DEVELOPMENT OF SUPERCONDUCTING UNDULATORS AT THE ADVANCED PHOTON SOURCE OF ARGONNE NATIONAL LABORATORY

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SCOPE

- Advanced Photon Source (APS) at Argonne National Laboratory (ANL)
- Advantage of superconducting undulators
- Undulators for APS
  - Planar undulators
  - Helical undulator
- Undulators for APS Upgrade
  - Planar undulators
  - SCAPE
- R&D on Nb3Sn undulator
- Summary

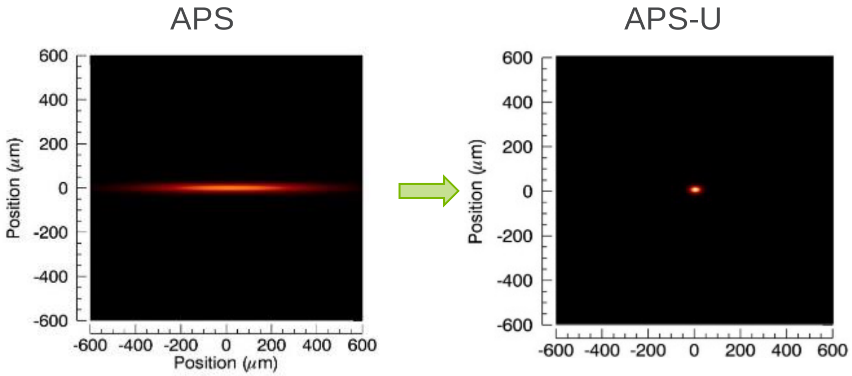
ADVANCED PHOTON SOURCE AT ARGONNE NATIONAL LABORATORY

ADVANCED PHOTON SOURCE (APS) AT ARGONNE NATIONAL LABORATORY (ANL)

Aerial view of the APS

Electron energy	7 GeV
Storage ring circumference	1104 m
Number of straight sections	40
Number of users	>5000

- **APS Upgrade**: building a world leading hard x-ray facility
  - New storage ring
    - 6 GeV MBA lattice
    - 200 mA current
    - Improved electron/photon stability
  - New insertion devices
    - Incorporate SCUs on selected beamlines



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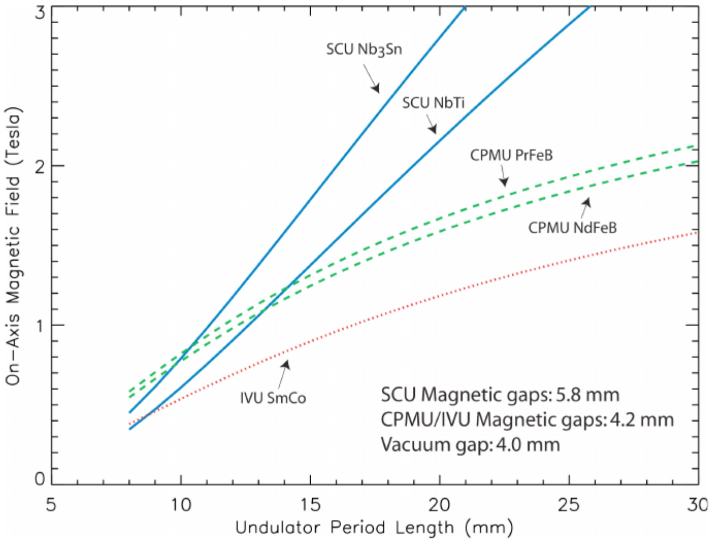
ADVANTAGE OF SUPERCONDUCTING UNDULATORS

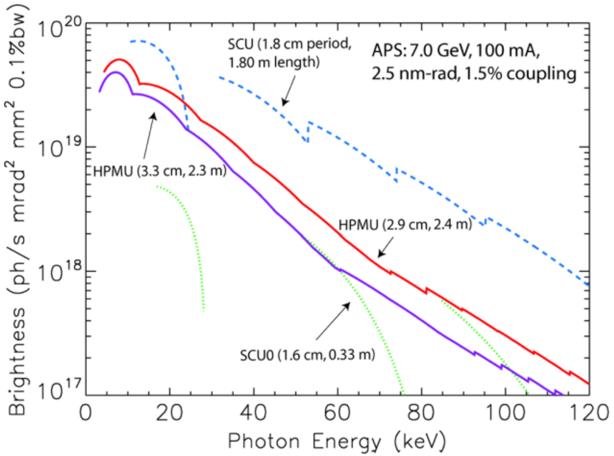
MAGNETIC FIELD OF VARIOUS INSERTION DEVICE TECHNOLOGIES

- A superconducting undulator (SCU) is an electromagnetic undulator that utilizes superconducting coils for generating magnetic field.
- Superconducting technology-based undulators outperform all other technologies in terms of peak magnetic field and, hence, energy tunability of the radiation
- Superconducting technology opens a new avenue for insertion devices



Calculated on-axis magnetic fields of two cryogenic permanent magnet undulators (CPMUs), two superconducting undulators (SCUs) and on in-vacuum undulator (IVU) for a vacuum gap of 4.0 mm for period length from 8 mm to 30 mm.

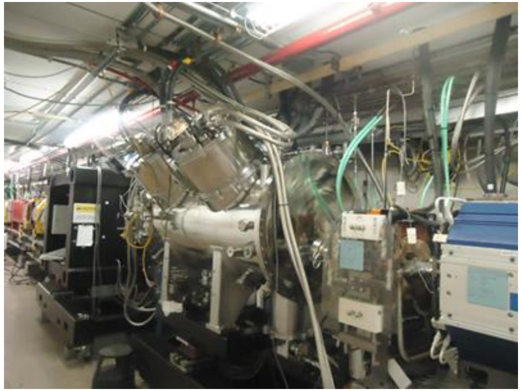
Calculated tuning curves for SCUs and for hybrid undulators.



E. Moog, R. Dejus, and S. Sasaki, "Comparison of Achievable Magnetic Fields with Superconducting and Cryogenic Permanent Magnet Undulators – A Comprehensive Study of Computed and Measured Values", ANL/APS/LS-348, 2017.

DEVELOPMENT OF SUPERCONDUCTING UNDULATORS AT THE APS

- SCU0 [1]:
  - 16-mm period length
  - 0.33-m long magnet
  - In operation: Jan2013-Sep2016
- SCU1(SCU18-1) [2]:
  - 18-mm period length
  - 1.1-m long magnet
  - In operation: since May2015
- SCU18-2:
  - 18-mm period length
  - 1.1-m long magnet
  - In operation: since Sep2016



SCU18-2 in Sector 6 of the APS ring.

- LCLS R&D SCU:
  - 21-mm period length
  - 1.5-m long magnet
  - Project completed in 2016
- Helical SCU [3]:
  - 31.5-mm period length
  - 1.2-m long magnet
  - Installed in Dec2017
- R&D projects [4]:
  - HTS SCU – completed
  - SCAPE – in progress
  - Nb_3Sn – in progress

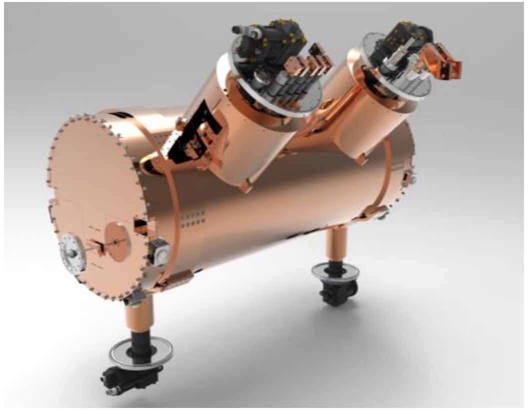
[1] Y. Ivanyushenkov et al., “Development and operating experience of a short-period superconducting undulator at the Advanced Photon Source,” Phys. Rev. ST Accel. Beams 18, 040703 (2015).
[2] Y. Ivanyushenkov et al., “Development and operating experience of a 1.1-m-long superconducting undulator at the Advanced Photon Source,” Phys. Rev. Accel. Beams 20, 100701 (2017).
[3] M. Kasa et al., "Development and operating experience of a 1.2-m long helical superconducting undulator at the Advanced Photon Source," Phys. Rev. Accel. Beams 23, 050701 (2020).
[4] Yury Ivanyushenkov and Efim Gluskin. "Development of Superconducting Undulators at the Advanced Photon Source." ICFA Beam Dynamics Newsletter, No. 78, December 2019: 8-26.

SUPERCONDUCTING UNDULATORS FOR APS

SCU LAYOUT

Assembled cryostat.

Inside the SCU vacuum vessel.

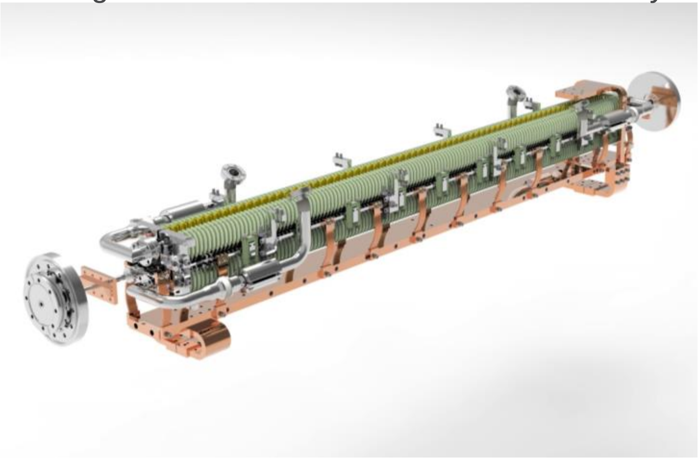


SCU cold mass.

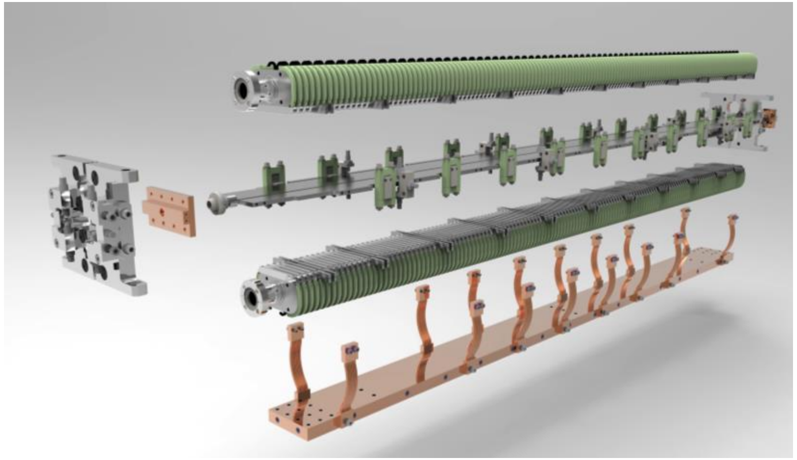
- SCU cryostat consists of vacuum vessel, thermal shield and a cold mass
- Cooling is provided by cryocoolers
- Closed-loop LHe circuit

PLANAR SCU MAGNET

Magnet – beam vacuum chamber assembly.



Magnet cores and beam vacuum chamber.

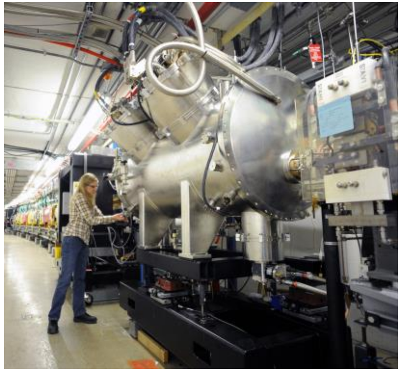


- A two-core SCU magnet structure
- LHe is contained in a tank connected with the magnet
- NbTi coils are cooled indirectly with LHe passing through channels in the magnet cores
- Beam chamber is thermally isolated from the magnet, and cooled independently

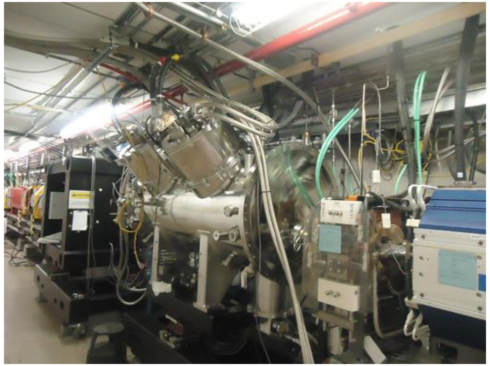
SCU18-1 (SCU1) AND SCU18-2

- Two similar undulators, SCU18-1 and SCU18-2, were completed and installed on APS storage ring
- The SCU18-1 has been in operation since May 2015 and SCU18-2 started operation in September 2016

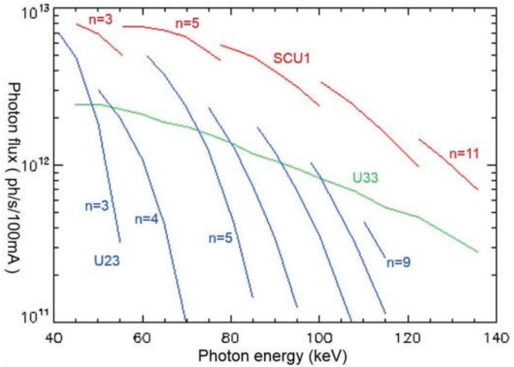
Parameter	SCU18-1 and SCU18-2
Cryostat length (m)	2.06
Magnetic length (m)	1.1
Undulator period (mm)	18
Magnetic gap (mm)	9.5
Beam vacuum chamber vertical aperture (mm)	7.2
Undulator peak field (T)	0.97
Undulator parameter K	1.63



SCU18-1 in Sector 1 of the APS ring.



SCU18-2 in Sector 6 of the APS ring.



Measured SCU18-1 tuning curves in comparison with those of hybrid undulator U33 (Undulator A) and undulator U23.

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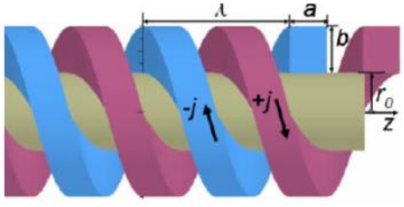
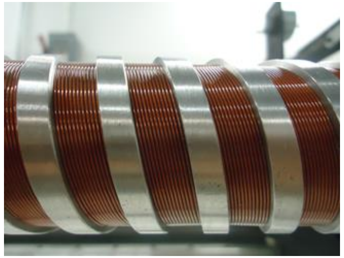
HELICAL SCU FOR APS

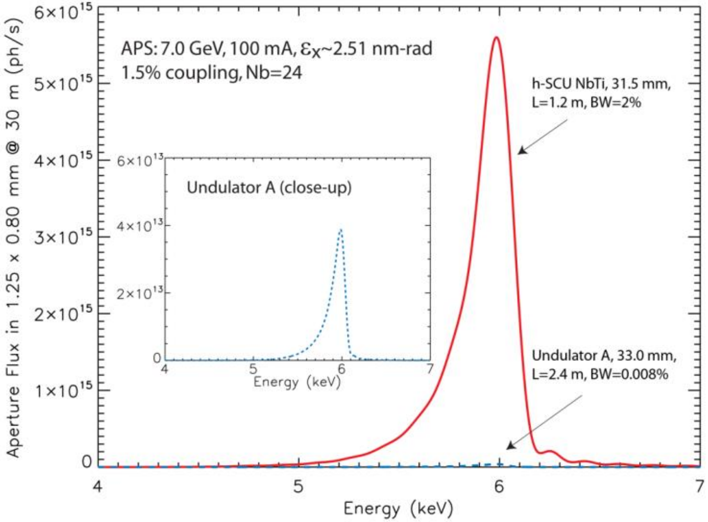
- SCU technology offers the possibility of building circular polarizing helical undulators
- A helical SCU (HSCU) was installed on APS ring in December 2017. In operation since January 2018
- X-ray photon correlation spectroscopy program at the APS benefits from the increased brilliance provided by an HSCU



Magnetic model of HSCU.



HSCU prototype coil winding.

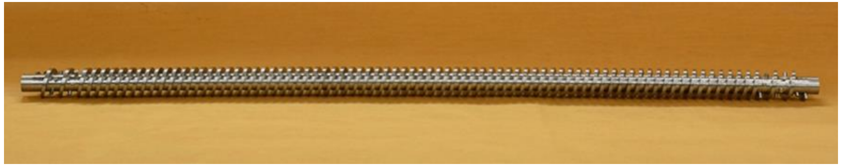


Calculated photon spectrum of helical SCU.

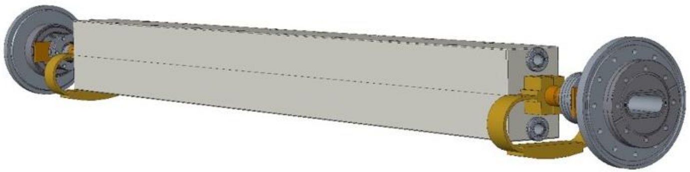
Parameter	HSCU
Cryostat length (m)	1.85
Magnetic length (m)	1.2
Undulator period (mm)	31.5
Magnetic bore diameter (mm)	31.0
Beam vacuum chamber vertical aperture (mm)	8
Beam vacuum chamber horizontal aperture (mm)	26
Undulator peak field Bx=By (T)	0.4
Undulator parameter Kx=Ky	1.2

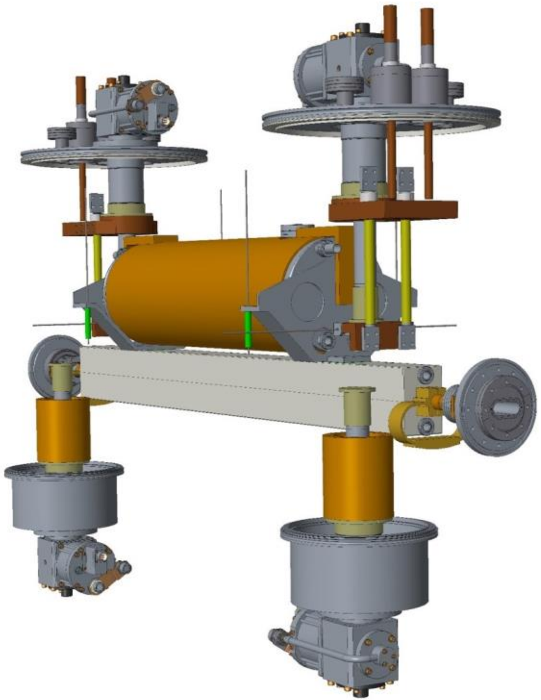
HSCU COLD MASS

HSCU magnet core



HSCU magnet assembly



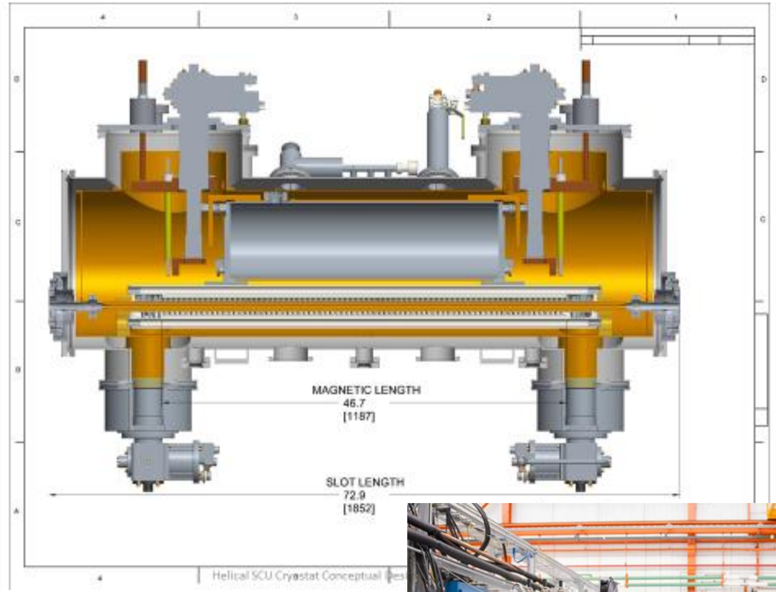


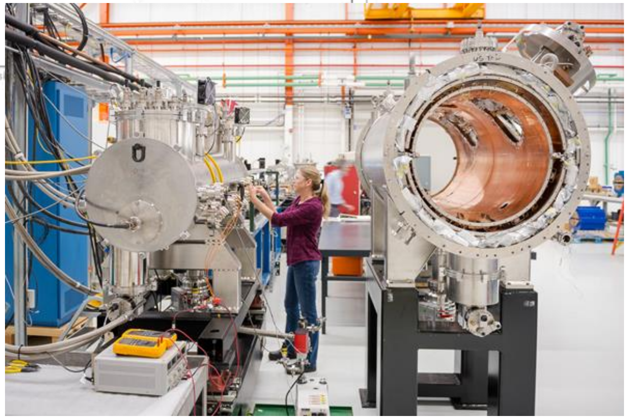
Four 4.2 K cryocoolers provide excess cooling capacity. Vertical orientations improve maintenance access and performance.

HSCU CRYOSTAT

- One thermal shield
- Four RDK415D cryocoolers
- Two temperature stages
- Reduced diameter of the vacuum vessel
- Vertical turrets
- Standard flanges for the end covers
- Simplified design of He filling port

J. Fuerst et al., “A second-generation superconducting undulator cryostat for the APS,” Proceedings of CEC-ICMC 2017, Madison, 2017.

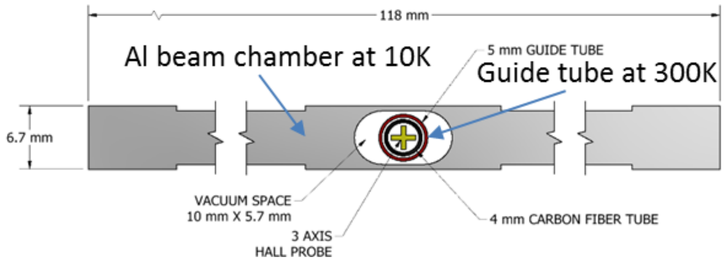




HSCU cryostat (left) and SCU0/SCU1 cryostat (right)

MEASURING SCU FIELD

- Warm sensor concept:
  - Metallic guide tube is stretched inside the beam chamber cold bore (concept by Budker Institute, Russia)
  - Guide tube is heated by the current passing through it
  - Guide tube bore is open to atmosphere
- Sensor (Hall probe or wire coil) operates at the room temperature
  - Hall probe:
  - 3-axis commercial Hall sensor measures By, Bx, Bz components
  - Attached to fiber tube and driven by precise 3.5-m linear stage
  - Bz- field is used to measure vertical position of the sensor
- Stretched wire coils:
  - Rectangular, delta and ‘figure- 8’ coils stretched between two linear and rotation stages
  - Measure static and dynamic field integrals and multipole components



Warm-sensor concept

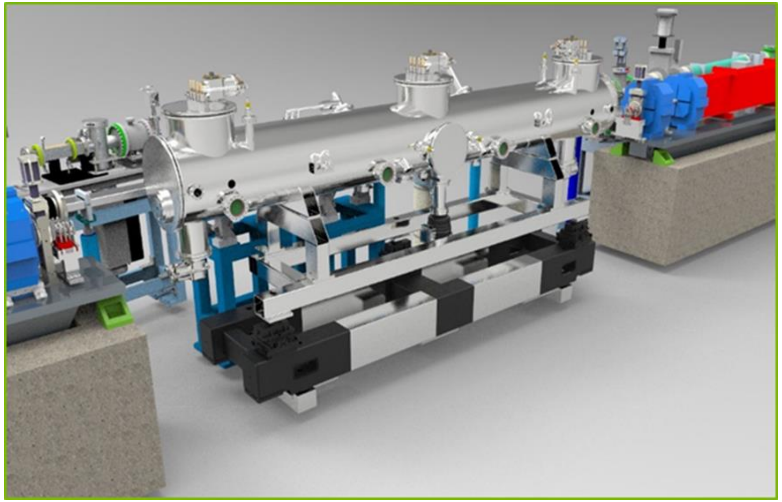
SCU horizontal measurement system

SUPERCONDUCTING UNDULATORS FOR APS UPGRADE

SCUs FOR APS UPGRADE

- Four planar SCUs:
  - Two in-line SCUs (each with two in-line undulator sources in a long cryostat)
  - Two canted SCUs (each with two canted undulator sources in a long cryostat)
- Variably polarizing SCU:
  - SCAPE

Location	Configuration	Upstream device	Downstream device
01-ID	Dual Inline in Long Cryostat	SCU1.65	SCU 1.65
11-ID	Canted in Long Cryostat	SCU1.65	SCU 1.65
20-ID	Dual Inline in Long Cryostat	SCU1.65	SCU 1.65
28-ID	Canted in Long Cryostat	SCU1.85	SCU1.85



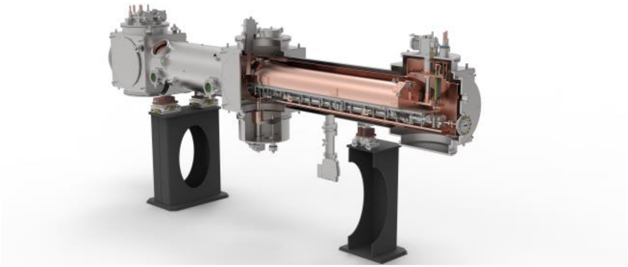
Design model of APS-U ID straight section with an SCU

APSU SCUs

- Magnet design is based on a proven design of existing SCU magnets:
  - up to 1.9-m long core with a channel for LHe
  - proven winding scheme
- Cryostat design is based on a proven design of the 2-m cryostat for Helical SCU:
  - 4.8-m long 20”-diameter vacuum vessel;
  - single thermal shield;
  - off-shelf vacuum components;
  - three thermal stages (4K – 20K – 40K);
  - 6 cryocoolers (two types) with a possibility of adding one if required
- Article #1 is in fabrication

Completed 1.9-m long core

Cryostat design model

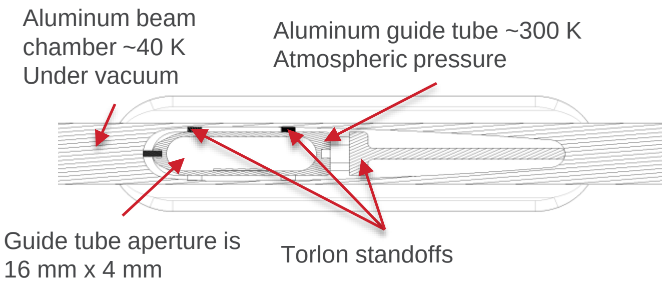


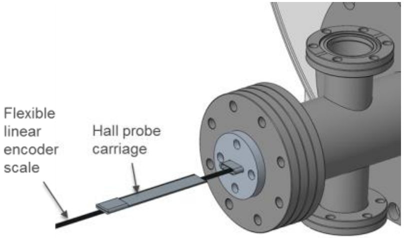
Cryostat vacuum vessel

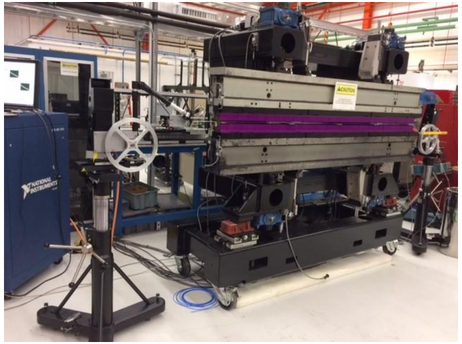
LHe tank

NEW SCU MEASUREMENT SYSTEM

- New design is based on experience of using a 2-m long measurement system for the APS SCUs:
  - a proven concept of a warm guiding tube
  - Hall probe carriage is moved with a flexible linear encoder scale
  - does not require a long holder attached to a long travel linear stage
- System is fabricated, assembled and tested. It’s being used to measure a well characterized HPMU.



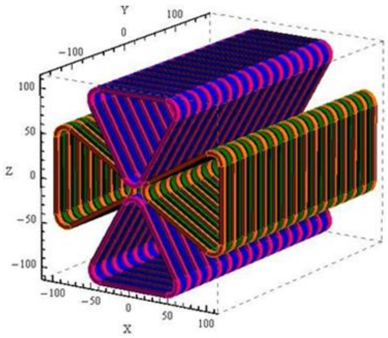




SCAPE

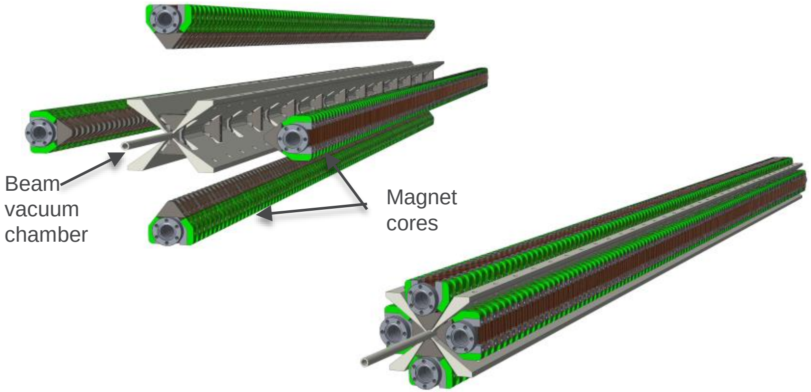
VARIABLY POLARIZING SCU— SCAPE

- 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 Arbitrary Polarizing Emitter, or SCAPE
- This electromagnetic superconducting undulator employs 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 is tested in a prototype



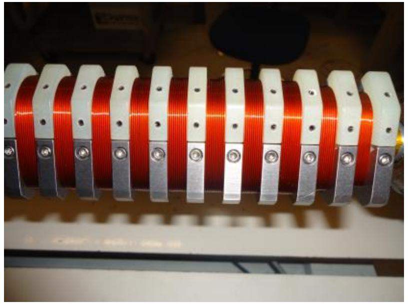
Concept of SCAPE: a universal SCU with four planar superconducting coil structures. A beam chamber is not shown.

SCAPE 3d design model



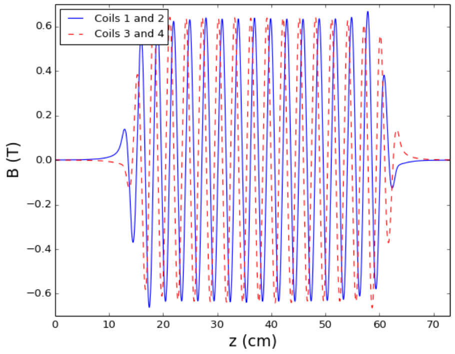
SCAPE PROTOTYPE

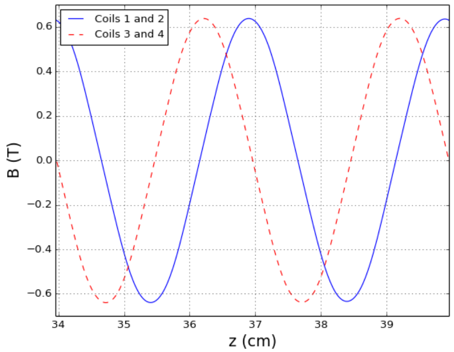
- SCAPE 0.5-m long prototype magnet is built:
  - period length – 30 mm
  - magnetic gap – 10 mm
- The prototype has been tested in a LHe bath cryostat equipped with a movable Hall probe
- Max quench current is 680 A → operating current is around 540 A → field on axis is 0.7 T


SCAPE core winding

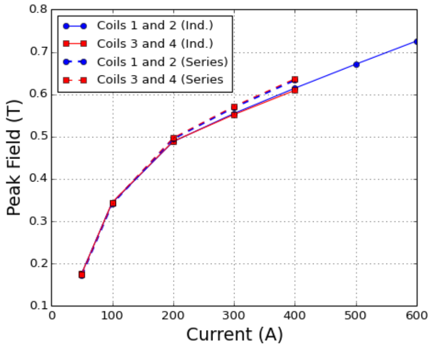

SCAPE mechanical structure

Measured field profiles





Excitation curves



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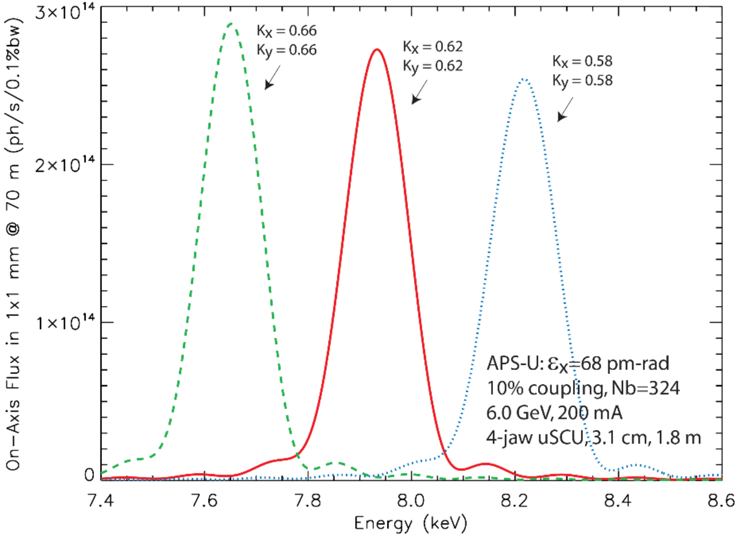
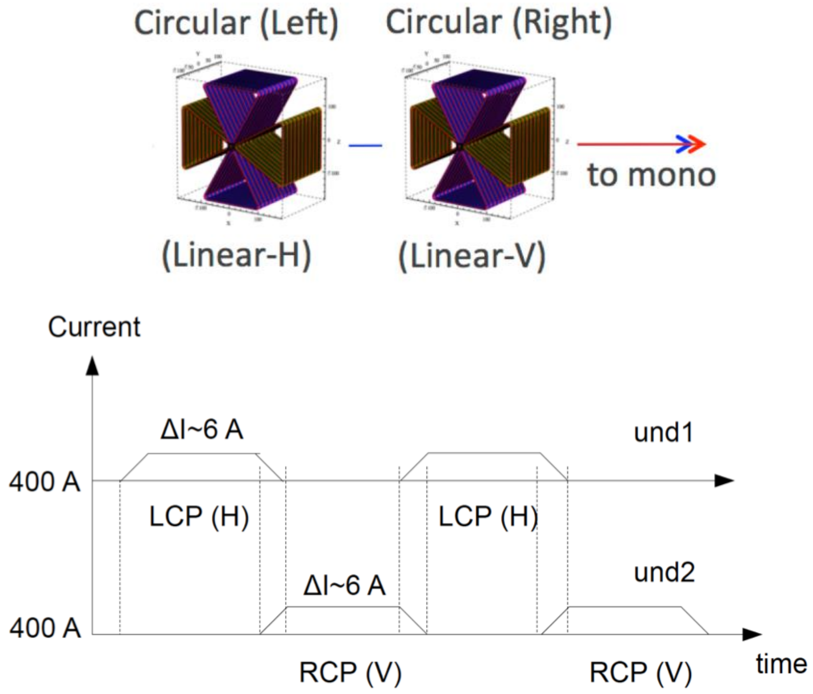
SCAPE OPERATION IN POLARIZATION SWITCHING MODE

- Two SCAPE undulators assembled in one cryostat and operating in a “push-pull” mode could be used as a fast-switching source of linear/circular polarized radiation [1]



First harmonic energy vs. K value.



SCAPE operation in polarization switching mode.

[1] D. Haskel, private communication, June 2018.

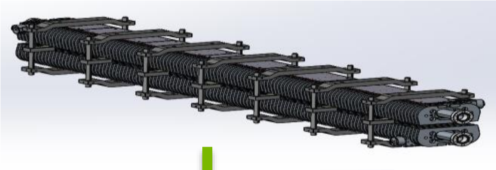
R&D ON NB_3SN UNDULATOR

NB3SN UNDULATOR FOR APS

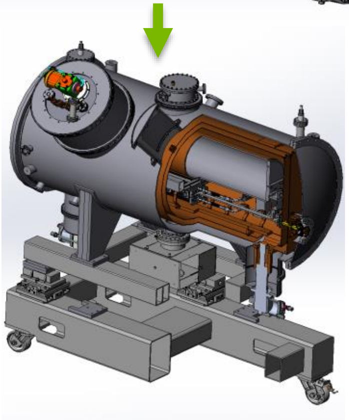
- A 3-year project
- Goal: Develop, build and install on the APS ring a Nb_3Sn undulator (in a modified SCU0 cryostat) a year before the APS-U ‘dark time’ starts
- Collaboration with FNAL and LBNL
- Plan:
  – R&D phase – build and test short magnet models (complete)
  – 0.5-m long prototype (complete)
  – Full scale magnet and cryostat
  – Undulator assembly, test, installation on the APS ring

84 mm

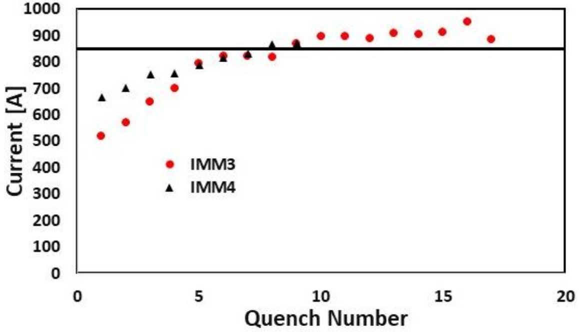
0.5 m



1.1 m

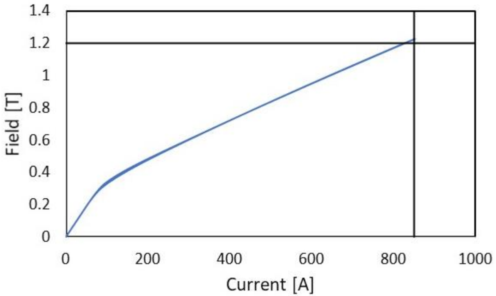


Quench training profile of individual cores



Nb_3Sn SCU did not require any training to reach the design current in 2nd cooldown and demonstrated excellent training memory.

Excitation curve of 0.5-m long Nb_3Sn SCU



The performance exceeded the design current and undulator field of ~850 A and 1.2 T, respectively. The magnetic field simulations agreed well with the measured field values. Nb_3Sn SCU offers at least 20% undulator field increase compared to a NbTi SCU with the same magnetic gap (9.5 mm) and period length (18 mm).

I. Kesgin[1], M. Kasa[1], S. MacDonald[1], Y. Ivanyushenkov[1], E. Barzi[2], D. Turrioni[2], D. Arbelaez[3], Q. Hasse[1], A. Zlobin[2], S. Prestemon[3] and E. Gluskin[1], "Fabrication and Testing of 18-mm-Period, 0.5 m Long Nb3Sn Superconducting Undulator," in *IEEE Transact. on Applied Supercond.*, vol. 31,no 5.

[1] Argonne National Laboratory
[2] Fermilab
[3] Lawrence Berkeley National Laboratory

SUMMARY

- SUPERCONDUCTING UNDULATOR TECHNOLOGY OPENS A NEW AVENUE FOR INSERTION DEVICES OFFERING HIGHER MAGNETIC FIELD THAN OTHER UNDULATOR TECHNOLOGIES
- VARIOUS TYPES OF UNDULATORS CAN BE BUILT IN SUPERCONDUCTING TECHNOLOGY
- SUPERCONDUCTING UNDULATORS ARE SUCCESSFULLY EMPLOYED AT THE ADVANCED PHOTON SOURCE. MORE UNDULATORS WILL BE BUILT FOR APS UPGRADE.
- WE ARE READY TO USE OUR EXPERIENCE IN SCUs TO DEVELOPING AND BUILDING SUPERCONDUCTING UNDULATORS FOR LINEAR COLLIDERS

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* NOW WITH SLAC

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