REVIEW OF NEW DEVELOPMENTS IN SUPERCONDUCTING UNDULATOR TECHNOLOGY AT THE APS

JOEL FUERST

ADVANCED PHOTON SOURCE

ARGONNE NATIONAL LABORATORY

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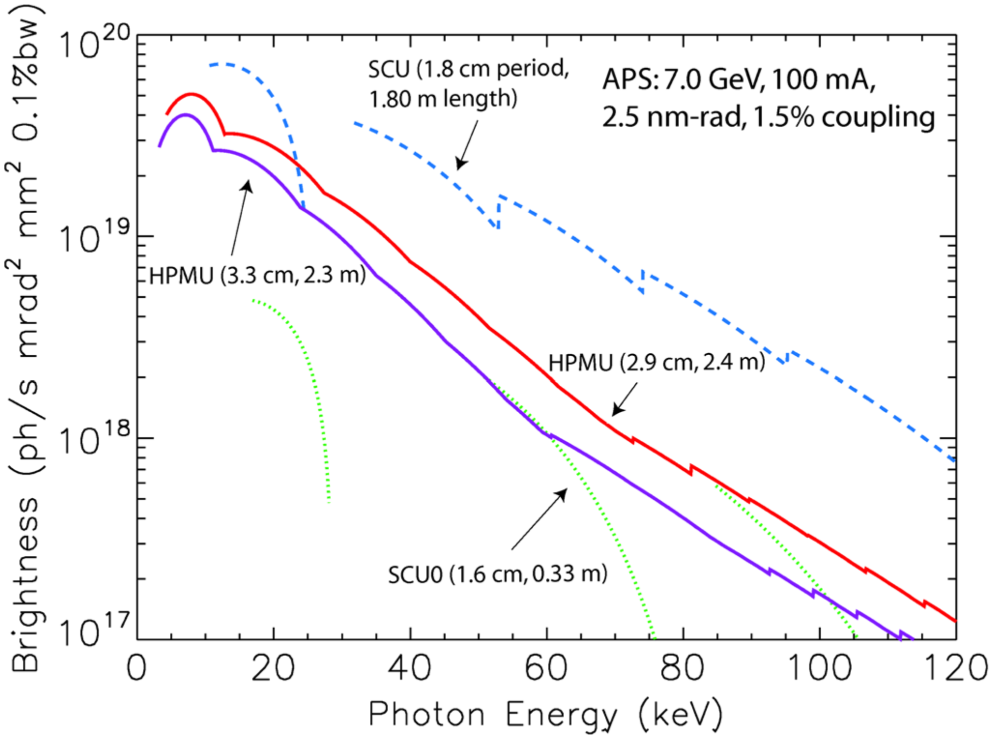
OUTLINE

- **SCU history at the APS**
- **New developments**
  - Magnets
  - Cryostats
- **Summary**

WHY SUPERCONDUCTING UNDULATORS?

- A superconducting undulator (SCU) is an electromagnetic undulator that utilizes superconducting coils for generating magnetic field.
- For a given period length and magnetic gap, SCU technology outperforms all other technologies in terms of the undulator peak field [1].
- The higher undulator field leads to higher photon fluxes, especially at higher photon energies. This has been demonstrated at the APS with the operating experience of the first test SCU – SCU0 [2].
- The SCU0 was in continuous operation for 3.5 years and was replaced by SCU18-2 in September 2016.



Calculated tuning curves for SCUs and for hybrid undulators.

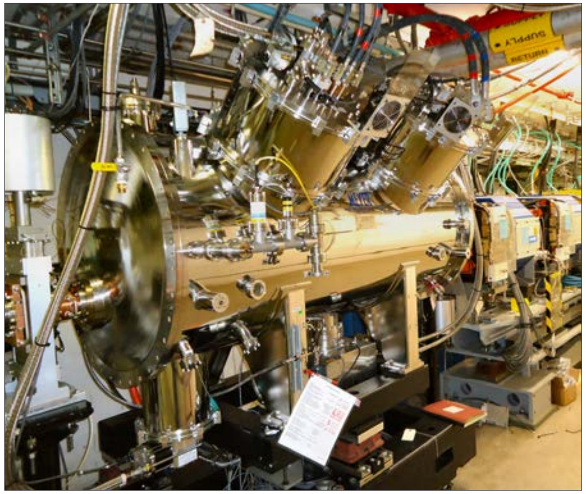
[1] P. Elleaume et al., *NIM* A 455, pp.503-523, 2000.
[2] Y. Ivanyushenkov et al., *PRST-AB,* 18, 040703, 2015.

HISTORY OF SCUS AT APS

- SCU0:
  - 16-mm period length
  - 0.33-m long magnet
  - Operation: Jan2013-Sep2016 [1].
- SCU1(SCU18-1):
  - 18-mm period length
  - 1.1-m long magnet
  - Operation: since May2015 [2].
- SCU18-2:
  - 18-mm period length
  - 1.1-m long magnet
  - Operation: since Sep2016.

[1] Y. Ivanyushenkov et al., PRST-AB, 18, 040703 (2015).

[2] Y. Ivanyushenkov et al., Phys Rev AB, 20, 100701 (2017).



SCU18-1 in Sector 1 of the APS ring.

Helical SCU in Sector 7 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.
  - Operation: since Jan2018

APS SCU RELIABILITY

- SCU0, SCU18-1 and SCU18-2 have been essentially transparent to the APS SR beam
- Most quenches occur during unplanned beam dumps; only 3 self-quenches in 2017
- SCU0/SCU18-2 quenches decreased dramatically after beam abort system added Jan 2016

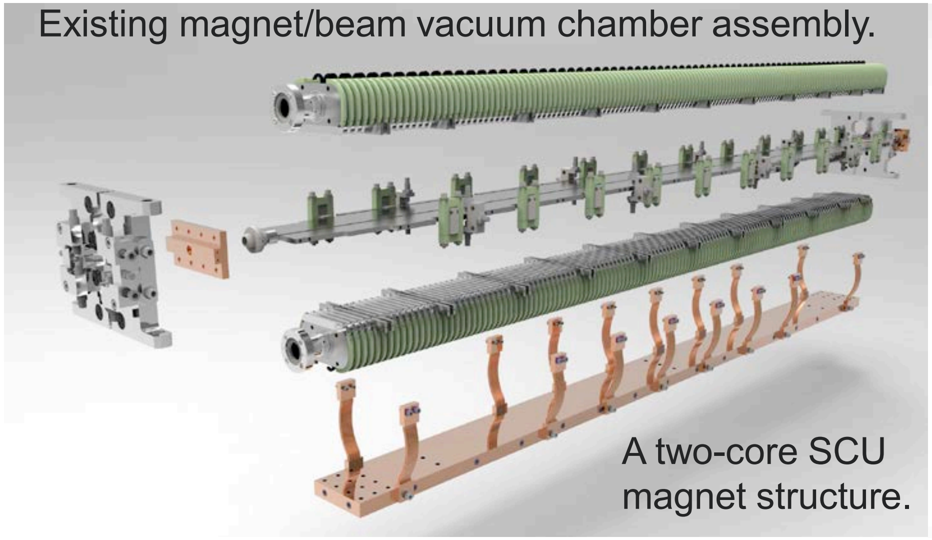
Calendar year	APS delivered	SCU0/ SCU18-2 operating	SCU0/ SCU18-2 down	SCU0/ SCU18-2 quenches	SCU0/ SCU18-2 avail. %	SCU18-1 operating	SCU18-1 down	SCU18-1 quenches	SCU18-1 avail. %
2013	4871 h	4189 h	20 h	*34* + 3	99.6	-	-	-	-
2014	4926 h	4391 h	174 h **[1]**	*32* + 2	96.5	-	-	-	-
2015	4940 h	4834 h	0 h	*26* + 1	100	3059 h **[2]**	0.1 h	*5* + 0	99.997
2016	4941 h	4647 h **[3]**	0 h	*9* + 0	100	4585	0.3 h	*11* + 1	99.990
2017	4840 h	4756 h	0 h	*8* + 1	100	4818	0.75 h	*13* + 2	99.984
Total	24518 h	22817 h	194 h	*109* + 7	**99.16**	12462 h	1.15 h	*29* + 3	**99.99**

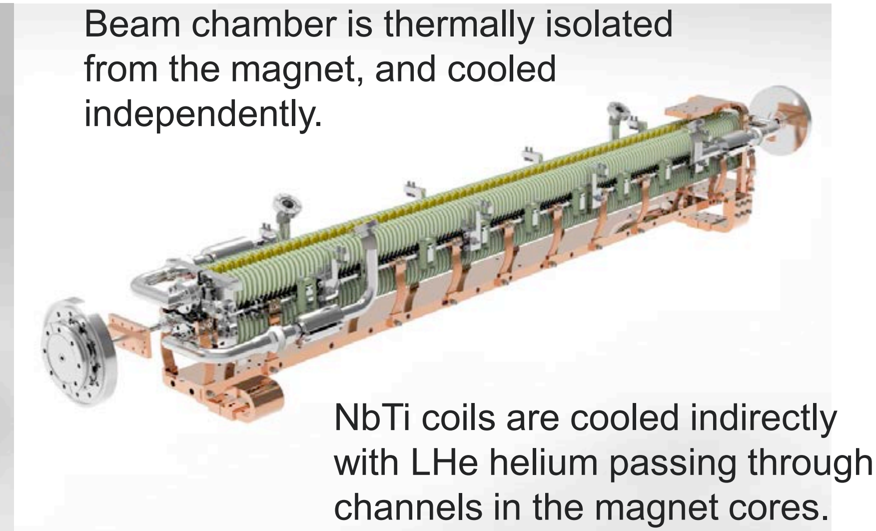
- e-beam has never been lost due to self-quenches
- *Red = beam dump-induced quench*
- Blue = self-induced quench

Data courtesy K. Harkay

[1] November: Partial loss of one cryocooler capacity
[2] Installed in May; operated May – Dec. 2015
[3] SCU18-2 replaced SCU0 in Sep.; SCU0=3310 h, SCU6=1337 h in 2016

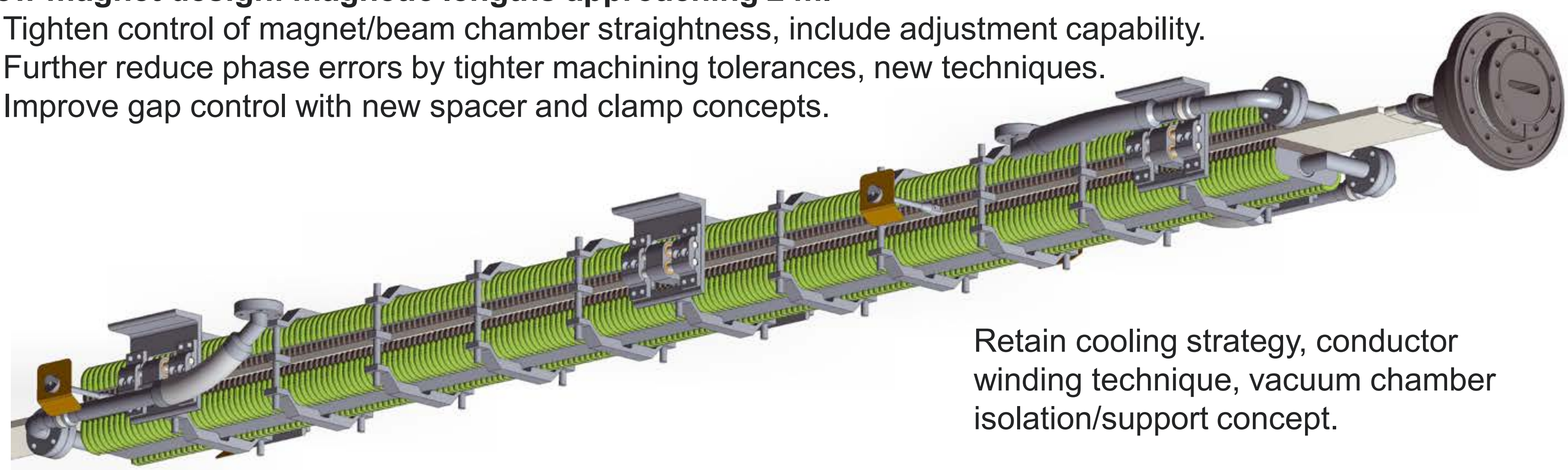
NEW MAGNET DEVELOPMENTS: PLANAR





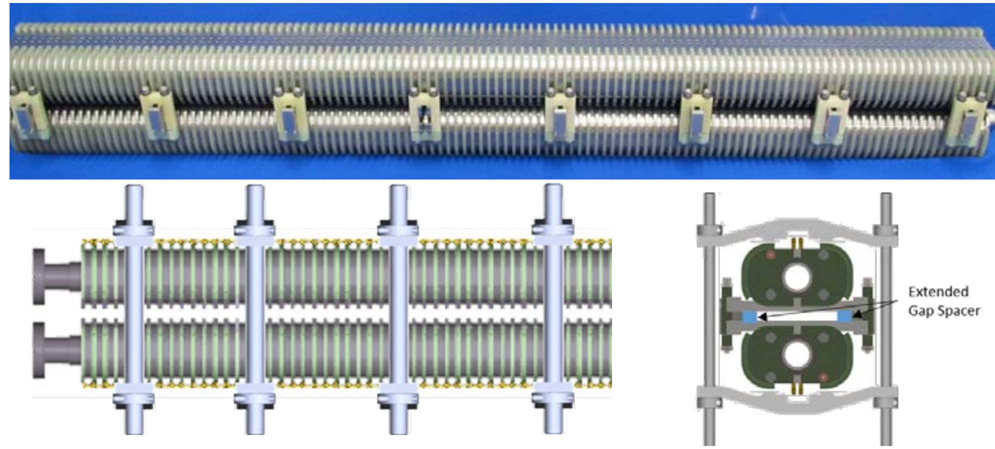
New magnet design: magnetic lengths approaching 2 m.

- Tighten control of magnet/beam chamber straightness, include adjustment capability.
- Further reduce phase errors by tighter machining tolerances, new techniques.
- Improve gap control with new spacer and clamp concepts.



PHASE ERROR CONTROL

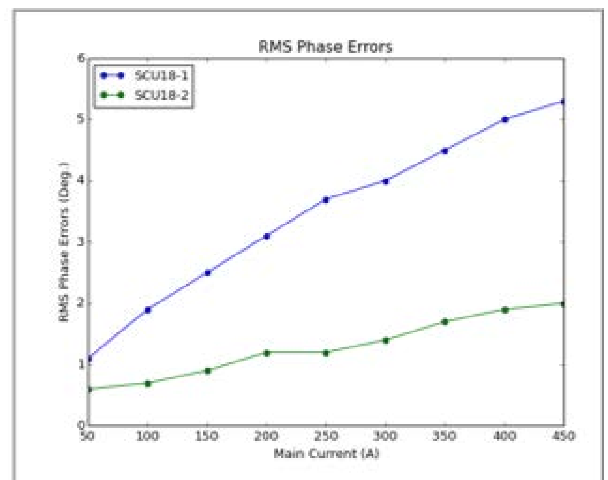
- The SCU field quality depends on:
  - Precise machining of a magnet former [1]
  - Quality of conductor winding [2]
  - Uniformity of the magnetic gap
- A dedicated R&D program was targeted at achieving a very uniform gap [3].
  - A gap correction scheme was developed and implemented using a set of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



Planar SCU magnetic assembly with a concept of gap correction.

Undulator	Measured phase errors (º 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.

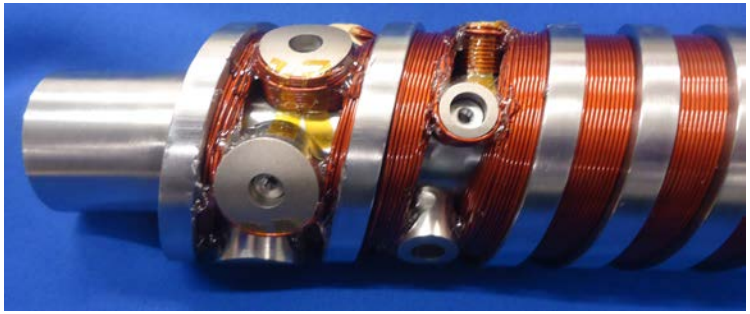
[2] E. Gluskin, "Development and Performance of Superconducting Undulators at the Advanced Photon Source," *Synchrotron Radiation News*, Vol. 28, Issue 3, 2015.

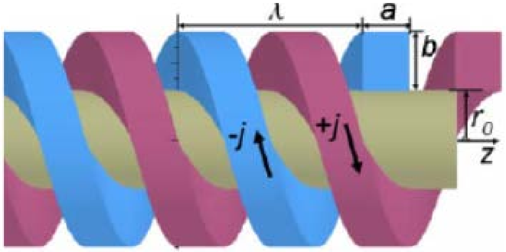
[3] M. Kasa et al., "Progress on the Magnetic Performance of Planar Superconducting Undulators," NA-PAC'16.

CIRCULAR POLARIZING: HELICAL SCUs

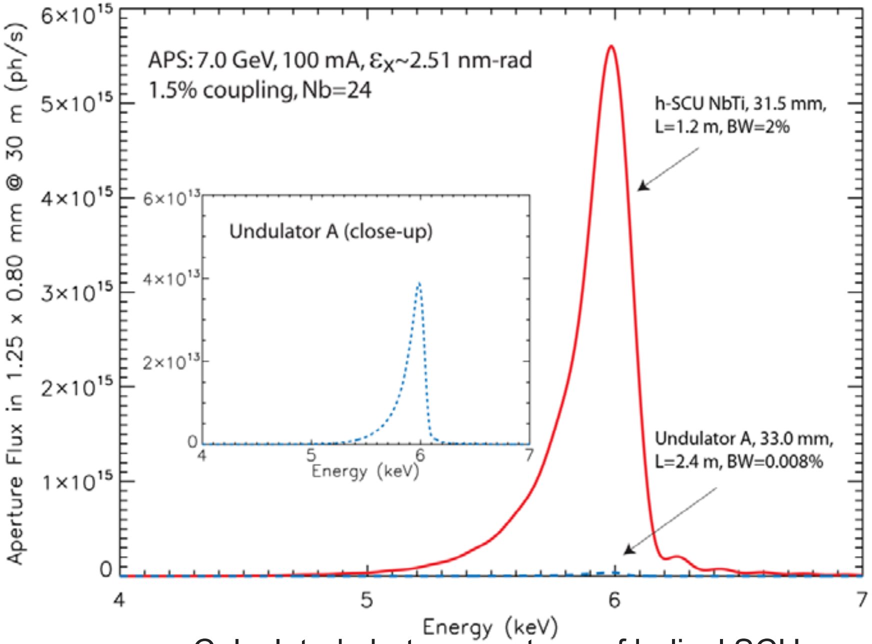
- SCU technology offers the possibility of building circular polarizing helical undulators.
- We have recently completed a helical SCU (HSCU) for the APS.
- X-ray photon correlation spectroscopy program at the APS will benefit from the increased brilliance provided by an HSCU.
- Future helical SCUs may be optimized for FEL applications.

Parameters for APS HSCU	
Cryostat length (m)	1.85
Magnetic length (m)	1.2
Undulator period (mm)	31.5
Magnetic bore diameter (mm)	29.0
Beam vacuum chamber vertical aperture (mm)	8
Beam vacuum chamber horizontal aperture (mm)	26
Undulator peak field Bx=By (T)	0.42
Undulator parameter Kx=Ky	1.2


HSCU prototype coil winding showing end detail.



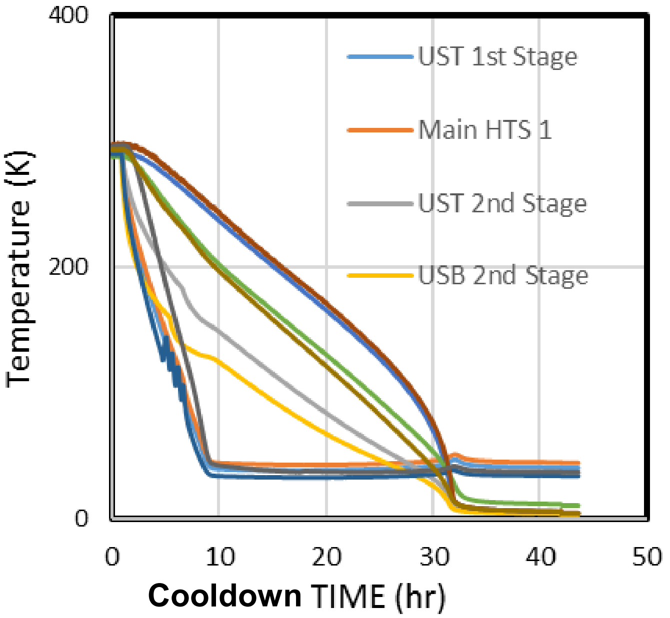
Magnetic model of HSCU.

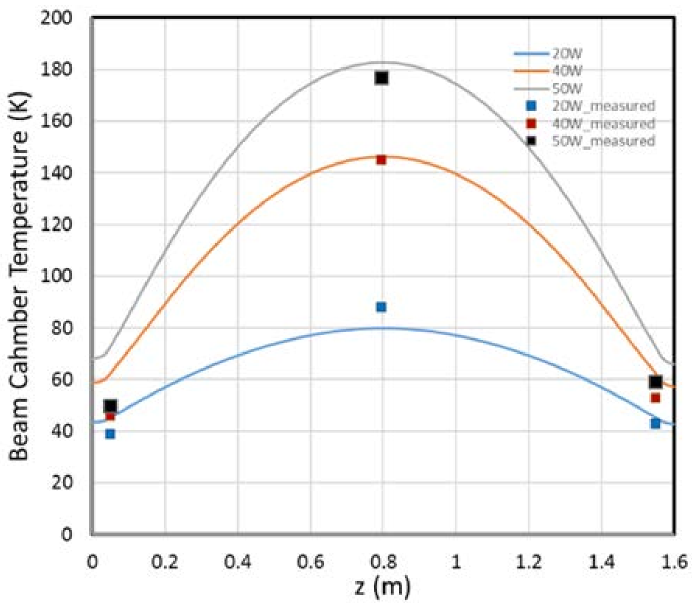


Calculated photon spectrum of helical SCU.

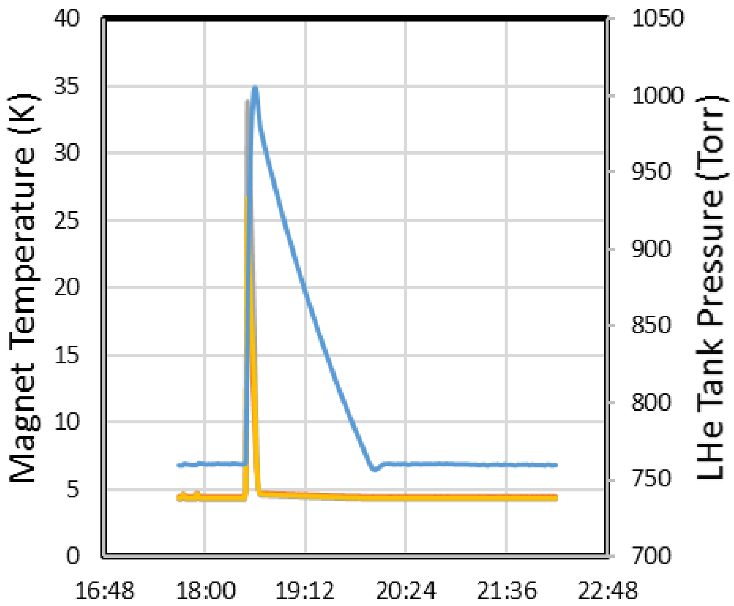
HSCU CRYOGENIC TESTS

- Cryogenic performance of the cryostat has been evaluated through a series of test cooldowns.
- Cool down time is about 30 hr – 1.5 times less than for SCU1.
- Quench recovery time (ready for beam) is <1hr.
- Data confirm the predicted beam chamber temperature profile associated with cooling only at the chamber ends (chamber is inaccessible inside the magnet bore).



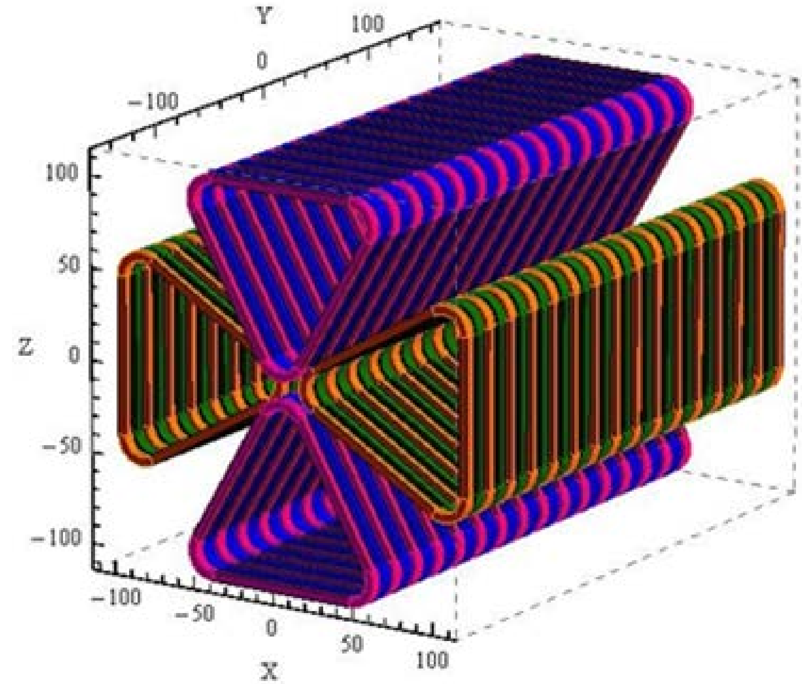


Beam chamber temperature profile with different applied heat loads.



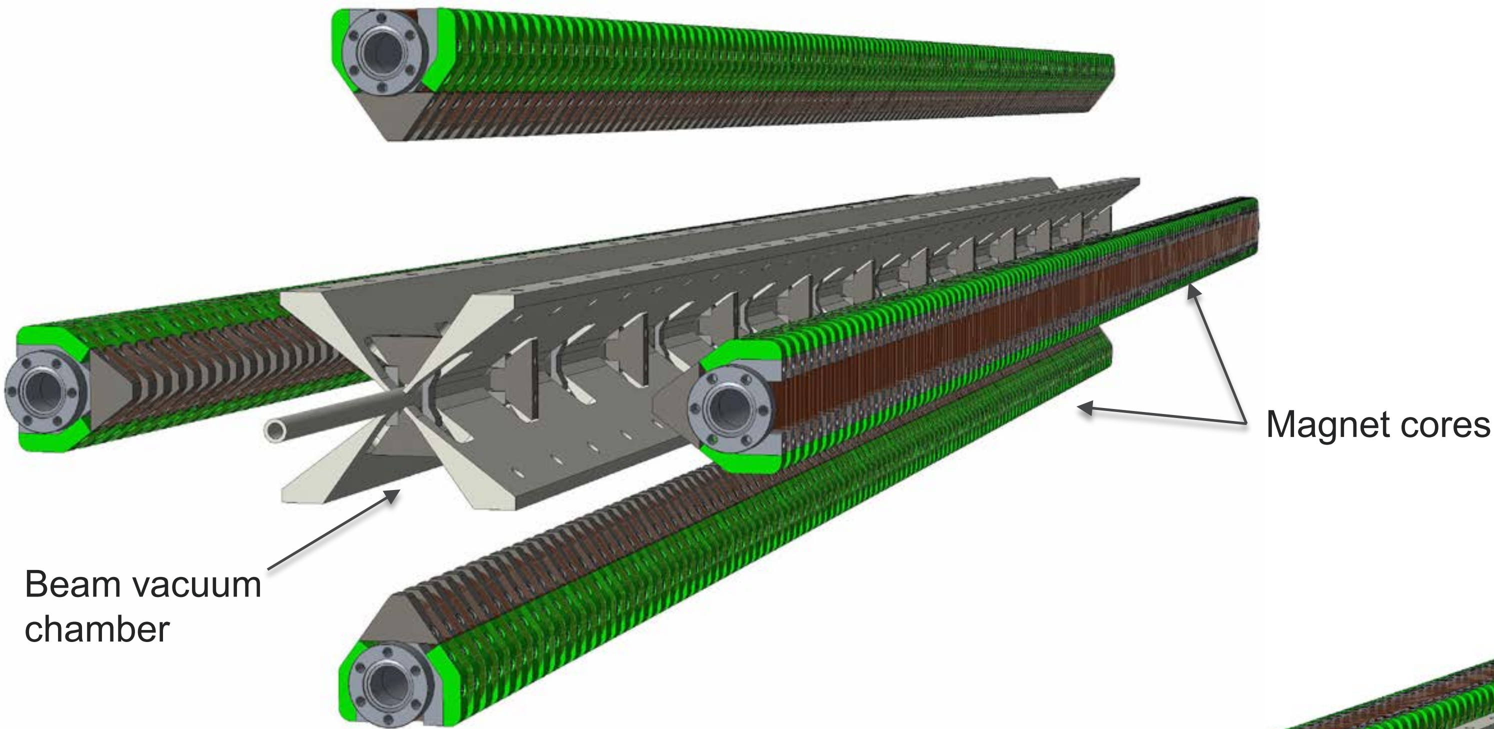
UNIVERSAL POLARIZING SCU

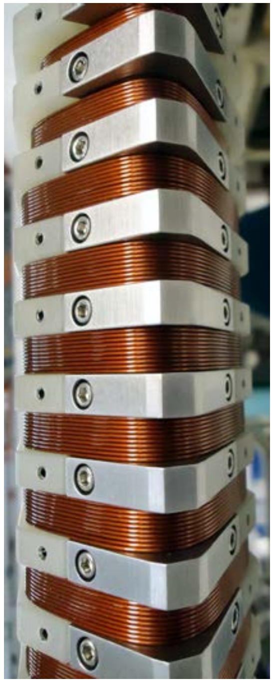
- Users of APS POLAR beamline would like to have an undulator that can generate both circular and planar polarized photons.
- To answer this challenging request, we have developed the concept of a Super Conducting Arbitrarily Polarizing Emitter (SCAPE).
- This electromagnetic superconducting undulator 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 will be tested in a prototype.

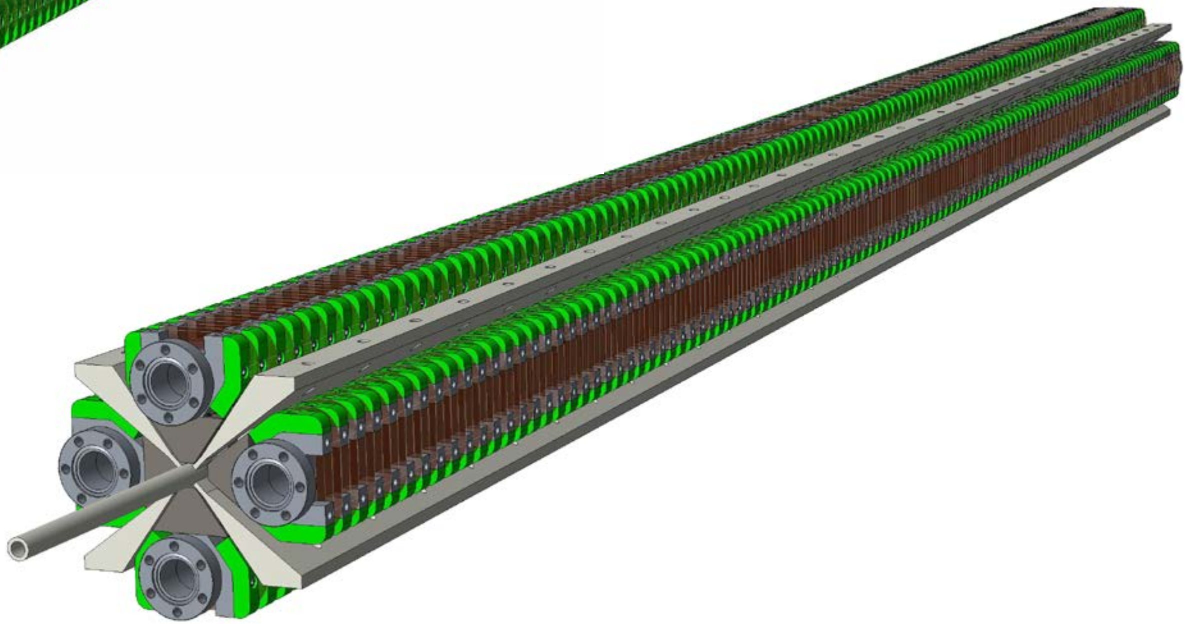


Concept of SCAPE: a universal SCU with four planar superconducting coil structures. A beam chamber is not shown.

SCAPE MAGNET MECHANICAL DESIGN



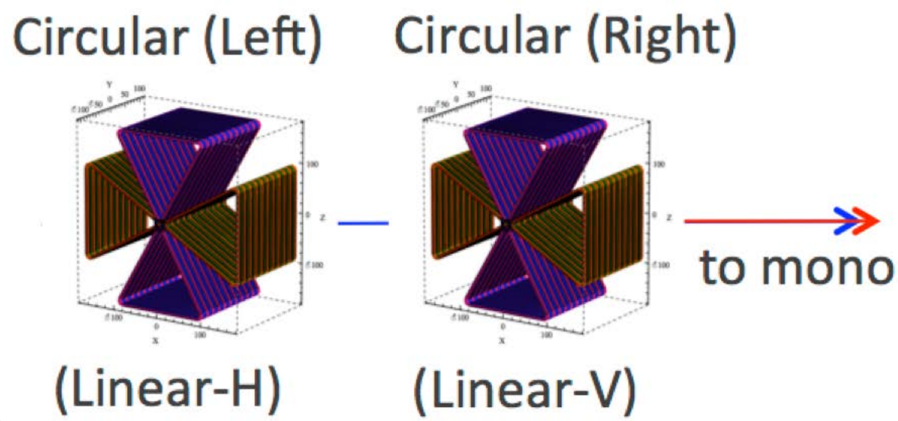


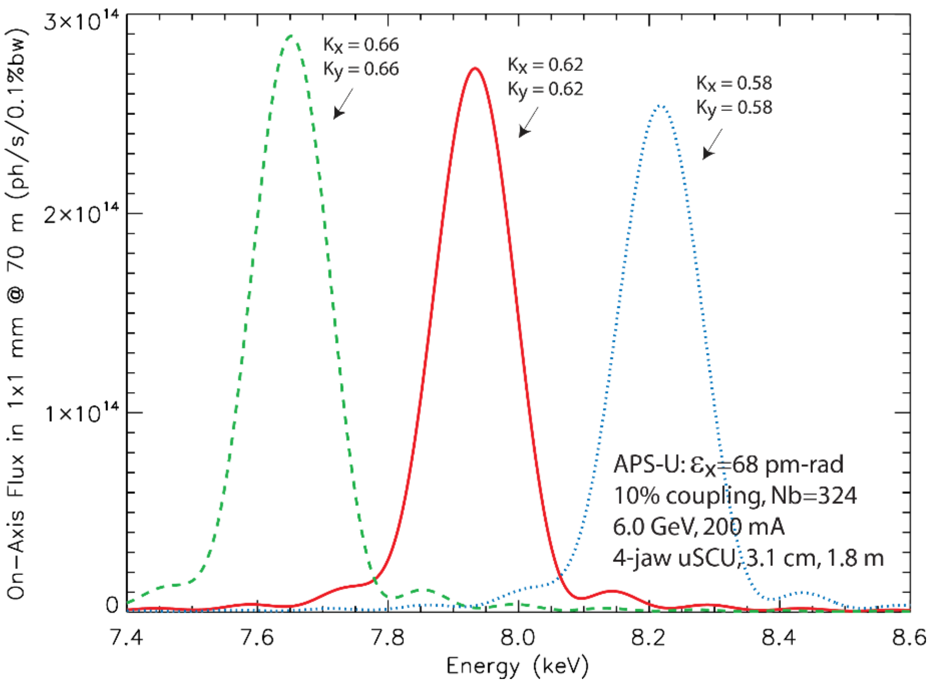


- Two orthogonal magnet pairs
- ¼-period longitudinal offset
- Beam vacuum chamber operates at elevated temperature, screens magnet from beam heating

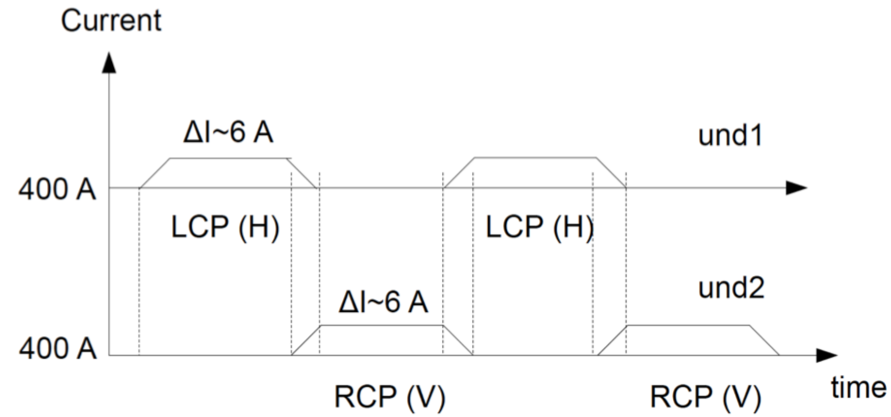
SCAPE OPERATION IN POLARIZATION SWITCHING MODE

Two SCAPE undulators assembled in one cryostat and operating in a "push-pull" mode could be used as a fast switching source of linear or circular polarized radiation.



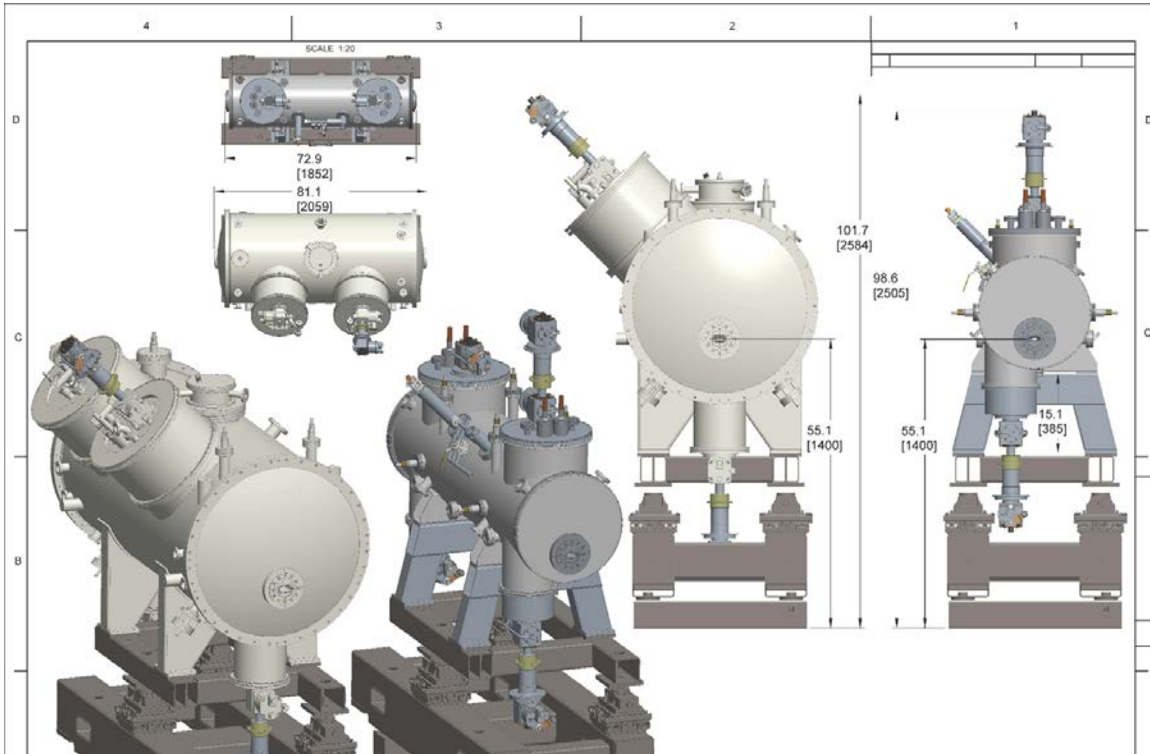


First harmonic energy vs K value.



SCAPE operation in polarization switching mode.

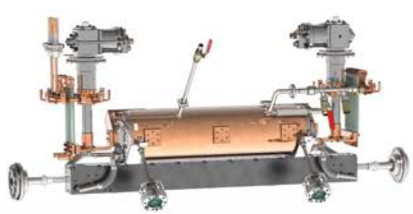
CRYOSTAT EVOLUTION: HSCU vs. SCU0/SCU1



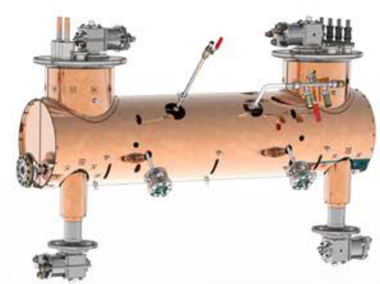
HSCU cryostat developed by APS

SCU0/SCU1 cryostat designed by V. Syrovatin (BINP) and ANL

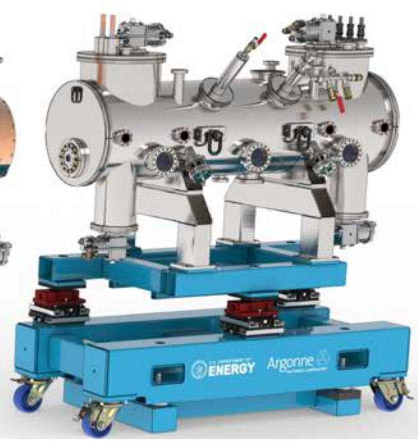
Beam vacuum chamber



4.2 K cold mass



Thermal shield installed

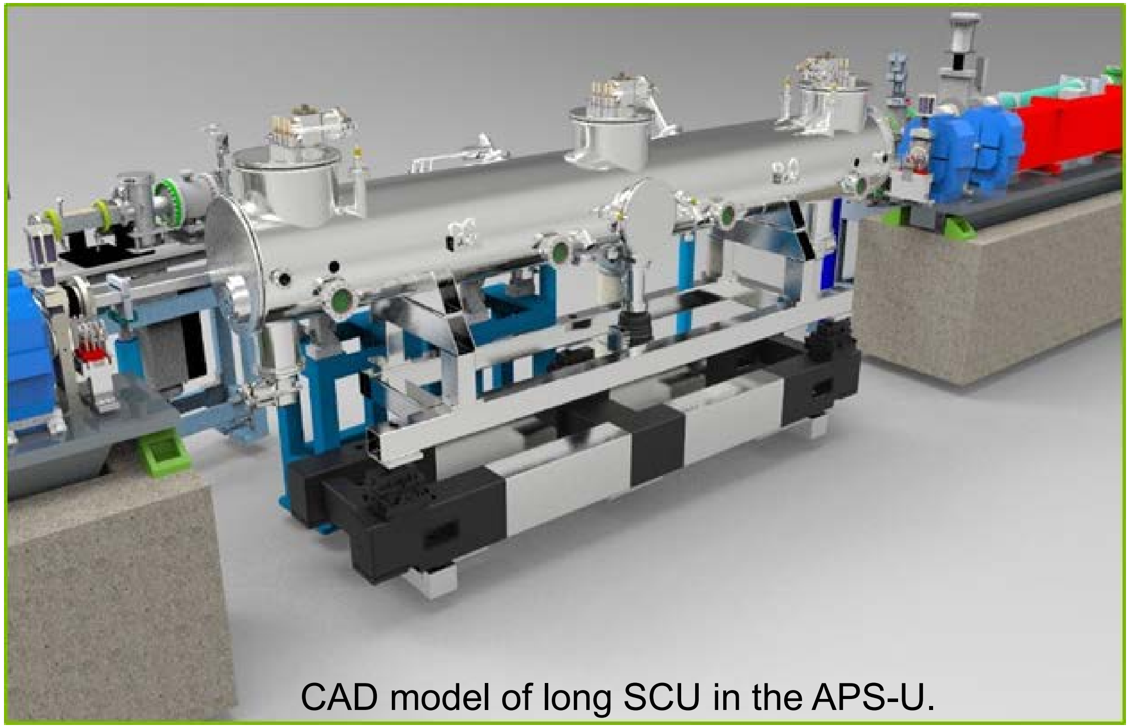


CAD render of HSCU assembly

NEW CRYOSTAT DEVELOPMENTS – STORAGE RINGS

- The APS Upgrade includes four full-ID-length SCUs, each with two 1.8-m planar SCU magnets in series separated by either a phase shifter (QTY2) or a canting magnet (QTY2).
- The Upgrade also includes one ½-ID-length SCAPE SCU and re-uses one existing SCU.
- New long SCU cryostats will be modeled on the HSCU 2nd-generation design.
- Higher-power, lower vibration pulse-tube cryocoolers can increase cooling capacity margin and reduce quench recovery time.
- Continue to rely on a "trim heater" to dissipate excess capacity and provide a key diagnostic for the cryogenic system.

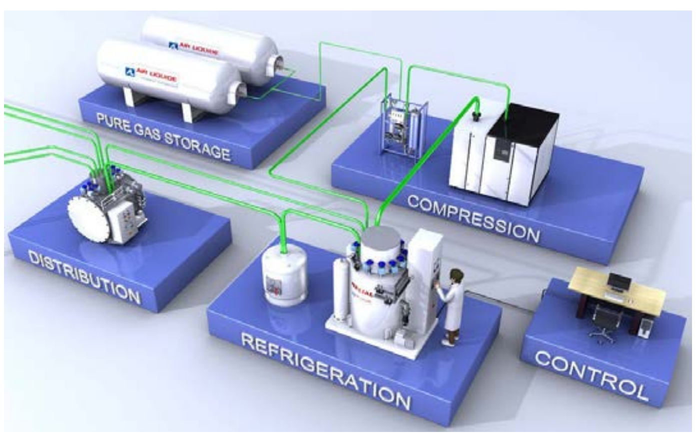
Alternative cryocoolers provide 1/3-more cooling power at 4.2 K (image from Cryomech)



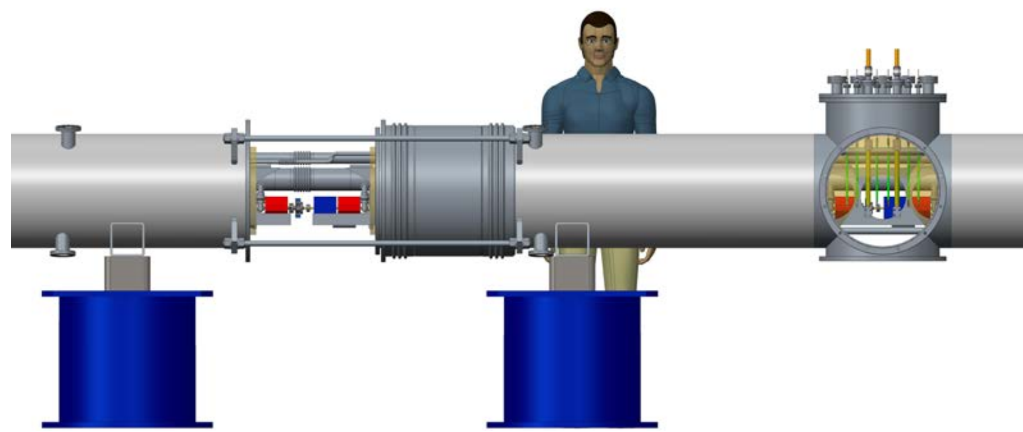
CAD model of long SCU in the APS-U.

NEW CRYOSTAT DEVELOPMENTS – FELs (1): refrigeration and array segmentation

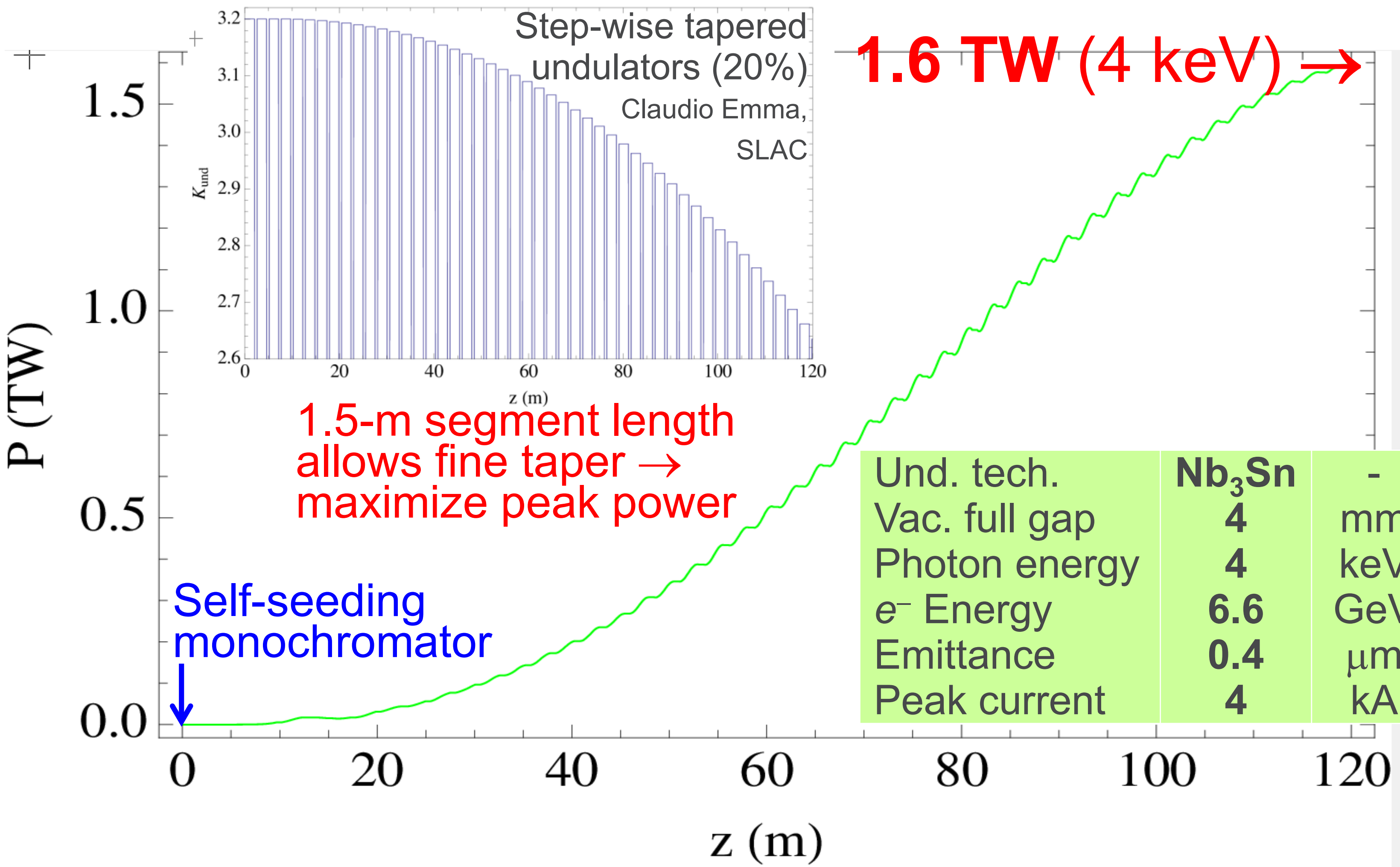
- The topology of an FEL SCU array makes a centralized helium cryoplant plus distribution system attractive on cost and performance over cryocoolers. The higher available cooling power can impact cryostat design choices - for example, 4.2 K beam chamber operation may simplify design and reduce magnetic gap.
- Cryogenic distribution can reside either internal (XFEL, LCLS-II) or external (CEBAF, SNS, FRIB) to the SCU cryostats. This choice affects the degree to which the SCU array is ***segmented*** (how frequently the cryogenic insulating vacuum breaks occur) and impacts system heat load and maintainability.
- Individual SCU cryostat lengths may be set by transportation limits while the active length of individually powered magnets should support optimal field taper.



A small helium cryoplant (Air Liquide)

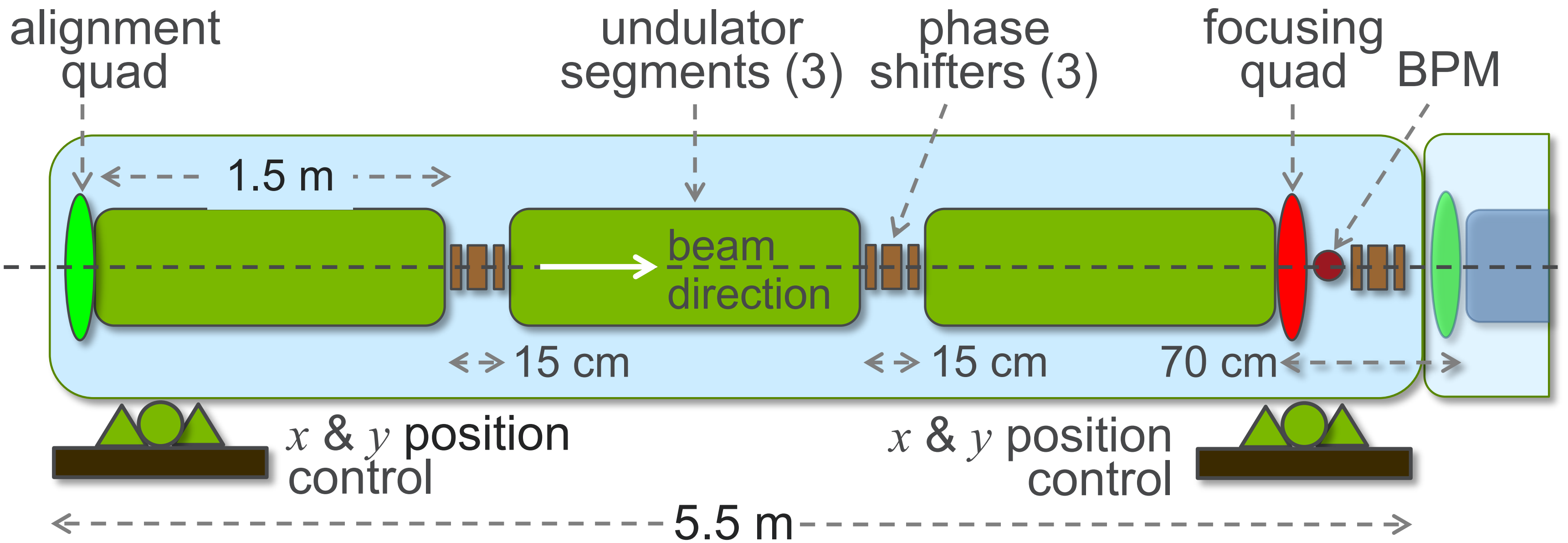

SCU cryostat interconnect showing internal cryogenic distribution

MOTIVATION: "TW FEL" with SCU and Cu-Linac @LCLS-II (P. Emma, SLAC)



Und. tech.	**Nb_3Sn**	-
Vac. full gap	**4**	mm
Photon energy	**4**	keV
e^- Energy	**6.6**	GeV
Emittance	**0.4**	µm
Peak current	**4**	kA

FEL SCU CRYOMODULE CONCEPT (P. Emma, SLAC + ANL/LBNL)

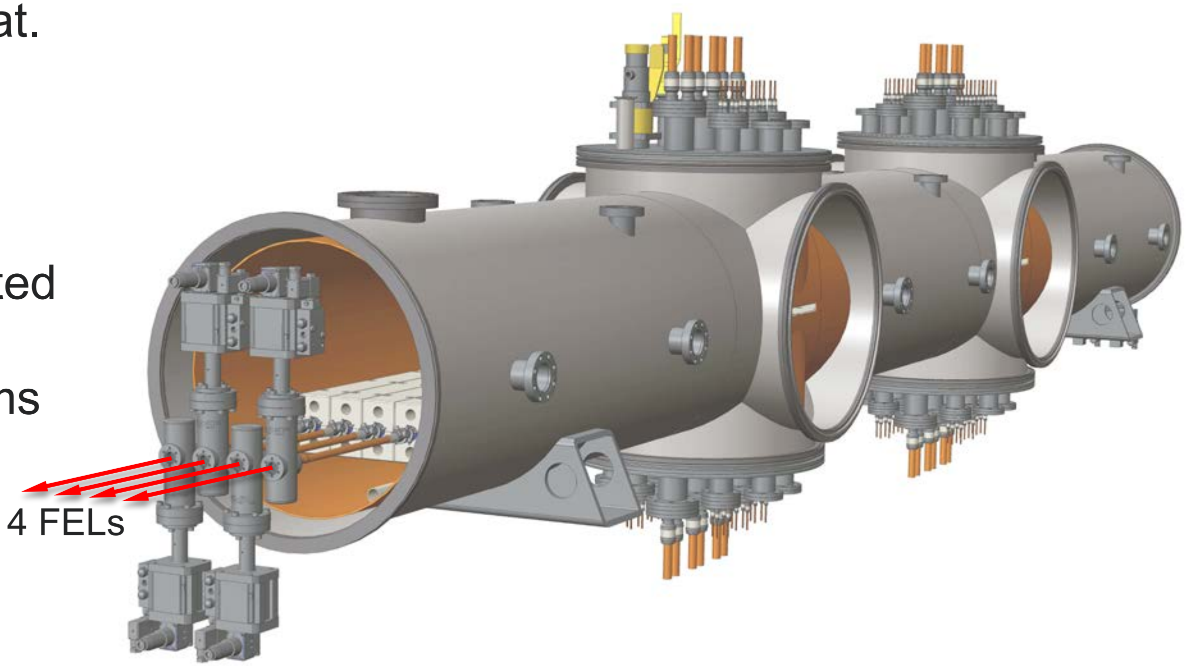


- Three 1.5-m long undulator segments in one 5.5-m cryostat
- Short segments (1.5-m) easier to fabricate, measure, tune, and taper
- Each segment independently powered to allow optimized TW-taper
- Ancillary components include cold BPM, cold phase-shifters, cold quads
- Cryogenic refrigeration/distribution system concept has been developed
- Magnet alignment is critical (300 K $\rightarrow$4 K)
- Beam-based alignment as final correction using motorized pads

NEW CRYOSTAT DEVELOPMENTS – FELs (2): alignment & multi-FEL beamlines

- FEL requirements may need active, beam-based component positioning.
- Individual control of magnetic elements (undulators, quads, phase shifters).
- Adjustment may be external and/or internal to the cryostat.
- Mechanical and piezo adjusters may play a role.
- Position sensing via laser-displacement (as implemented on HSCU) or fiber-optic interferometer-based systems are being explored.

- SCU magnets are compact objects.
- Multiple SCU magnet strings can be housed in a common cryostat without magnetic crosstalk.
- Cooling via central cryoplant is ideal.
- Current lead management is an issue.



SUMMARY

- There are three SCUs currently in operation at the APS (2 planar, 1 helical).
- Development is underway for a new generation of SCUs for the APS Upgrade.
- SCU technology is well suited to FEL applications.
- The APS is working to develop the next generation of SCU technology for future storage ring and FEL light sources.