Experience at APS with novel cooling schemes for SC insertion devices

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on behalf of the APS SCU Team

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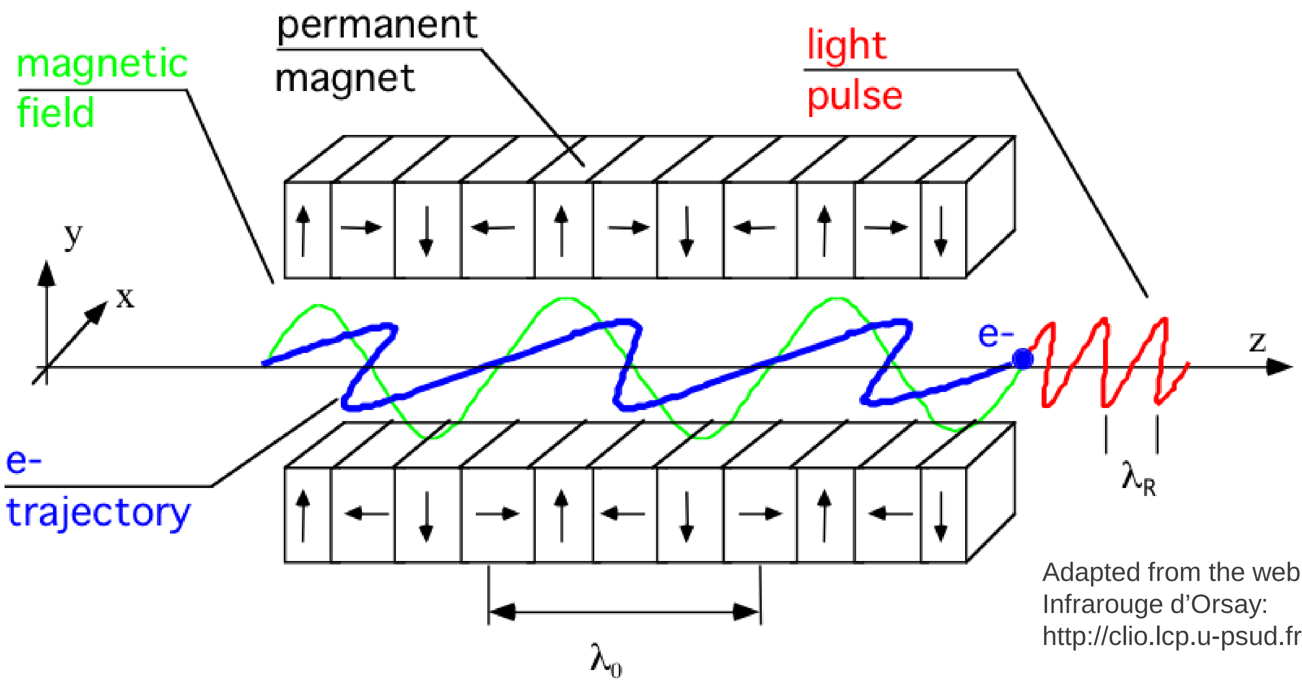
Scope

- Why a superconducting-technology based undulators (SCUs)?
- SCU challenges
- SCU0 heat loads and cooling scheme
- SCU0 cryogenic performance
- Summary

Undulator radiation



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

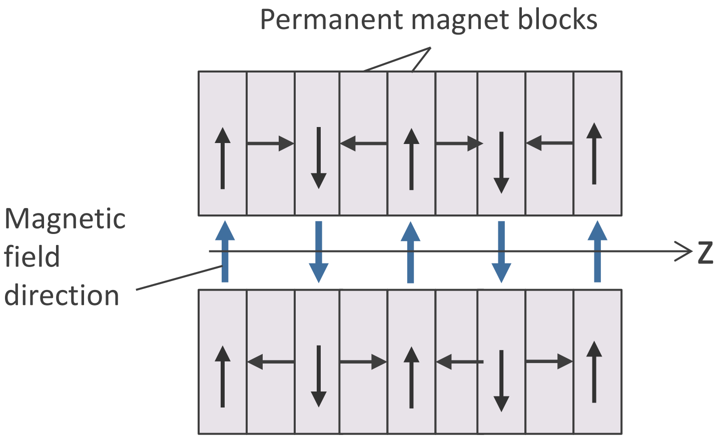
In coordinate frame that moves with an electron in Z:
Electron 'sees' the magnetic structure with the period length λ_0/γ moving towards it, and emits as a dipole at the wavelength $\lambda^*=\lambda_0/\gamma$, where γ is the relativistic Lorentz factor.

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 $\lambda_R = \lambda^*\gamma(1\text{-}\beta) = \lambda_0(1\text{-}\beta) = \lambda_0/2\gamma^2$.

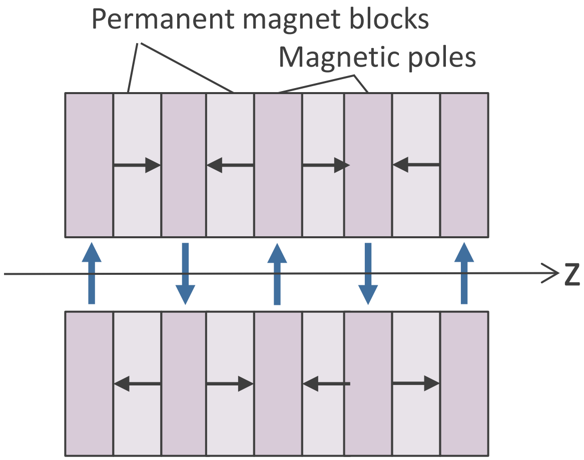
As a result, a 3.3-cm undulator can emit 10-keV photons on a 7-GeV electron storage ring (γ = 13700).

Planar undulator magnetic structure

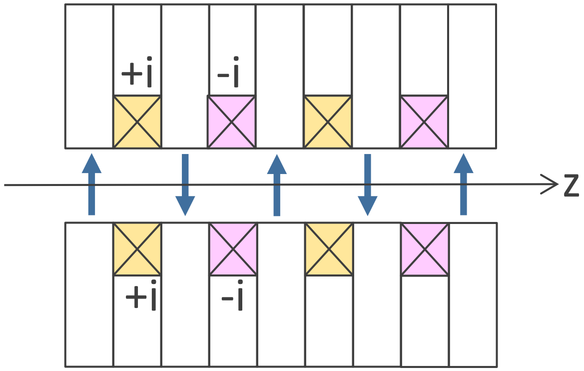
Permanent magnet structure



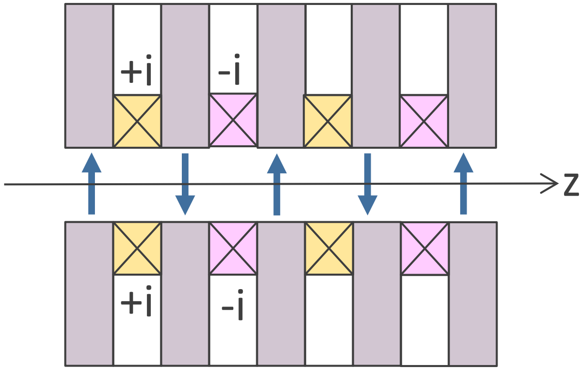
Hybrid structure



Electromagnet structure



Electromagnet structure with magnetic poles

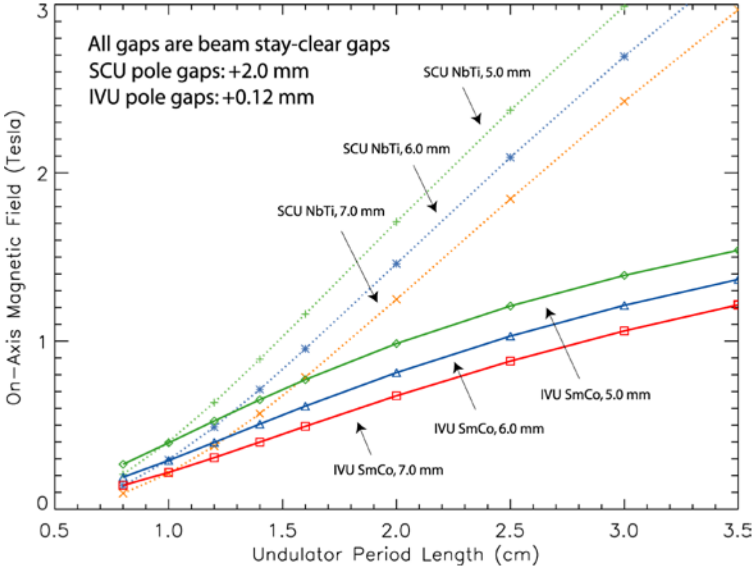


SCU motivation - Higher undulator field

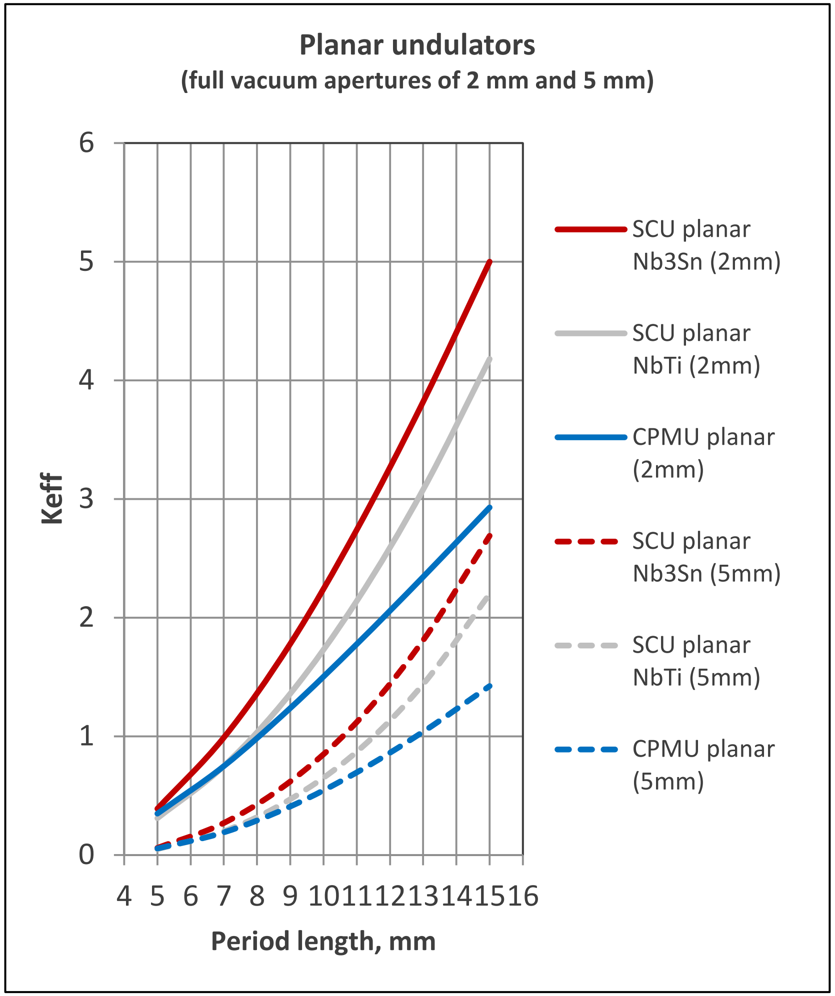
	CPMU PrFeB	SCU NbTi	SCU NbTi-APC
Undulator period, mm	15	15	15
Pole gap, mm	5.2	6	6
Undulator field, T	1.0	1.18	1.46
Undulator parameter K	1.40	1.65	2.05

S. Casalbuoni et al,, “Test of short mockups for optimization of superconducting undulator coils,” presented at MT23, Boston, 2013.

Magnetic fields for in-vacuum undulators (IVUs) and superconducting undulators (SCUs)



R. Dejus et al., “On-Axis Brilliance and Power of In-Vacuum Undulators for the Advanced Photon Source,” MD-TN-2009-004


Planar undulators
(full vacuum apertures of 2 mm and 5 mm)

J. Bahrdt and Y. Ivanyushenkov, “Short Period Undulators for Storage Rings and Free Electron Lasers,” Journal of Physics: Conference Series 425 (2013) 032001.

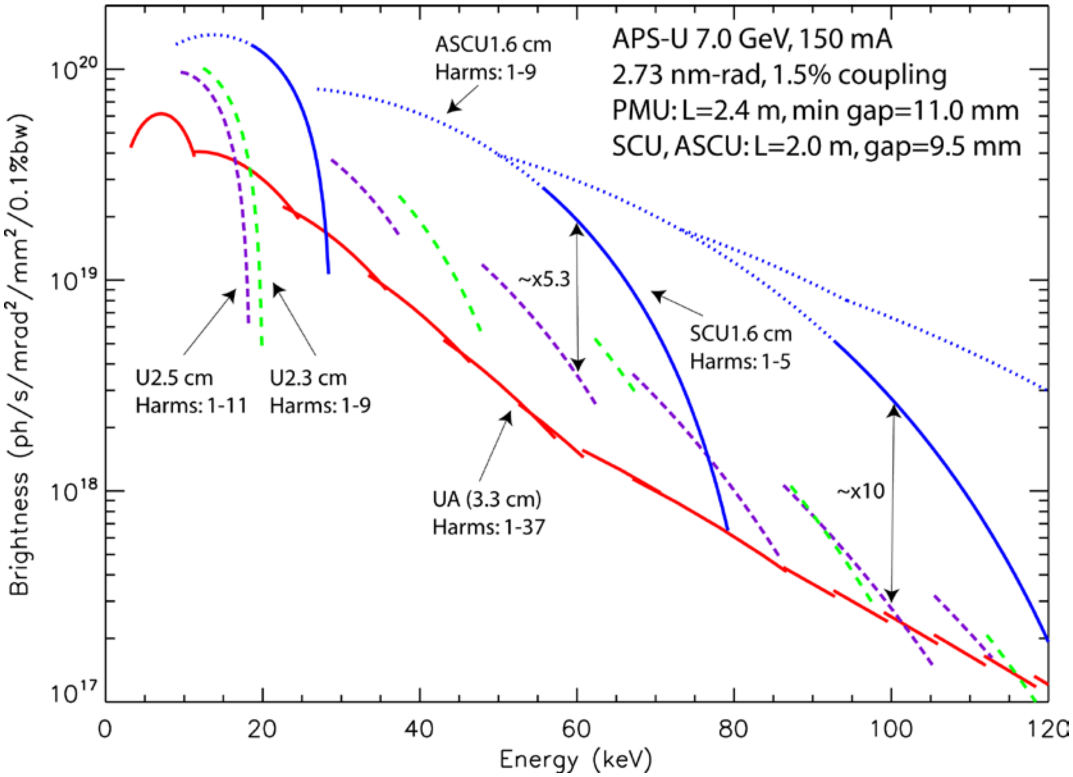
SCU motivation - Higher photon fluxes

Superconducting planar undulator at 3-GeV Diamond Light Source(DLS) will increase photon flux of ~ 15 times and brightness of ~ 20 times at 40 keV when compared to the current in-vacuum undulator [1].

[1] J. Clarke et al., "Status of the UL Superconducting Planar Undulator Project," Proc. of IPAC2013, WEPWA062, p. 2259.

Advanced Photon Source (APS)
undulator brightness tuning curves [2]

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

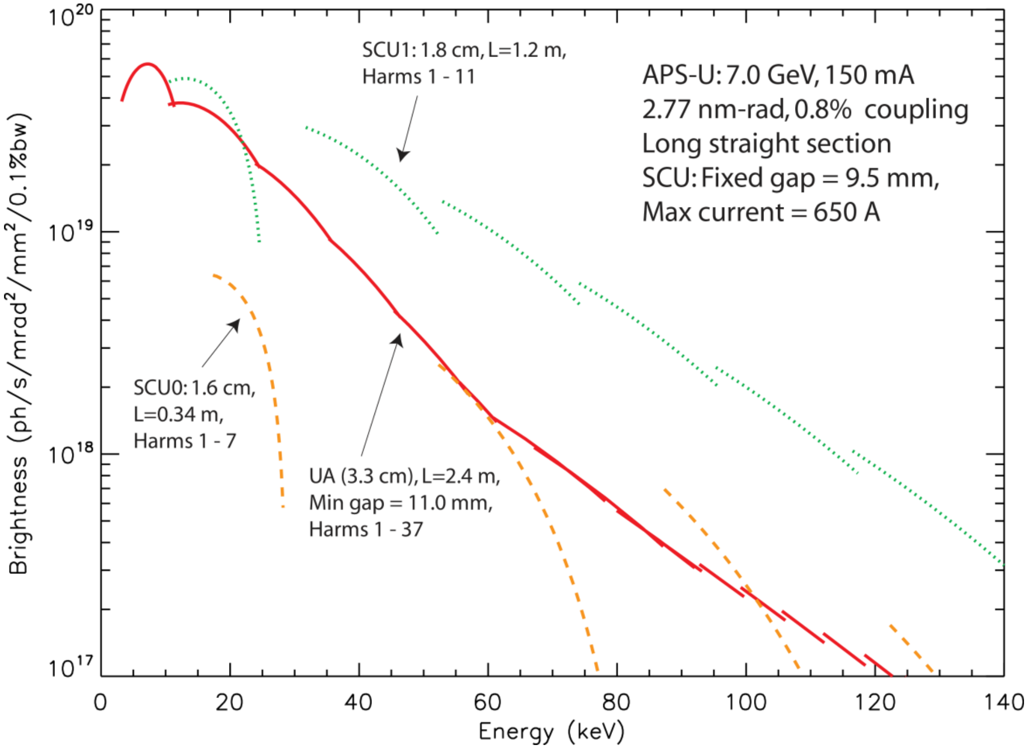


First undulators for the APS

APS superconducting undulator specifications

	Test Undulator SCU0	Prototype Undulator SCU1
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.

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.

SCU0 heat loads

Estimated cw beam-induced heat loads on the SCU0 chamber, in 100-mA user operations [1]

Heat Source	Value at 20 K (60/300 K)
Resistive wall	4.7 W (9.7 W)
Wakefields	< 0.5 W (0.8 W)
Injection losses	2 W (non-top-up mode) 0.1 W (top-up mode)
Synchrotron radiation	0.2 W
Beam lifetime losses	<< 1 W
Electron cloud	< 2 W
Total	10 W (11 W)

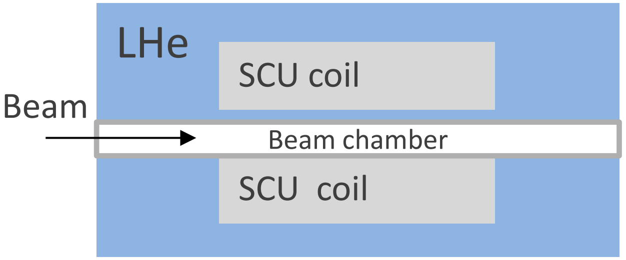
Calculated SCU0 heat loads, W [2]

Heat Source	4 K	20 K	60 K
Beam induced heat		10	11
Thermal radiation	0.017	0.205	0.3
Beam chamber bellows			4.8
Beam chamber support at 20 K	0.08		
He vent bellows	0.0004	0.008	0.6
Cold mas supports	0.08		
Thermal shield supports		0.22	3.3
Correction current leads (70 A)	0.064		8.0 (12)
Main current leads (650 A)	0.285		47 (64)
Total	0.53	10.43	75 (96)

[1] K. Harkay et al., “Beam-induced Heat Load Predictions and Measurements in the APS Superconducting Undulator,” Proc . of NA-PAC’13, WEPSM06 , 2013.
[2] Y. Shiroyanagi et al., “Thermal Modeling of the Prorotype Superconducting Undulator (SCU0),” Proc. of Na-Pac’13, THPAC07, 2013.

SCU cooling schemes

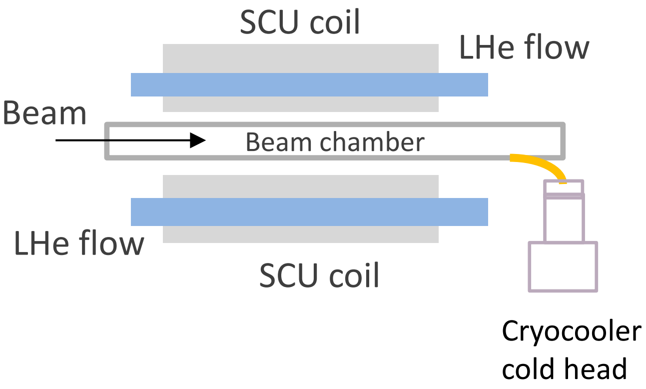
Direct cooling of SCU coils



Pros:
- SCU coils is direct contact with LHe

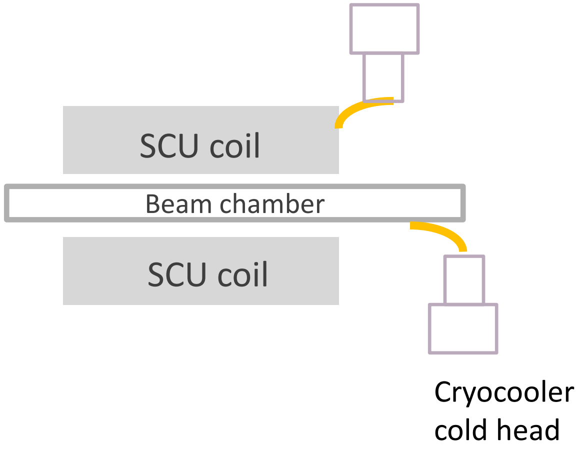
Cons:
- Beam heats LHe

Indirect cooling of SCU coils



Pros:
- No heating of LHe by beam

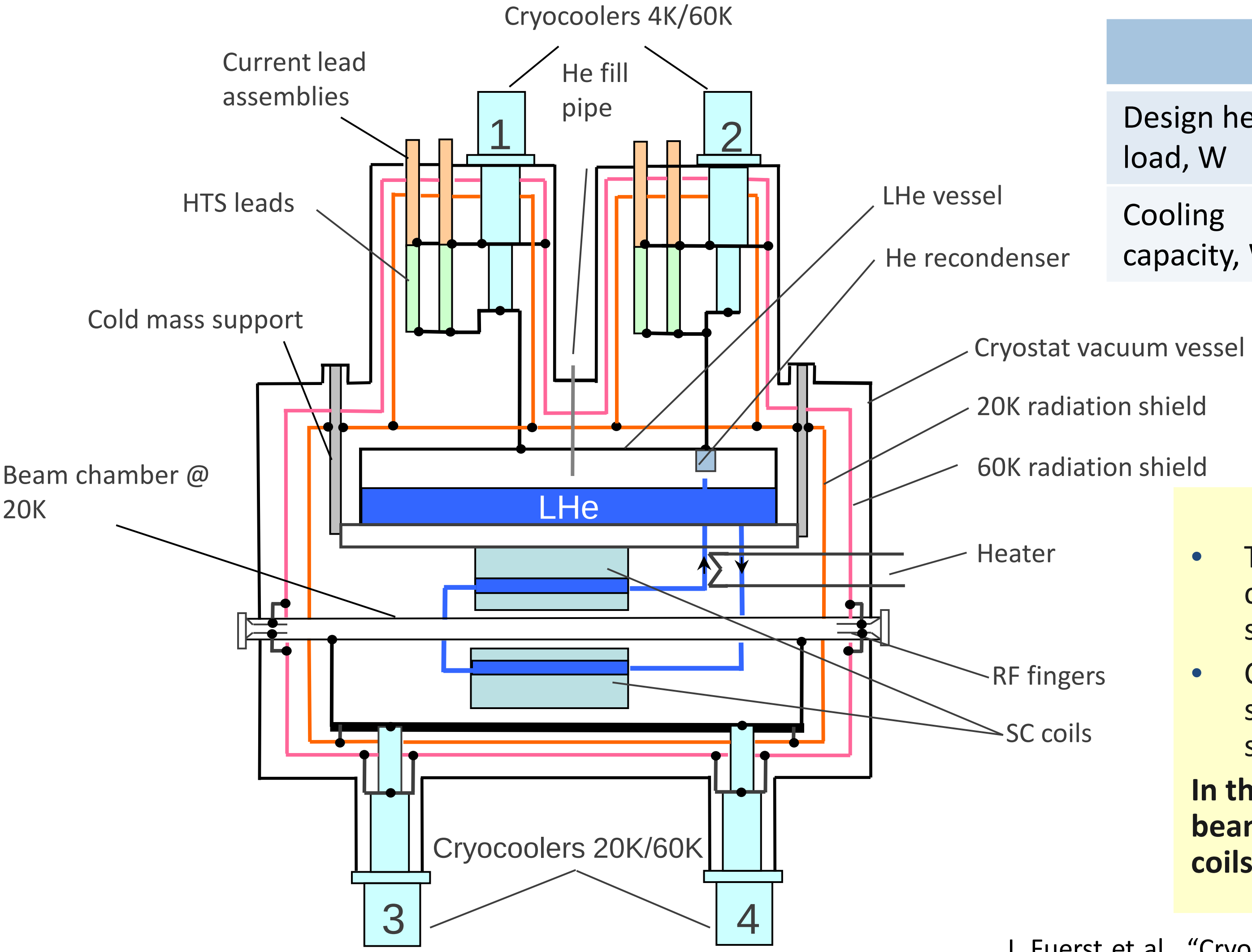
Cons:
- Possible temperature difference between the LHe and the coil;
- LHe pump



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

Cons:
- Temperature difference between the LHe and the coil

SCU0 cooling scheme



	4 K	20 K	60 K
Design heat load, W	0.5	10	96
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!

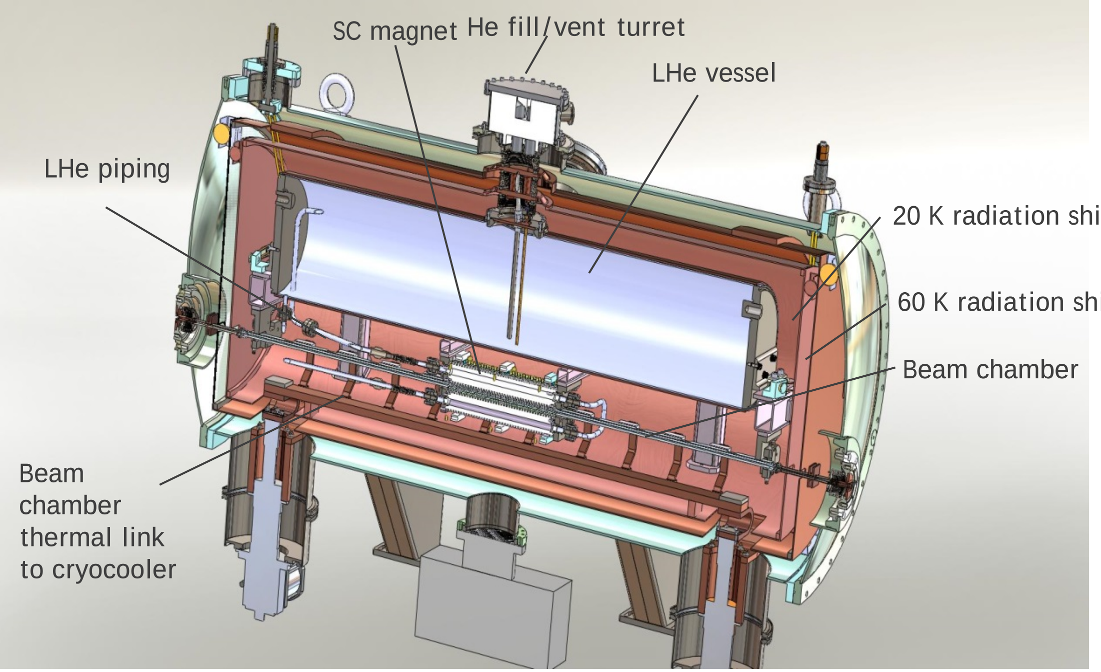
J. Fuerst et al., "Cryostat design and development for a superconducting undulator for the APS," Advances in Cryogenic Engineering, 57A: 901-908, 2012.

SCU0 design

SCU0 Design Conceptual Points:

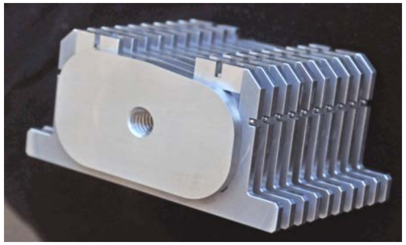
- Cooling power is provided by four cryocoolers
- Beam chamber is thermally insulated from superconducting coils and is kept at 15-20 K
- Superconducting coils are indirectly cooled by LHe flowing through the channels inside the coil cores
- LHe is contained in a 100-liter buffer tank which with the 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

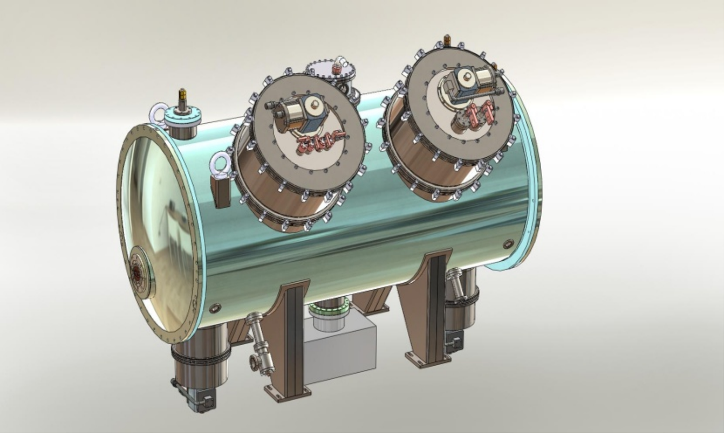


SCU0 – from an idea to real device

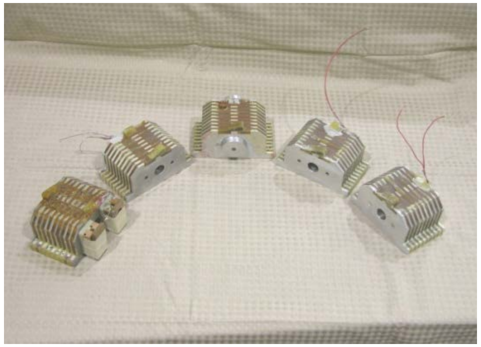
A model of test coil



SCU0 3d design model

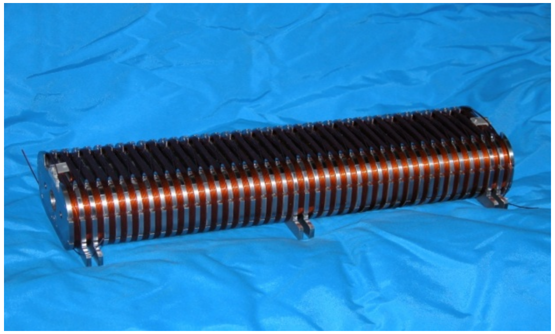


The first five 10-pole test coils



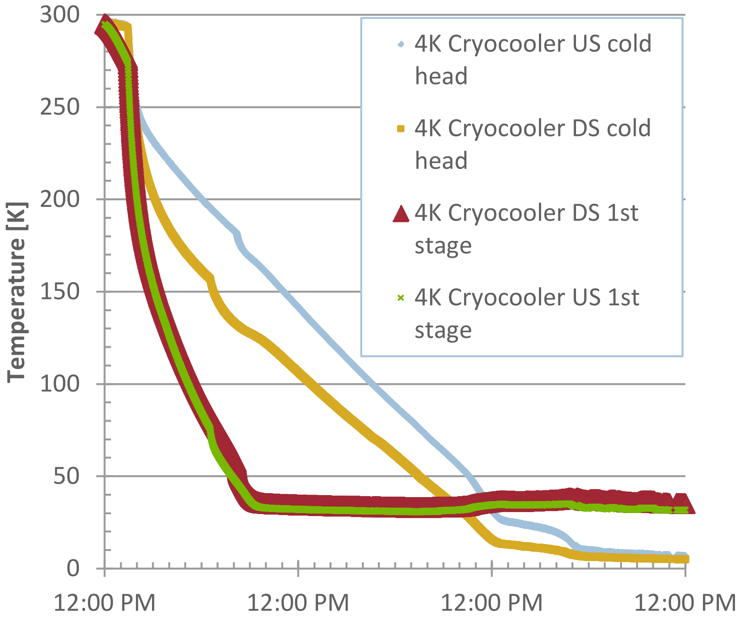
SCU0 in the APS storage ring

First wound 42-pole test coil



SCU0 cold test – Cryogenic performance: Cool down

- A design concept of cooling the undulator down with compact cryocoolers has been confirmed.
  The system achieved cool-down during a day, using cryocooler power alone requiring total three days to stabilize at LHe temperature.

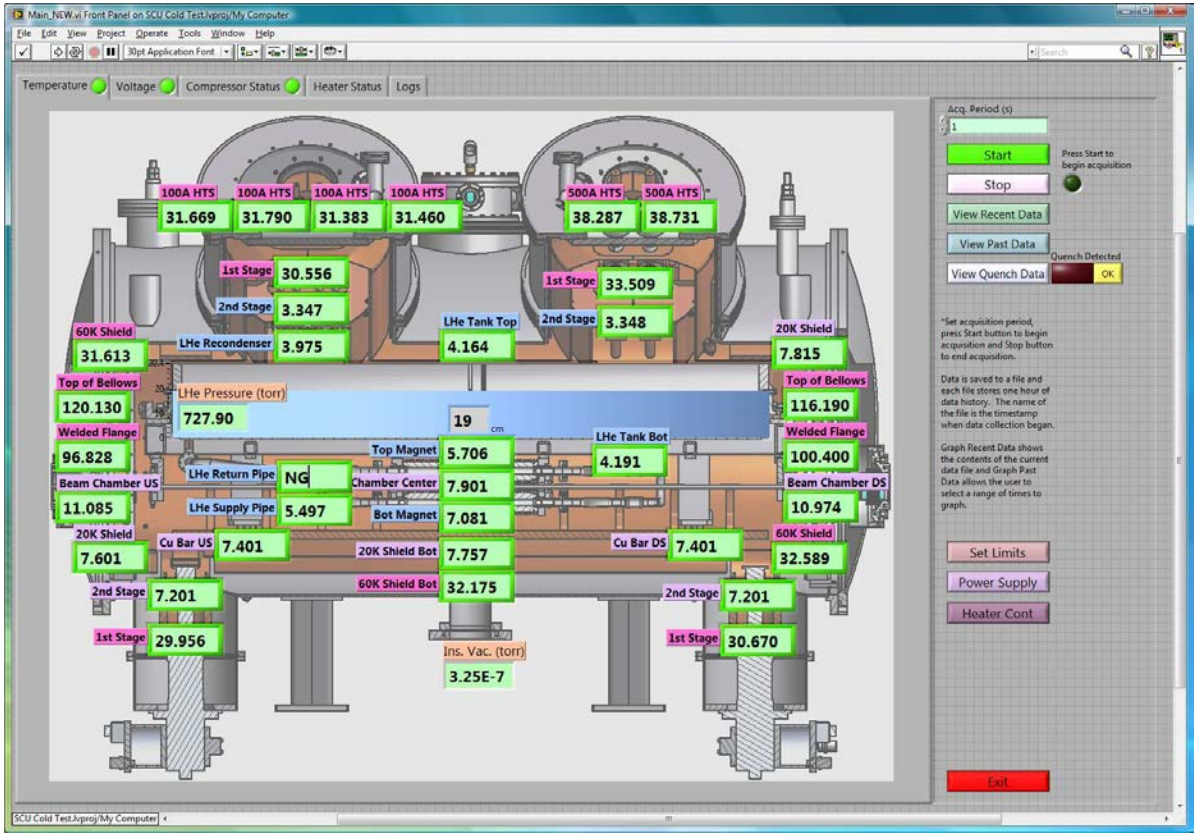


The temperatures of the 4-K cryocoolers during initial cool-down of SCU0. The cryocoolers are 2-stage devices, with the 1st stage providing shield cooling and the 2nd stage cooling the liquid helium reservoir and superconducting magnet.

SCU0 cold test – Cryogenic performance: Steady state operation

- Steady state cryogenic performance of the SCU0 has met all design goals.
  - The observed temperatures in the system are below the design temperatures.

Component	Observed temperature, K
60-K shield	32-33
20-K shield	8
Beam chamber	8-11
LHe circuit	4.2



Acq. Period (s) 1

Press Start to begin acquisition

Quench Detected

*Set acquisition period, press Start button to begin acquisition and Stop button to end acquisition.

Data is saved to a file and each file stores one hour of data history. The name of the file is the timestamp when data collection began.

Graph Recent Data shows the contents of the current data file and Graph Past Data allows the user to select a range of times to graph.

100A HTS 31.669
100A HTS 31.790
100A HTS 31.383
100A HTS 31.460
500A HTS 38.287
500A HTS 38.731
1st Stage 30.556
2nd Stage 3.347
LHe Recondenser 3.975
1st Stage 33.509
2nd Stage 3.348
LHe Tank Top 4.164
60K Shield 31.613
20K Shield 7.815
Top of Bellows 120.130
Top of Bellows 116.190
LHe Pressure (torr) 727.90
19 cm
Welded Flange 96.828
Welded Flange 100.400
Top Magnet 5.706
LHe Tank Bot 4.191
LHe Return Pipe NG
Chamber Center 7.901
Beam Chamber US 11.085
Beam Chamber DS 10.974
LHe Supply Pipe 5.497
Bot Magnet 7.081
20K Shield 7.601
Cu Bar US 7.401
20K Shield Bot 7.757
Cu Bar DS 7.401
60K Shield 32.589
60K Shield Bot 32.175
2nd Stage 7.201
2nd Stage 7.201
1st Stage 29.956
1st Stage 30.670
Ins. Vac. (torr) 3.25E-7

Temperature window of the LabVIEW control system

SCU0 cold test – Cryogenic performance: Helium circuit operation

- Stable operation of superconducting magnet coils indirectly cooled by LHe:

  a concept of using horizontal thermal syphon loop was proven.

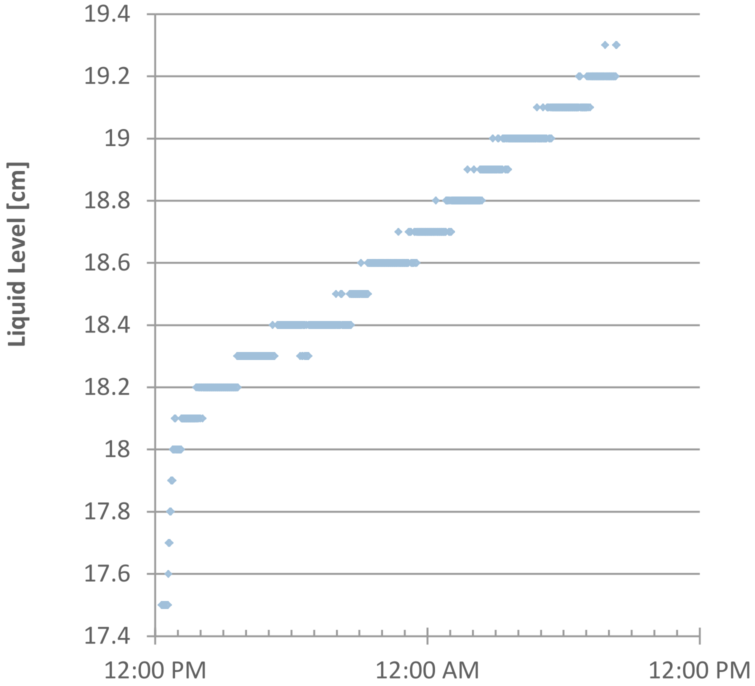
- Helium loss-free operation for 1.5 months
- Cooling power exceeds the heat load :

  Ability to liquefy warm helium supplied from a gas bottle instead of using a liquid helium Dewar.

  Ability to operate below 4.2 K –

    operation at 700 A (140% of the maximum operating current) at the temperature of 3.8 K in the LHe tank was demonstrated.

    This opens a way to higher fields.



This figure shows increasing liquid helium level achieved by using the excess 4 K capacity of the system to re-liquefy helium gas added from an external cylinder to increase the LHe inventory in the reservoir.

SCU0 cold test – Cryogenic performance: Heat load tests

- Beam heat load was simulated by using a heater attached to the cold part of the SCU0 beam chamber.
- A heat load of 0-45 W was applied to the beam chamber at full operating current of 500 A
- The beam chamber temperature raised from 11 K to 30 K
- The LHe circuit temperature raised from 4.3 K to 4.4 K indicating a very good thermal insulation between the two circuits
- The magnet did not quench during the heat load tests

Heater power, W	**0**	**10**	**20**	**45**
Main coil current, A	500	500	500	500
Beam chamber temperature, K	10.6	13.5	16.3	30.0
LHe tank temperature, K	4.29	4.30	4.30	4.44

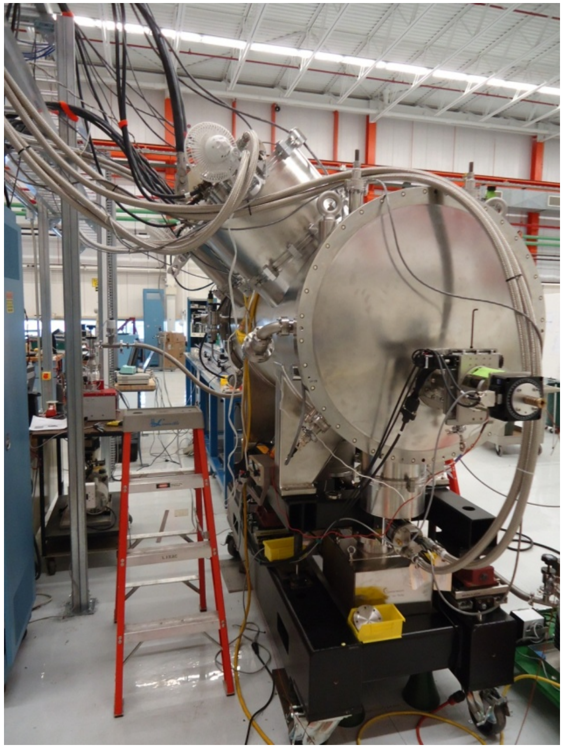
SCU0 cold test results summary

- **The SCU0 is cryogenically stable**.
  Since the initial cool-down and then filling the SCU0 with liquid helium on July 3, 2012, the device was kept cold until August 20, 2012.

- **The SCU0 magnet is working at full design current.**
  The SCU0 magnet coils achieved the design excitation current of 500 A upon the first current ramp without quenching.

- **The magnet has at least 20 % margin in operation current.**
  The magnet has continuously been energized for up to a week at the maximum design current of 500 A, and for several days at 600 A without inadvertent quenching. At the LHe temperature of 3.8 K the magnet operated at a current of 700 A.

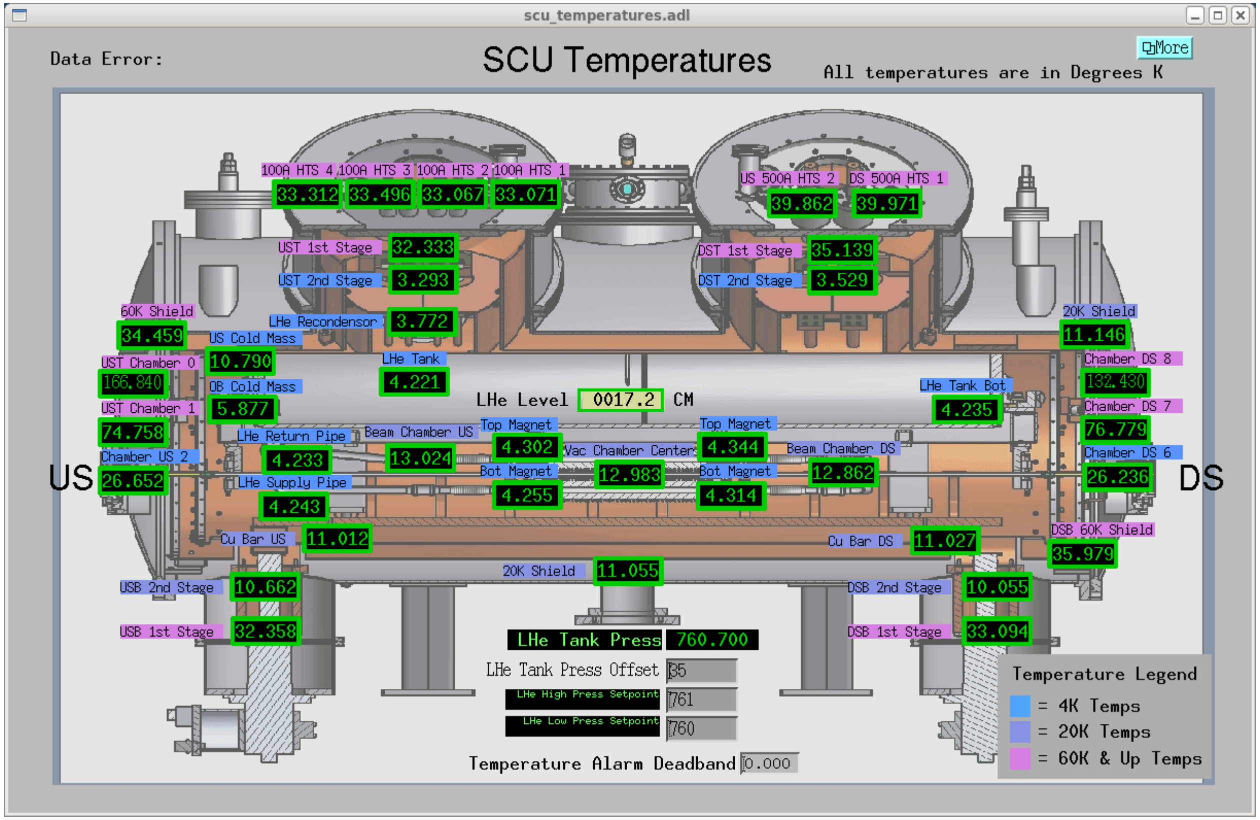
- **The device has successfully passed a thermal load test.**
  SCU0 did not quench at 500 A with 45 W of heat applied to the beam chamber for at least 1.5 hours.



SCU0 being tested in July-August 2012

SCU0 performance in storage ring

- Designed for operation at 500 A, operates reliably at 650 A.
- Did not quench except when electron beam was unintentionally dumped, and once with uncontrolled beam steering while ramping
- No loss of He is observed in about 15-month period



scu_temperatures.adl

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
OB Cold Mass 5.877
Chamber DS 8 132.430
LHe Level 0017.2 CM
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
Vac Chamber Center 12.983
Top Magnet 4.344
Beam Chamber DS 12.862
Chamber US 2 26.652
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 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). The magnet cores remain at 4 K even with 14 W of beam power on the beam chamber.

SCU0 measured temperatures and heat loads

Temperature stage	Design temperature, K	Measured temperature, K
4 K	4.2	4.2-4.3
20 K	20	11-13
60 K	60	34-36

Beam current, mA	0	100	100	100	100
Bunch mode	0	24	324	24	24
SCU current, A	0	0	0	500	690
Heat load, W (*)					
4-K stage	1.20 (0.5 **)	1.19	1.16	1.30	1.45
20-K stage	0.1	14.6 (10 **)	4.1	14.5	15.3
60-K stage	80 (75 **)	97	85	112	128

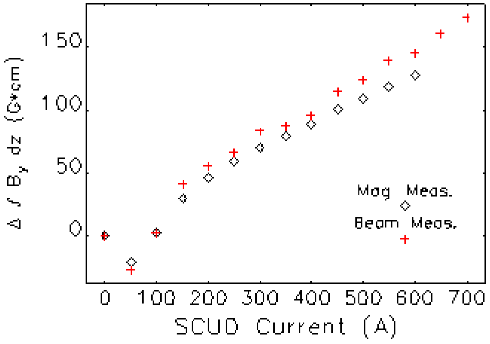
(*)
- Heat loads as obtained from the cryocooler load maps.
- RDK 408S load map by Sumitomo.
- RDK 415D load map is measured at the APS.
- Work in progress.

(**) Design calculation

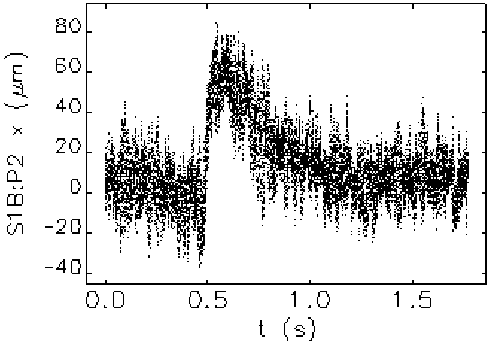
Experience with SCU0 operation at APS

SCU0 in the APS storage ring

Field integral variation measured with beam

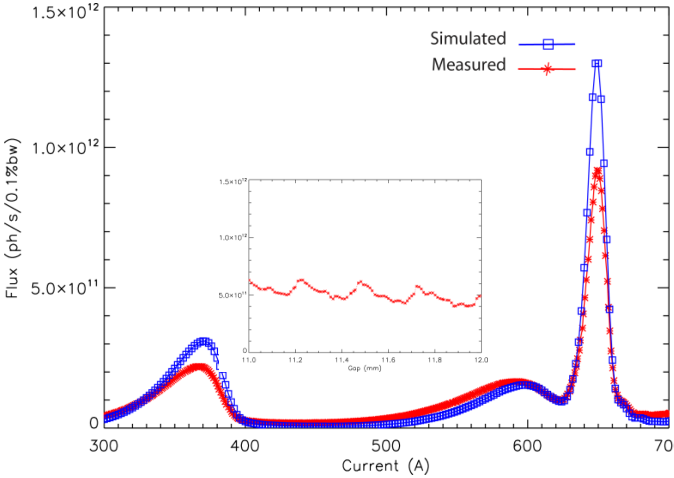


Effect of induced quench on the beam

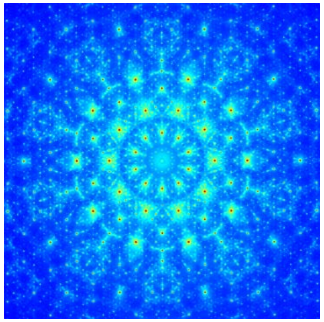


SCU0 Performance [1]:

- Designed for operation at 500 A, operates reliably at 650-680 A.
- SCU0 flux at 85 keV is 1.4 times higher than the one of 2.4-m U33 (Undulator A)
- E-beam is not affected by quenches. Didn't quench except of when the e-beam was intentionally dumped.
- No loss of He is observed in about 14-month run period.



Photon flux comparisons at 85 keV.
Main: Simulated and measured SCU0 photon flux.
Inset: Measured photon flux of in-line U33.



First experiments with SCU0. Diffraction pattern from Al-Co-Ni decagonal quasicrystal showing ten-fold symmetry.
Data provided by A. Kreyssig and A. Goldman – Iowa State University and Ames Lab.

[1] K. Harkay et al., "APS Superconducting Undulator Beam Commissioning Results", WEOAA3, presented NA-PAC'13.

Experience with SCU0 operation at APS - Summary

- Beam heat load can be correctly estimated
- Cryocooler-based cooling system can be efficient
- Cryocooler vibrations does not disturb the electron beam
- Helium loss-free operation is possible
- SCU quench does not cause beam dump
- SCU beam chamber does not need baking
- **SCU can be successfully operated in user mode**