APS Superconducting Undulator Beam Commissioning Results

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Outline

- Introduction
- Commissioning plan
- Unpowered effect on beam
- Powered effect on beam
- Thermal analysis
- Beam-based alignment
- Performance
- Conclusions
Introduction

- Superconducting undulators allow a higher peak magnet field compared to conventional devices, which can greatly benefit light sources.*
- Superconducting technology was used to build a fully-functioning short-period test undulator (SCU0) at the Advanced Photon Source. Unique features: out-of-vacuum, thermally isolated beam chamber, cryocoolers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy at 1st harmonic, keV</td>
<td>20-25 keV</td>
</tr>
<tr>
<td>Period length</td>
<td>16 mm</td>
</tr>
<tr>
<td>Magnetic gap</td>
<td>9.5 mm</td>
</tr>
<tr>
<td>Design magnetic field</td>
<td>0.64 T</td>
</tr>
<tr>
<td>Design operating current</td>
<td>500 A</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>0.34 m</td>
</tr>
<tr>
<td>Cryostat length</td>
<td>2.063 m</td>
</tr>
<tr>
<td>Beam operating current</td>
<td>100 mA</td>
</tr>
</tbody>
</table>

* Y. Ivanyushenkov, FRYBB1 (invited)

SCU0 installed in the APS storage ring in Dec, 2012.
Commissioning goals

Overview:
- Detailed commissioning plan completed during extended machine startup, Jan 2013.
- SCU0 released for User operation on Jan 29.

Assess:
- Thermal sensor and **vacuum monitoring**
- Vacuum chamber layout and chamber transition heating
- Cryogenic system performance
- **Orbit stability** with given limits on field integral rate-of-change and absolute error requirements
- **Quench response**
- Field correction coil response
- Vibration effects of the cryocoolers on beam motion
- **Validity of estimates of beam-induced heat load**
- **Alignment procedures**
- **X-ray performance**
- Storage ring operation procedures
## Vacuum performance

<table>
<thead>
<tr>
<th>Vacuum pressure history, cold cathode gauge</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>After installation, rough-down prior to bakeout</td>
<td>$\sim 2 \times 10^{-7}$ Torr</td>
</tr>
<tr>
<td>After bakeout of up/downstream transitions</td>
<td>3 nTorr</td>
</tr>
<tr>
<td>After SCU0 cooldown, prior to beam injection</td>
<td>0.4 nTorr</td>
</tr>
<tr>
<td>After first 100-mA beam (transients)</td>
<td>$\sim 10$ nTorr</td>
</tr>
<tr>
<td>After 10 Amp-hr of beam operation (~4 days)</td>
<td>$\sim 3$ nTorr</td>
</tr>
<tr>
<td>After 200 Amp-hr of beam operation (~3 mos.)</td>
<td>$\sim 0.8$ nTorr</td>
</tr>
</tbody>
</table>

No beam chamber vacuum pressure issues and no negative effects observed on the beam.
Impact of SCU0 on beam operation

- Field integral measurement with beam
  - Variation in field integral was inferred from effort of nearby steering correctors.
  - Field integrals agree reasonably well with magnet measurements* in preliminary comparison.

- Effect of induced quench on beam
  - Beam motion is small, even without fast orbit feedback running, as in this example.
  - Quench does not cause loss of beam
  - Beam position limit detectors were not triggered.

* C. Doose, M. Kasa, THPBA06
Quenches

- Device has quenched during unintentional beam dumps. Procedures to mitigate these quenches are under investigation. Device is powered down prior to planned beam dumps.
- With the exception of beam dumps, the device quenched only twice in 8 months of user operations, operating above its 500-A design current. Stored beam was not lost, and total SCU0 downtime was < 1 hr.

Quench event induced by sudden loss of 20 mA

Magnet temperatures recover quickly (2-3 min).
Thermal analysis, beam-induced heat load in SCU0

- Protection of SCU0 from excessive beam-induced heat load a key requirement.
- All standard bunch modes were tested at 100 mA; also in a special 150-mA run.
- Predicted image-current heat loads* were compared with the measured heat load using the cryocooler thermal load map (20-K circuit).
- Remarkable agreement, within 1-2 W.

<table>
<thead>
<tr>
<th>Total beam current/ number of bunches</th>
<th>Calculated heat load * (W)</th>
<th>Measured heat load, cryocooler load map (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>100 mA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>16.0</td>
<td>14.3</td>
</tr>
<tr>
<td>324</td>
<td>2.0</td>
<td>3.4</td>
</tr>
<tr>
<td>1+56</td>
<td>11.1</td>
<td>10.8</td>
</tr>
<tr>
<td><strong>150 mA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>324</td>
<td>4.6</td>
<td>6.2</td>
</tr>
</tbody>
</table>

* Synchrotron radiation and wakefield heat load is < 1 W.

* K. Harkay et al., WEPSM06 (poster)
Measured SCU0 chamber temperatures vs. thermal modeling*

- Analytical image-current heat load modeled using ANSYS.*
- Modeled chamber temperatures are within 10% of the measured temperatures.

* Y. Shiroyanagi et al., THPAC07 (poster)
Beam-based alignment (BBA) of SCU0 chamber using thermal sensors

- Net resistive wall heating increases when the beam is not centered in the chamber.
- This can be used to find the vertical center of the chamber.
- Radiation from the upstream bending magnet can potentially strike the cold chamber.
- BPMs at the dipole are used to steer the beam and minimize the temp.**
- Beam steering in the dipole also shows a vertical chamber displacement, consistent with the ID beam steering.

** L. Boon et al., THPAC06 (poster)
A vertical chamber offset of ~0.3 mm was detected with 100-μm accuracy. Accuracy is 10× better than with aperture scan. Further benefits of thermal sensor-based BBA:

- Isolates SCU0 chamber alignment from other vacuum components in the orbit bump.
- Provides longitudinal spatial resolution (1.6 m length shown).

* K. Harkay, WEPSM07 (poster)
SCU0 performance

- Designed for operation at 500 A; operates reliably at 650-700 A over 50% of the time.
- Designed for 100 mA beam; operated with 150 mA and no significant issues were identified.
- Magnet cores held at ~4 K even with 16 W of beam power on the beam chamber.
- No loss of He was observed in an 8-month period.

Measured temperatures in the SCU0 cryostat at beam current of 100 mA (24 bunches), SCU0 magnet is off.
SCU0 X-ray performance

- Photon flux of SCU0 was compared with an in-line 3.3-cm-period length permanent magnet hybrid undulator (U33), using a bent-Laue monochromator.
- At 85 keV, the 0.34-m-long SCU0 produced ~45% higher photon flux than the 2.3-m-long U33.

Photon flux comparisons at 85 keV. Main: Simulated and measured SCU0 photon flux. Inset: Measured photon flux for in-line U33.
Conclusions

- An almost decade-long R&D program on development of superconducting undulators at APS was successfully completed in Dec. 2012 with the installation of the first test undulator in the APS storage ring.

- Beam commissioning was highly successful and the measured parameters agree very well with the predictions. All the requirements were satisfied:
  - Cryomodule integrity/operability preserved during installation.
  - Unpowered SCU0 transparent to normal user operation; i.e., does not measurably increase storage ring impedance, or decrease injection efficiency or lifetime.
  - Powered SCU0 does not perturb the beam more than allowed.
  - SCU0 sufficiently protected from beam-induced heat loads.

- Device is in user operation since Jan. 2013, operating reliably above its design current, delivering enhanced photon flux at energies above 50 keV.
Mechanical vibration

- Cryocooler vibration measured at three locations:
  1. Beam chamber, 40 cm upstream of SCU0
  2. Vacuum vessel, beam height
  3. Support girder base (not shown)

- Results for beam chamber shown at right.

- Cryocooler vibration was not observed to adversely affect the beam motion.

### Integrated power density ($\mu$m rms), from 2 Hz to 100 Hz

<table>
<thead>
<tr>
<th></th>
<th>Cryocoolers off</th>
<th>Cryocoolers on</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.38</td>
<td>0.68</td>
</tr>
</tbody>
</table>

### Amplitude at 8.375 Hz ($\mu$m rms)

<table>
<thead>
<tr>
<th></th>
<th>Cryocoolers off</th>
<th>Cryocoolers on</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.06</td>
<td>0.57</td>
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