trivial → It can be done
  - RHS  x-horizontal, z-vertical, y-longitudial

- **Opera 3D / Tosca**
  - Preprocessor → complicated shaped object difficult
  - Modeller → meshing errors hard to analyze
  - Making parametrized model difficult

- **ANSYS / Emag**
  - Quick Optimizer
  - Can be combined with stress analysis
Recent Magnetic Models
Quadrupole Magnet (Meng)

Quadrupole Magnet

- Magnet designs must be robust. Field quality (harmonic contents) should remain within specified tolerances after repeated disassembly and reassembly.
- Several different designs (SPEAR, SLS, APS) are being evaluated.
- A 2-segment quadrupole design is being developed.
A 2-segment sextupole design is being developed.
# List of NSLS-II IDs

<table>
<thead>
<tr>
<th>Name</th>
<th>U14</th>
<th>U19</th>
<th>U45</th>
<th>U100</th>
<th>DW-1.8T</th>
<th>3PW</th>
<th>SCW</th>
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<tbody>
<tr>
<td>Type</td>
<td>SCU</td>
<td>CPMU</td>
<td>EPU</td>
<td>QEPU</td>
<td>PMW</td>
<td>PMW</td>
<td>SCW</td>
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<tr>
<td>Photon energy range</td>
<td>Hard x-ray (1.8-30keV)</td>
<td>Hard x-ray (1.5-20keV)</td>
<td>Soft x-ray (180eV-7keV)</td>
<td>VUV (8eV-4keV)</td>
<td>Broad band (&lt;10eV-100keV)</td>
<td>Broad band (&lt;10eV-40keV)</td>
<td>Very hard x-ray (&lt;10eV-200keV)</td>
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<td>Type of straight section</td>
<td>5m</td>
<td>5m</td>
<td>8m</td>
<td>8m</td>
<td>8m</td>
<td>8m</td>
<td>5m</td>
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<tr>
<td>Period length (mm)</td>
<td>14</td>
<td>19</td>
<td>45</td>
<td>100</td>
<td>100</td>
<td>60</td>
<td></td>
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<tr>
<td>Total undulator length (m)</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
<td>4.0</td>
<td>7.0</td>
<td>0.3</td>
<td>1.0</td>
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<tr>
<td>Number of periods</td>
<td>143</td>
<td>158</td>
<td>89</td>
<td>40</td>
<td>70</td>
<td>17</td>
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<td>Magnetic gap (mm)</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>15</td>
<td>32</td>
<td>15</td>
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<tr>
<td>Peak magnetic field strength B (T)</td>
<td>1.68</td>
<td>1.21</td>
<td>0.68 (Heli)</td>
<td>1.03 (Lin)</td>
<td>1.50</td>
<td>1.80</td>
<td>1.1</td>
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<td>$K$</td>
<td>2.20</td>
<td>2.03 (eff)</td>
<td>2.87 (eff)</td>
<td>4.67 (eff)</td>
<td>14.01</td>
<td>15.92 (eff)</td>
<td>19.61</td>
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<td>$h\nu$ fundamental, eV</td>
<td>1788.8</td>
<td>1469.7</td>
<td>183.1</td>
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<td>$h\nu$ critical, keV</td>
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<td></td>
<td></td>
<td>11.8</td>
<td>21.0</td>
<td>6.8</td>
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<tr>
<td>Total power (kW)</td>
<td>16.08</td>
<td>11.18</td>
<td>12.09</td>
<td>25.64</td>
<td>64.60</td>
<td>0.32</td>
<td>34.89</td>
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<tr>
<td>$G(K)$</td>
<td>0.9842</td>
<td>0.9818</td>
<td>0.9959</td>
<td>0.9996</td>
<td>0.9997</td>
<td>0.9998</td>
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<tr>
<td>On-axis power density (kW/mrad$^2$)</td>
<td>103.70</td>
<td>77.86</td>
<td>40.03</td>
<td>26.33</td>
<td>55.30</td>
<td>25.60</td>
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</tr>
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Quantities to Characterize an Undulator

- Good Field Region (less than 0.5% reduction in peak field)
  - Determined by the pole&magnet width. Closely related to multipoles

- Trajectory (Gap dependence)
  - Straightness
  - 1st integrals (normal/skew dipole) $\rightarrow$ kick angle
  - 2nd integrals $\rightarrow$ trajectory shift

- Phase Error
  - Spectral brightness in higher harmonics

- Integrated Higher Order Multipoles
  - Normal / Skew Quadrupoles, Sextupoles, etc.
Wiggler Design Issues

• Angular Power Density / Total Power
  - Limited by absorber / optics designs

• Fan Angle
  - $\sim \pm K/\gamma$
  - Flux User $\rightarrow$ Big fan can be shared
  - Brightness User $\rightarrow$ Off-Axis radiation not preferable

• Longitudinal Harmonics Content
  - Related to fan angle and DA

• Dynamic Integral
  - For long period device, wiggling amplitude is not negligible
Canting of Damping Wigglers

- A 7 m long damping wiggler can be divided into two ~3 m long wigglers with canting magnets in between.
- The DW absorber system can handle the radiation with the total fan angle of 6 mrad.

Possibilities are:

- Straight DW (7m long) with ±3 mrad fan as with 100 mm period DW
- or
- 2 mrad canting of two DW (~3 m long) with ±2.3 mrad fan as with 80 mm period DW

- ± 0.25 mrad beam deviation from its nominal orbit and an additional ± 1 mm machining and alignment tolerance can be allowed. The electron beam is dumped by interrupting RF if it deviates more than ± 0.25 mrad.
PM-Damping Wiggler

- **CDR DW** (\(\lambda_w=100\text{mm}, \text{Gap}=15\text{mm}\))
  - \(B_r=1.35T\)
  - Integral of \(B^2=0.1459\ T^2.m\) (90.0% of ideal 1.8T sinusoidal field=0.162 T^2.m)
  - \(K_{\text{eff}}/\gamma = 2.71\ \text{mrad}\)
- **New Design with side magnets** (\(\lambda_w=80\text{mm}, \text{Gap}=12\text{mm}\))
  - \(B_r=1.30T\)
  - Integral of \(B^2=0.1334\ T^2.m\) (103% of ideal 1.8T sinusoidal field=0.1296 T^2.m)
  - \(K_{\text{eff}}/\gamma = 2.32\ \text{mrad}\)
Importing BH file to Radia

• Non-linear material properties are described with:
  - \( \mu_0 \* H(A/m) \ vs \ \mu_0 \* M(A/m) \)
  - \( \mathbf{M} = (H/H) \* [ms1*tanh(ks1*|H|/ms1) + ms2*tanh(ks2*|H|/ms2) + ms3*tanh(ks3*|H|/ms3)]. \)

• Changing “H(Oe) vs B(G)” to \( \mu_0 \* H(A/m) \ vs \ \mu_0 \* M(A/m) = B(T) - \mu_0 \* H(A/m) \)
  - Use \{h,m\} array in “radMatSatIso[{{h1,m1},{h2,m2},...}]”

• Extrapolation appears to be used in higher field
  - Last two sets should represent saturation
• Apple-II v.s. HiSOR EPU

• Gap / Phase dependent first integral must be minimized.
  ▪ End effects due to non-unity anisotropic permeability of PM

• Multipoles must be minimized.
  ▪ Skew terms problematic
3 Pole Wiggler

- Requirements:
  - More than 2 mrad of radiation fan above 1T field
  - Use narrow gap dipole (35 mm Gap) chamber
  - Fixed gap and removable from one side of the chamber
  - Simple and economical

- Preliminary Magnetic Design
  - $Br=1.35T$
  - Permnendur Center Pole
  - Soft Iron (1006) Side Poles
  - Rectangular Magnets

Main Magnets: 120 x 44 x 90 mm
Center Pole: 120 x 20 x 65 mm
End Poles: 95 x 40 x 86 mm
By, Angle, Trajectory

Hybrid 3 Pole Vertical Field

Hybrid 3 Pole Horizontal Angle

Hybrid 3 Pole Horizontal Trajectory
3-Pole Wiggler with Nearby Dipole

- Model 2 dipoles for symmetry
- Multipole change due to
  ONE dipole = 1/2 of Total
3-Pole Wiggler + Dipole

3-Pole Wiggler Fringe Fields

Deflection for 2 Dipoles

DIPOLE PROFILE

BROOKHAVEN SCIENCE ASSOCIATES
Cryo-Permanent Magnet Undulator (Hara, *et. al*, 2004)

- **Simple Concept.** NdFeB has a negative thermal coefficient of remanent field (Br) [-0.1 % / K@20°C], and of intrinsic coercivity (Hcj) [-0.5% / K@20°C ]
- **PrFeB** (53CR by Hitachi-Metal) shows no “spin reorientation” at the lower temperature. However, it does not have high enough coercivity at the high temperature needed for baking.

**Remanence**

**Coercivity**
Simulation Challenge for CPMU

• Mechanical sizes (period, width, etc.) are temperature dependent
  - Thermal expansion coefficients are material dependent

• Low temperature BH curve for material should be used
  - Permanent magnet
  - Pole material

• Thermal calculations
  - Sources are difficult to quantify
5) **Superconducting Insertion Devices**

- **Low Temperature Superconducting Undulator/ Wiggler**
  - Test APC-NbTi wire
- **Low Temperature Superconducting EPU**
  - Design study, especially winding technique
- **High Temperature SC Devices**
  - Rapid conductor development in the industry
  - New type such as coated conductor and thin film available → *More design flexibility*
  - Once the conductor exceeds the necessary performance level, it will be very promising candidates for future IDs

*YBCO HTS tape undulator*

*MgB$_2$ etched conductor pattern*
Minimizing Perpendicular Field

- $J_e = 1000 \text{A/mm}^2$, $\lambda_u = 13.5 \text{mm}$, Gap = 3.8 mm, $B_{\text{peak}} = 1.4 \text{T}$,

- Radia cannot take diamagnetic properties of SC coil material

- End Calculations have to be done with TOSCA 3D model
SC-EPUs and a HTS Undulator

Sasaki Snake

HTSU by T. Tanabe

S. Chouhan

Rossmanith
Superconducting Wiggler

- **CDR-SCW**
  - 17 pole @ 6.0T (\(\lambda_u=6.0\,\text{cm}\), \(g_{\text{pole}}=15.0\,\text{mm}\))
  - \(K_{\text{peak}} = 33.6\)
  - Critical Photon Energy = 35.9 keV
  - Total Power = 102.6 kW
  - Peak on-axis angular power density = 36.7 kW / mrad
$B_y$, $X_{\text{angle}}$, $X_{\text{trajectory}}$

**SCW Vertical Field**

**SCW Horizontal Angle**

**SCW Horizontal Trajectory**

*With 1006 Steel,*

*Required Current Density = 1300 A/ mm²*

Too much for conventional NbTi wire
Summary

• **Lattice Magnet**
  • Dipole - Opera 3D / Tosca (preprocessor) & ANSYS
  • Quadrupole / Sextupole /Corrector - Opera 3D / Tosca (preprocessor)

• **PM Insertion Device**
  • Radia with external BH file is most useful with parametric model
  • CPMU simulation requires low temperature BH curve as well as other thermal parameters to be accurate.

• **Super Conducting ID**
  • Complicated conductor shape in combination with yoke
  • Material data between at 4K and 77K not readily available