

Superconducting wigglers and undulators

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Superconducting shifters and multipole wigglers at the BINP

Types of superconducting magnet systems used as generators of synchrotron radiation:

Superconducting 3 (5) pole shifters with 7-10 Tesla field:
manufactured 5, 3 of them are working for about 20 years.

Superconducting high field 7-7.5 Tesla multipole wigglers:
fabricated- 4, 3 of them are working and 1 is ready to put in operation this year.

Superconducting multipole wiggler with a medium period of 48 to 60 mm and field of 3-4.3 Tesla:
fabricated- 10, 8 of them are working and 2 are ready to put in operation this year.

Superconducting multipole wiggler with a short period of 30-34 mm and field of 2-2.2 Tesla:
fabricated 2, both are working.

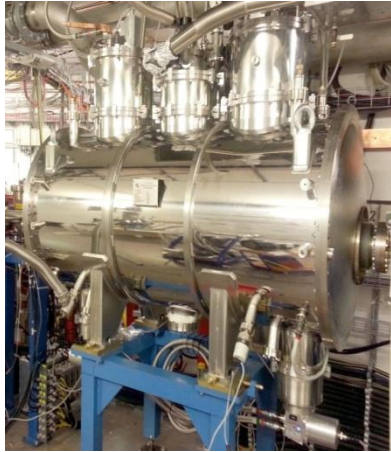
Superconducting undulator with period 15.6 mm and field 1.2 Tesla is under fabrication now.
Should be ready this year.

International collaboration on SR generators

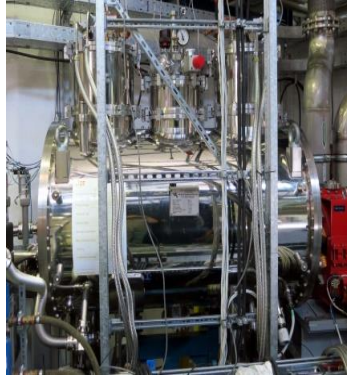
Germany:



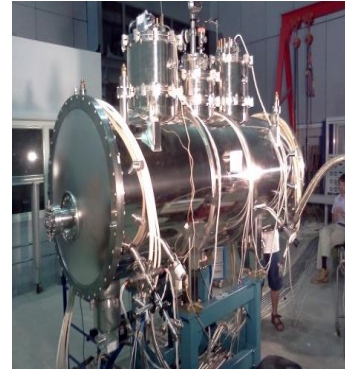
Two superconducting
7 Tesla shifters for
BESSY-2 light source
(Berlin). 2000,2001



17 poles 7 Tesla, $\lambda=148$ mm
superconducting wiggler for
BESSY-2 light source (Berlin)
2002



44-pole 2.5 Tesla, $\lambda=48$ mm
superconducting wiggler
for ANKA light source
(Karlsruhe) 2014



72-pole 3Ttsla, $\lambda=51$
mm superconducting
wiggler for ANKA-CLIC
(Karlsruhe)
Indirect cooling system.
2016

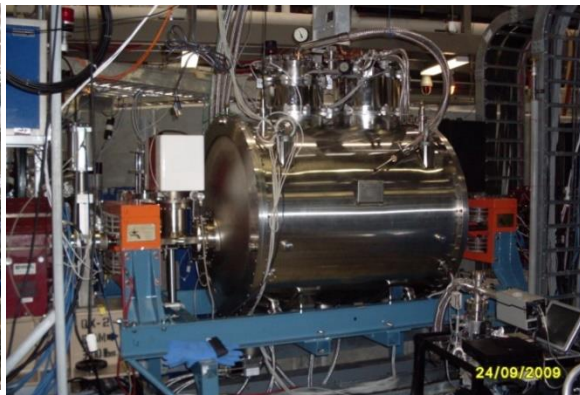


22-pole 7Ttsla, $\lambda=125$ mm
superconducting wiggler for
DELTA (Dortmund)
2019

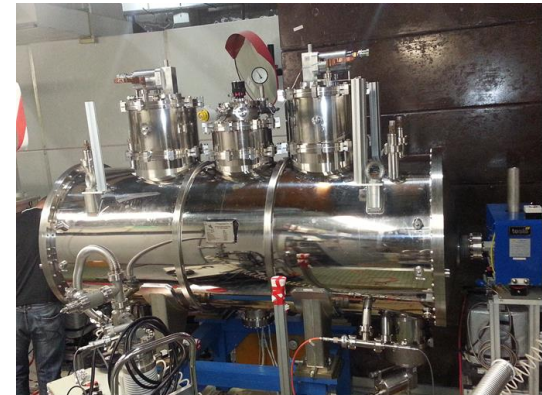
USA



15-pole 7.5 Tesla, $\lambda=198$ mm
superconducting wiggler for LSU
CAMD light source (Baton Rouge)
2013



7 Tesla superconducting shifter for LSU
CAMD light source (Baton Rouge) 1997



49-pole 3.5 Tesla, $\lambda=60$ mm
superconducting wiggler for
ELETTRA light source (Trieste) 2002

Italy

England

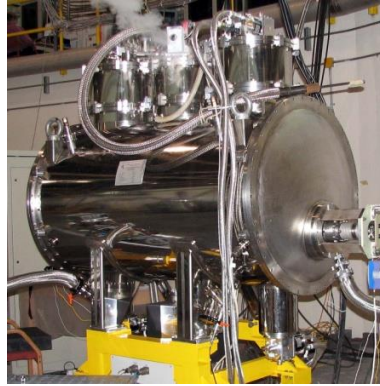


49-pole 3.5 Tesla, $\lambda=60$ mm superconducting wiggler for Diamond Light source. 2006



49-pole 4.2 Tesla, $\lambda=48$ mm superconducting wiggler for Diamond Light source. 2009

Canada



27-pole 4.2 Tesla, $\lambda=48$ mm superconducting wiggler for Canadian Light source. 2007



63-pole 2.2 Tesla, $\lambda=32$ mm superconducting wiggler for Canadian Light source. 2005

Brasil



35-pole 4.2 Tesla, $\lambda=60$ mm superconducting wiggler for LNLS light source. 2009

Australia



49-pole 4.2 Tesla, $\lambda=52$ mm superconducting wiggler for AS light source. 2012

Spain



119-pole 2.1 Tesla, $\lambda=30$ mm superconducting wiggler for ALBA light source. 2010

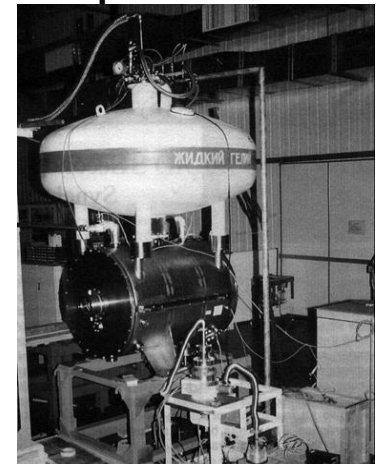
Japan

10 Tesla WLS for Spring-8 Slow Positron Source



10 Tesla superconducting shifter for SPring-8. 2000

Republic Korea



7.5 Tesla superconducting shifter for PLS light source. 1996.

History of superconducting magnet activity for 40 years

1979 – first in the world 3.5 Tesla superconducting 20 pole wiggler (SCW) for VEPP-3	NbTi/Cu
1984 – 5 pole 8 Tesla superconducting wiggler for VEPP-2	NbTi/Cu
1985 – 4.5 Tesla Superconducting Wave Length Shifter (WLS) for Siberia-1, Moscow	NbTi/Cu
1992 – 6 Tesla superbend (SB) prototype for compact storage rings	NbTi/Cu
1996 - 7.5 Tesla superconducting WLS for PLS, South Korea	NbTi/Cu
1997 - 7.5 T superconducting WLS with fixed point of radiation for CAMD-LSU (USA)	NbTi/Cu
2000 – 10 Tesla WLS for Spring-8, Japan	Nb3Sn/Cu
2000 – 7 Tesla WLS with fixed radiation point for BESSY-2, Germany	NbTi/Cu
2001 – 7 Tesla WLS with fixed radiation point for BESSY-2, Germany	NbTi/Cu
2002 – 3.5 Tesla 49 pole SCW for ELETTRA, Italy	NbTi/Cu
2002 – 7 Tesla 17 pole SCW for BESSY-2, Germany	NbTi/Cu
2004 – 9 Tesla Superbend for BESSY-2, Germany	Nb3Sn/Cu

Red- in operation, **black-** not in operation

History of superconducting magnet activity for 40 years

2005 – 13 Tesla superconducting solenoids for VEPP-2000	Nb ₃ Sn/Cu
2005 – 2 Tesla 63 pole SCW for CLS, Canada	NbTi/Cu
2006 – 3.5 Tesla 49 pole for DLS, England	NbTi/Cu
2006 – 7.5 Tesla 21 pole SCW for Siberia-2, Moscow	NbTi/Cu
2007 – 4.2 Tesla 27 pole SCW for CLS, Canada	NbTi/Cu
2009 – 4.2 Tesla 49 pole SCW for DLS, England	NbTi/Cu
2009 – 4.1 Tesla 35 pole SCW for LNLS, Brasil	NbTi/Cu
2010 - 2.1 Tesla 119 pole SCW for ALBA, Spain	NbTi/Cu
2012 - 4.2 Tesla 63 pole SCW for AS (Australia)	NbTi/Cu
2013 - 7.5 Tesla 15 pole wiggler for LSU CAMD, USA	NbTi/Cu
2014 - 2.5 Tesla 44 pole wiggler for ANKA-CATAC, Germany	NbTi/Cu
2016 - 3 Tesla 72 pole wiggler for ANKA/CLIC, Germany/CERN	NbTi/Cu
2018 – 7 Tesla 22 pole wiggler for DELTA, Dortmund, Germany	NbTi/Cu
2018 – 3 Tesla 54 pole 2 wigglers for Siberia -2, Moscow, Russia	NbTi/Cu

Red- in operation, **green-** ready to install

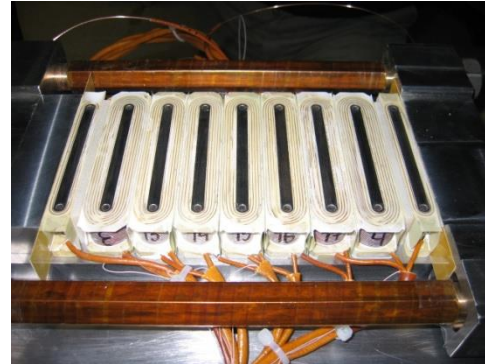
Beam Tests and Commissioning of Low
Emittance Storage Rings, Feb.18-20,2019

3 groups of SC wiggler

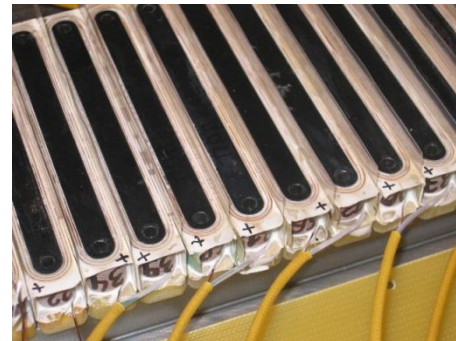
High field SC multipole wigglers
($B=7-7.5$ Tesla, $\lambda \sim 125-200$ mm)



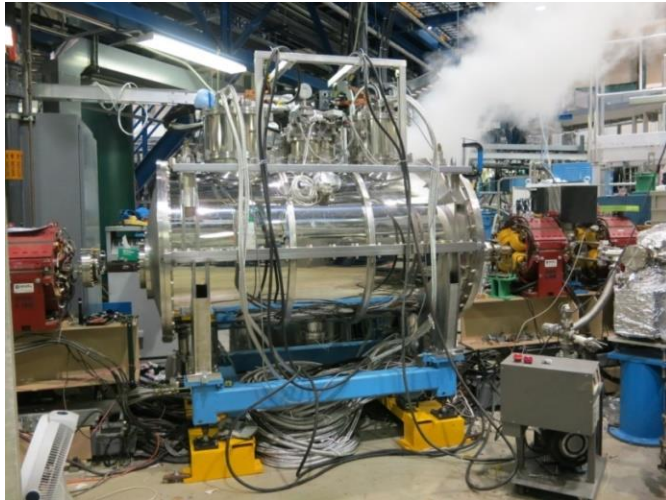
Medium field SC wigglers
($B=3.5-4.2$ Tesla, $\lambda \sim 48-60$ mm)



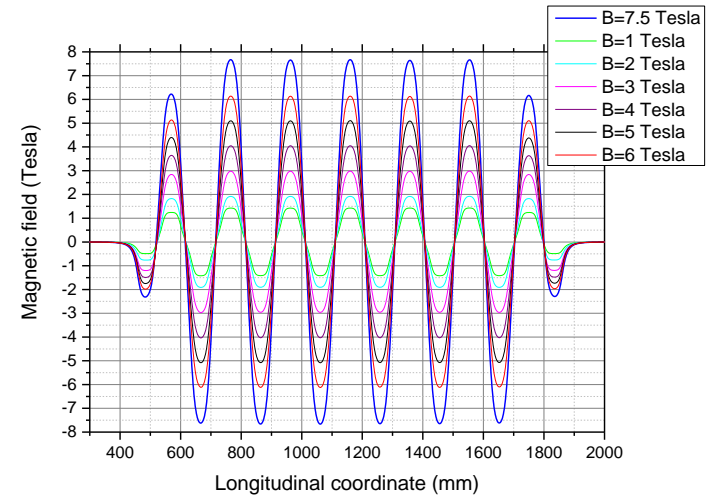
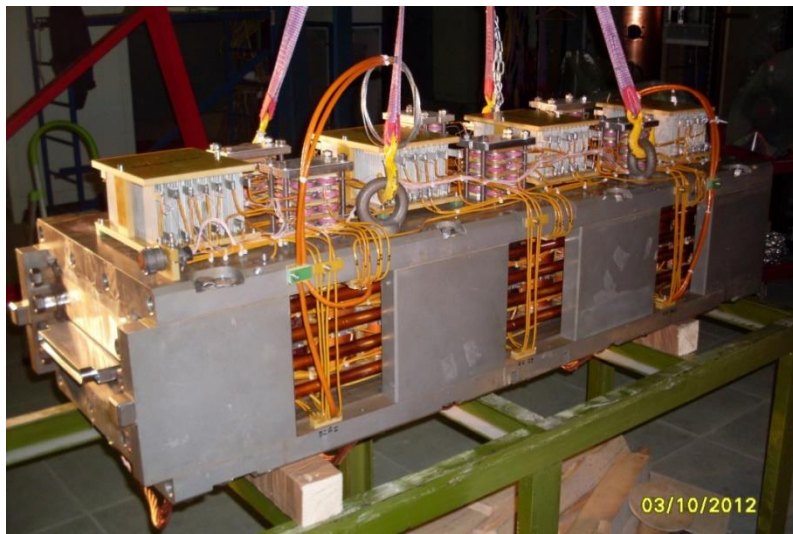
Short period SC wigglers
($B=2-2.2$ Tesla, $\lambda \sim 30-34$ mm)



High field long period superconducting multipole wigglers are used for production of hard X-rays on storage rings with low electron energy (BESSY 1.7 GeV, CAMD LSU 1.35 GeV, Siberia-2 2.5 GeV, Dortmund university 1.5GeV)



7.5 Tesla 15 pole superconducting wiggler (CAMD LSU, USA)



Magnetic field distribution at different field levels



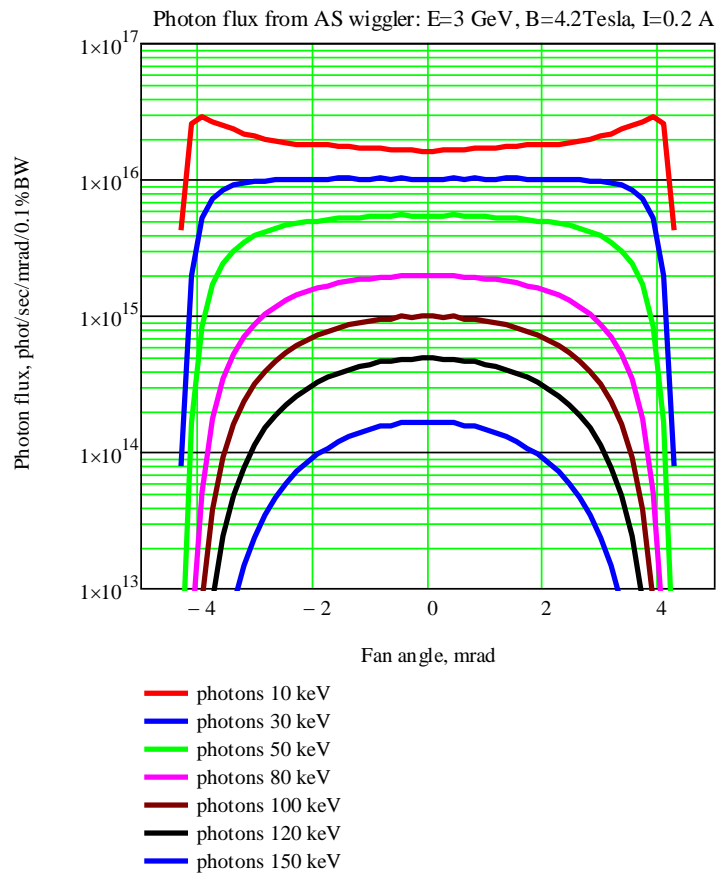
The installation of an insertion device with so high field at an accelerator working energy of 1.35 GeV is quite a complex accelerating challenge, as considerable effort was required for compensation of the influence of the magnetic field on the magnetic structure of the storage ring. All problems connected with the influence of the wiggler field on the beam dynamics were successfully solved during the wiggler commissioning with electron beam.

A PRELIMINARY REPORT FROM LOUISIANA STATE UNIVERSITY
CAMD STORAGE RING OPERATING WITH AN 11 POLE 7.5
TESLA WIGGLER R. S. Amin et al, Proceedings of IPAC2015,
Richmond, VA, USA

Superconducting multipole wigglers with medium period

Angular-spectral photon distribution from the wiggler (63 poles):

$B_0=4.2\text{ T}$, $E=3\text{ GeV}$, $I=0.2\text{ A}$,



Australian Light Source



Assembled magnet



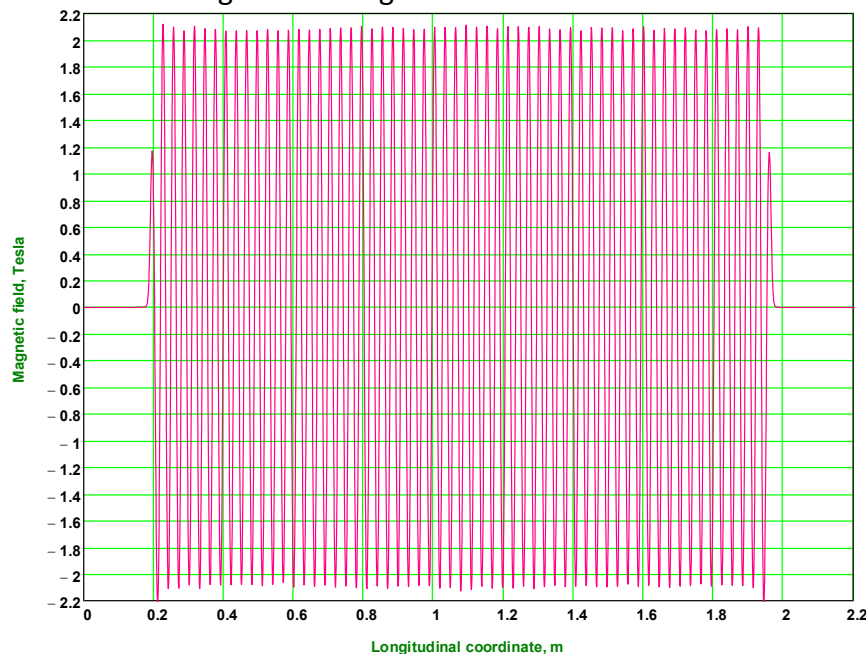
[140 m long Imaging and medical beamline](#)



End of beamline- extraction window

Short period superconducting multipole wigglers

Longitudinal magnetic field distribution

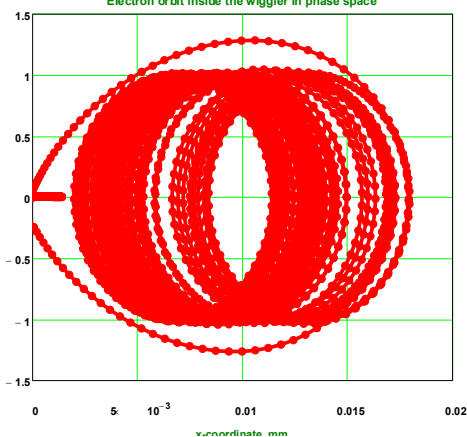


119-pole 2.1 Tesla SC wiggler for ALBA CELLS



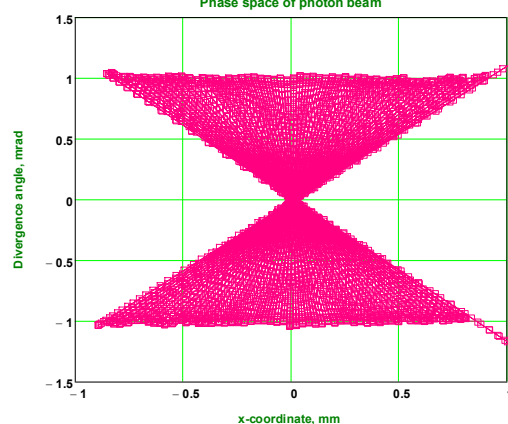
½ of the wiggler magnet

Electron orbit inside the wiggler in phase space



Electron beam orbit in x-x' coordinate

Phase space of photon beam



Phase space of the photon beam



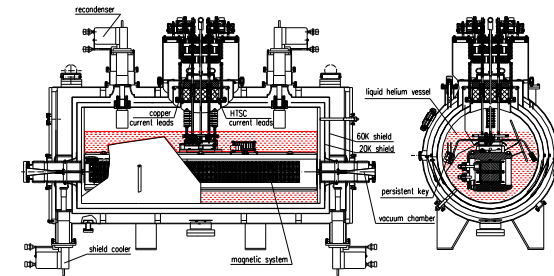
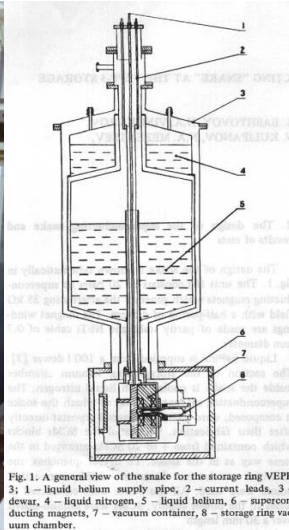
Magnet pole – main element of the magnet

<http://accelconf.web.cern.ch/AccelConf/IPAC2011/papers/thpc172.pdf>

Cryogenic system 1979

Cryogenic system of SC insertion devices progress (Budker INP)

2002

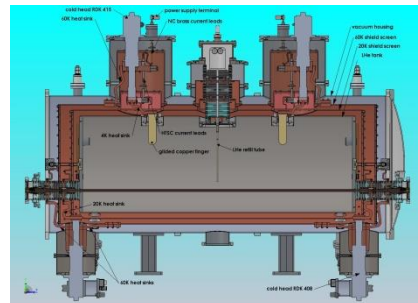


Liquid helium consumption ~ 0.6 l/hr

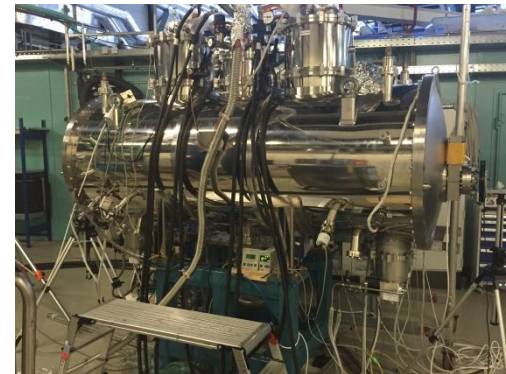
2015

Liquid helium consumption ~ 4 l/hr

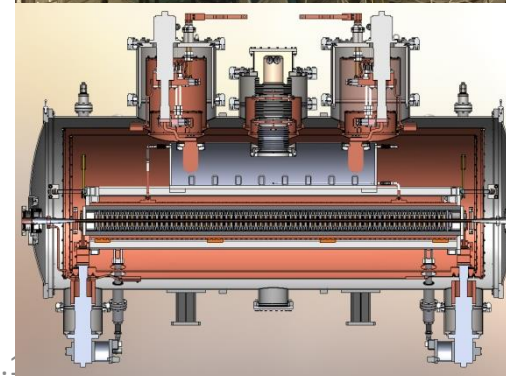
2007



Liquid helium consumption < 0.03 l/hr



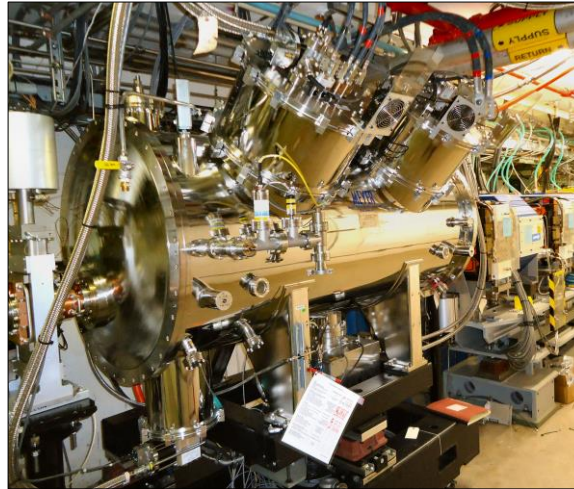
Indirect cooling system. Liquid helium used as cooling agent



For initial cooling of the magnet thermal tubes on the basis of nitrogen and helium are developed, fabricated and tested.

SCUs at the APS (on behalf Efim Gluskin)

- 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

APS SCUs operational performance

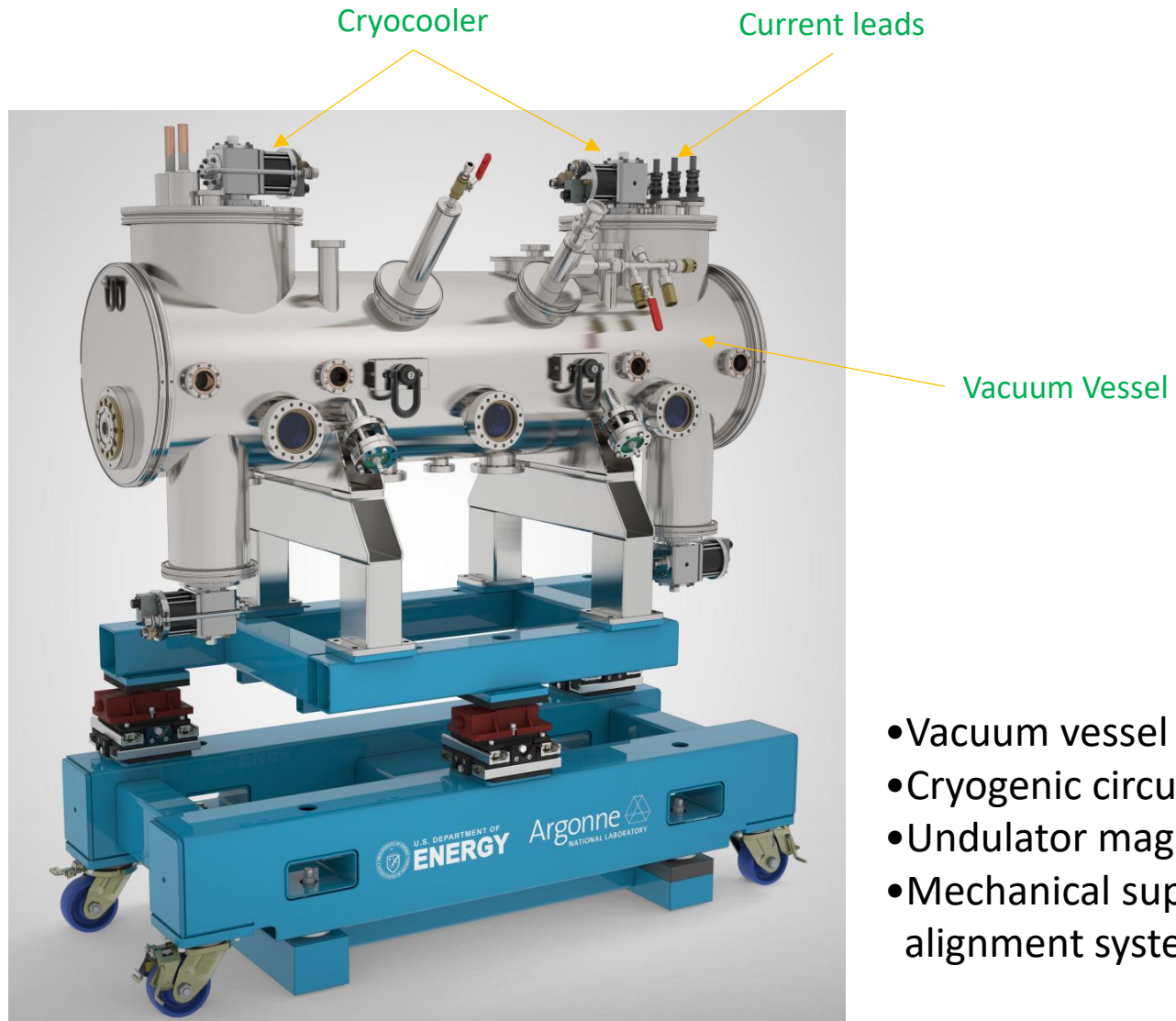
- SCUs have been essentially transparent to the APS SR beam
- Most quenches occur during unplanned beam dumps
- SCU0,18-2 quenches decreased dramatically after beam abort system added in January 2016

	λ (mm)	# of periods	B (T)	2013			2014			2015			2016			2017			2018	
				Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	Run 1	Run 2
SCU0	16	20.5	0.8																	
SCU18-1	18	59.5	0.97																	
SCU18-2	18	59.5	0.97																	
HSCU	31.5	38.5	0.41																	

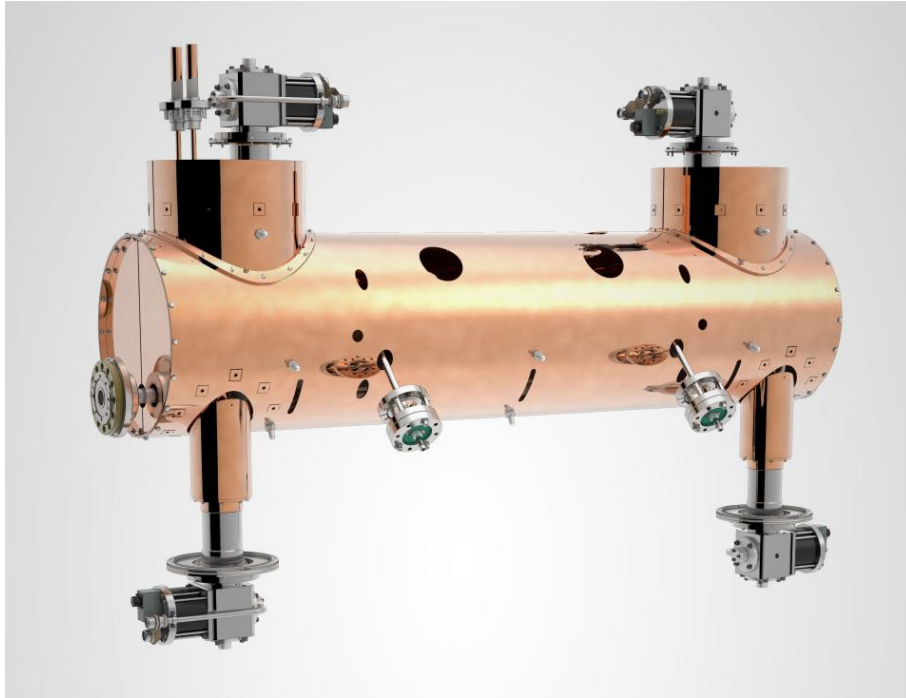
Year	APS delivered	SCU0 and SCU18-2				SCU18-1				HSCU			
		Oper.	Down	quench	avail. %	Oper.	Down	quench	avail. %	Oper.	Down	quench	avail. %
2013	4871 h	4189 h	20 h	34 + 3	99.5	-	-	-	-	-	-	-	-
2014	4926 h	4391 h	174 h [1]	32 + 2	96.2	-	-	-	-	-	-	-	-
2015	4940 h	4834 h	0 h	26 + 1	100	3059 h [2]	0.1 h	5 + 0	99.997	-	-	-	-
2016	4941 h	4647 h [3]	0 h	9 + 0	100	4585 h	0.3 h	11 + 1	99.990	-	-	-	-
2017	4840 h	4756 h	0 h	8 + 1	100	4818 h	0.75 h	13 + 2	99.984	-	-	-	-
2018 [4]	3327 h	3236 h	5 h	11 + 1	99.8	3199 h	0.59 h	9 + 2	99.981	533 h	0 h	0 + 0	100
Total	27845 h	26053 h	199 h	120 + 8	99.24	15661 h	1.74 h	29 + 3	99.99	533 h	0 h	0 + 0	100

- 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 2018 through September 2018

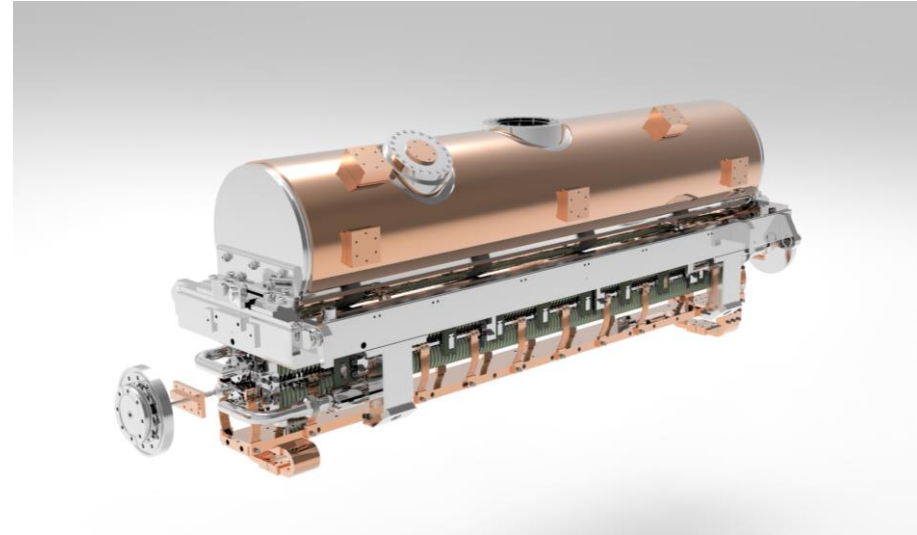
APS SCU cryostat



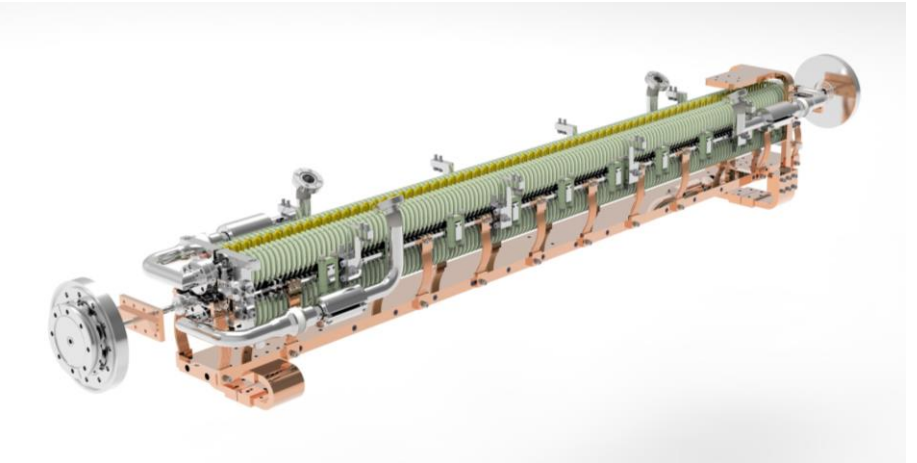
Thermoshield with cryocoolers



Planar SCU – “cold mass”: LHe tank and undulator magnet

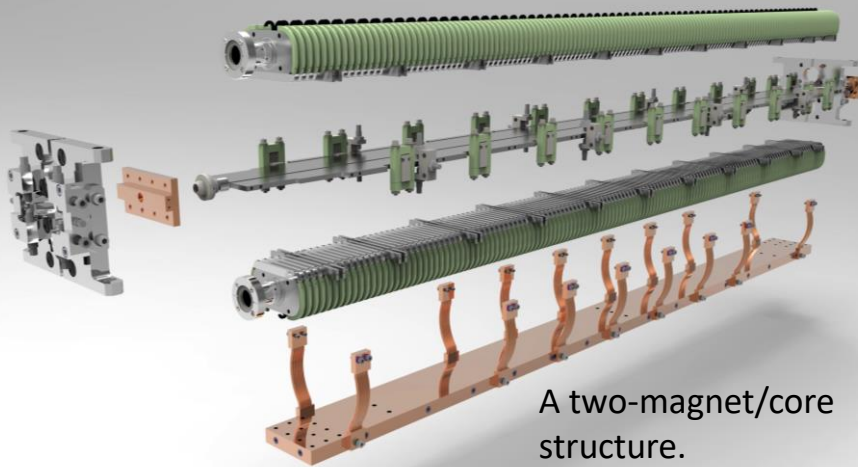


Planar SCU – magnet and vacuum chamber

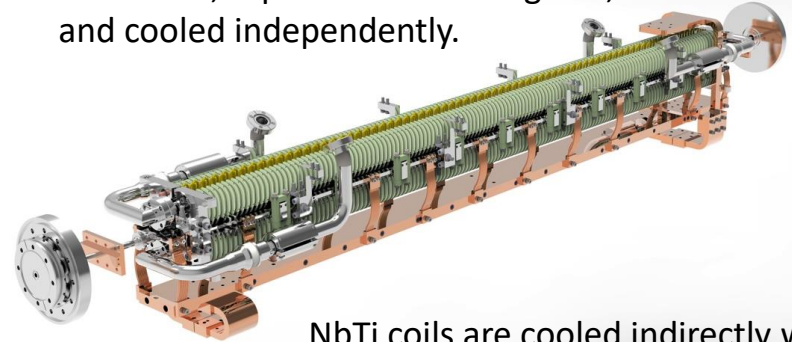


Planar SCU: magnets/cores

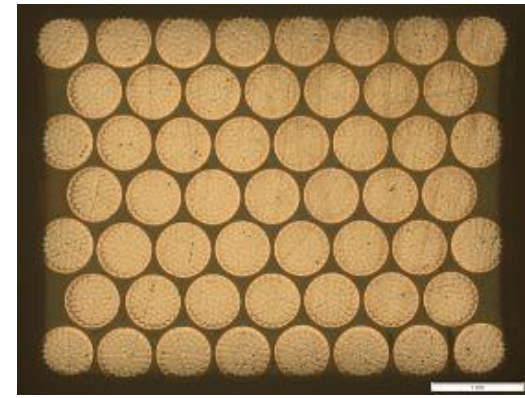
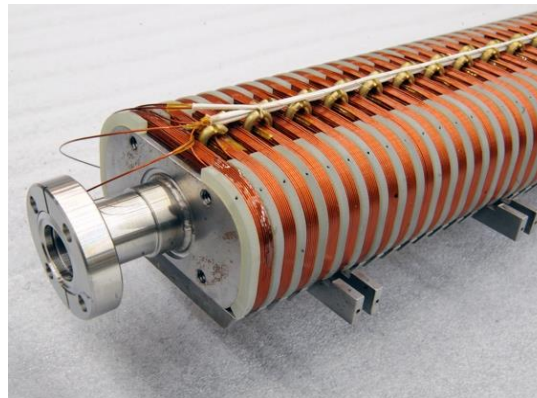
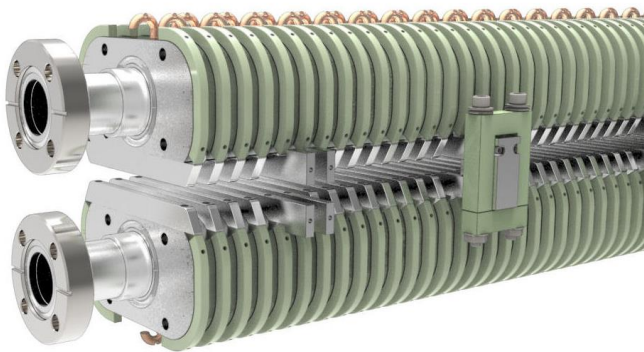
Existing magnet/beam vacuum chamber assembly.



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

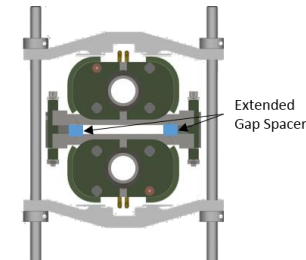


NbTi coils are cooled indirectly with LHe helium passing through channels in the magnet cores.



Phase errors control

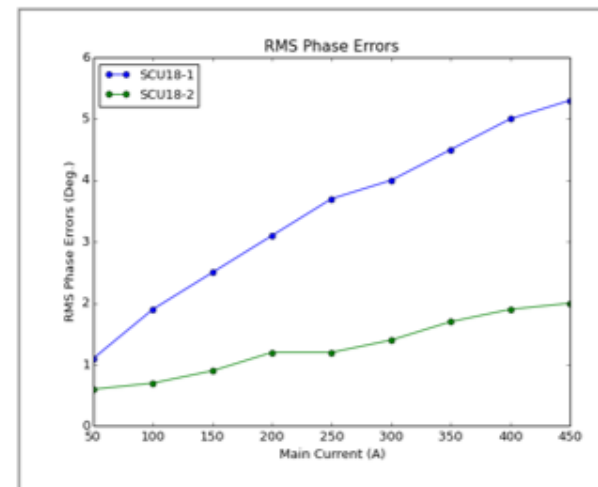
- The SCU field quality depends on:
 - Precise machining of a magnet core
 - Quality of conductor winding
 - Uniformity of the magnetic gap
- A dedicated R&D program was targeted at achieving a very uniform gap.
 - A gap correction scheme was developed and implemented using a set of mechanical clamps



Planar SCU magnetic assembly with a gap correction.

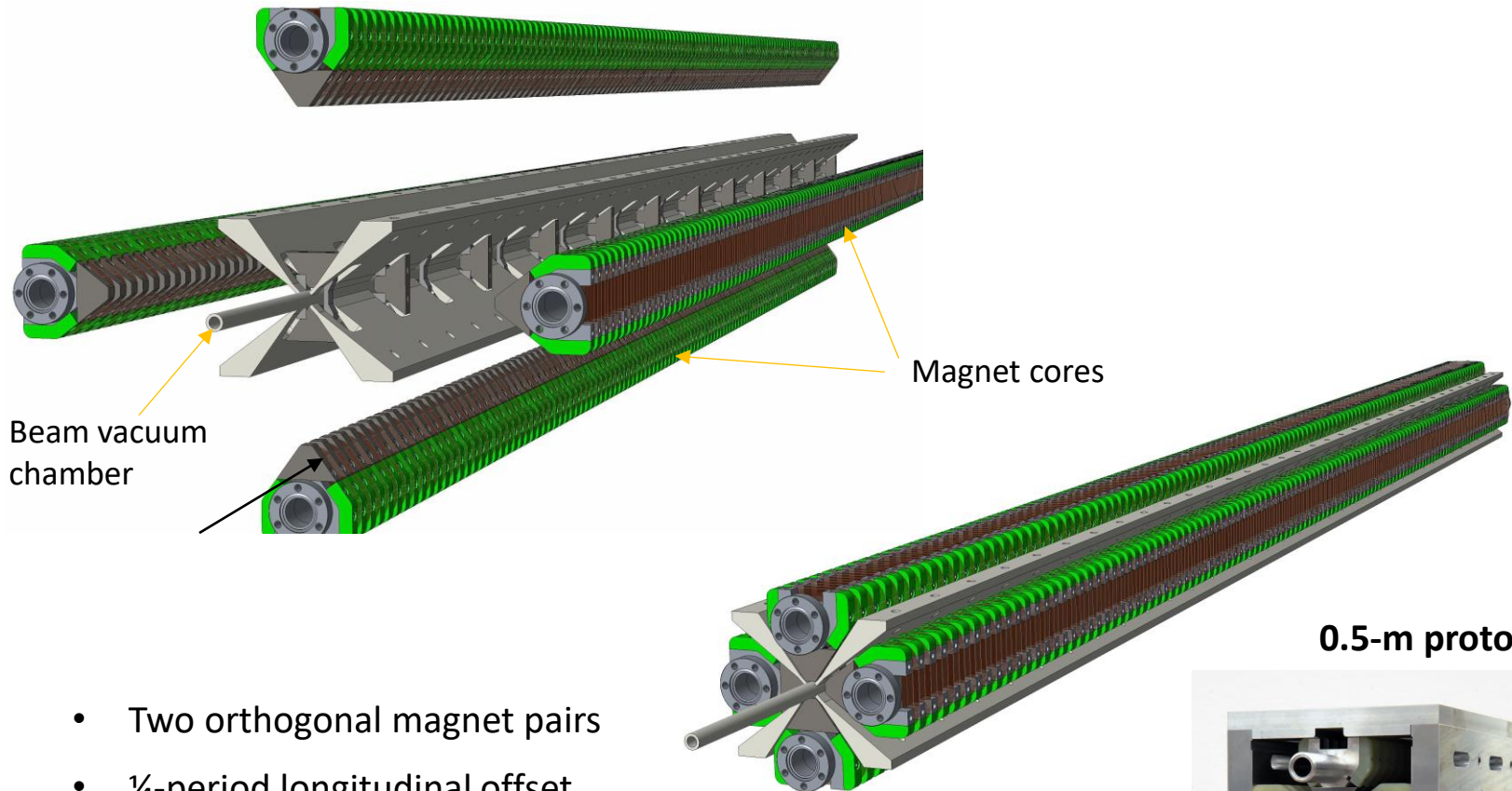
Undulator	Measured phase errors (° rms)
SCU18-1	5*
SCU18-2	2
LCLS R&D SCU	3.8

* without gap correction



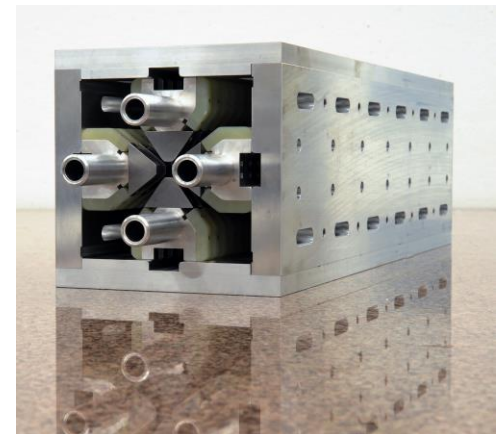
Measured phase errors in SCU18-1 and SCU18-2.

SCAPE magnet and vacuum chamber design

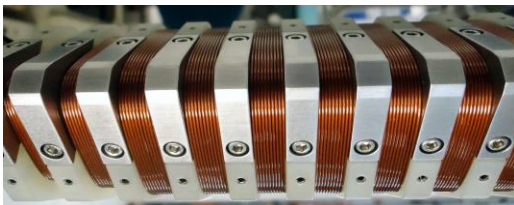
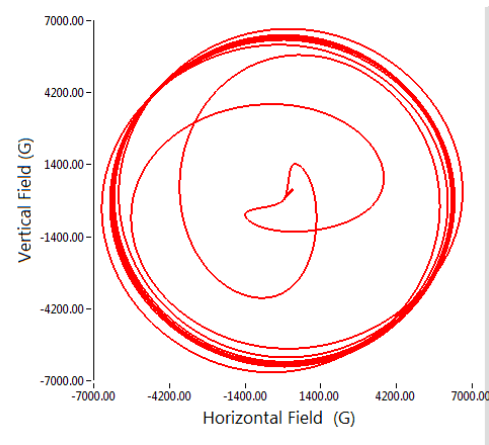
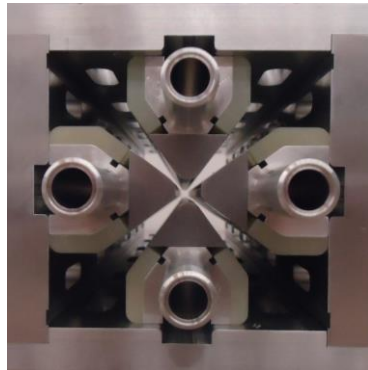
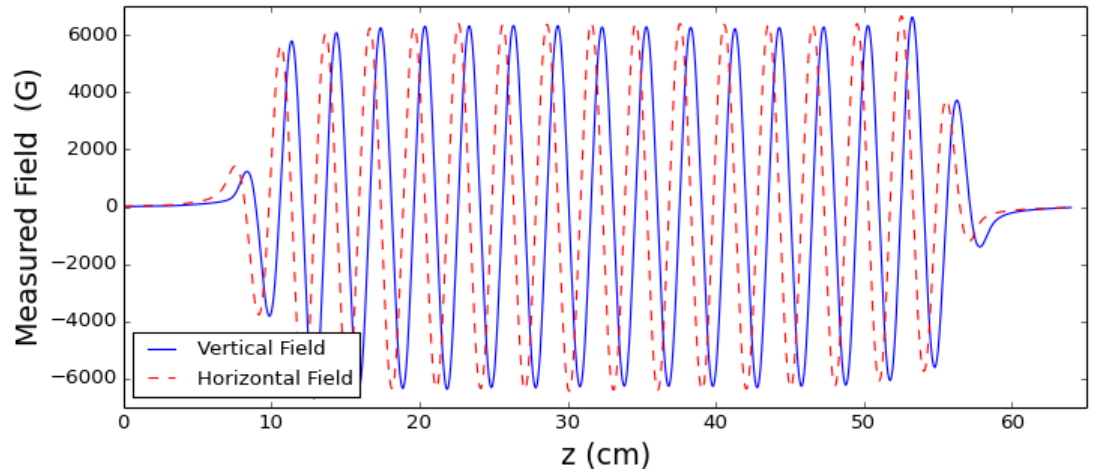


- Two orthogonal magnet pairs
- $\frac{1}{4}$ -period longitudinal offset
- Beam vacuum chamber operates at elevated temperature, screens magnet from beam heating

0.5-m prototype

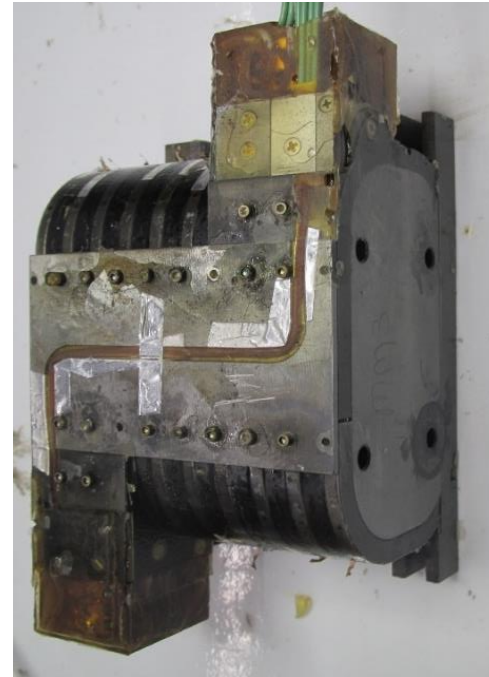


SCAPE: 0.5m prototype tests

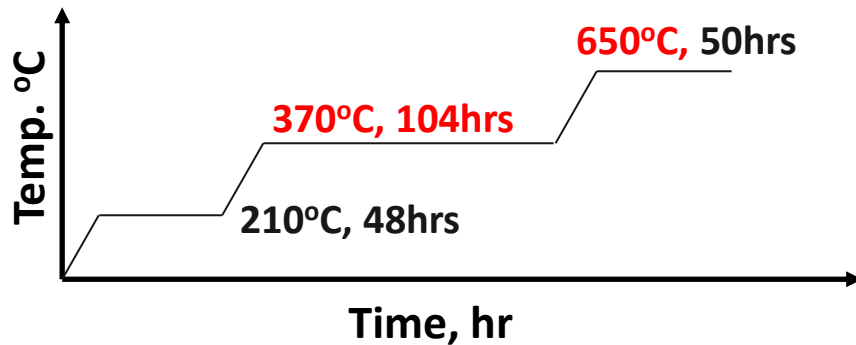


- 30 mm period
- 10 mm pole gap
- Four 0.5 m long magnets
- Planar, circular, and elliptical modes were measured in a vertical LHe bath cryostat

Nb₃Sn short undulator prototype

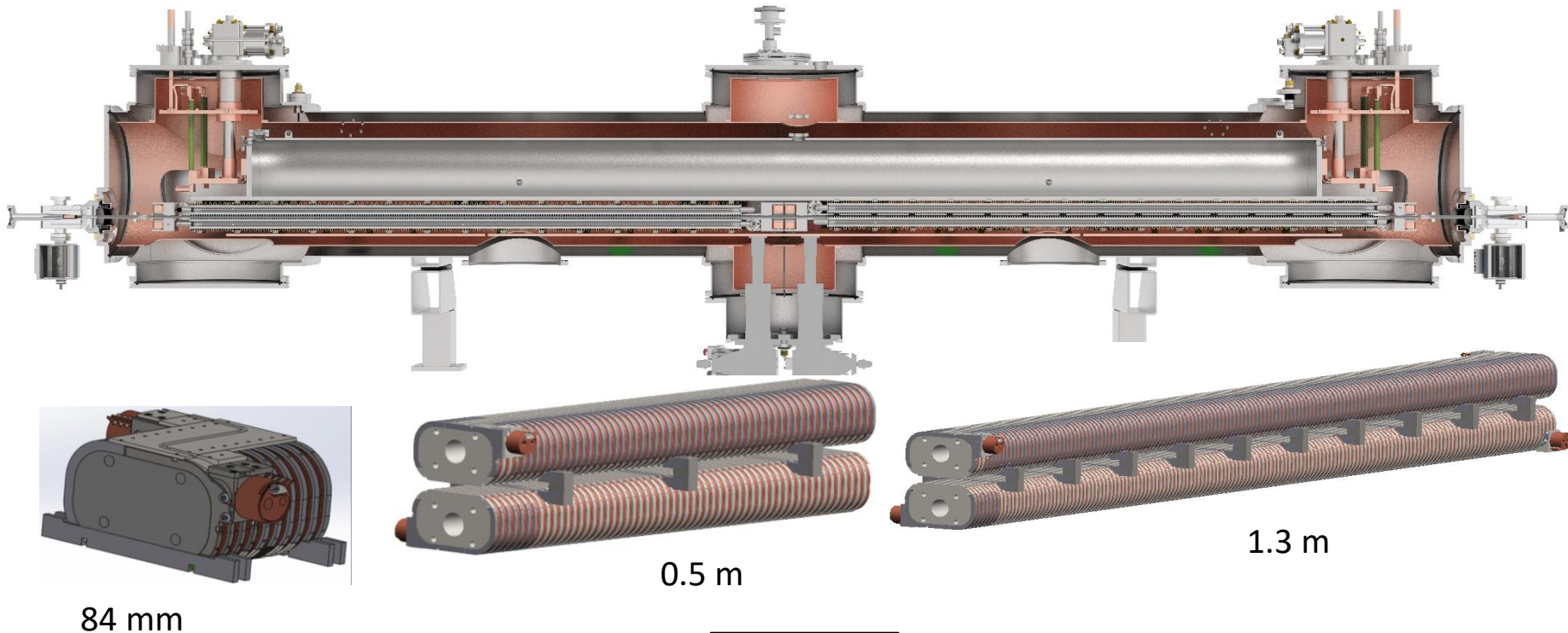


B-OST suggested the HT profile
modified by FNAL



- 0.6 mm diameter conductor with filament diameter of 35 microns
- No thick epoxy build-ups
- HT cycle optimized

In-line double Nb₃Sn unduator for APS



Schedule

Short Magnets R&D

12/18

*Go, no go decision

12/18

0.5 m Magnets R&D

8/19*

8/19

1.3 m Full Scale SR grade Magnets

11/20

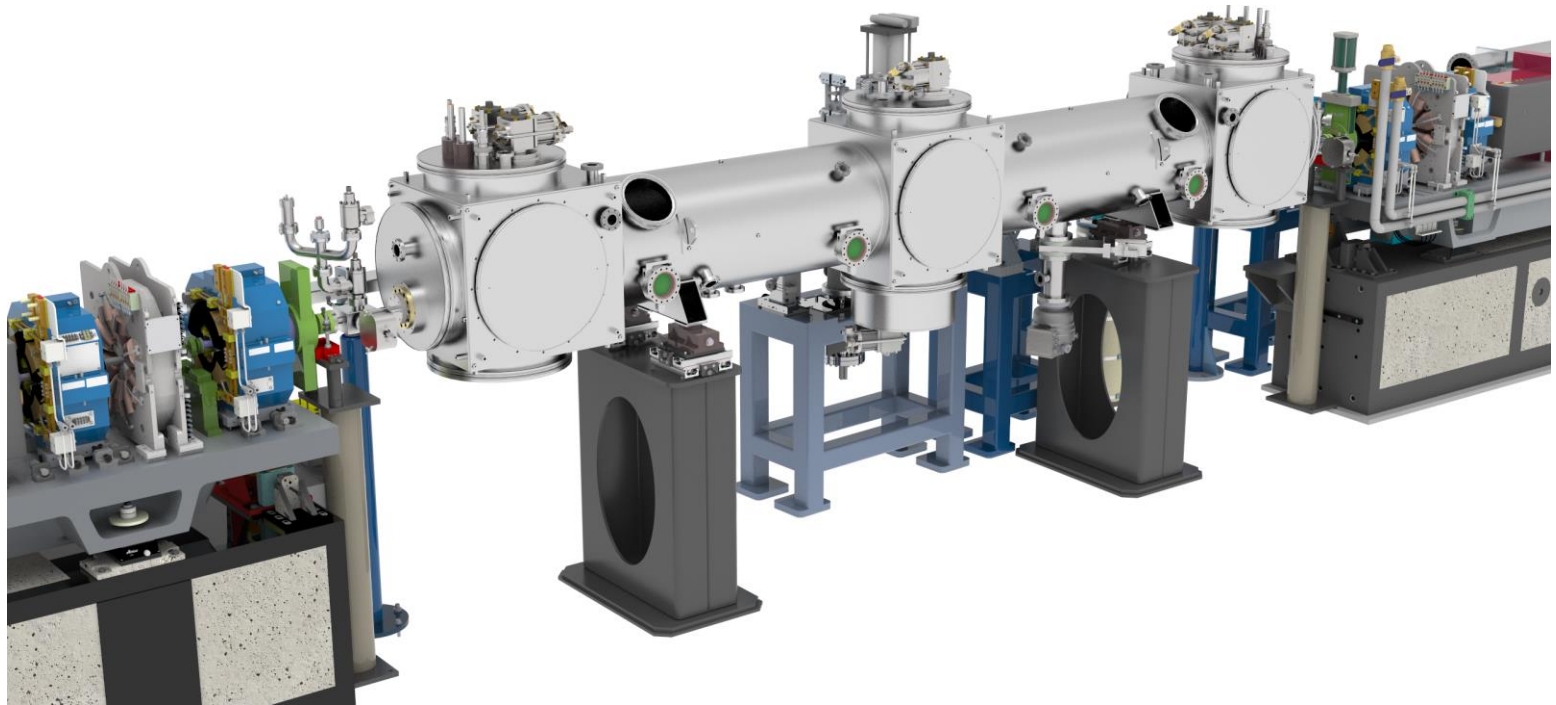
9/19

Cryostat fabrication & Assembly

4/21

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.

Thanks for attention