APS Superconducting Undulator Beam Commissioning Results

Katherine Harkay
for the APS SU0 Team

NA-PAC 2013, Pasadena, CA
October 1, 2013

Outline

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

SCU Team

Y. Ivanyushenkov (ASD)
Technical Lead and
Commissioning Co-Lead

Core Team

Management: E. Gluskin*(ASD-MD) E. Moog**
Simulation: R. Dejus (ASD-MD)
S. Kim (ASD-MD)
R. Kustom (ASD-RF)
Y. Shiroyanagi (ASD-MD)
Design: D. Pasholk (AED-DD)
D. Skiadopoulos (AES-DD)
E. Trakhtenberg (AES-MED)
Cryogenics: J. Fuerst (ASD-MD)
Q. Hasse (ASD-MD)
Measurements: M. Abliz (ASD-MD)
C. Doose (ASD-MD)
M. Kasa (ASD-MD)
I. Vasserman (ASD-MD)
Controls: B. Deriy (ASD-PS)
M. Smith (AES-CTL)
Tech. support: S. Bettenhausen (ASD-MD)
K. Boerste (ASD-MD)
J. Gagliano (ASD-MOM)
M. Merritt (ASD-MD)
J. Terhaar (ASD-MD)

Budker Institute Collaboration
(Cryomodule and Measurement System Design)
N. Mezentsev
V. Syrovatin
V. Tsukanov
V. Lev

FNAL Collaboration
(Resin Impregnation)
A. Makarov

UW-Madison Collaboration
(Cooling System)
J. Pfotenhauer
D. Potratz
D. Schick

K. Harkay (ASD-AOP)
Commissioning Co-Lead

Commissioning Team
L. Boon (ASD-AOP)
M. Borland (ASD-ADD)
G. Decker* (ASD-DIA)
J. Dooling (ASD-AOP)
L. Emery* (ASD-AOP)
R. Flood (ASD-AOP)
M. Jaski (ASD-MD)
J. Lang (ASD-ESH/QA)
J. Lang (XSD-ADD)
F. Lenkszus (AES-CTL)
D. Robinson (XSD-MM)
V. Sajaev (ASD-AOP)
K. Schroeder (ASD-AOP)
N. Sereno (ASD-DIA)
H. Shang (ASD-AOP)
R. Soliday (ASD-AOP)
X. Sun (ASD-DIA)
A. Xiao (ASD-AOP)
A. Zholents (ASD-DD)

Technical Support
R. Bechtold (AES-MOM)
J. Collins (AES-MED)
R. Farnsworth* (AES-CTL)
J. Hoyt (AES-MOM)
J. Penicka* (AES-SA)
J. Wang* (ASD-PS)
D. Capatina (AES-MED)
P. Den Hartog* (AES-MED)
G. Goeppner* (AES-MOM)
W. Jansma (AES-SA)
S. Wesling (AES -SA)

*Group Leader
** Former Group Leader

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.

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

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

*** Y. Ivanyushenkov, FRYBB1 (invited)**

Commissioning goals

Overview:

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

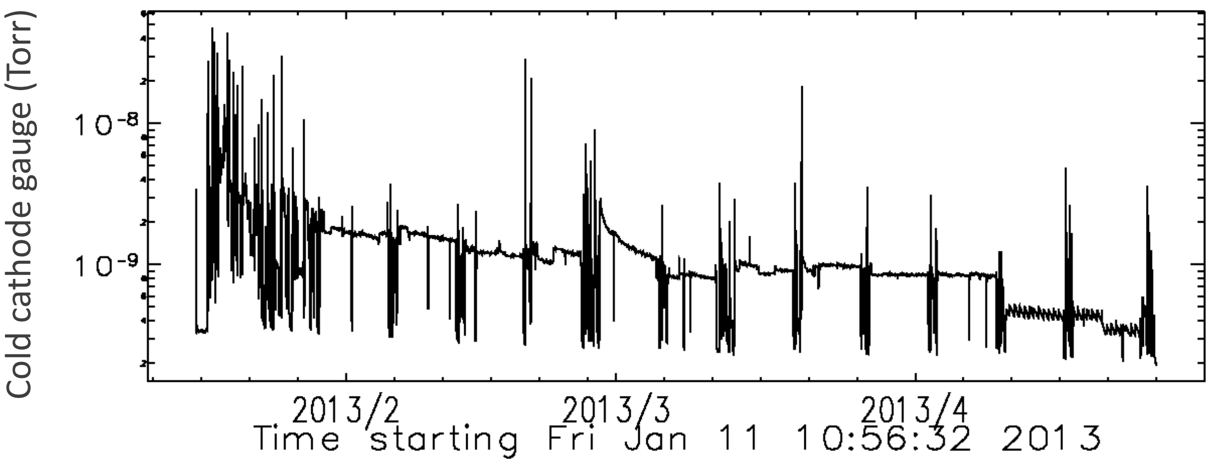
Assess:

- 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

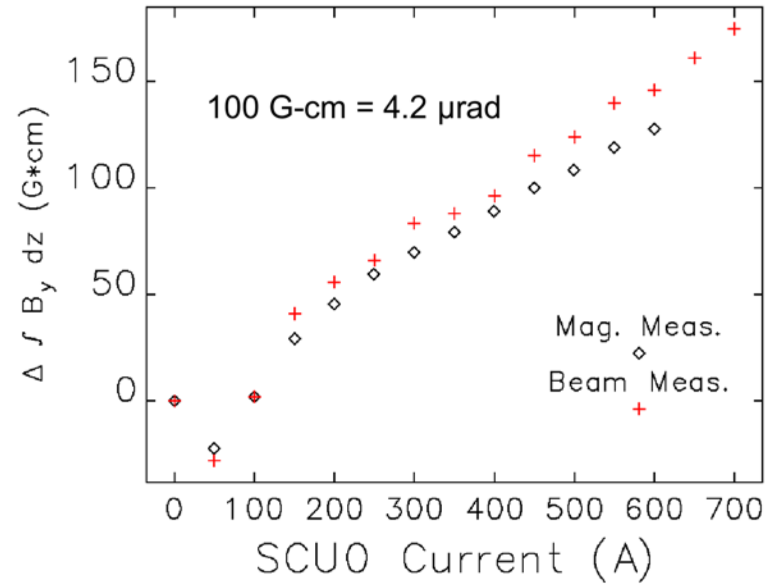
Vacuum pressure history, cold cathode gauge	
After installation, rough-down prior to bakeout	~2×10^{-7} Torr
After bakeout of up/downstream transitions	3 nTorr
After SCU0 cooldown, prior to beam injection	0.4 nTorr
After first 100-mA beam (transients)	~10 nTorr
After 10 Amp-hr of beam operation (~4 days)	~3 nTorr
After 200 Amp-hr of beam operation (~3 mos.)	~0.8 nTorr

No beam chamber vacuum pressure issues and no negative effects observed on the beam.

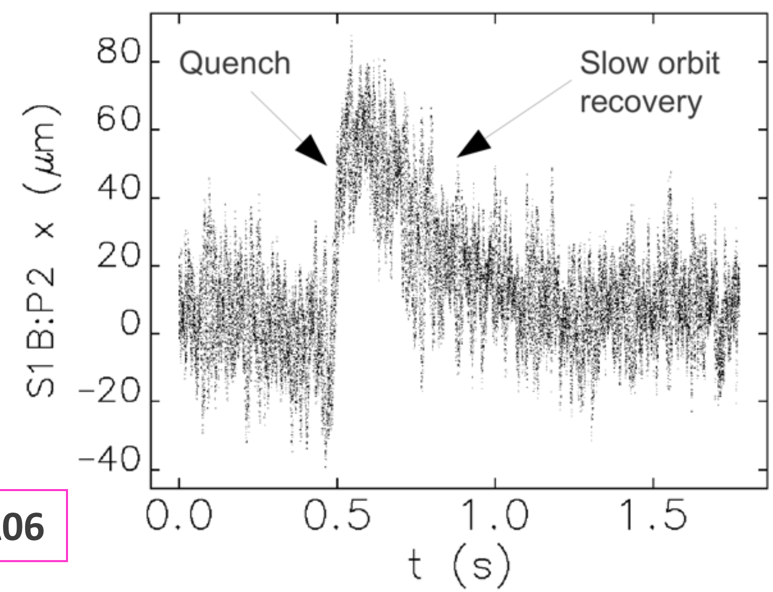


Impact of SCU0 on beam operation

- 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.



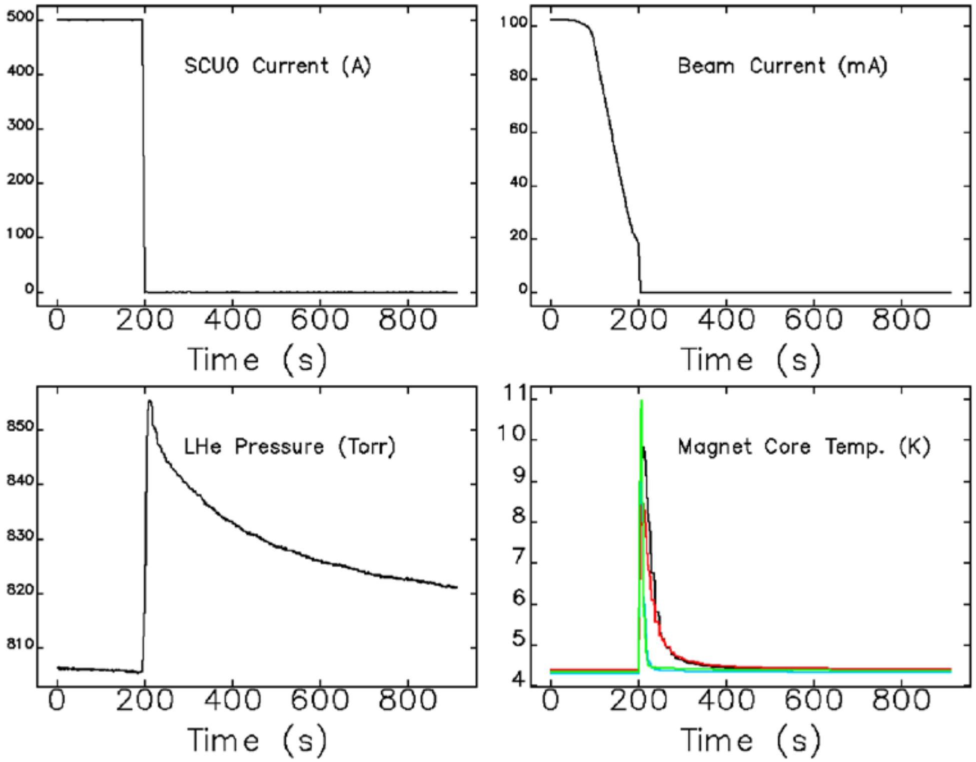
- Effect of induced quench on beam
  - Beam motion is small, even without fast orbit feedback running, as in this example.
  - Quench does not cause loss of beam
  - Beam position limit detectors were not triggered.



* 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

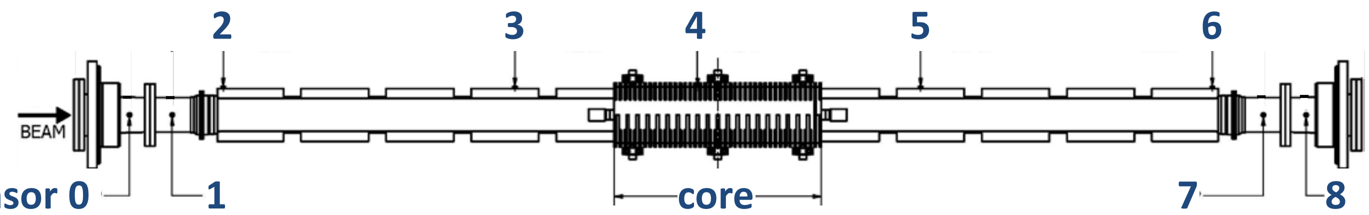
- Protection of SCU0 from excessive beam-induced heat load a key requirement.
- All standard bunch modes were tested at 100 mA; also in a special 150-mA run.
- Predicted image-current heat loads* were compared with the measured heat load using the cryocooler thermal load map (20-K circuit).
- Remarkable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

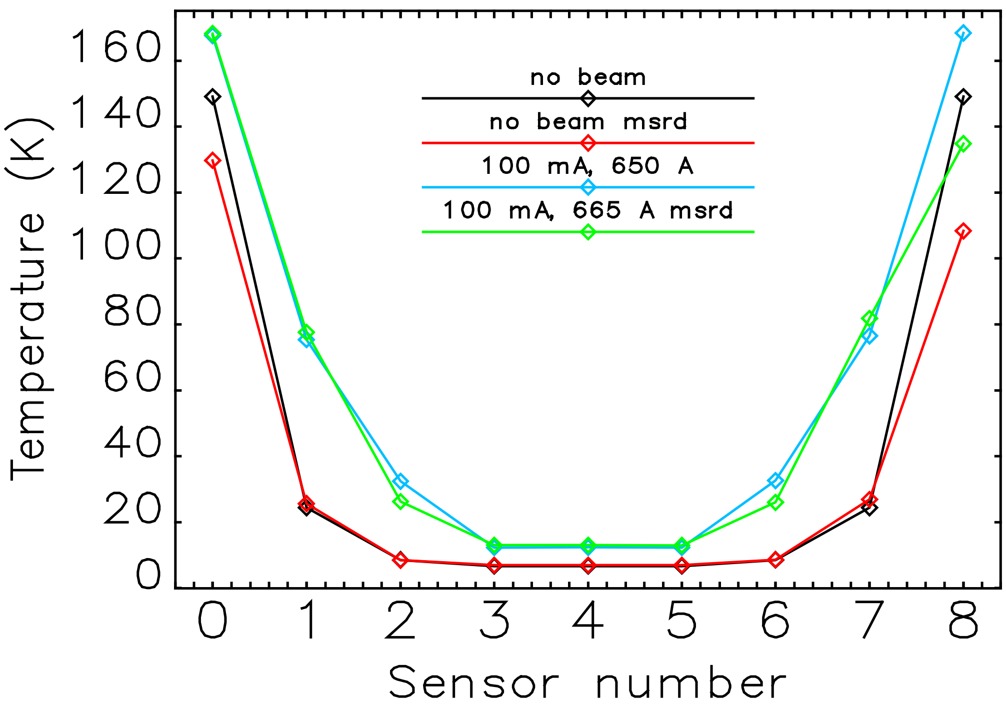
Total beam current/ number of bunches	Calculated heat load * (W)	Measured heat load, cryocooler load map (W)
100 mA		
24	16.0	14.3
324	2.0	3.4
1+56	11.1	10.8
150 mA		
324	4.6	6.2

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

*** K. Harkay et al., WEPSM06 (poster)**

Measured SCU0 chamber temperatures vs. thermal modeling*



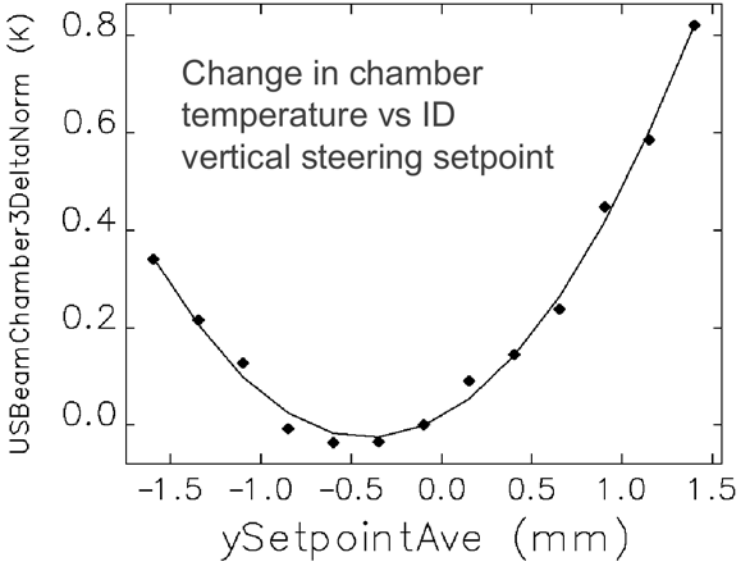


- Analytical image-current heat load modeled using ANSYS.*
- Modeled chamber temperatures are within 10% of the measured temperatures.

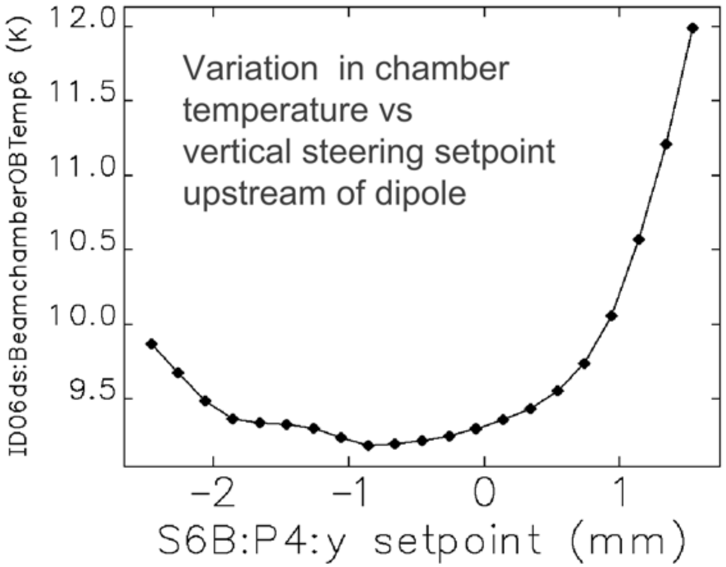
*** Y. Shiroyanagi et al., THPAC07 (poster)**

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.



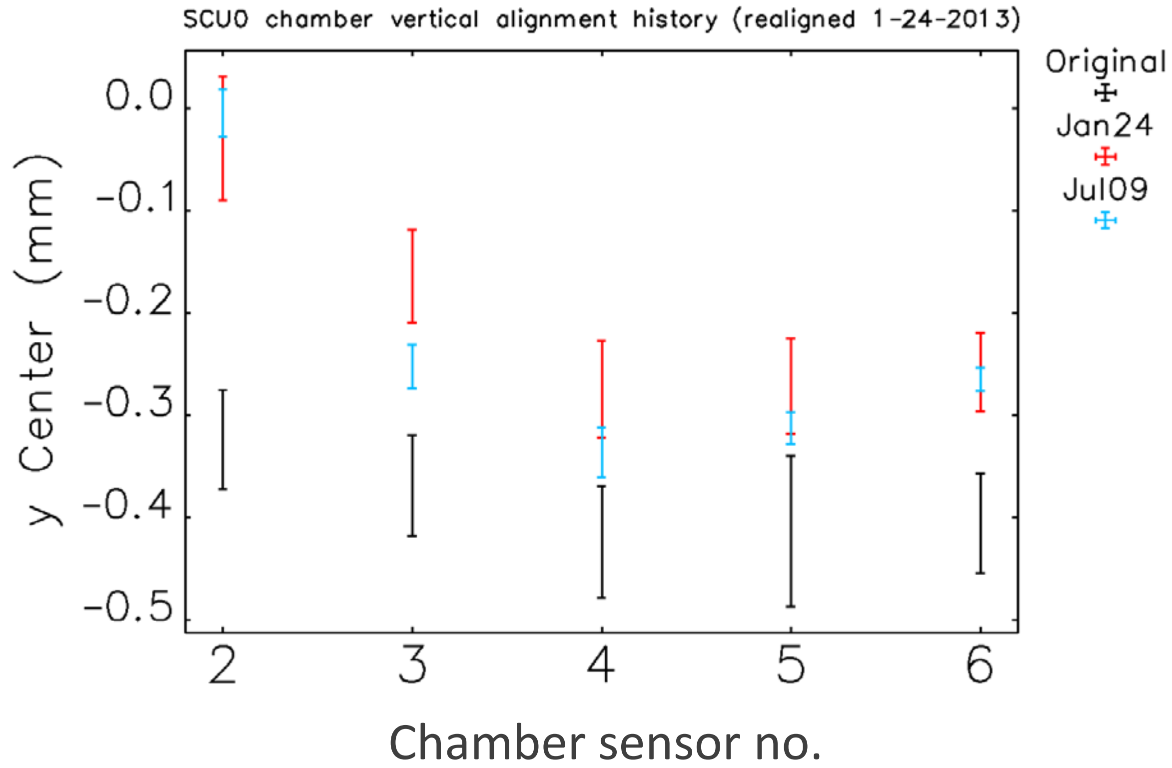
- Radiation from the upstream bending magnet can potentially strike the cold chamber.
- BPMs at the dipole are used to steer the beam and minimize the temp.**
- Beam steering in the dipole also shows a vertical chamber displacement, consistent with the ID beam steering.



** L. Boon et al., THPAC06 (poster)

Measured SCU0 chamber alignment* (ID steering)

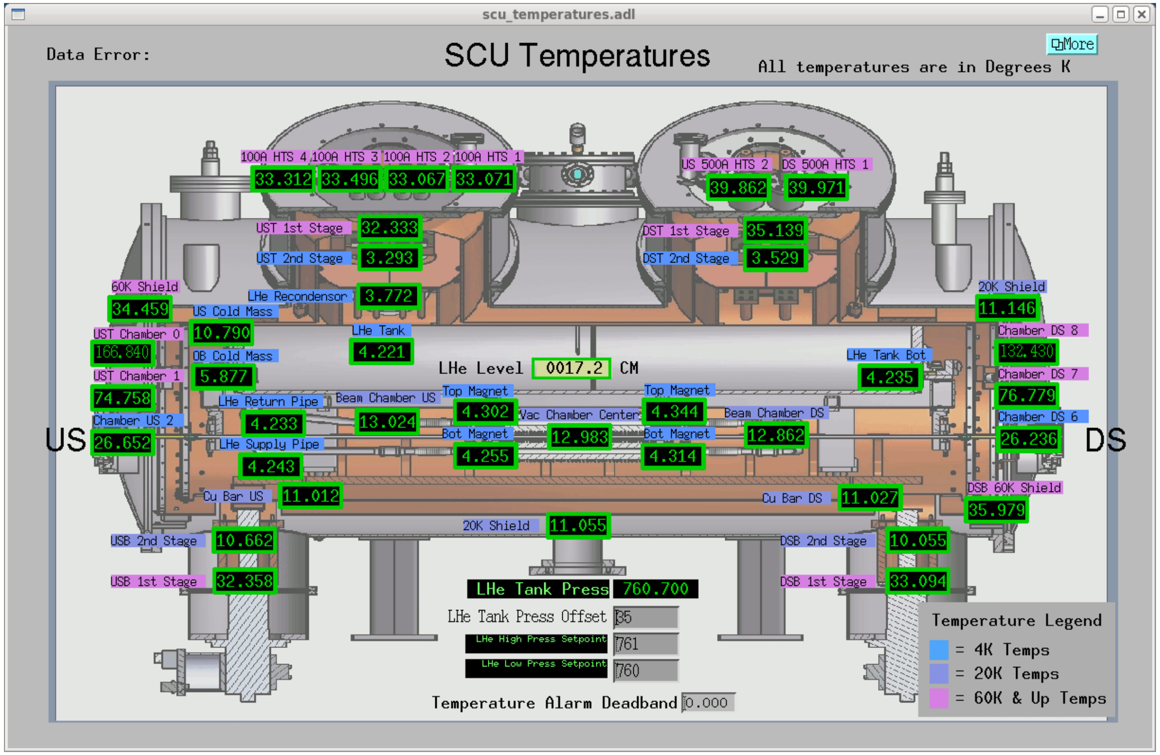
- A vertical chamber offset of ~0.3 mm was detected with 100-µm accuracy.
- Accuracy is 10× better than with aperture scan.
- Further benefits of thermal sensor-based BBA:
    - Isolates SCU0 chamber alignment from other vacuum components in the orbit bump.
    - Provides longitudinal spatial resolution (1.6 m length shown).



* K. Harkay, WEPSM07 (poster)

SCU0 performance

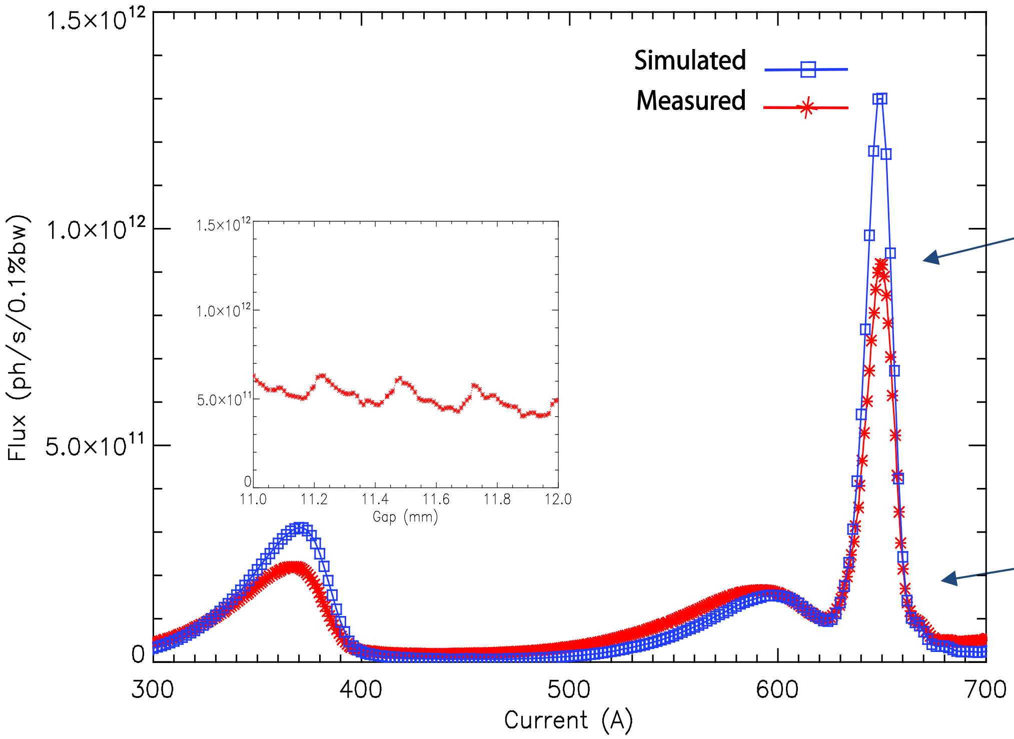
- Designed for operation at 500 A; operates reliably at 650-700 A over 50% of the time.
- Designed for 100 mA beam; operated with 150 mA and no significant issues were identified.
- Magnet cores held at ~4 K even with 16 W of beam power on the beam chamber.
- No loss of He was observed in an 8-month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

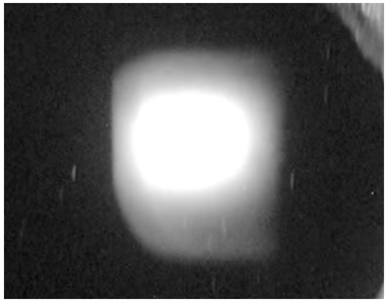


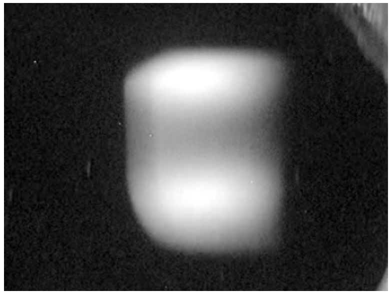
Measured temperatures in the SCU0 cryostat at beam current of 100 mA (24 bunches), SCU0 magnet is off.

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.







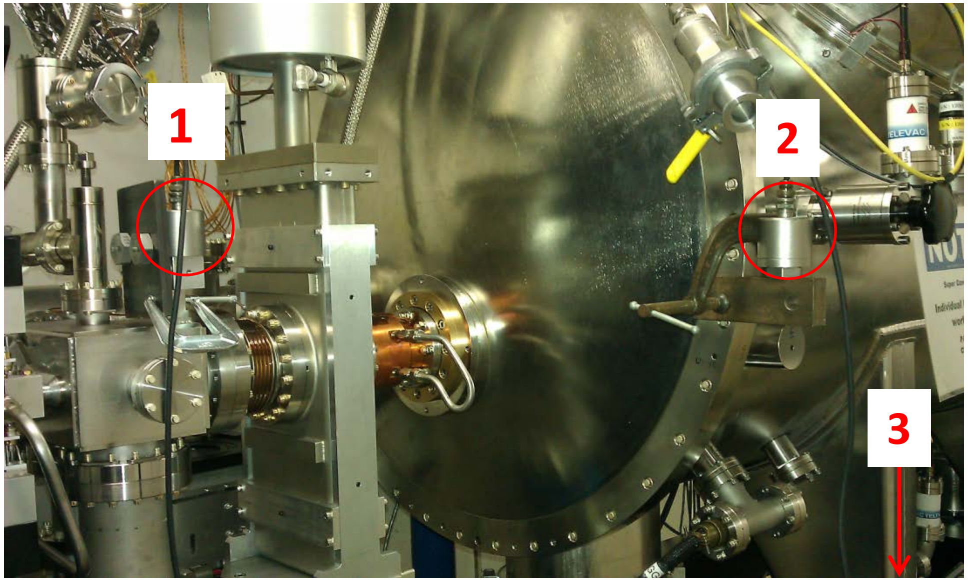
Photon flux comparisons at 85 keV. Main: Simulated and measured SCU0 photon flux . Inset: Measured photon flux for in-line U33.

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 (μm rms), from 2 Hz to 100 Hz	
Cryocoolers off	0.38
Cryocoolers on	0.68

Amplitude at 8.375 Hz (μm rms)	
Cryocoolers off	0.06
Cryocoolers on	0.57