PROGRESS IN THE DEVELOPMENT OF SUPERCONDUCTING UNDULATORS AT THE ADVANCED PHOTON SOURCE

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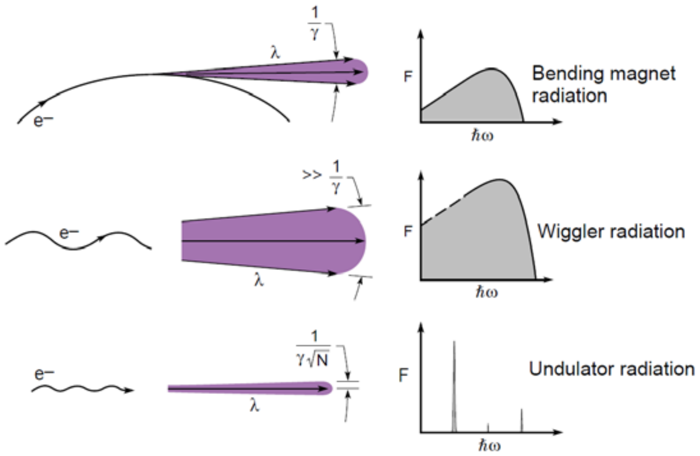
SCOPE

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

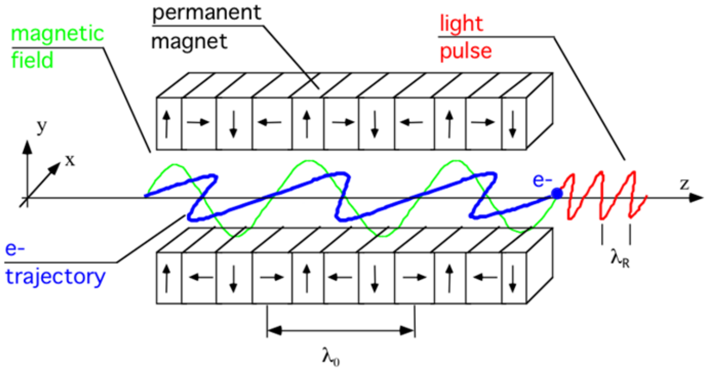
ADVANTAGE OF SUPERCONDUCTING UNDULATORS

UNDULATOR RADIATION



Prof. David T. Attwood, https://people.eecs.berkeley.edu/~attwood/srms//2007/Lec08.pdf

Magnetic field profile and electron trajectory in an undulator



From Centre Laser Infrarouge d'Orsay:http://clio.lcp.u-psud.fr/clio_eng/FELrad.html

Undulator radiation wavelength and photon energy:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$E(\text{keV}) = \frac{0.9496 E_e^2(\text{GeV})}{\lambda_u(\text{cm})\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)}$$

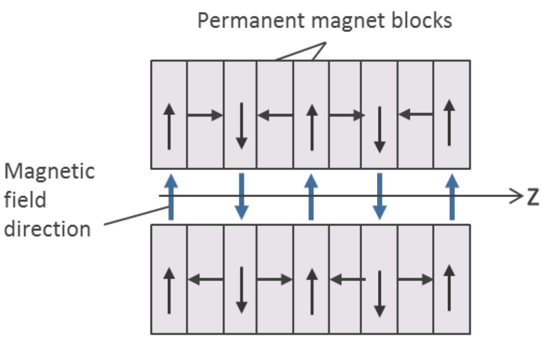
$$\text{where} \quad K \equiv \frac{eB_0\lambda_u}{2\pi mc} = 0.9337 B_0(\text{T})\lambda_u(\text{cm})$$

- Smaller undulator period lengths – higher photon energies
- Higher undulator parameter K – higher photon flux and wider tuning range

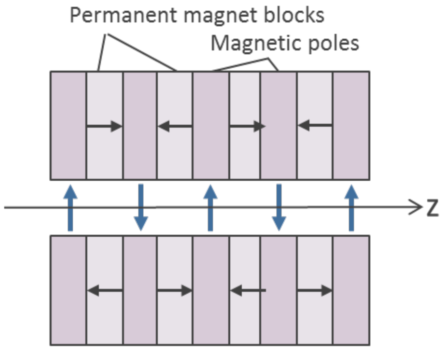
A need for undulator technology that provides max K at low period lengths

UNDULATOR MAGNETIC STRUCTURE

Permanent magnet structure

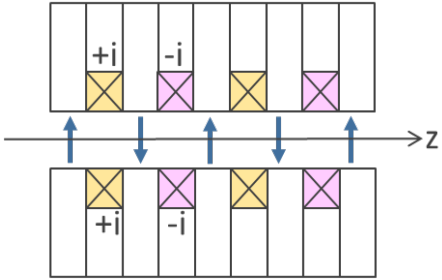


Hybrid structure

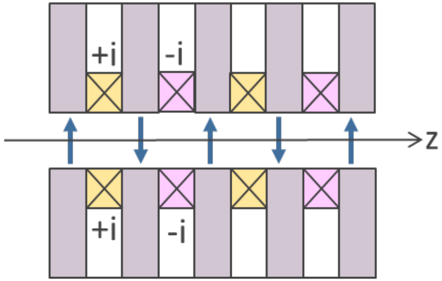


Magnetic field varies with gap

Electromagnet structure



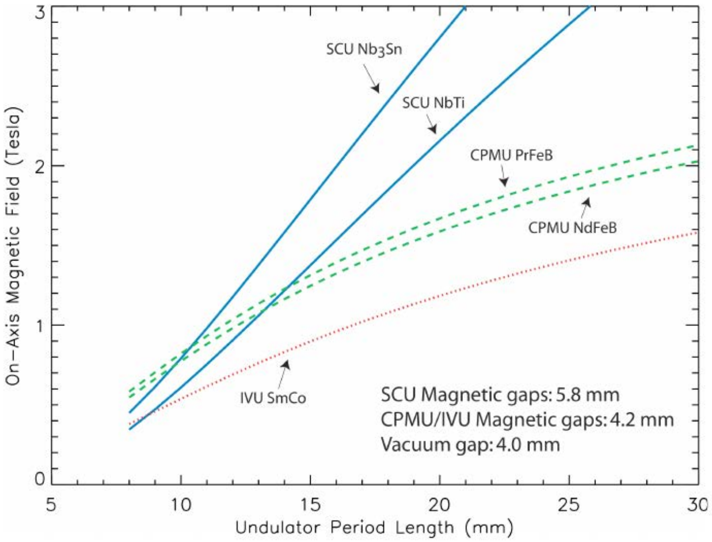
Electromagnet structure with magnetic poles



Magnetic field varies with electrical current

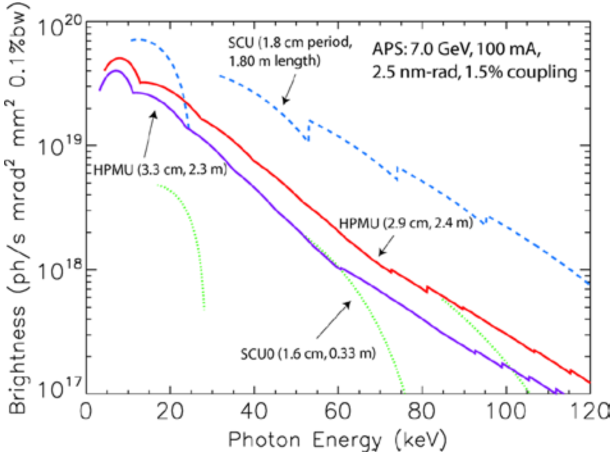
MAGNETIC FIELD OF VARIOUS INSERTION DEVICE TECHNOLOGIES

- 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

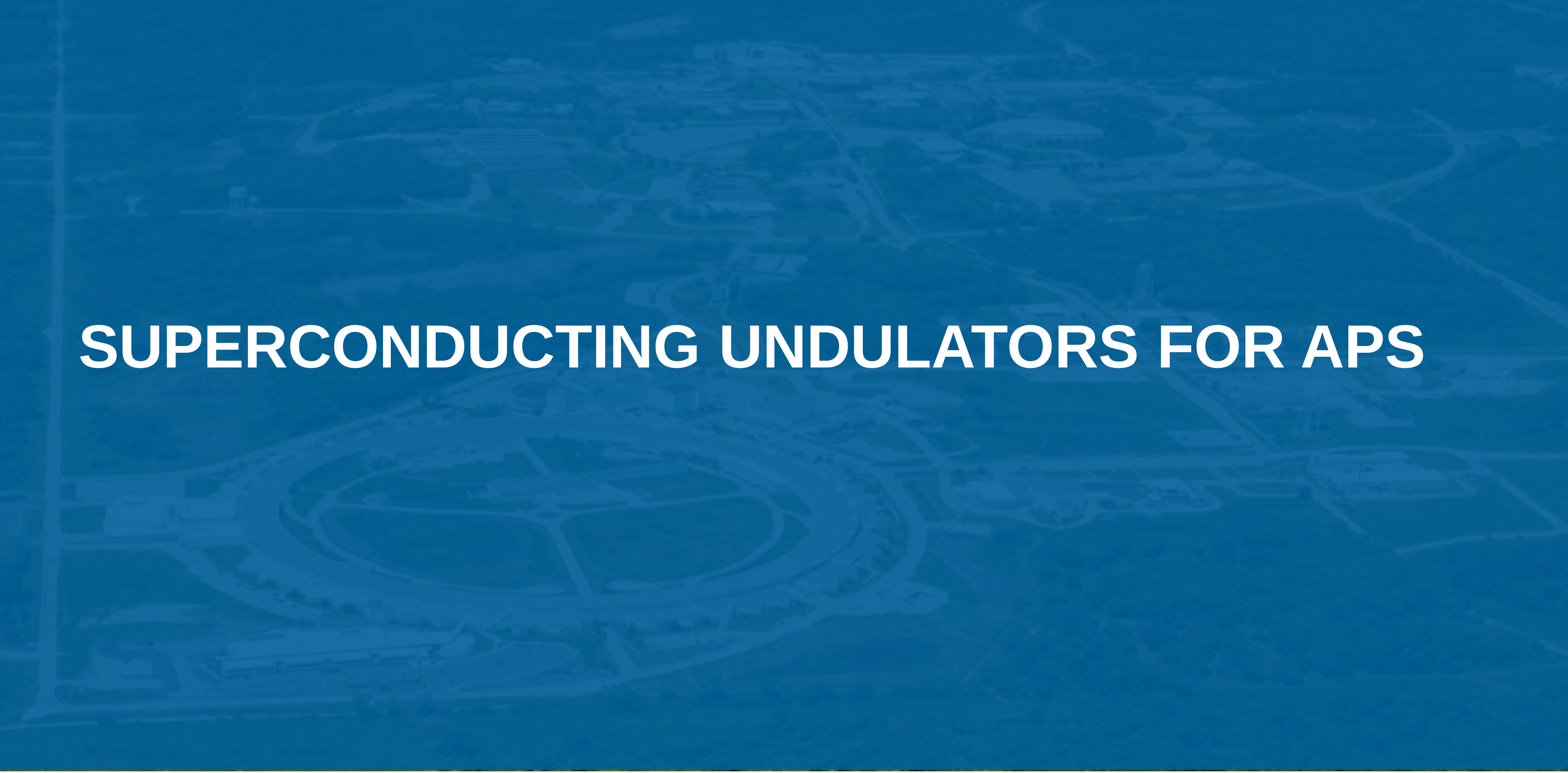


Calculated on-axis magnetic fields of two cryogenic permanent magnet undulators (CPMUs), two superconducting undulators (SCUs) and on in-vacuum undulator (IVU) for a vacuum gap of 4.0 mm for period length from 8 mm to 30 mm.

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.

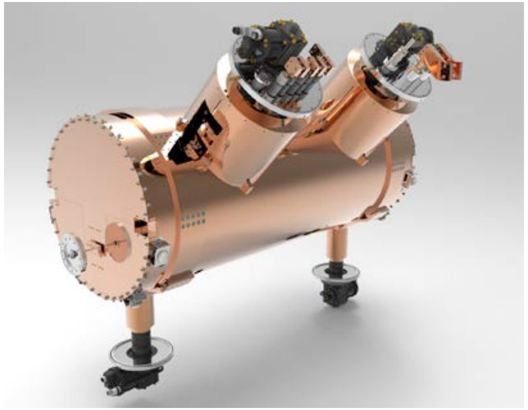


SUPERCONDUCTING UNDULATORS FOR APS

SCU LAYOUT

Assembled cryostat.

Inside the SCU vacuum vessel.

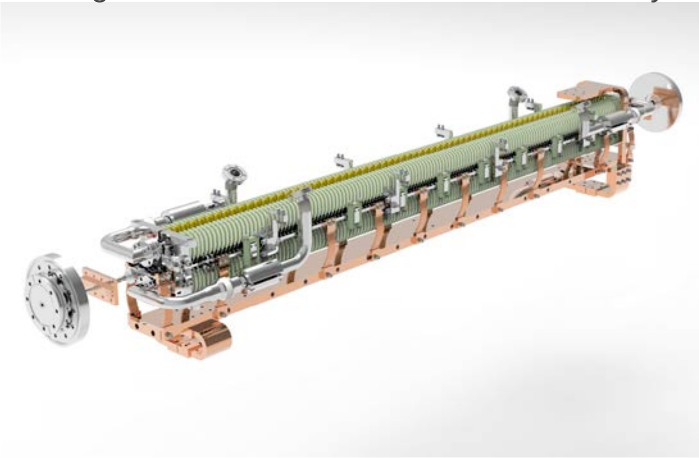


SCU cold mass.

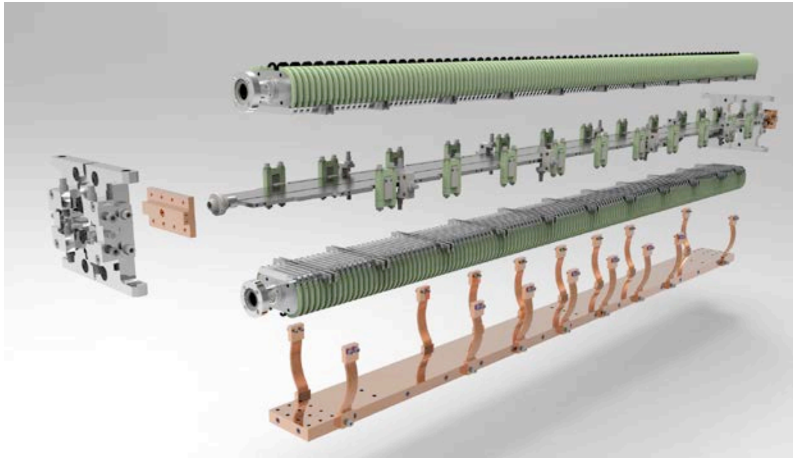
- SCU cryostat consists of vacuum vessel, thermal shield and a cold mass
- Cooling is provided by cryocoolers
- Closed-loop LHe circuit

PLANAR SCU MAGNET

Magnet – beam vacuum chamber assembly.



Magnet cores and beam vacuum chamber.



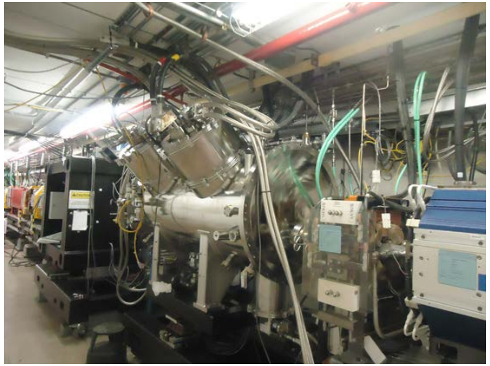
- A two-core SCU magnet structure
- LHe is contained in a tank connected with the magnet
- NbTi coils are cooled indirectly with LHe passing through channels in the magnet cores
- Beam chamber is thermally isolated from the magnet, and cooled independently

SCU18-1 (SCU1) AND SCU18-2

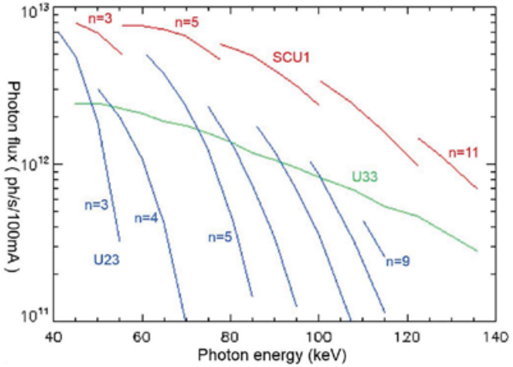
- Two similar undulators, SCU18-1 and SCU18-2, were completed and installed on APS storage ring over the last three years
- The SCU18-1 has been in operation since May 2015 and SCU18-2 started operation in September 2016

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.

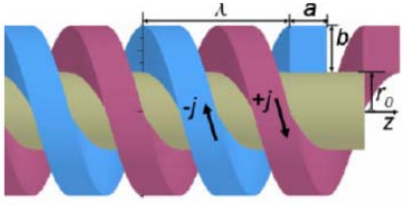


Measured SCU18-1 tuning curves in comparison with those of hybrid undulator U33 (Undulator A) and undulator U23.

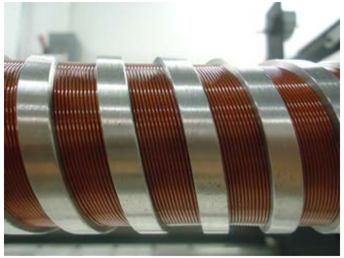
HELICAL SCU FOR APS

- 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

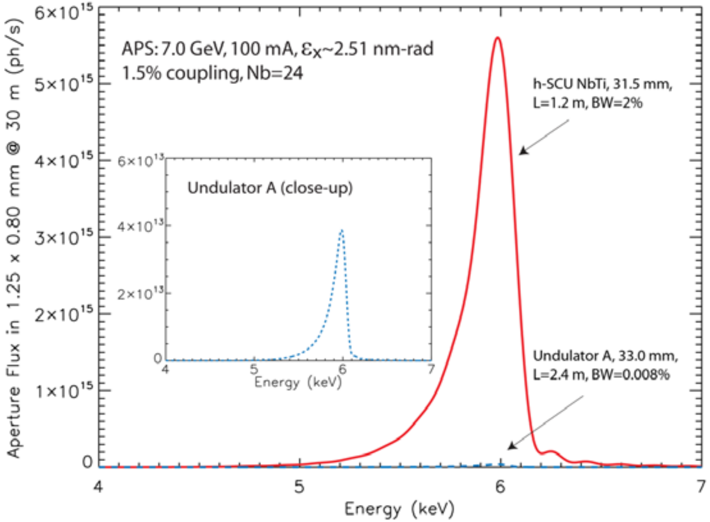
Parameter	HSCU
Cryostat length (m)	1.85
Magnetic length (m)	1.2
Undulator period (mm)	31.5
Magnetic bore diameter (mm)	31.0
Beam vacuum chamber vertical aperture (mm)	8
Beam vacuum chamber horizontal aperture (mm)	26
Undulator peak field Bx=By (T)	0.4
Undulator parameter Kx=Ky	1.2



Magnetic model of HSCU.



HSCU prototype coil winding.

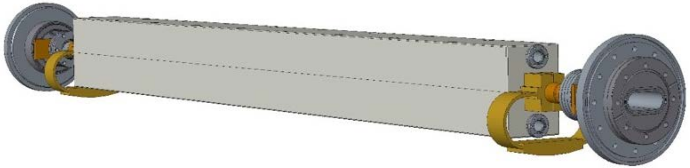


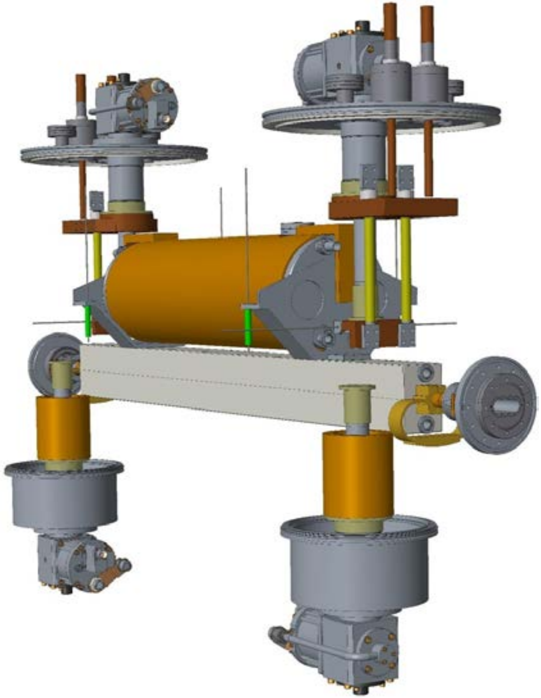
Calculated photon spectrum of helical SCU.

HSCU COLD MASS

HSCU magnet core

HSCU magnet assembly

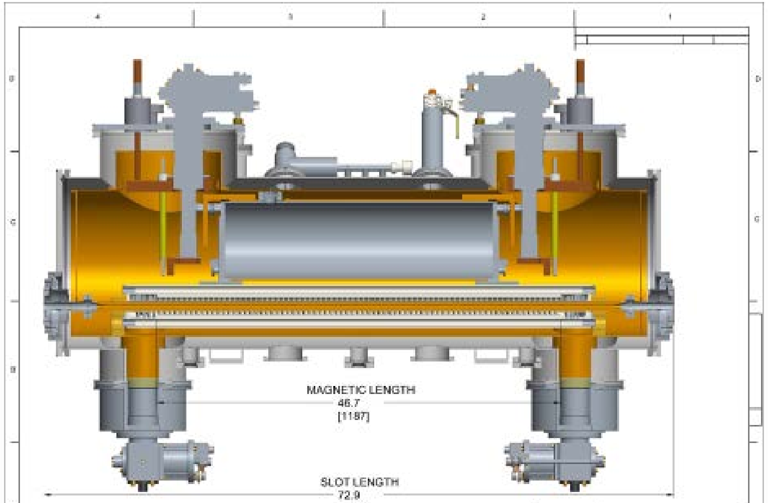


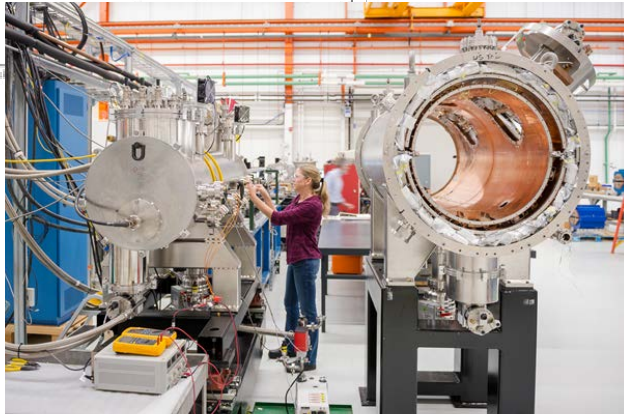


Four 4.2 K cryocoolers provide excess cooling capacity. Vertical orientations improve maintenance access and performance.

HSCU CRYOSTAT

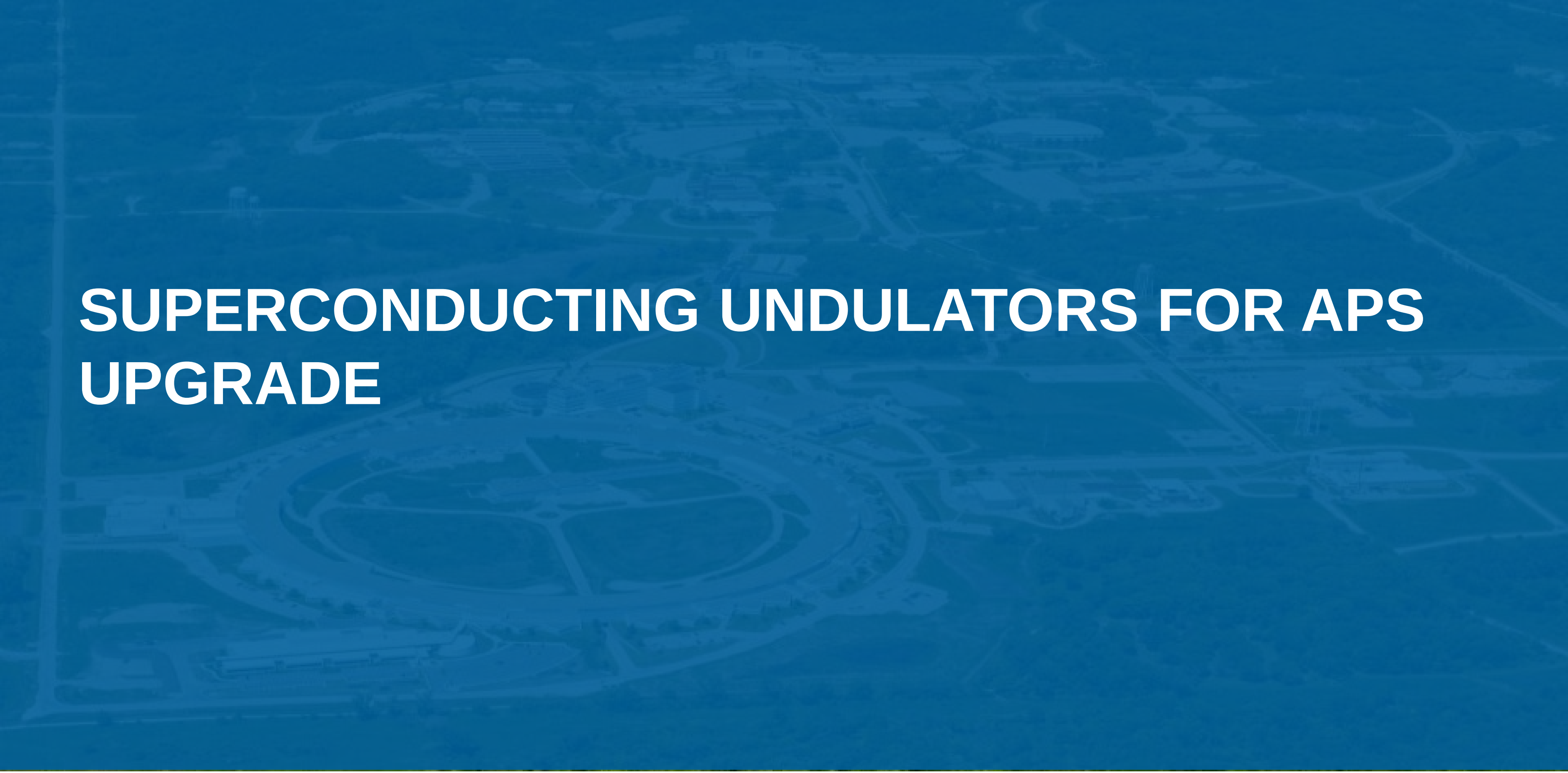
- One thermal shield
- Four RDK415D cryocoolers
- Two temperature stages
- Reduced diameter of the vacuum vessel
- Vertical turrets
- Standard flanges for the end covers
- Simplified design of He filling port





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

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



SUPERCONDUCTING UNDULATORS FOR APS UPGRADE

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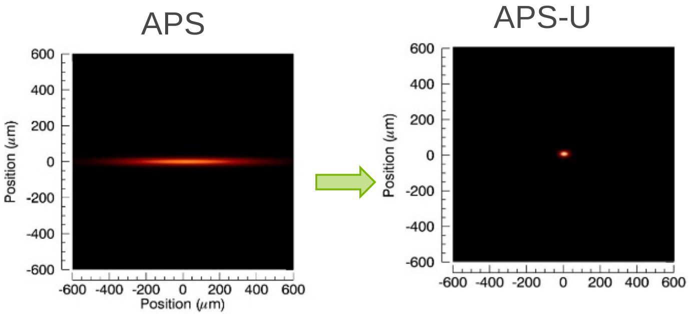
SUPERCONDUCTING UNDULATORS FOR APS UPGRADE: BUILDING A WORLD LEADING HARD X-RAY FACILITY

- 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

Aerial view of the APS



- Superconducting undulators for APS Upgrade
  - Planar SCUs:
    - Two undulators (1.8-m long each) with a phase shifter in a long cryostat – two locations
    - Two undulators (1.5-m long each) with a canting magnet in a long cryostat – two locations
    - Undulator periods are 18.5 mm and 16.5 mm for generating high energy x-rays
  - Variably polarizing SCU:
    - SCAPE

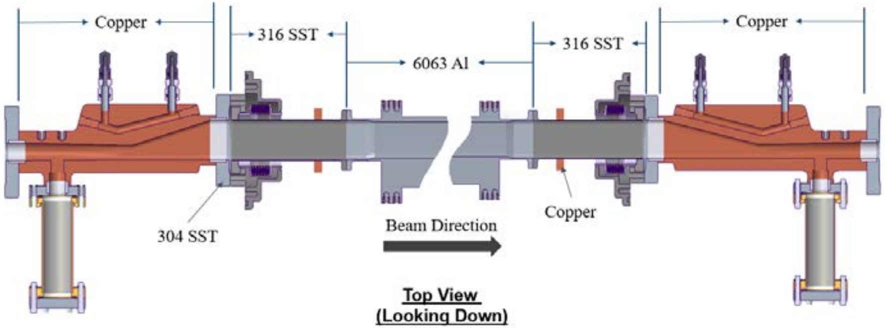
Design model of APS-U straight section with an SCU

SCU MAGNET DESIGN

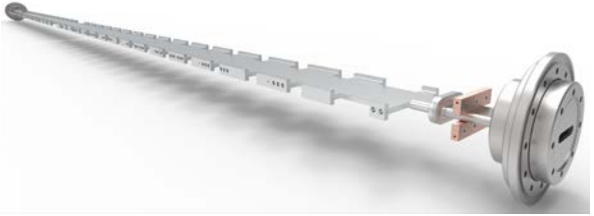
- Magnet design is based on a proven design of existing SCU magnets:
  - long central core with a channel for LHe
  - proven winding scheme with turn-around pins
- The APS-U design is simpler than the APS design:
  - with the poles integrated into the core and side blocks
  - tiny screws or pins needed to hold magnetic poles, are eliminated
- Fabrication is challenging:
  - From 1.5-m cores to 1.9-m cores without compromising on precision
- Design is complete, fabrication has been started by two vendors

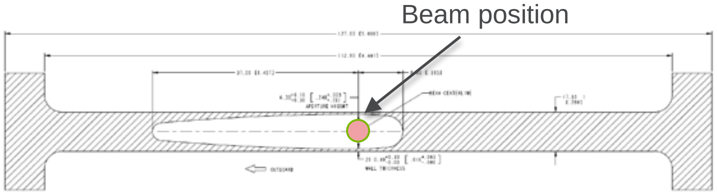
SCU BEAM CHAMBER DESIGN

- Design is based on experience of fabricating and utilizing beam chambers for existing SCUs:
  - Aperture 6.3 mm (H) x 45 mm (W) was determined through an optimization study
  - Outboard side of extrusion has been optimized to allow all bending magnet radiation to pass through the vacuum chamber.
  - Machined chamber has a minimum wall thickness of 400 microns across ~4.43m
- Design is complete. Extrusion is received. Full-length test machining of a thin-wall chamber is successfully done



Vacuum Chamber Extrusion Sample from Cardinal Aluminum Company

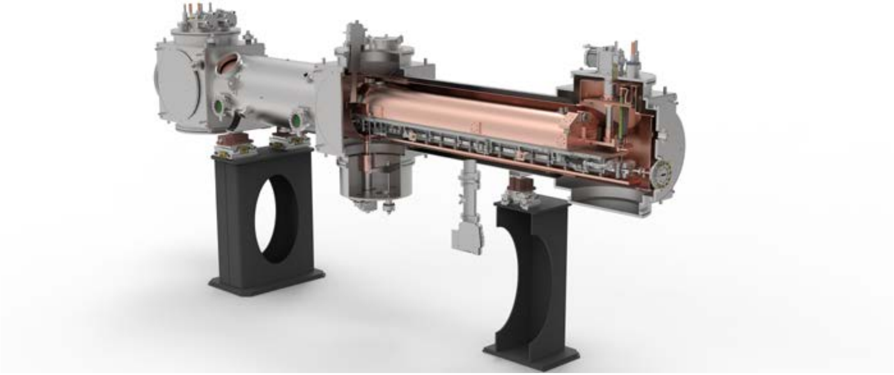


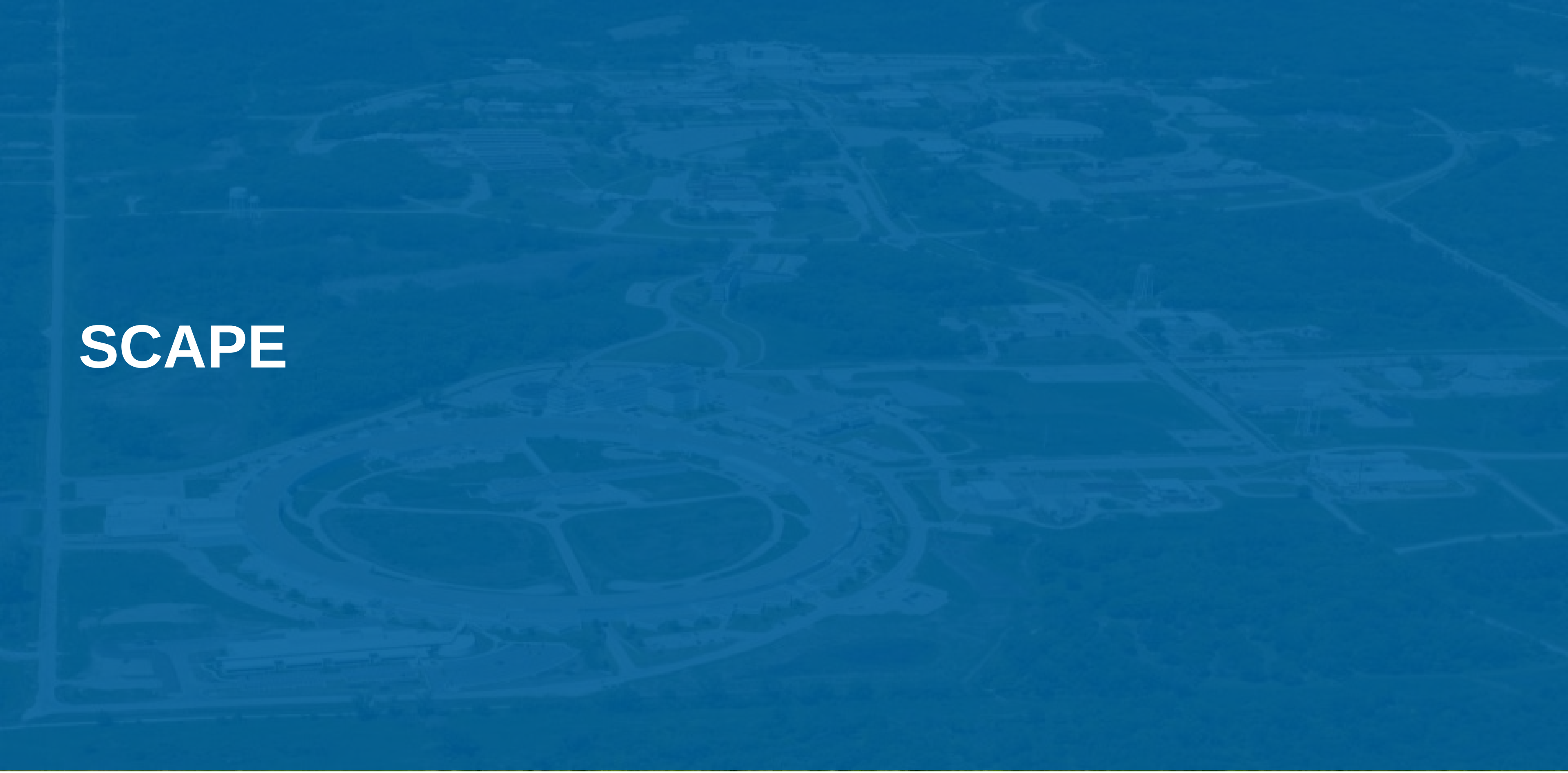


Machined Cross Section

SCU CRYOSTAT DESIGN

- Design is based on a proven design of the 2nd generation 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
- Main cryostat package (vacuum vessel, thermal shield, LHe tank) is in fabrication

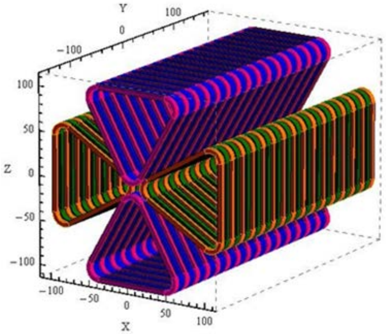




SCAPE

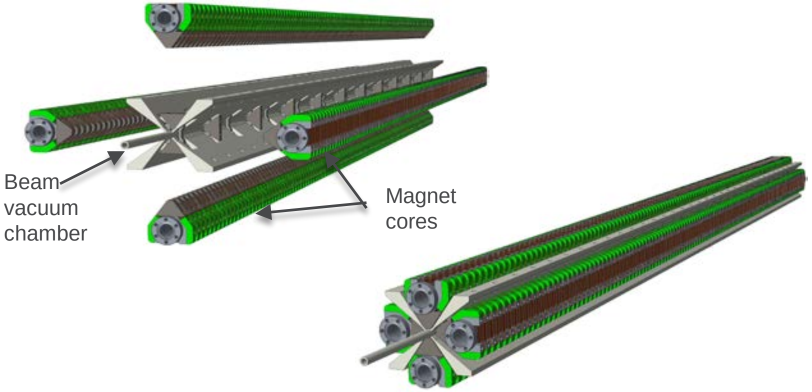
VARIABLY POLARIZING SCU— SCAPE

- 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



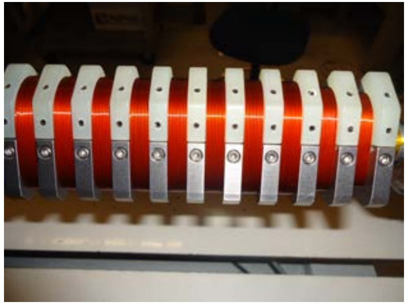
Concept of SCAPE: a universal SCU with four planar superconducting coil structures. A beam chamber is not shown.

SCAPE 3d design model



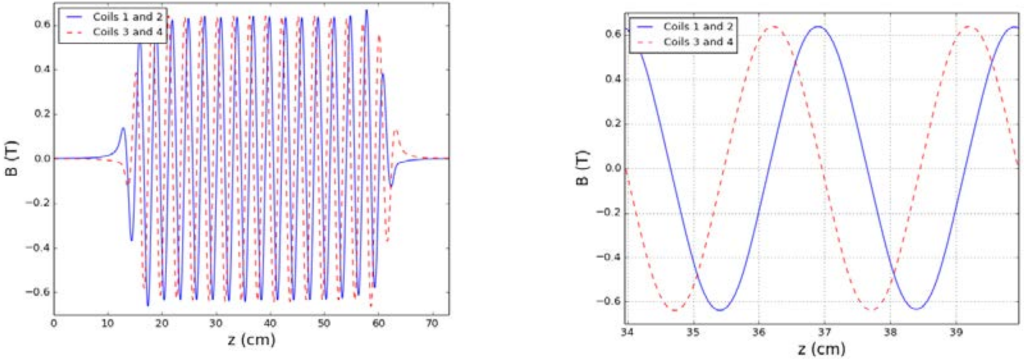
SCAPE PROTOTYPE

- 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

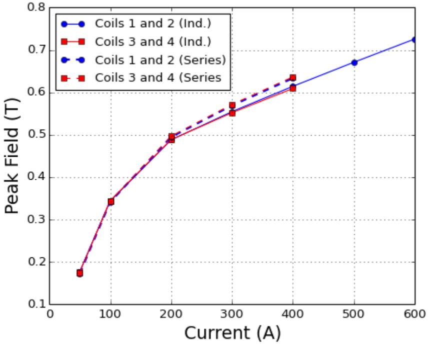

SCAPE core winding


SCAPE mechanical structure

Measured field profiles

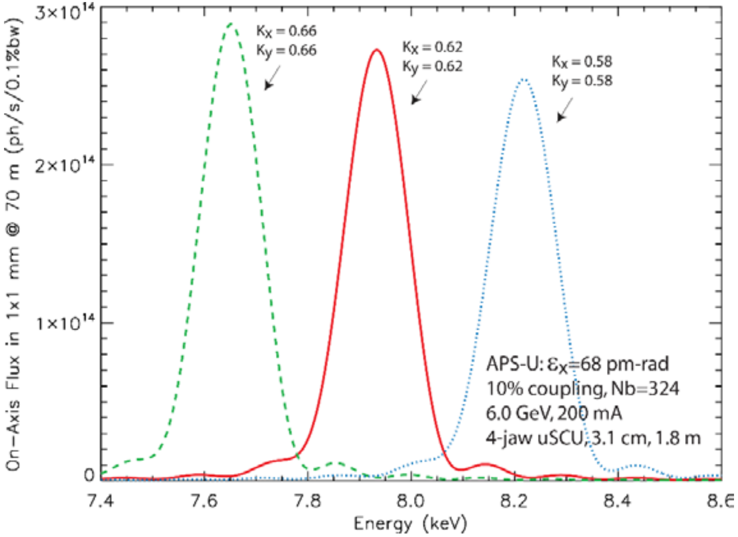


Excitation curves

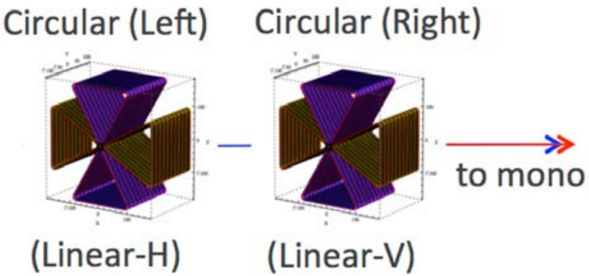


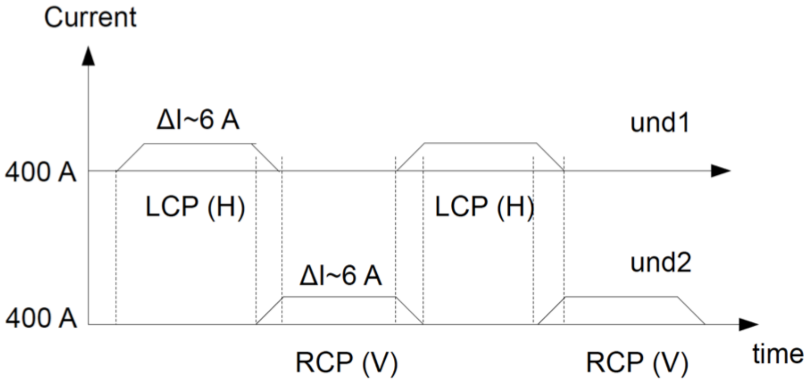
SCAPE OPERATION IN POLARIZATION SWITCHING MODE

- 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.



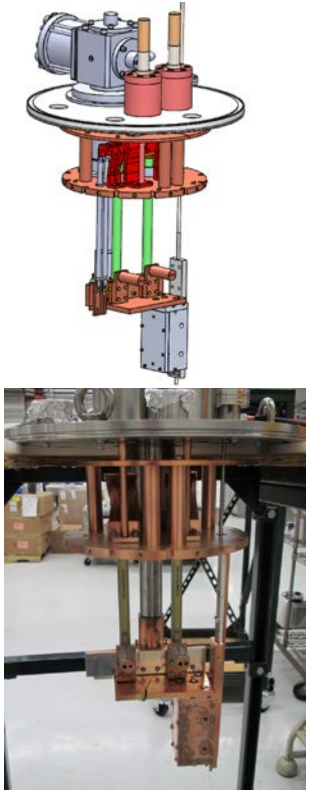


SCAPE operation in polarization switching mode.

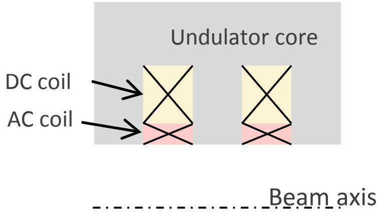
[1] D. Haskel, private communication, June 2018.

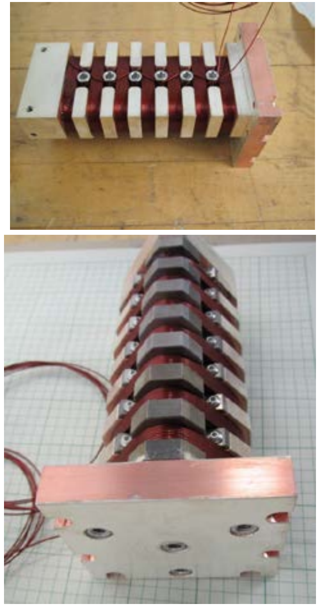
DEVELOPING FAST CURRENT-MODULATED SCAPE

- Strategy to decrease AC heating:
  - Divide conductor winding pack into DC part (constant current) and AC part (AC current)
  - Wind DC part with conventional conductor;
  - Wind AC part with AC-optimized conductor;
  - Study AC heating in a short prototype. Measure the AC heat load using a cryocooler.
  - Develop a technique to calculate AC heating.
  - Design a SCAPE prototype with a min AC heating.
  - Fabricate and test fast AC modulated SCAPE prototype.
- A two–year laboratory directed R&D project on fast current modulated SCAPE is in progress



Design model (top) and a photo (bottom) of experimental setup based on a cryocooler, to measure AC heating in SCAPE magnet.

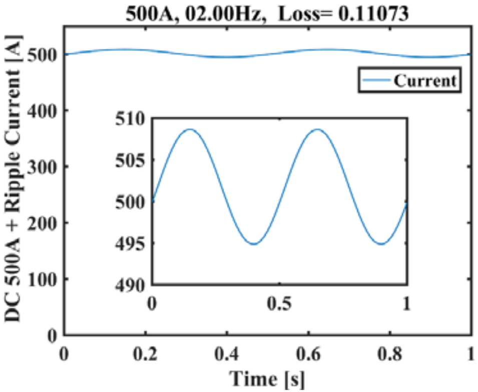


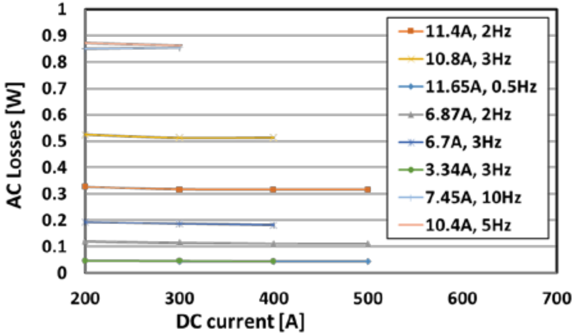


SCAPE magnet 3.5-period model.

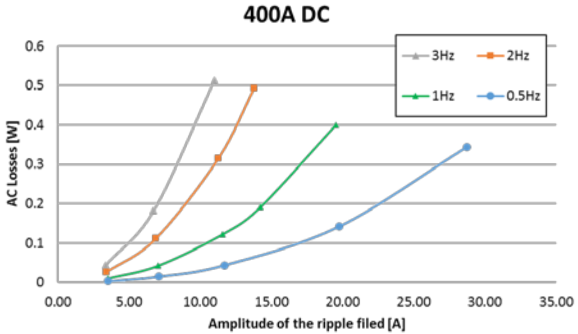
AC LOSSES IN SCAPE COIL – FIRST RESULTS

AC losses in SCAPE coil wound with a ‘standard’ superconductor.

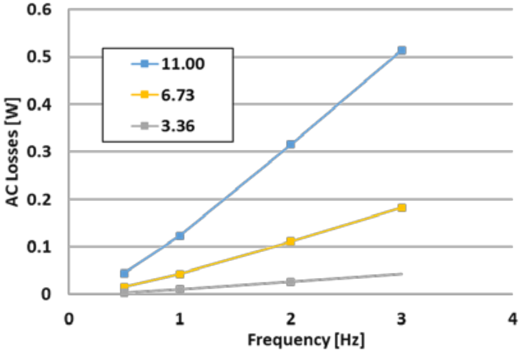




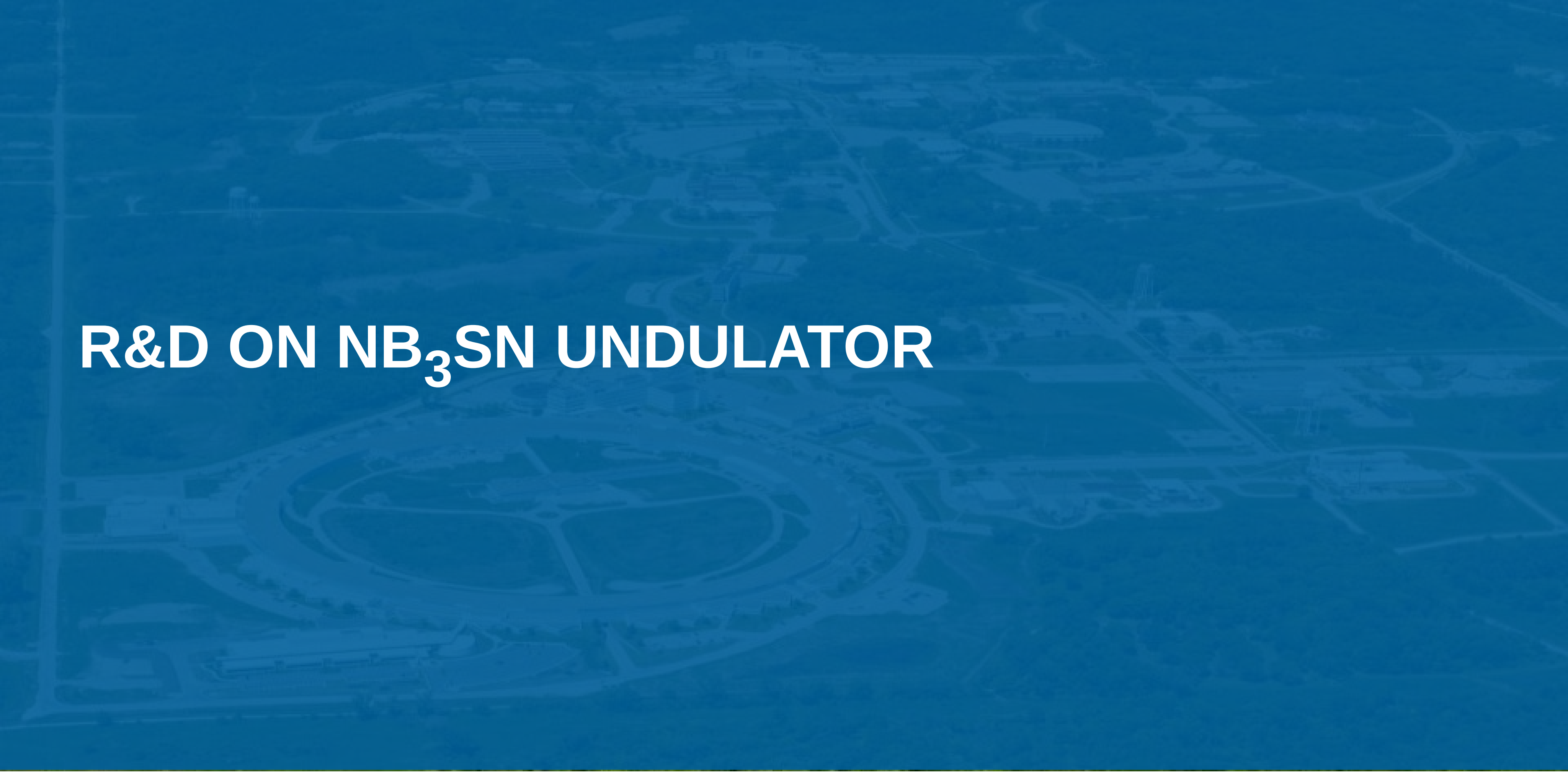
The losses are independent from the DC current



The losses quadratically depend on the AC ripple field amplitude



The losses linearly depend on the AC ripple field frequency



R&D ON NB$_3$SN UNDULATOR

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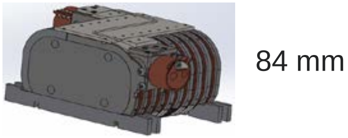
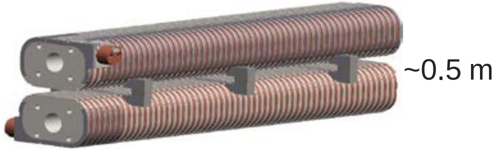
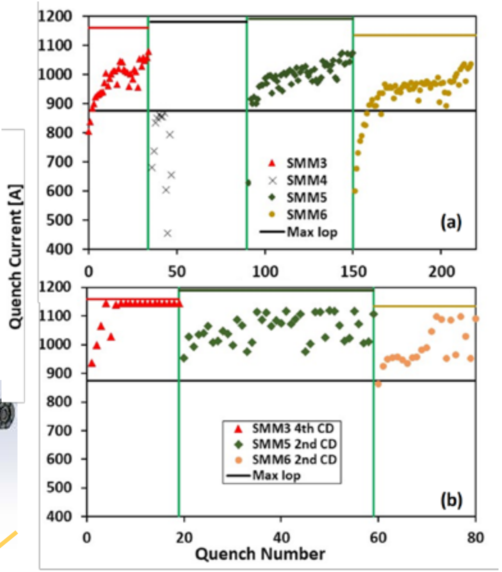
NB$_3$SN UNDULATOR FOR APS

- A 3-year project
- Goal: Develop, build and install on the APS ring a two-magnet Nb$_3$Sn undulator (in a long 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
  - 0.5-m long prototype
  - Full scale magnet and cryostat
  - Undulator assembly, test, installation on the APS

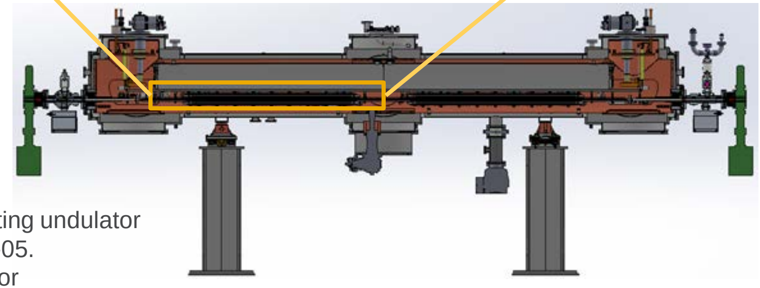




Training of short models



For comparison: max training current of NbTi undulator is about 650A.



Based on magnetic measurements of magnet model #3: the Nb$_3$Sn undulator will generate about 25% higher magnetic field than the NbTi one

I. Kesgin et al., “Development of a Nb$_3$Sn superconducting undulator for the Advanced Photon Source,” poster Wed-Af-Po316-05.
E. Barzi et al., “Heat treatment studies of Nb$_3$Sn wires for superconducting planar undulators,” poster Wed-Af-Po3.21-12.

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
- EXISTING AND NEW LIGHT SOURCES WILL BENEFIT FROM SUPERCONDUCTING UNDULATORS

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