Superconducting Undulator Status

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Scope

- Why a superconducting-technology based undulators (SCUs)?
- Superconducting helical undulator at Rutherford Appleton Laboratory
- Superconducting planar undulator at Advanced Photon Source
- Conclusions

Why a superconducting technology-based undulator ?

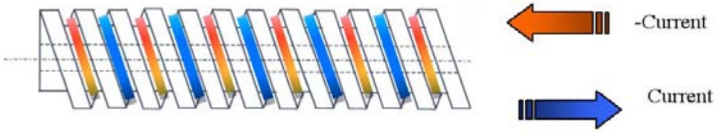
- A superconducting undulator is an electromagnetic undulator that employs high-current superconducting windings for magnetic field generation -
    - total current in winding block is up to 10-20 kA -> high peak field
    - poles made of magnetic material enhance field further -> coil-pole structure ("super-ferric" undulator)
- Superconducting technology compared to conventional pure permanent magnet or hybrid IDs offers:
    - **higher peak field for the same period length**
    - **or smaller period for the same peak field**

- 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 storage ring insertion devices.

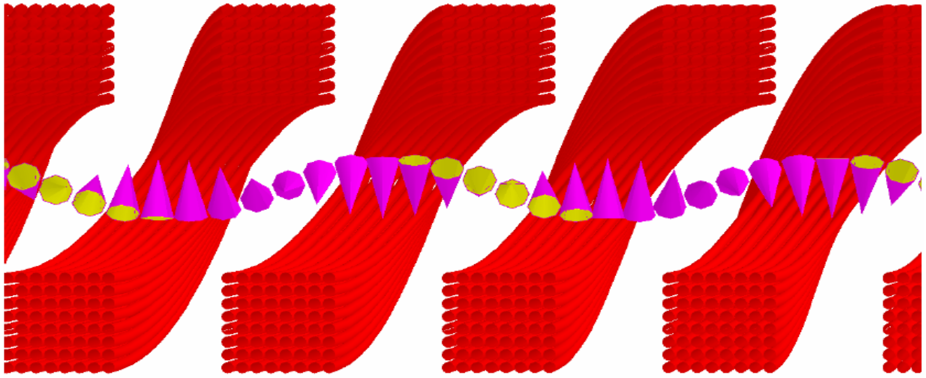
Development of superconducting helical undulator at Rutherford Appleton Laboratory

ILC Helical undulator requirements

UNDULATOR PARAMETERS	Symbol	Value	Units
Undulator Period	λ	1.15	cm
Undulator Strength	K	0.92	
Undulator Type		helical	
Undulator Length	L_u	147	m
Field on Axis	B	0.86	T
Beam Aperture		5.85	mm
Photon Energy (1^{st} harmonic cutoff)	E_{c10}	10.06	MeV



Multi-wire winding model in Opera 3d



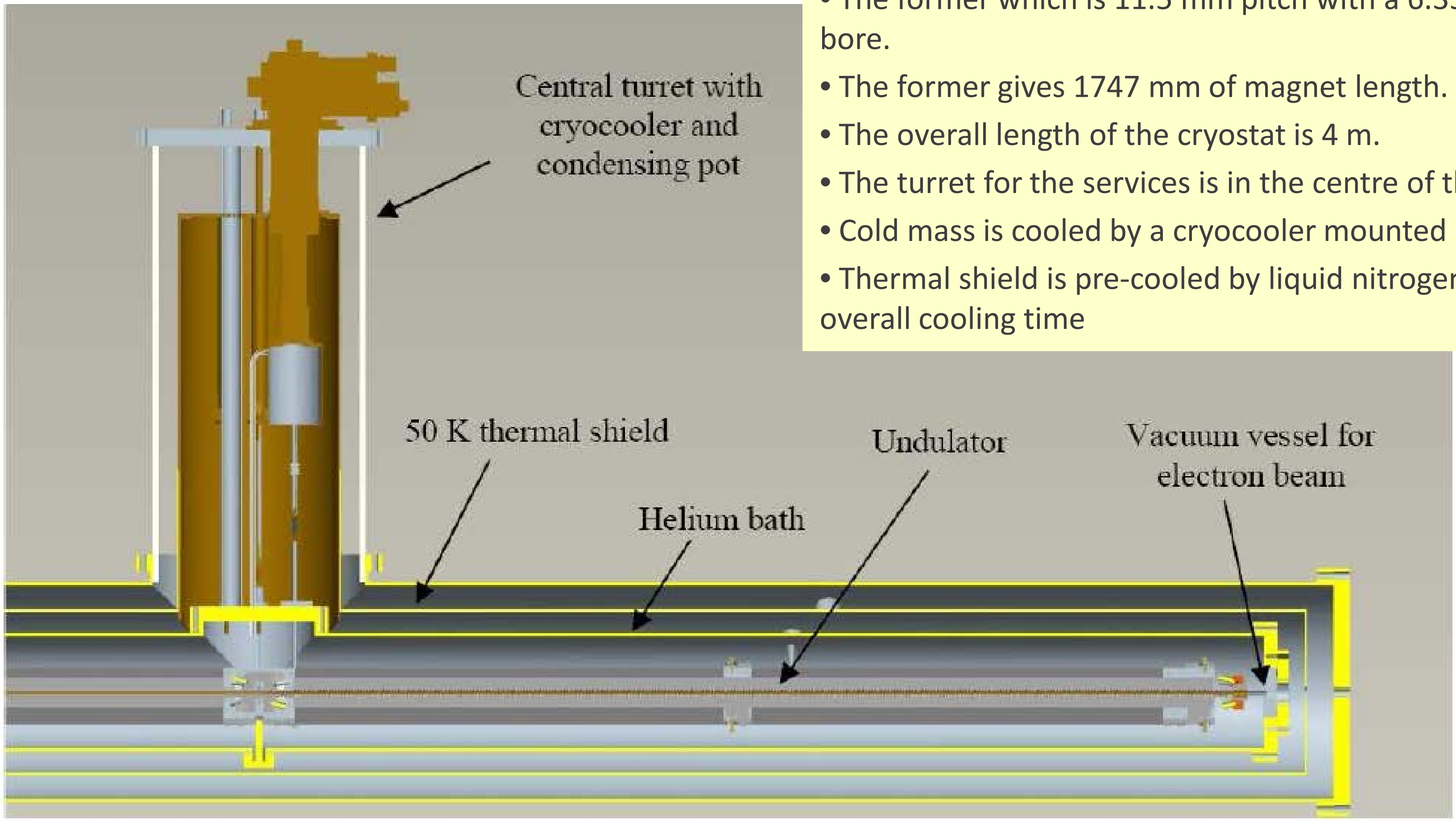
Model parameters:
dimensions and positions of individual wires;
wire current

VECTOR FIELDS

Undulator 4m module layout

The main features of the undulator module are:

- The module is made up of a magnet (two sections), helium bath, thermal shield and a cryostat.
- The former which is 11.5 mm pitch with a 6.35 DIA winding bore.
- The former gives 1747 mm of magnet length.
- The overall length of the cryostat is 4 m.
- The turret for the services is in the centre of the cryostat.
- Cold mass is cooled by a cryocooler mounted in the turret.
- Thermal shield is pre-cooled by liquid nitrogen to reduce overall cooling time



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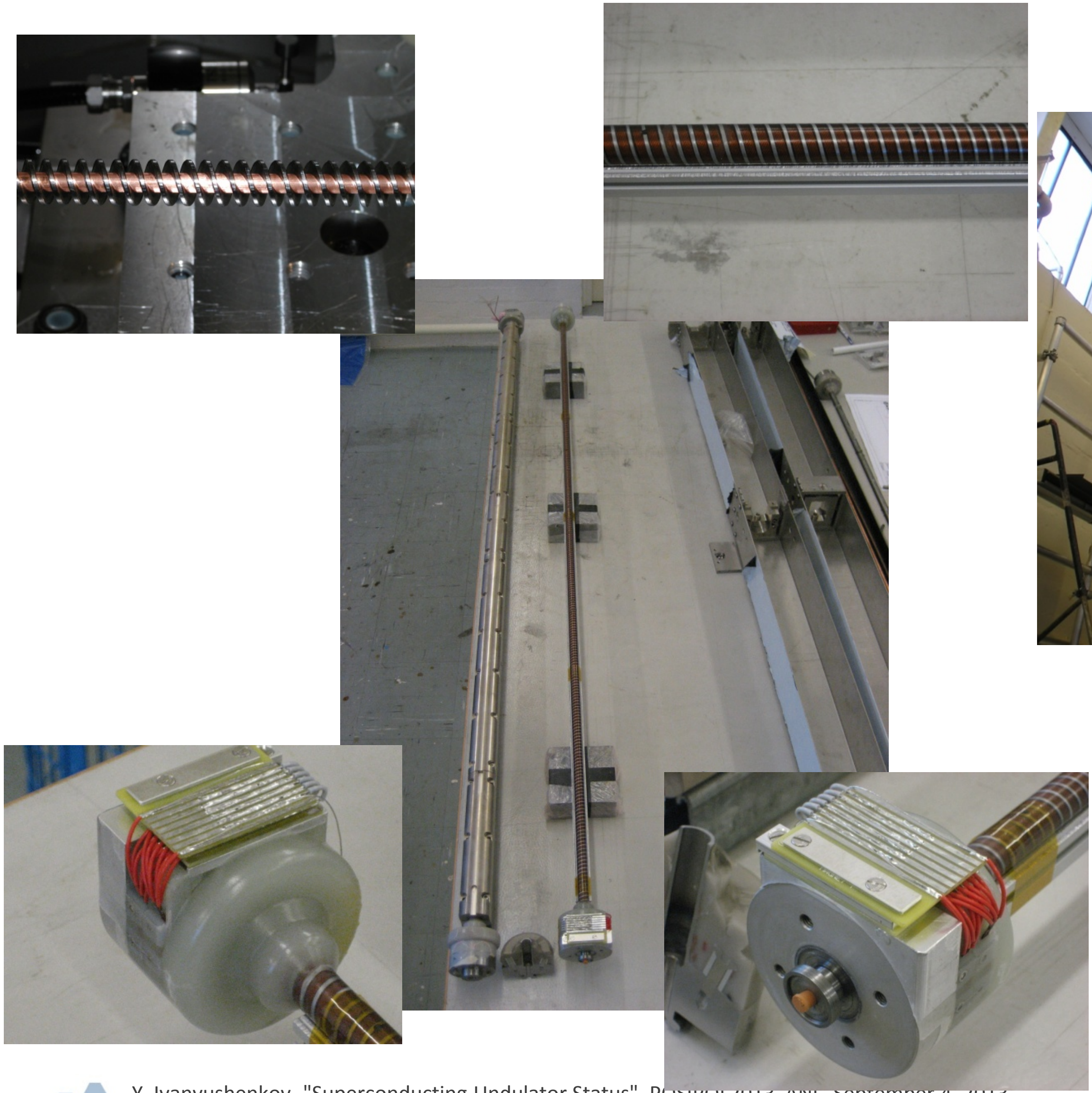
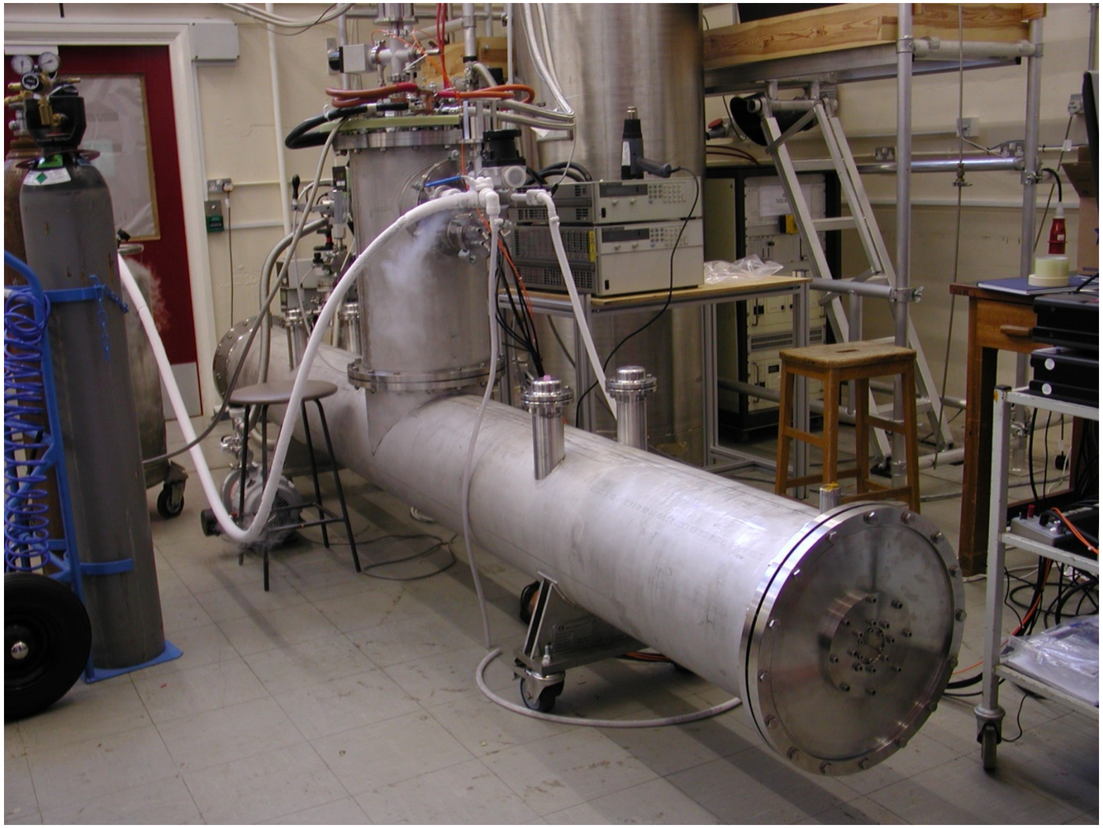
1.7-m helical magnet

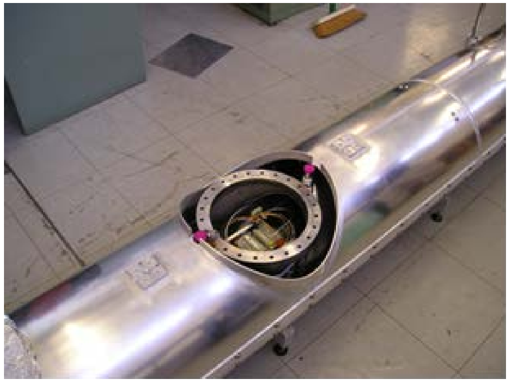


Design spec:
Current: 214 A
Field on axis: 0.86 T

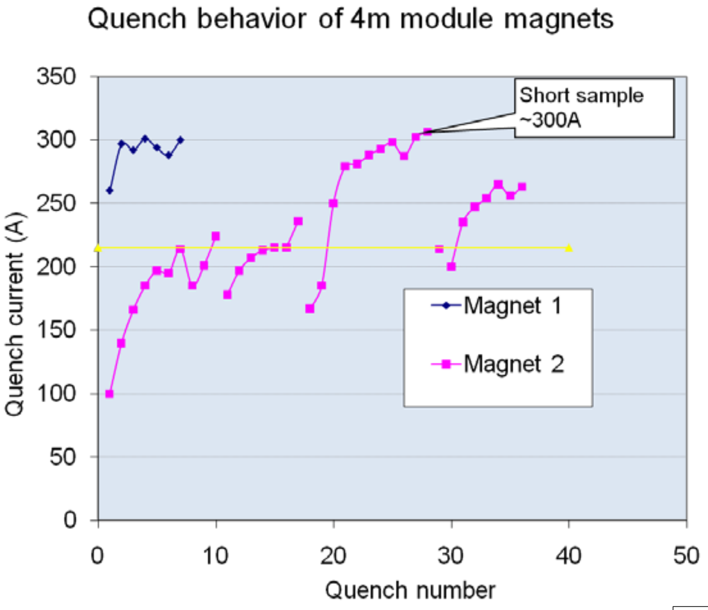
Test results:
Magnet went straight to 214 A without quenching;
Measured field at 214 A: 0.86 T

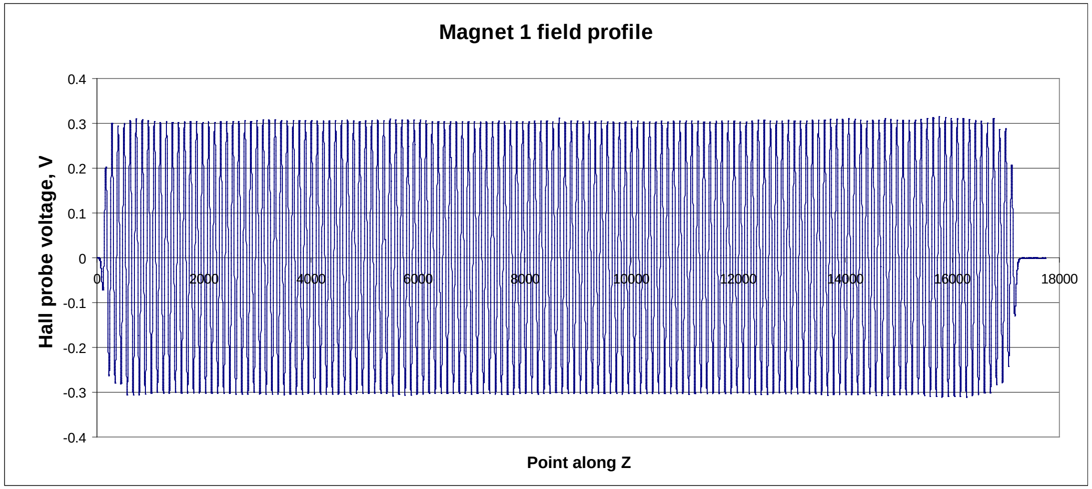
4-m module fabrication and cryogenic tests



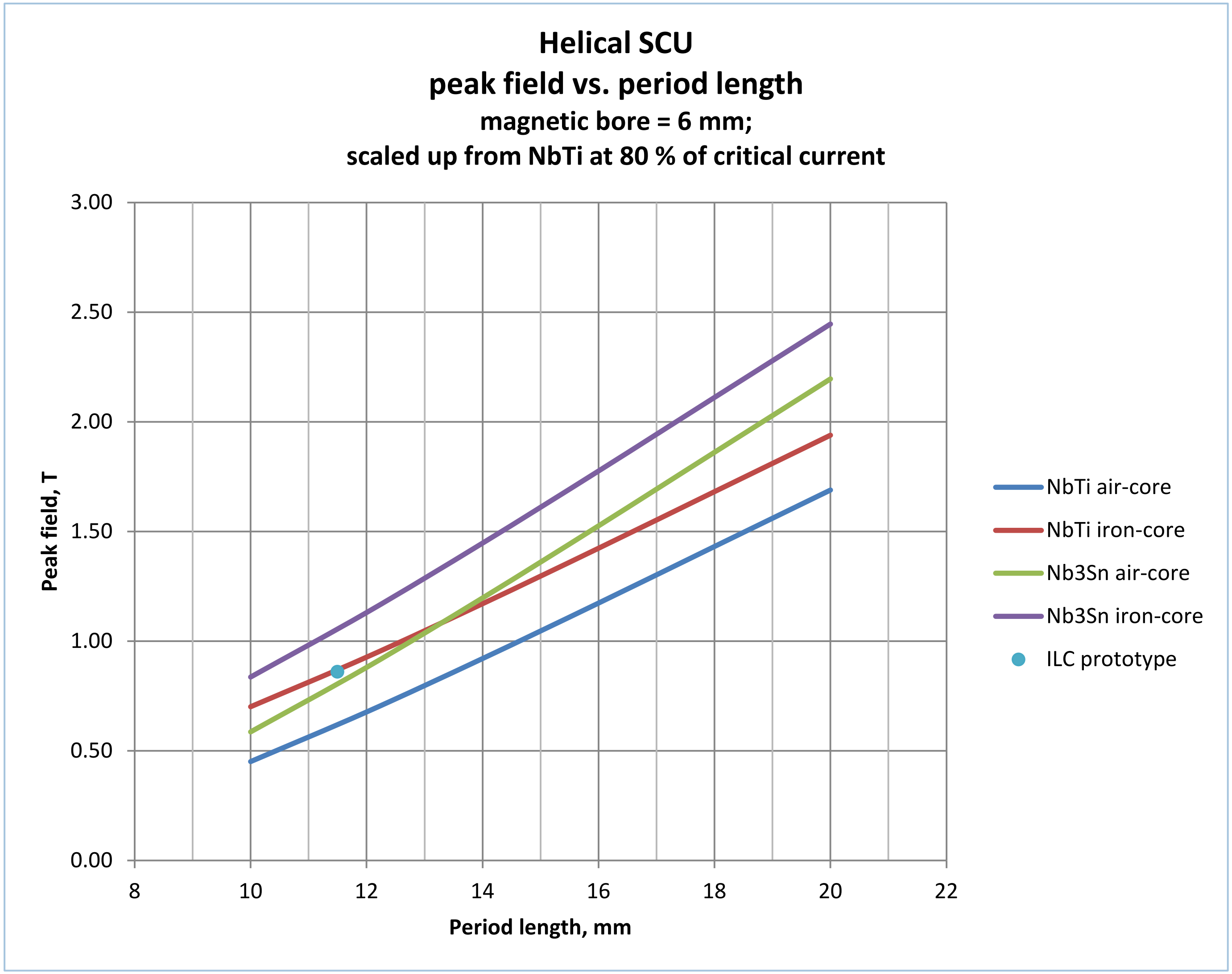


4-m module magnets test





Expected field from a helical SCU



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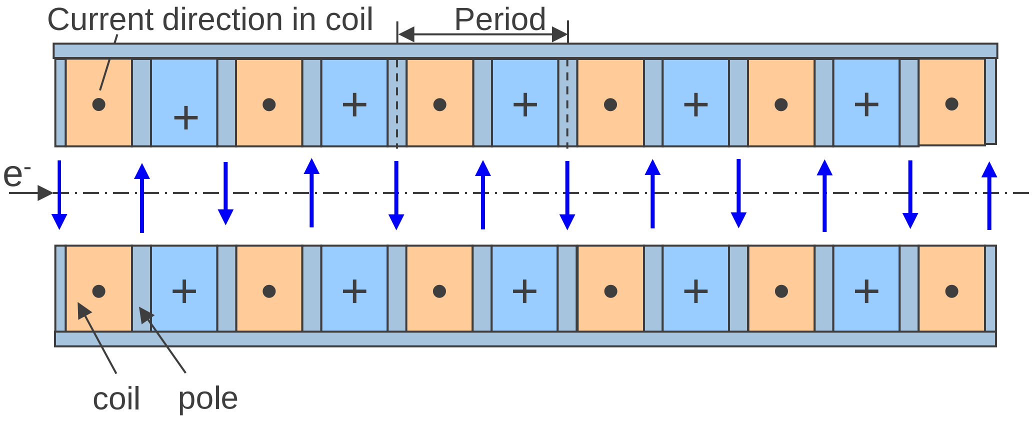
Lessons learned at RAL

- Define and agree the device spec
  (don’t promise unrealistic performance for the first device)
- Start with NbTi superconductor but not with Nb_3Sn for the first device
- Make magnetic design
- Develop technological techniques of fabricating a former, winding a coil, resin impregnation
- Verify the techniques by building short magnets first, then go for longer magnets in sequential steps
- Understand heat loads (part of the spec)
- Design cooling system (put a lot of margin on cooling capacity)
- Make conceptual design of a complete undulator
- Run a conceptual design review (listen to comments by experts in the field)
- Make detail design
- Fabricate the device
- Test magnets in LHe bath cryostat
- Build a measurement system and use it to measure the device performance.

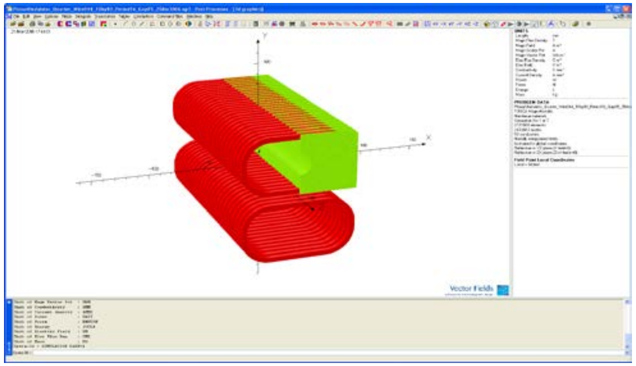
Development
of superconducting planar undulator
at Advanced Photon Source

Superconducting planar undulator topology

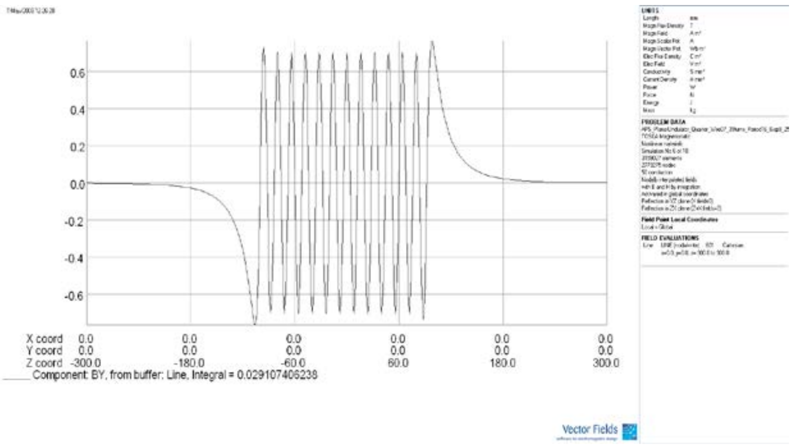
Current directions in a planar undulator



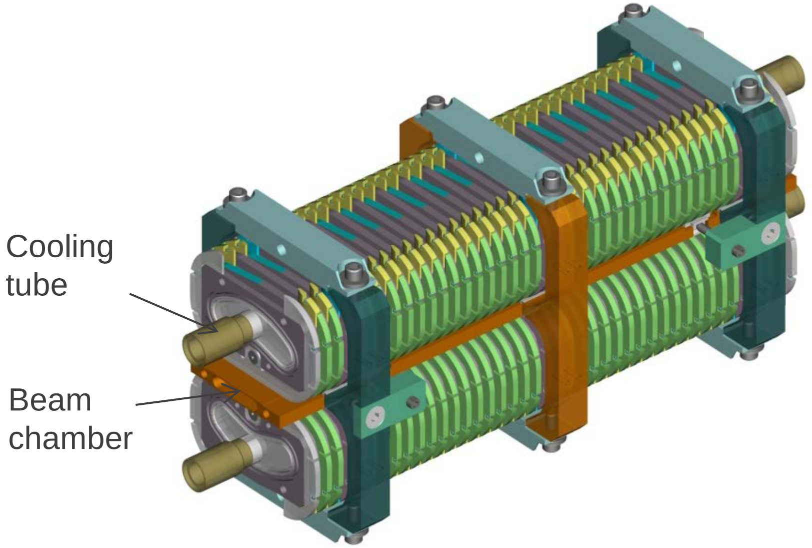
Planar undulator winding scheme



On-axis field in a planar undulator



Magnetic structure layout



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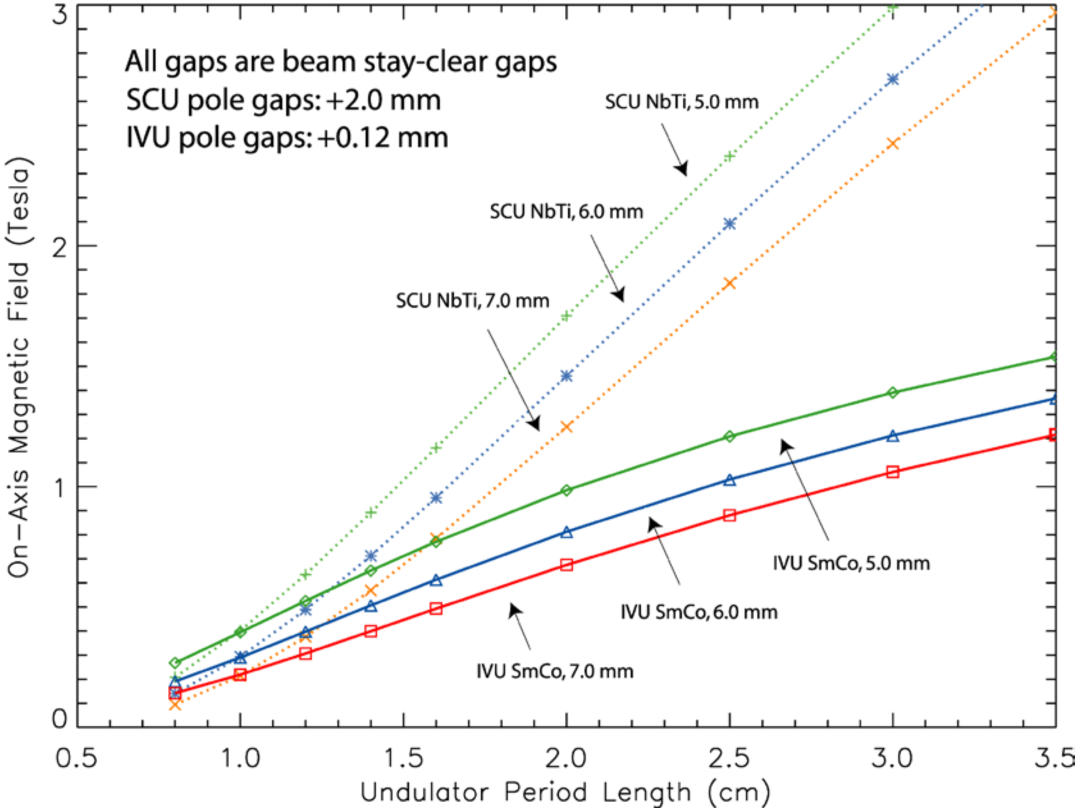
Undulator peak field for various planar insertion device technologies

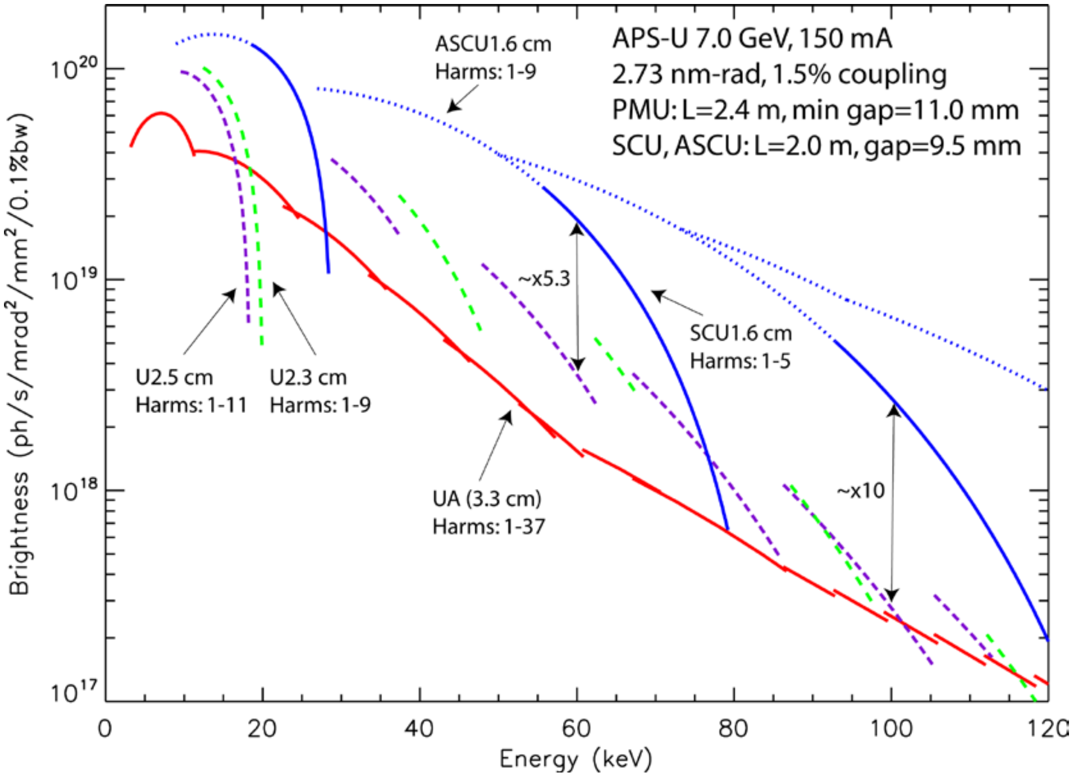


Comparison of the magnetic field in the undulator midplane for in-vacuum SmCo undulators (B_{eff}) and NbTi superconducting undulators (B_0) versus undulator period length for three beam stay-clear gaps. The actual undulator pole gaps were assumed to be 0.12 mm larger for the IVUs and 2.0 mm larger for 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.)

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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
SCU0 is a user device	Since January 2013

SCU program at APS

SCU0 – Test device

The device is built, installed into Sector 6 of the APS, and in operation since January 2013.

SCU1 – Prototype device

SCU1 will use a modified SCU0-type cryostat with a 1-m long magnet.

SCU2

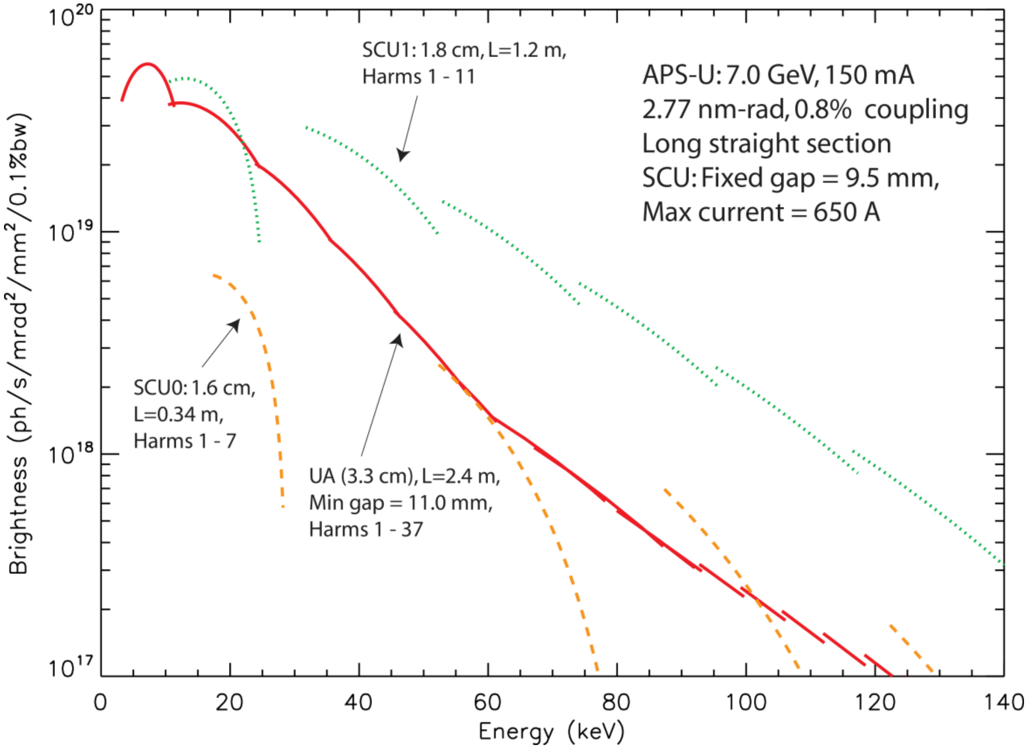
SCU2 will use a longer cryostat with a 2-m long magnet.

First undulators for the APS

APS superconducting undulator specifications

	Test Undulator SCU0	Prototype Undulator SCU1
Goal	- Check design concept; - Study SCU behavior in SR	- Increase magnetic length
Photon energy at 1st harmonic	20-25 keV	12-25 keV
Undulator period	16 mm	18 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

SCU0 and SCU1 spectral tuning curves



This plot shows the large increases in high-energy flux provided by superconducting devices.

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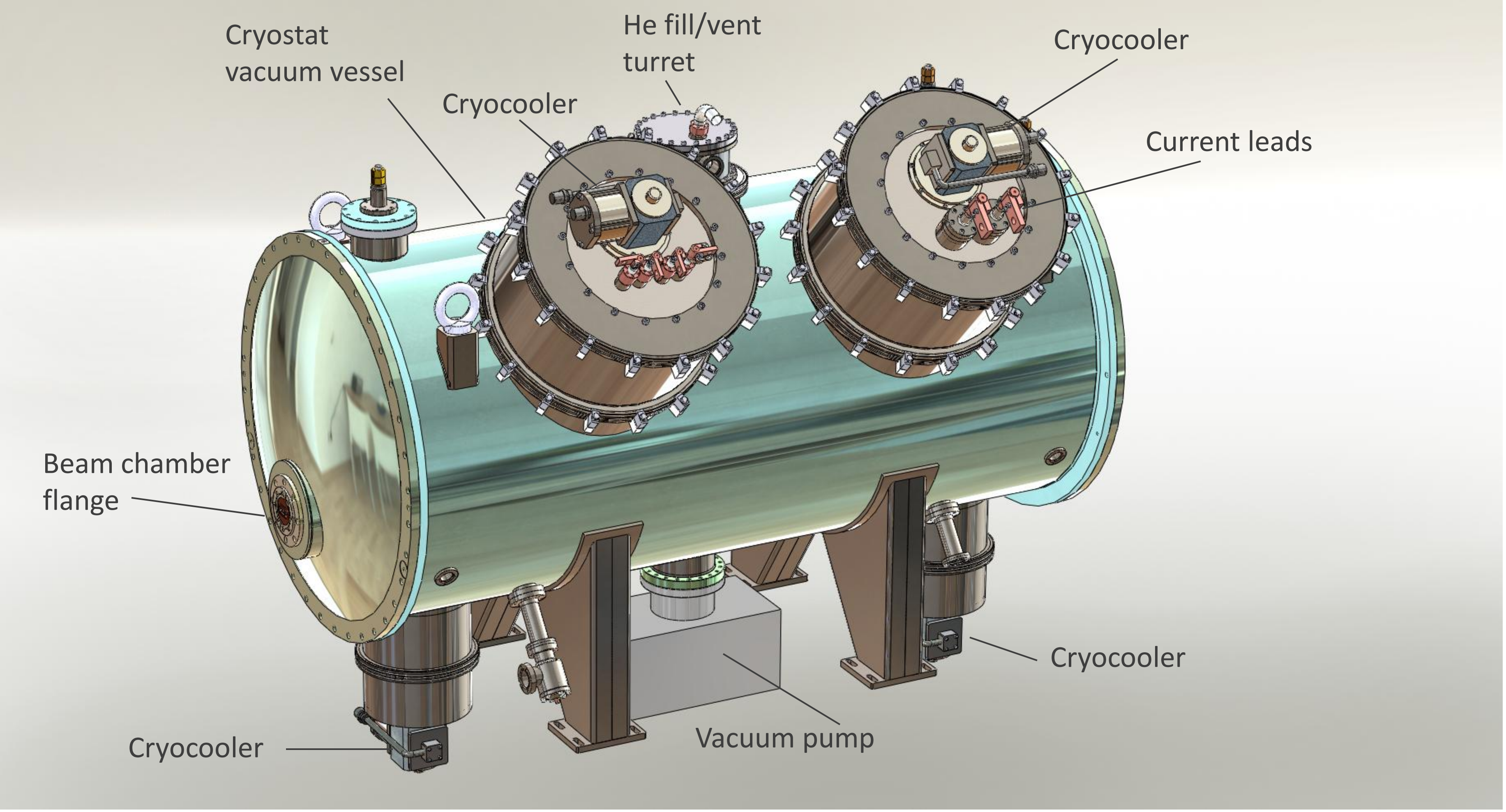
SCU0 cryostat layout

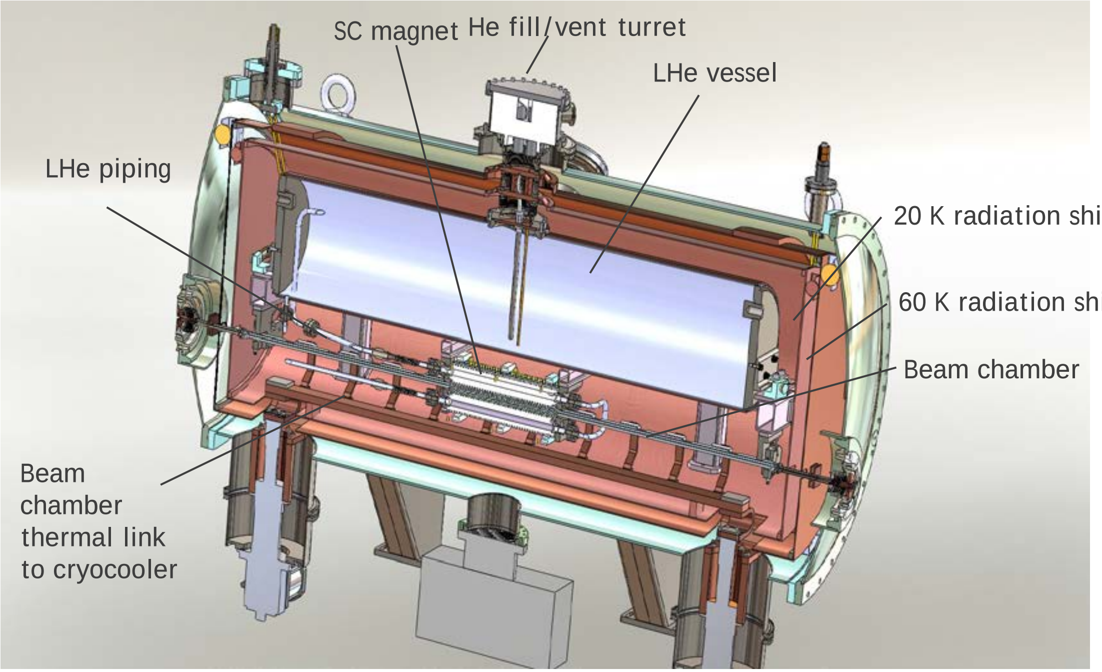


SCU0 design

SCU0 Design Conceptual Points:

- Cooling power is provided by four cryocoolers
- Beam chamber is thermally insulated from superconducting coils and is kept at 12-20 K
- Superconducting coils are indirectly cooled by LHe flowing through the channels inside the coil cores
- LHe is contained in a 100-liter buffer tank which with the LHe piping and the cores makes a closed circuit cooled by two cryocoolers
- Two other cryocoolers are used to cool the beam chamber that is heated by the electron beam

SCU0 structure



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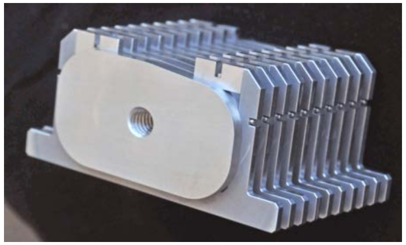
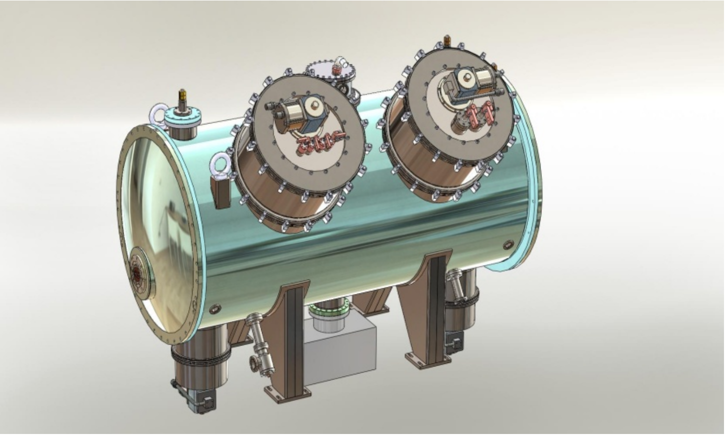
SCU0 – from an idea to real device

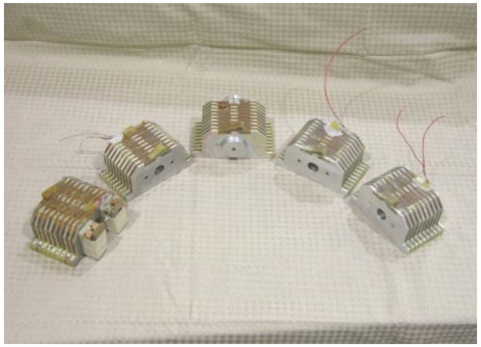
A model of test coil



SCU0 3d design model

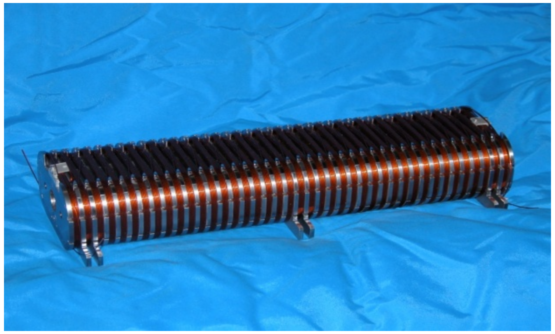


The first five 10-pole test coils



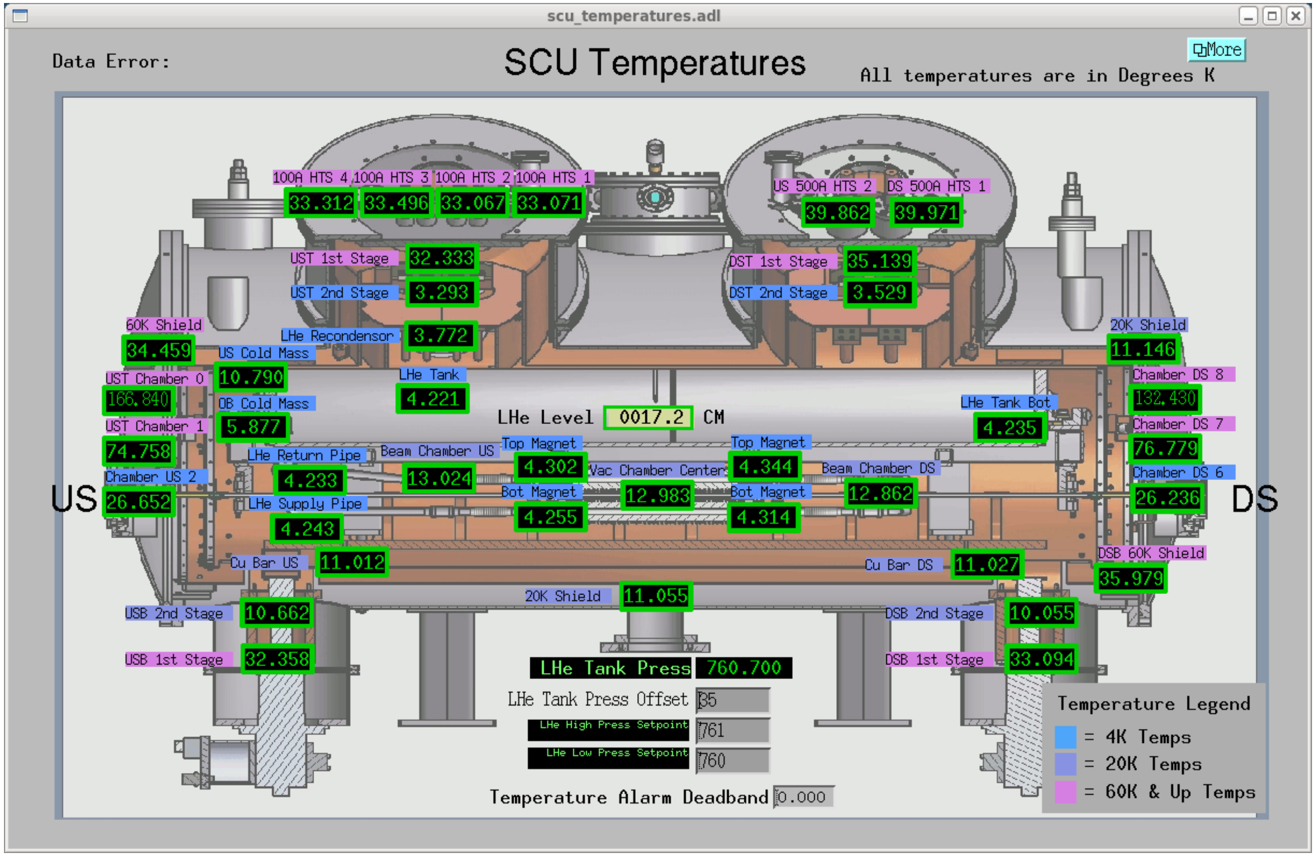
SCU0 in the APS storage ring

First wound 42-pole test coil



SCU0 performance

- Designed for operation at 500 A, operates reliably at 650 A-680 A.
- Did not quench except when electron beam was unintentionally dumped, and once with uncontrolled beam steering while ramping
- The magnet cores remain at 4 K even with 16 W of beam power on the beam chamber
- No loss of He is observed in about 6-month period



Data Error:

SCU Temperatures

All temperatures are in Degrees K

100A HTS 4 33.312
100A HTS 3 33.496
100A HTS 2 33.067
100A HTS 1 33.071
US 500A HTS 2 39.862
DS 500A HTS 1 39.971
UST 1st Stage 32.333
UST 2nd Stage 3.293
DST 1st Stage 35.139
DST 2nd Stage 3.529
60K Shield 34.459
LHe Recondensor 3.772
US Cold Mass 10.790
20K Shield 11.146
UST Chamber 0 166.840
LHe Tank 4.221
Chamber DS 8 132.430
OB Cold Mass 5.877
LHe Tank Bot 4.235
UST Chamber 1 74.758
Chamber DS 7 76.779
LHe Return Pipe 4.233
Beam Chamber US 13.024
Top Magnet 4.302
Top Magnet 4.344
Chamber US 2 26.652
Vac Chamber Center 12.983
Beam Chamber DS 12.862
Chamber DS 6 26.236
Bot Magnet 4.255
Bot Magnet 4.314
LHe Supply Pipe 4.243
Cu Bar US 11.012
Cu Bar DS 11.027
DSB 60K Shield 35.979
20K Shield 11.055
USB 2nd Stage 10.662
DSB 2nd Stage 10.055
USB 1st Stage 32.358
DSB 1st Stage 33.094

LHe Level 0017.2 CM

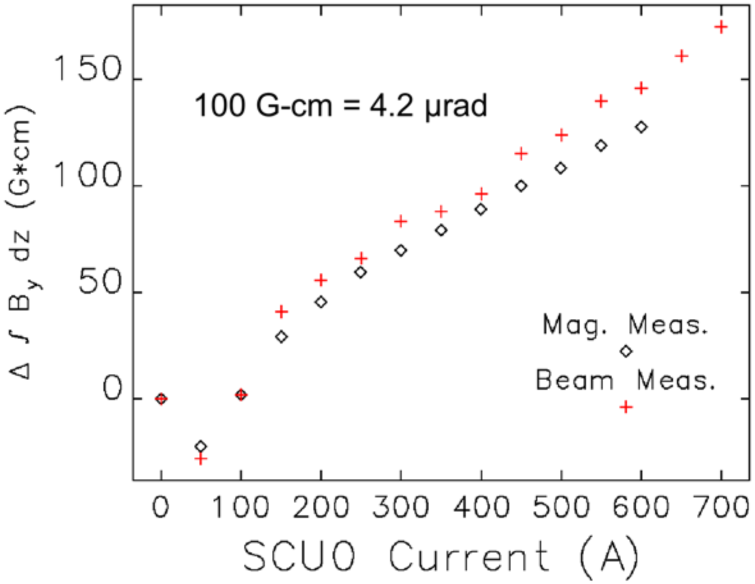
LHe Tank Press 760.700
LHe Tank Press Offset 35
LHe High Press Setpoint 761
LHe Low Press Setpoint 760
Temperature Alarm Deadband 0.000

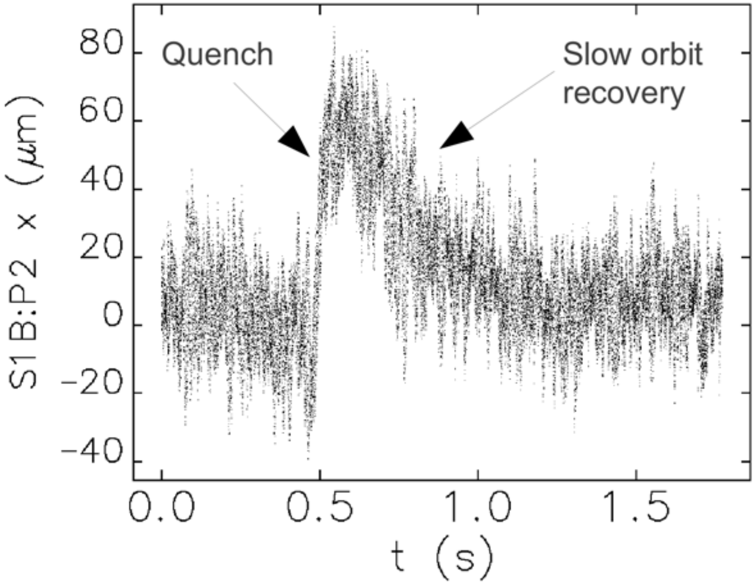
Temperature Legend
- 🟦 = 4K Temps
- 🟪 = 20K Temps
- 🟪 = 60K & Up Temps

The measured temperatures in the SCU0 cryostat at beam current of 100 mA (24 bunches), SCU0 magnet is off.

Impact of SCU0 on beam operation

- Field integral measured with beam
  - Variation in field integral was inferred from effort of nearby steering correctors.
  - Field integrals agree reasonably well with magnetic measurements in stand-alone tests.
- Effect of quench on beam
  - Beam motion is small, even without fast orbit feedback running, as in this example.
  - Quench does not cause loss of beam
  - Beam position limit detectors were not triggered.





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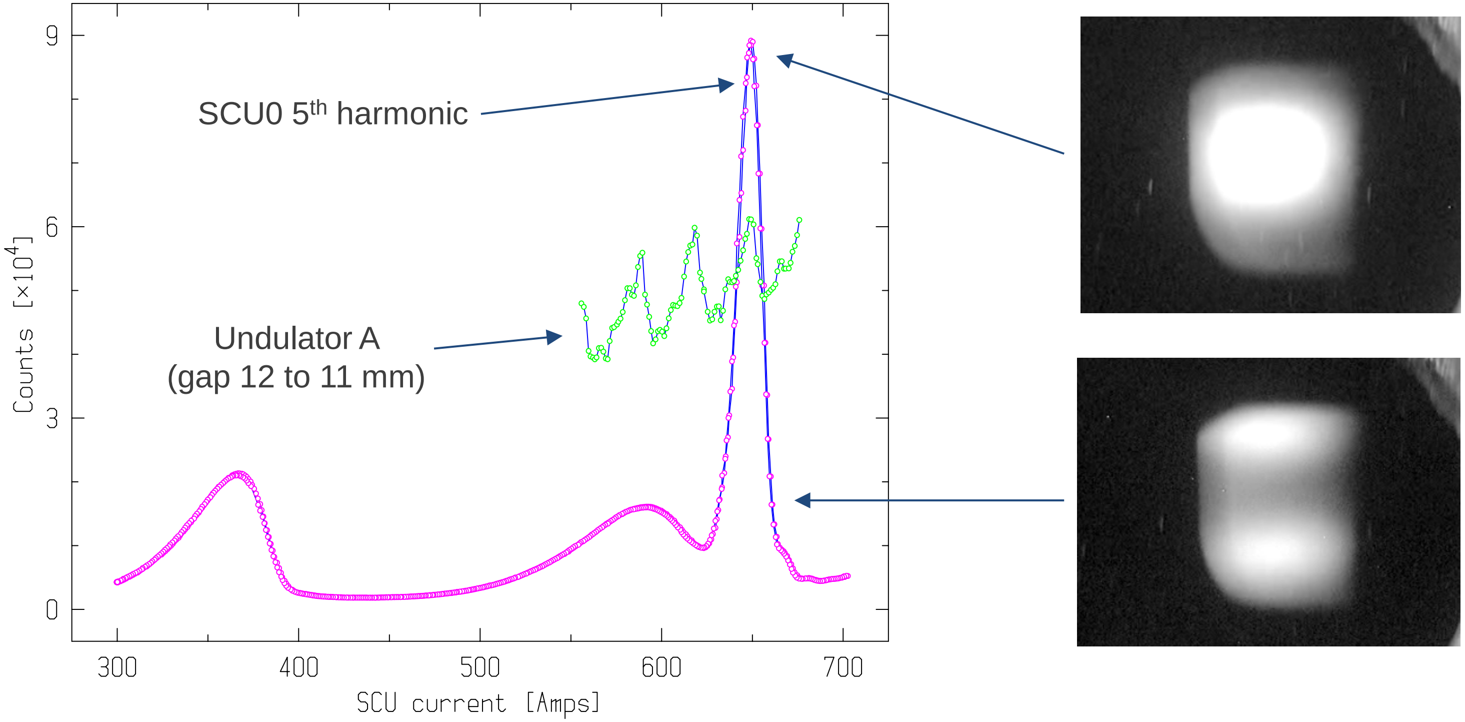
SCU0 X-ray flux characterization

Measured flux passing through a bent-Laue monochromator at 85 keV compared with Undulator A

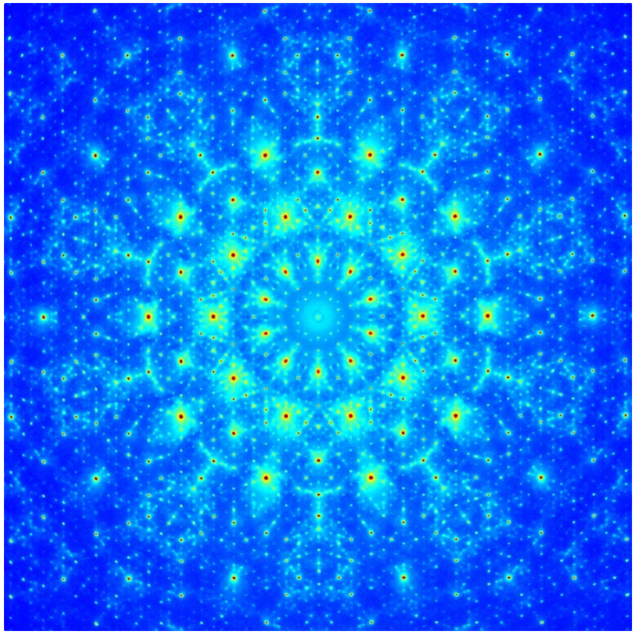


The measured flux at 85 keV as SCU0 current is increased from 300 A to 700 A (cyan) compared with the flux obtained from Undulator A as gap is reduced from 12 mm to 11 mm (green). Images on the right show beam profile on a scintillator screen at the peak of the SCU0 5th harmonic and for slightly higher current where two lobes develop.

Initial user experiments

After installation and characterization, the SCU0 device was used as the radiation source for some initial user experiments. The experiments took advantage of the enhanced high energy x-ray (>100 keV) flux provided by the SCU0.

Diffraction pattern from Al-Co-Ni decagonal quasicrystal showing ten-fold symmetry. High-energy diffraction provides an undistorted view of reciprocal space enabling a quantitative analysis of both the Bragg peaks and diffuse scattering.



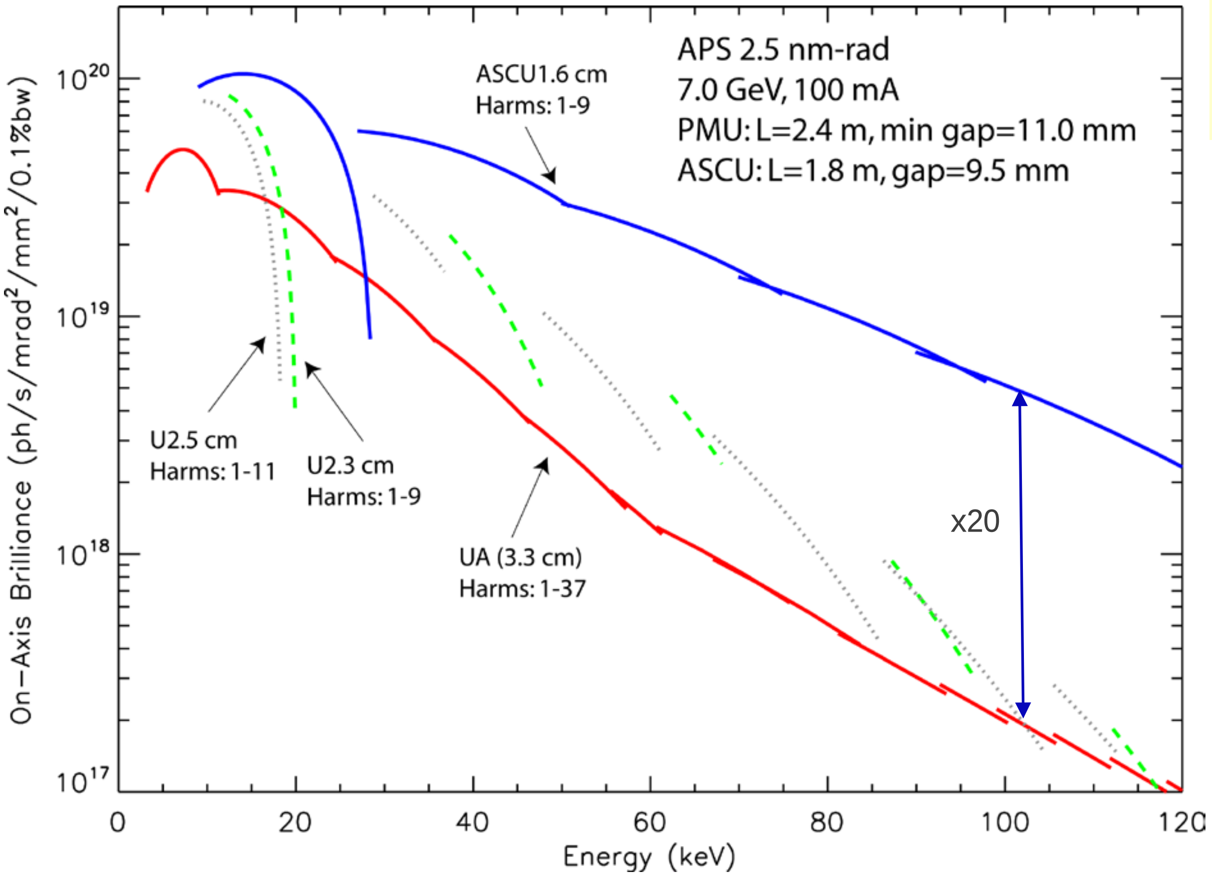
Data provided by A. Kreyssig and A. Goldman – Iowa State University and Ames Lab.

Next SCUs

- The APS Upgrade program includes SCU1 and SCU2:
  - SCU1: a 1-m long magnet in 2-m long SCU0-type cryostat
  - SCU2: a 2.0−2.3-m long magnet in 3-m long cryostat

- The APS SCU team is currently working on SCU1

Future SCUs: 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 !

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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.

- 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.
  - High-temperature superconductors (HTS) operating at temperatures around and above 77 K will allow the use of simpler (less costly) cooling systems. Development of HTS superconductors with larger effective thickness might lead to HTS-based undulators with very high peak fields.

- **Superconducting technology opens a new avenue for insertion devices.**

Conclusions

- A 4-m helical undulator prototype has been built by RAL team for the ILC positron source project. This project demonstrated a feasibility of building ILC helical indulator.
- The first planar superconducting undulator has been built at the APS, and is currently in user operation. This project demonstrates that an SCU can successfully operate in a storage ring.
- The experience gained in those projects, could be now used for building undulators for Linear Collider.

Acknowledgements

The success in SCU development could not be possible without great contributions by:

- The members of the UK HeLiCal Collaboration.
- The APS Superconducting Undulator Team.