Superconducting Undulator R&D at LBNL

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Outline

• On-going research at LBNL
  – Coil winding issues
  – Protection issues
  – Design and manufacture of a 6-period Nb3Sn prototype

• Near term R&D
  – Estimate tolerances, determine field quality
  – Propose and test possible active shimming methods

• Performance modeling and Engineering design issues
  – Calculated attainable fields for different assumptions
  – RF/beam heating and cryocooler operation considerations
  – Examples of possible device performances at the ALS

• Review of superconducting materials
  – Materials currently available
  – Anticipated advances in material performance
  – Advantages/disadvantages of material and wire cable configurations
SCU’s at the ALS

• Why should we be interested in SCU’s?
  – Higher fields, shorter periods
    • Increased brightness and/or shorter devices
    • Extended spectral range
  – IV
    – $g_m = 5$ mm
  – NT
    – $g_m = 10$ mm (4.2 K)
    – $g_v = 7$ mm (20 K)
    – NbTi
  – LT
    – $g_m = 8$ mm (4.2 K)
    – $g_v = 5$ mm (20 K)
    – Nb$_3$Sn

7/1/2003 Workshop on Superconducting Undulators & Wigglers, ESRF
On going R&D at LBNL

• LBNL has provided in-house funds to investigate design issues associated with superconducting undulators
• The on-going R&D concentrates on
  – understanding potential device performance for a range of operating parameters,
  – coil winding methodology,
  – quench protection methods,
  – the manufacture of a 6-period prototype
• The prototype design parameters are aggressive (low copper fraction and very high current density) in order to test the limits of the protection system
  – The prototype is not designed to be incorporated in a ring, and issues relating to field quality and field quality control are not being addressed in its design
Goals of LDRD

- **Determine the most critical limiting factors in superconducting undulator design**
  - Quench detection?
  - Active or passive protection mechanism?
  - Mechanical (structural) issues (e.g. training due to epoxy cracking,…)?
  - Conductor stability?

- **Propose realistic design criteria for future superconducting undulator designs**
  - Acu/Asc ratios
  - Fraction of Jc for “reliable” operation
  - Superconductor parameters
  - Winding techniques
  - Optimal geometry
Superconductor for undulators

- **Superconductor parameters**
  - Nb3Sn for maximum Jc and lower Cu:SC
  - Cu/SC ratio ~1:1 (or less!)
  - wire:
    - cable (6 or 7 strand) or tape; need to compromise between windability, current, and packing considerations

- **Coilpack parameters**
  - Epoxy impregnated (adiabatic)
  - Upper and lower device halves wound from a single wire/cable, connected in series
  - Low stored energy ⇒ self-protected, using diodes to dissipate energy during a quench

(Courtesy Lucio Rossi, "Superconducting Magnets")

7/1/2003 Workshop on Superconducting Undulators & Wigglers, ESRF
Motivation for superconducting undulator R&D

- **Jc value** provides an upper limit for the attainable field (stability driven)
  - Significantly higher values may be reached by using Nb3Sn conductor or novel APC NbTi conductor

- **Higher Jc values** result in higher copper (stabilizer) current densities and/or higher copper fractions (protection driven)
  - Need to reduce quench detection time
  - Need to maximize quench propagation velocity

- **Jc advantage** of Nb3Sn is offset by engineering complications
  - Conductor needs to be wound and then reacted; design analysis must take into account temperature regimes from ~950 K to 4.2 K!

**Notes:**
- Basic load line depends on geometry
- Jcu – limited load lines are theoretical; Acu/Asc is changing with peak field

Workshop on Superconducting Undulators & Wigglers, ESRF
What are we Building?

10-period undulator device

- Yoke
- Electron beam
- Period
- Gap

Section view of a quarter-period, with coil shown

Coil

Nb3Sn cable, made of 37 wires

Sub-elements composed of Niobium, Tin, and copper

Epoxy

Coilpack structure (~120 turns)

7/1/2003 Workshop on Superconducting Undulators & Wigglers, ESRF
Selection of Nb$_3$Sn Conductor

- Tape of Nb$_3$Sn
  - Mono-element strands are unstable
    - Could not measure critical current below 10T
    - M-H curve not smooth

0.25mm diameter
Selection of Nb$_3$Sn Conductor Cont.

- Internal Sn multi-element wire cannot be rolled into tape without Ic reduction

- Ic (6T,4.2K) ~ 510A
  - 52% Cu

![Graph showing V-I curve for series 1 at 6T, 4.2K](image)

- V-I curve Ore 0021B14B for 6T, 4.2K
Cable Fabrication

• Cable with 6 strands:
  – 0.90 mm x 1.75 mm (bare cable) Area= 1.575 mm$^2$
  – packing factors - cable
    ~0.72
• Optimized edge and surface compaction to prevent strand damage
Cable Critical Current of Sample

\[ J_c (5.9T, 4.2K) = 6115A/mm^2 \]

- \( I_c \sim 3,000A \)
- \( B_0 \sim 3.2T \)
Superconductor for Undulator

- **Superconductor parameters**
  - Oxford jelly-roll processed strand, 0.48 mm diameter, 52% Cu
  - $J_c (5 \text{ T}, 4.2 \text{ K}) = 8060 \text{ A/mm}^2$; $J_{cu} = 7440 \text{ A/mm}^2$
  - Dimensions of cable with 6 strands:
    - 0.90 mm x 1.75 mm (bare cable) Area= 1.575 mm$^2$
      - packing factors - cable $\sim$0.72
    - 1.022 mm x 1.883 mm (insulated with S-glass) Area= 1.924 mm$^2$
      - Insulation area = 0.35 mm$^2$
      - Compromise between windability, current, and packing considerations

- **Coil pack parameters**
  - Eng. $J_c [5 \text{ T}, 4.2 \text{ K}] 2,000 \text{ A/mm}^2$
    - packing factors - insulation $\sim$0.182
  - Vacuum impregnate with CTD-101
  - Upper and lower device halves wound from same cable, connected in series
  - Low stored energy $\Rightarrow$ self-protected, using diodes and resistors to dissipate energy during a quench
Net forces acting on the coilpack

*Preliminary results*

- Forces are generally away from the beam, due to the influence of the magnetized steel.
Estimated surface stresses

- Small coilpack size (10.2 x 5.41 mm²) results in large perimeter/area ratio and rather small force build-up. Steel reduces field on coilpack.
- All coilpack sides that have outward facing forces will be supported on the outside by external plates.
- Without supporting plates, the force/unit area on coilpack walls (neglecting longitudinal coilpack stiffness) would be <0.43 Mpa., at Jeng=1000A/mm².
- => epoxy can support loads; external support structure should reduce risk of training.
Prototype design

Coil Geometry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ [mm]</td>
<td>30</td>
</tr>
<tr>
<td>$p_w$ [mm]</td>
<td>4.8</td>
</tr>
<tr>
<td>$c_w$ [mm]</td>
<td>10.2</td>
</tr>
<tr>
<td>$c_h$ [mm]</td>
<td>5.4</td>
</tr>
<tr>
<td>$y_h$ [mm]</td>
<td>28</td>
</tr>
<tr>
<td>Average turn length [mm]</td>
<td>21.9</td>
</tr>
<tr>
<td>Turns/layer</td>
<td>5</td>
</tr>
<tr>
<td>Number of layers</td>
<td>5</td>
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Conductor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand diameter [mm]</td>
<td>0.48</td>
</tr>
<tr>
<td>Number of strands in cable</td>
<td>6</td>
</tr>
<tr>
<td>Cable width (bare) [mm]</td>
<td>1.75</td>
</tr>
<tr>
<td>Cable height (bare) [mm]</td>
<td>0.90</td>
</tr>
<tr>
<td>Insulation thickness [mm]</td>
<td>0.065</td>
</tr>
<tr>
<td>Cu:SC</td>
<td>1.08:1</td>
</tr>
<tr>
<td>RRR</td>
<td>21</td>
</tr>
<tr>
<td>Cabling packing factor</td>
<td>0.72</td>
</tr>
<tr>
<td>Overall SC fraction</td>
<td>0.24</td>
</tr>
<tr>
<td>$J_e (5.9T, 4.2K)$ [A/mm$^2$]</td>
<td>6115</td>
</tr>
</tbody>
</table>

Anticipated performance (gap=10 mm)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_0$ [T]</td>
<td>3.2</td>
</tr>
<tr>
<td>$B_{max}$ [T]</td>
<td>5.9</td>
</tr>
<tr>
<td>$I_{max}$ [A]</td>
<td>3200</td>
</tr>
<tr>
<td>$E$ (stored energy/period) [J]</td>
<td>2000</td>
</tr>
</tbody>
</table>

Jindulators & Wigglers, ESRF
Short Period (30mm)
$Nb_3Sn$ Superconducting Undulator at LBNL
June 2003
General performance curve calculation

For design optimization, we consider a design variable set \( \{ h, \lambda \} \) and the design parameters \( \{ r_{pc}, c_h, y_h \} \). For a given average current density \( J_{av} \) the figure of merit \( f_m = B_{\text{max}} / B_0 \) can be minimized with respect to the design parameters. An “optimal load line” \( B_0(J_{av}) \) for each design variable set, i.e. magnetic gap and period, can then be determined.

Peak performance for an actual device is derived from \( J_c \) data and the superconductor cross section, which is used to relate \( J_{av} \) to \( J_c \). The peak attainable field is defined by the intersection of the “optimal load lines” with the \( J_c \) curve, i.e. when \( J_{sc} = J_c(B_{\text{max}}) \).

Data for “optimal load lines” has been calculated for design variables in the range \( 15 < \lambda [\text{mm}] < 30 \) and \( 4 < \text{gap}[\text{mm}] < 16 \), using a parametric 2D TOSCA script.
Calculated performance curves for NbTi conductors

Design assumptions:
1. SC-ID Data reduced from 3920 point design calculations. Each data point has an associated optimal pole/coil ratio and coil height, defined by minimizing B_{\text{max}}/B_0.
2. Attainable centerfield is defined by the intersection of the load line with the Jc(B_{\text{max}}) curve for existing NbTi conductor; area of superconductor assumed 27% to account for stabilizer, insulation, and packing factor.
3. Data correspond to 1010 steel pole and yoke structure.

Soren Prestemon
Steve Marks
Ross Schlueuter
LBL, Feb. 4, 2003
Calculated performance curves for Nb3Sn conductors

![Graph showing calculated performance curves for Nb3Sn conductors. The graph plots period [mm] on the x-axis and field [T] on the y-axis. Different curves are represented for different values of g (4mm, 6mm, 8mm, 10mm, 12mm, 14mm) and K (1, 2, 3, 4, 5).]
Anticipated performance of the LBNL prototype

Beamline field ($B_0$) and maximum field on superconductor ($B_{\text{max}}$) load lines for the prototype $\text{Nb}_3\text{Sn}$ undulator with a period of 30mm and 10mm gap.

At 4.2K the peak field on the conductor is 5.9T and the field at the beam is 3.2T. The inserted photograph is the cable for the prototype. It is about 1mm thick by 1.85mm wide.
Possible field quality control mechanisms

The left sketch shows possible line-current corrections. A single line current (blue) or two symmetrically located line currents with opposite current direction (green) are possible scenarios. The right sketch is a crude model of a magnetic steel shim that may be a possible candidate for passive field correction.
SCU’s at ALS

<table>
<thead>
<tr>
<th>ALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_e = 1.9 \text{ GeV}$</td>
</tr>
<tr>
<td>$I = 0.4 \text{ A}$</td>
</tr>
<tr>
<td>$L = 4.5 \text{ m}$</td>
</tr>
<tr>
<td>$\sigma_x = 0.26 \text{ mm}$</td>
</tr>
<tr>
<td>$\sigma_x' = 0.023 \text{ mrad}$</td>
</tr>
<tr>
<td>$\sigma_y = 0.023 \text{ mm}$</td>
</tr>
<tr>
<td>$\sigma_y' = 0.006 \text{ mrad}$</td>
</tr>
</tbody>
</table>
SCU’s at ALS

- IV
  - $g_m = 5 \text{ mm}$
- NT
  - $g_m = 10 \text{ mm}$ (4.2\textdegree K)
  - $g_v = 7 \text{ mm}$ (20\textdegree K)
  - NbTi
- LT
  - $g_m = 8 \text{ mm}$ (4.2\textdegree K)
  - $g_v = 5 \text{ mm}$ (20\textdegree K)
  - Nb$_3$Sn
Period-doubling scheme

<table>
<thead>
<tr>
<th>Regular pattern</th>
<th>- + - + - + - + - + - + - + - ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period-doubled</td>
<td>+ - - + + - - + + - - + + ...</td>
</tr>
</tbody>
</table>

Coils that remain unchanged during period doubling
Coils that reverse current direction for period doubling
RF heating estimates

Estimates of RF heating for different rings, using different vacuum chamber surface materials. Estimates are derived using the Piwinski formulation as developed by Boris Podobedov. Note: BNL device is 2m; ALS devices assume 1.5m; Max-Lab and ESRF data correspond to 1m devices. Note: These numbers may need updating, particularly after the talks of Boris and Eric later this afternoon!

Source: Intro to Solid State Physics, 5th edition, C. Kittel

<table>
<thead>
<tr>
<th>electron charge [C]</th>
<th>1.602E-19</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron mass [kg]</td>
<td>9.1E-31</td>
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<table>
<thead>
<tr>
<th>Cu</th>
<th>Al</th>
<th>Ag</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>resistivity (ρ) [Ohm-m]</td>
<td>1.74E-08</td>
<td>2.68E-08</td>
<td>1.59E-08</td>
</tr>
<tr>
<td>conductivity [1/Ohm-m]</td>
<td>5.75E+07</td>
<td>3.73E+07</td>
<td>6.29E+07</td>
</tr>
<tr>
<td>electron density [1/m^3]</td>
<td>8.54E+28</td>
<td>1.81E+29</td>
<td>5.85E+28</td>
</tr>
<tr>
<td>electron velocity on Fermi surface [m/s]</td>
<td>1.57E+06</td>
<td>2.02E+06</td>
<td>1.39E+06</td>
</tr>
<tr>
<td>collision time [s]</td>
<td>2.39E-14</td>
<td>7.33E-15</td>
<td>3.81E-14</td>
</tr>
<tr>
<td>mean-free path length (l) [m]</td>
<td>3.75E-08</td>
<td>1.48E-08</td>
<td>5.30E-08</td>
</tr>
<tr>
<td>ρ*l [Ohm-m^2]</td>
<td>6.52E-16</td>
<td>3.97E-16</td>
<td>8.43E-16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cu</th>
<th>Al</th>
<th>Ag</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boris example (BNL)</td>
<td>51.89</td>
<td>9.84</td>
<td>64.70</td>
</tr>
<tr>
<td>ALS present</td>
<td>3.94</td>
<td>0.66</td>
<td>4.91</td>
</tr>
<tr>
<td>ALS 2-bunch present</td>
<td>11.08</td>
<td>1.85</td>
<td>13.81</td>
</tr>
<tr>
<td>ALS upgrade</td>
<td>13.19</td>
<td>2.20</td>
<td>16.45</td>
</tr>
<tr>
<td>ALS upgrade 2-bunch X</td>
<td>21.49</td>
<td>3.86</td>
<td>26.80</td>
</tr>
<tr>
<td>Max-Lab II</td>
<td>0.73</td>
<td>0.13</td>
<td>0.90</td>
</tr>
<tr>
<td>ESRF uniform</td>
<td>1.95</td>
<td>0.31</td>
<td>1.95</td>
</tr>
<tr>
<td>ESRF 16-bunch</td>
<td>6.59</td>
<td>0.91</td>
<td>6.59</td>
</tr>
<tr>
<td>ESRF 1-bunch</td>
<td>2.77</td>
<td>0.36</td>
<td>2.77</td>
</tr>
</tbody>
</table>
SCUs at 8°K

Cryocooler capacity
- @ 4.2°K ~ 1W
- @ 8°K ~ 5-10W
- @ 20°K ~ 50W
Superconductors for SCID’s

• Depending on the application, we can consider:
  – NbTi
  – APC NbTi
  – Nb3Sn
  – HTc (e.g. BSSCO or YBCO)

• Things to consider:
  – Jc performance (stability at design point; operating temperature)
  – Protection (stabilizer material and cross-section)
  – Insulation (material, cross-section)
  – Conductor compatible with winding methodology
  – Conductor strength / mechanical design issues
  – Availability of sufficient conductor length
• NbTi modeling is based on the classic Summers model

Jc data for diverse conductors

Critical current density [A/mm²] vs Applied field [T]

<table>
<thead>
<tr>
<th></th>
<th>Nb3Sn</th>
<th>Nb3Sn, strain=0.2%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tc₀(e) [K]</td>
<td>Bc₂₀(e) [T]</td>
</tr>
<tr>
<td>NbTi</td>
<td>9.3</td>
<td>14</td>
</tr>
<tr>
<td>Nb3Sn</td>
<td>18</td>
<td>14</td>
</tr>
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</table>
Concluding remarks

• The ALS is very interested in SCID’s
• Preliminary work suggests currently attainable field strengths are of interest
• We consider RF heating/cryogenics and field quality control to be key issues that must be addressed in order for SCID’s to be incorporated at the ALS
• We are very interested in the progress and experience of others in the field!