DEVELOPMENT OF SUPERCONDUCTING UNDULATORS AT THE ADVANCED PHOTON SOURCE

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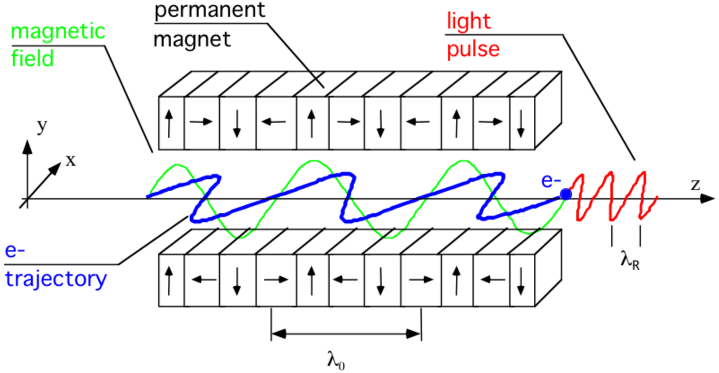
2018 Midwest Regional Workshop on Accelerator Stewardship Test Facility Program,
ANL, December 6, 2018

SCOPE

- Why superconducting undulators?
- Making superconducting undulators work
- Superconducting undulators for the APS Upgrade
- R&D on Nb_3Sn undulator
- Conclusions

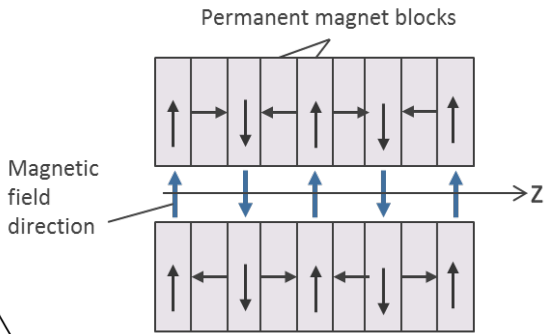
WHY SUPERCONDUCTING UNDULATORS

UNDULATOR MAGNETIC STRUCTURE

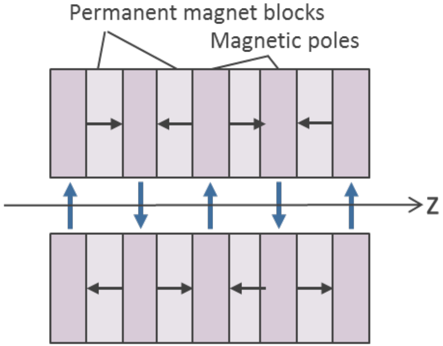


Centre Laser Infrarouge d'Orsay:
http://clio.lcp.u-psud.fr/clio_eng/FELrad.html

Permanent magnet structure

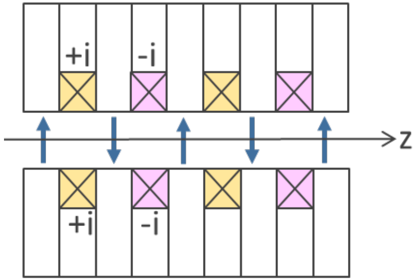


Hybrid structure

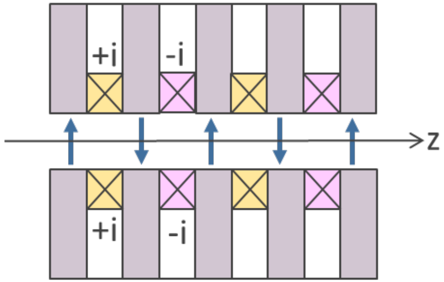


Magnetic field varies with gap

Electromagnet structure



Electromagnet structure with magnetic poles



Magnetic field varies with electrical current

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SUPERCONDUCTING UNDULATORS

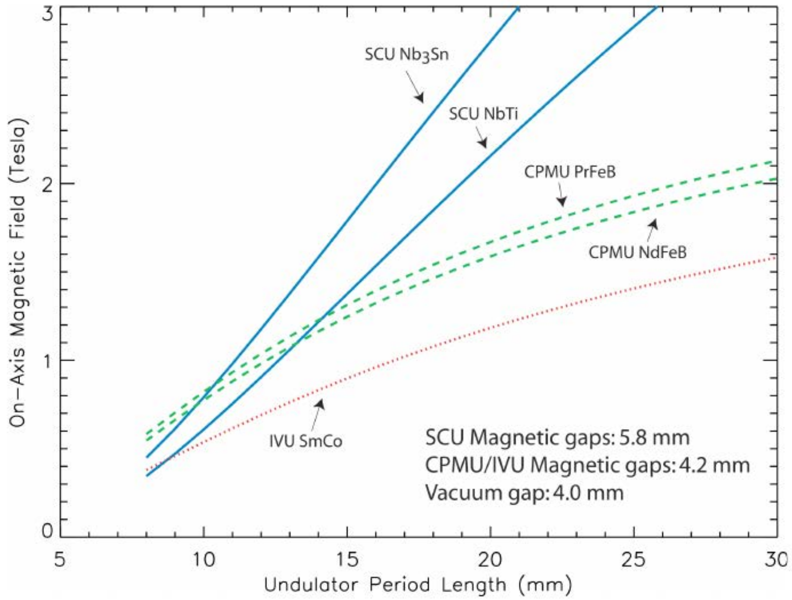
- A superconducting undulator is an electromagnetic undulator that employs high current superconducting windings for magnetic field generation -

  total current in winding block is up to 10-20 kA-turns → high peak field

  poles made of magnetic material enhance field further → coil-pole structure (“super-ferric” undulator)

- Superconducting technology compared to conventional pure permanent magnet or hybrid insertion devices (IDs) offers:
  - higher peak field for the same period length
  - or smaller period for the same peak field

MAGNETIC FIELD OF VARIOUS INSERTION DEVICE TECHNOLOGIES

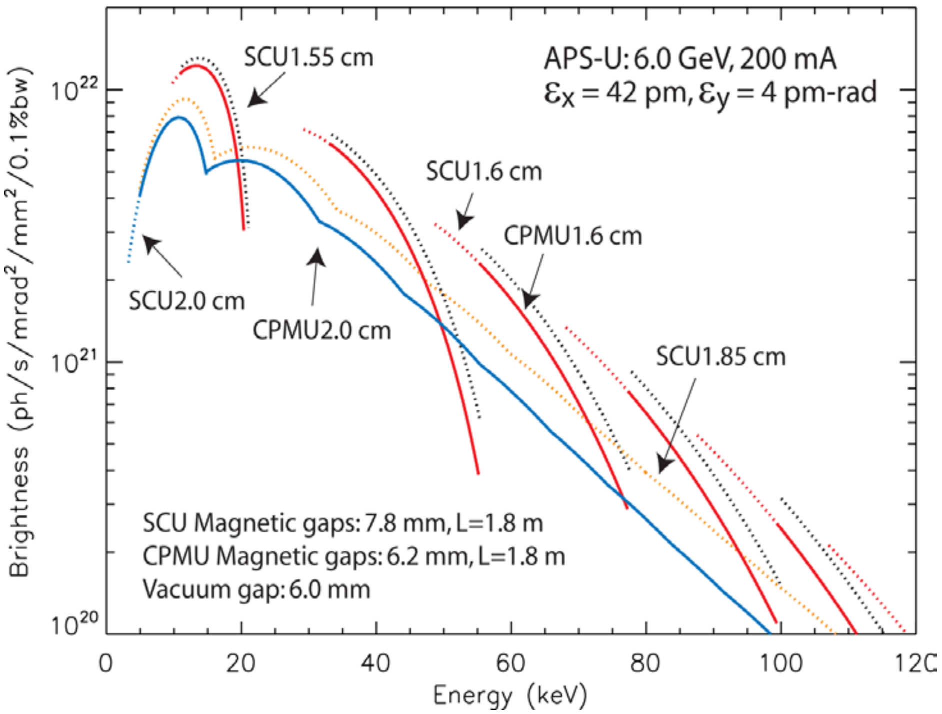


Calculated on-axis magnetic fields of two cryogenic permanent magnet undulators (CPMUs), two superconducting undulators (SCUs) and on in-vacuum undulator (IVU) for a vacuum gap of 4.0 mm for period length from 8 mm to 30 mm.

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.

UNDULATOR TUNING CURVES

Brightness tuning curves for various undulators at the APS Upgrade



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.

WHY A SUPERCONDUCTING TECHNOLOGY-BASED UNDULATOR ?

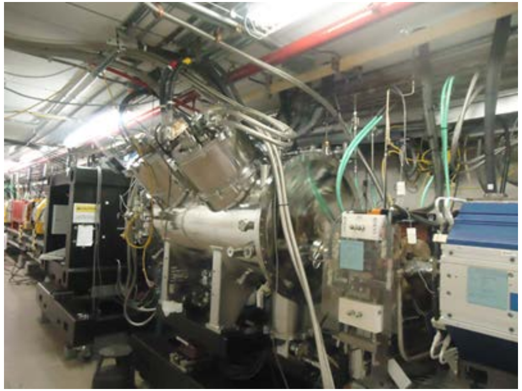
- Superconducting technology-based undulators outperform all other technologies in terms of peak magnetic field and, hence, energy tunability of the radiation

- Superconducting technology opens a new avenue for insertion devices

MAKING SUPERCONDUCTING UNDULATORS WORK

DEVELOPMENT OF SUPERCONDUCTING UNDULATORS AT THE APS

- SCU0:
  - 16-mm period length
  - 0.33-m long magnet
  - In operation: Jan2013-Sep2016 [1,2]
- SCU1(SCU18-1):
  - 18-mm period length
  - 1.1-m long magnet
  - In operation: since May2015 [3]
- 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:
  - 31.5-mm period length
  - 1.2-m long magnet
  - Installed in Dec2017
- R&D projects:
  - HTS SCU – completed
  - SCAPE – in progress
  - Nb_3Sn undulator – in progress

[1] E. Gluskin, "Development and Performance of Superconducting Undulators at the Advanced Photon Source," Synchrotron Radiation News, 28 (3), pp. 4-8, 2015.

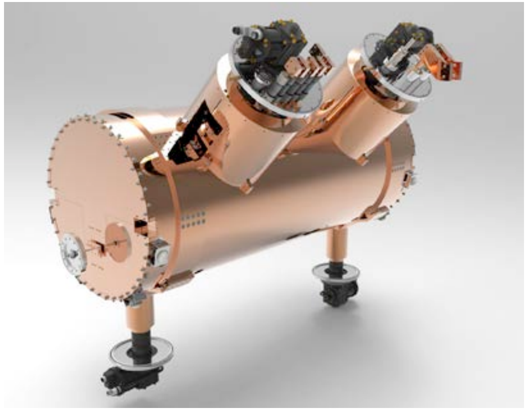
[2] Y. Ivanyushenkov et al., "Development and operating experience of a short-period superconducting undulator at the Advanced Photon Source," Physical Review Special Topics- Accelerators and Beams, 18, 040703 (2015).

[3] Y. Ivanyushenkov et al., "Development and operating experience of a 1.1-m-long superconducting undulator at the Advanced Photon Source," Physical Review Accelerators and Beams, 20, 100701 (2017).

SCU LAYOUT

Assembled cryostat.

Inside the SCU vacuum vessel.

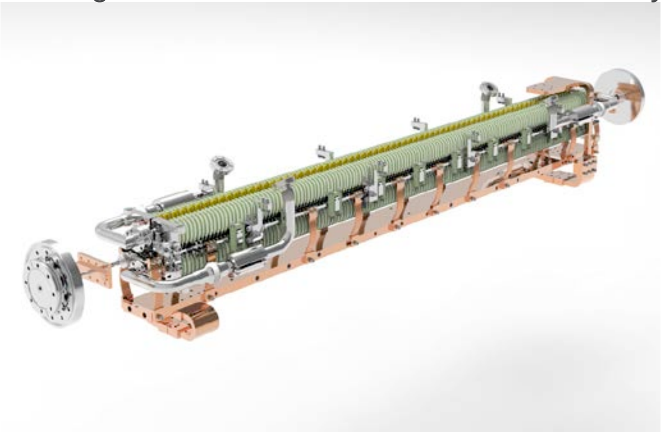


SCU cold mass.

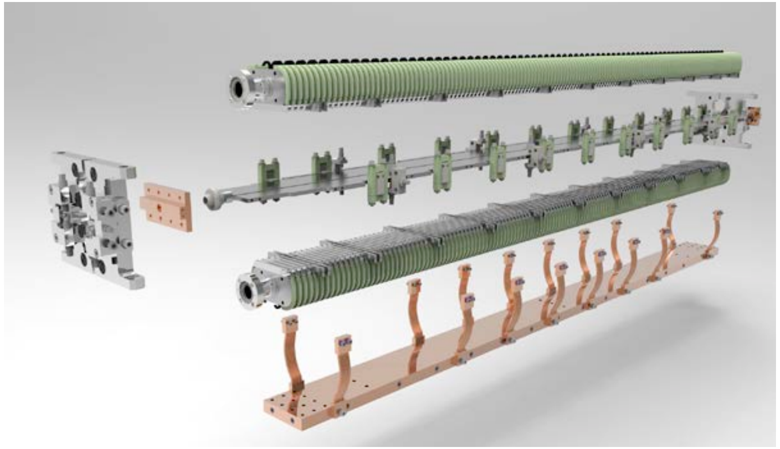
- SCU cryostat consists of vacuum vessel, thermal shield and a cold mass
- Cooling is provided by cryocoolers
- Closed-loop LHe circuit

PLANAR SCU MAGNET

Magnet – beam vacuum chamber assembly.



Magnet cores and beam vacuum chamber.



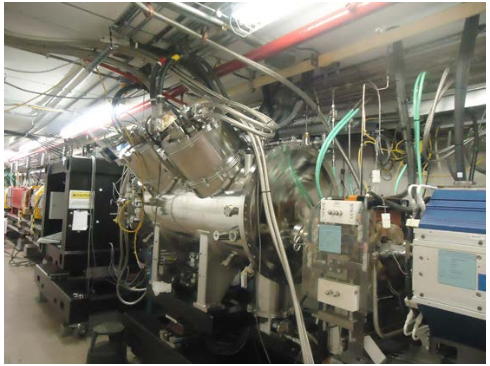
- A two-core SCU magnet structure
- LHe is contained in a tank connected with the magnet
- NbTi coils are cooled indirectly with LHe helium passing through channels in the magnet cores
- Beam chamber is thermally isolated from the magnet, and cooled independently

SCU18-1 (SCU1) AND SCU18-2

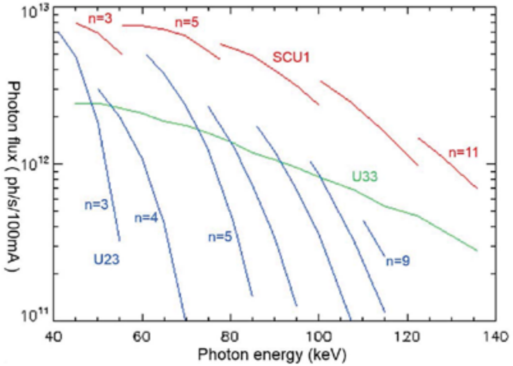
- Two similar undulators, SCU18-1 and SCU18-2, were completed and installed on APS storage ring over the last three years
- The SCU18-1 has been in operation since May 2015 and SCU18-2 started operation in September 2016

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.



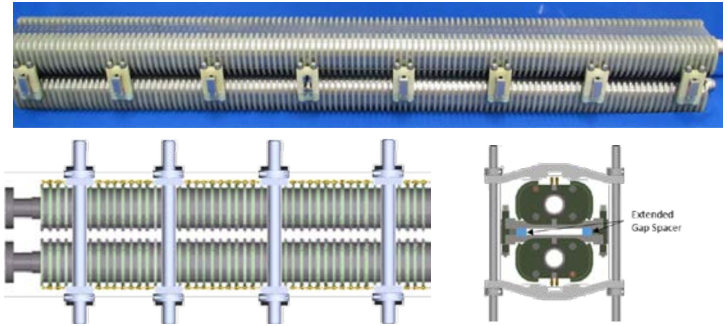
SCU18-2 in Sector 6 of the APS ring.



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

ACHIEVING HIGH FIELD QUALITY

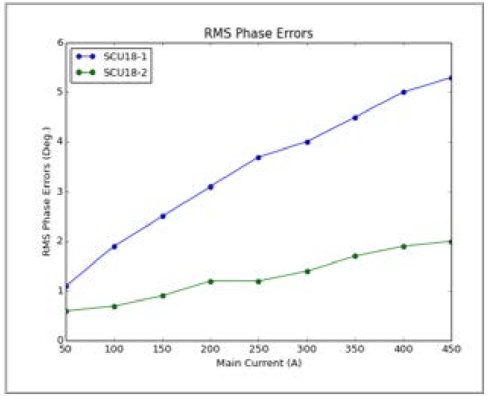
- The SCU field quality depends on:
  - Precise machining of a magnet former [1]
  - Quality of conductor winding [2]
  - Uniformity of the magnetic gap
- A dedicated R&D program was targeted at achieving a very uniform gap [3]
  - A gap correction scheme was developed and implemented using a set of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



Planar SCU magnetic assembly with a concept of gap correction.

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

* without gap correction



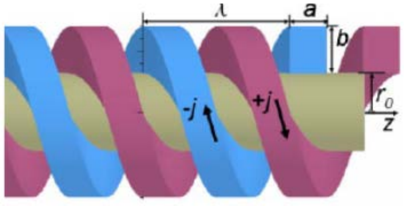
Measured phase errors in SCU18-1 and SCU18-2.

[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.

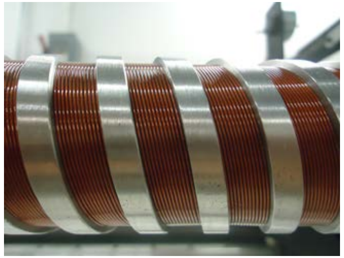
HELICAL SCU FOR APS

- SCU technology offers the possibility of building circular polarizing helical undulators
- We have recently completed a helical SCU (HSCU) for the APS. The HSCU is now in operation in Sector 7
- X-ray photon correlation spectroscopy program at the APS will benefit from the increased brilliance provided by an HSCU

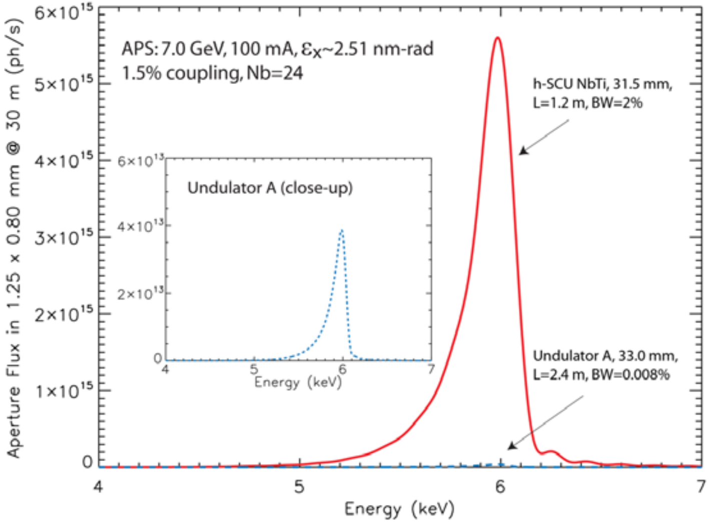
Parameter	HSCU
Cryostat length (m)	1.85
Magnetic length (m)	1.2
Undulator period (mm)	31.5
Magnetic bore diameter (mm)	31.0
Beam vacuum chamber vertical aperture (mm)	8
Beam vacuum chamber horizontal aperture (mm)	26
Undulator peak field Bx=By (T)	0.4
Undulator parameter Kx=Ky	1.2



Magnetic model of HSCU.



HSCU coil winding.

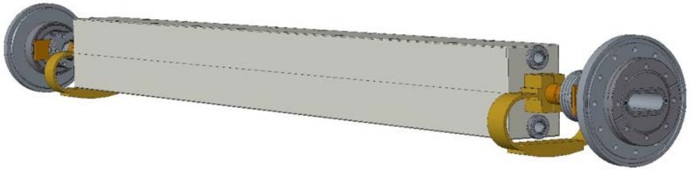


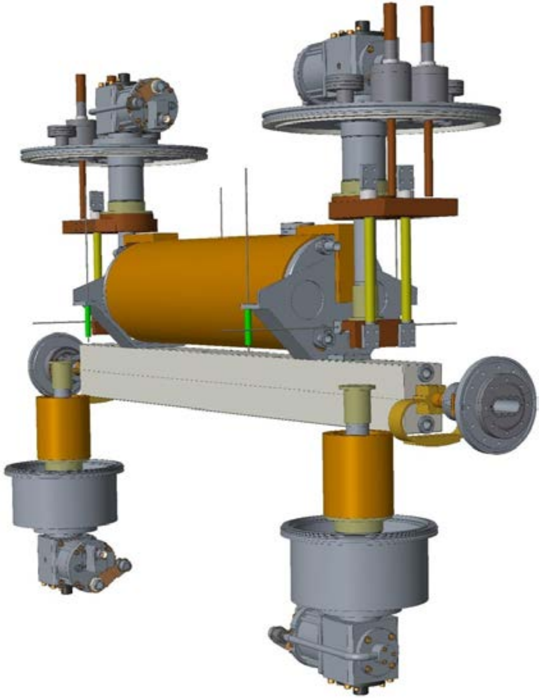
Calculated photon spectrum of helical SCU.

HSCU COLD MASS

HSCU magnet core

HSCU magnet assembly

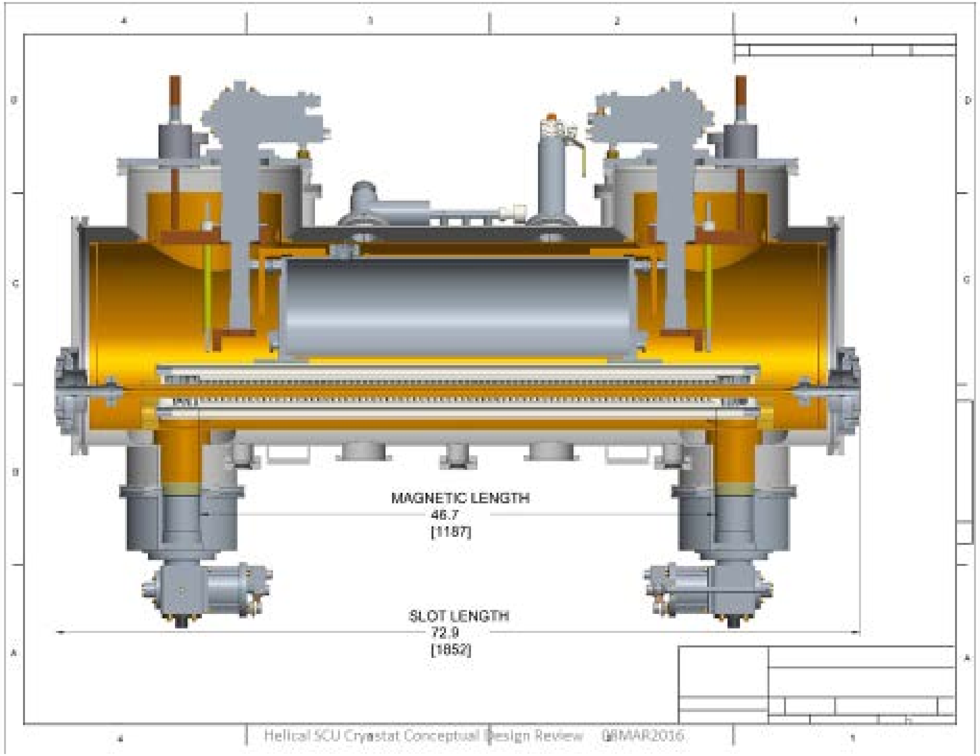




Four 4.2 K cryocoolers provide excess cooling capacity. Vertical orientations improve maintenance access and performance.

HSCU CRYOSTAT

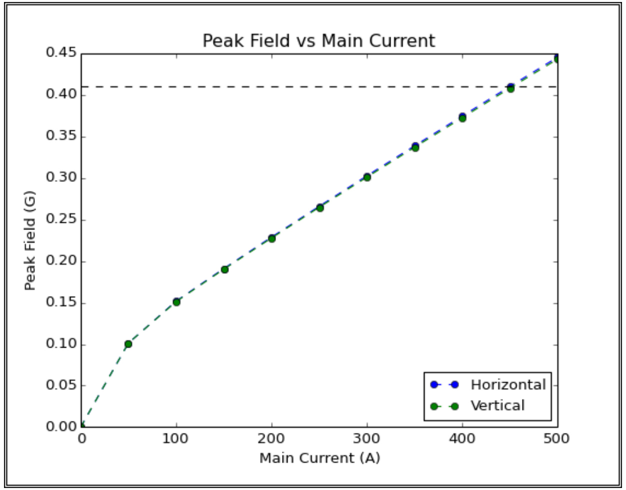
- One thermal shield
- Four RDK415D cryocoolers
- Two temperature stages
- Reduced diameter of the vacuum vessel
- Vertical turrets
- Standard flanges for the end covers
- Simplified design of He filling port

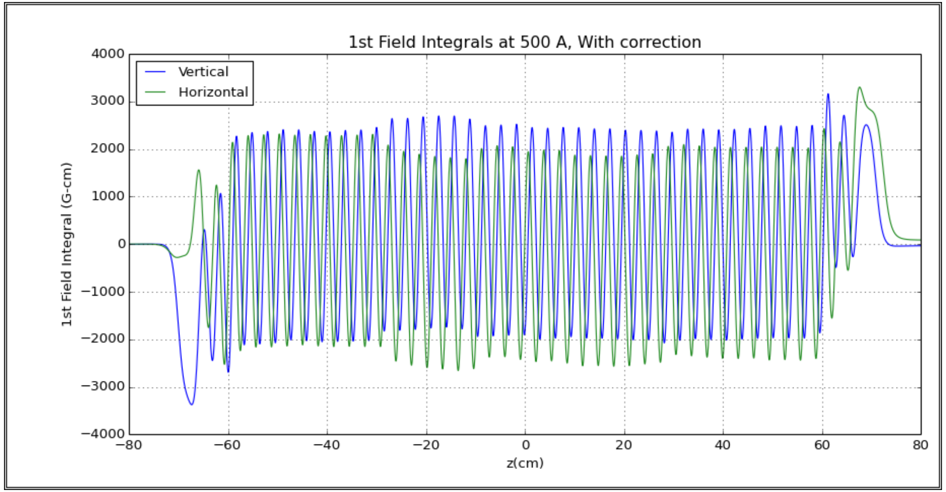


J. Fuerst et al., “A second-generation superconducting undulator cryostat for the APS,” Proceedings of CEC-ICMC 2017, Madison, 2017.

Y. Shiroyanagi et al., “Thermal Analysis of a Helical Superconducting Undulator Cryostat”, 2LPo2J-01, ASC2018, Seattle, 2018.

HSCU FIELD





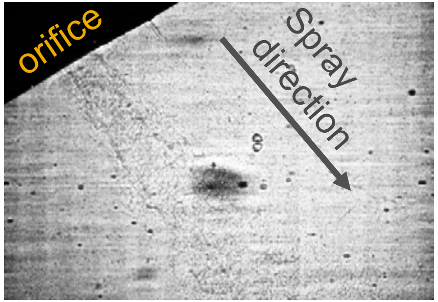
	SCU0	SCU1	HSCU
Photon energy at 1st harmonic (keV)	20-25	12-25	6-12
Period length (mm)	16	18	31.5
Magnetic gap or winding radius (mm)	9.5	9.5	15.6
Magnetic length (m)	0.330	1.075	1.2
Cryostat length (m)	2.063	2.063	1.85
Peak design magnetic field (T)	0.38 (200 A) 0.65 (500 A)	0.96 (450 A)	0.45 (500 A)

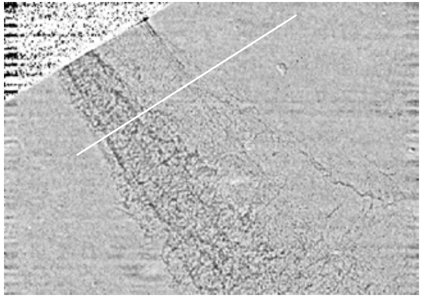
SINGLE-PULSE X-RAY WHITE-BEAM IMAGING AT USING HSCU AT 7-ID
(PRESENTED BY STEFAN VOGT AT SRI 2018)

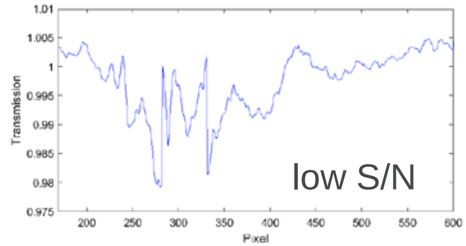
- Fuel-spray experiments require single-pulse (100 ps) white-beam to image high-speed, transient liquid jet/spray
- Undulator A @6 keV (15.5 mm gap): power density > 100 W/mm^2 10× more unwanted higher-energy x-rays
  - Requires harmonic rejection mirror that introduce artifacts.
- HSCU white beam @6 keV: low central power density <20 W/mm^2, NO need of a mirror.
  - 5× times beam intensity

Raw images | Normalized (transmission) | Line scans

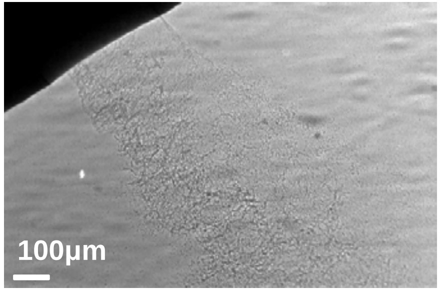
UA @ 6 keV
>100 W/mm^2 power
10× high-energy content
Need mirror
Intensity: 150/pixel

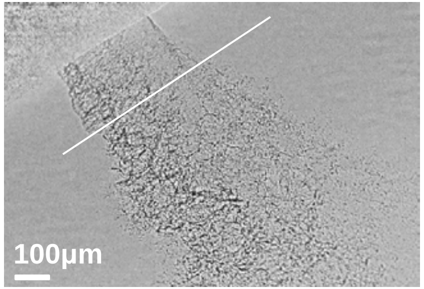


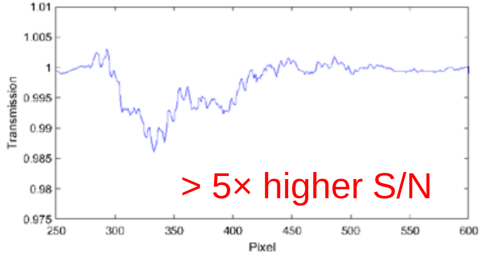




SCHU @ 6 keV
< 20 W/mm^2 power
Low high-energy content
No mirror needed
Intensity: 750/pixel







High image quality enables quantitative analysis!

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SUPERCONDUCTING UNDULATORS FOR APS UPGRADE

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

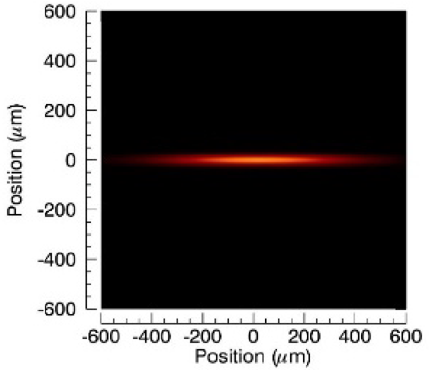
- New storage ring
  - 6 GeV multi-bend achromat (MBA) lattice
  - 200 mA current
  - Improved electron/photon stability

- New insertion devices
  - Incorporate SCUs on selected beamlines

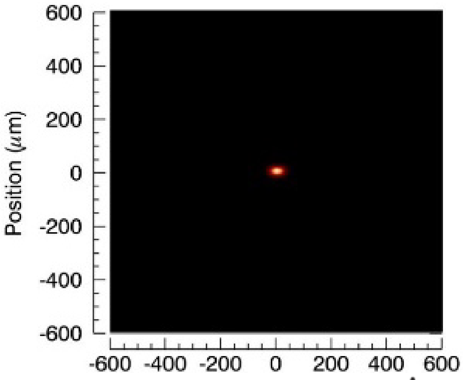
- New/upgraded front-ends
  - Common design for maximum flexibility

- Feature beamlines
  - Suite of beamlines designed for best-in-class performance

APS

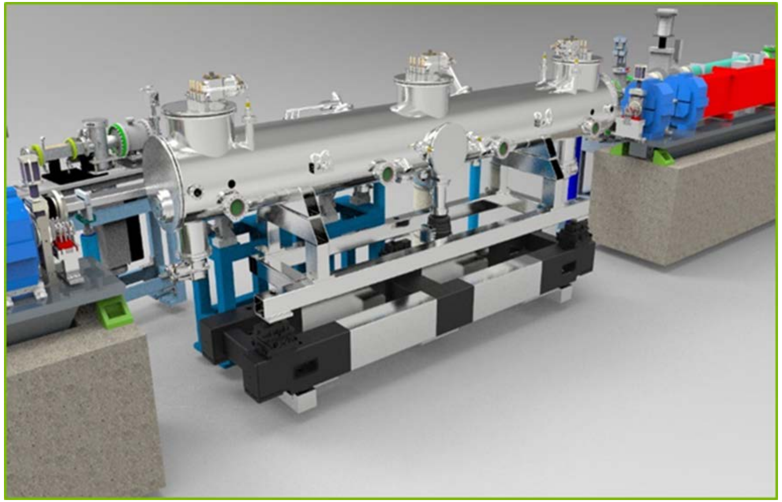


APS-U



SCUs FOR APS UPGRADE

- Planar SCUs:
  - Two undulators (1.8-m long each) with a phase shifter in a 4.8-m long cryostat – two locations
  - Two undulators (1.5-m long each) with a canting magnet in a long cryostat – two locations
  - Planned periods are 18.5 mm and 16.5 mm for generating high energy x-rays
  - One existing superconducting undulator located co-linear with a planar hybrid permanent magnet undulator (HPMU)
- Variably polarizing SCU:
  - SCAPE



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

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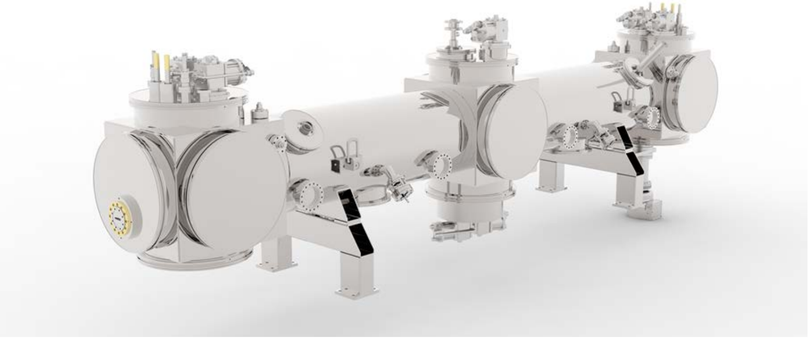
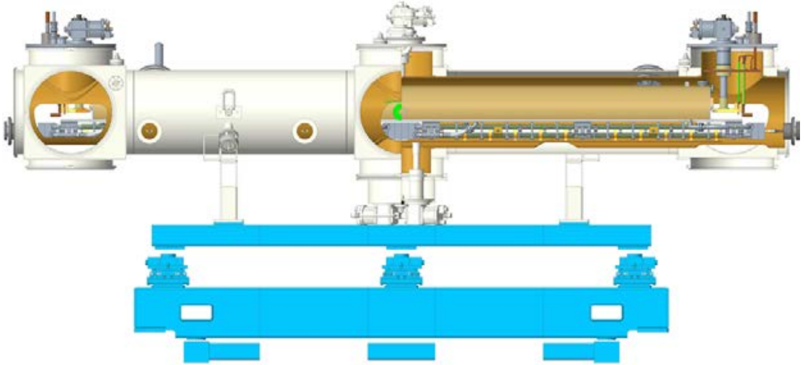
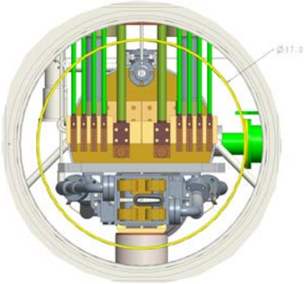
APS-U SCU CRYOSTAT DESIGN

- Design is based on a proven design of the 2nd generation cryostat for Helical SCU;
  - 20”-diameter vacuum vessel;
  - single thermal shield;
  - off-shelf vacuum components;
  - three thermal stages (4K – 20K – 40K);
  - 6 cryocoolers with a possibility of adding one if required

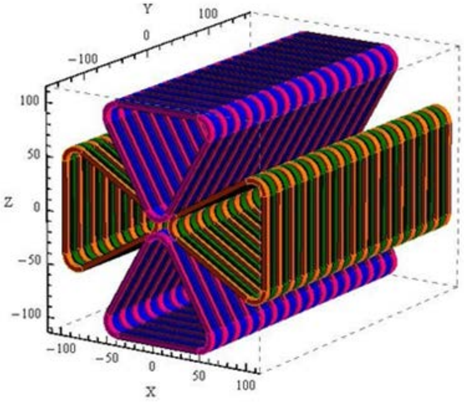




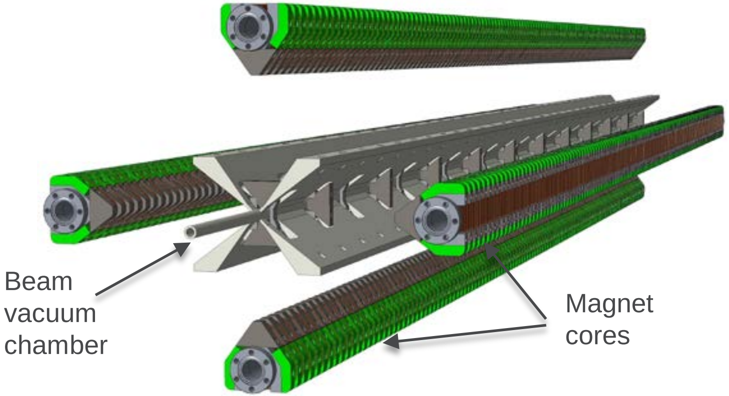


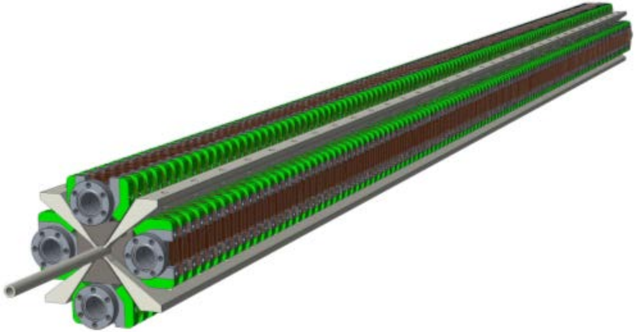
VARIABLY POLARIZING SCU— SCAPE

- 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 Arbitrarily Polarizing Emitter, or SCAPE
- This electromagnetic superconducting undulator employs four planar magnetic cores assembled around a cylindrical beam vacuum chamber.



Concept of SCAPE: a universal SCU with four planar superconducting coil structures.



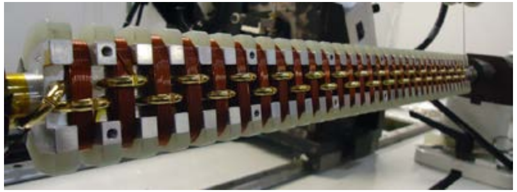


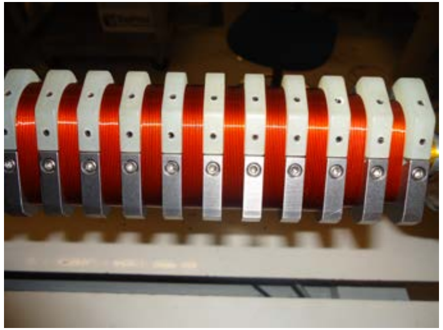
SCAPE PROTOTYPE

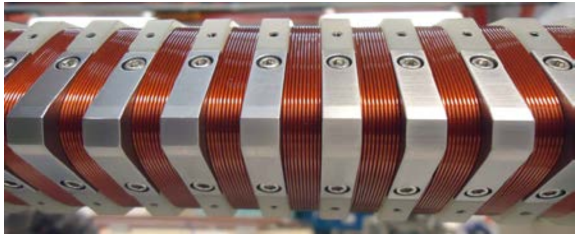
- SCAPE 0.5-m long prototype magnet was built:
  - period length – 30 mm
  - magnetic gap – 10 mm
- The prototype was successfully tested in a LHe bath cryostat equipped with a movable Hall probe.

SCAPE mechanical structure

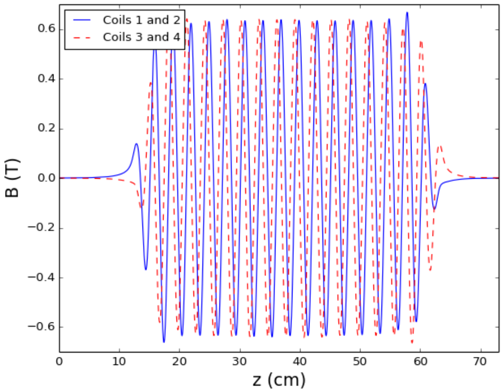
SCAPE core winding

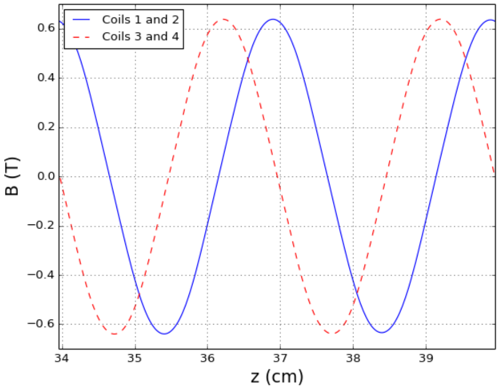






Measured field profiles





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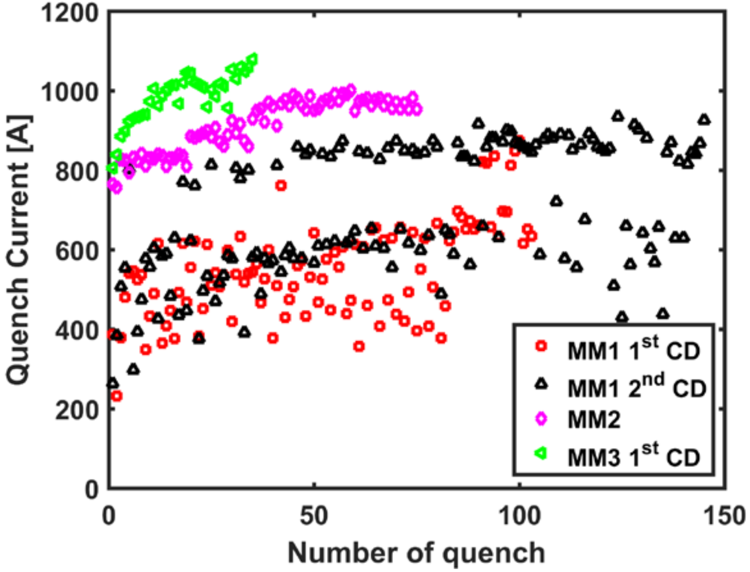
R&D ON NB_3SN UNDULATOR

R&D ON NB3SN UNDULATOR

- New 3-year project
- Goal: Develop, build and install on the APS ring a two-magnet Nb_3Sn 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
  – A 0.5-m long prototype
  – Full scale magnet and cryostat
  – Undulator assembly, test, installation on the APS ring.

Training of short models



- A 100% short sample current limit of 1150A is achieved.
- For comparison: max training current of NbTi conductor is about 650A.

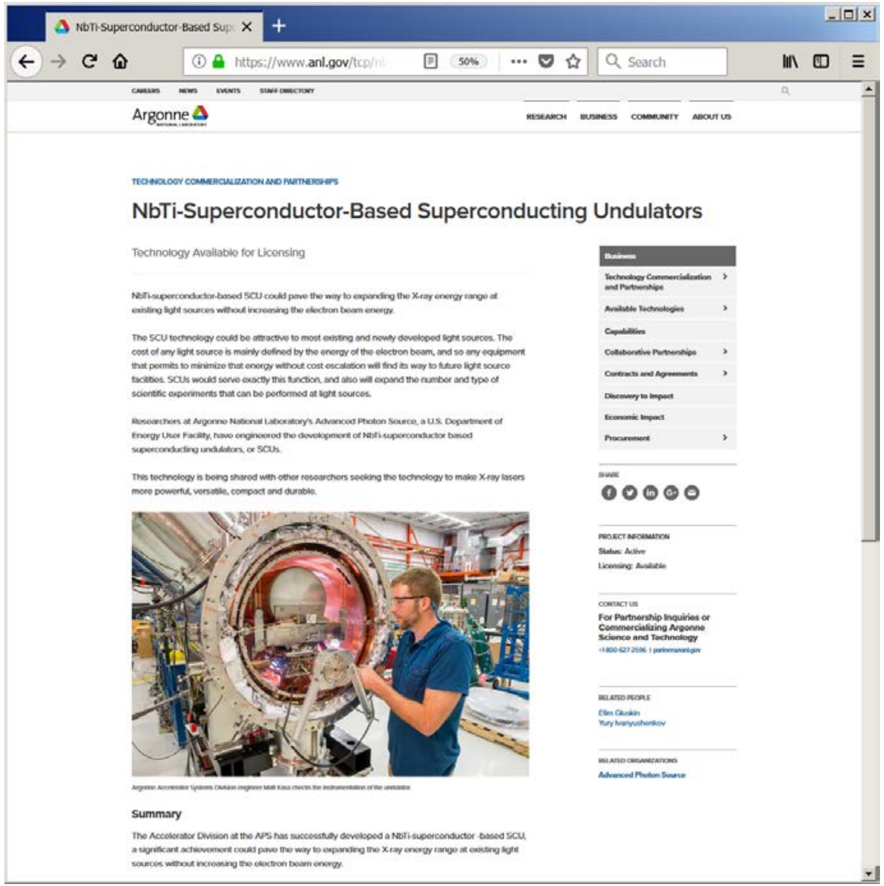
Based on magnetic measurements of magnet model #3: the Nb_3Sn undulator will generate about 25% higher magnetic field than the NbTi one

I. Kesgin et al., " Development of Short-Period Nb_3Sn Superconducting Planar Undulator", 1LPo2F-07, ASC2018, Seattle, 2018.

SCU TECHNOLOGY TRANSFER

PLANAR SCU TECHNOLOGY IS READY FOR LICENSING

- NbTi SCU technology is developed at the APS to the level when it can be transferred to the industry.
- Planar SCU is available for licensing. Contact information is on the Argonne website
  https://www.anl.gov/tcp/nbtisuperconductorbased-superconducting-undulators



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
- PLANAR SCU TECHNOLOGY IS AVAILABLE FOR COMMERCIALIZATION