Superconducting Undulators – from an idea to real devices

Yury Ivanyushenkov

on behalf of the APS superconducting undulator project team

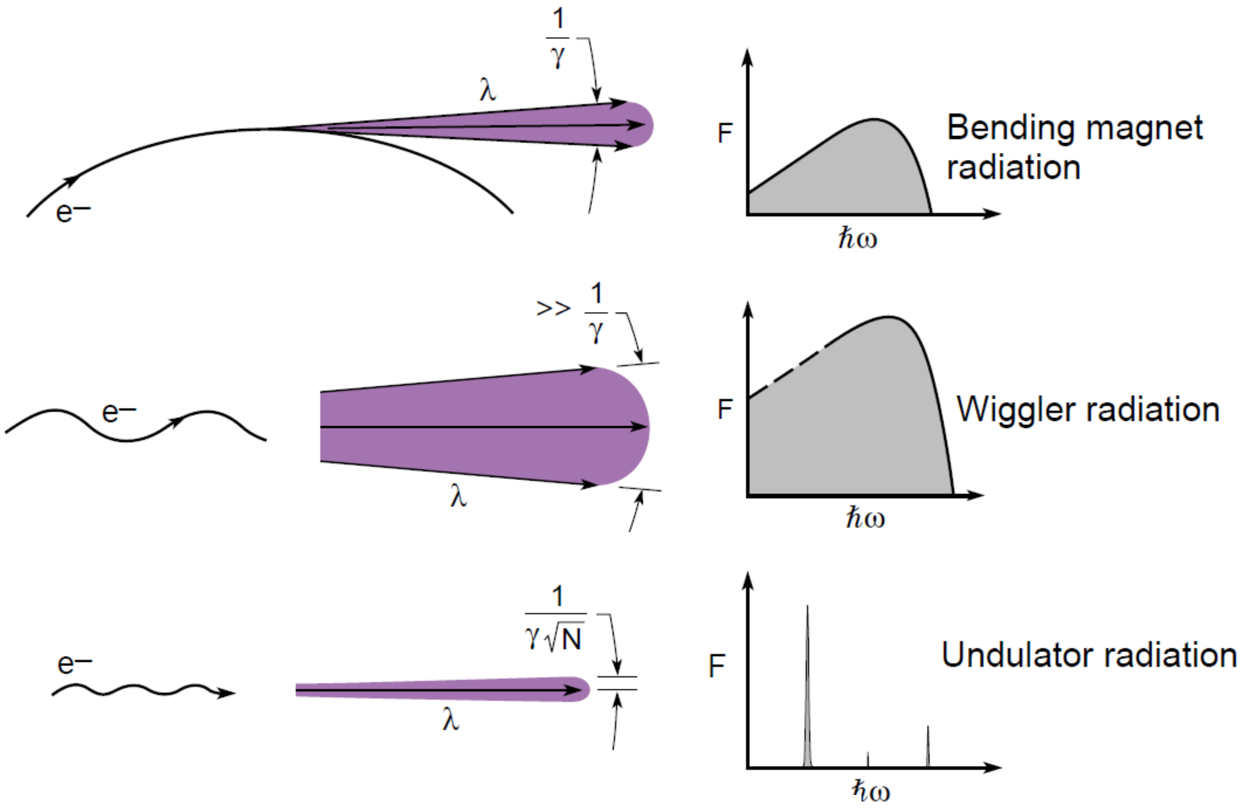
ASD Seminar, March 18, 2013

Work supported by U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

Scope

- Undulator radiation and magnetic structures
- Why a superconducting-technology based undulator (SCU)?
- Expected SCU performance
- SCU challenges and solutions
- Work on superconducting insertion devices around the world
- Development of SCU at the APS
- SCU0
- What’s next?
- Conclusions

Forms of synchrotron radiation



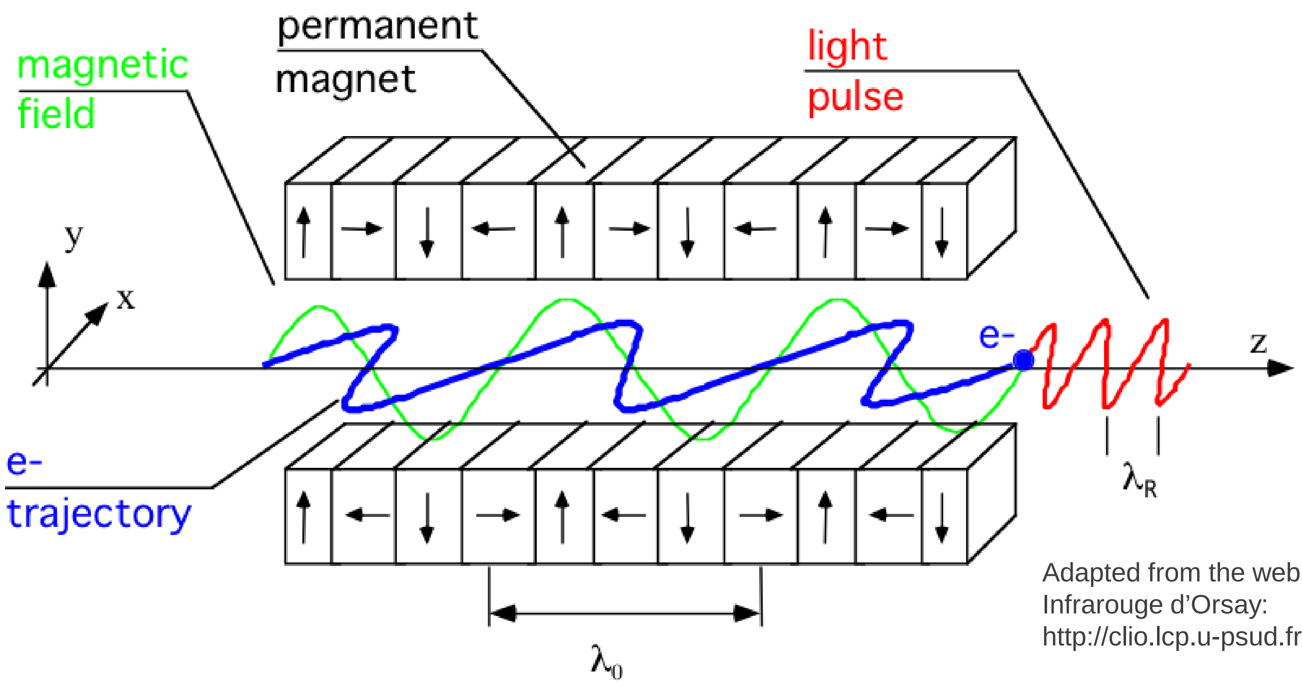
Undulator radiation wavelength and photon energy:

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

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

Adapted from lectures by Prof. David T. Attwood, http://ast.coe.berkeley.edu/sxreuv/

Undulator radiation



Adapted from the web-site of Centre Laser Infrarouge d’Orsay: http://clio.lcp.u-psud.fr/clio_eng/FELrad.html

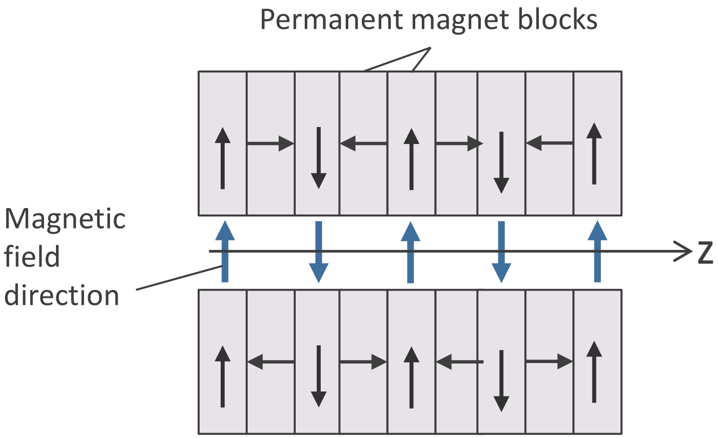
In coordinate frame that moves with an electron in Z:
Electron ‘sees’ the magnetic structure with the period length λ_0/γ moving towards it, and emits as a dipole at the wavelength $\lambda^*=\lambda_0/\gamma$, where γ is the relativistic Lorentz factor.

In laboratory (observer) frame:
Observer sees this dipole radiation shifted to even shorter wavelength, through the relativistic Doppler effect.
In the forward direction, the observed wavelength of the radiation is $\lambda_R = \lambda^*\gamma(1-\beta) = \lambda_0(1-\beta) = \lambda_0/2\gamma^2$.

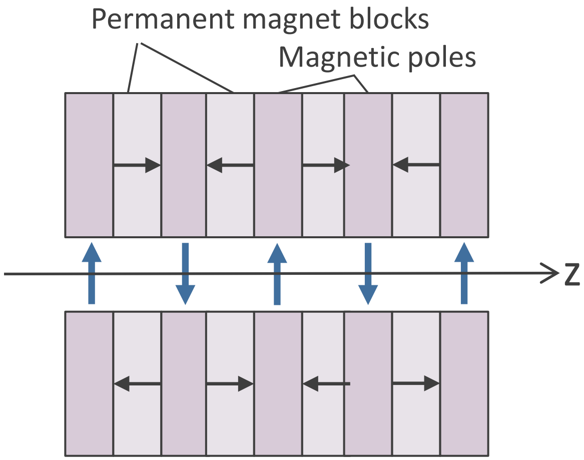
As a result, a 3.3-cm undulator can emit 10-keV photons on a 7-GeV electron storage ring (γ = 13700).

Planar undulator magnetic structure

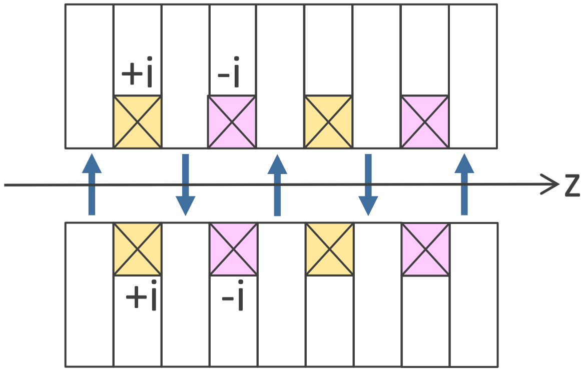
Permanent magnet structure



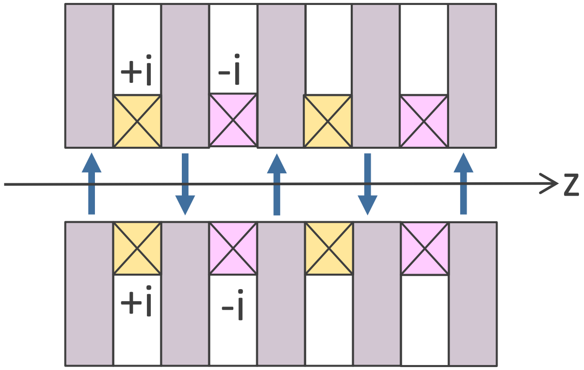
Hybrid structure



Electromagnet structure



Electromagnet structure with magnetic poles



Why a superconducting technology-based undulator ?

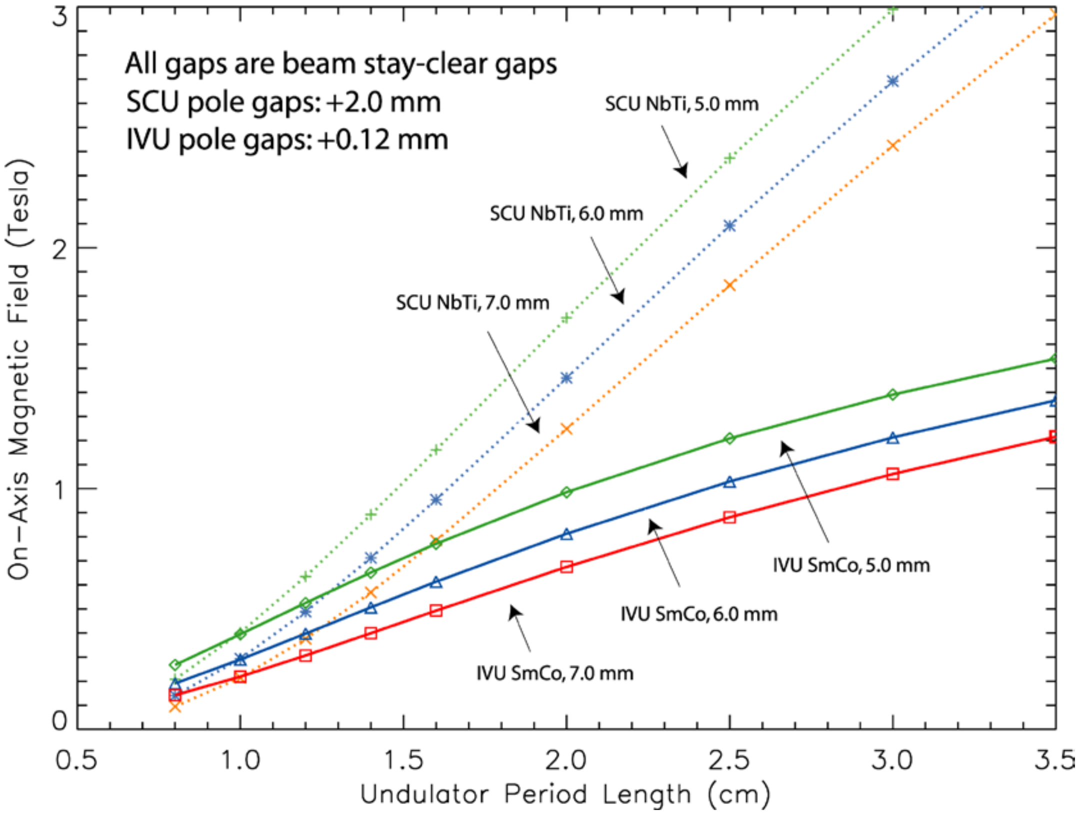
- A superconducting undulator is an electromagnetic undulator that employs high current superconducting windings for magnetic field generation -

  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

Undulator peak field for various planar insertion device technologies

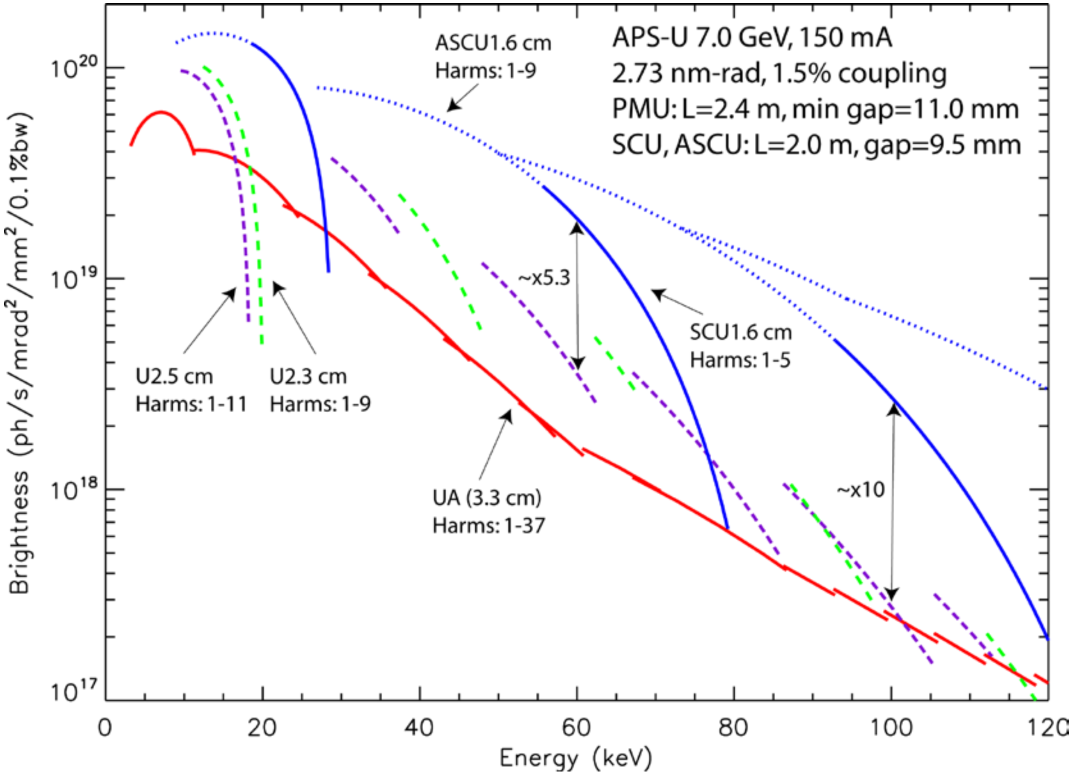


Comparison of the magnetic field in the undulator midplane for in-vacuum SmCo undulators (B_{eff}) and NbTi superconducting undulators (B_0) versus undulator period length for three beam stay-clear gaps. The actual undulator pole gaps were assumed to be 0.12 mm larger for the IVUs and 2.0 mm larger for the SCUs. Under these assumptions, an SCU can achieve the same field at about 2 mm larger gap than an IVU.

R. Dejus, M. Jaski, and S.H. Kim, "On-Axis Brilliance and Power of In-Vacuum Undulators for The Advanced Photon Source," MD-TN-2009-004

SCU performance comparison

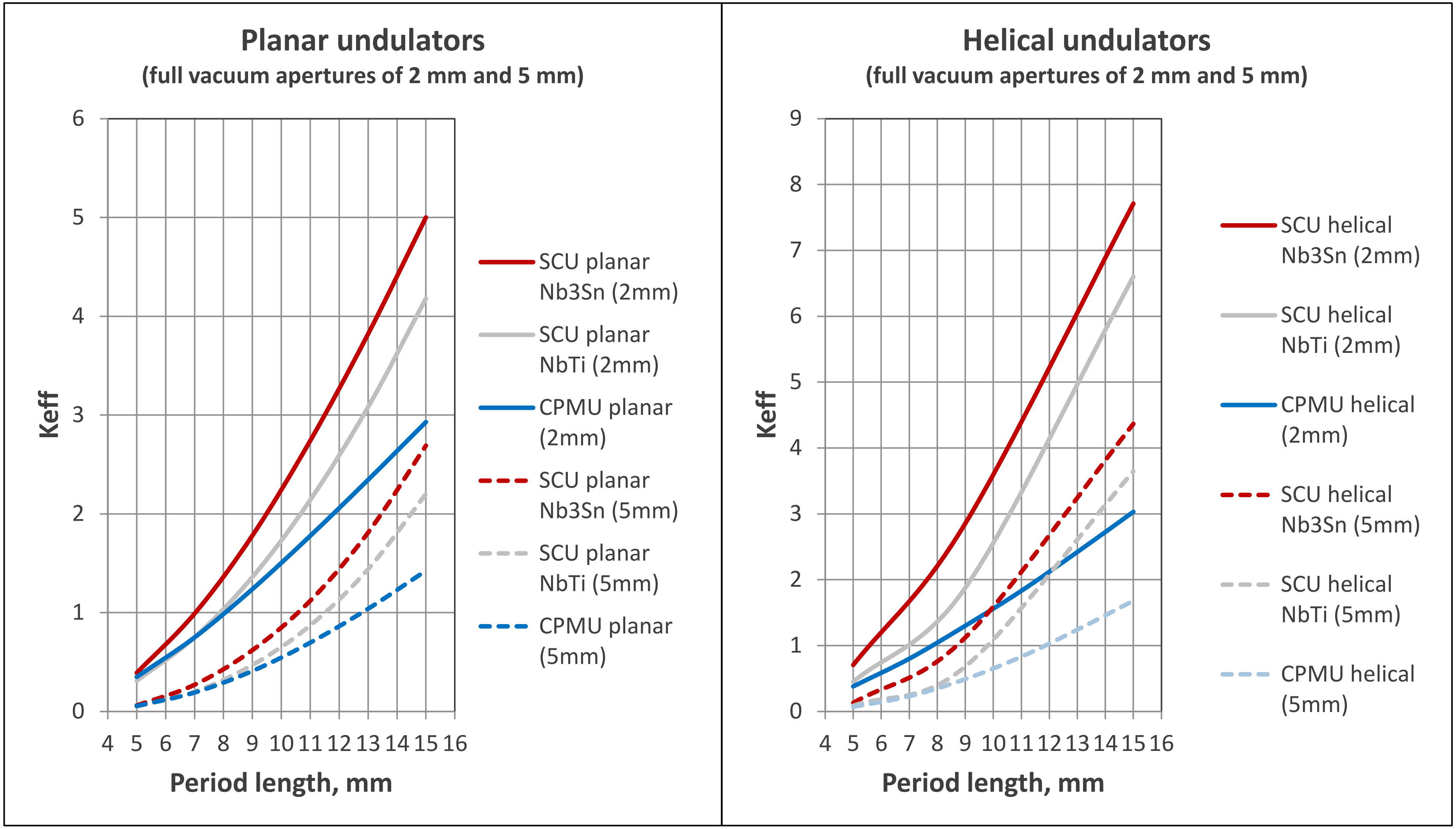
Brightness Tuning Curves (SCUs1.6 cm vs. UA 3.3 cm vs. Revolver U2.3 cm & U2.5 cm)



- Tuning curves for odd harmonics of the SCU and the “Advanced SCU” (ASCU) versus planar permanent magnet hybrid undulators for 150 mA beam current.
- The SCU 1.6 cm surpasses the U2.5 cm by a factor of ~ 5.3 at 60 keV and ~ 10 at 100 keV.
- The tuning range for the ASCU assumes a factor of two enhancement in the magnetic field compared to today’s value – 9.0 keV can be reached in the first harmonic instead of 18.6 keV.
- Reductions due to magnetic field errors were applied the same to all undulators (estimated from one measured Undulator A at the APS.)

Y. Ivanyushenkov, ASD Seminar, March 18, 2013

SCUs for free electron lasers



J. Bahrdt and Y. Ivanyushenkov, “Short Period Undulators for Storage Rings and Free Electron Lasers,” presented at SRI2012.

Why a superconducting technology-based undulator ?

- Superconducting technology-based undulators outperform all other technologies in terms of peak field and, hence, energy tunability of the radiation.
- Superconducting technology opens a new avenue for IDs.

Work on superconducting insertion devices around the world

Country	Organization	Activity
Taiwan	TLS	SC wigglers, R&D on SCUs
Russia	Budker Institute	SC helical undulator for HEP; SC wavelength shifters; SC wigglers
France	ACO, Orsay	SCU
Germany	ANKA	SCU for Mainz Microtron, R&D on SCUs
	ACCEL	Two SCUs (for ANKA and for SSLS/NUS, Singapore)
	Babcock Noell	New SCU for ANKA
UK	RAL and DL	Helical SCU for ILC
Sweden	MAX-Lab	SC wiggler
USA	Stanford	Helical SCU for FEL demonstration
	BNL	R&D on SCUs
	LBNL	R&D on SCUs
	Cornell	SC wiggler
	NHFML	R&D on SCUs

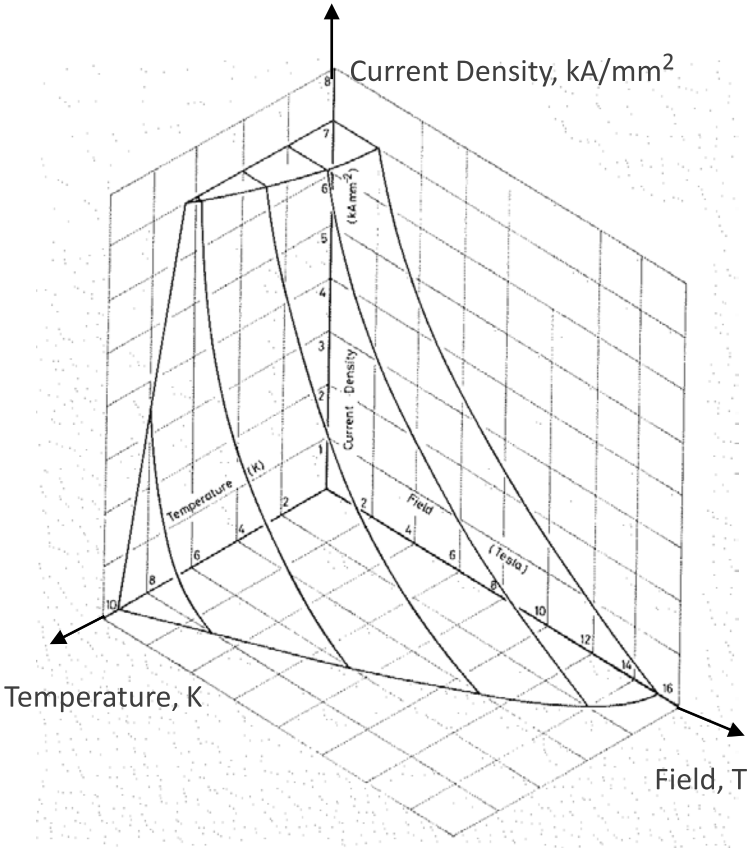
* The list might not be complete

SCU challenges

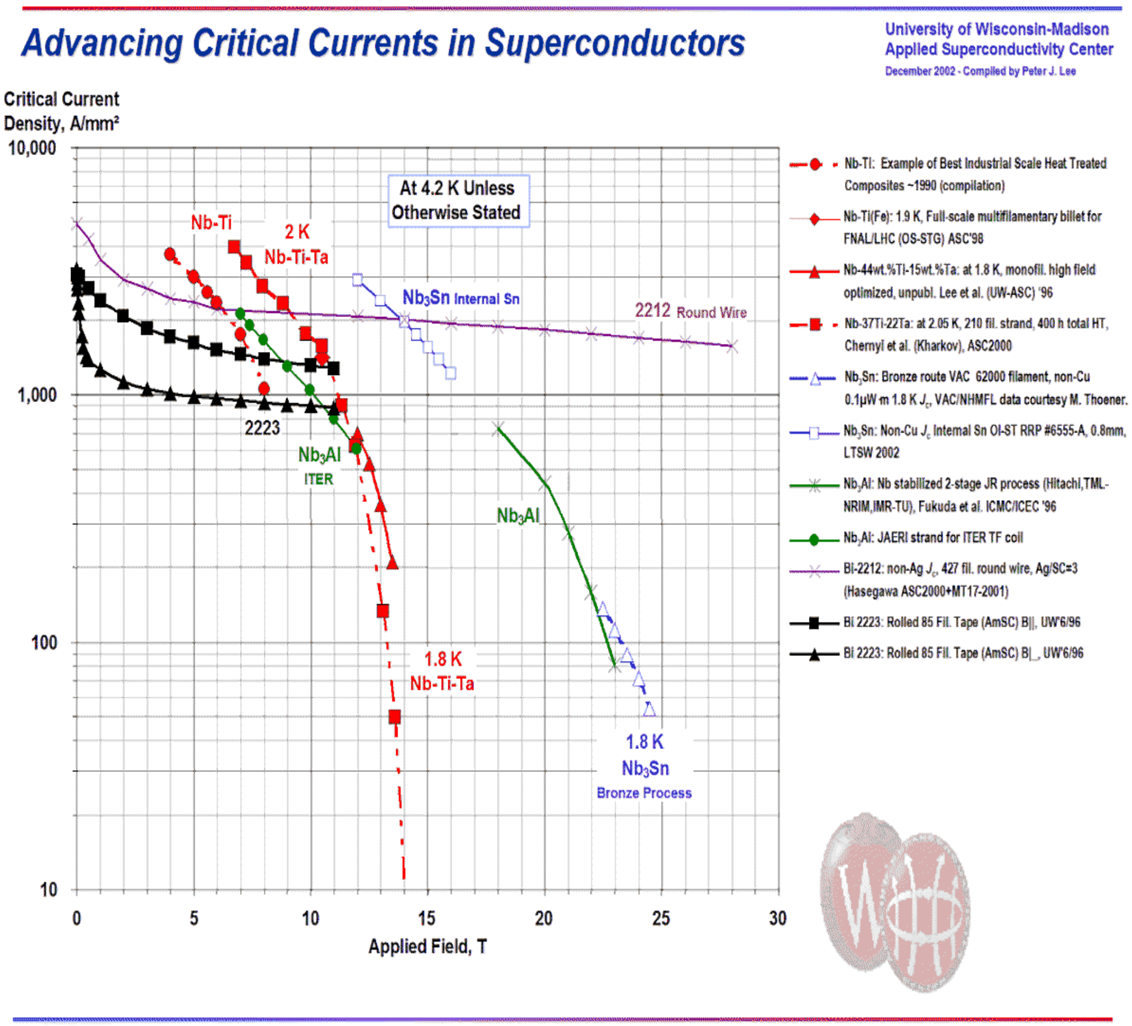
SCU as a superconducting magnet	SCU as an insertion device	SCU as a photon source
- Choice of superconductor; - Design and fabrication of magnetic structure; - Cooling of superconducting coils in presence of beam heat load; - Design and fabrication of SCU cryomodule.	- Low field integrals; - Measurement of SCU performance before installation into storage ring.	- High quality field: • Trajectory straightness; • Low phase error. - Shimming technique.

Superconductors

Critical-current surface for NbTi



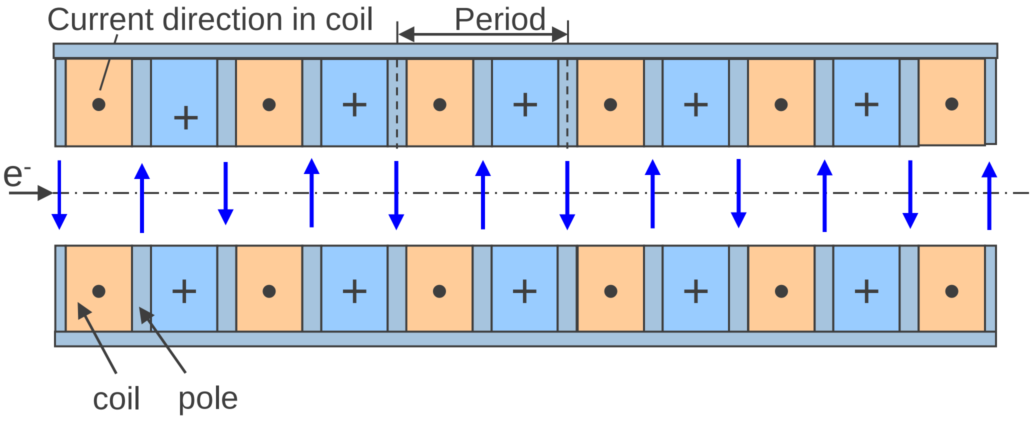
From Martin N. Wilson “Superconducting Magnets”



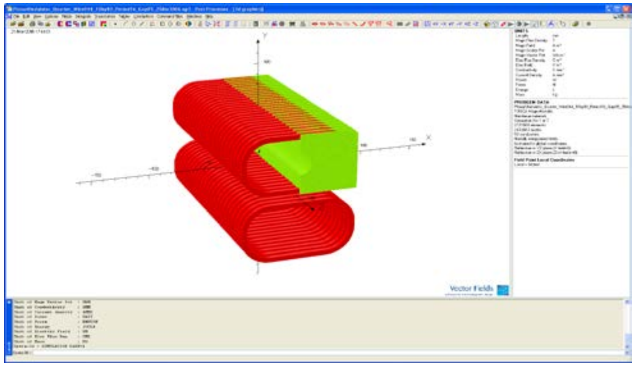
Courtesy of Peter J. Lee, NHMFL

Planar SCU magnet

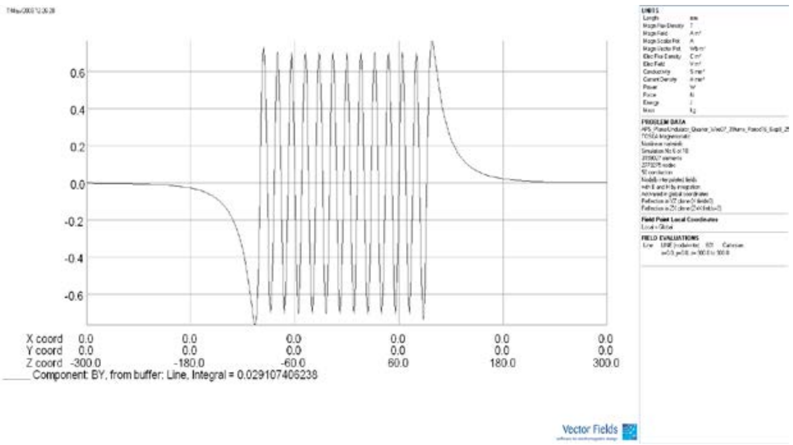
Current directions in a planar undulator



Planar undulator winding scheme

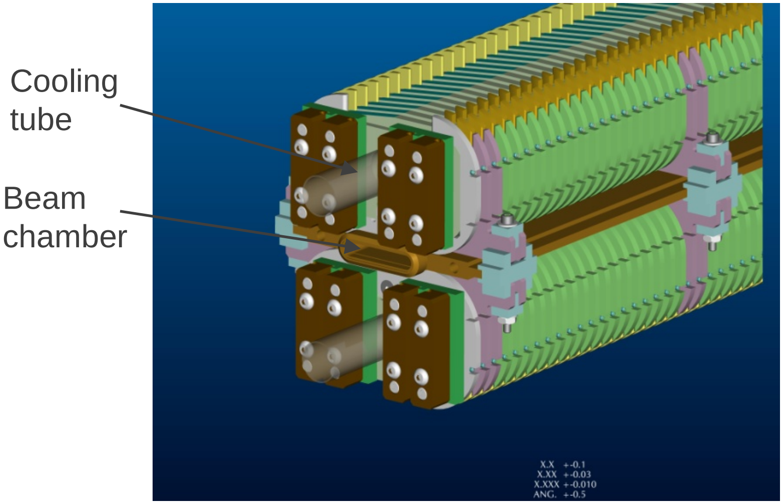


On-axis field in a planar undulator



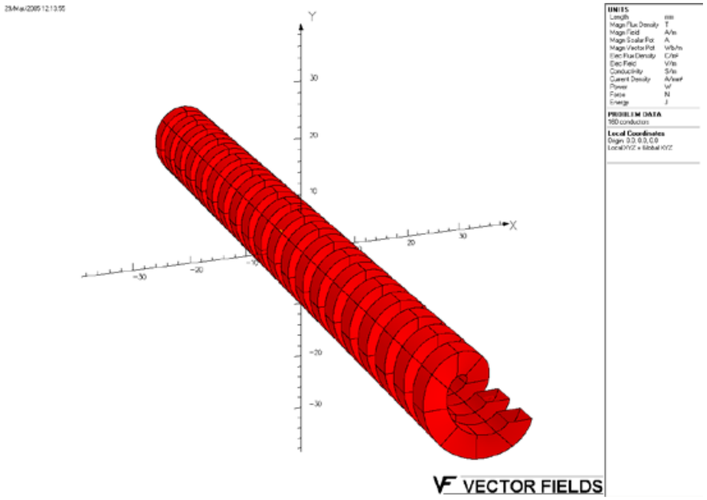
Component: BY, from buffer: Line, Integral = 0.029107406238

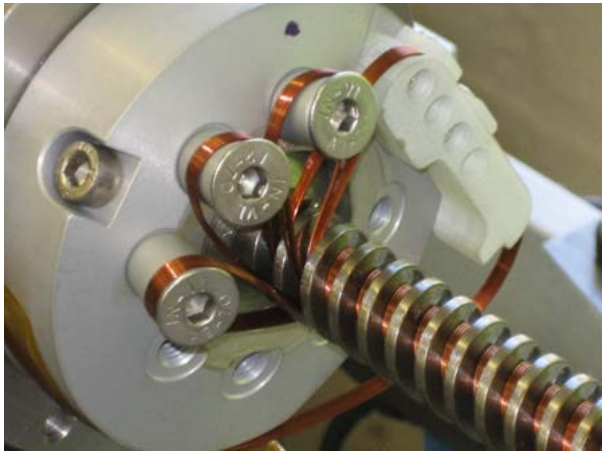
Magnetic structure layout

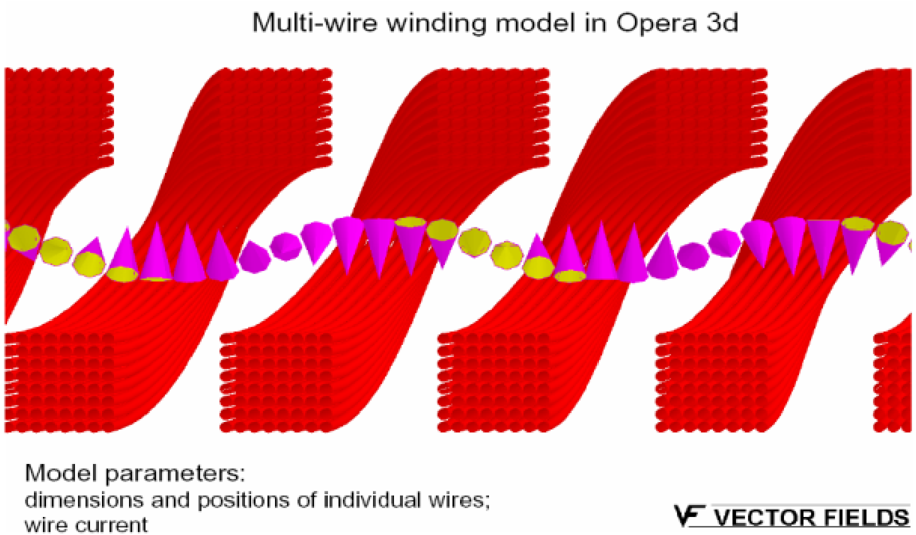


Helical SCU magnet

Helical undulator structure

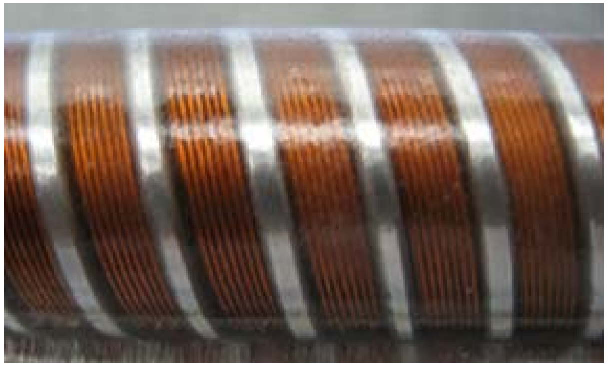






Multi-wire winding model in Opera 3d

Model parameters:
dimensions and positions of individual wires;
wire current

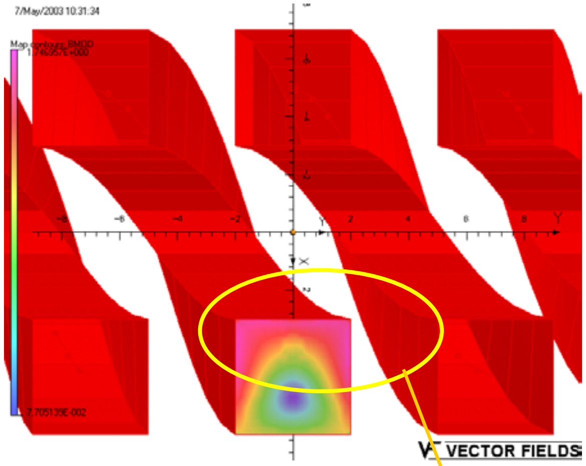


Conductor operation in a short-period SCU

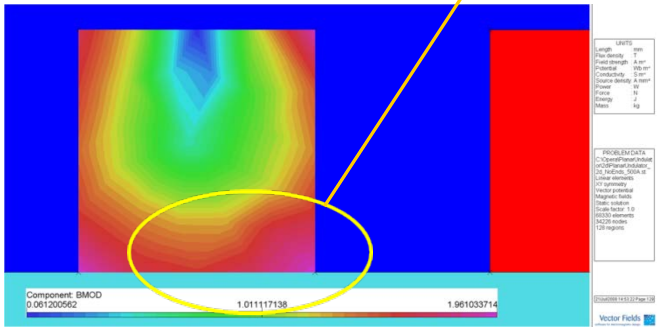
In a short-period (10-15 mm) SCU conductor operates:

- In the field of 2-4 T
- With the ratio of the peak field in the conductor to the peak field on axis of 2-4
- At $J_{eng} > 1200$ A/mm^2
- Close (< 1mm) to or in contact with a beam chamber which is heated by the particle beam at a level of 5-10 W/m (at synchrotron light sources)

3d Opera model of helical undulator structure



Region with the highest peak field



2d Opera model of planar undulator structure

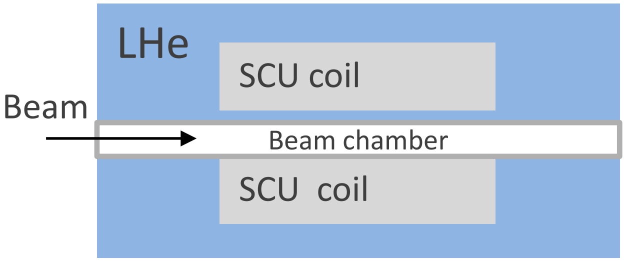
Ideal superconductor for a short-period SCU

Parameter	Desirable value	Comments
Working peak field region	2 – 4 T	
Non-copper current density at 3 T	≥ 5000 A/mm^2	To exceed parameters of available NbTi wires
Filament diameter	≤ 40 µm	For stable conductor operation
SC- copper ratio	about 1	For good conductor cooling
Wire diameter	≈ 0.5 mm	Max wire current < 1000 A to limit heat leak through the current leads; also, for a possibility of winding small coil packs.
Insulation	≤ 20 µm	To not reduce a packing factor
Heat treatment	Not required	To exclude heating a long undulator coil after winding and a possible coil deformation due to heating
Operating temperature	> 4 K	To use cryocoolers operating at about 10K in a cryogen-free cooling system

SCU cooling

Sources of heat in the SCU:
- Static heat load (by radiation, heat conduction through supports and current leads)
- Dynamic heat load by beam

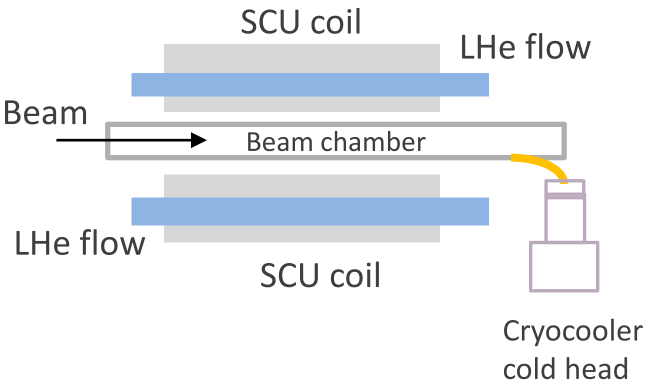
SCU coils in LHe bath



Pros:
- SCU coils is direct contact with LHe

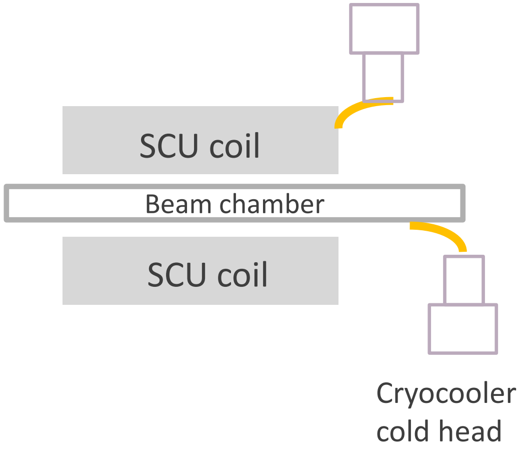
Cons:
- Beam heats LHe

Indirect cooling of SCU coils



Pros:
- No heating of LHe by beam

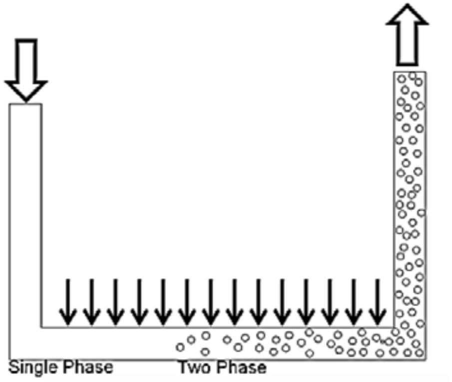
Cons:
- Possible temperature difference between the LHe and the coil;
- LHe pump



Pros:
- No heating of LHe by beam;
- Cryogen-free system

Cons:
- Temperature difference between the LHe and the coil

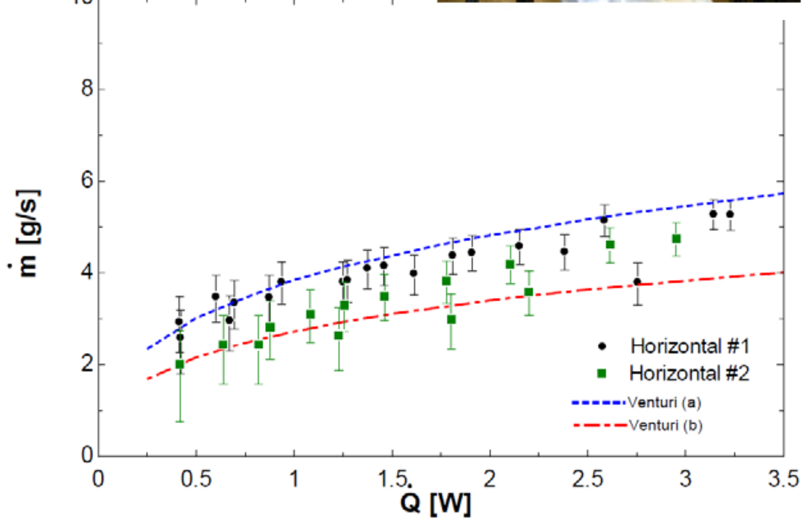
Thermosiphon cooling circuit tests



Cartoon representing thermosiphon operation.

Helium vessel with a model of SCU cores.

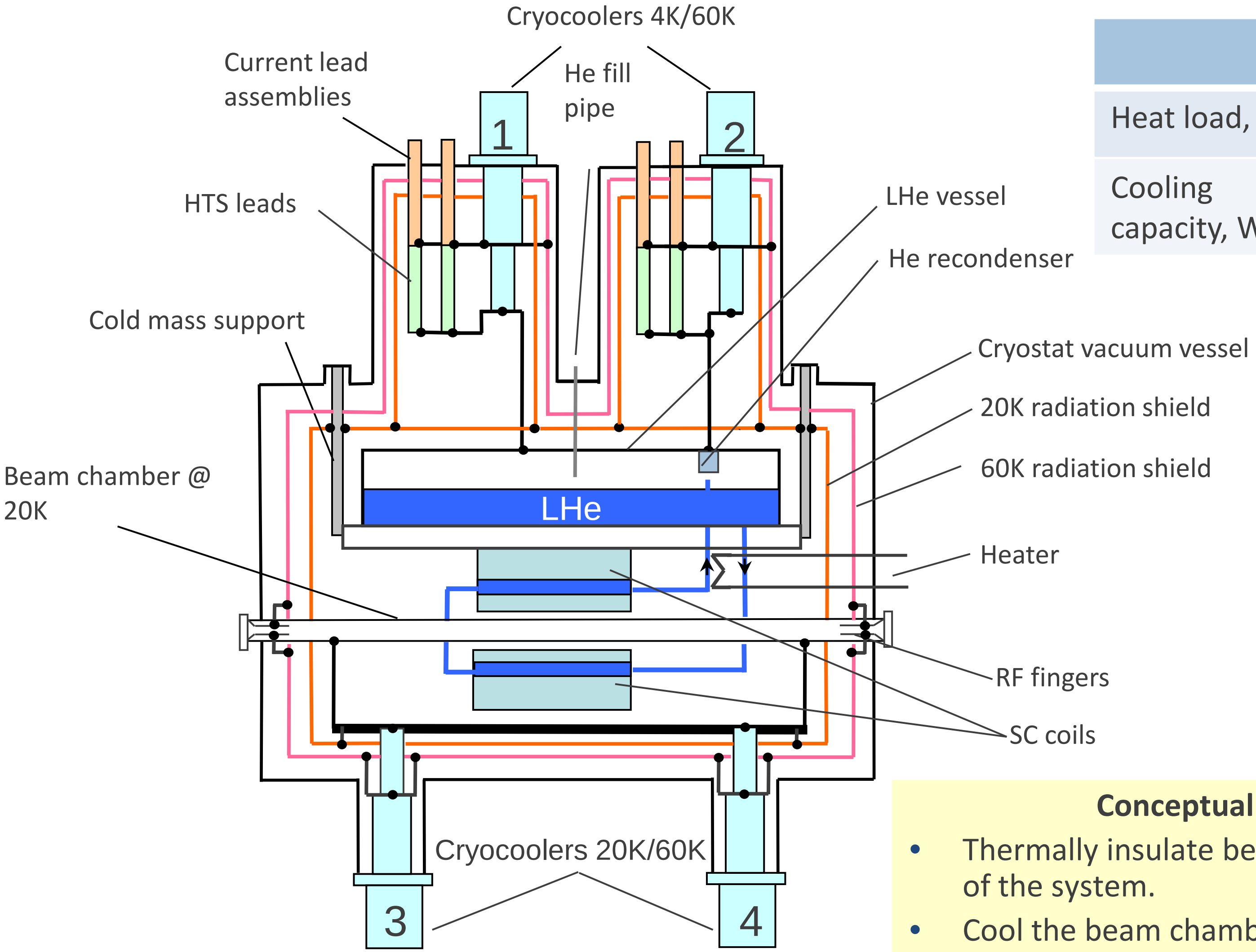
Three-channel test assembly installation.



Average mass flow rate as a function of horizontal heat load for single channel test.

Daniel C. Potratz, “Development and Experimental Investigation of a Helium Thermosiphon”, MS Thesis, University of Wisconsin-Madison, 2011

SCU0 cooling scheme



	4 K	20 K	60 K
Heat load, W	0.7	12.5	86
Cooling capacity, W	3	40	224

Conceptual points:

- Thermally insulate beam chamber from the rest of the system.
- Cool the beam chamber separately from the superconducting coils.

In this approach beam heats the beam chamber but not the SC coils!

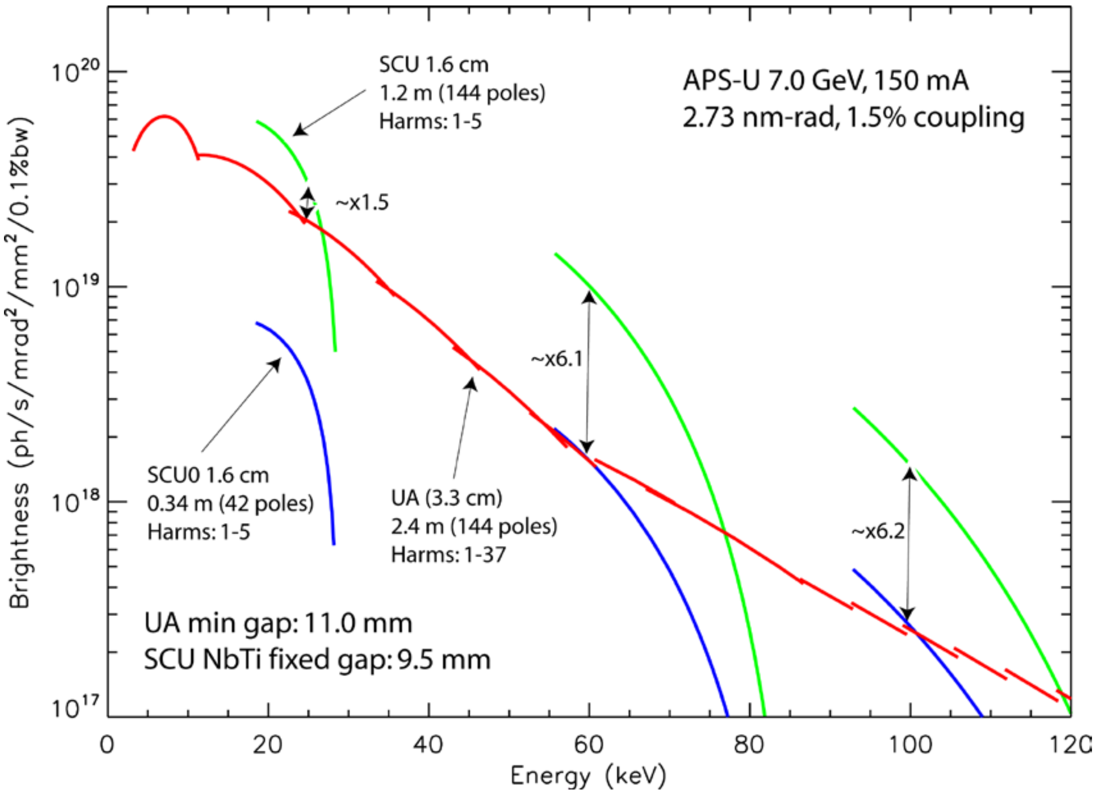
Development of SCU at the APS

Activity	Years
A proposal of helical SCU for the LCLS	1999
Development of the APS SCU concept	2000-2002
R&D on SCU in collaboration with LBNL and NHFML	2002-2008
R&D on SCU0 in collaboration with FNAL and UW-Madison	2008-2009
Design (in collaboration with BINP) and manufacture of SCU0	2009-2012
SCU0 installed into the APS storage ring	December 2012

First undulators for the APS

APS superconducting undulator specifications

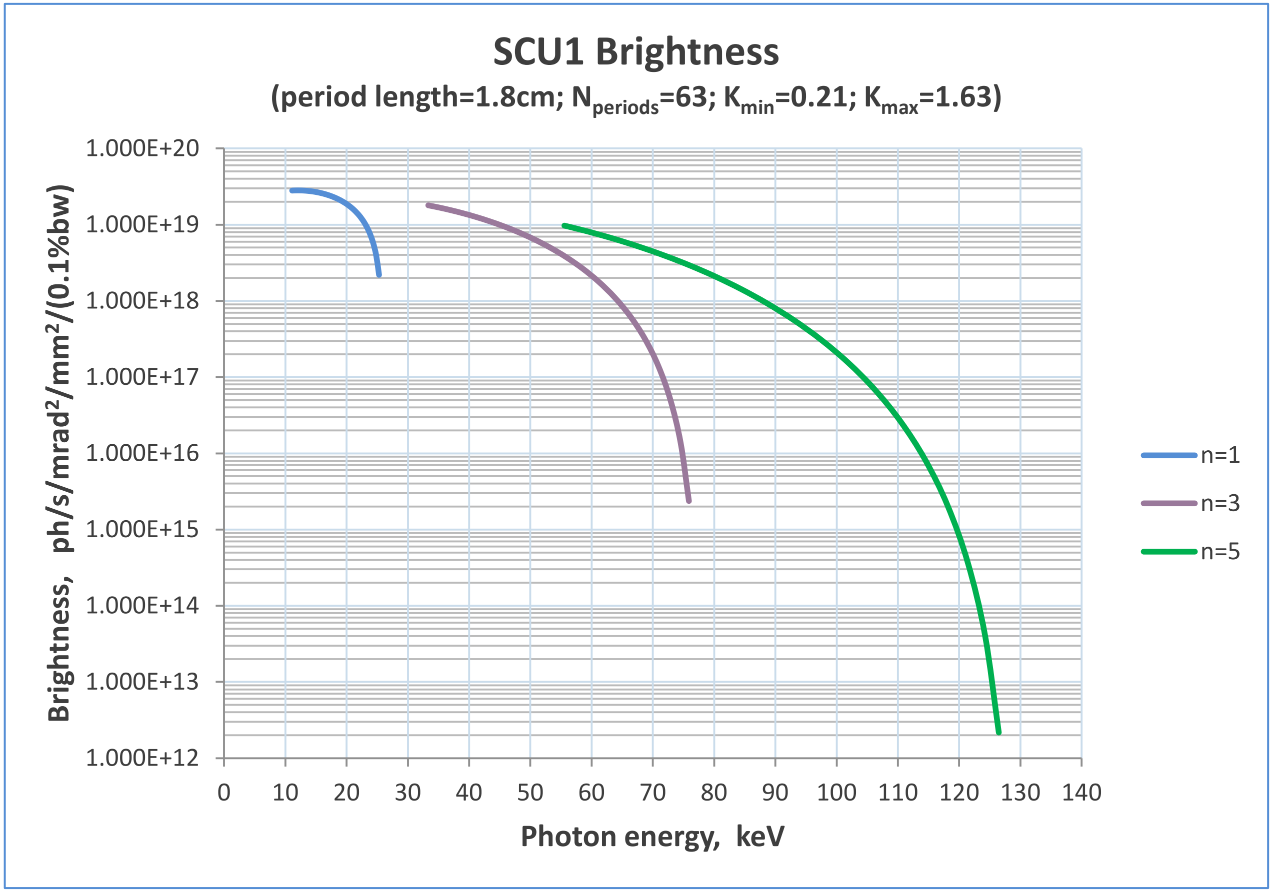
	Test Undulator SCU0	Test Undulator SCU0-Long
Photon energy at 1st harmonic	20-25 keV	20-25 keV
Undulator period	16 mm	16 mm
Magnetic gap	9.5 mm	9.5 mm
Magnetic length	0.330 m	1.140 m
Cryostat length	2.063 m	2.063 m
Beam stay-clear dimensions	7.0 mm vertical × 36 mm horizontal	7.0 mm vertical × 36 mm horizontal
Superconductor	NbTi	NbTi



- Tuning curves for odd harmonics for two planar 1.6-cm-period NbTi superconducting undulators (42 poles, 0.34 m long and 144 poles, 1.2 m long) versus the planar NdFeB permanent magnet hybrid undulator A (144 poles, 3.3 cm period and 2.4 m long). Reductions due to magnetic field error were applied the same to all undulators (estimated from one measured undulator A at the APS). The tuning curve ranges were conservatively estimated for the SCUs.

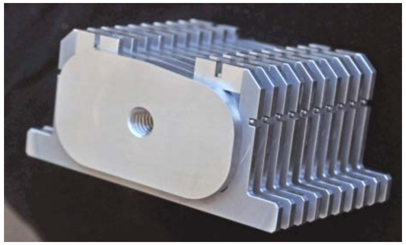
SCU1’ and SCU1

	Prototype Undulator SCU1’
Photon energy at 1st harmonic	12-25 keV
Undulator period	18 mm
Magnetic gap	9.5 mm
Magnetic length	1.140 m
Cryostat length	2.063 m
Beam stay-clear dimensions	7.0 mm vertical × 36 mm horizontal
Superconductor	NbTi

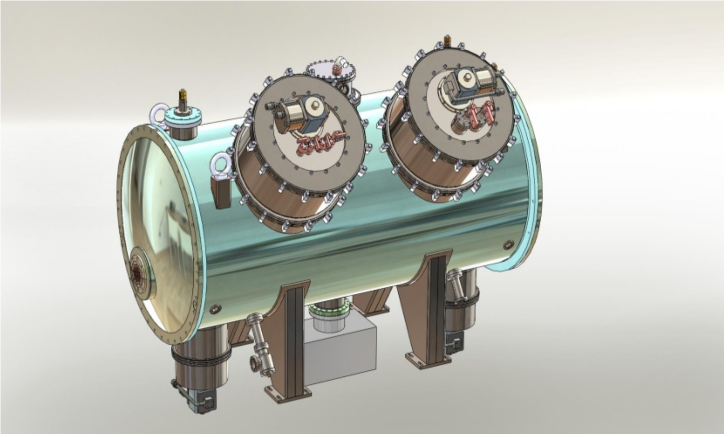


SCU0 – from an idea to real device

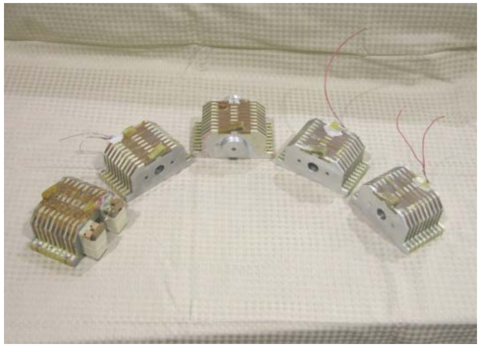
A model of test coil



SCU0 3d design model

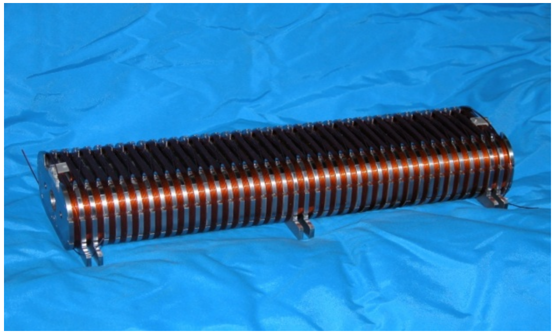


The first five 10-pole test coils

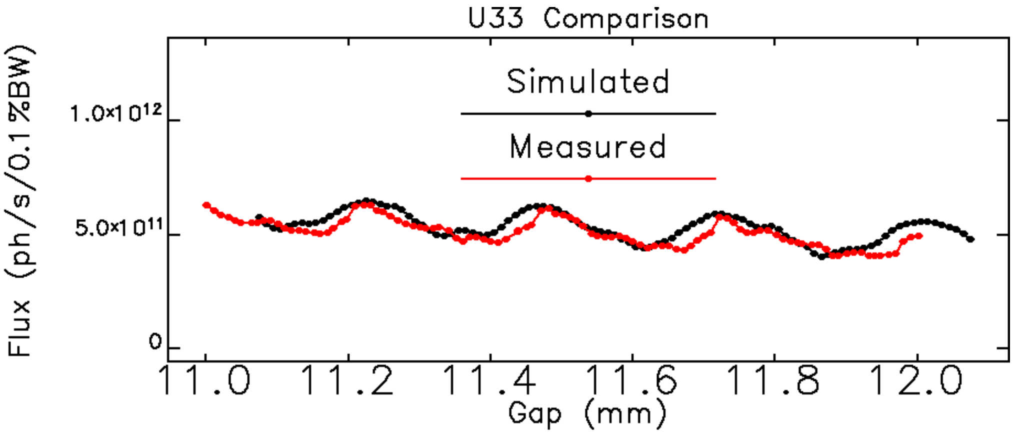


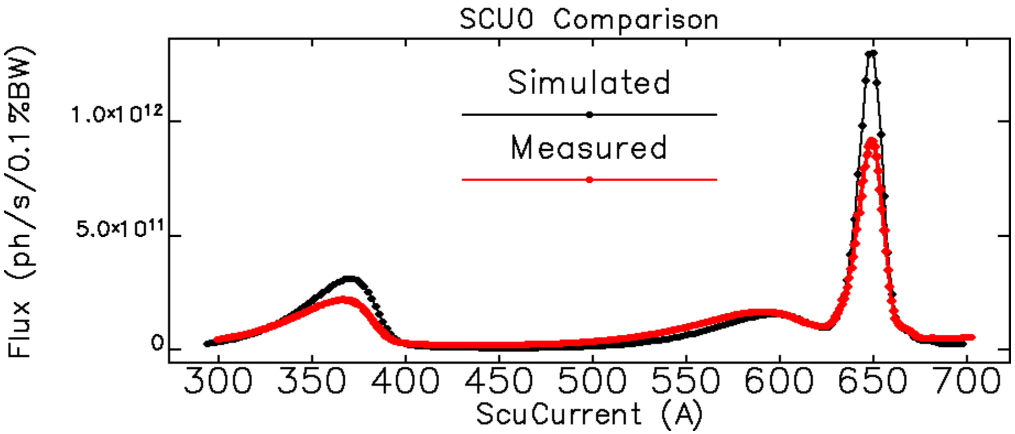
SCU0 in the APS storage ring

First wound 42-pole test coil



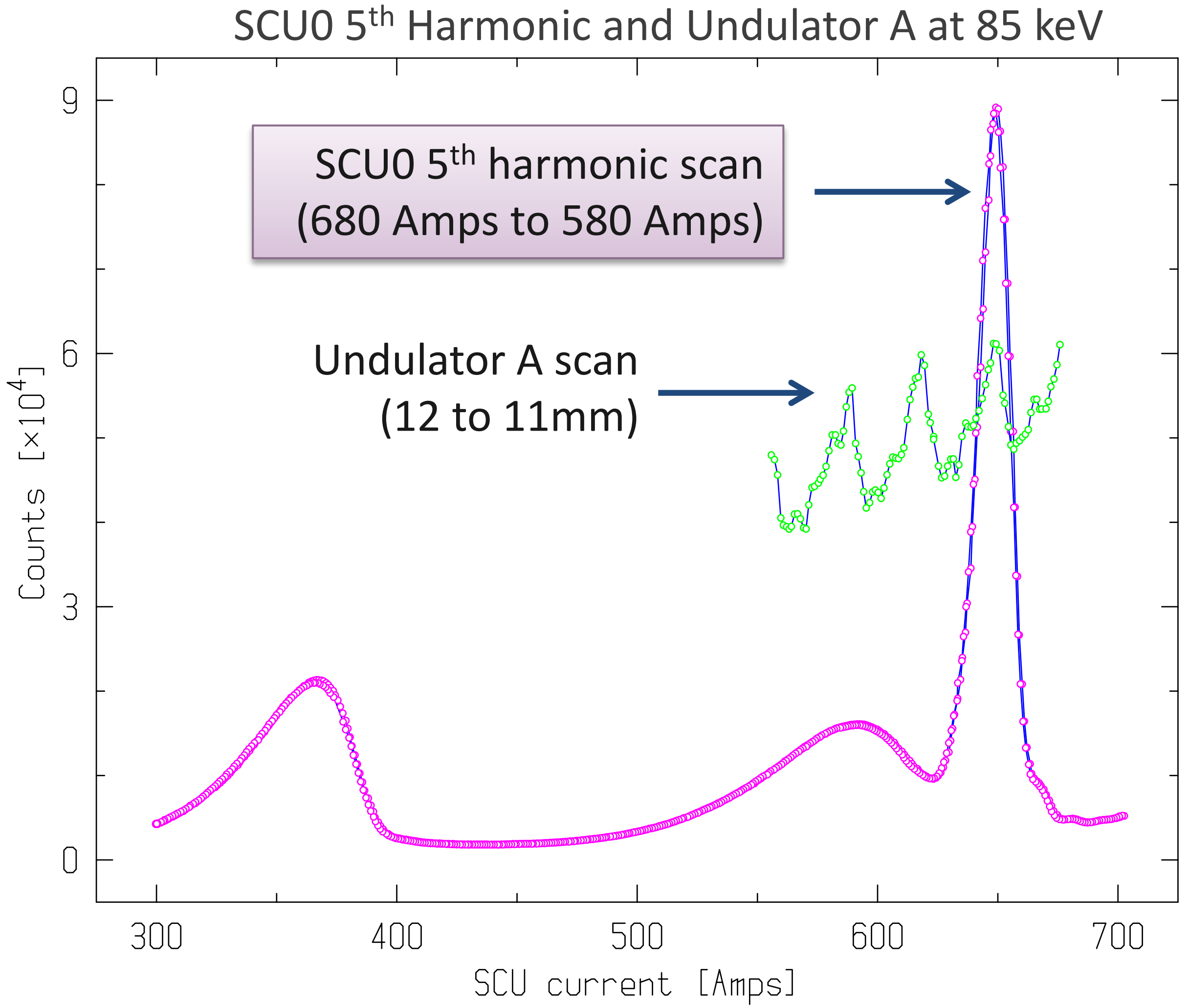
SCU0 performance





- The measured flux of the U33#25C (3.3 cm period, 70 periods) was scaled to coincide with the simulated flux (top figure). The same scale factor was then applied to the measured flux of the SCU0.
- The SCU0 (1.6 cm period, 21 periods) shows a measured flux of about 70% of the simulated flux for the 5th harmonic at 85.3 keV (bottom figure). It shows about 45% higher flux than that of the U33#25C. (The rms phase error of the SCU0 is about 2.3 degrees at 650 A and about 3.9 degrees for the U33#25C over the range gap 11 – 12 mm).

SCU0 Performance (2)



SCU0 flux at 85 keV is 1.4x higher than Undulator A

Why is the SCU0 project successful ?

The SCU0 project is successful because of:

- Long-term vision by the APS management
- Financial support by the APS management
- Enthusiastic and highly professional technical team
- Effective collaboration with other institutions
- Full support and contributions by many APS groups

SCU team

M. White (APS-U)
Associate Project Manager

Y. Ivanyushenkov (ASD)
Technical Leader

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

Core Team

Management: E. Gluskin*(ASD-MD)
E. Moog (ASD-MD)
Simulation: R. Dejus (ASD-MD)
S. Kim (ASD-MD)
R. Kustom (ASD-RF)
Y. Shiroyanagi (ASD-MD)
M. Jaski (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)
J. Xu (AES-CTL)
Tech. support: S. Bettenhausen (ASD-MD)
K. Boerste (ASD-MD)
J. Gagliano (ASD-MD)
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

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)
F. Lenkszus (AES-CTL)
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)

*Group Leader

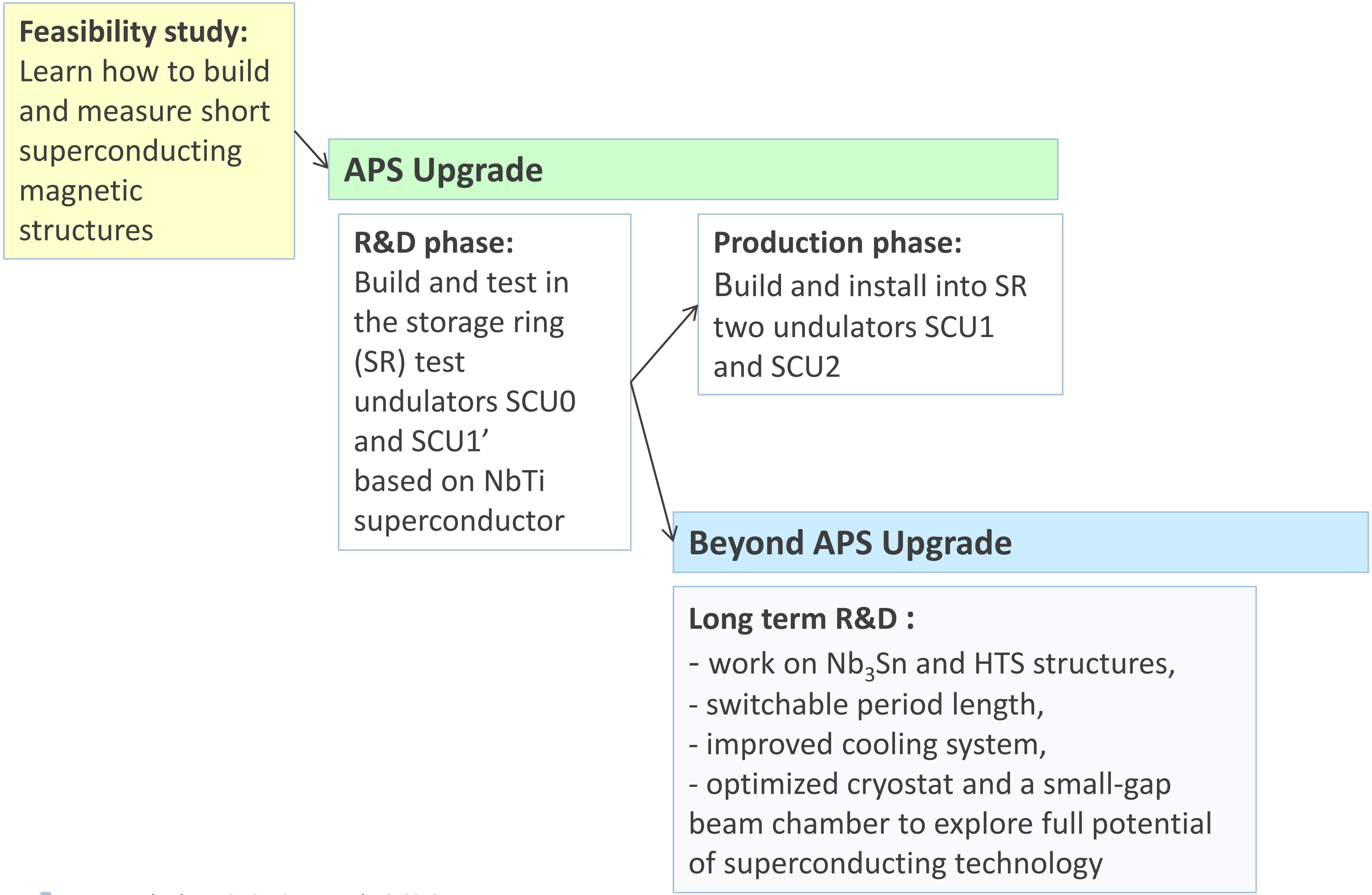
Technical Support

P. Den Hartog* (AES-MED)
D. Capatina (AES-MED)
J. Collins (AES-MED)

G. Goeppner* (AES-MOM)
J. Hoyt (AES-MOM)
R. Bechtold (AES-MOM)
E. Theres (AES-MOM)
J. Gagliano (AES-MOM)

J. Penicka* (AES-SA)
W. Jansma (AES-SA
S. Wesling (AES -SA)

SCU technology roadmap



Feasibility study:
Learn how to build and measure short superconducting magnetic structures

APS Upgrade

R&D phase:
Build and test in the storage ring (SR) test undulators SCU0 and SCU1’ based on NbTi superconductor

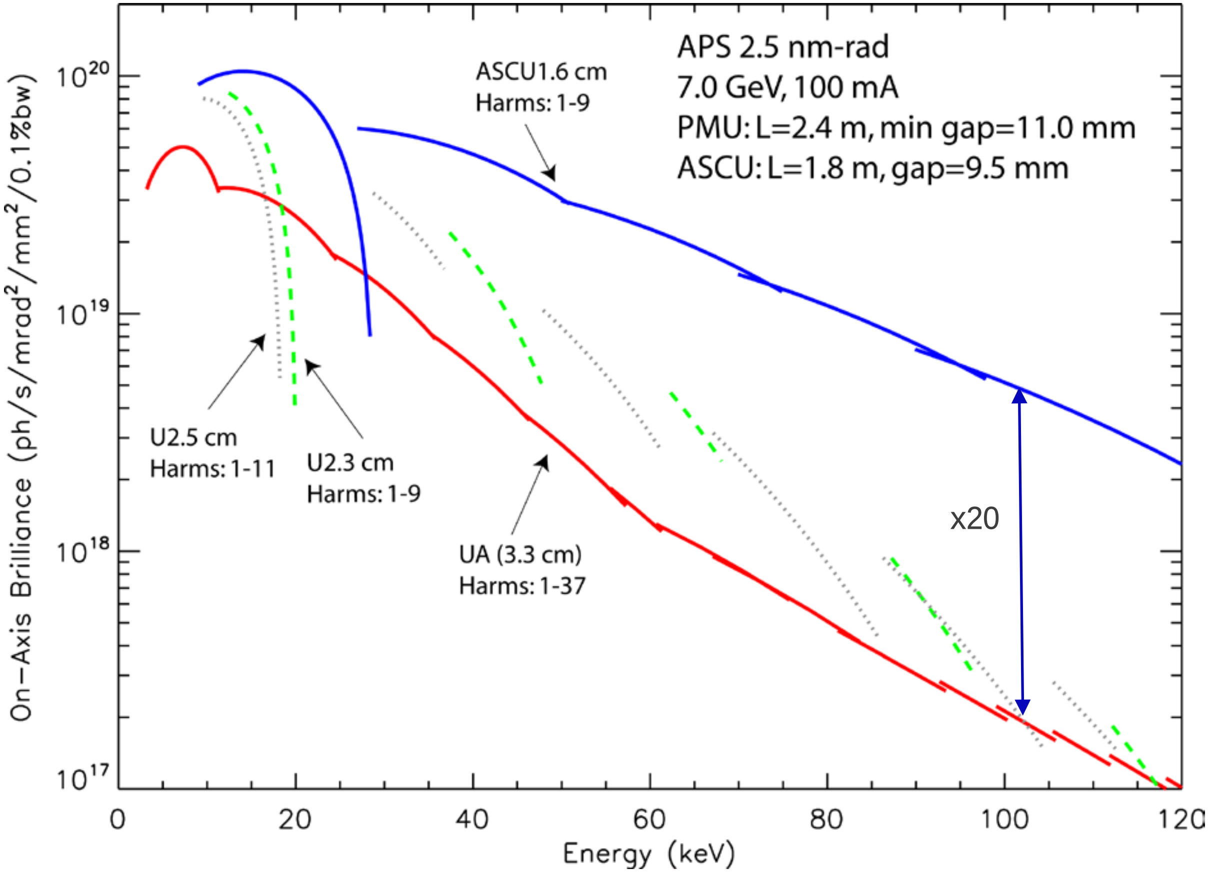
Production phase:
Build and install into SR two undulators SCU1 and SCU2

Beyond APS Upgrade

Long term R&D :

- work on Nb_3Sn and HTS structures,
- switchable period length,
- improved cooling system,
- optimized cryostat and a small-gap beam chamber to explore full potential of superconducting technology

Advanced SCU concept



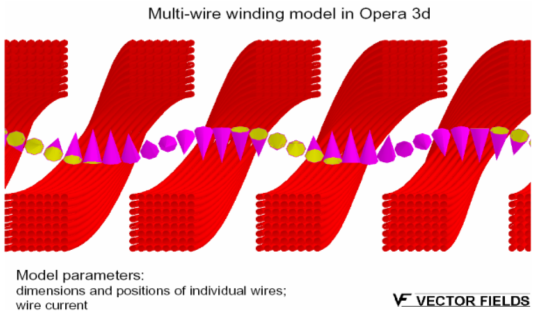
ASCU is an **Advanced SCU** with peak field increased by factor of 2 as compared to SCU0.

Design / Operation Change	**Peak Field Gain Factor**
Nb_3Sn conductor	1.3
Higher operating current	1.2
Decreased operating temperature	1.1
Better magnetic poles	1.1
Decreased magnetic gap	1.1
Total:	2.1

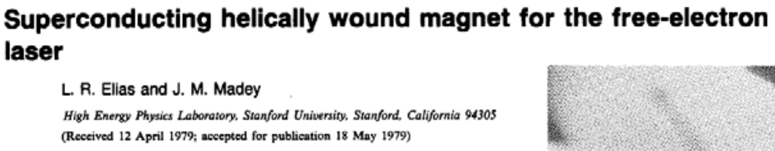
- Tuning curves for odd harmonics for planar permanent magnet hybrid undulators and one superconducting undulator.
- The ASCU 1.6 cm surpasses the revolver-type undulator by a factor of 20 above 100 keV !

Superconducting undulators for HEP and FELs

Helical undulator structure



Free electron lasers started in the 1970s with this superconducting undulator:



Superconducting helically wound magnet for the free-electron laser

L. R. Elias and J. M. Madey

High Energy Physics Laboratory, Stanford University, Stanford, California 94305

(Received 12 April 1979; accepted for publication 18 May 1979)

Rev. Sci. Instrum. 50(11), Nov. 1979.

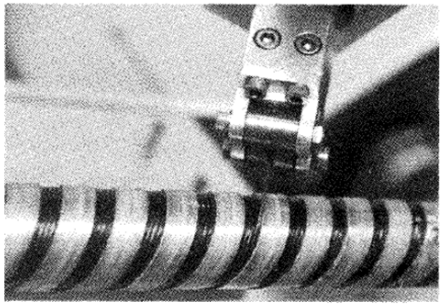
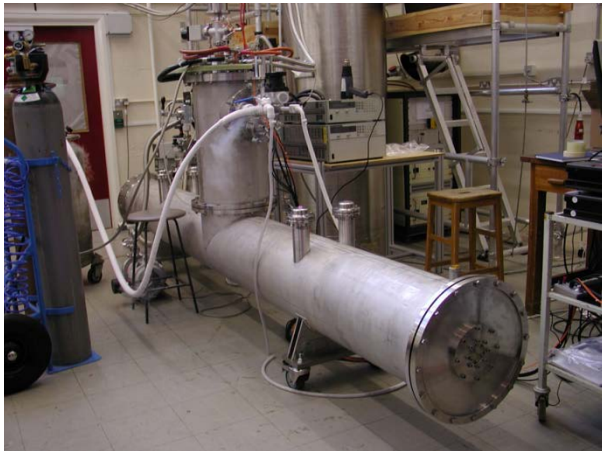


FIG. 5. Wire winding tool and partially completed magnet.

The 4-m long superconducting helical undulator has been built in the UK as a part of the ILC positron source project



D.J. Scott et al., *Phys. Rev. Lett.* 107, 174803 (2011).

In principle, SCUs could already be employed in FELs

A long line of hybrid undulators in the LCLS Undulator Hall

Picture from *SLAC Today*, March 30, 2009

http://today.slac.stanford.edu/feature/2009/lcls-21-undulators.asp

Why a superconducting technology-based undulator? (2)

- Superconducting technology-based undulators outperform all other technologies in terms of peak field and, hence, energy tunability of the radiation.
- Superconducting technology opens a new avenue for IDs.
- Superconducting technology allows various types of insertion devices to be made – planar, helical, quasi-periodic undulators, devices with variable polarization.
- We have started with a relatively simple technology based on NbTi superconductor. A Nb_3Sn superconductor will offer higher current densities and, therefore, higher peak fields combined with increased margin in operation temperature. HTS superconductors operating at temperatures around and above 77 K will allow the use of simpler (less costly) cooling systems.

Superconductors - R&D plan

NbTi:

- Develop cheaper magnetic cores
- Learn how to reliably operate magnet at 90% of critical current
- Try APC (artificial pining center) NbTi conductor once it’s available

Nb_3Sn:

- Chose the best conductor and try winding and testing short coils
- Keep an eye on development of thin ceramic insulation for Nb_3Sn
- Learn how to make long coils

HTS tapes and round wires:

- Learn how to wind short coils
- Keep an eye on development in the field

Establish collaboration with conductor developers

SCU cooling – R&D Plan

Cooling scheme:
- Develop conduction-cooled superconducting coils
- Develop cryogen-free cryostat

Cryostat design:
- Develop cheaper cryostats

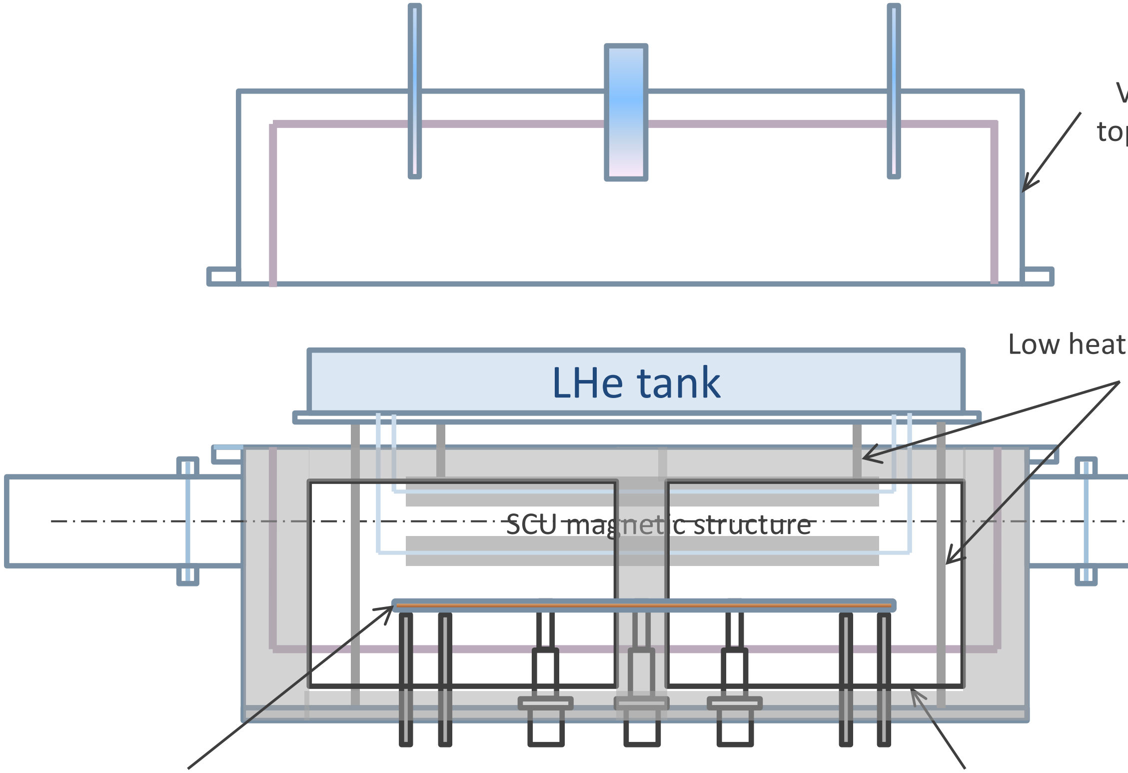
A need for SCU test cryostat

SCU R&D requires a dedicated test facility to verify new ideas and techniques.

Purpose of the test cryostat:

- Cryogenic tests of R&D coils
- Tests of R&D cryogenic schemes
- Magnetic measurements of R&D coils
- Magnetic measurements of magnetic shimming techniques
- Tests of instrumentation

SCU Test cryostat concept - Easy access to cold mass



Vacuum vessel
top part removed

LHe tank

Low heat leak supports

SCU magnetic structure

Copper Thermal Bus

Side panels removed

CASPER II at ANKA

Andreas Grau, “Measurement Devices for Magnetic Fields of Superconducing Coils, Presented at IMMW17, 2011

Conclusions

- Superconducting technology opens a new avenue for insertion devices
- The first test superconducting undulator – SCU0 has been successfully built and installed into the APS storage ring. It’s a user device since January 2013.
- More advanced devices could be built with better superconductors.