DEVELOPMENT AND OPERATIONAL EXPERIENCE OF APS SUPERCONDUCTING UNDULATORS

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Advanced Photon Source
Argonne National Laboratory

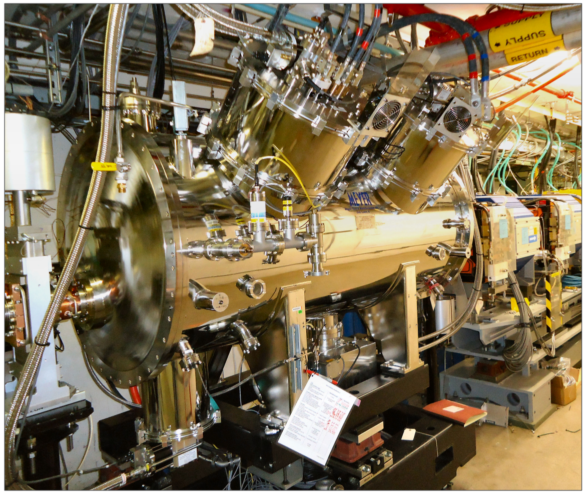
IPAC 2018, Vancouver, CA

OUTLINE

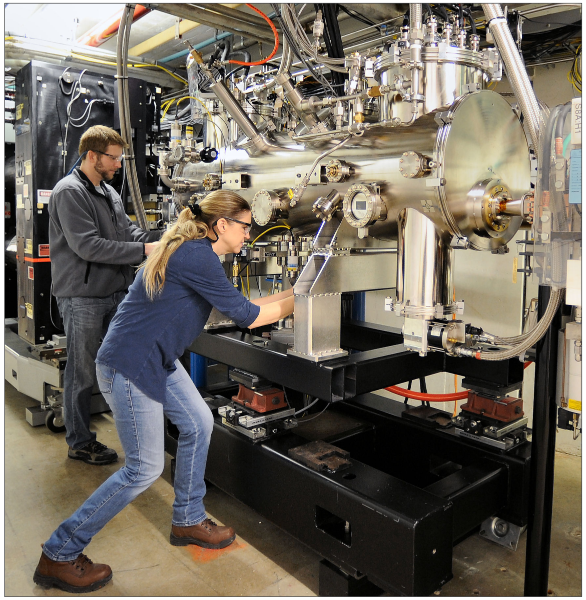
- **SCUs at the APS: motivation, short history**
- **Four areas of recent developments**
  - cryogenic system
  - undulator magnet
  - alignment
  - magnetic measurements
- **Helical SCU**
- **Operational statistics**
- **New developments**
- **Future directions**

SCUs at the APS

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



SCU18-1 in Sector 1 of the APS ring.

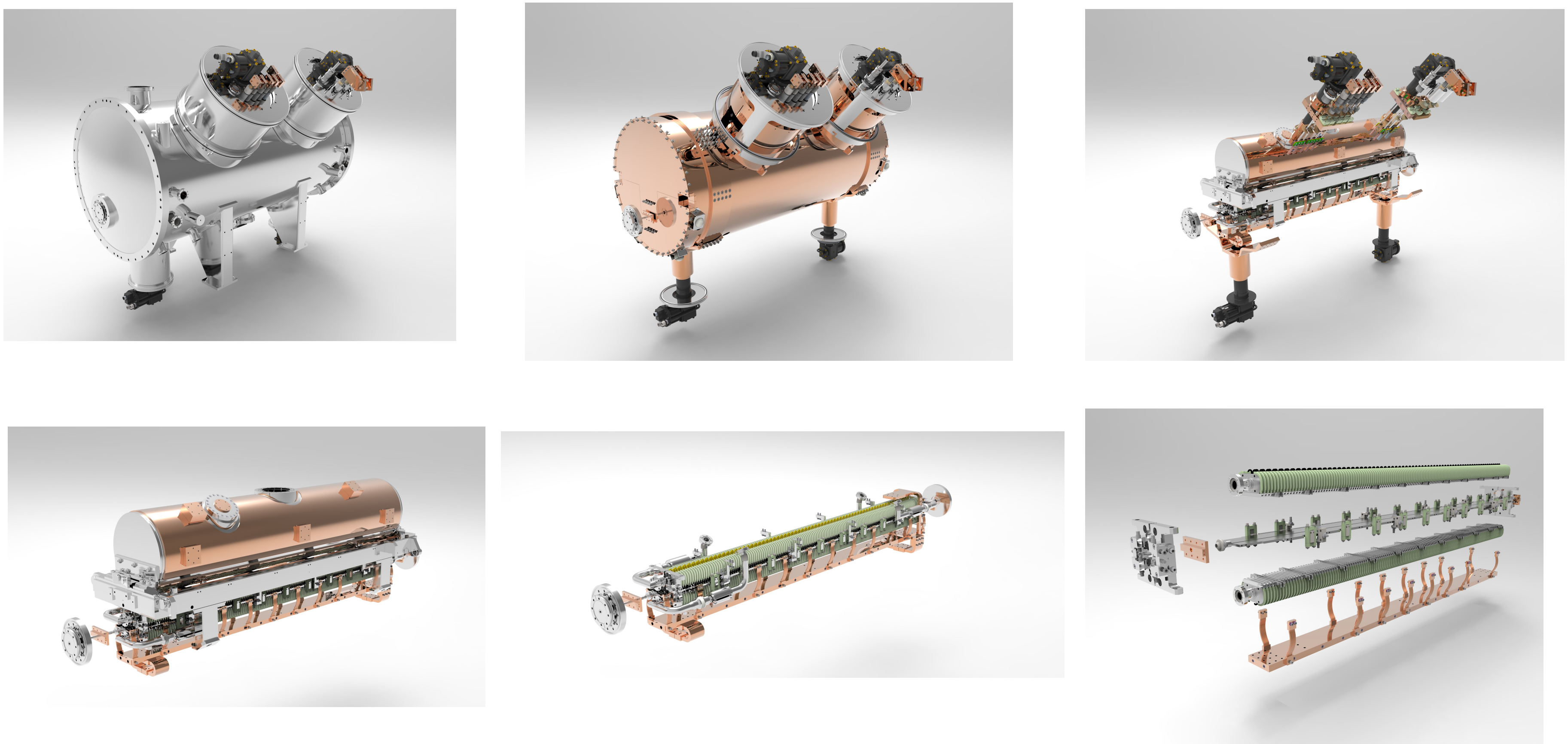


Helical SCU in Sector 7 of the APS ring.

- 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

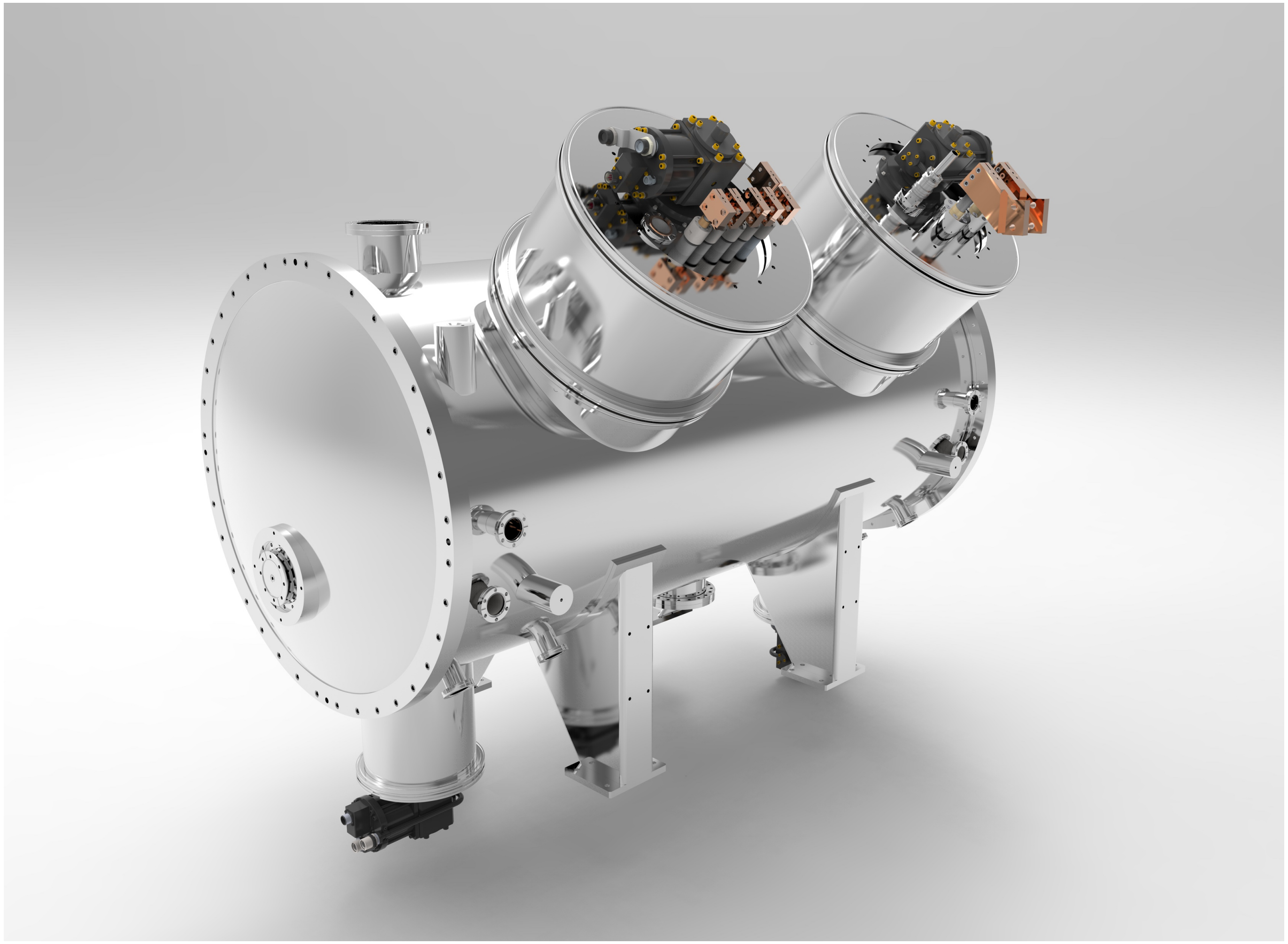
Generation 1 of APS SCU Cryostats

The planar SCU: layer by layer

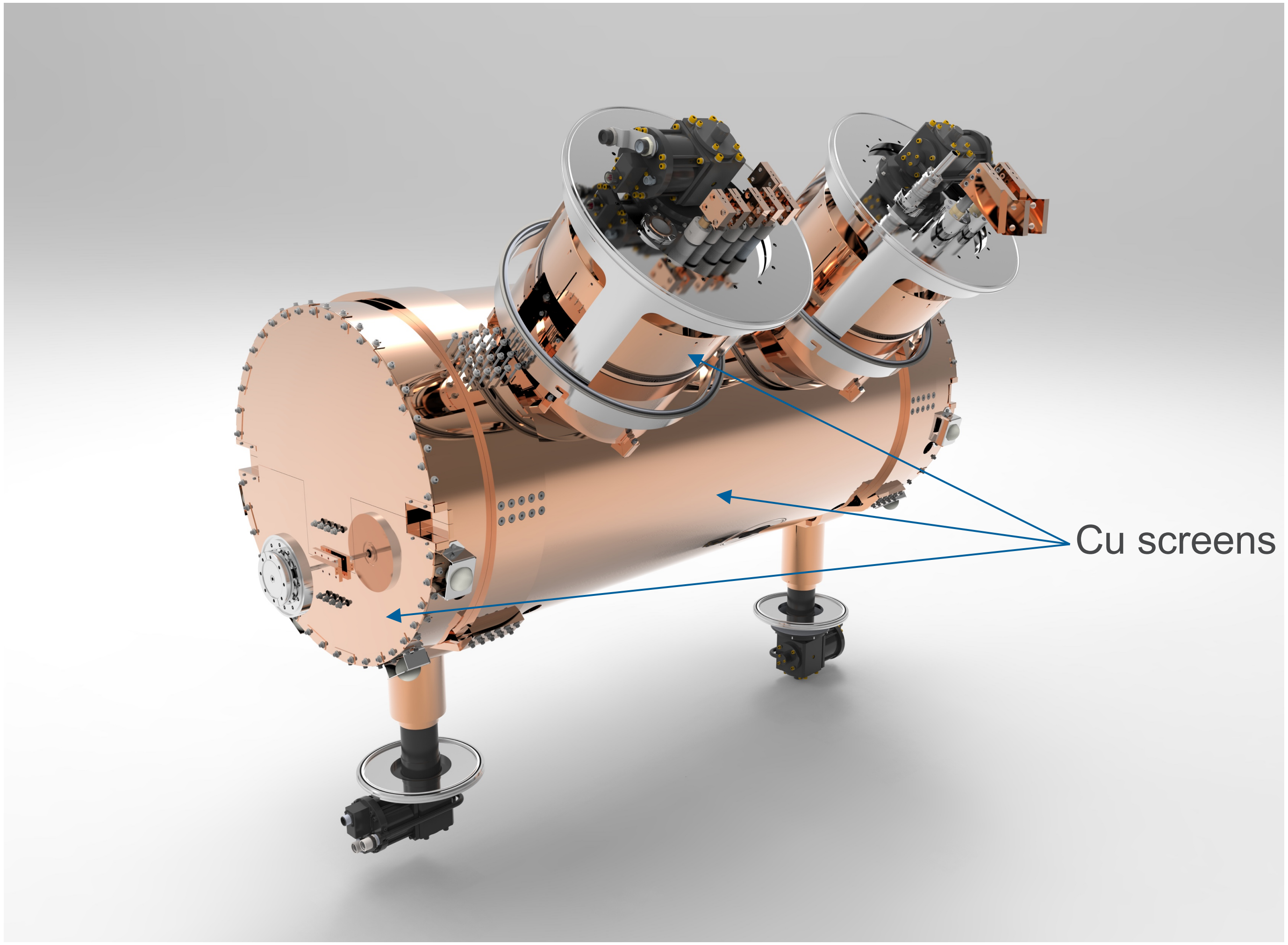


SCU – assembled

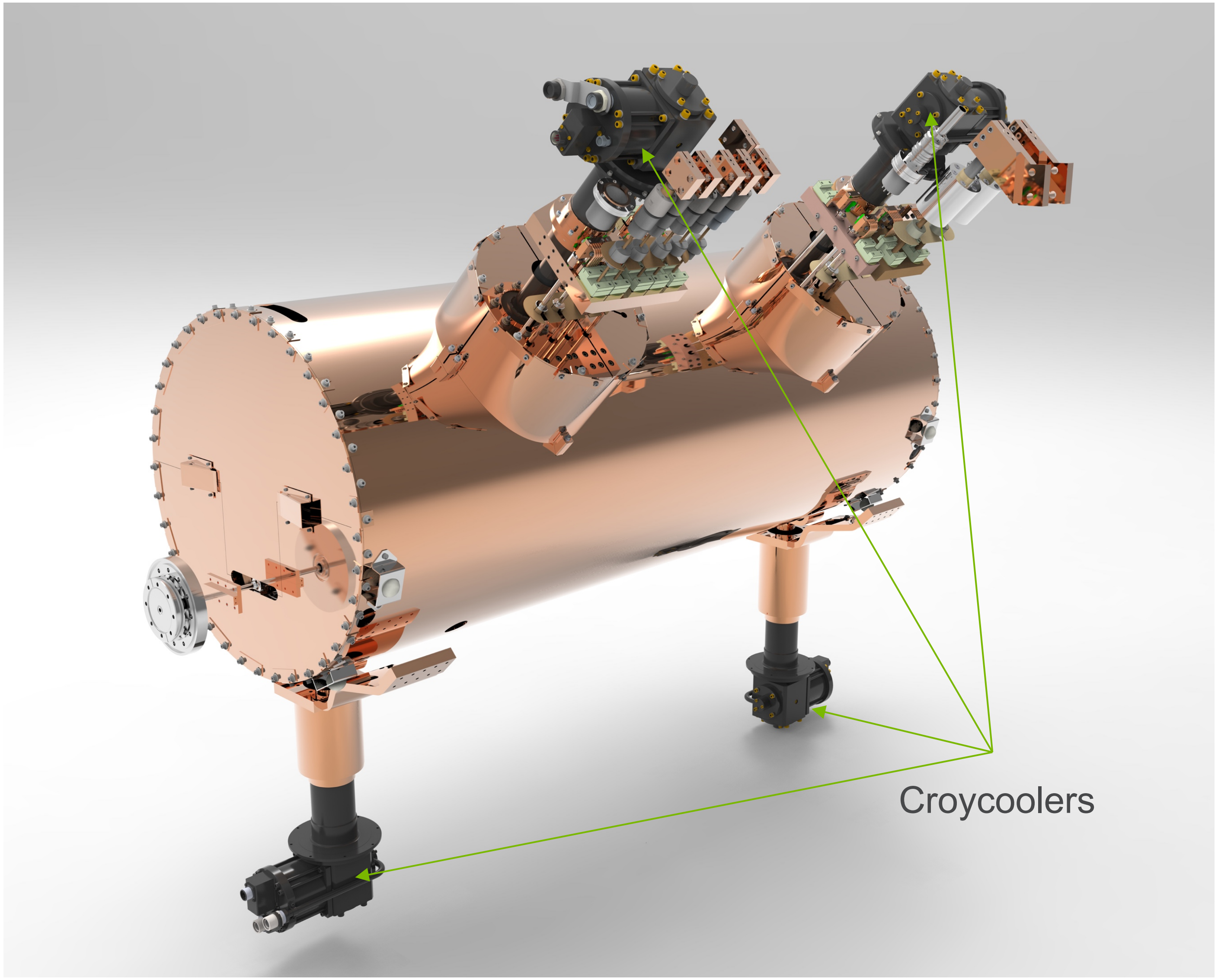
2-meters long, 0.9-meter diameter



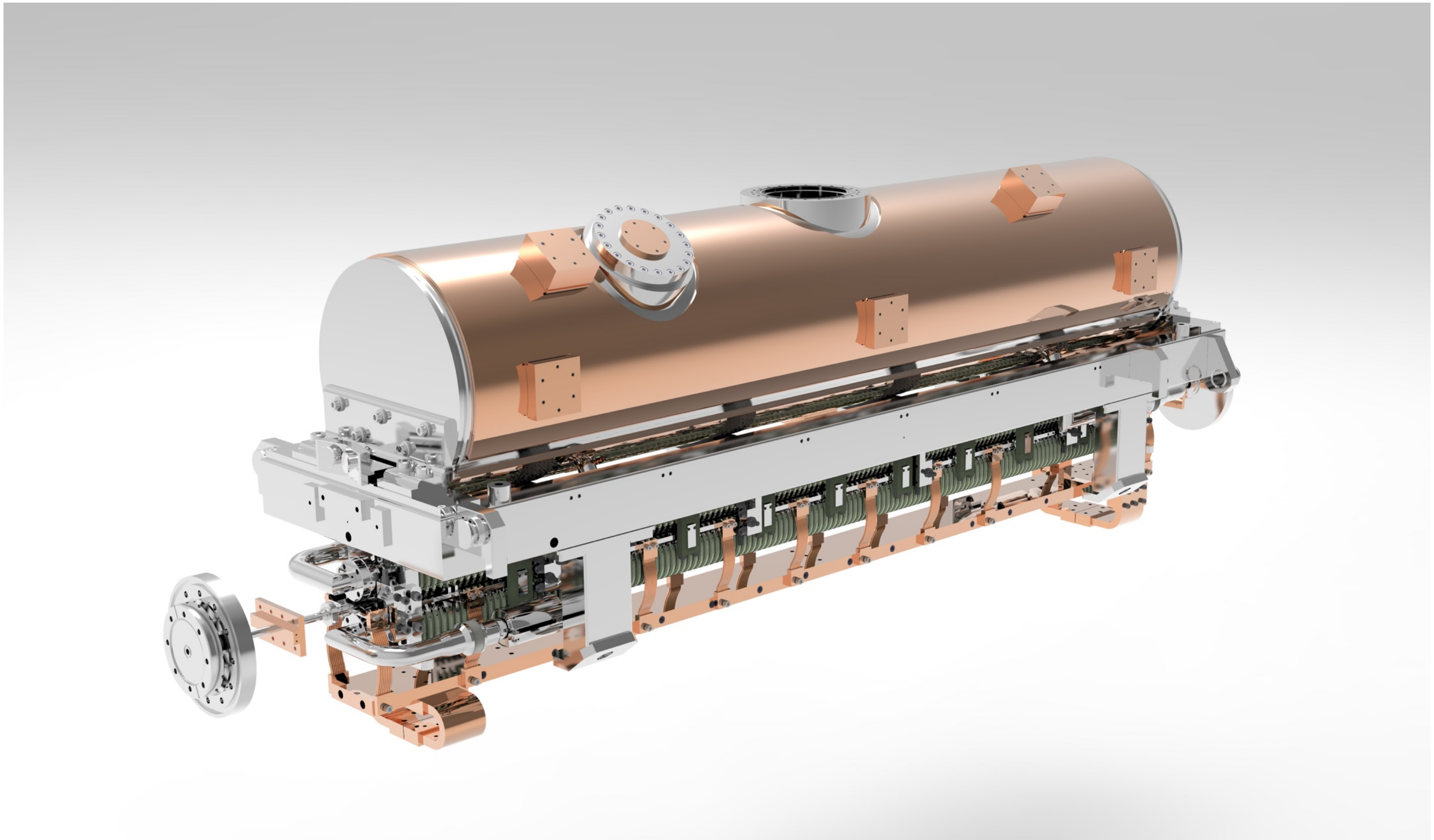
SCU – first thermoshield



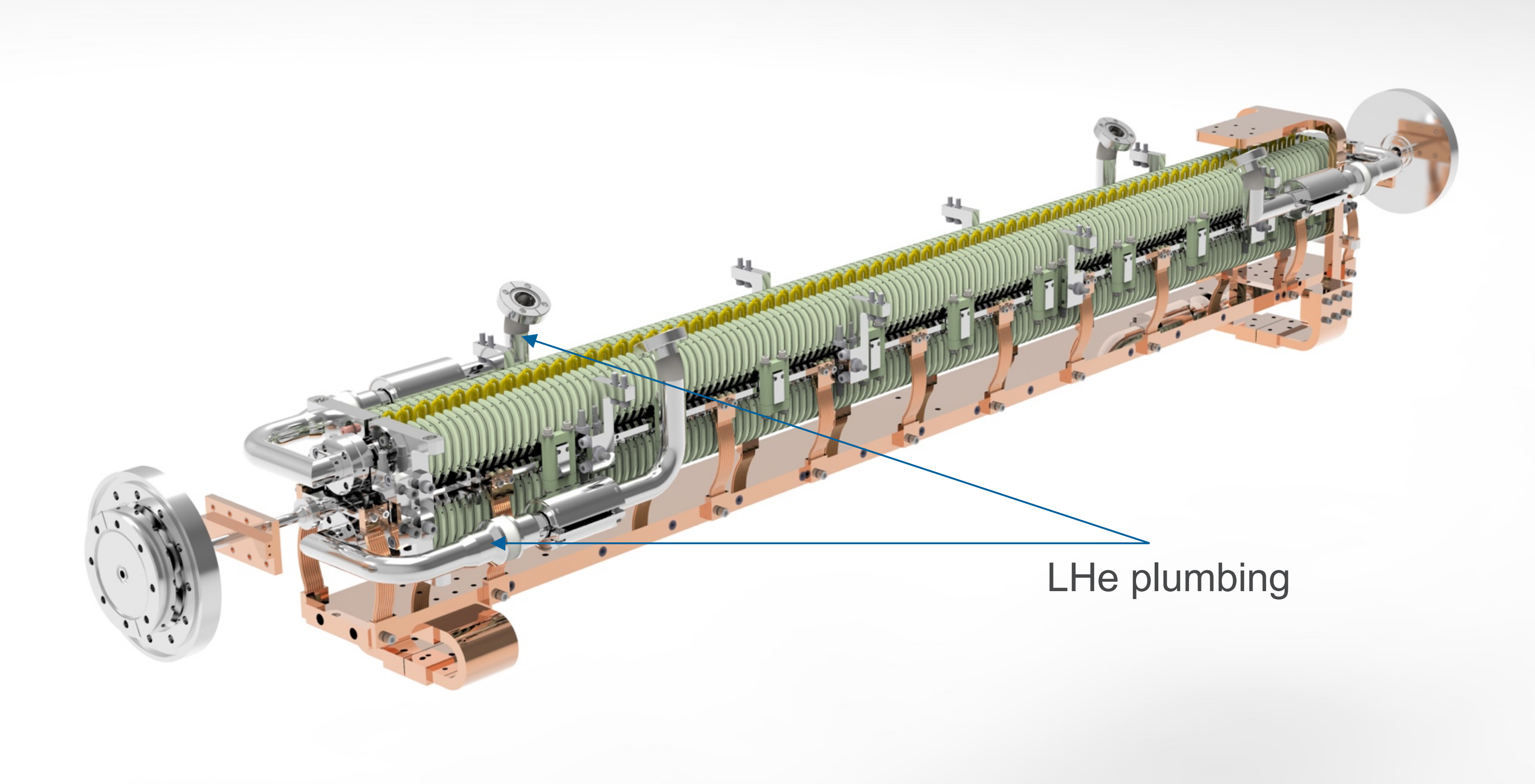
SCU – second thermoshield


Croycoolers

SCU – cold mass: LHe tank and undulator magnet

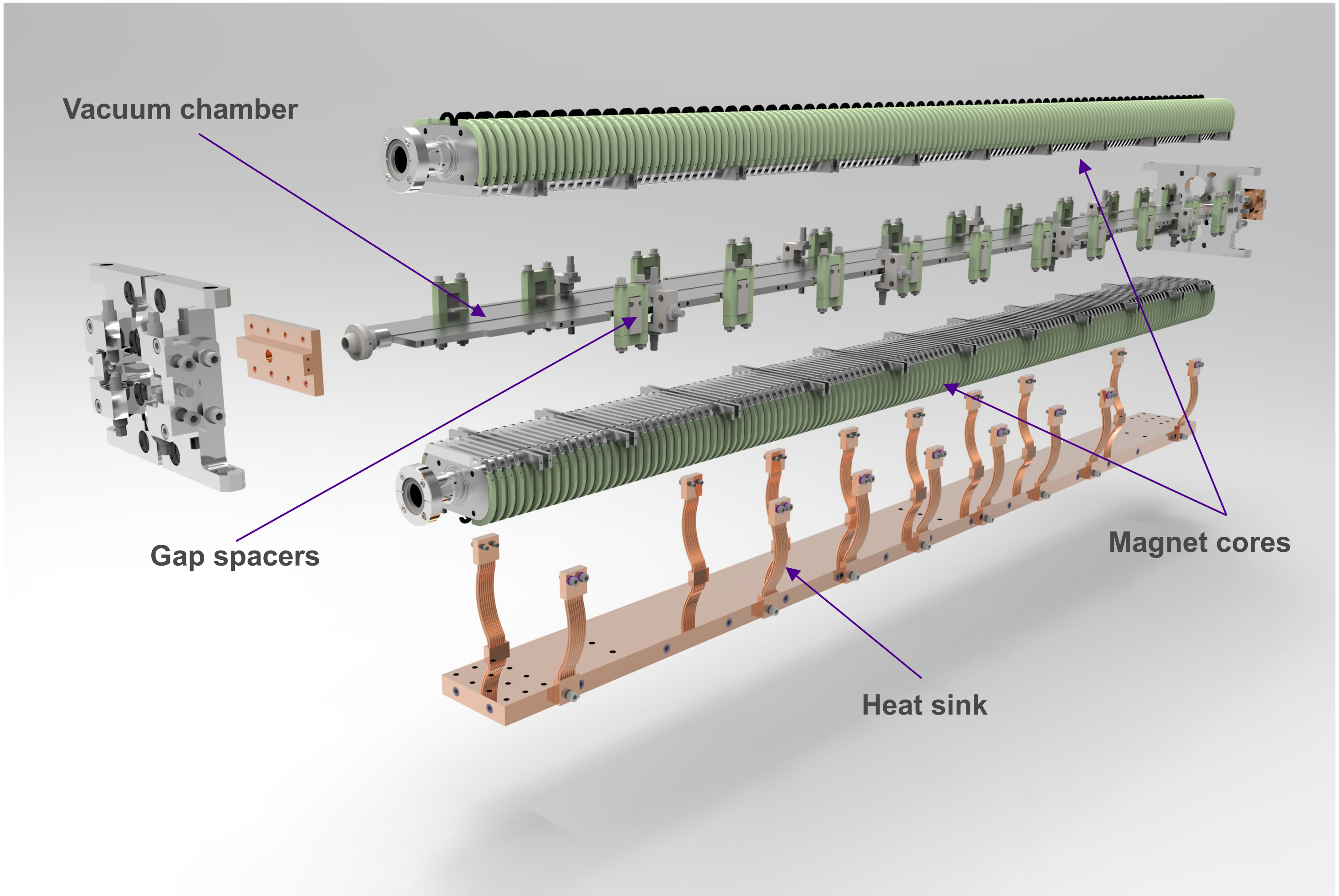


SCU – magnet and vacuum chamber

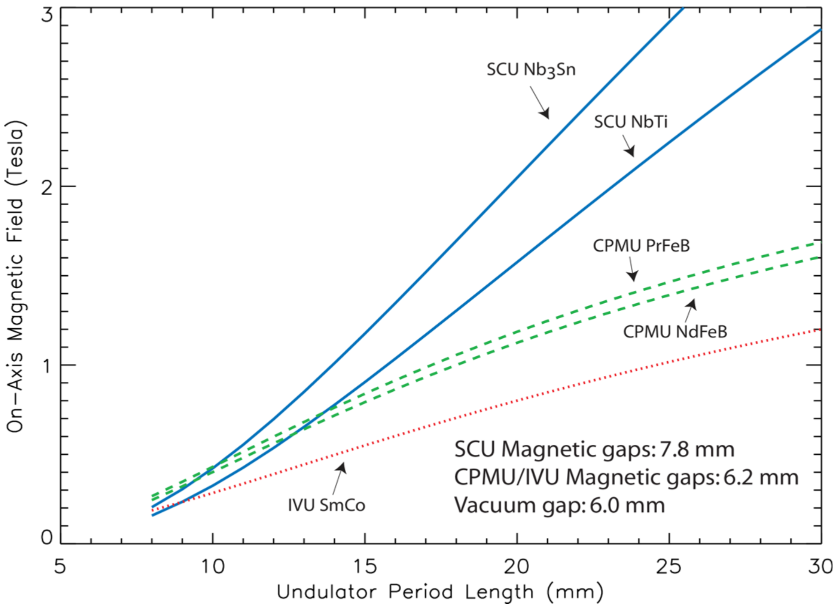


LHe plumbing

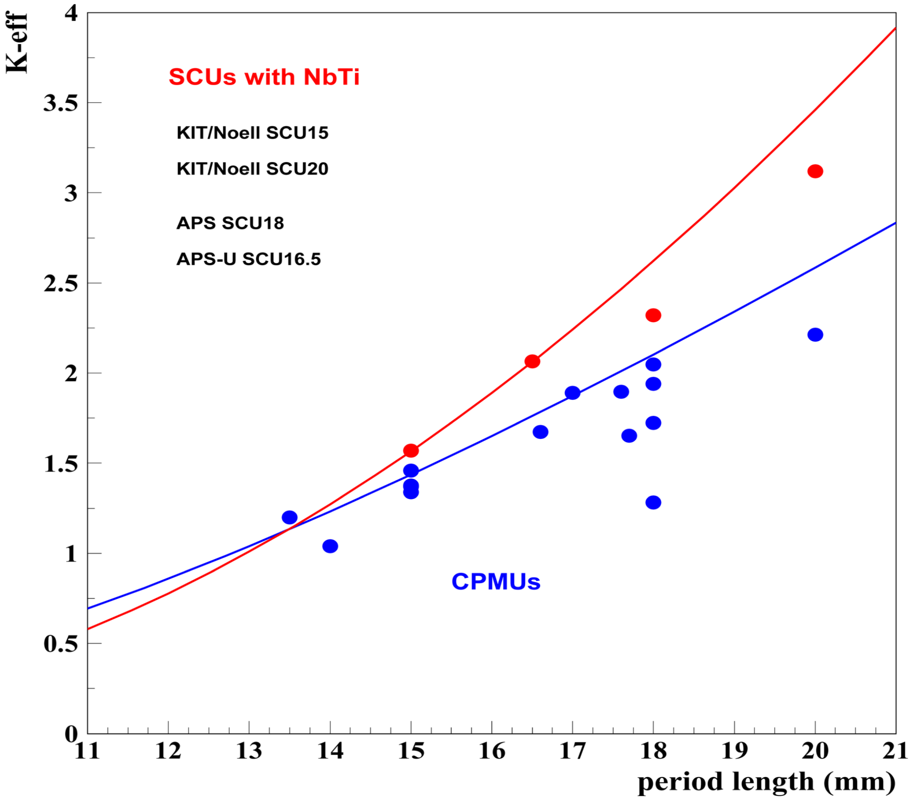
SCU: separated magnet cores; vacuum chamber; magnet gap spacers; vacuum chamber heat sink.



SCUs versus CPMUs



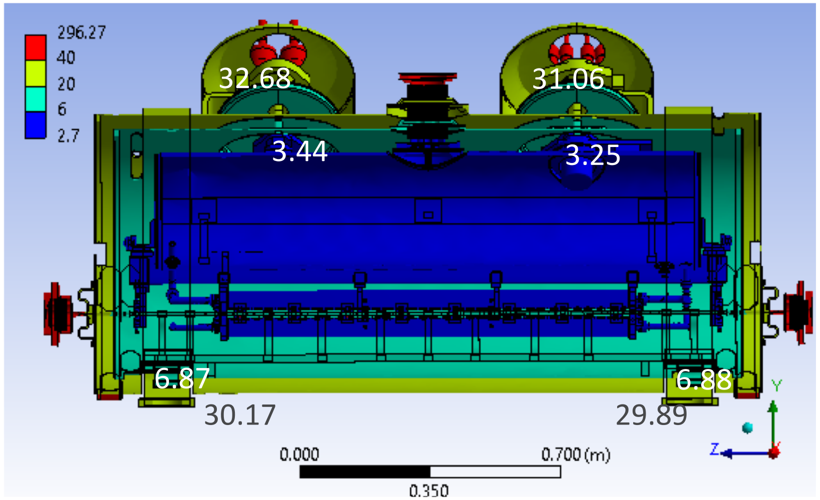
Calculated on-axis magnetic fields of two CPMUs (PrFeB, NdFeB), two SCUs (NbTi, Nb_3Sn), and one IVU (SmCo) for a *vacuum gap of 6.0 mm* for period lengths from 8 mm to 30 mm.

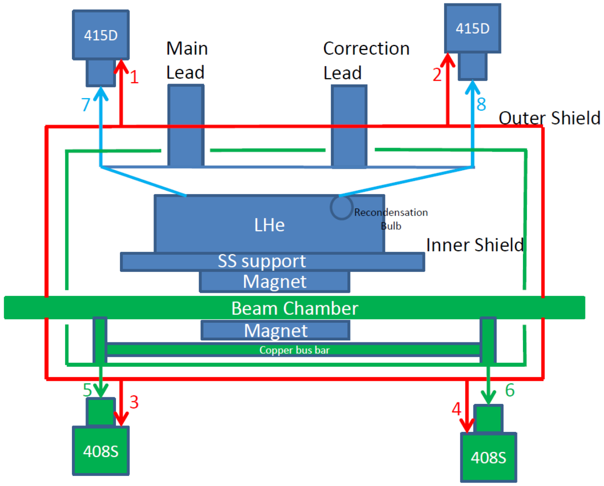


Effective K-values of built CPMUs and SCUs in comparison with calculated curves

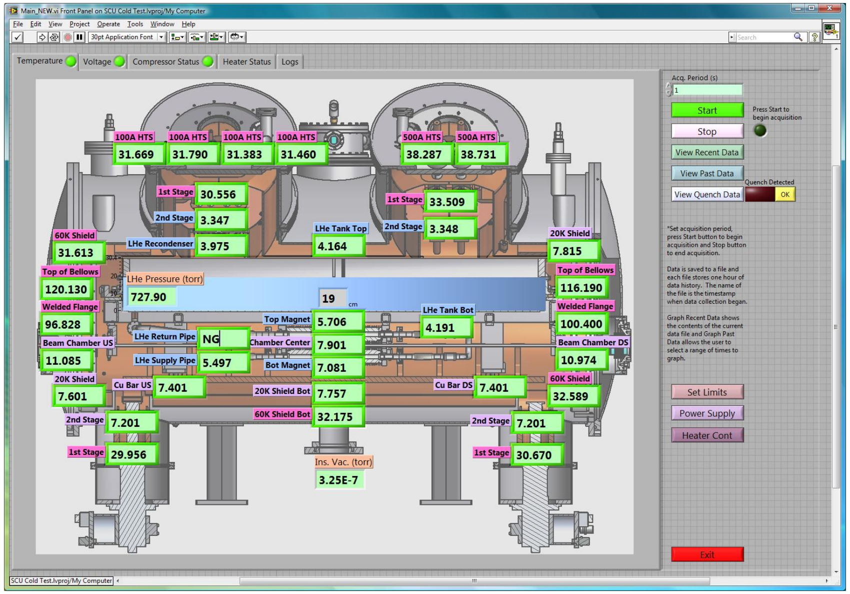
APS SCU generation one cryostat: calculated and measured temperatures

ANSYS model of SCU18.1





Screenshot of temperature sensors readings for SCU18.1



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
Top of Bellows 120.130
Welded Flange 96.828
Beam Chamber US 11.085
20K Shield 7.601
2nd Stage 7.201
1st Stage 29.956
LHe Pressure (torr) 727.90
19 cm
Top Magnet 5.706
LHe Return Pipe NG
Chamber Center 7.901
LHe Supply Pipe 5.497
Bot Magnet 7.081
Cu Bar US 7.401
20K Shield Bot 7.757
60K Shield Bot 32.175
Ins. Vac. (torr) 3.25E-7
LHe Tank Bot 4.191
Cu Bar DS 7.401
20K Shield 7.815
Top of Bellows 116.190
Welded Flange 100.400
Beam Chamber DS 10.974
60K Shield 32.589
2nd Stage 7.201
1st Stage 30.670
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.

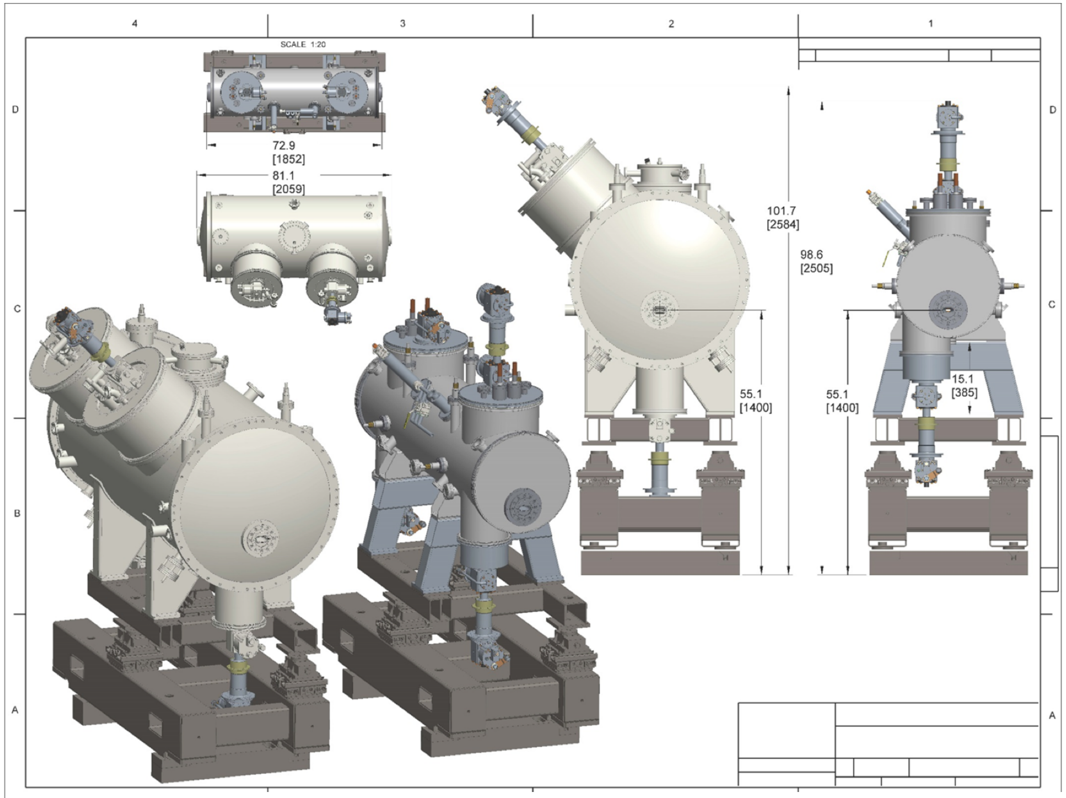
Data is saved to a file and each file stores one hour of data history. The name of the file is the timestamp when data collection began.

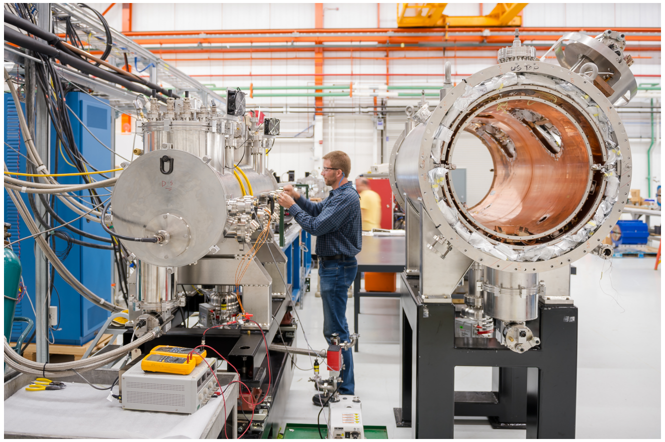
Graph Recent Data shows the contents of the current data file and Graph Past Data allows the user to select a range of times to graph.

Original cryostat: three thermal circuits

Static case: no magnet current, no e-beam

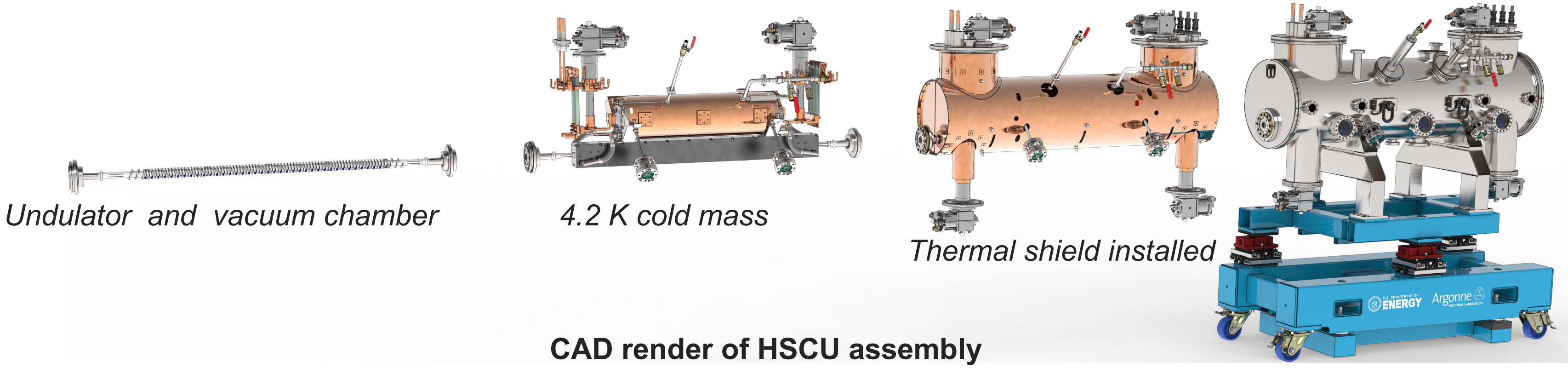
Cryostat evolution: from SCU0/SCU18.1 to HSCU





HSCU cryostat developed by APS

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



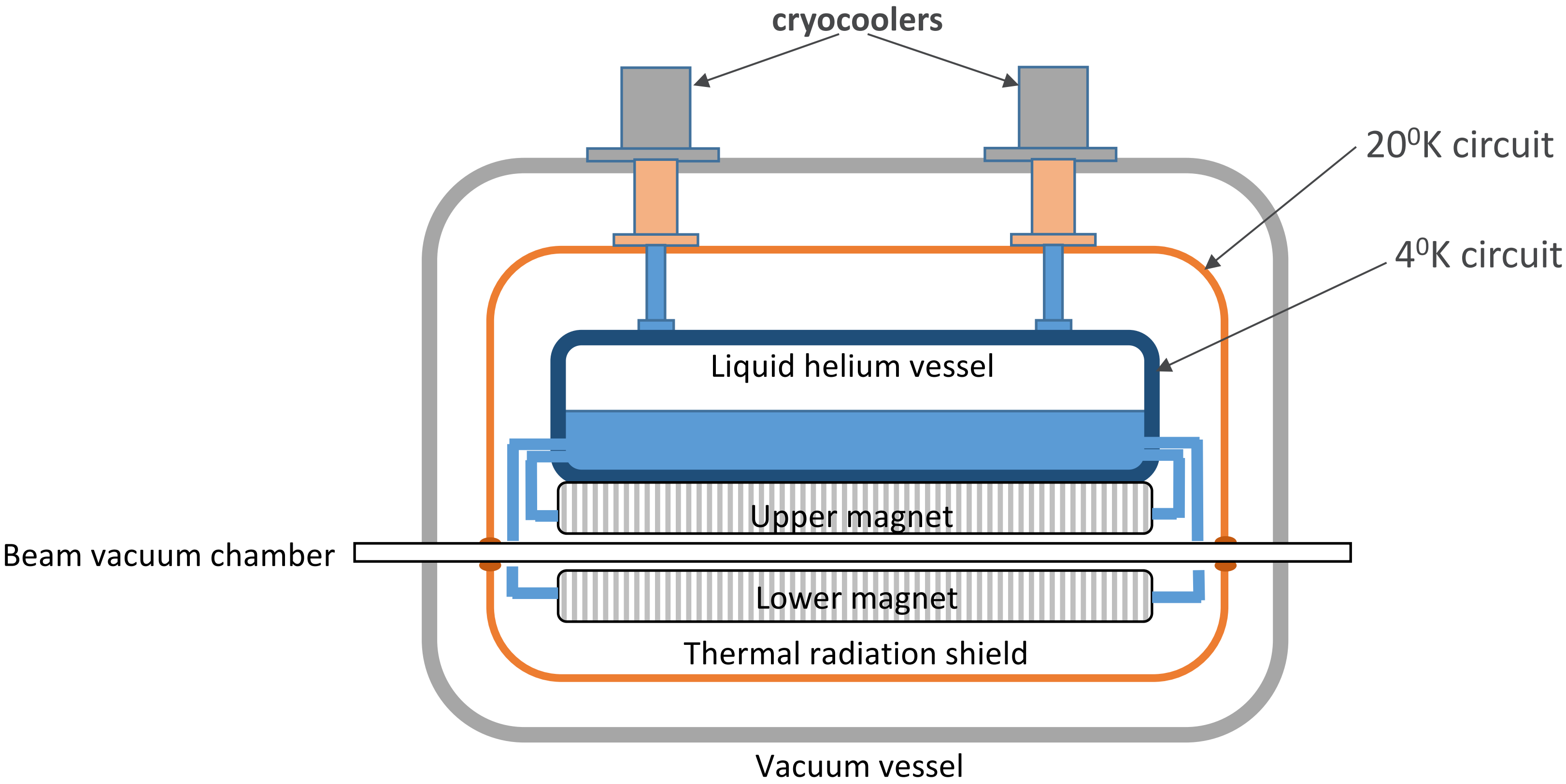
Undulator and vacuum chamber

4.2 K cold mass

Thermal shield installed

CAD render of HSCU assembly

Diagram of HSCU cryo-circuits

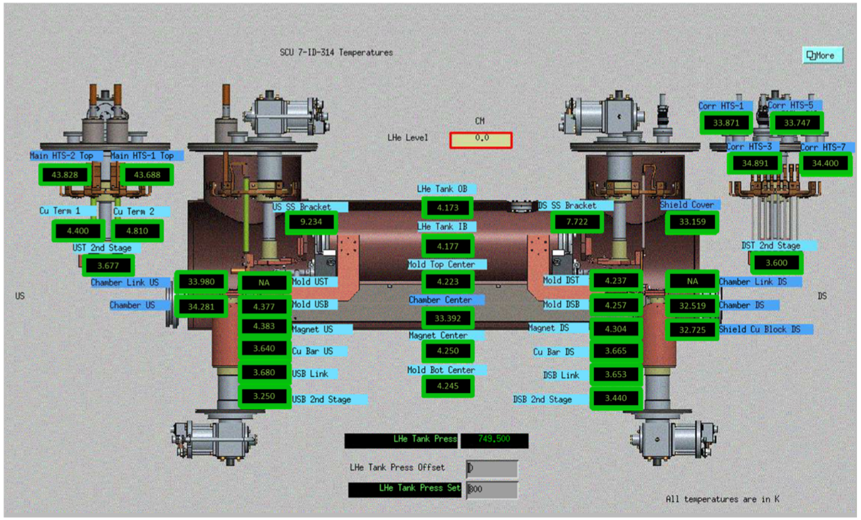


Cooling capacity of 4 Sumitomo RDK415D cryocoolers at ~20^{0}K: 200 – 60 W

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

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).



SCU 7-ID-314 Temperatures

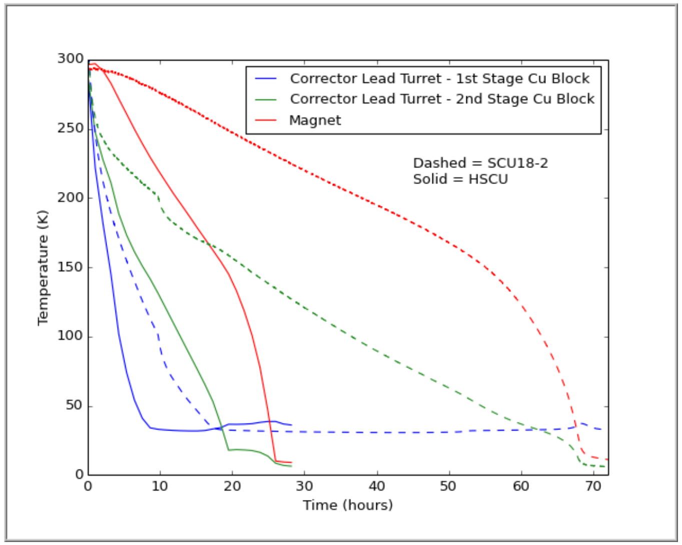
LHe Level 0.0

Main HTS-2 Top 43.828
Main HTS-1 Top 43.688
Cu Term 1 4.400
Cu Term 2 4.810
UST 2nd Stage 3.677
Chamber Link US 33.980
Chamber US 34.281
US SS Bracket 9.234
Mold UST NA
Mold USB 4.377
Magnet US 4.383
Cu Bar US 3.640
USB Link 3.680
USB 2nd Stage 3.250
LHe Tank OB 4.173
LHe Tank IB 4.177
Mold Top Center 4.223
Chamber Center 33.392
Magnet Center 4.250
Mold Bot Center 4.245
DS SS Bracket 7.722
Mold DST 4.237
Mold DSB 4.257
Magnet DS 4.304
Cu Bar DS 3.665
DSB Link 3.653
DSB 2nd Stage 3.440
Shield Cover 33.159
Chamber Link DS NA
Chamber DS 32.519
Shield Cu Block DS 32.725
Corr HTS-1 33.871
Corr HTS-5 33.747
Corr HTS-3 34.891
Corr HTS-7 34.400
DST 2nd Stage 3.600

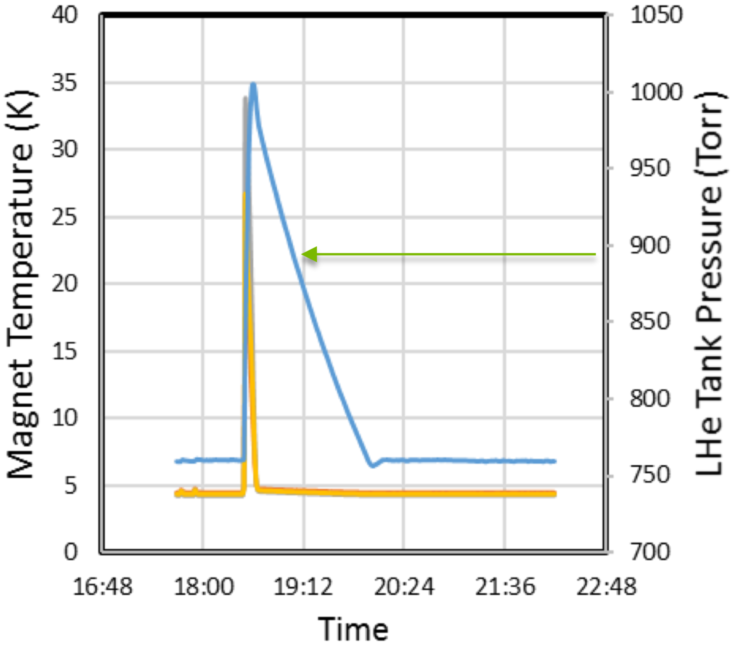
LHe Tank Press 749.500
LHe Tank Press Offset 0
LHe Tank Press Set 800

All temperatures are in K

Screenshot of temperature readings

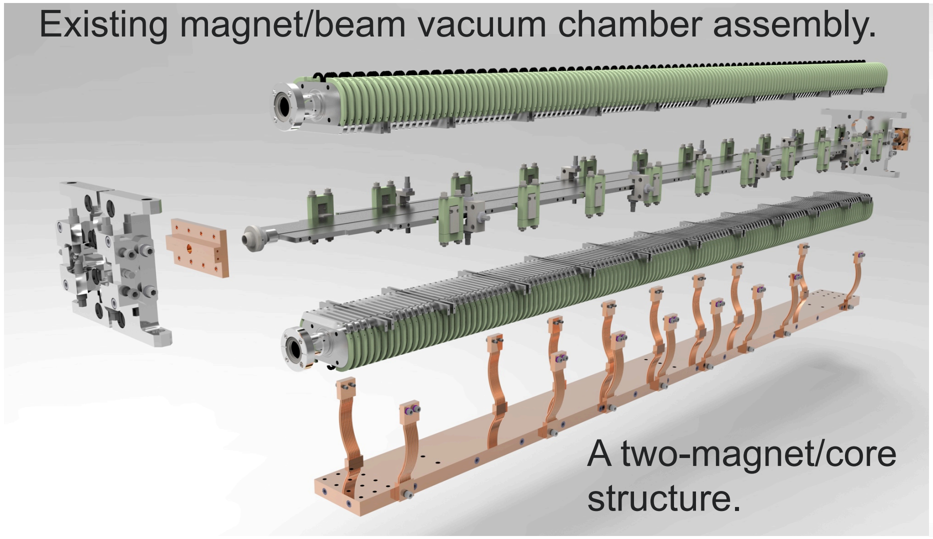


Cooldown



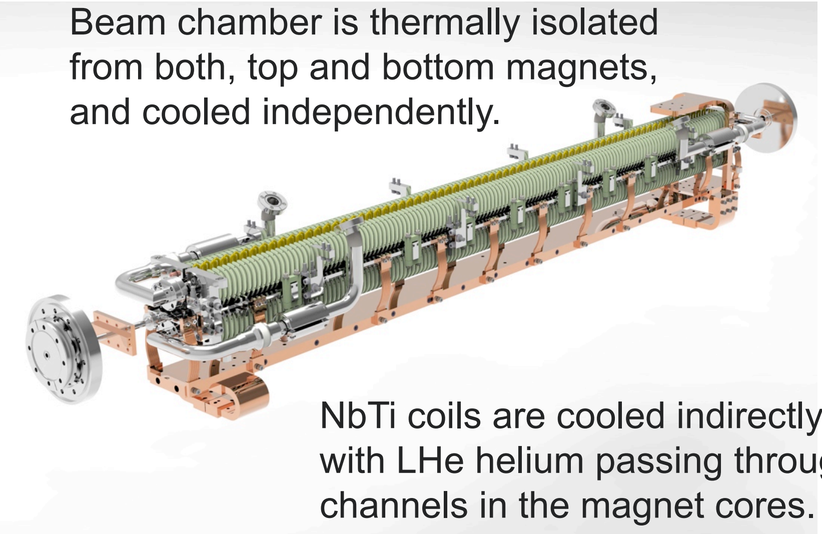
Quench recovery

Planar SCU: magnets/cores



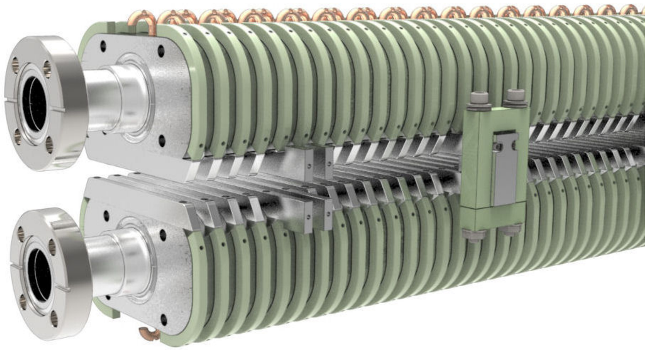
Existing magnet/beam vacuum chamber assembly.

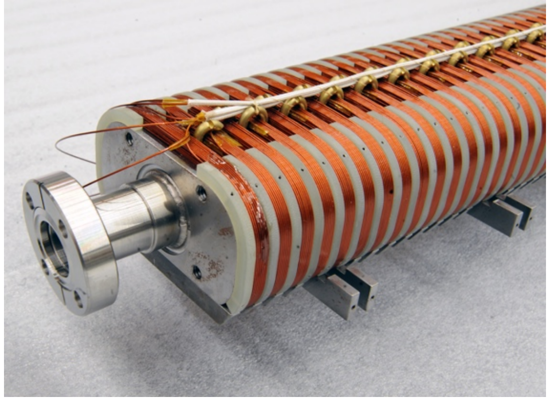
A two-magnet/core structure.

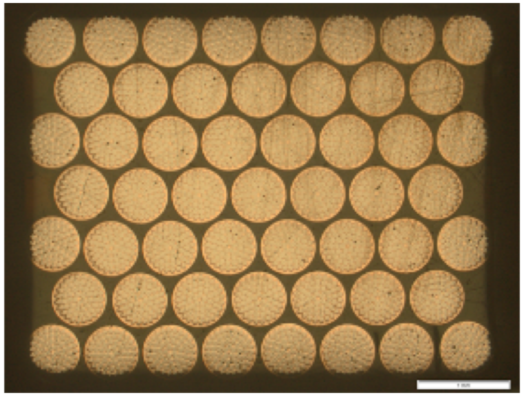


Beam chamber is thermally isolated from both, top and bottom magnets, and cooled independently.

NbTi coils are cooled indirectly with LHe helium passing through channels in the magnet cores.

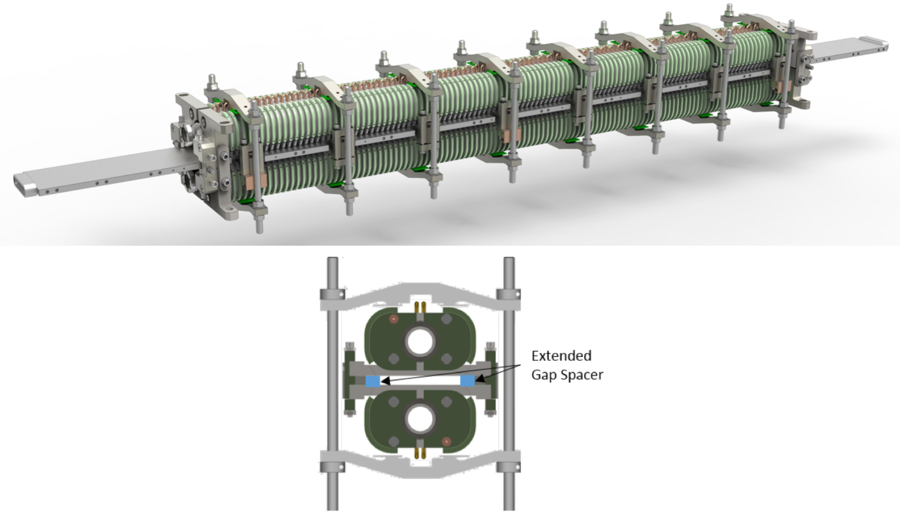






Phase Errors Control

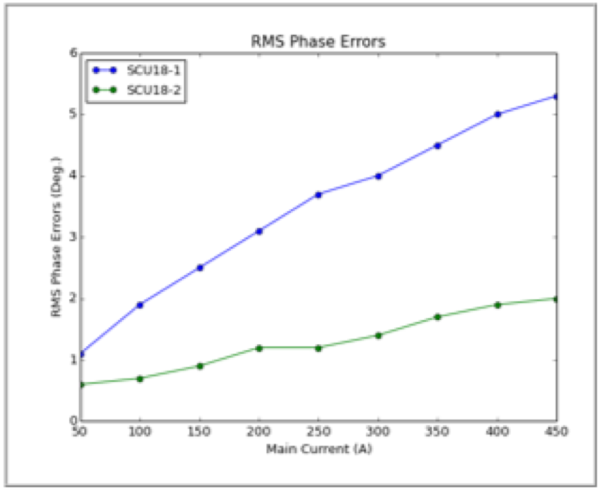
- The SCU field quality depends on:
  - Precise machining of a magnet core
  - Quality of conductor winding
  - Uniformity of the magnetic gap
- A dedicated R&D program was targeted at achieving a very uniform gap.
  - A gap correction scheme was developed and implemented using a set of mechanical clamps



Planar SCU magnetic assembly with a gap correction.

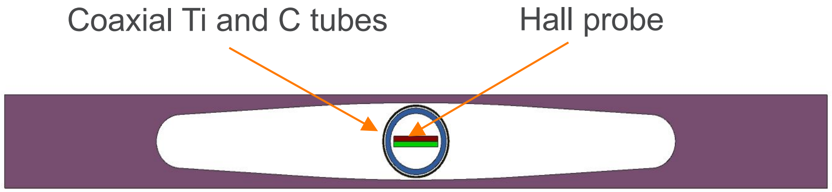
Undulator	Measured phase errors (º rms)
SCU18-1	5*
SCU18-2	2
LCLS R&D SCU	3.8

* without gap correction



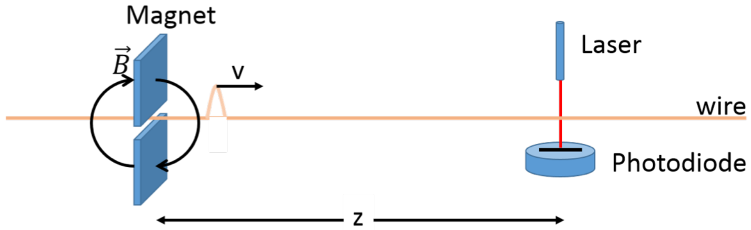
Measured phase errors in SCU18-1 and SCU18-2.

Progress in Magnet Measurement techniques



Coaxial Ti and C tubes

Hall probe



Magnet

$\vec{B}$

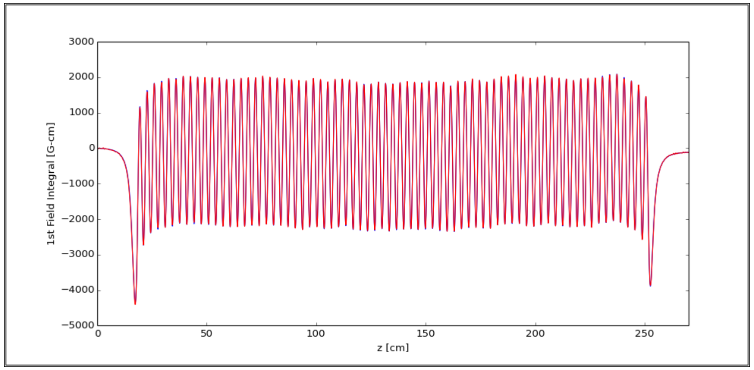
v

Laser

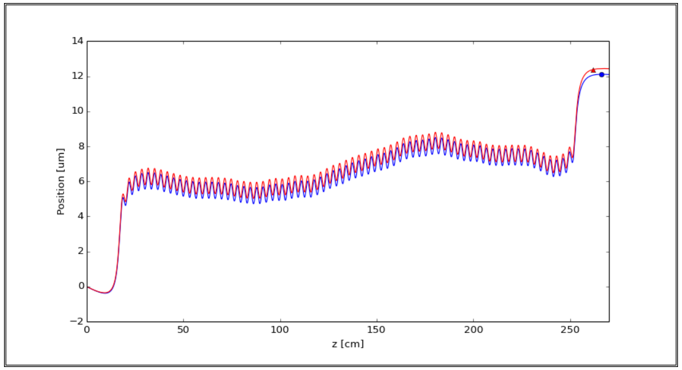
wire

Photodiode

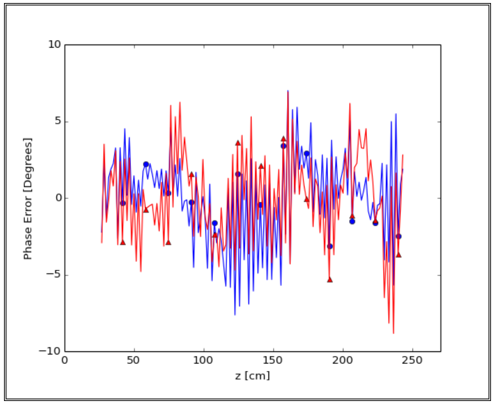
z



Short pulse – 1^{st} integral – and Hall probe data



Long pulse – 2^{nd} integral – and Hall probe data



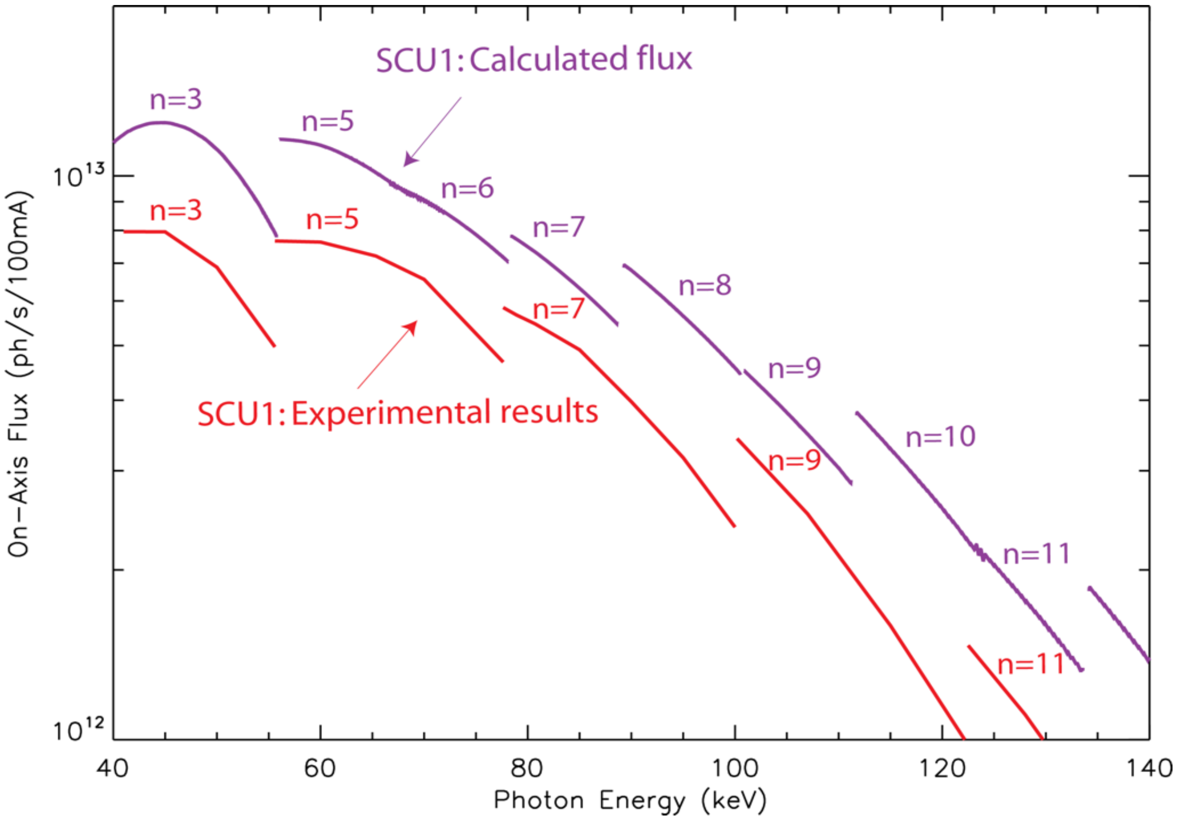
Phase errors measured with Hall probe – blue, and with pulsed wire - red

Challenge: dispersion of multi-frequency waves propagation.

Solution: new signal processing algorithm, based on well developed method of the dispersion modeling of waves propagating in a string of a musical instrument. New algorithm allows a lot of flexibility in the benchmarking process.

M.Kasa, Measurement, Vol. 122, 2018, pp. 224-231.

Radiation performance of SCU18.1

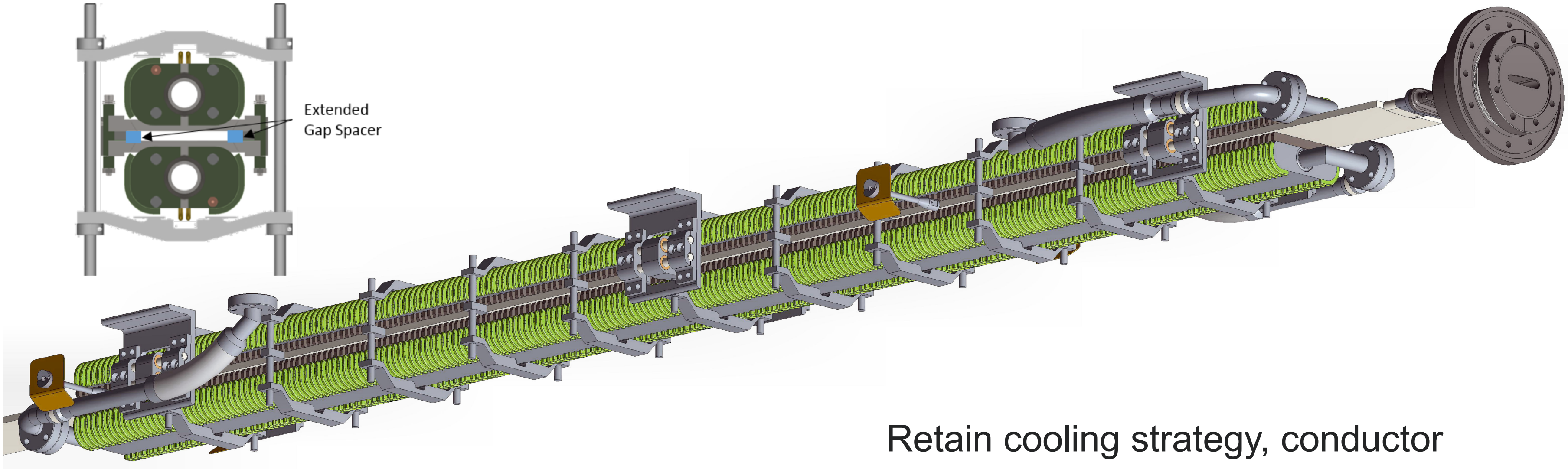


SCU18.1 calculated and measured monochromatic flux through a 0.5x0.5 mm^2 aperture at 27.5 m for harmonics from n=3 to n=11.

Next step in planar undulator developments: Long magnet

New magnet is approaching length of 2 m

- Capitalize on the successful design of 1.1-1.5 m long undulators.
- Precise control of magnet/beam chamber straightness; adjustment capability.
- Maintain low phase errors by achieving tight machining and winding tolerances, and most importantly, by controlling precisely uniform magnetic gap: adequate number of spacers and clamps.

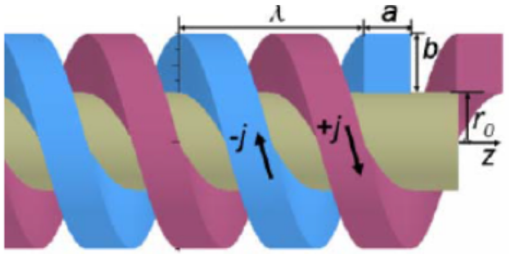


Retain cooling strategy, conductor winding technique, vacuum chamber isolation/support concept.

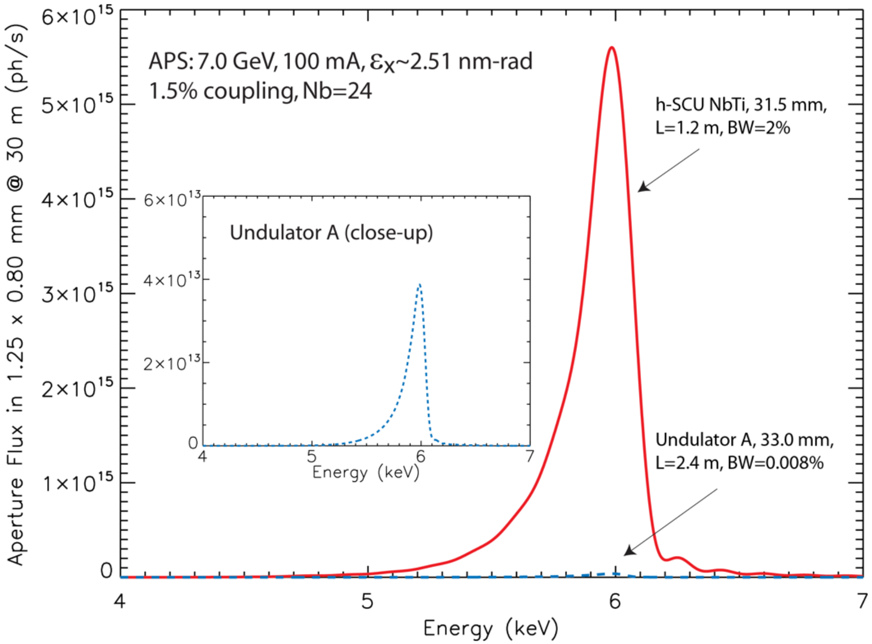
Helical SCU

- 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



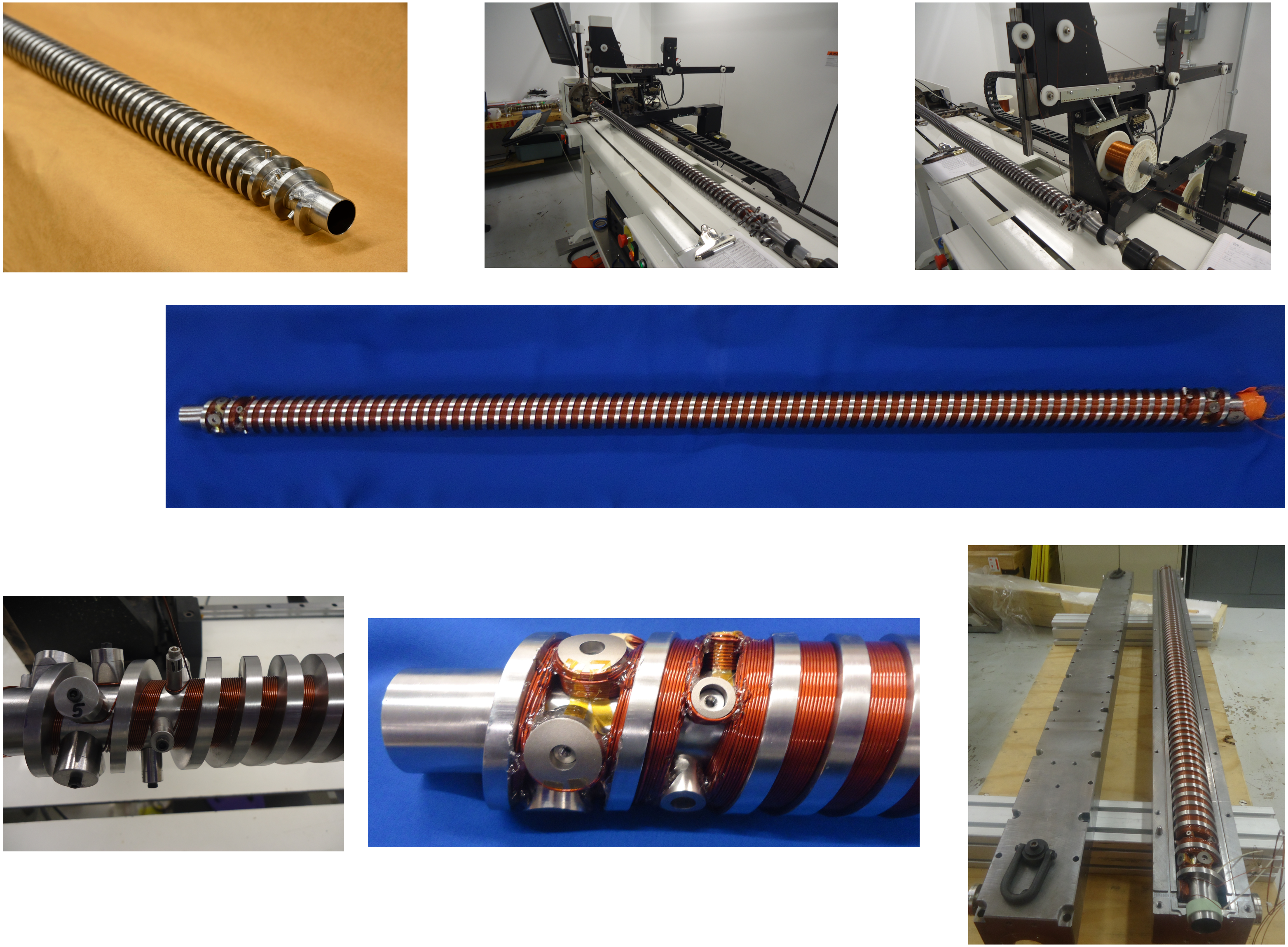
Magnetic model of HSCU.



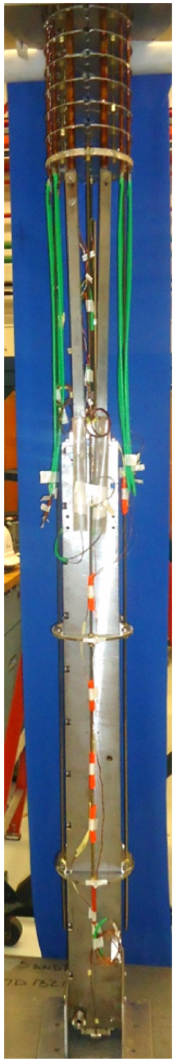
Calculated photon spectrum of helical SCU.

See also poster TUPMF007

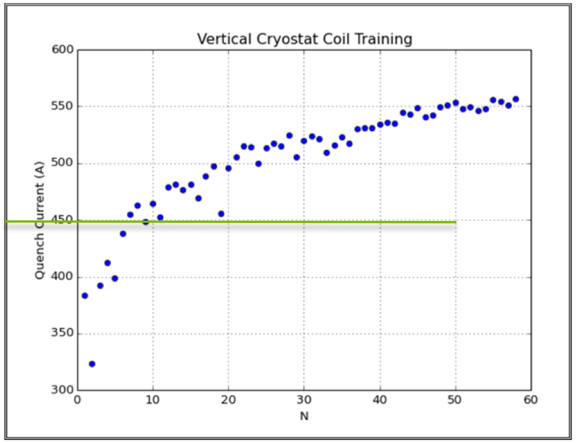
HSCU magnet fabrication

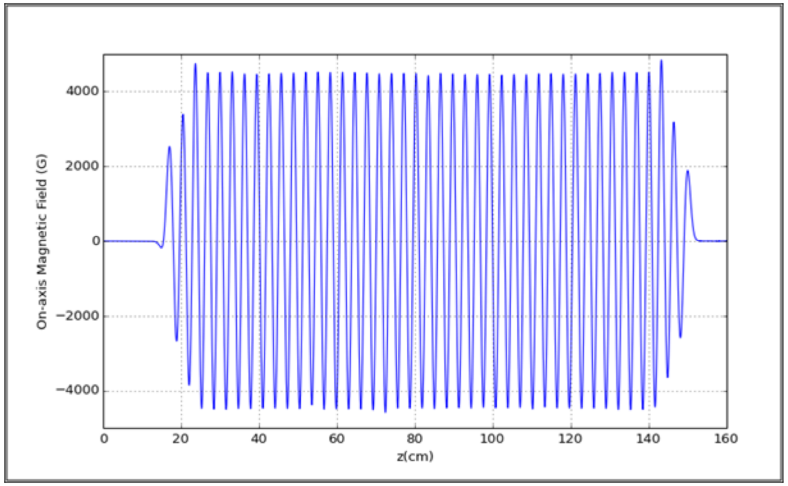


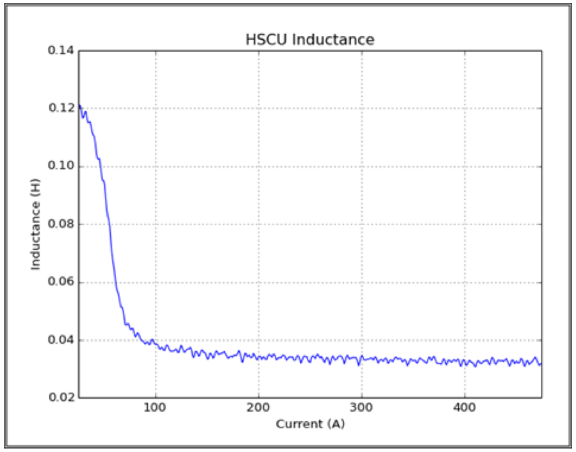
HSCU magnet test and quench training in Liquid He bath: vertical cryostat



- Coil training to verify the undulator can reach the required operating current – 500 A
- Preliminary magnetic measurements
  - Verify designed field of 0.41 T
  - Measured 0.45 T @ 500 A
- Inductance measurements for stored energy calculations

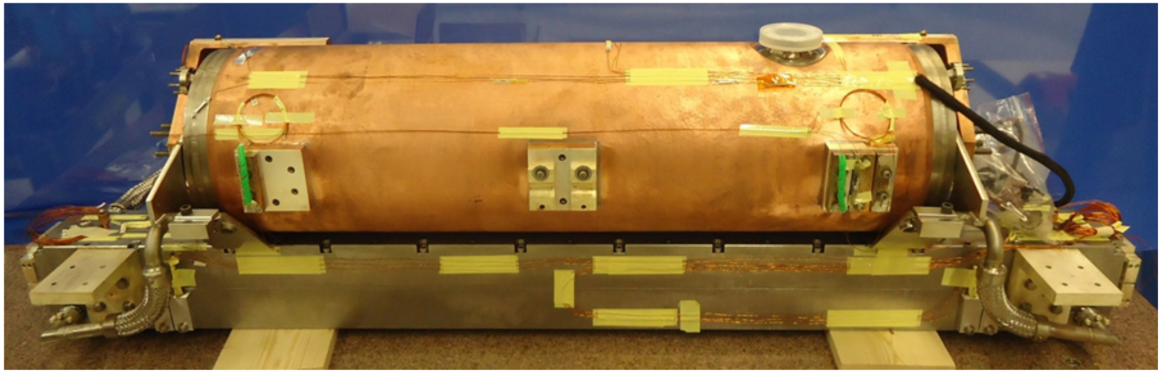


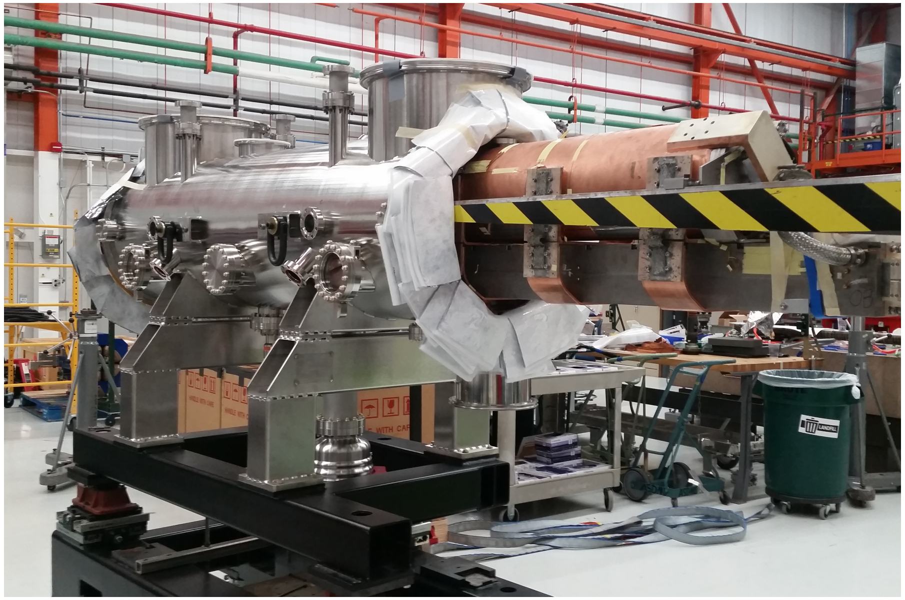




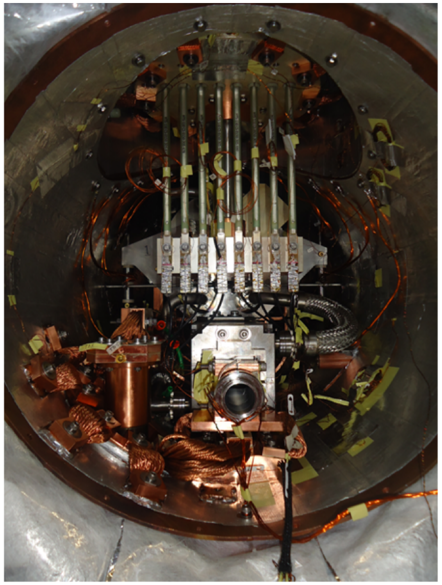
HSCU assembly

Cold mass: LHe tank and mold with the magnet



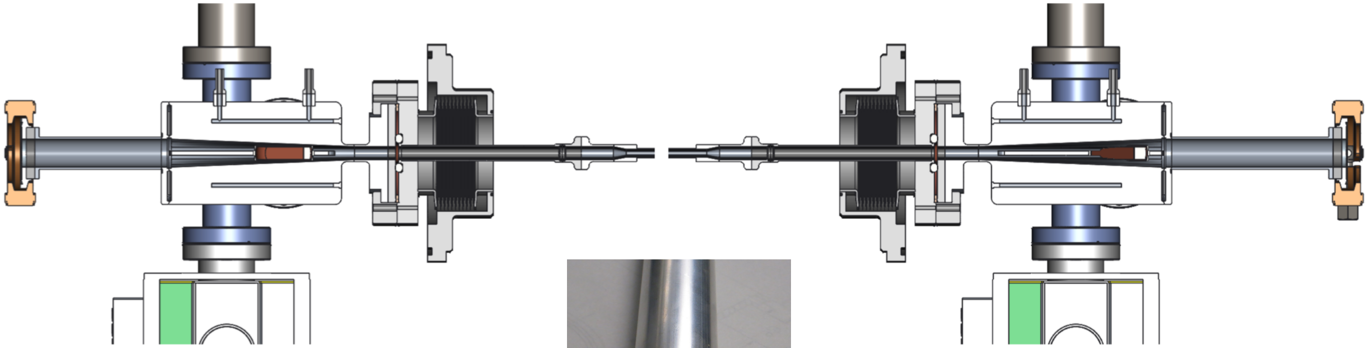


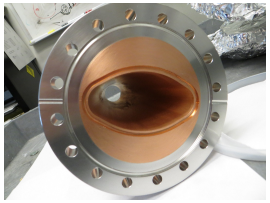
Cold mass is inserted in the cryostat

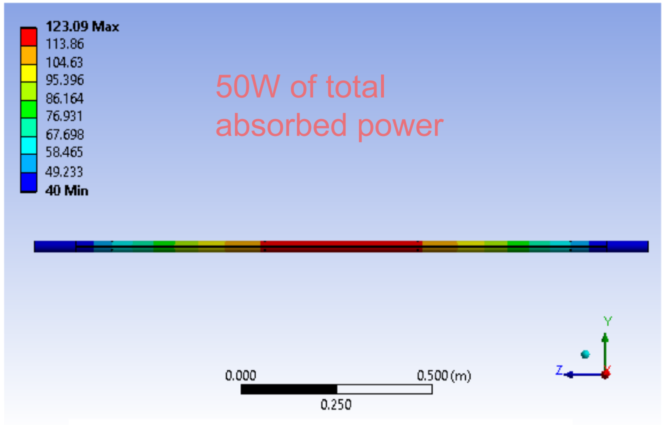


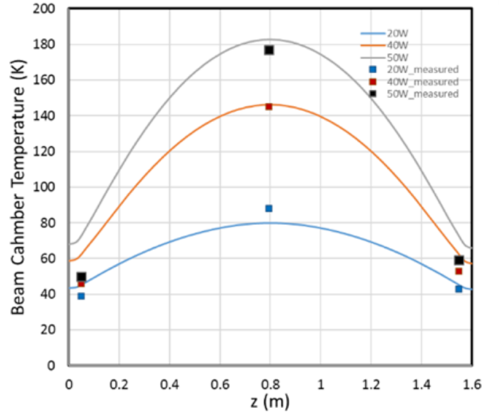
Thermal and electrical links

HSCU Vacuum Chamber





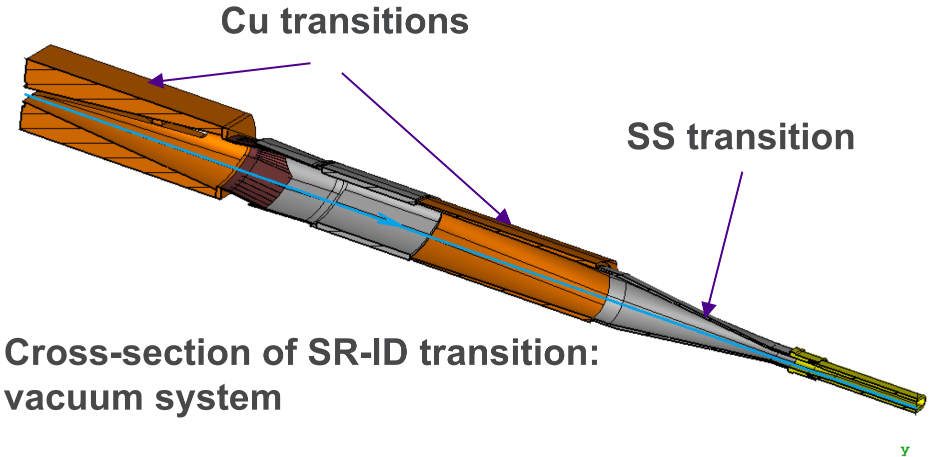




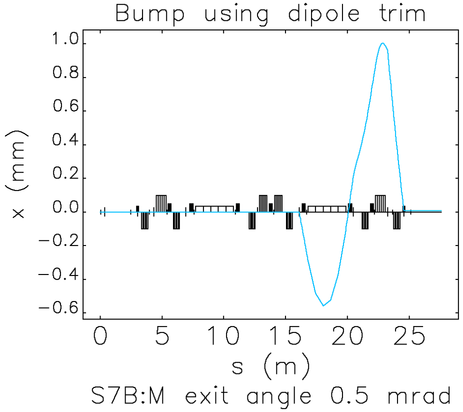
With 50W of total power introduced by SR and e-beam, the power transferred to the HSCU 4^0K cooling circuit is about 0.3W. All other heat sources generate 0.65W load. It leaves the ***excess*** in the cooling capacity at 4^0K of four HSCU cryocoolers approximately equal to the total heat load.

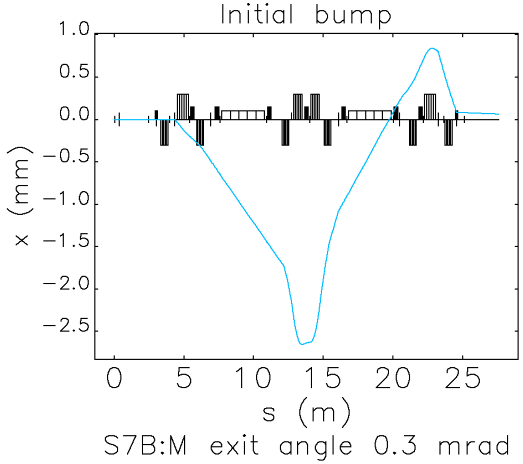
Unexpected Heat Source:
Hard x-ray scattered toward the magnet

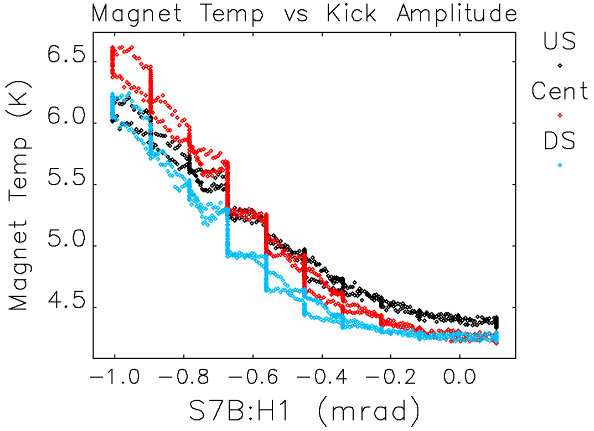
Horizontal trajectory bump in BM suppresses the heat source



Cross-section of SR-ID transition: vacuum system

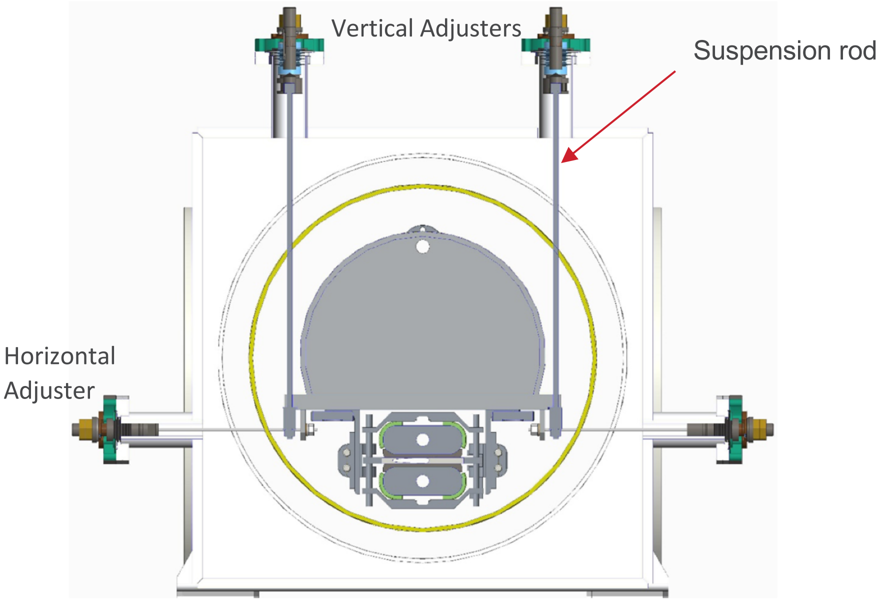


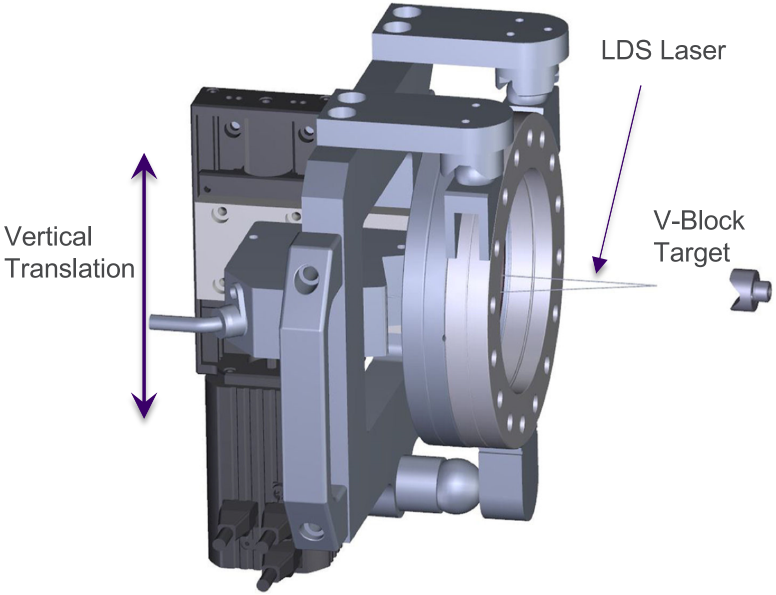




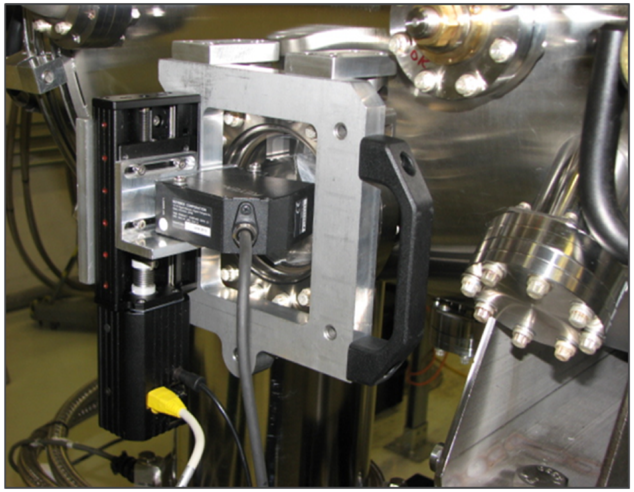
V.Sajaev, L.Emery, AOP-TN-2018-011

Cold Mass Suspension and Alignment System; Portable Cryoscanner





- 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**



Reliability of APS SCUs

- 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

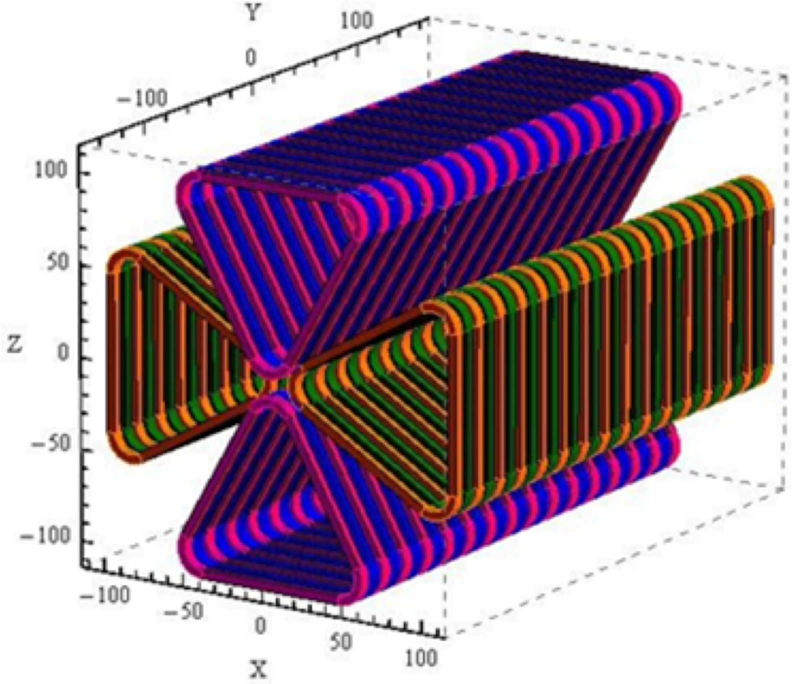
Calendar year	**APS delivered**	**SCU0/ SCU18-2 operating**	**SCU0/ SCU18-2 down**	**SCU0/ SCU18-2 quenches**	**SCU0/ SCU18-2 avail. %**	**SCU18-1 operating**	**SCU18-1 down**	**SCU18-1 quenches**	**SCU18-1 avail. %**
2013	4871 h	4189 h	20 h	*34* + 3	99.6	-	-	-	-
2014	4926 h	4391 h	174 h **[1]**	*32* + 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

[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

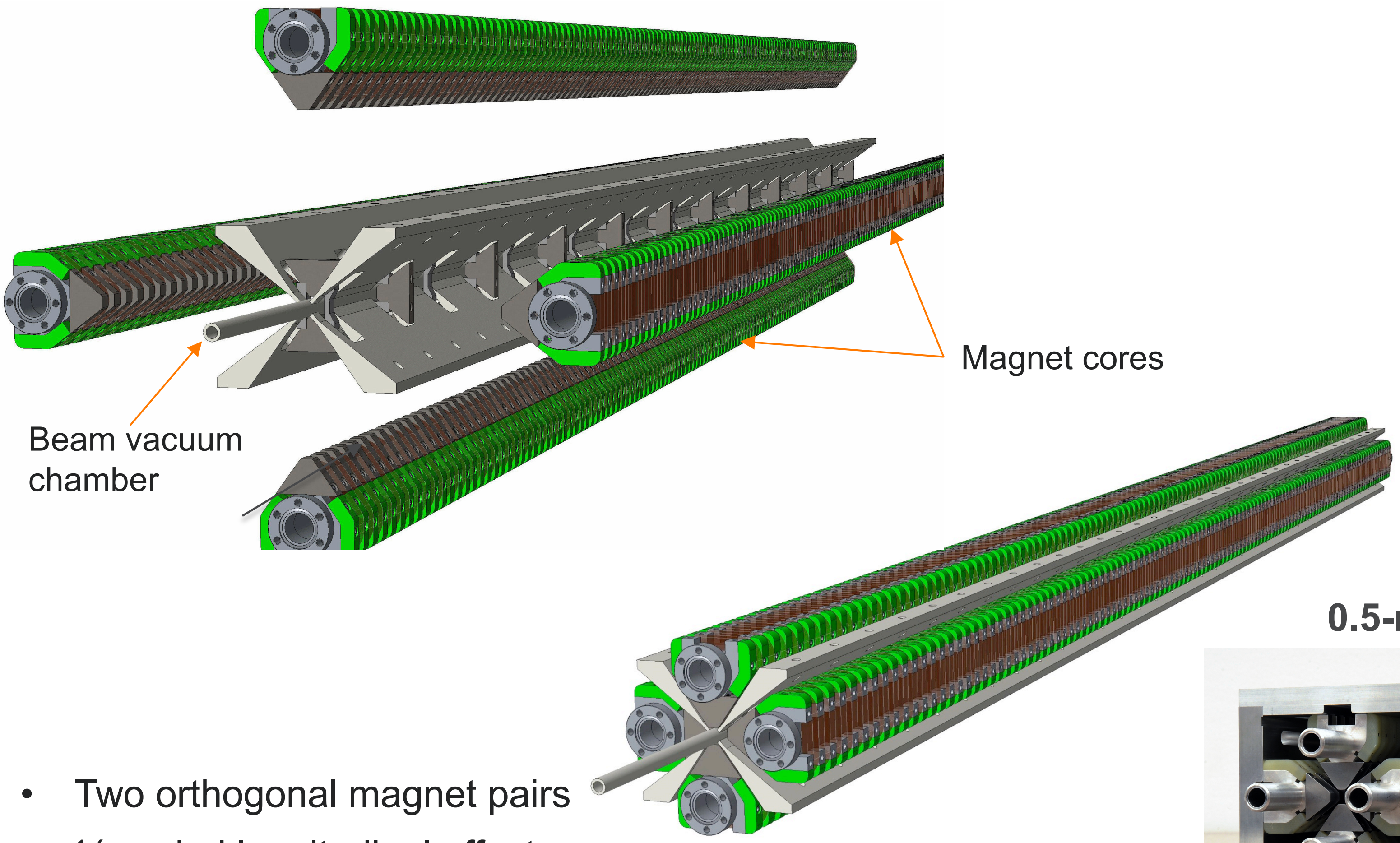
UNIVERSAL POLARIZING SCU

- APS POLAR beamline will have an undulator that can generate both circular and planar polarized photons.
- To meet this requirement the concept of a Super Conducting Arbitrarily Polarizing Emitter (SCAPE) was developed.
- 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 is now tested in a prototype.



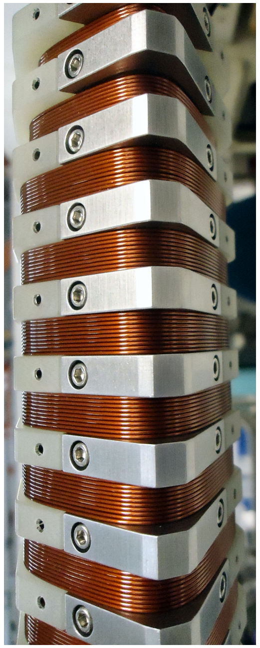
Concept of SCAPE: a universal SCU with four planar superconducting coil structures. A beam chamber is not shown.

SCAPE magnet and vacuum chamber design

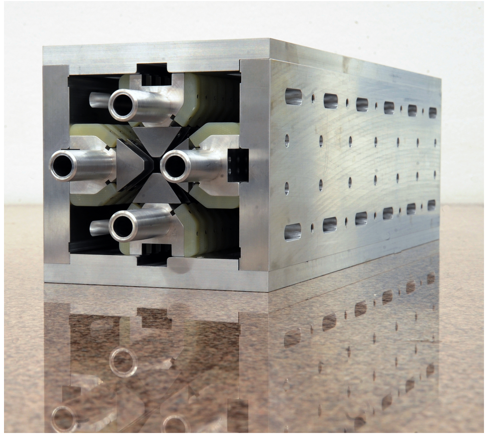


Beam vacuum chamber

Magnet cores



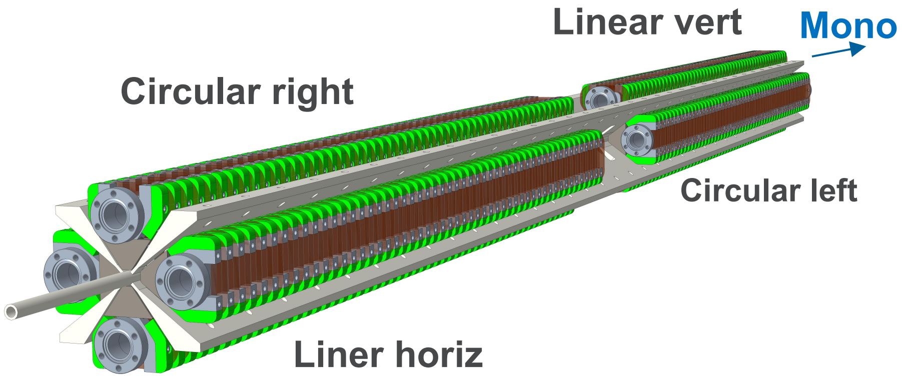
0.5-m prototype

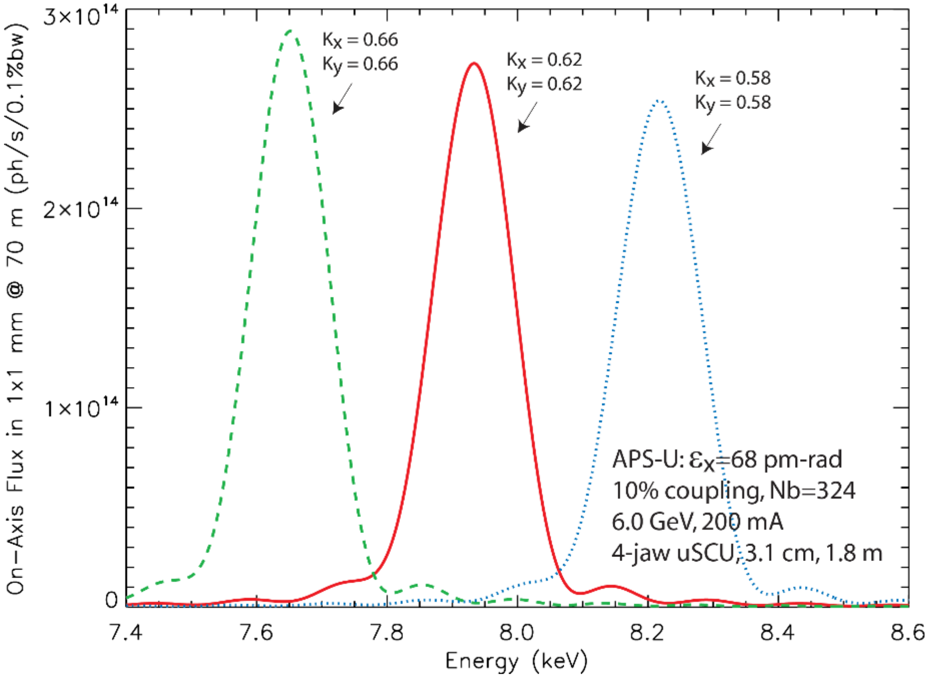


- Two orthogonal magnet pairs
- ¼-period longitudinal offset
- Beam vacuum chamber operates at elevated temperature, screens magnet from beam heating

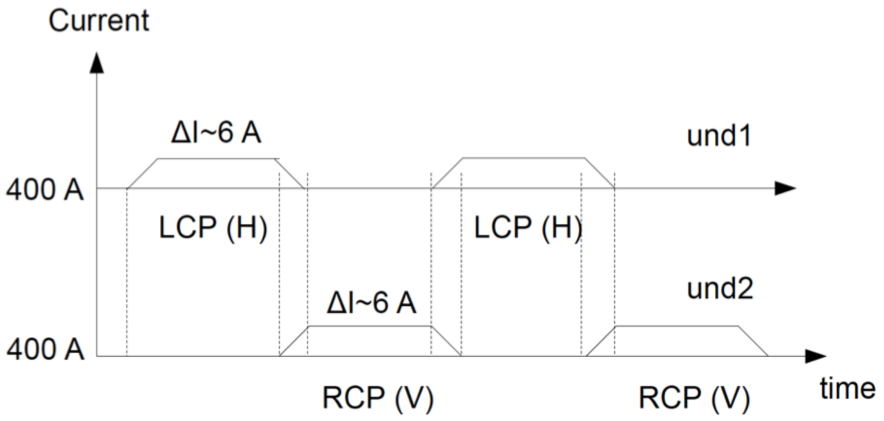
SCAPE: Polarization switching mode

Two SCAPE in-line 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.





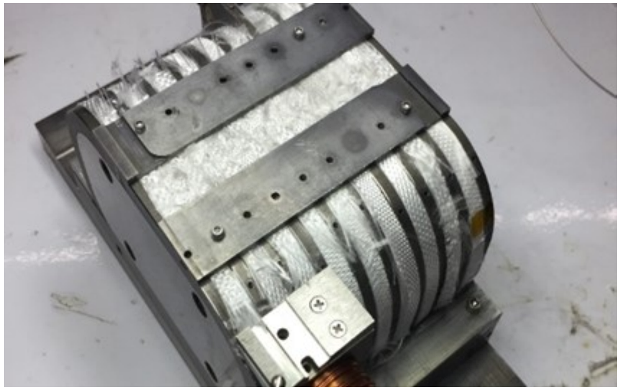
First harmonic energy vs K value.



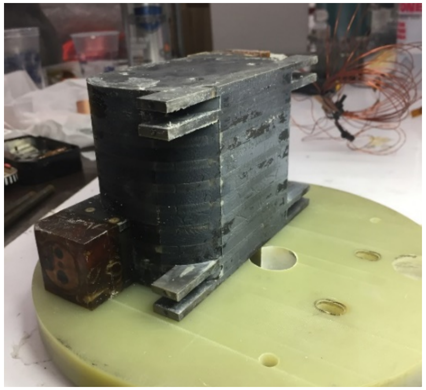
SCAPE operation in polarization switching mode.

Development of APS Nb$_3$Sn SCU prototype

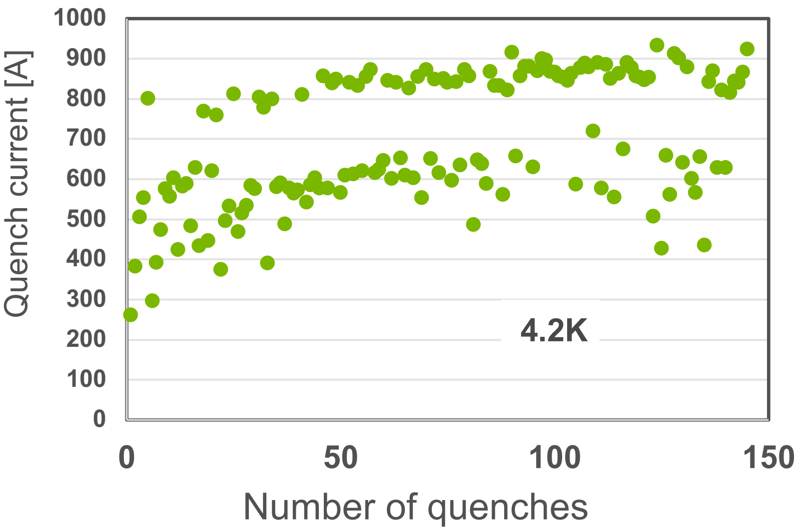
Wound model magnet



After heat treatment, impregnation & testing in LHe



- 4.5 period, 10-pole model magnet
- # of turns in a coil pack is 42
- Period length is 18 mm
- Conductor filament diameter is 45 microns (127 stack RRP)



Reached 935A after many quenches

- This is 20% higher than NbTi, but gives similar undulator field values due to larger insulation thickness
- 75% of the short sample limit

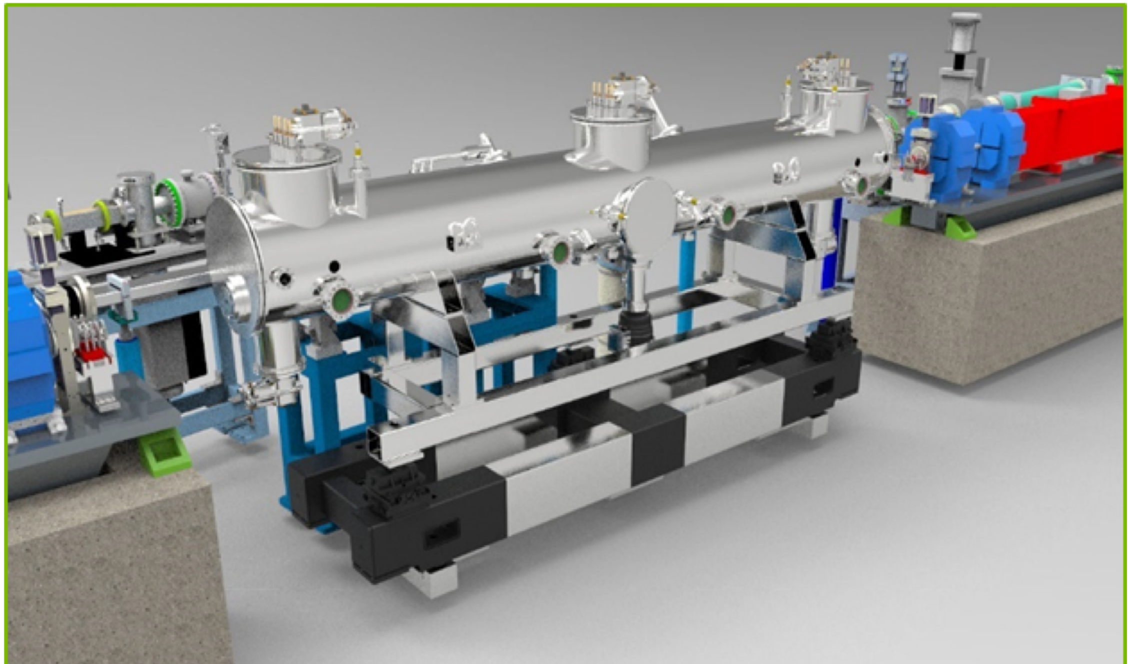
Instabilities, Lorentz forces and/or possible conductor damage limit the performance

Currently new model magnets are being fabricated to address these problems

- Magnet will supported mechanically to compensate the Lorentz forces
- Wire with smaller filament diameter, 35 microns (169 stack RRP), will be used to overcome the instabilities

APS-U SCU Developments

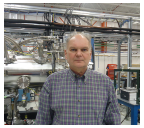
- The APS Upgrade includes four full-ID-length SCUs, each with two 1.8-m planar SCU magnets in series separated by either a phase shifter or a canting magnet.
- The APS Upgrade also includes one SCAPE SCU and re-uses one existing SCU.
- New long SCU cryostats will be modeled on the HSCU 2nd-generation design.



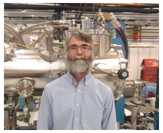
CAD model of long SCU in the APS-U.

APS SCU team and AP&DD support

Yury Ivanyushenkov – team leader



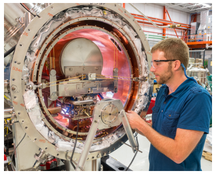
Joel Fuerst – cryogenic and mechanical design



Yuko Shiroyanagi – thermal and mechanical analysis

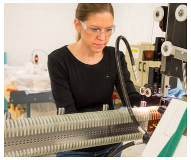
Quentin Hasse – epoxy impregnation, vacuum

Matt Kasa – magnet windings, magnet measurements,
assembly, controls



Ibrahim Kesgin – Nb$_3$Sn and HTS developments

Sue Bettenhausen – magnet winding,
assembly



Accelerator Physics support: ***Yipeng Sun, Vadim Sajaev, Aimin Xiao ---*** **lattice design and beam dynamics;** ***Ryan Lindberg, Xiang Sun---*** **wakefied analysis;** ***Kathy Harkay---*****ray tracing and beam heat load;** ***Roger Dejus, Michael Borland ---*** **device parameters optimization.**

Engineering Design support: ***E.Trakhtenberg, D.Skiadopoulos, E.Anliker.***

Alignment: ***W.Jansma***, ***Rendering:*** ***O.Schmidt***

Conclusions

- There are three SCUs currently in operation at the APS (2 planar, 1 helical). All of them are highly reliable, user-controlled devices
- Development is underway for a new generation of SCUs for the APS Upgrade.
- The APS is preparing to transfer already established SCU technology to a qualified industrial partner.
- The APS is working to develop the next generation of SCU technology for future storage ring and FEL light sources.