Superconducting undulators - a novel source of radiation for synchrotron and FEL light sources

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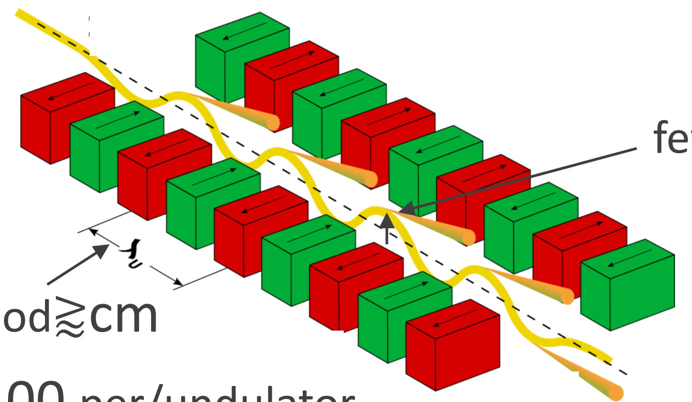
Outline

- Quick reminder of undulator basics, and why SCU?
  - small period, but strong enough field
- List of engineering challenges for SCU
- SCU magnets
  - magnet cores fabrication
  - winding, chemical cures
- SCU cryostat and cryogenic performance
- SCU magnet measurements
- SCU in the storage versus FEL undulator line
- Bold forecast

Undulator basics – quick reminder



$$\lambda_n = \frac{\lambda_u}{n \cdot 2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

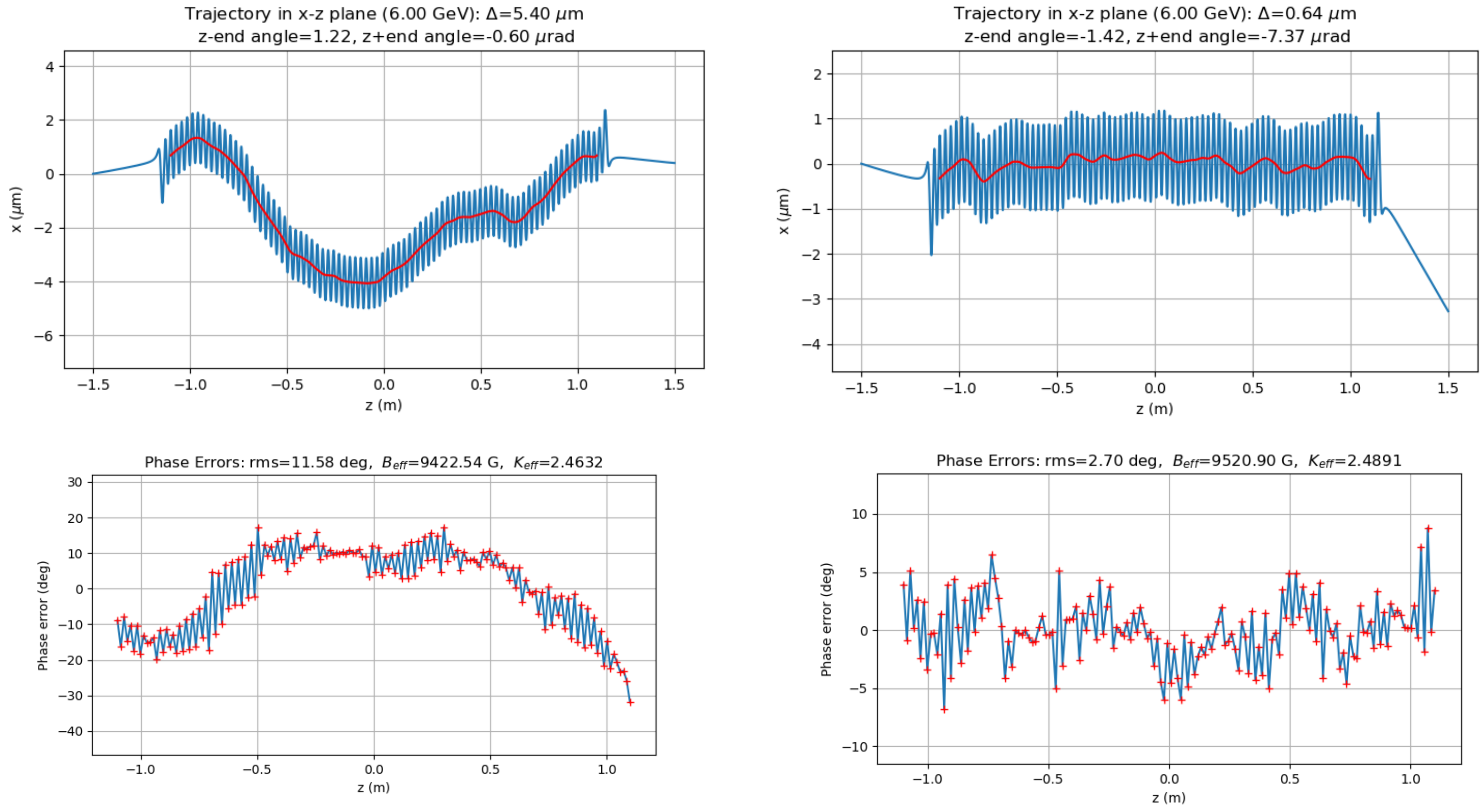
$$K \cong 0.9\lambda_u H$$

$$P_{tot} \propto (\gamma H)^2 \cdot I_e \cdot L_u$$

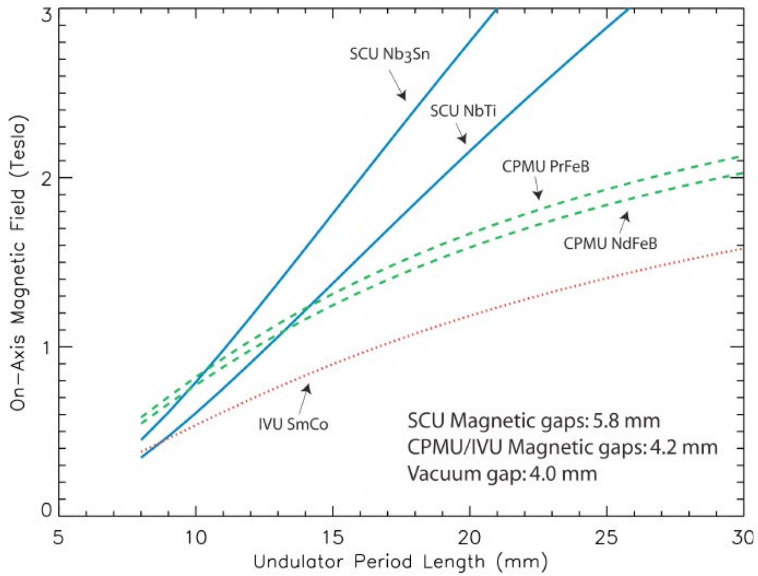
$$L_u = N\lambda_u$$

$$\frac{\textbf{Number of photons}}{\textbf{sec, 0.1\% bandwidth}} \propto N \cdot I_e \cdot H^2$$ (in central cone; K<2)

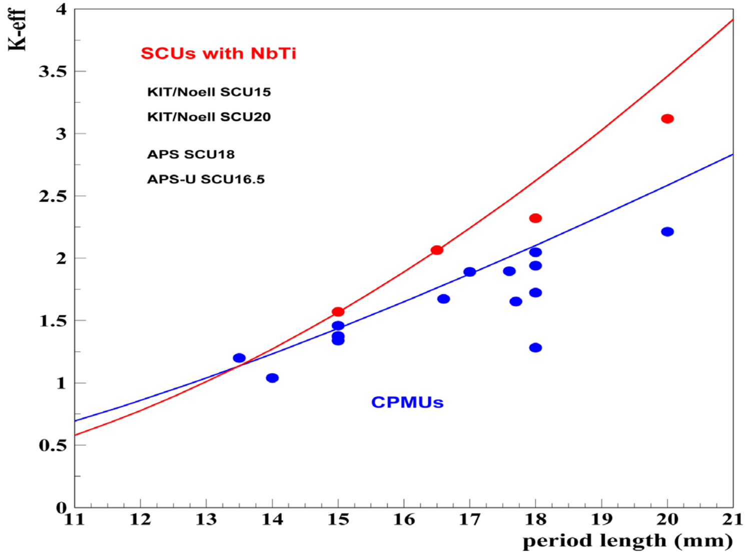
Undulator basics – phase errors



SCU versus in-vacuum cryogenic hybrid ID



Calculated on-axis magnetic fields of two cryogenic permanent magnet undulators (CPMUs), two superconducting undulators (SCUs), and one in-vacuum undulator (IVU) for a vacuum gap of 4.0 mm for a period length from 8 mm to 30 mm.



Effective K-values for built CPMUs and SCUs

List of engineering challenges in the design and construction of SCU

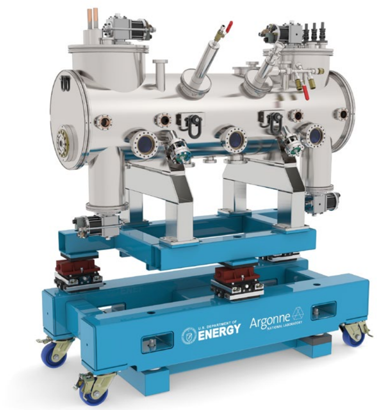
- High quality of magnetic performance:
  - Machining tolerances of magnet cores and precise, consistent winding of magnets
  - Preserving mechanical tolerances through multiple steps of magnet fabrication
- High reliability in cryogenic performance:
  - “Warm to cold” turnaround time
  - Balance between low capacity of cooling system and demands for precise, repeatable magnet motion
  - Super-protection from incoming radiation
  - Long, precise beam vacuum chamber with high quality surface and minimal “cold to warm” transitions
- Magnetic measurements, aka in-situ QC of SCU

SCU developments in the world

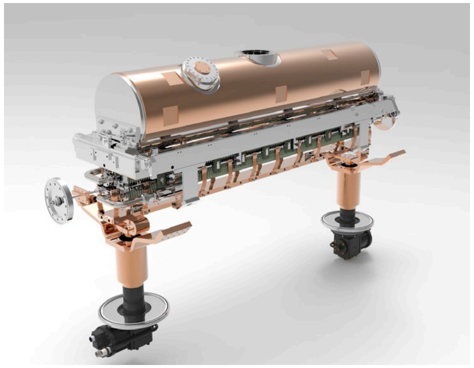
- First SCUs were built in the 70s and 80s : one for FEL experiments at Stanford University and another for HE physics experiments at BINP, Novosibirsk.
- There were several small R&D programs that didn't lead to an operating device.
- Operating SCU at ANKA, Germany: designed and built by Babcock Noell GmbH (currently Bilfinger Noell) – very limited open technical information.
- Operational SCUs at the APS – all detailed technical information is available.
- BINP built SCU for Diamond Light Source – unorthodox magnet design.
- SCU for SHINE FEL, Shanghai, China – undulator design from BINP.

APS SCU main components

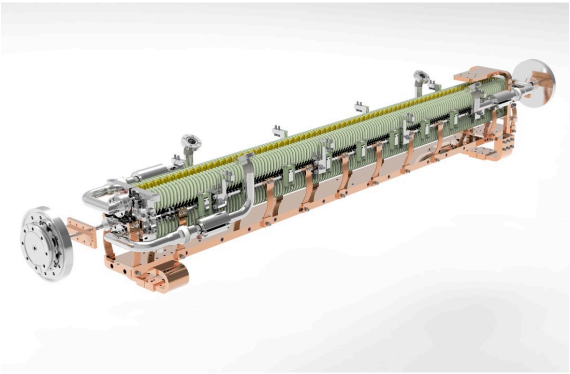
Assembled cryostat



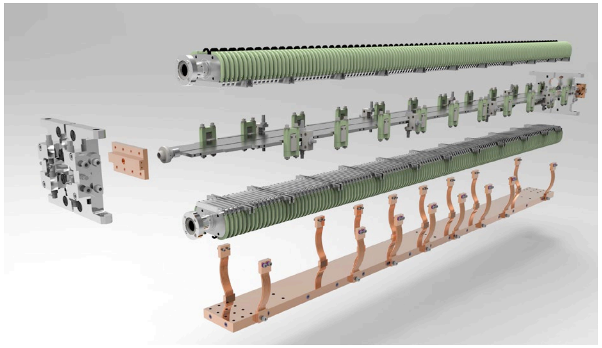
SCU cold mass



Magnet – beam vacuum chamber assembly



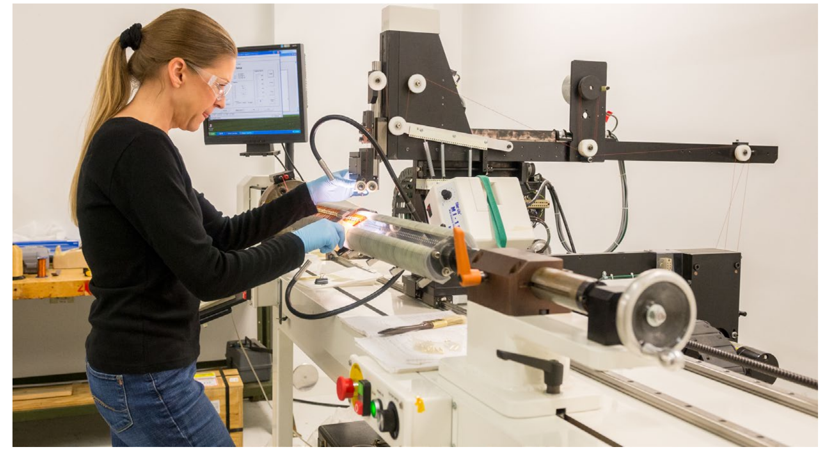
Magnet cores and beam vacuum chamber

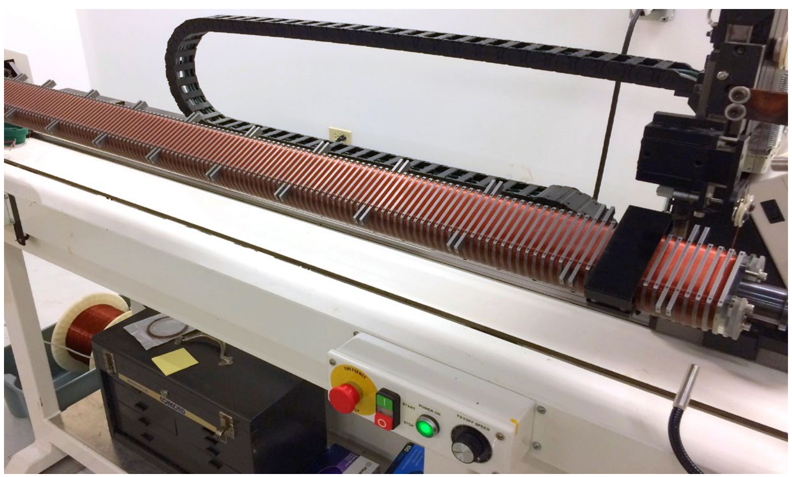


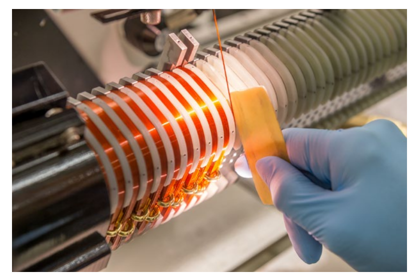
- SCU cryostat consists of vacuum vessel, thermal shield, and a cold mass
- Cooling is provided by 4 cryocoolers
- Closed-loop LHe circuit
- LHe is contained in a tank connected with the magnet
- Two NbTi-based magnets form SCU
- NbTi magnets are cooled indirectly with LHe passing through channels in the magnet iron cores
- Beam chamber is thermally isolated from the magnet and cooled independently

SCU magnet's core and winding process

Precise grooves for controlled wire location

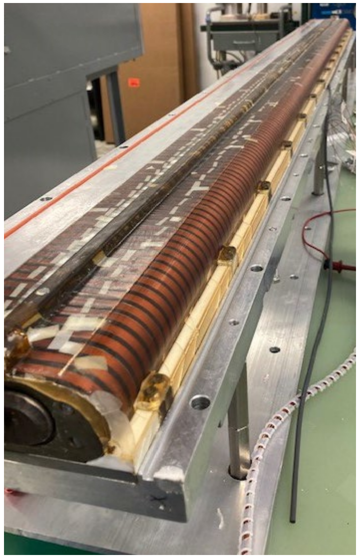




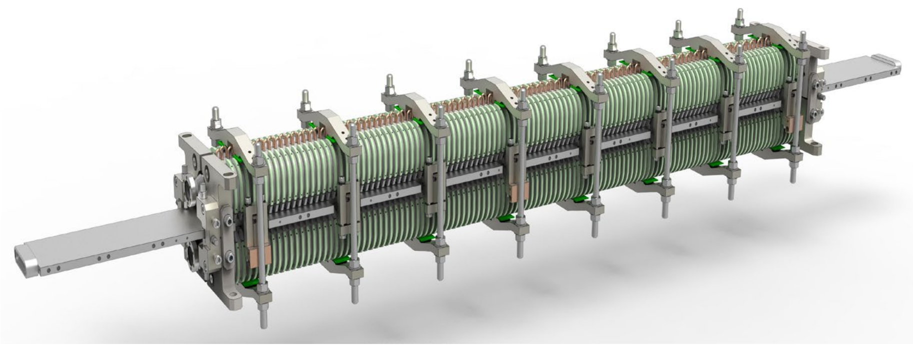


6 mm

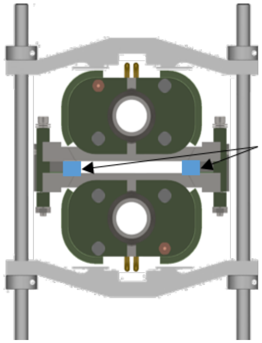
SCU magnet's assembly

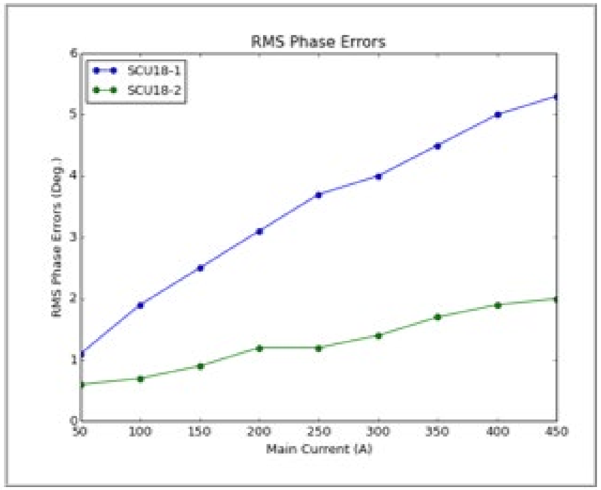


Magnet core after epoxy coating



Assembled SCU magnet

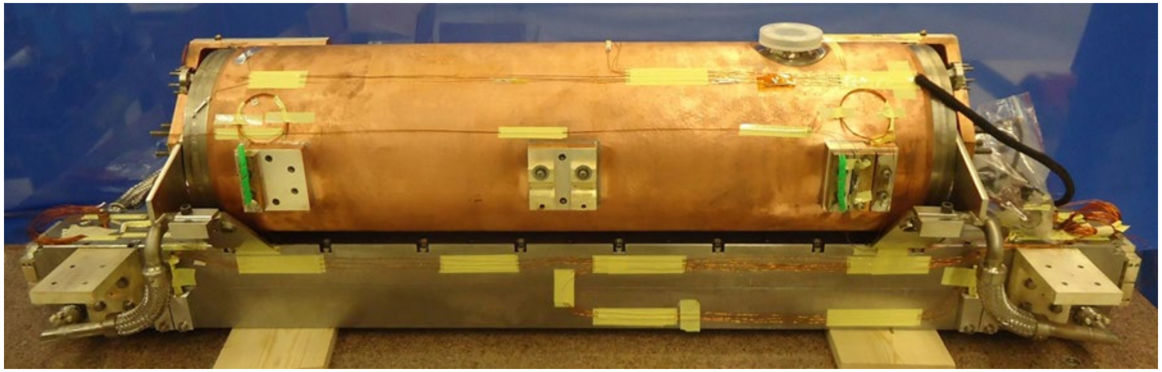


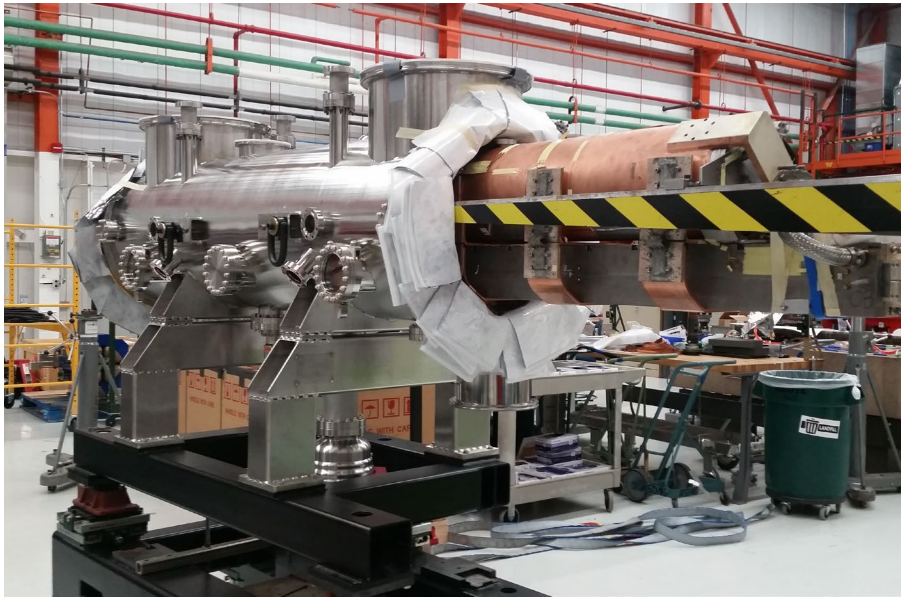


Phase errors versus SCU magnet current

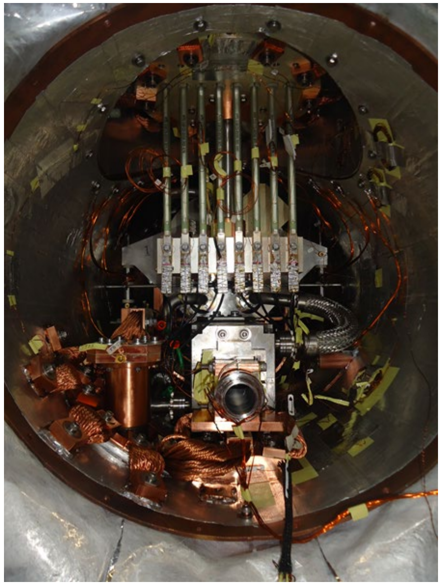
Helical SCU assembly

Cold mass: LHe tank and mold with the magnet



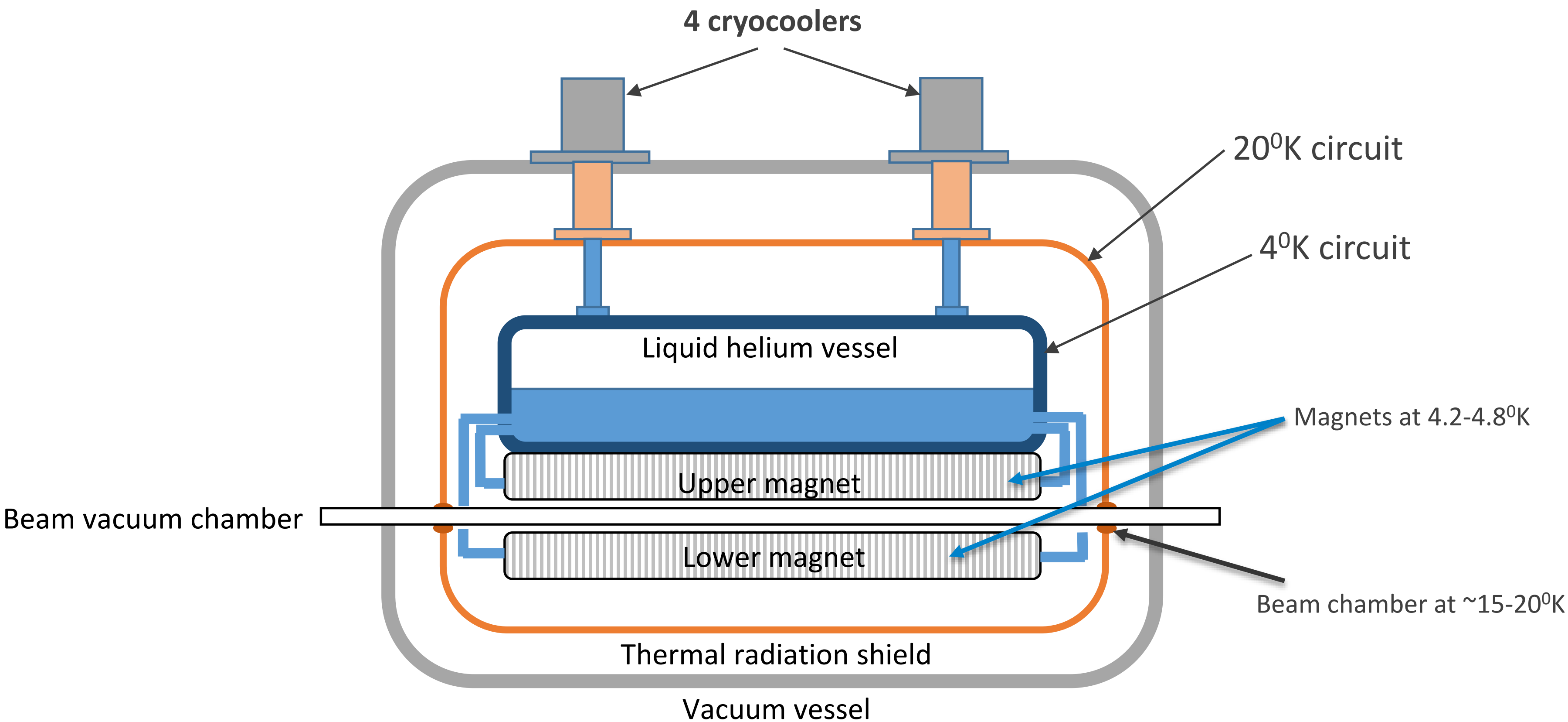


Cold mass is inserted in the cryostat



Thermal and electrical links

Diagram of APS SCU cryo-circuits



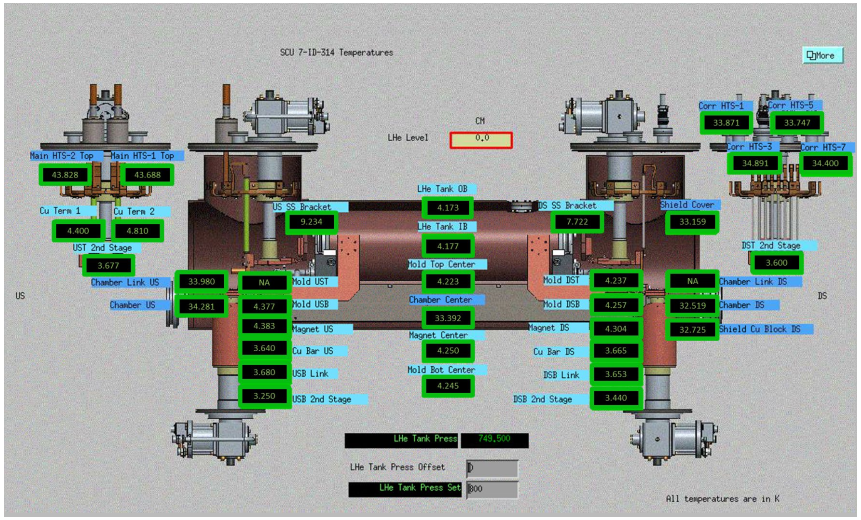
Cooling capacity of 4 Sumitomo RDK415D cryocoolers at ~20^0K: 200 – 60 W

Cooling capacity of 4 Sumitomo RDK415D cryocoolers at ~4^0K: 6 – 2 W

Typical thermal load on 20^0K circuit is < 50W

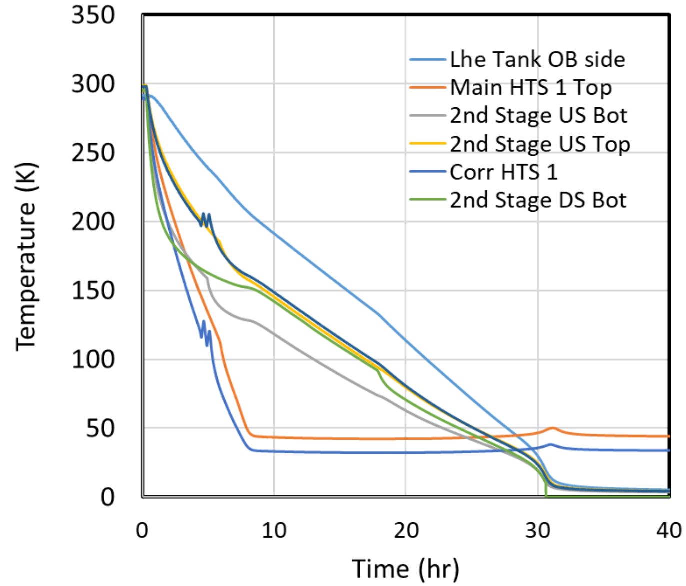
Typical thermal load on 4^0K circuit is ~ 1W

SCU cryogenic tests

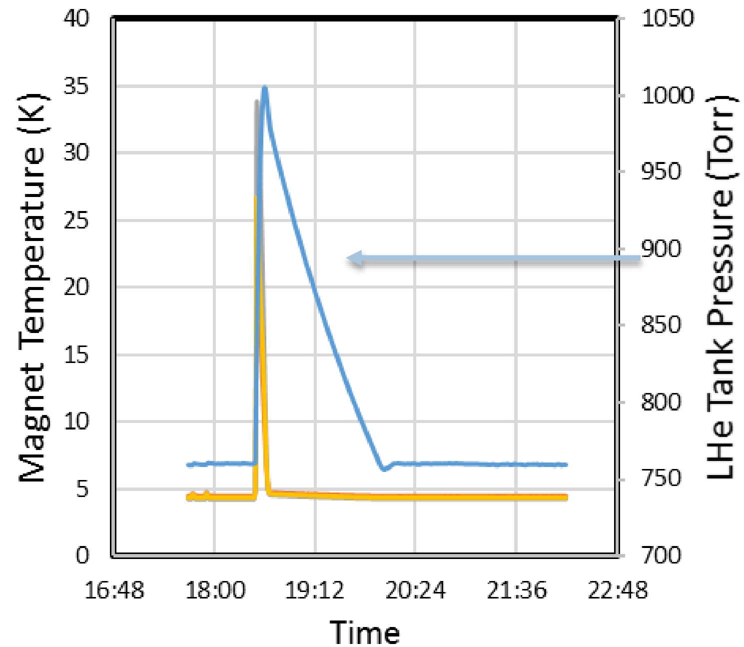


Screenshot of temperature readings

- Modeled/numerically calculated temperature map is in quite good agreement with measured one
- Cool down time is about 30 hours
- Quench recovery time (ready for beam) is <1 hr

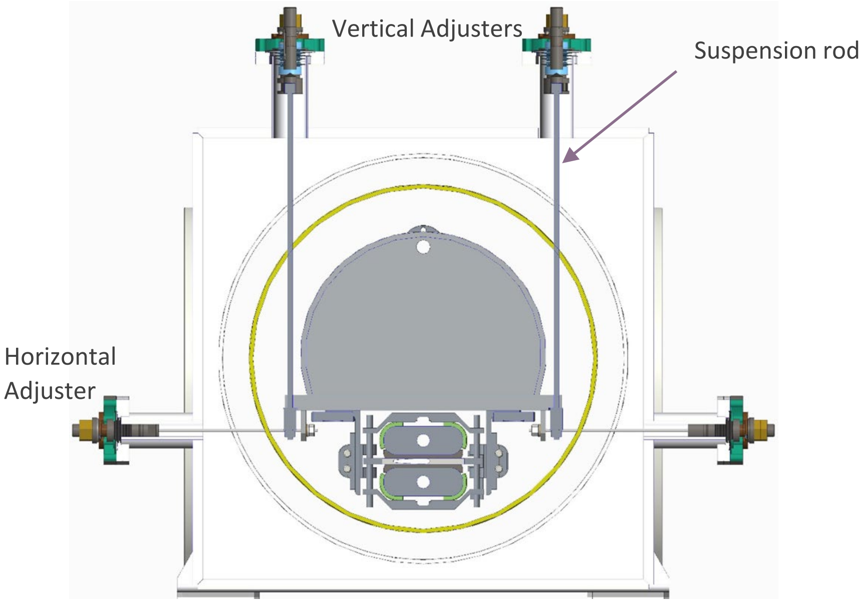


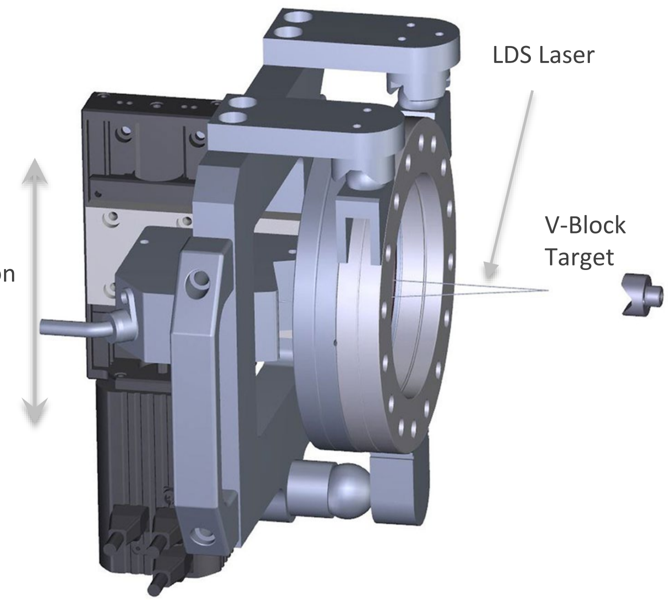
Cooldown



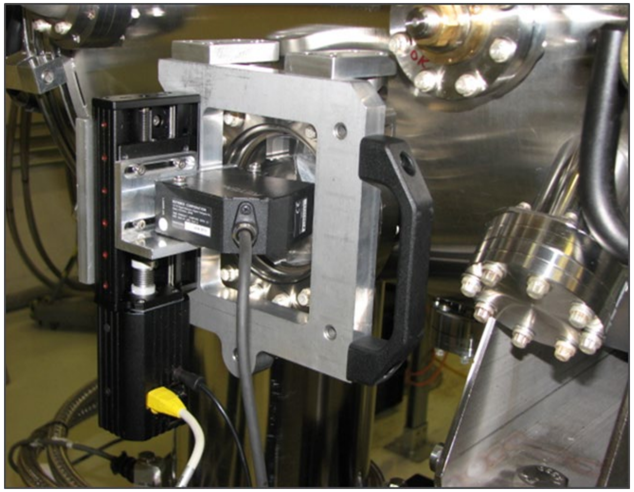
Quench recovery

Cold Mass Suspension and Alignment System; Portable Cryo-scanner



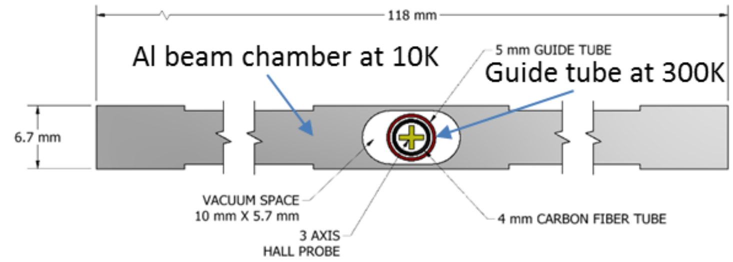


- Cold mass is suspended on invar rods
- Measures displacement of cold mass inside a cryostat through glass viewports
- Kelvin kinematic couple interfaces *Cryoscanner* device with cryostat vessel at multiple locations
- CCD laser displacement sensor (LDS) is mounted to a vertical linear translation stage
- LDS laser is scanned across V-block target surface to acquire 2-D coordinates (X,Y)
- **Cold mass position is adjustable with <10 μm resolution and reproducibility**



Measuring SCU magnetic field

- Warm sensor concept (by Budker Institute, Russia):
  - Metallic guide tube is stretched inside the beam chamber cold bore
  - Guide tube is heated by the current passing through it
  - Guide tube bore is open to atmosphere
- Sensor (Hall probe or wire coil) operates at room temperature
  - Hall probe:
  - 3-axis commercial Hall sensor measures By, Bx, Bz components
  - Attached to fiber tube and driven by precise 3.5-m linear stage
  - Bz- field is used to measure vertical position of the sensor
- Stretched wire coils:
  - Rectangular, delta, and 'figure- 8' coils stretched between two linear and rotation stages
  - Measure static and dynamic field integrals and multipole components

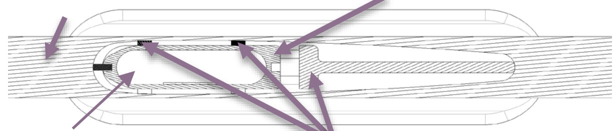


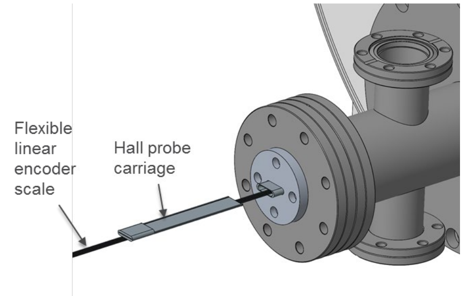
Warm-sensor concept

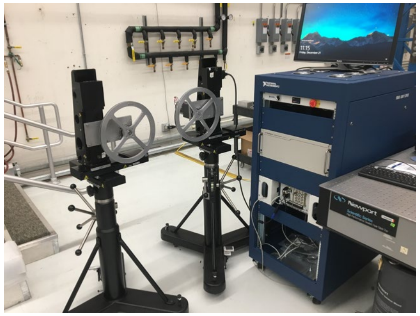
SCU horizontal measurement system

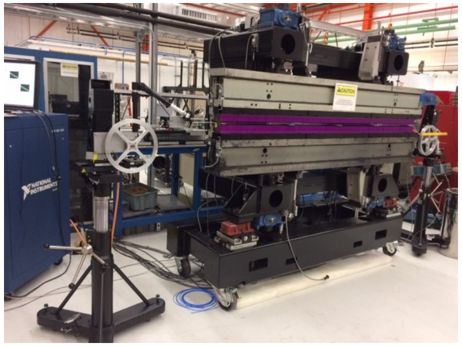
Magnet Measurement System for a long SCU

- New design is based on experience of using a 2-m-long measurement system for the APS SCUs:
  - a proven concept of a warm guiding tube
  - Hall probe carriage is moved with a flexible linear encoder scale
  - does not require a long holder attached to a long travel linear stage
- System is fabricated, assembled and tested; it’s being used to measure a well-characterized HPMU



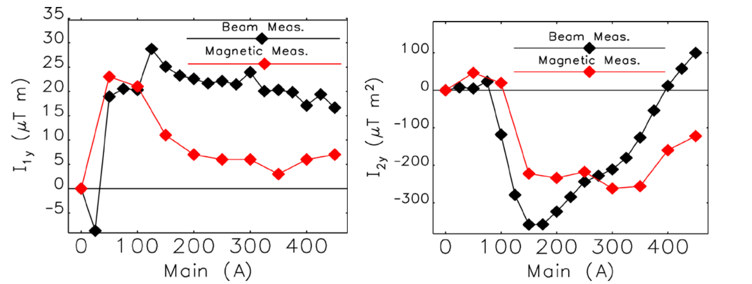




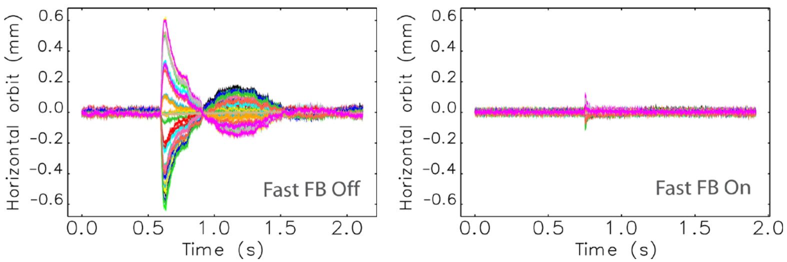


SCU effects on the electron beam

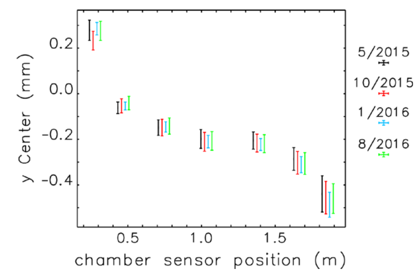
- SCU field integrals satisfy the physics specifications
- SCU quench produces only small beam motion and does not cause loss of the beam
- Position of the SCU vacuum chamber is stable and does not require realignment
- SCU cryocooler vibrations do not affect beam stability
- SCU operation does not affect the beam lifetime



Vertical-field integrals of initial correction as measured using the stored beam, before final beam-based adjustments. The first integral is on the left and the second integral is on the right [1].



Effect of induced quench on the beam orbits at all the insertion devices. Left panel: Slow orbit correction only. Right panel: Fast orbit correction (FB) turned on [1].



Measured vertical position of the vacuum chamber inside the cryostat over a one-year period using the beam-based method [1,2].

APS SCUs operations statistics

- SCU0, SCU18-1, and SCU18-2 have been essentially transparent to the APS SR beam
- Most quenches occur during unplanned beam dumps
- SCU18-1/18-2 quenches decreased dramatically after beam abort system added Jan 2016

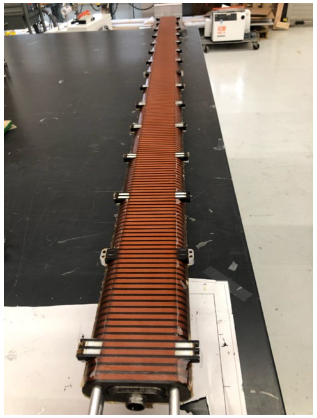
		SCU0 and SCU18-2				SCU18-1				HSCU			
Year	**APS delivered**	**Operation**	**Down**	**Quench**	**Avail. %**	**Operation**	**Down**	**Quench**	**Avail. %**	**Operation**	**Down**	**Quench**	**Avail. %**
2013	4871 h	4189 h	20 h	*34* + 3	99.5	-	-	-	-	-	-	-	-
2014	4926 h	4391 h	174 h [1]	*32* + 2	96.2	-	-	-	-	-	-	-	-
2015	4940 h	4834 h	0 h	*26* + 1	100	3059 h [2]	0.1 h	*5* + 0	99.99	-	-	-	-
2016	4941 h	4647 h [3]	0 h	*9* + 0	100	4585 h	0.3 h	*11* + 1	99.99	-	-	-	-
2017	4840 h	4756 h	0 h	*8* + 1	100	4818 h	0.75 h	*13* + 2	99.98	-	-	-	-
2018	4853 h	4755 h	5 h	*11* + 1	99.9	4710 h	0.59 h	*14* + 2	99.99	751.5 h	0 h	*0* + 0	100
2019	4899 h	3064 h	4.88 h	*9* + 2	99.8	4872 h	0.01 h	*5* + 0	99.99	1106.2 h	0 h	*0* + 0	100
2020	4874 h	3624 h	0 h	*7* + 1	100	3822 h	0.48 h	*5* + 0	99.99	421.9 h	84.5 h	*0* + 0	83.3
2021 [4]	2306 h	2256 h	0 h	*3* + 0	100	2295 h	0.01 h	*2* + 0	99.99	245.8	0 h	*0* + 0	100
Total	41450 h	36516 h	203.9 h	*142* + 11	**99.44**	28161 h	2.24 h	*55* + 5	**99.99**	2525.5 h	84.5 h	*0* + 0	**96.76**

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

[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, SCU18-2 1337 h
[4] January 2021 through June 2021

SCUs for APS Upgrade project

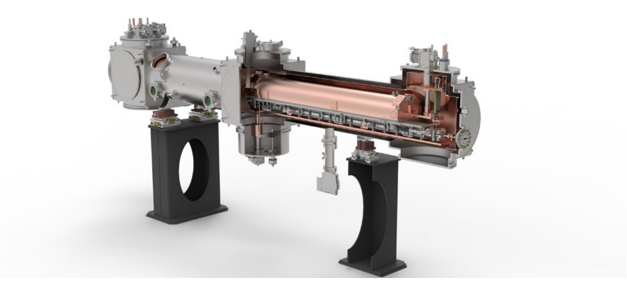
- SCU magnet assembly :
  - up to 1.9-m-long core with a channel for LHe
  - proven winding scheme
- Cryostat consists of:
  - 4.8-m-long 20”-diameter vacuum vessel
  - off-the-shelf vacuum components
  - three thermal stages (4K – 20K – 40K)
  - 6 cryocoolers (two types)



Completed 1.9-m-long core

- APS-U SCU #1 is being assembled

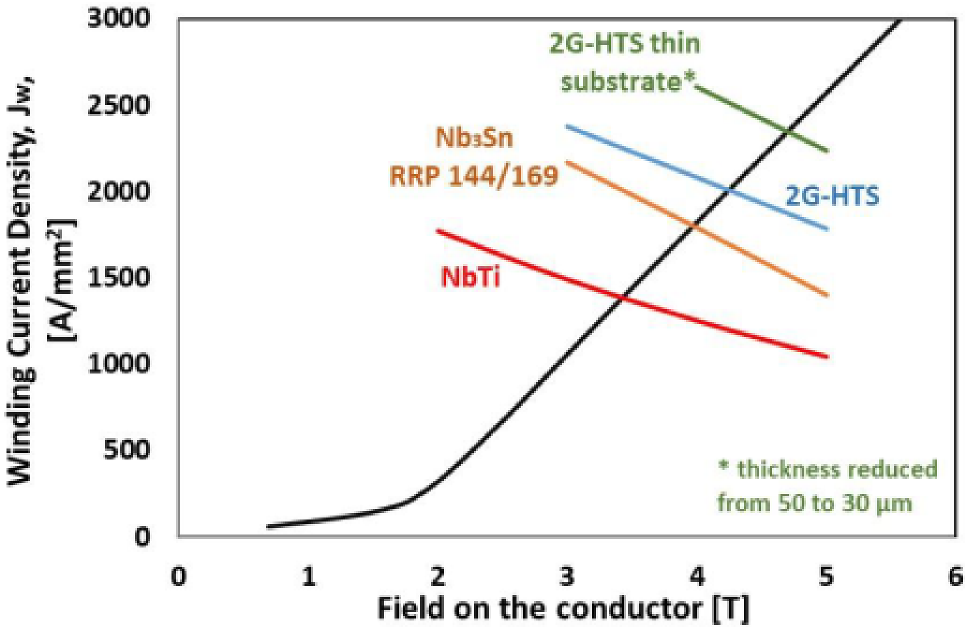
Cryostat design model



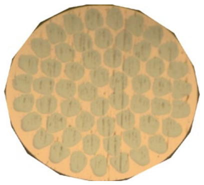
Cryostat vacuum vessel

LHe tank

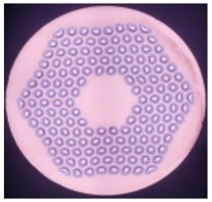
Superconductor wires for undulators



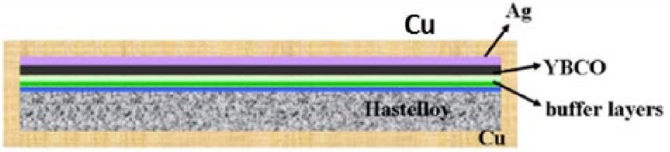
- **NbTi**
  - Predictable, controlled characteristics; well-established handling procedures.



- **Nb_3Sn**
  - Requires exposure to high T~650^{0}C to become SC; wire becomes brittle, needs special care to handle.
  - What level of field enhancement, field quality and reliability can be achieved?

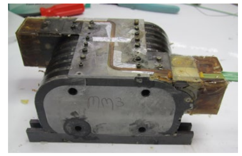


- 2G-**HTS -** *ribbon*
  - Operation at high T
  - Ready to wind
  - Ic uniformity
  - Length is limited

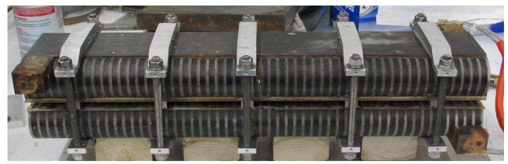


ANL-FNAL-LBNL collaboration on Nb_3Sn SCU for APS

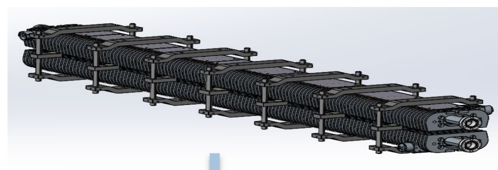
- Goal: Develop, build, and install on the APS ring a Nb_3Sn undulator (in a modified SCU0 cryostat) a year before the APS-U 'dark time' starts
- Collaboration with FNAL and LBNL
- Project funded by ADRP at BES DOE
- Status:
  - R&D phase almost completed
  - 1.1-m-long magnets are fabricated
  - The cryostat is under preparation



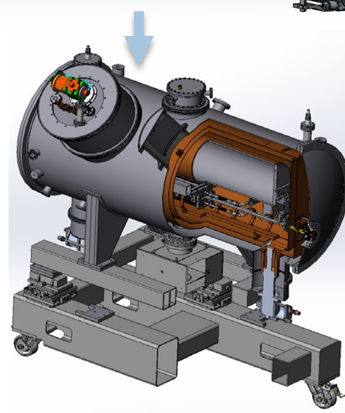
84 mm



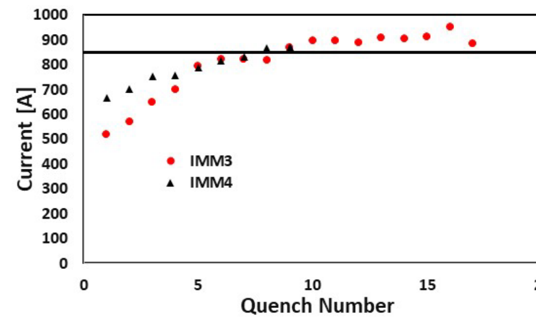
0.5 m



1.1 m

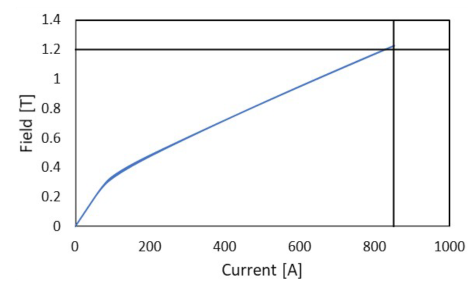


Quench training profile of individual cores



0.5-m-long Nb_3Sn SCU prototype did not require any training to reach the design current in 2nd cooldown and demonstrated excellent training memory.

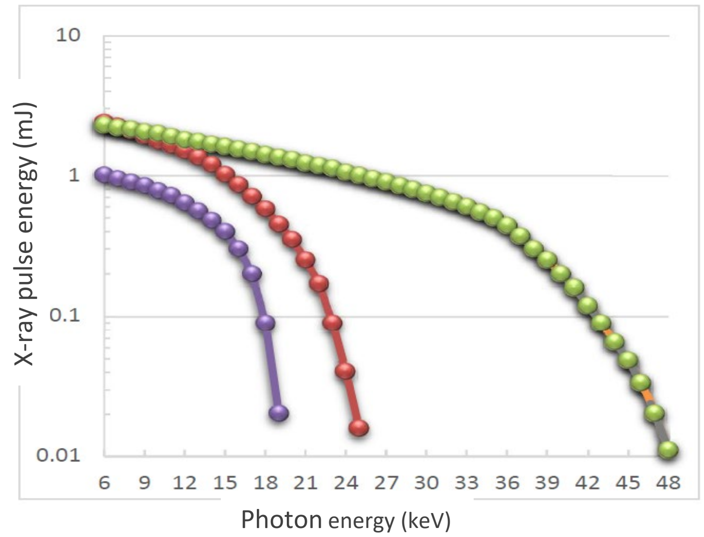
Excitation curve of 0.5-m-long Nb_3Sn SCU



The performance exceeded the design current and undulator field of ~850 A and 1.2 T, respectively. The magnetic field simulations agreed well with the measured field values. Nb_3Sn SCU offers at least 20% undulator field increase compared to a NbTi SCU with the same magnetic gap (9.5 mm) and period length (18 mm).

SCUs versus HPMUs for LCLS-II

- SCUs increase the high X-ray energy reach for XFELs; Example: LCLS Cu linac with SCU can reach 48 keV
- Possibly less susceptible to radiation damage, temperature drifts
- Cryo-pumped e-beam pipes provide excellent vacuum
- Combined with the high-repetition-rate SRF linac, SCU XFELs will increase the average coherent X-ray flux

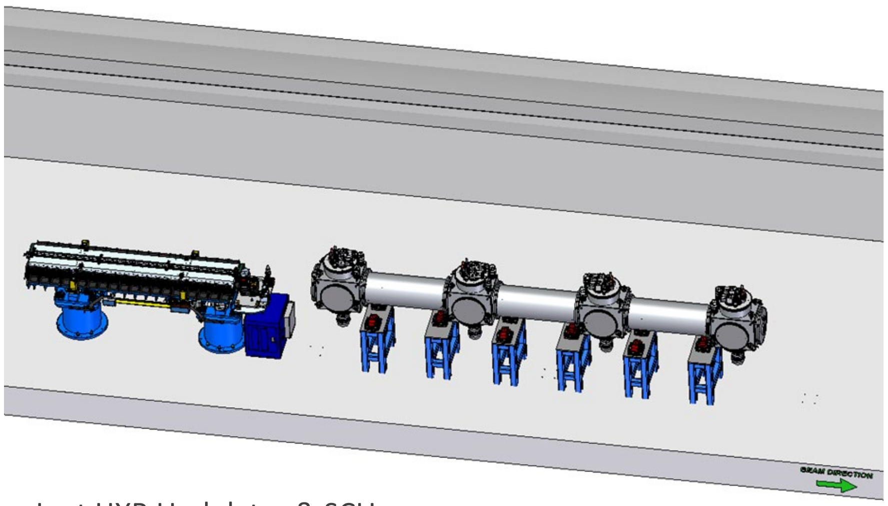


Parameter	Value	Factor driving requirement
Period length (mm)	21	Design Choice
Gap (mm)	8	Design Choice
B_0 @ full current	> 1.67 T	Matching with HXR FEL wavelength
$\Delta B/B_0$ variation along undulator	$\pm 5.5 \times 10^{-4}$	FEL requirement
$\lvert\int B_{x,y} dz\rvert$	< 50 μT-m	FEL requirement
$\lvert\iint B_{x,y} dz^2\rvert$	< 100 μT-m^2	FEL requirement
Phase Shake (rms)	< 5°	FEL requirement

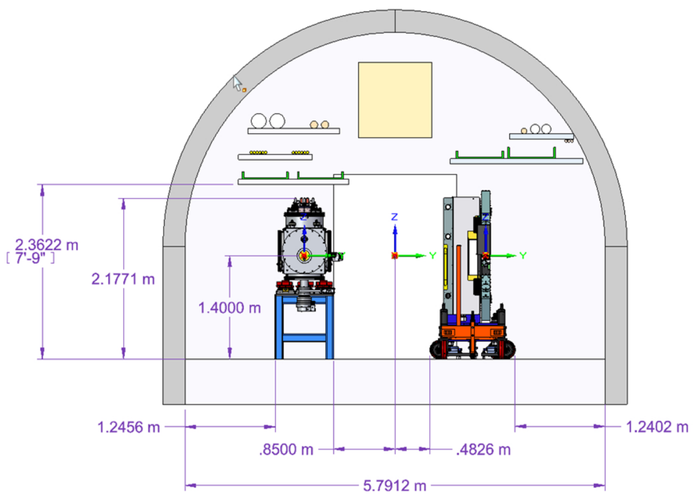
LCLS-II-HE can produce 2-mJ pulse energy with low emittance e- beams and SCUs

SCU performance tests at the LCLS-II

SLAC and Argonne National Laboratory started this R&D project with the goal of building and testing the SCU's performance at the LCLS. The SCUs will be installed on the Hard X-ray Undulator beamline to test the alignment procedures and to measure FEL gain at the SCU module.



Last HXR Undulator & SCUs



Undulator Hall cross-section

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Outlook: remaining SCU engineering challenges

- Optimizing NbTi magnet design
- Establishing optimized design and reliable fabrication technology of Nb_3Sn magnets
- Creating novel magnet designs
- Significantly reducing cost of magnet fabrication
- Creating optional cryostat designs
- Optimizing mechanical and optical systems for precise alignment of “cold FEL SCU components”
- Furthering advancements in magnetic measurements system
- Establishing industrial production of SCUs or SCUs components

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- Significant contributions in the engineering design of the first APS SCU cryostat were made by BINP engineer V. Syrovatin and lead scientist N. Mezentsev.