WE START WITH YES.

SUPERCONDUCTING UNDULATOR AT ANL

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Advanced Photon Source


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INTRODUCTION: ADVANCED PHOTON SOURCE
SCU DEVELOPMENT TIMELINE

<table>
<thead>
<tr>
<th>Activity</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>A proposal of the helical SCU for the LCLS</td>
<td>1999</td>
</tr>
<tr>
<td>Development of the APS SCU concept</td>
<td>2000-2002</td>
</tr>
<tr>
<td>R&amp;D on SCU in collaborations with LBNL and NHFML</td>
<td>2002-2008</td>
</tr>
<tr>
<td>R&amp;D on SCU0 in collaborations with FNAL and UW-Madison</td>
<td>2008-2009</td>
</tr>
<tr>
<td>Design (in the collaboration with the BINP) and manufacture of SCU0</td>
<td>2009-2012</td>
</tr>
<tr>
<td>SCU0 installed into the APS storage ring</td>
<td>December 2012</td>
</tr>
<tr>
<td>SCU0 is in routine user operation</td>
<td>Since February 2013</td>
</tr>
<tr>
<td>SCU1 installed into the APS storage ring and is in user operation</td>
<td>April 2015</td>
</tr>
<tr>
<td>FEL/LCLS 1.5-m long prototype designed, built and successfully tested</td>
<td>October 2015</td>
</tr>
<tr>
<td>SCU18-2 (&quot;upgraded&quot; SCU1 copy) replaces SCU0</td>
<td>September 2016</td>
</tr>
<tr>
<td>Helical SCU prototype to be installed in APS storage ring</td>
<td>December 2017</td>
</tr>
</tbody>
</table>
PERFORMANCE COMPARISON: SCU AND HYBRID UNDULATOR AT THE APS

- Tuning curves for odd harmonics of the SCU and the “Advanced SCU” (ASCU) versus planar permanent magnet hybrid undulators for 150 mA beam current. ASCU is Nb$_3$Sn undulator with optimized performance.
- The SCU 1.6 cm surpasses the U2.5 cm by a factor of $\sim 5.3$ at 60 keV and $\sim 10$ at 100 keV.
- The tuning range for the ASCU assumes a factor of two enhancement in the magnetic field compared to today’s value – 9.0 keV can be reached in the first harmonic instead of 18.6 keV.
SCU HISTORY & NEAR-TERM PLANS

- Two SCUs presently installed in the APS storage ring (SCU0 and SCU1)
- SCU0 to be upgraded with a copy of SCU1 (SCU18-2) in September 2016
- 1.2-meter Helical SCU (HSCU) to be installed in Sector 7 in December 2017

SCU0 installed in APS Sector 6
DEC 2012 (0.3-m magnetic length)

SCU1 installed in APS Sector 1
APR 2015 (1.1-m magnetic length)
APS SCU RELIABILITY

- Both SCU0 and SCU1 have been essentially transparent to the APS SR beam
- All but one quench (for SCU1) has occurred during an unintended beam dump
- SCU0 quenches decreased dramatically after beam abort system added JAN2016

<table>
<thead>
<tr>
<th>Calendar year</th>
<th>APS delivered</th>
<th>SCU0 operating</th>
<th>SCU0 down</th>
<th>SCU0 quenches</th>
<th>SCU0 avail. %</th>
<th>SCU1 operating</th>
<th>SCU1 down</th>
<th>SCU1 quenches</th>
<th>SCU1 avail. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>4871 h</td>
<td>4189 h</td>
<td>20 h</td>
<td>34 + 3</td>
<td>99.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2014</td>
<td>4926 h</td>
<td>4391 h</td>
<td>174 h [1]</td>
<td>32 + 2</td>
<td>96.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2015</td>
<td>4940 h</td>
<td>4834 h</td>
<td>0 h</td>
<td>26 + 1</td>
<td>100</td>
<td>3059 h [2]</td>
<td>0.1 h</td>
<td>5 + 0</td>
<td>99.997</td>
</tr>
<tr>
<td>2016 [3]</td>
<td>2871 h</td>
<td>2797</td>
<td>0 h</td>
<td>6 + 0</td>
<td>100</td>
<td>2695</td>
<td>0.3 h</td>
<td>7 + 1</td>
<td>99.990</td>
</tr>
<tr>
<td>Total</td>
<td>17608 h</td>
<td>16211 h</td>
<td>194 h</td>
<td>108 + 6</td>
<td><strong>98.80</strong></td>
<td>5754 h</td>
<td>0.4 h</td>
<td>12 + 1</td>
<td><strong>99.993</strong></td>
</tr>
</tbody>
</table>

- e-beam has never been lost due to quenches
- **Red = beam dump-induced quench**
- **Blue = self-induced quench**

Data thanks to K. Harkay

[1] November: Partial loss of one cryocooler capacity
[2] Installed in May; operated May – December 2015
CRYOSTAT DESIGN:
BUDKER INSTITUTE OF NUCLEAR PHYSICS

- Proven cryostat design, suitable for magnets up to 1.5 meters long.

- Closed cycle (zero boil-off) liquid helium bath-cooled magnets with cryocooler-based recondensation. Excess 4 K capacity is about 0.5 W for most recent cryostat.

- Helium bath pressure/temperature is regulated using a heater.

- Beam chamber is cooled at a higher temperature level due to high beam-induced heat loads (up to 20 W) in storage ring applications.
PLANAR MAGNET FABRICATION DEVELOPMENT: from 300 mm TO 1500 mm

- Techniques and tooling scale to “full-length” magnets
  - Precision core machining
  - Winding/potting
Magnet, vacuum chamber, & helium tank are assembled, checked out, and loaded into the cryostat.
- Final electrical connections are made between the cold mass and the current lead/cryocooler turrets.
- Vacuum vessel turret and end covers are installed.
- Cryostat is moved to the measurement bench and aligned.
MEASURED UNDULATOR FIELD: 1.5-METER LCLS R&D MAGNET

Measured field profile

Measured excitation curve

Achieved field

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Design</th>
<th>Measured</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal on-axis, peak field (at 80% short-sample limit)</td>
<td>$</td>
<td>B_0</td>
<td>$</td>
<td>1.67</td>
</tr>
<tr>
<td>Nominal peak undulator parameter (at 80% short-sample limit)</td>
<td>$K_0$</td>
<td>3.26</td>
<td>3.260</td>
<td>-</td>
</tr>
<tr>
<td>Nominal excitation current (at 80% short-sample limit)</td>
<td>$I_0$</td>
<td>~600</td>
<td>588</td>
<td>A</td>
</tr>
</tbody>
</table>
MEASURED PHASE ERRORS:
1.5-METER LCLS R&D MAGNET

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Design</th>
<th>Measured</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase shake error over undulator (rms)</td>
<td>$\Delta j_{\text{rms}}$</td>
<td>5</td>
<td>3.8±0.3</td>
<td>deg</td>
</tr>
</tbody>
</table>

The most challenging tolerance is achieved without magnetic ‘shimming’
MEASURED PHASE ERRORS – 1-METER “SCU18-2”

- Typical RMS phase error specification = 5°
- SCU18-2 RMS phase error at design current = 2.30°
- Phase errors were achieved with no magnetic shimming
Coil training was performed after each cooldown.
Magnets were trained above the operating current of 450 A.
Number of training quenches is reduced after each thermal cycle.
TYPICAL CRYOGENIC PERFORMANCE

Cool Down

Warm Up

Steady State Operation 12AUG2015

Quench response
INDUSTRIAL PARTICIPATION: EXISTING AND FUTURE PLANS

- Several subsystems on existing SCUs were fabricated in industry from ANL designs:
  - Vacuum vessel
  - Thermal shields
  - Liquid helium reservoir
  - Magnet cores

- Helical SCU currently in fabrication has extended industry participation:
  - Mechanical analyses (including ASME code)
  - Production drawings from ANL 3D CAD models

- Long-term (3-4 year) ANL goal is to develop a vendor for “turn-key” SCU production:
  - Magnetic design & analysis
  - Hardware design & fabrication
  - Magnet winding, full cryostat assembly
  - May include ANL collaboration for measurement & test
HELICAL SCU CONCEPTS:
APS STORAGE RING
HELICAL SCU MAGNET R&D

- Helical SCU magnet cores prototyped in plastic, Al, and steel
- Conductor turn-around is proven with practice-winds
Implementation of lessons learned:

- Improved alignment/fiducialization
- Better thermal performance (shield, cryocoolers)
- Smaller, cheaper
- Possible LHe-free cooling

FEA confirms suitability of QTY4 4.2K cryocoolers
### FEL SCU CRYOMODULE CONCEPT
(P. EMMA, SLAC + ANL/LBNL)

- Three 1.5-m long undulator segments in one 5.5-m cryostat
- Short segments (1.5-m) easier to fabricate, measure, tune, and taper
- Each segment independently powered to allow optimized TW-taper
- Ancillary components include cold BPM, cold phase-shifters, cold quads
- Cryogenic refrigeration/distribution system concept has been developed
- Magnet alignment is critical (300 K → 4 K)
- Beam-based alignment as final correction using motorized pads
FEL SCU ARRAY CONCEPT

Array Segmentation:
- Minimal (common insulating vacuum)
- Full (independent insulating vacuums)

Planar, horizontal gap magnet shown (could be vertical)
SCAPE (SUPERCONDUCTING ARBITRARY POLARIZATION EMITTER) – A UNIVERSAL PLANAR SCU

- Current concept suggested by E. Gluskin & Y. Ivanyushenkov
- Magnet pairs are displaced relative to each other along beam axis by $\frac{1}{4}$-period
- Can generate both planar and helical fields (confirmed by simulation)

Cryostat concept with two independent SCAPE devices
SUMMARY

- APS developed strong expertise in the design and construction of NbTi-based planar SCUs. A dedicated facility has been set up for construction and characterization of SCUs.

- APS SCU team acquired and developed all theoretical and technical tools needed for design and construction of the SCUs. Two SCUs are successfully operating at the APS with high availability.

- An FEL-specific SCU has been designed, built, and characterized which meets or exceeds all FEL undulator specifications.

- APS continues to develop SCU technology for future storage ring and FEL light sources.