STATUS OF THE DEVELOPMENT OF SUPERCONDUCTING UNDULATORS AT THE ADVANCED PHOTON SOURCE

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ADVANCED PHOTON SOURCE

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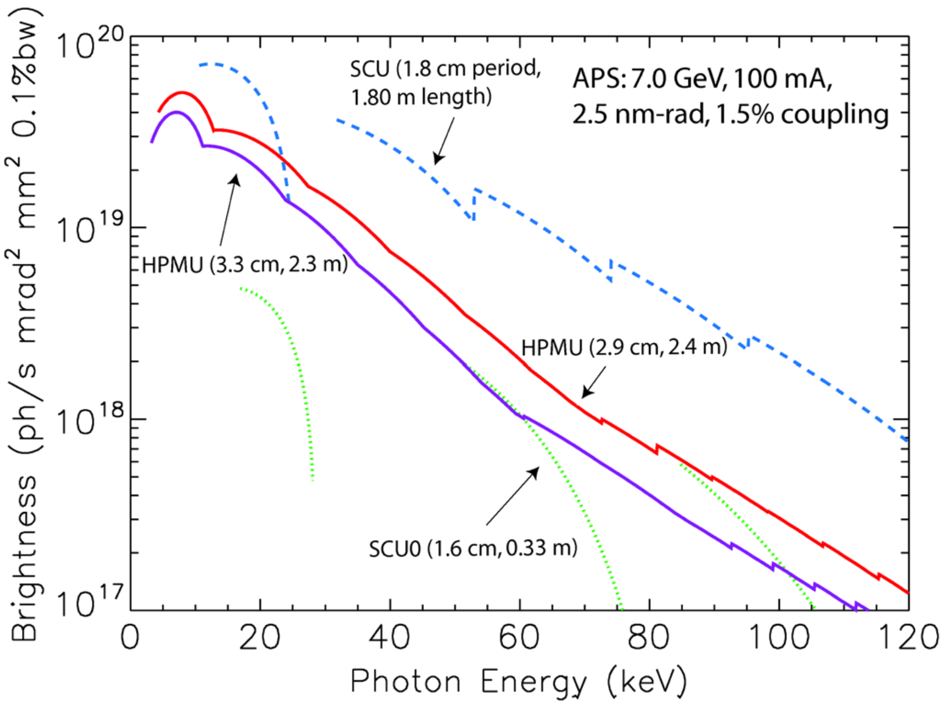
SCOPE

- Why superconducting undulators (SCUs) at the APS?
- Development of planar devices:
  - SCU18-1 and SCU18-2
  - LCLS R&D undulator
  - Achieving low phase errors
- Development of circular polarizing devices:
  - Helical SCU for APS
  - New SCU cryostat
  - New universal SCU – SCAPE
- Summary

WHY SUPERCONDUCTING UNDULATORS AT THE APS?

- A superconducting undulator (SCU) is an electromagnetic undulator that utilizes superconducting coils for generating magnetic field.
- For a given period length and magnetic gap, SCU technology outperforms all other technologies in terms of the undulator peak field [1].
- The higher undulator field leads to higher photon fluxes, especially at higher photon energies. This has been demonstrated at the APS with the operating experience of the first test SCU – SCU0 [2].
- The SCU0 was in continuous operation for 3.5 years and was replaced by SCU18-2 in September 2016.

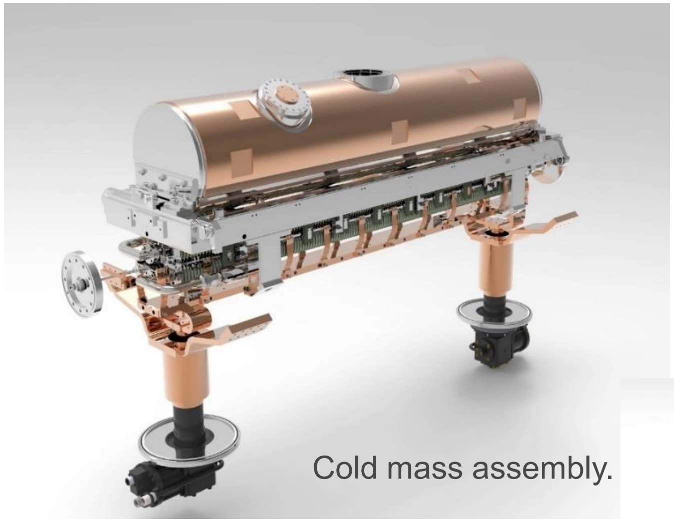


Calculated tuning curves for SCUs and for hybrid undulators.

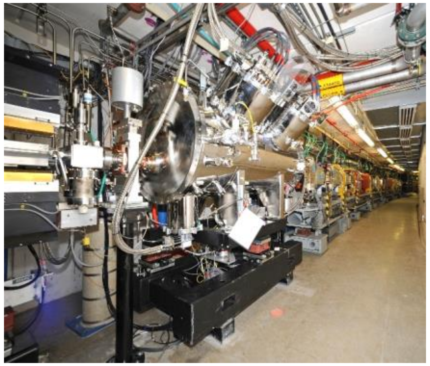
[1] P. Elleaume et al., *Nucl. Instr. Meth.* A 455, pp.503-523, 2000.
[2] Y. Ivanyushenkov et al., *Phys.Rev.ST Accel. Beams,* vol.18, 040703, 2015.

SCU LAYOUT

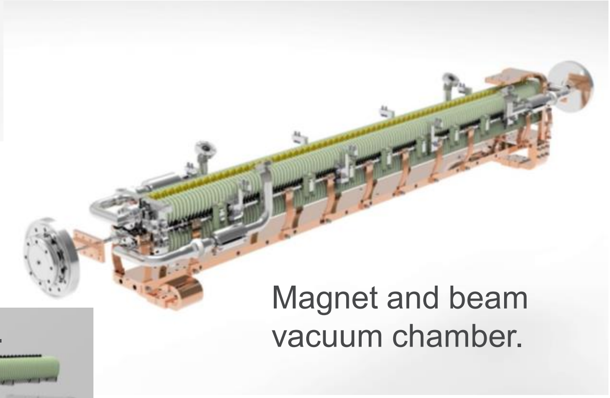
- Two-core planar SCU magnet.
- Magnet cores are cooled by LHe passing through the core channels.
- Closed-loop 4K circuit.
- Beam vacuum chamber is thermally isolated from the magnet cores.
- Cooling is provided by four cryocoolers with the total cooling power of about 1.2-2.5 W at 4.2K.



Cold mass assembly.

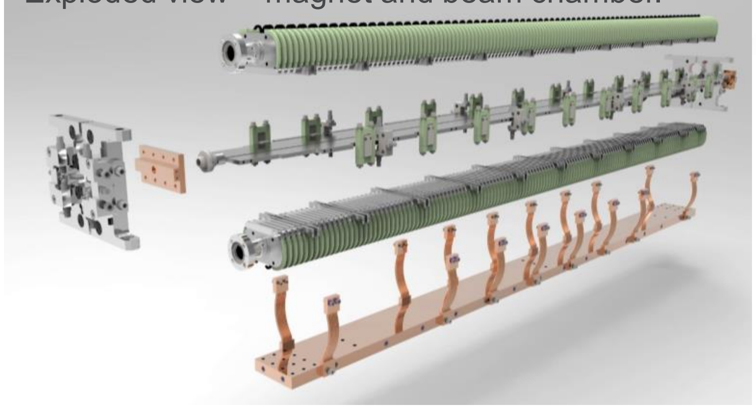


SCU installed in the APS storage ring.



Magnet and beam vacuum chamber.

Exploded view – magnet and beam chamber.

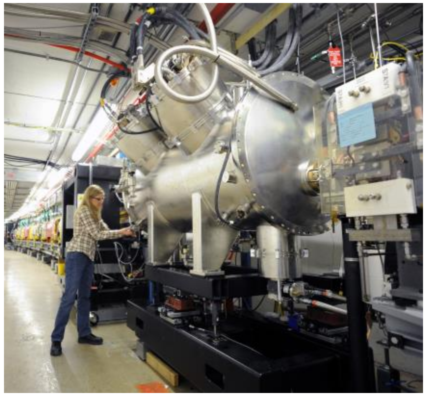


Photograph of 1.1-m long SCU magnet.

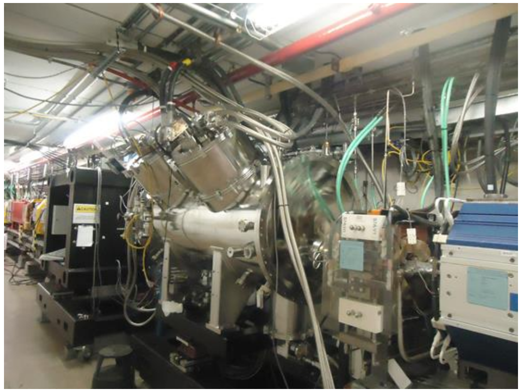
DEVELOPMENT OF PLANAR SUPERCONDUCTING UNDULATORS

SCU18-1 (SCU1) AND SCU18-2

- Two similar undulators, SCU18-1 and SCU18-2, were completed and installed on APS storage ring over the last two years.
- The SCU18-1 has been in operation since May 2015 and SCU18-2 started operation in September 2016.
- SCU reliability is the same as PMU.

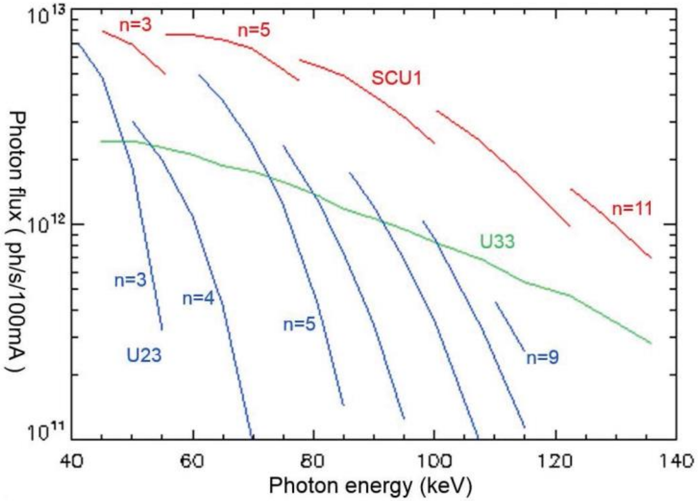


SCU18-1 in Sector 1 of the APS ring.



SCU18-2 in Sector 6 of the APS ring.

Parameter	SCU18-1 and SCU18-2
Cryostat length (m)	2.06
Magnetic length (m)	1.1
Undulator period (mm)	18
Magnetic gap (mm)	9.5
Beam vacuum chamber vertical aperture (mm)	7.2
Undulator peak field (T)	0.97
Undulator parameter K	1.63

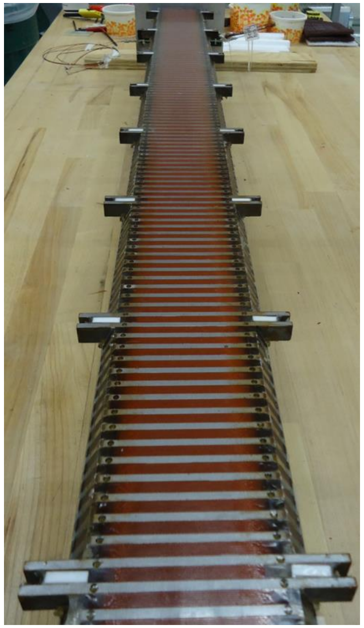


Measured SCU18-1 tuning curves in comparison with those of hybrid undulator U33 (Undulator A).

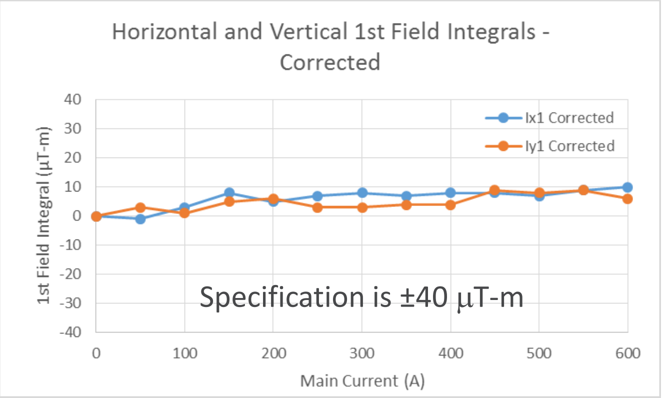
LCLS R&D UNDULATOR

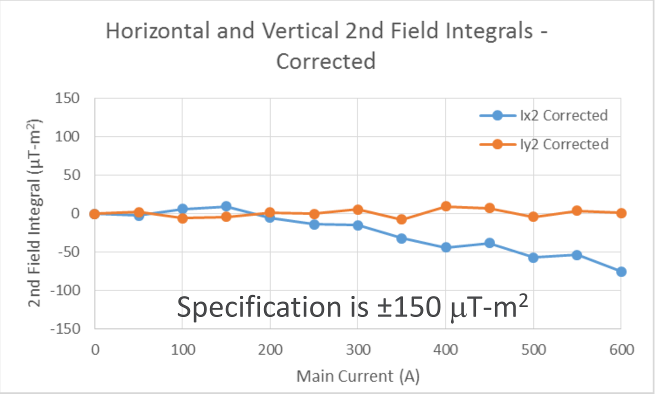
- This NbTi undulator was built as a part of the LCLS SCU R&D project aimed at demonstrating that SCU technology can achieve challenging specifications of FEL undulators [1].
- The undulator did achieve all the specifications including the most challenging requirement of 5º rms phase errors.

Parameter	**LCLS R&D SCU**
Cryostat length (m)	2.06
Magnetic length (m)	1.5
Undulator period (mm)	21
Magnetic gap (mm)	8.0
Beam vacuum chamber vertical aperture (mm)	5.7
Undulator peak field (T)	1.67
Undulator parameter K	3.26


Beam side of magnet core.

Measured first and second field integrals of LCLS R&D SCU.

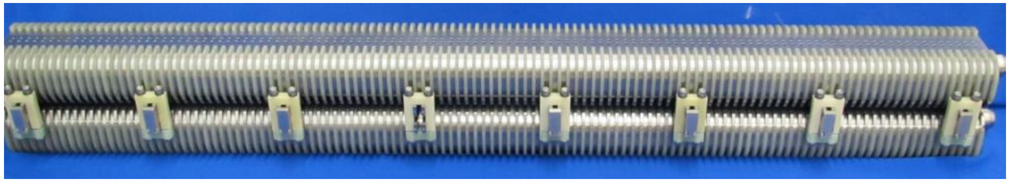


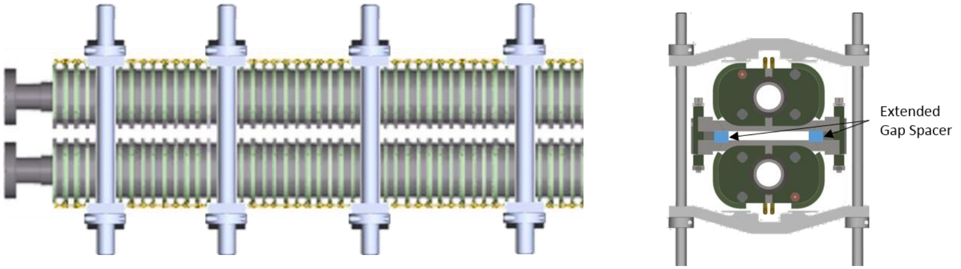


[1] P. Emma et al., in *Proc. of FEL2014*, Switzerland, 2014, paper THA03, pp.649-653.

ACHIEVING LOW PHASE ERRORS

- The SCU field quality depends on:
  - Precise machining of a magnet former [1]
  - Quality of conductor winding [2]
  - Uniformity of the magnetic gap
- A dedicated R&D program was targeted at achieving a very uniform gap [3].
  - A gap correction scheme was developed and implemented using a set of mechanical clamps

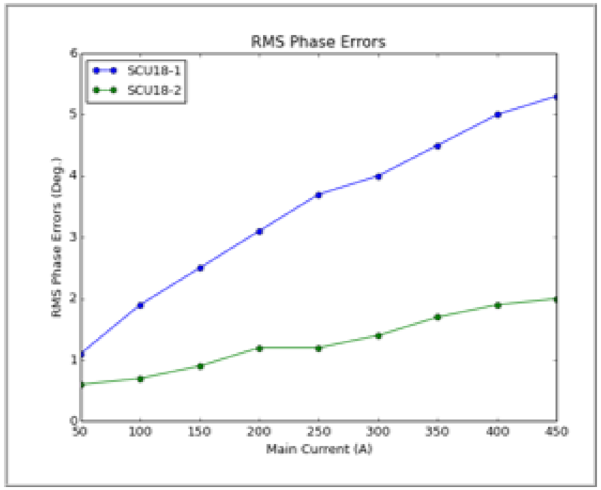




Planar SCU magnetic assembly with a concept of gap correction.

Undulator	Measured phase errors (º rms)
SCU18-1	5*
SCU18-2	2
LCLS R&D SCU	3.8

* without gap correction



Measured phase errors in SCU18-1 and SCU18-2.

[1] E. Trakhtenberg et al., “Evolution of the Design of the Magnet Structure for the APS Planar Superconducting Undulators,” NA-PAC’16.
[2] E. Gluskin, “Development and Performance of Superconducting Undulators at the Advanced Photon Source,” *Synchrotron Radiation News*, Vol. 28, Issue 3, 2015.
[3] M. Kasa et al., “Progress on the Magnetic Performance of Planar Superconducting Undulators,” NA-PAC’16.

DEVELOPMENT OF CIRCULAR AND ARBITRARY POLARIZING SUPERCONDUCTING UNDULATORS

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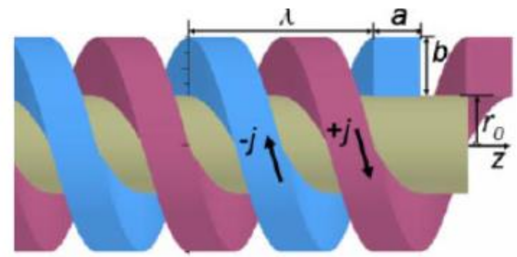
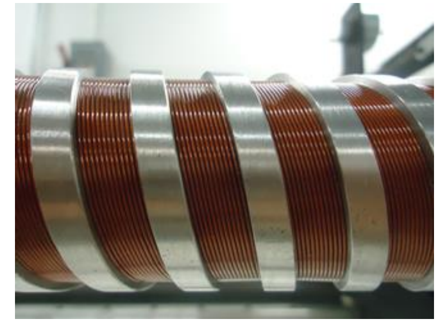
HELICAL SCU FOR APS

- SCU technology offers the possibility of building circular polarizing helical undulators.
- Helical SCU (HSCU) for the APS is in the final stage of the construction.
- X-ray photon correlation spectroscopy program at the APS will benefit from the increased brilliance provided by an HSCU.

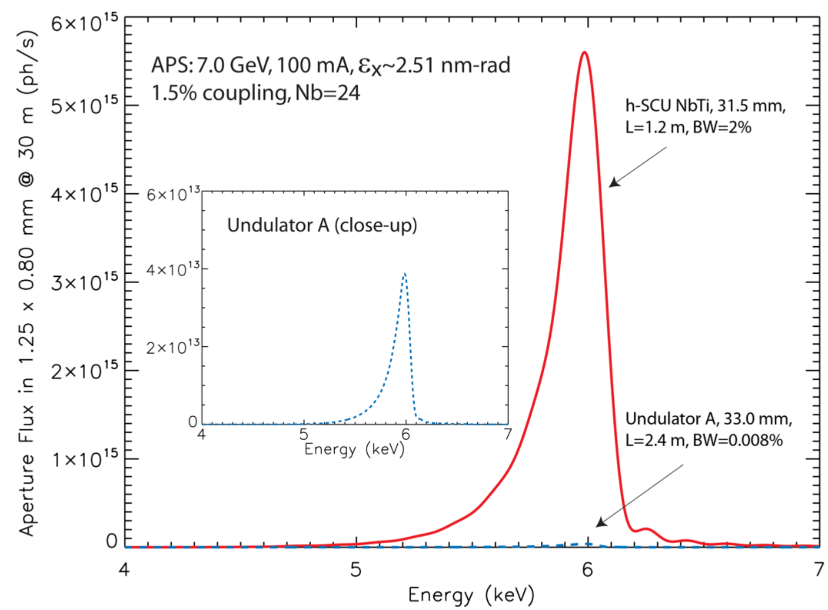


Magnetic model of HSCU.



HSCU prototype coil winding.

Parameter	HSCU
Cryostat length (m)	1.85
Magnetic length (m)	1.2
Undulator period (mm)	31.5
Magnetic bore diameter (mm)	31.0
Beam vacuum chamber vertical aperture (mm)	8
Beam vacuum chamber horizontal aperture (mm)	26
Undulator peak field Bx=By (T)	0.4
Undulator parameter Kx=Ky	1.2

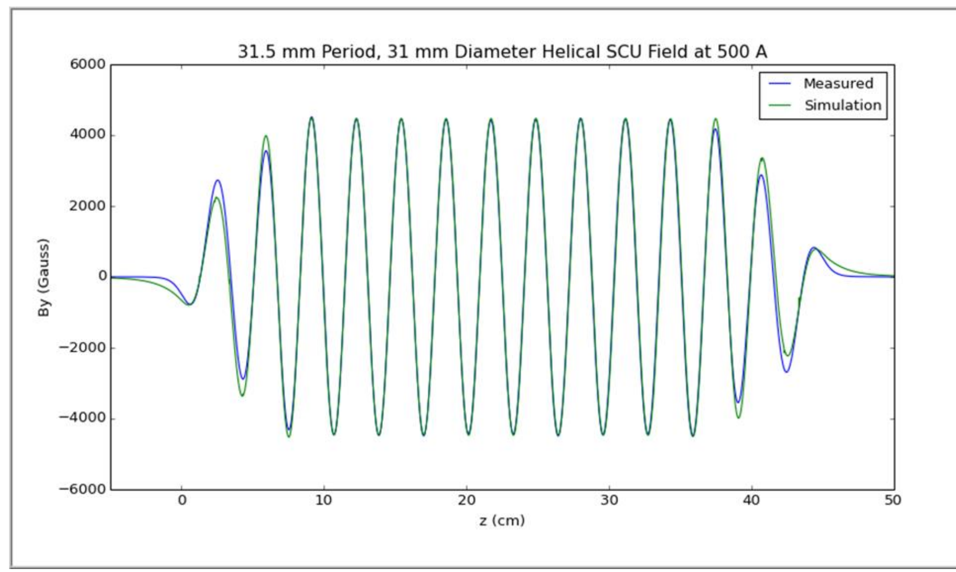


Calculated photon spectrum of helical SCU.

HELICAL SCU PROTOTYPE

- Fabrication of a helical core and a continuous winding scheme were tested on a 300-mm helical magnet prototype.
- The prototype magnet was built and tested in a LHe bath cryostat.
- Magnetic field profile was measured with a Hall probe.
- The magnet reached the design field of 0.4 T at design current.

Wound 300-mm long prototype core.

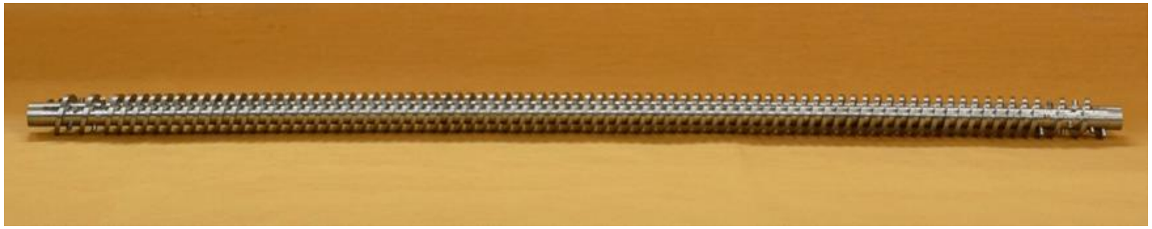


Measured and simulated field of HSCU prototype magnet.

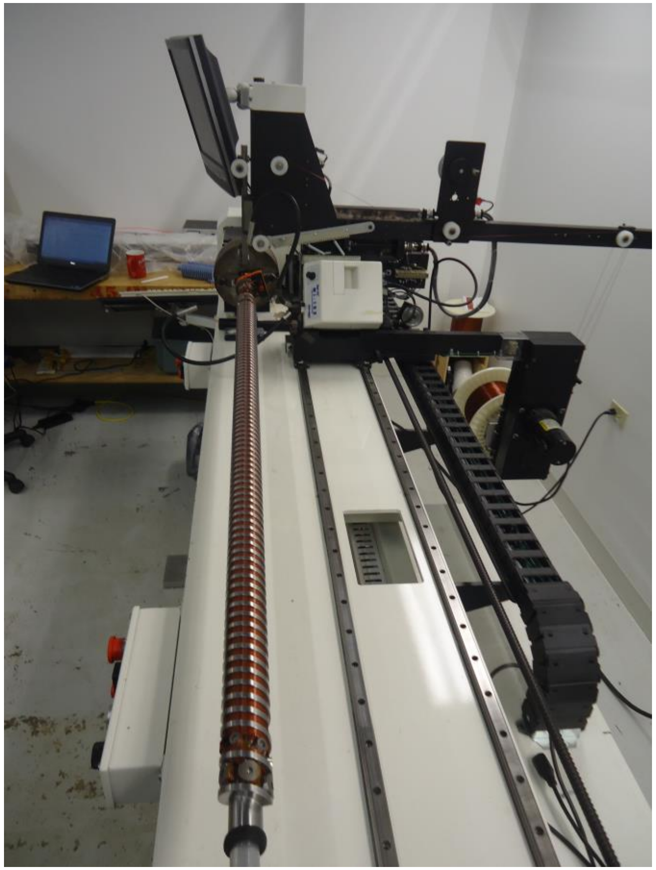
HELICAL SCU MAGNET

Helical SCU core during fabrication.

- Two 1.2-m cores were fabricated by a partner vendor with the precision of about 20 µm.
- Two cores are wound with NbTi wire and ready for impregnation with epoxy resin.



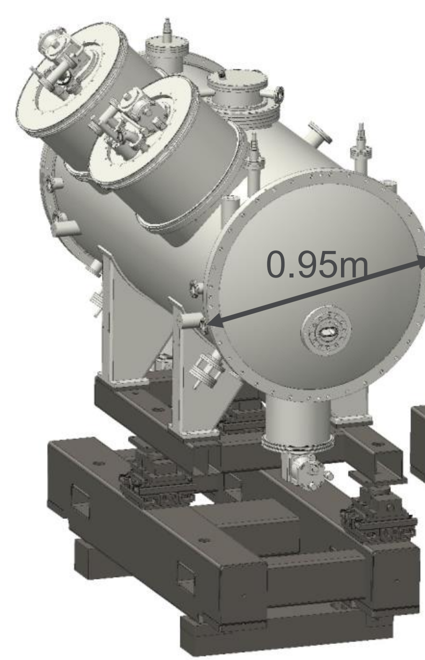
Completed 1.2-m long Helical SCU core.



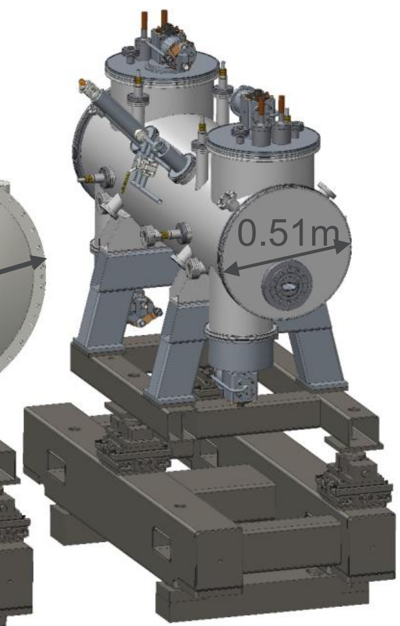
Winding of Helical SCU magnet.

NEW CRYOSTAT FOR SCUs

- All three APS planar SCUs used the SCU0-type cryostat that was designed in collaboration with the Budker Institute, Novosibirsk, Russia.
- Helical SCU will use a new cryostat.
- Design of the HSCU cryostat is based on the experience of operating three SCU0-type cryostats and a rigorous thermal analysis.
- HSCU cryostat is more compact and cheaper than the SCU0-type cryostat.
- HSCU cryostat is currently being tested.
- HSCU-type cryostat will likely become a standard cryostat for the next SCUs.



SCU0-type cryostat.

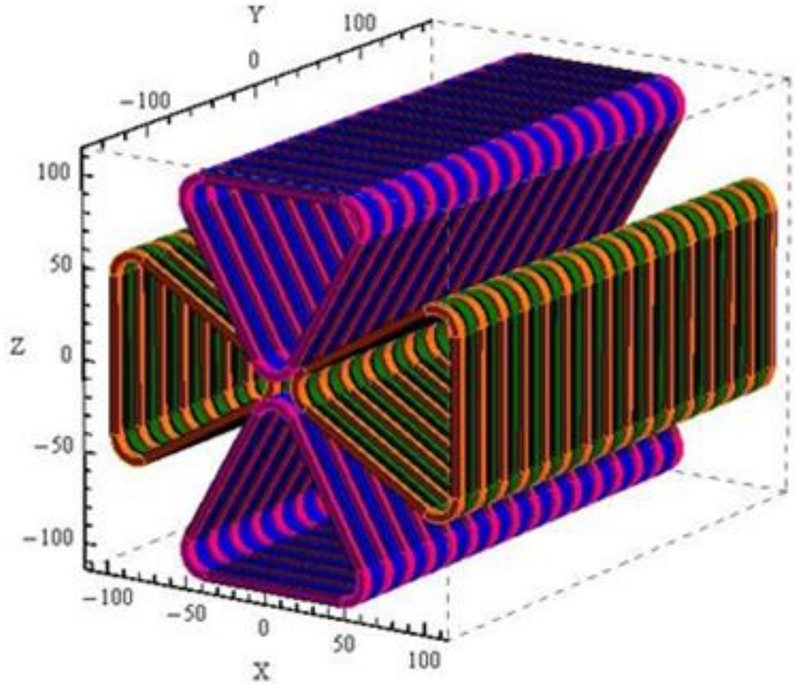


New HSCU cryostat.

Design model of long SCU installed in the APS-U.

ARBITRARY POLARIZING SCU— SCAPE

- Users of APS POLAR beamline would like to have an undulator that can generate both circular and planar polarized photons.
- To answer this challenging request, we have developed the concept of a Super Conducting Arbitrarily Polarizing Emitter, or SCAPE.
- This electromagnetic superconducting undulator uses four planar magnetic cores assembled around a cylindrical beam vacuum chamber.
- The APS Upgrade multi bend achromat lattice enables round beam chambers (6 mm ID) for insertion devices.
- The SCAPE concept will be tested in a prototype.
- A similar concept was realized with normal conducting coils in [1].

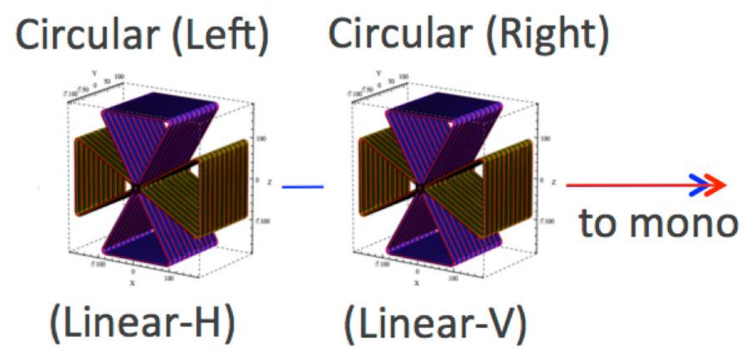


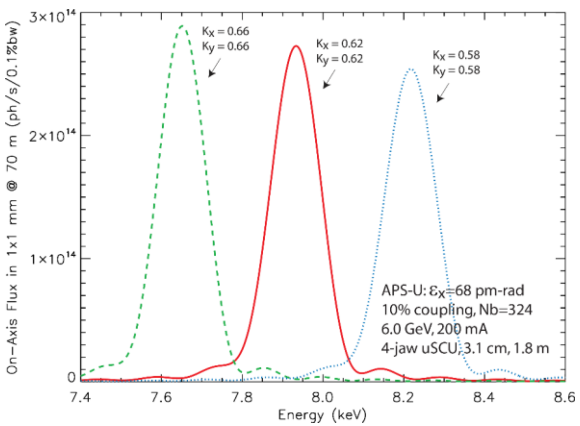
Concept of SCAPE: a universal SCU with four planar superconducting coil structures. A beam chamber is not shown.

[1] L. Nahon *et al., Nucl. Instrum. and Meth.,* vol. A396, pp. 237-250, 1997.

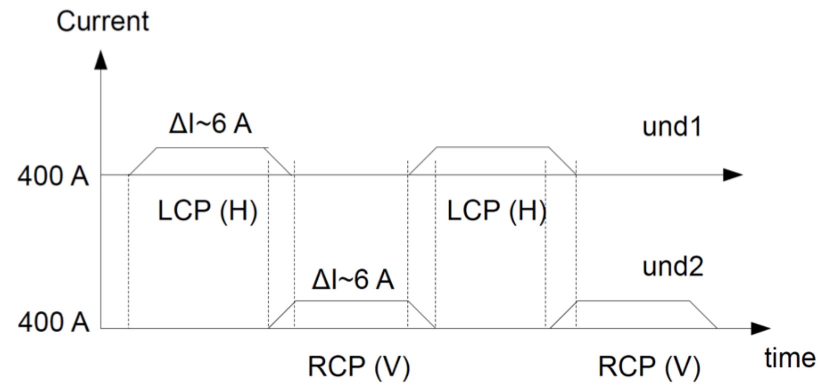
SCAPE OPERATION IN POLARIZATION SWITCHING MODE

- Two SCAPE undulators assembled in one cryostat and operating in a “push-pull” mode could be used as a fast switching (10 Hz) source of linear/circular polarized radiation.
- Fast switching mode requires a special superconductor which is optimized for AC operation, and will be addressed in the next phase of the project.





First harmonic energy vs. K value.

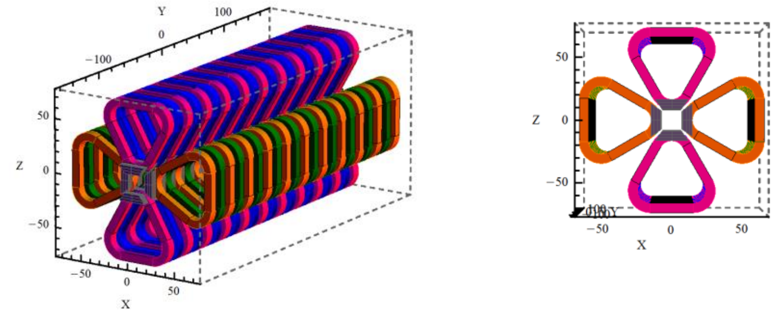


SCAPE operation in polarization switching mode.

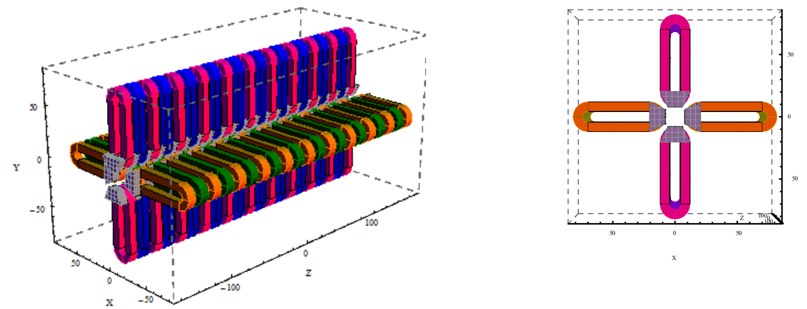
MAGNETIC MODELING OF SCAPE

- Magnetic simulation of SCAPE was performed in Radia.
- Several topologies were analyzed in order to maximize the magnetic field and minimize magnetic forces.
- A geometry with recessed triangular coils and magnetic poles has been chosen for mechanical design.

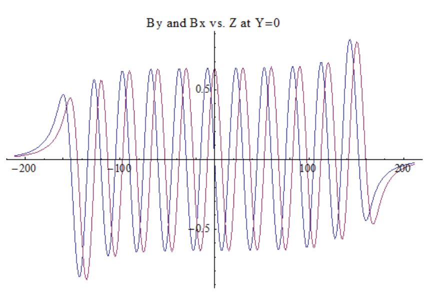
Parameter	Value
Undulator period length, mm	30
Beam chamber ID, mm	6
Beam chamber OD, mm	9
Magnetic gap (pole-to-pole), mm	10
Coil recess, mm	2
Coil-to-coil gap, mm	14
Coil cross sectional dimensions, mm × mm	7.5 × 7.5
Coil current density, A/mm^2	1200
Undulator peak field, T	1.03



SCAPE configuration with triangular coils.



SCAPE configuration with racetrack coils.



Typical SCAPE field profile.

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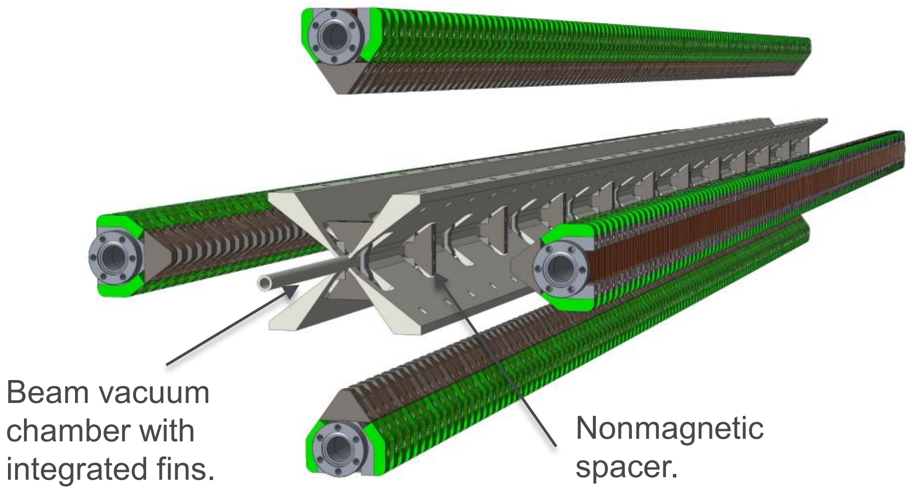
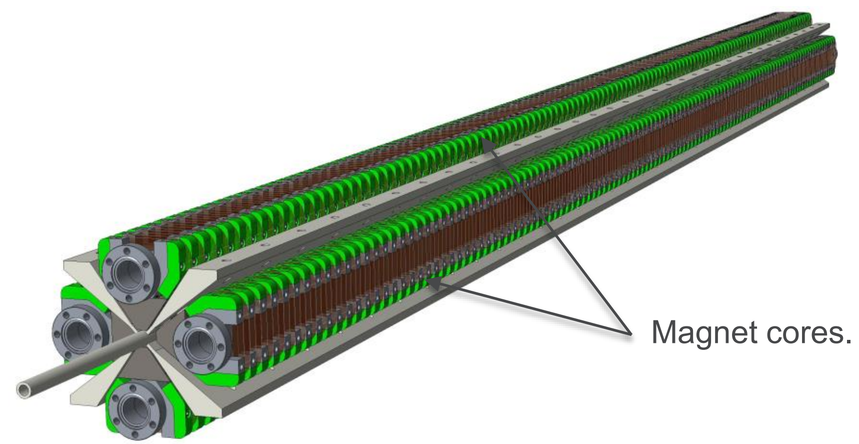
SCAPE MAGNET CONCEPTUAL DESIGN

- Mechanical design is based on the APS's experience of fabricating superconducting planar undulator cores, as well as the experience of machining extruded Al beam chambers.
- The Al round beam chamber is integrated with longitudinal fins that are used to extract heat from the beam chamber.
- The nonmagnetic spaces react the attractive forces between cores, and connect the cores through the openings in the beam chamber fins.
- The cores are cooled by LHe passing through the channels in the cores.
- A prototype of SCAPE magnet will be fabricated this year.





SUMMARY

- The first APS superconducting undulator, SCU0, was removed from the APS storage ring after 3.5 years of successful operation.
- Two SCUs – SCU18-1 and SCU18-2 – are currently in operation at the APS.
- Helical SCU for the APS is in the final stage of the construction.
- A concept of an arbitrary polarizing undulator, SCAPE, has been developed and will be tested in a prototype.