SUPERCONDUCTING UNDULATORS AT ANL*

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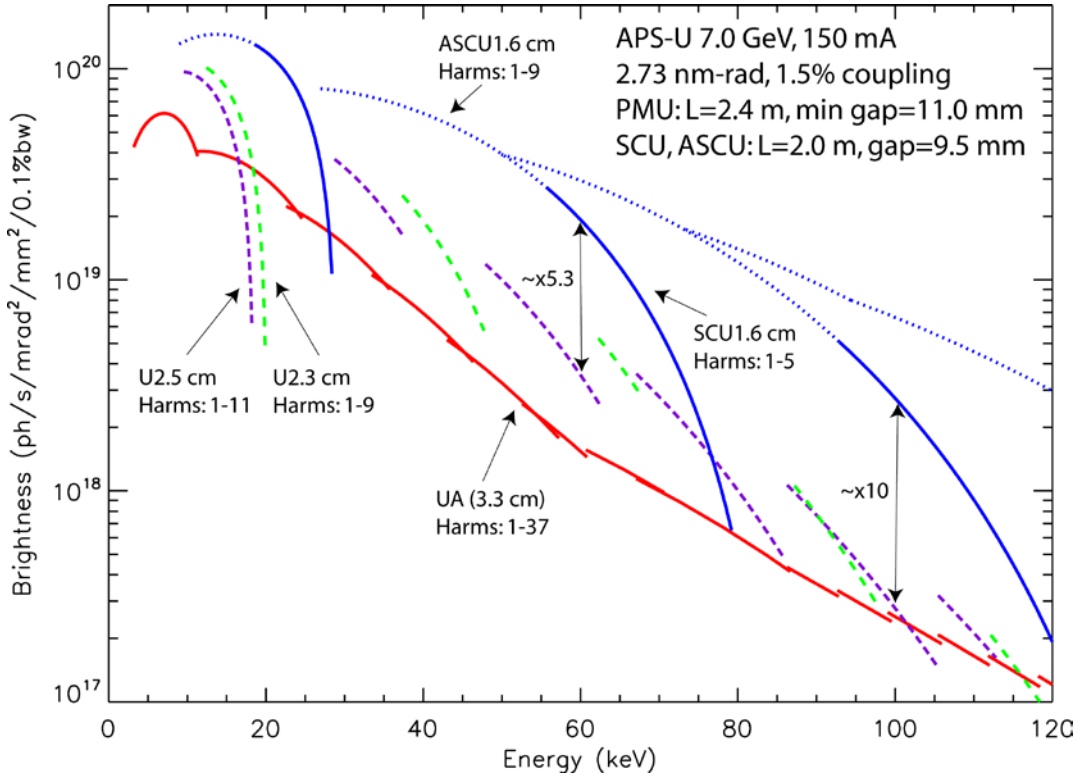
INTRODUCTION: ADVANCED PHOTON SOURCE SCU DEVELOPMENT TIMELINE

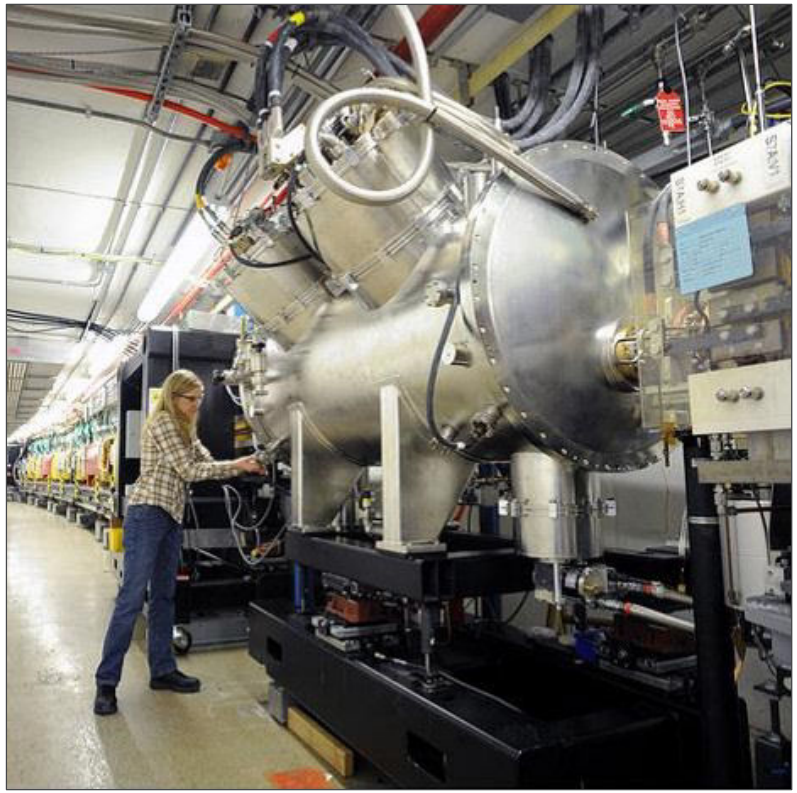
Activity	Years
A proposal of the helical SCU for the LCLS	1999
Development of the APS SCU concept	2000-2002
R&D on SCU in collaborations with LBNL and NHFML	2002-2008
R&D on SCU0 in collaborations with FNAL and UW-Madison	2008-2009
Design (in the collaboration with the BINP) and manufacture of SCU0	2009-2012
SCU0 installed into the APS storage ring	December 2012
SCU0 is in routine user operation	Since February 2013
SCU1 installed into the APS storage ring and is in user operation	April 2015
FEL/LCLS 1.5-m long prototype designed, built and successfully tested	October 2015
SCU18-2 (“upgraded” SCU1 copy) replaces SCU0	September 2016
Helical SCU prototype to be installed in APS storage ring	December 2017

PERFORMANCE COMPARISON: SCU AND HYBRID UNDULATOR AT THE APS

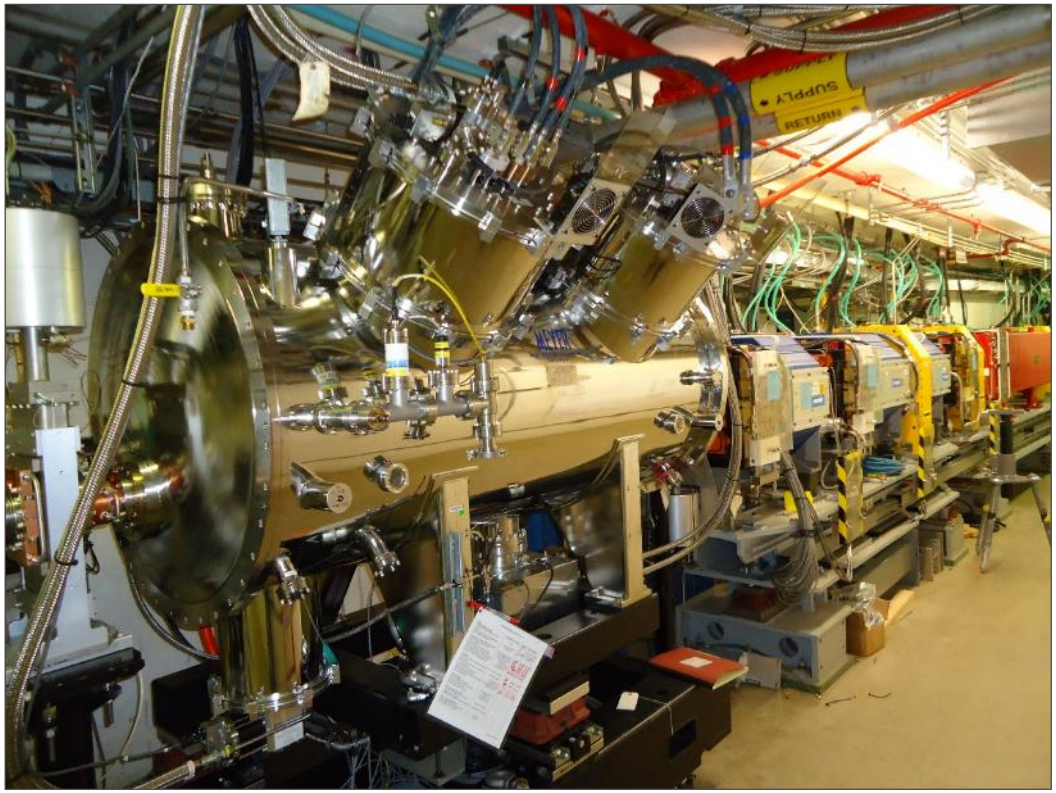


- Tuning curves for odd harmonics of the SCU and the "Advanced SCU" (ASCU) versus planar permanent magnet hybrid undulators for 150 mA beam current. ASCU is Nb_3Sn undulator with optimized performance.
- The SCU 1.6 cm surpasses the U2.5 cm by a factor of ~ 5.3 at 60 keV and ~ 10 at 100 keV.
- The tuning 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.

SCU HISTORY & NEAR-TERM PLANS



SCU0 installed in APS Sector 6
DEC 2012 (0.3-m magnetic length)



SCU1 installed in APS Sector 1
APR 2015 (1.1-m magnetic length)

- Two SCUs presently installed in the APS storage ring (SCU0 and SCU1)
- SCU0 to be upgraded with a copy of SCU1 (SCU18-2) in September 2016
- 1.2-meter Helical SCU (HSCU) to be installed in Sector 7 in December 2017

APS SCU RELIABILITY

- Both SCU0 and SCU1 have been essentially transparent to the APS SR beam
- All but one quench (for SCU1) has occurred during an unintended beam dump
- SCU0 quenches decreased dramatically after beam abort system added JAN2016

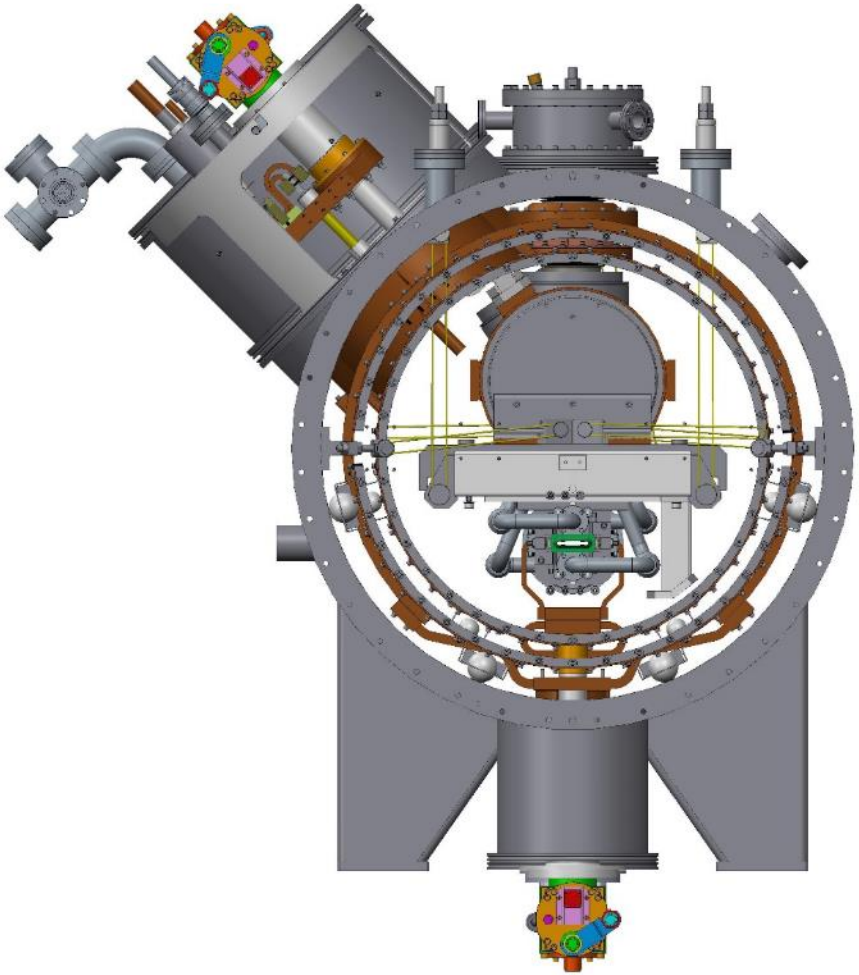
Calendar year	APS delivered	SCU0 operating	SCU0 down	SCU0 quenches	SCU0 avail. %	SCU1 operating	SCU1 down	SCU1 quenches	SCU1 avail. %
2013	4871 h	4189 h	20 h	*34* + 3	99.6	-	-	-	-
2014	4926 h	4391 h	174 h [1]	*32* + 2	96.5	-	-	-	-
2015	4940 h	4834 h	0 h	*26* + 1	100	3059 h [2]	0.1 h	*5* + 0	99.997
2016 [3]	2871 h	2797	0 h	*6* + 0	100	2695	0.3 h	*7* + 1	99.990
Total	17608 h	16211 h	194 h	*108* + 6	**98.80**	5754 h	0.4 h	*12* + 1	**99.993**

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

Data thanks to K. Harkay

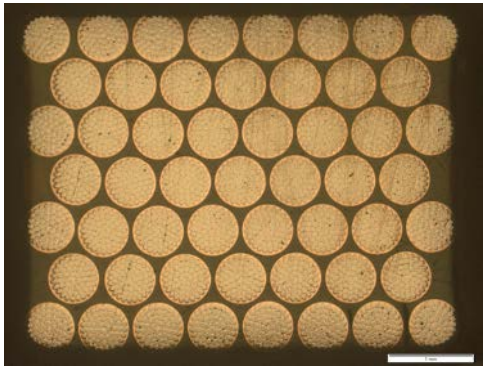
[1] November: Partial loss of one cryocooler capacity
[2] Installed in May; operated May – December 2015
[3] January through July 2016

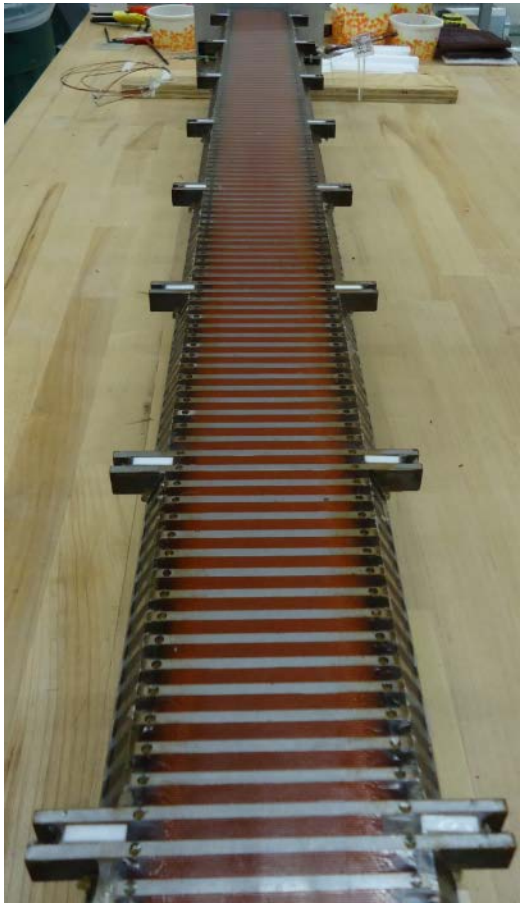
CRYOSTAT DESIGN: BUDKER INSTITUTE OF NUCLEAR PHYSICS

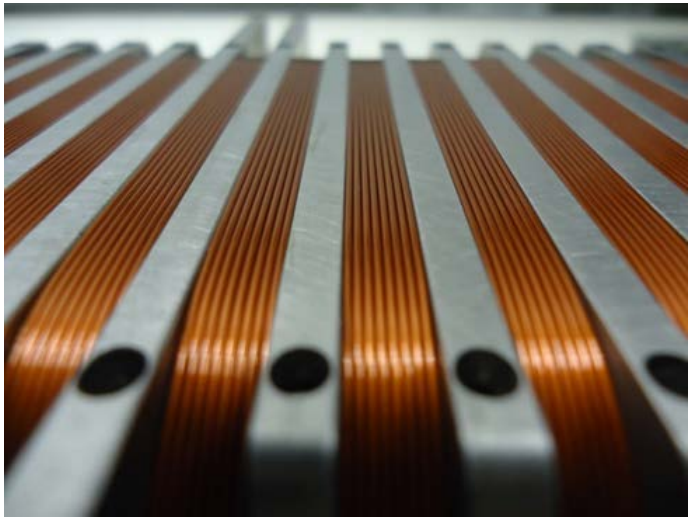


- Proven cryostat design, suitable for magnets up to 1.5 meters long.
- Closed cycle (zero boil-off) liquid helium bath-cooled magnets with cryocooler-based recondensation. Excess 4 K capacity is about 0.5 W for most recent cryostat.
- Helium bath pressure/temperature is regulated using a heater.
- Beam chamber is cooled at a higher temperature level due to high beam-induced heat loads (up to 20 W) in storage ring applications.

PLANAR MAGNET FABRICATION DEVELOPMENT: from 300 mm TO 1500 mm

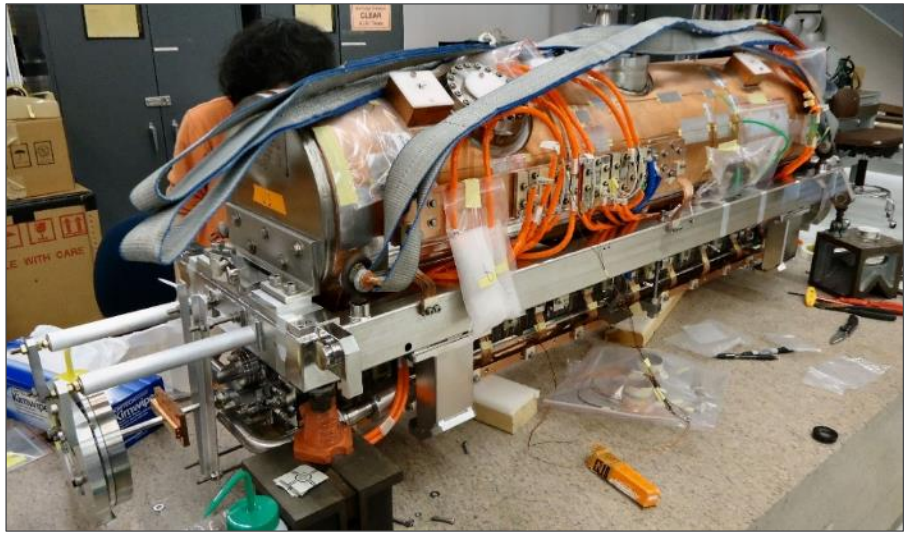


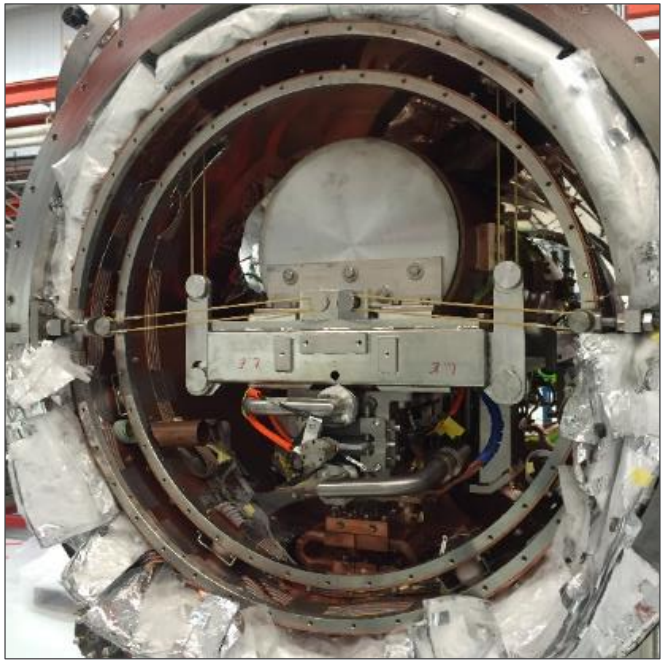




- Techniques and tooling scale to “full-length” magnets
  - Precision core machining
  - Winding/potting

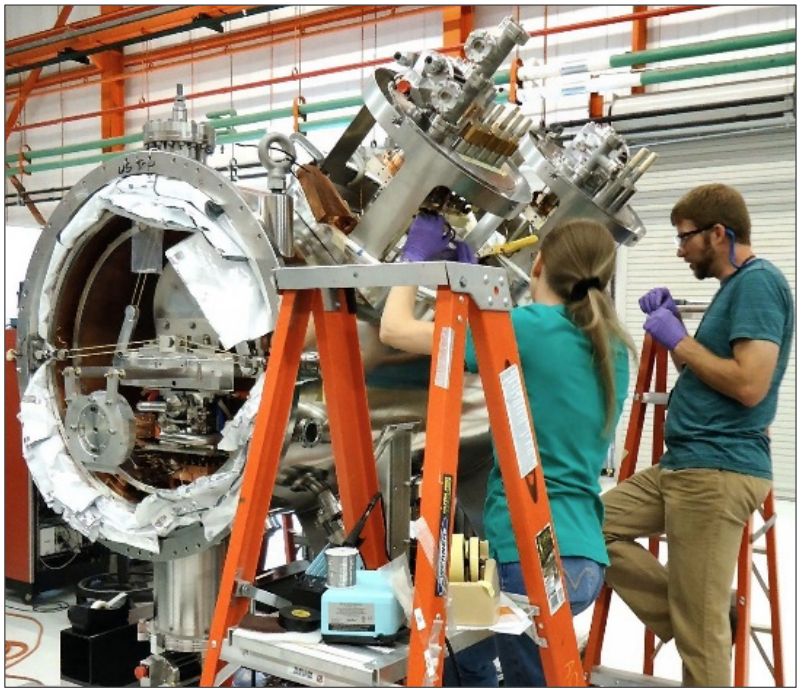
SCU ASSEMBLY



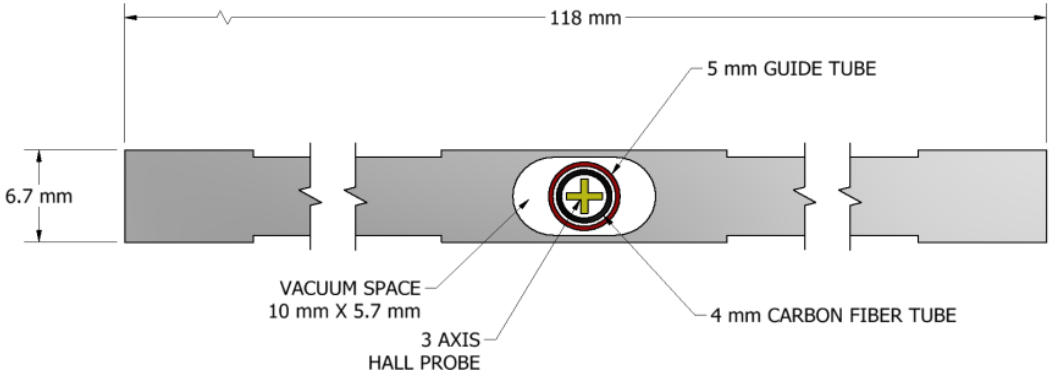


Magnet, vacuum chamber, & helium tank are assembled, checked out, and loaded into the cryostat.

FINAL ASSEMBLY (2), MAGNETIC MEASUREMENT



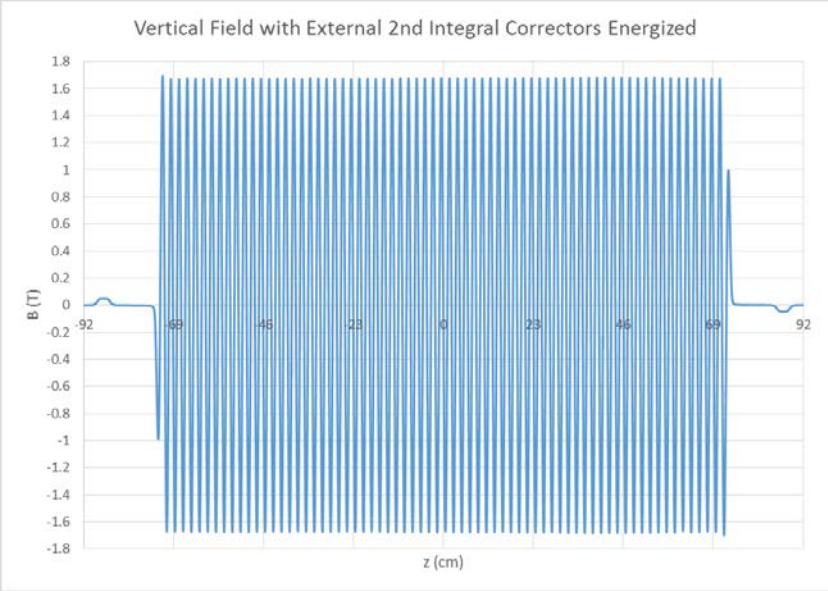
- Final electrical connections are made between the cold mass and the current lead/cryocooler turrets.
- Vacuum vessel turret and end covers are installed.
- Cryostat is moved to the measurement bench and aligned.



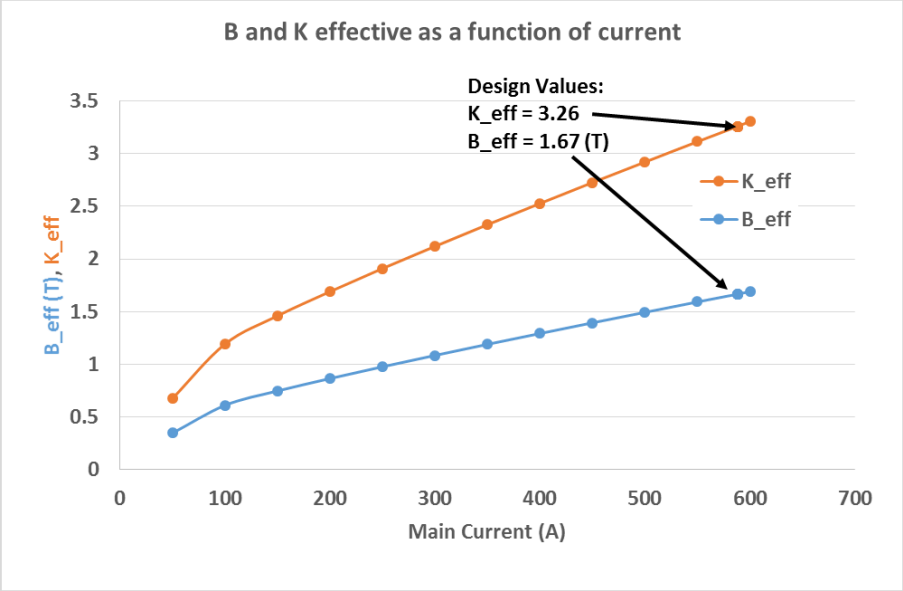
Beam vacuum chamber cross-section

MEASURED UNDULATOR FIELD: 1.5-METER LCLS R&D MAGNET

Measured field profile



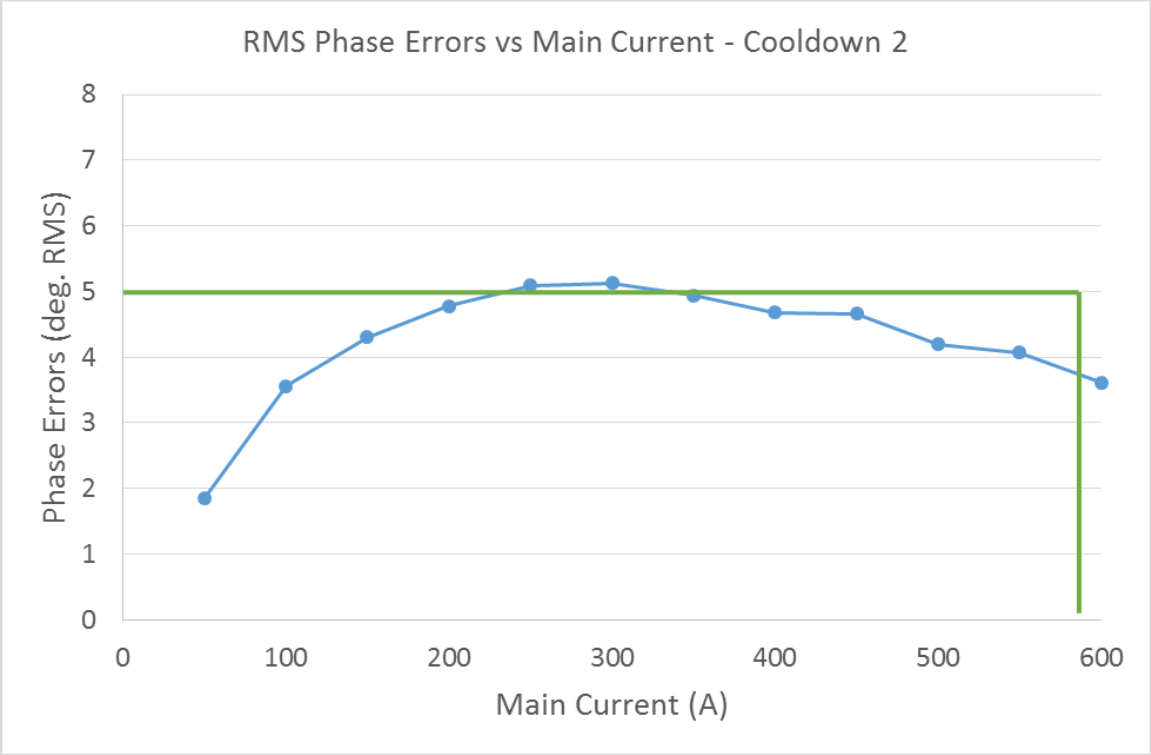
Measured excitation curve



Achieved field

Parameter	Symbol	Design	Measured	Units
Nominal on-axis, peak field (at 80% short-sample limit)	$\lvert B_0 \rvert$	1.67	1.6657	T
Nominal peak undulator parameter (at 80% short-sample limit)	K_0	3.26	3.260	-
Nominal excitation current (at 80% short-sample limit)	I_0	~600	588	A

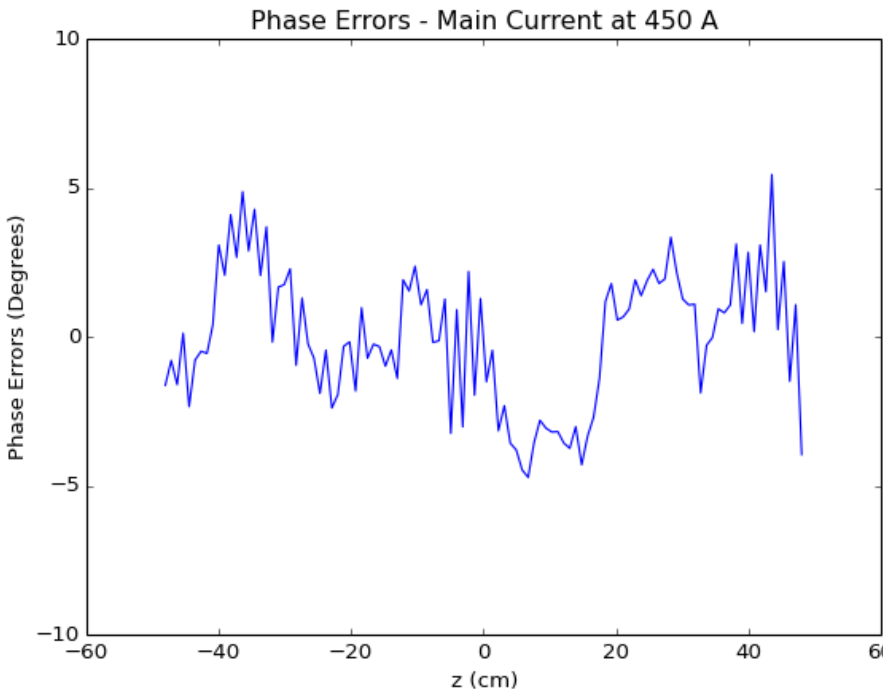
MEASURED PHASE ERRORS: 1.5-METER LCLS R&D MAGNET

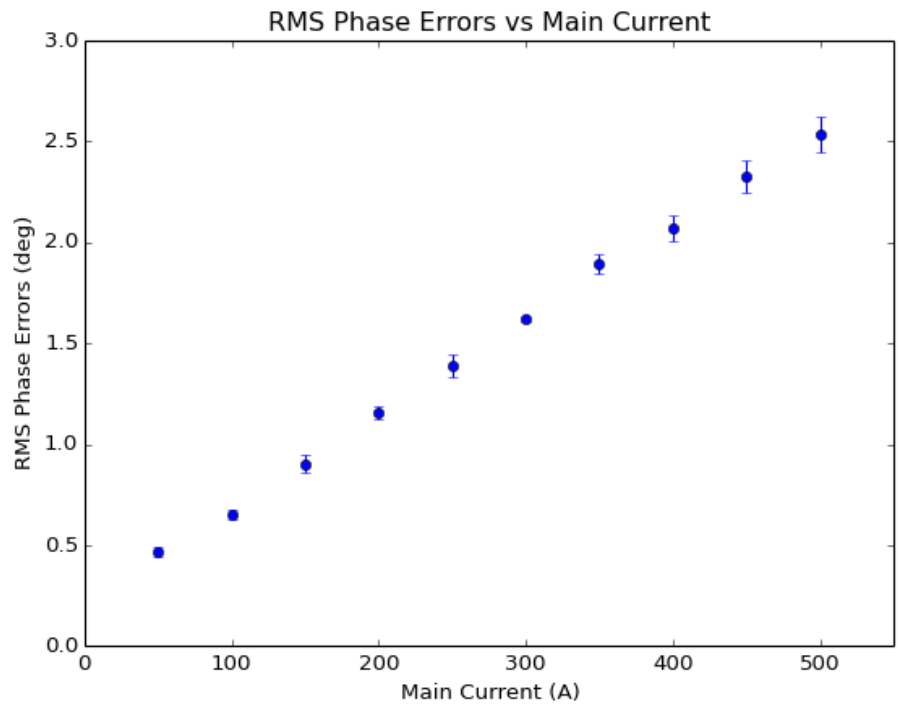


Parameter	Symbol	Design	Measured	Units
Phase shake error over undulator (rms)	Δj_{rms}	5	3.8±0.3	deg

The most challenging tolerance is achieved without magnetic ‘shimming’

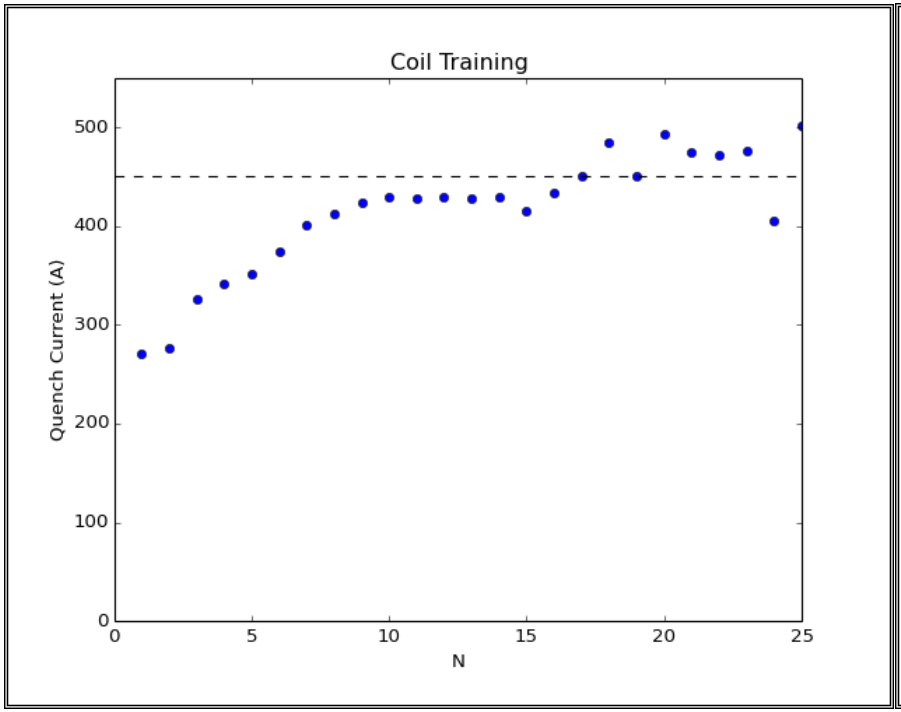
MEASURED PHASE ERRORS – 1-METER "SCU18-2"



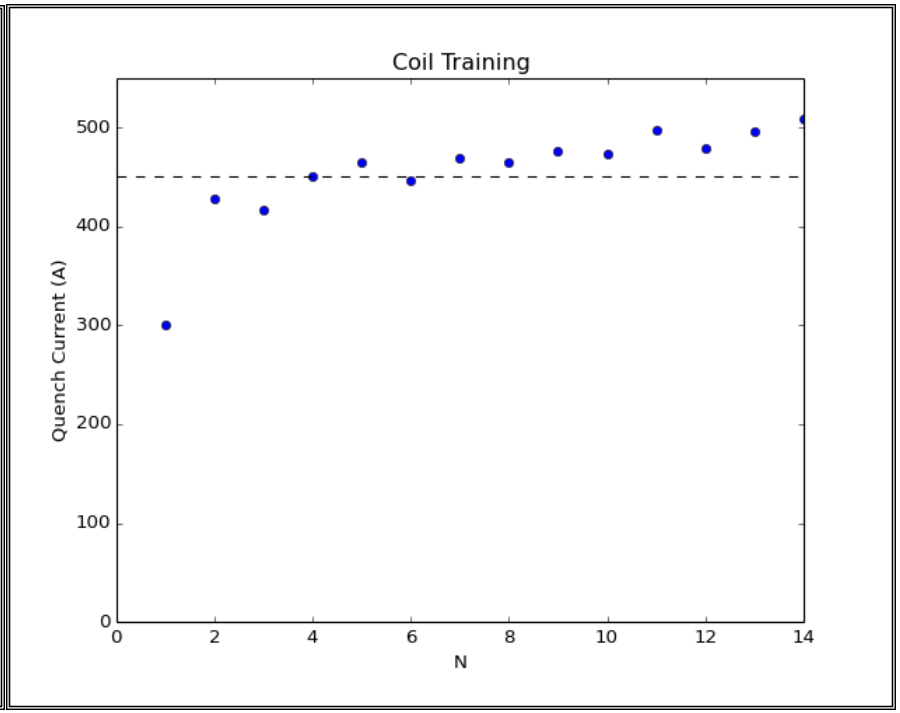


- Typical RMS phase error specification = 5°
- SCU18-2 RMS phase error at design current = 2.30°
- Phase errors were achieved with no magnetic shimming

MAGNET TRAINING – 1-METER "SCU18-2"



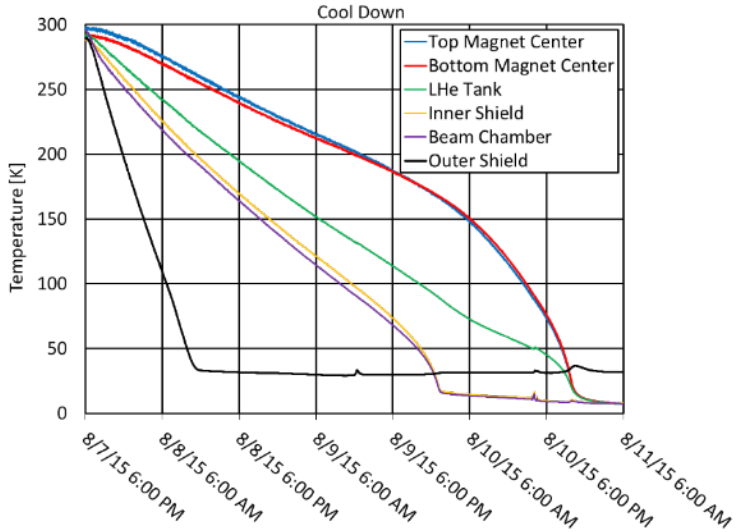
Cooldown 1:450 A reached on quench #15

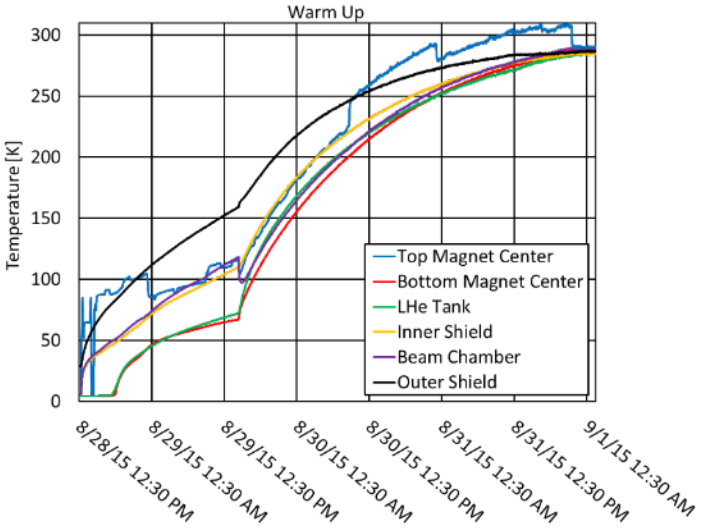


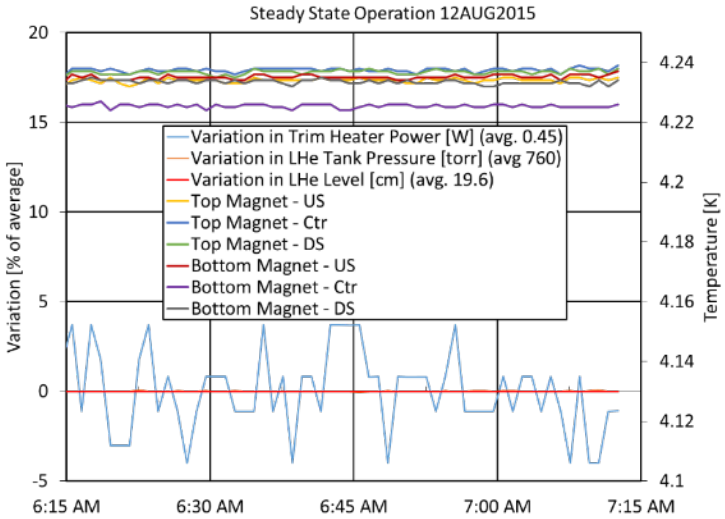
Cooldown 2: 450 A reached on quench #4

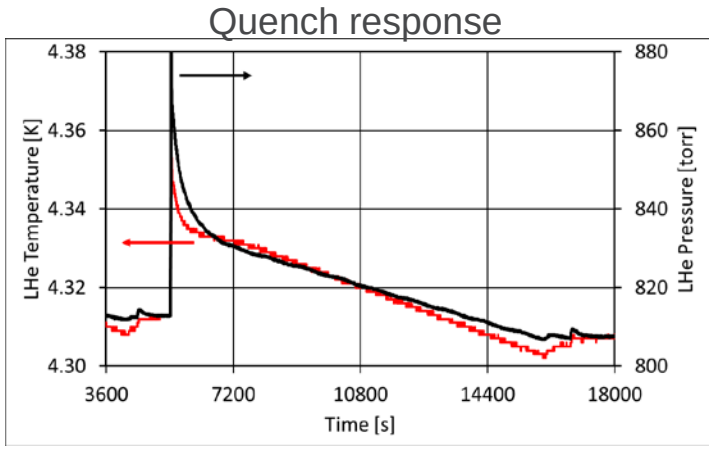
- Coil training was performed after each cooldown.
- Magnets were trained above the operating current of 450 A.
- Number of training quenches is reduced after each thermal cycle.

TYPICAL CRYOGENIC PERFORMANCE









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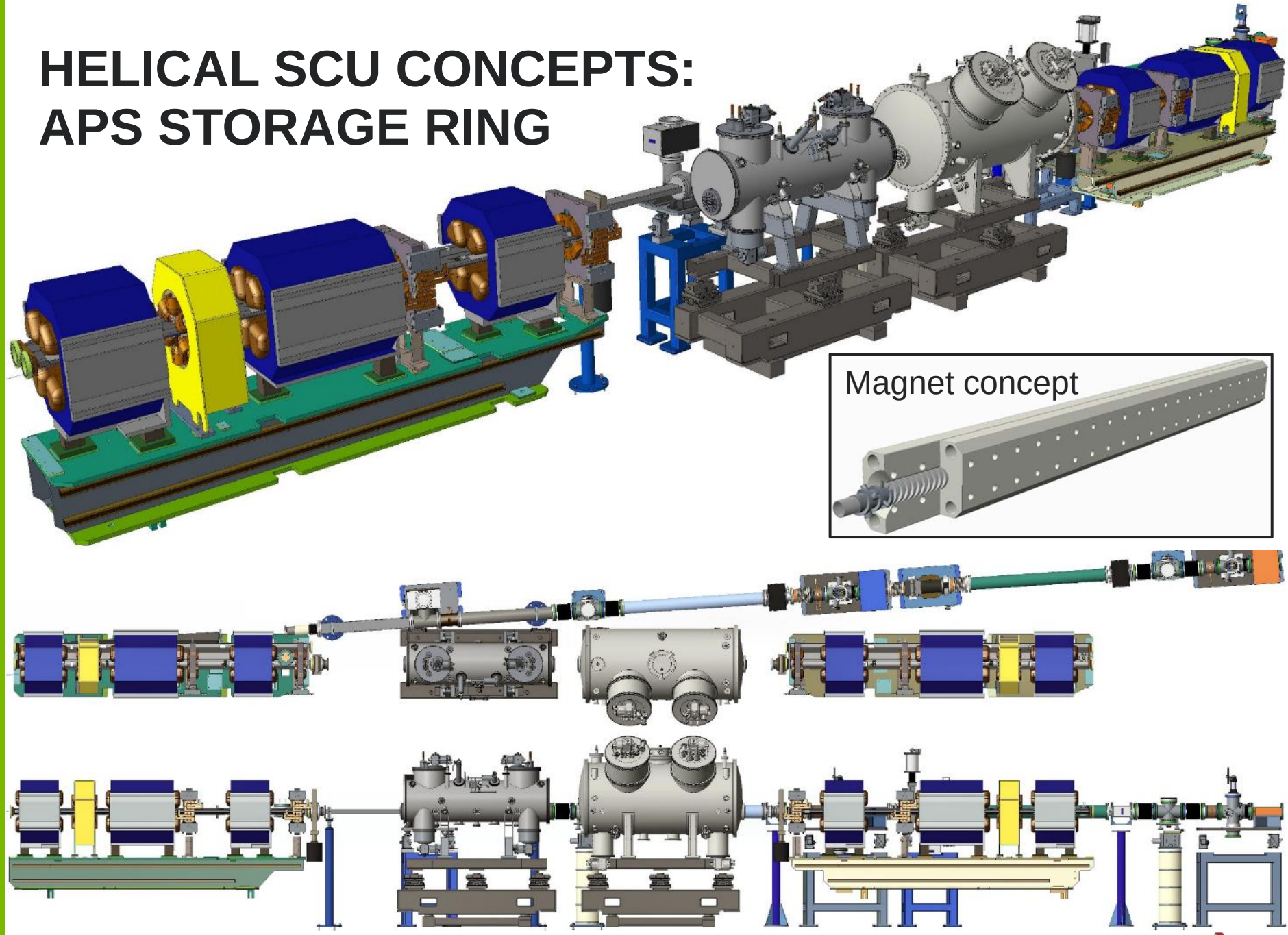
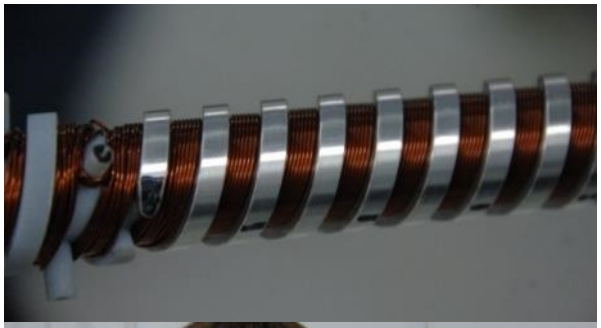
INDUSTRIAL PARTICIPATION: EXISTING AND FUTURE PLANS

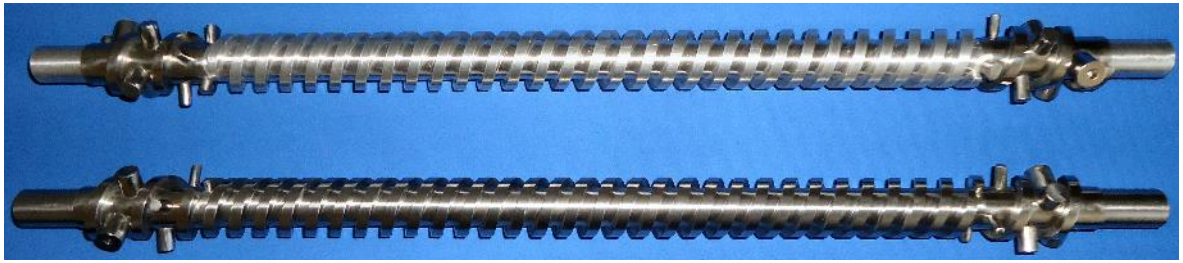
- Several subsystems on existing SCUs were fabricated in industry from ANL designs:
  - Vacuum vessel
  - Thermal shields
  - Liquid helium reservoir
  - Magnet cores
- Helical SCU currently in fabrication has extended industry participation:
  - Mechanical analyses (including ASME code)
  - Production drawings from ANL 3D CAD models
- Long-term (3-4 year) ANL goal is to develop a vendor for “turn-key” SCU production:
  - Magnetic design & analysis
  - Hardware design & fabrication
  - Magnet winding, full cryostat assembly
  - May include ANL collaboration for measurement & test

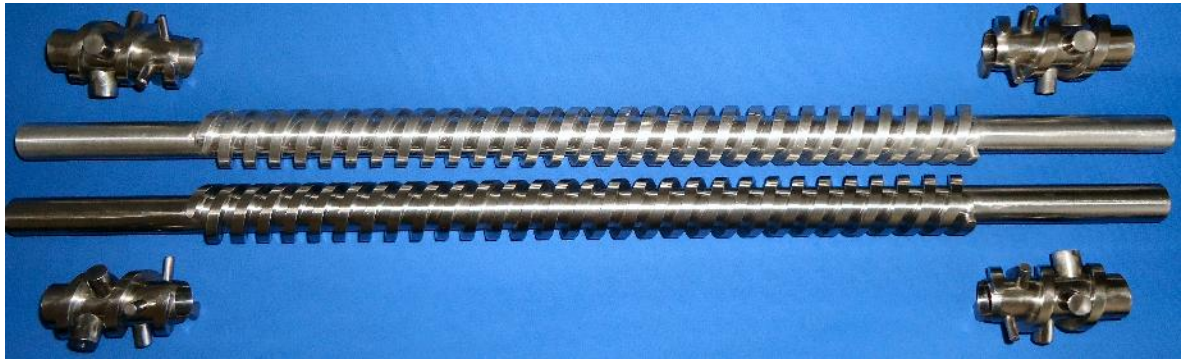
HELICAL SCU CONCEPTS: APS STORAGE RING

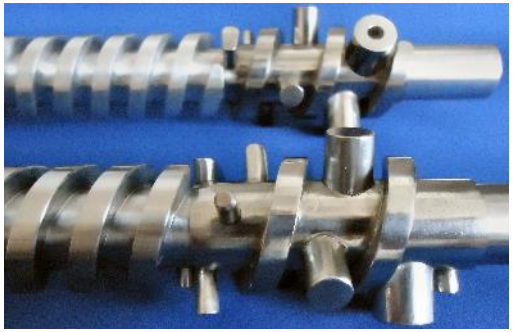


HELICAL SCU MAGNET R&D



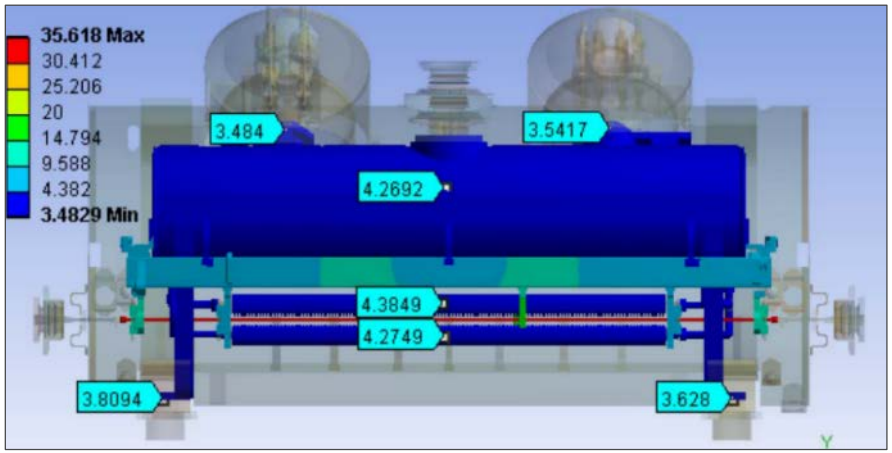




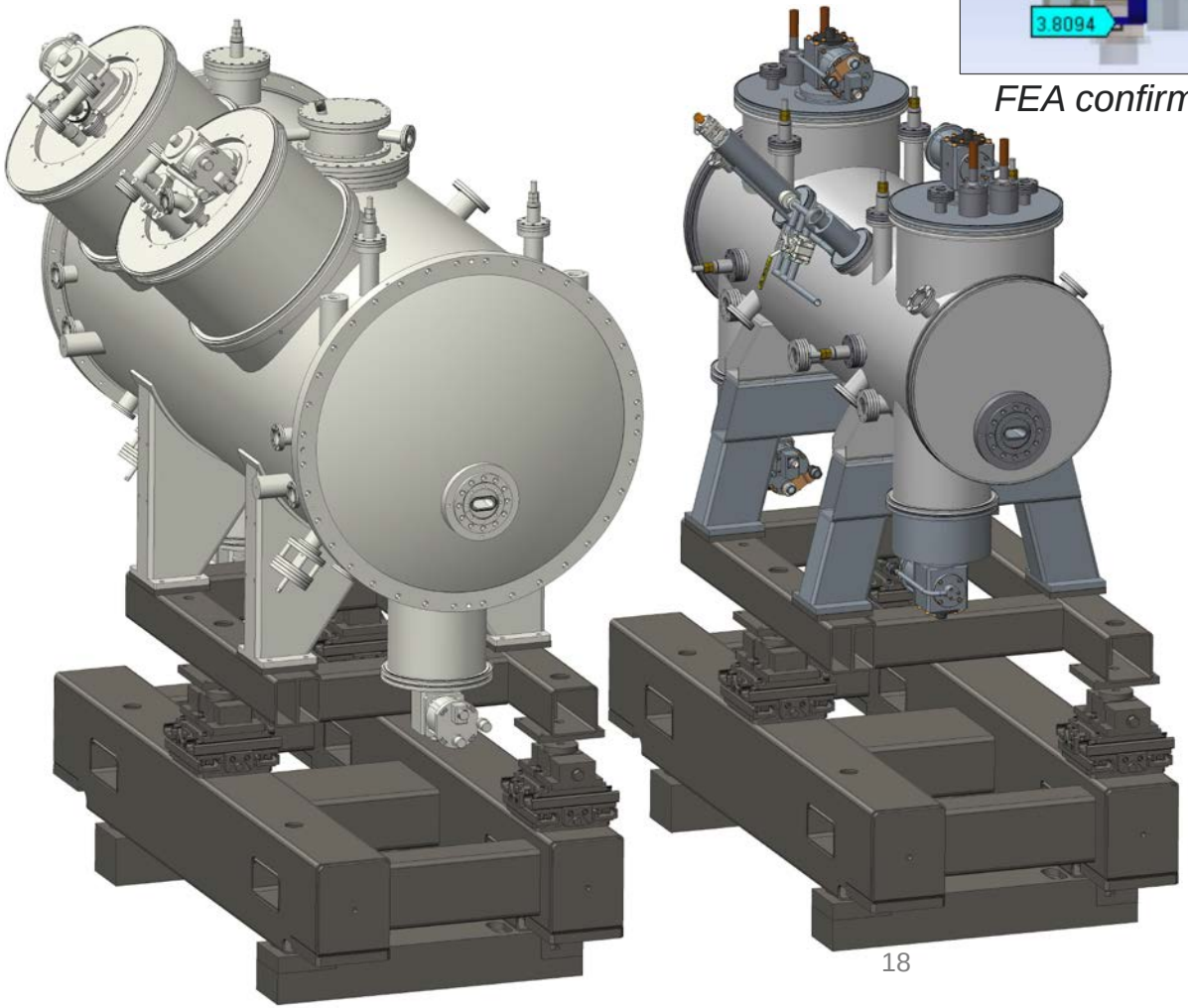


- Helical SCU magnet cores prototyped in plastic, Al, and steel
- Conductor turn-around is proven with practice-winds

CRYOSTAT EVOLUTION



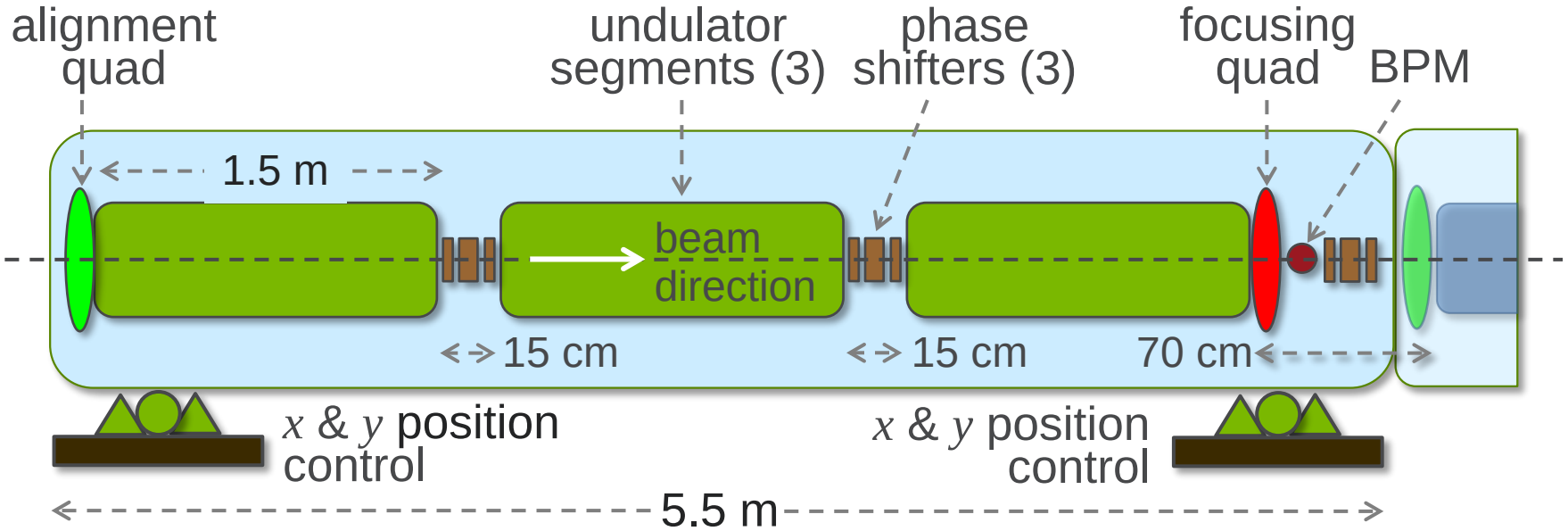
FEA confirms suitability of QTY4 4.2K cryocoolers



Implementation of lessons learned:

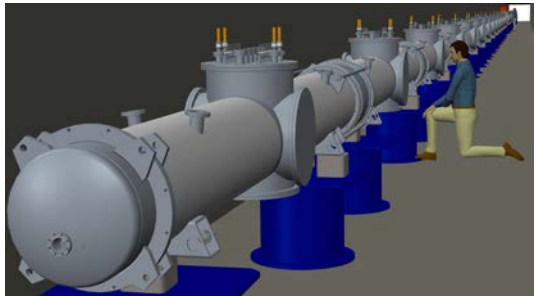
- Improved alignment/ fiducialization
- Better thermal performance (shield, cryocoolers)
- Smaller, cheaper
- Possible LHe-free cooling

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



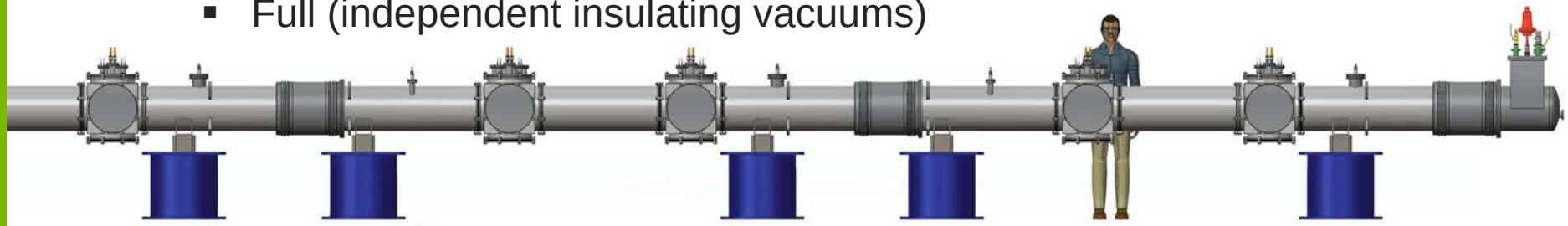
- Three 1.5-m long undulator segments in one 5.5-m cryostat
- Short segments (1.5-m) easier to fabricate, measure, tune, and taper
- Each segment independently powered to allow optimized TW-taper
- Ancillary components include cold BPM, cold phase-shifters, cold quads
- Cryogenic refrigeration/distribution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

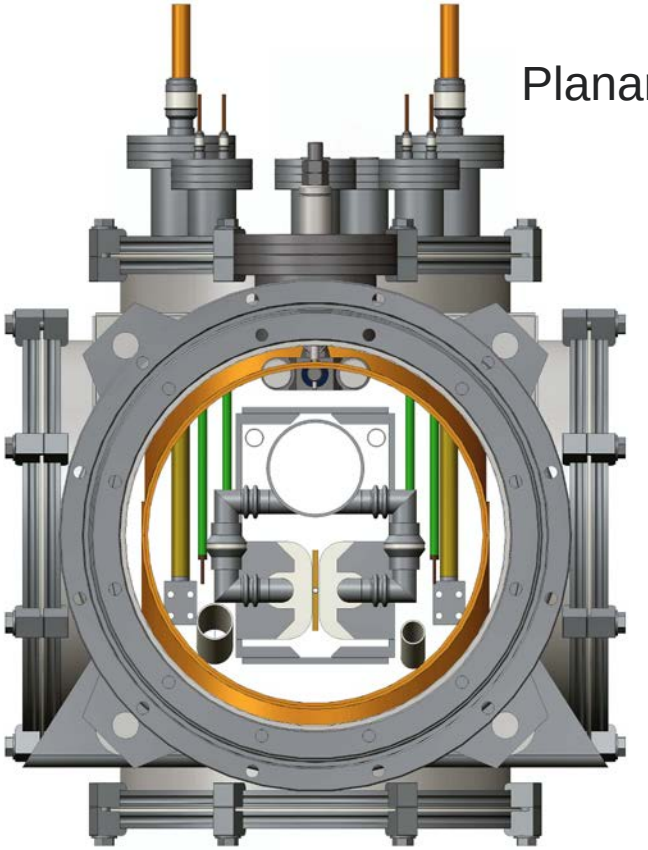
FEL SCU ARRAY CONCEPT



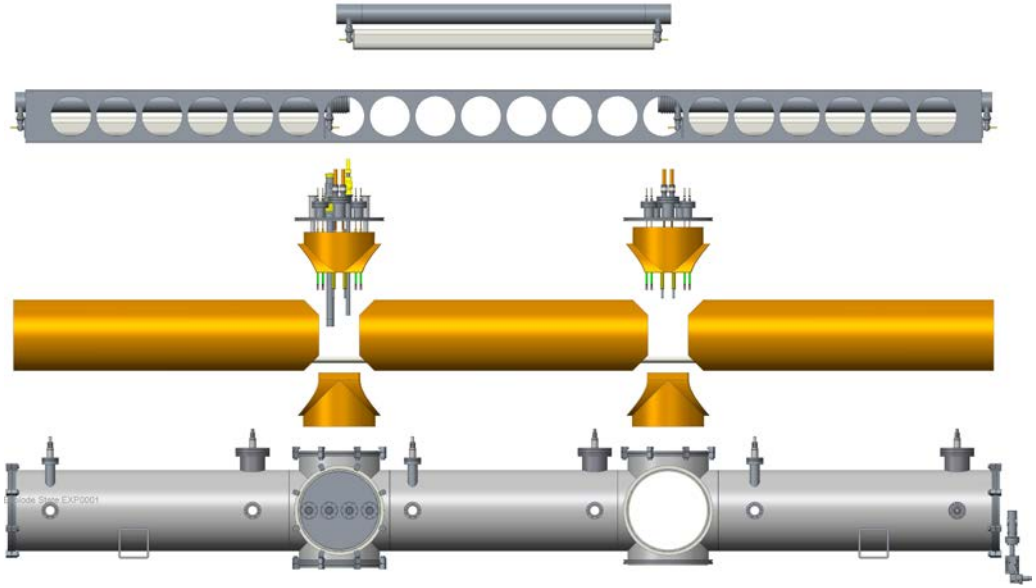
Array Segmentation:

- Minimal (common insulating vacuum)
- Full (independent insulating vacuums)



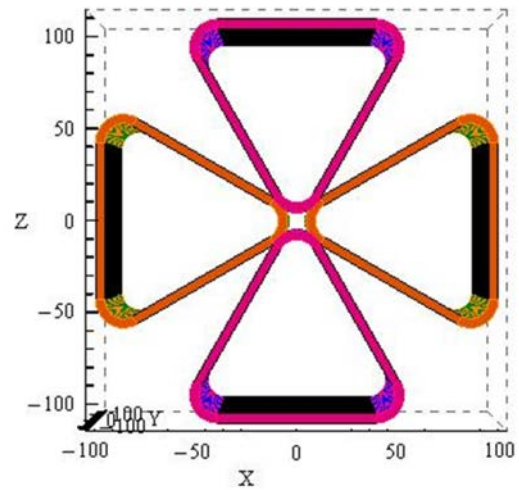


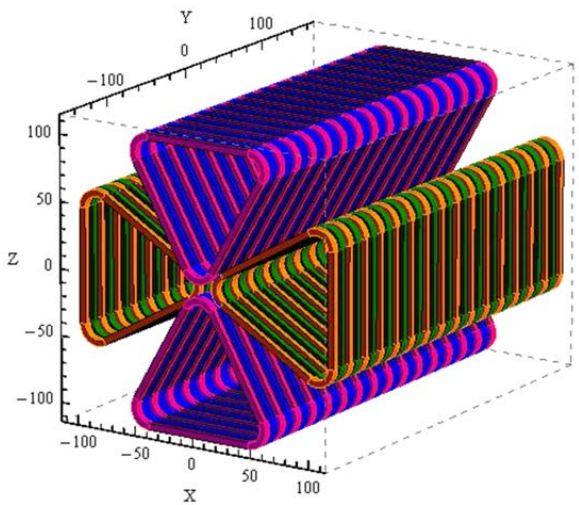
Planar, horizontal gap magnet shown (could be vertical)

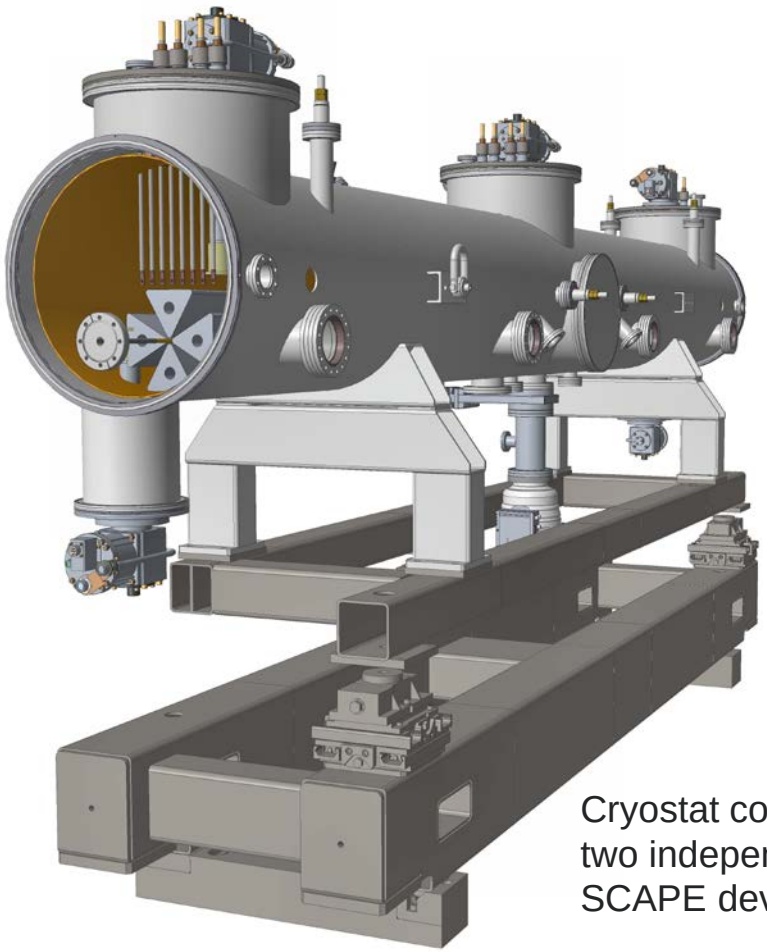


SCAPE (SUPERCONDUCTING ARBITRARY POLARIZATION EMITTER) – A UNIVERSAL PLANAR SCU

- Current concept suggested by E. Gluskin & Y. Ivanyushenkov
- Magnet pairs are displaced relative to each other along beam axis by ¼-period
- Can generate both planar and helical fields (confirmed by simulation)







Cryostat concept with two independent SCAPE devices

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SUMMARY

- APS developed strong expertise in the design and construction of NbTi-based planar SCUs. A dedicated facility has been set up for construction and characterization of SCUs.

- APS SCU team acquired and developed all theoretical and technical tools needed for design and construction of the SCUs. Two SCUs are successfully operating at the APS with high availability.

- An FEL-specific SCU has been designed, built, and characterized which meets or exceeds all FEL undulator specifications.

- APS continues to develop SCU technology for future storage ring and FEL light sources.