Superconducting Undulators -
Magnetic Performance and Universality

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on behalf of the SCU Team

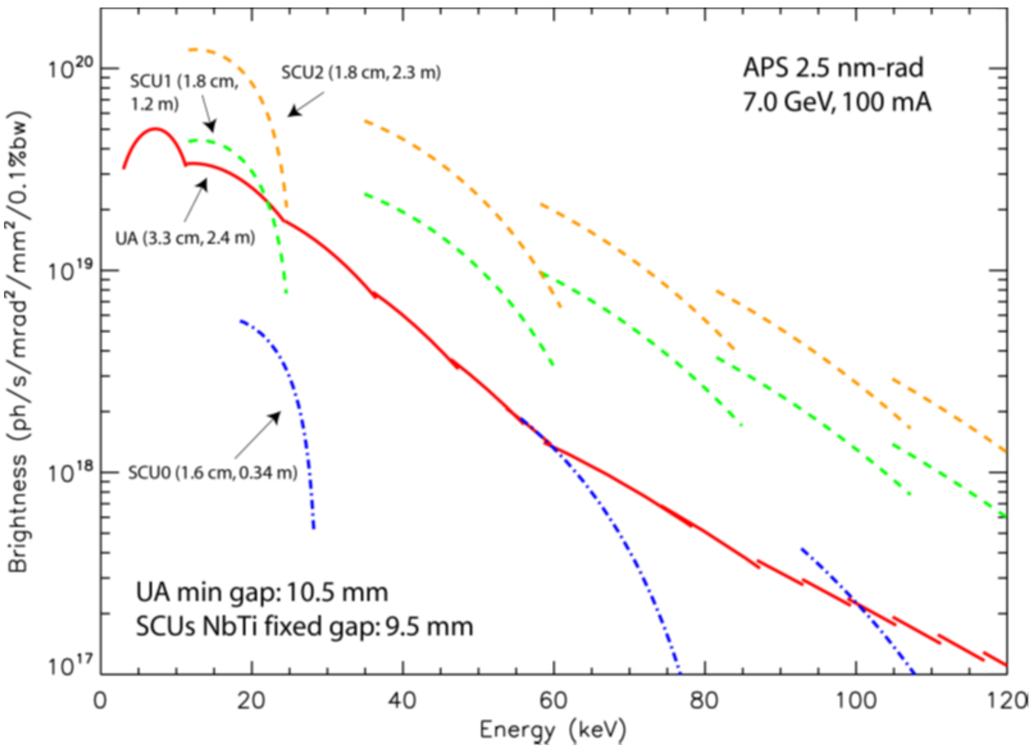
Scope

- Magnetic performance:
  - Specs achieved with 1.5-m long NbTi magnet

- SCU technology versatility:
  - Planar structure
  - Helical structure
  - Universal helical structure
  - Universal planar structure

Development of SCUs at APS

- **SCU0:**
  - 0.33-m long magnet
  - 16-mm period
  - In operation since January 2013
  - Will be replaced with SCU18-2
- **SCU1 (SCU18-1):**
  - 1.1-m magnet
  - 18-mm period length
  - In operation since May 2015
- **LCLS R&D SCU:**
  - 1.5-m magnet
  - 21-mm period length
  - Magnet met all the specs
  - Project complete in March 2016
- **SCU18-2:**
  - Assembly in progress
  - Installation in August-September 2016
- **Helical SCU:**
  - Magnet R&D in progress
  - New cryostat design in progress
  - Machine lattice study in progress



Calculated brightness of SCU1 compared to APS hybrid permanent magnet undulators.

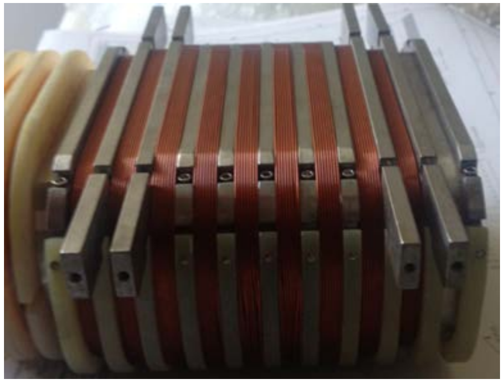
LCLS SCU R&D magnet

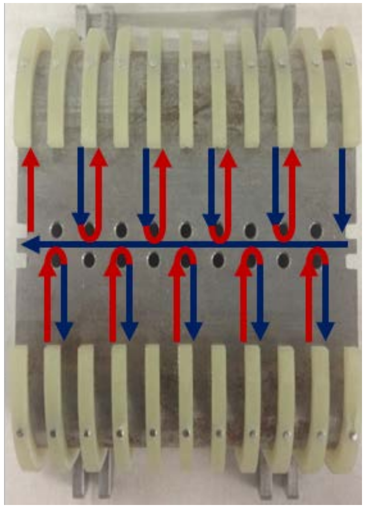
- SLAC-Berkeley-Argonne collaboration
- Argonne's responsibility:
  - Cryostat
  - NbTi magnet
- Berkeley's responsibility:
  - Nb_3Sn magnet

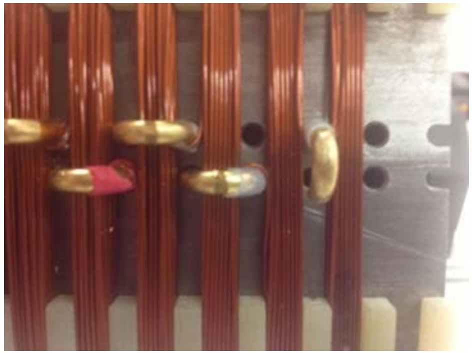
- NbTi Magnet:
  - Length: 1.5 m
  - Period length: 21 mm
  - Magnetic gap: 8.0 mm
  - Conductor: NbTi wire
- Specs:
  - On axis peak field: 1.67 T
  - Phase error: ≤ 5 deg rms

NbTi Magnet Winding

- SCU magnet consists of 2 jaws (cores) separated by magnetic gap
- Each core is a series of vertical racetrack coils wound into the core grooves
- Conductor: commercial NbTi 0.7-mm round wire
- Winding scheme: continuous winding with 180° turn after each 53-turn coil pack







NbTi Magnet Impregnation

- Each magnet core is epoxy impregnated
- Technique of vacuum impregnation in a mold is employed:
  - Place wound magnet core into the mold (Fig. 1)
  - Create rough vacuum in the mold
  - Prepare and pre-heat epoxy resin
  - Pre-heat the mold
  - Fill the mold with epoxy resin (Fig. 2)
  - Cure resin at about 120 C (Fig. 3)
  - Cooldown the mold with the core
  - Extract the core from the mold (Fig. 4)

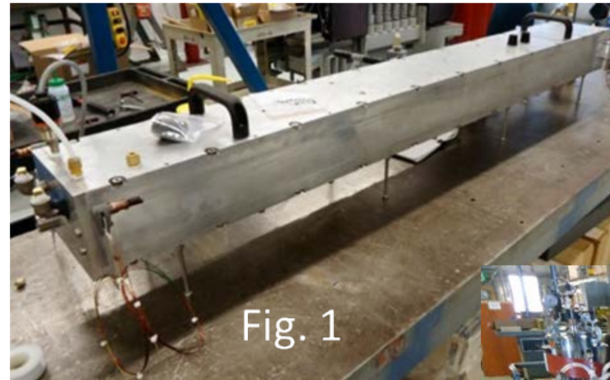


Fig. 1


Fig. 2

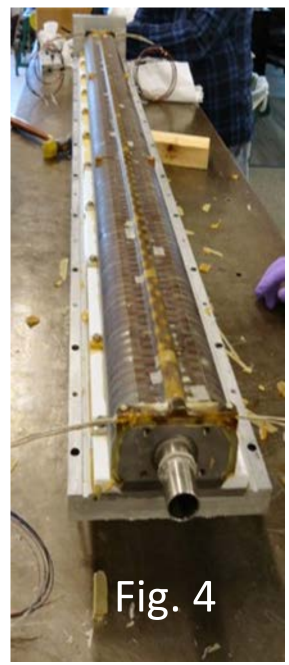
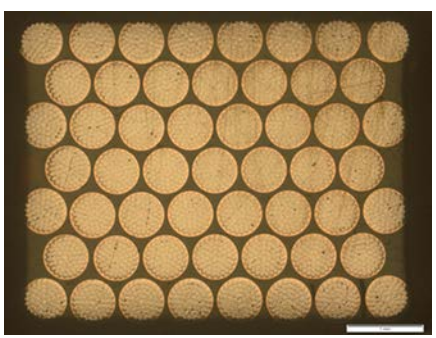


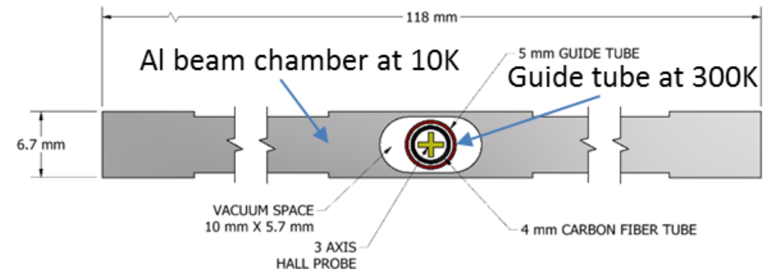
Fig. 4


Fig. 3



SCU Magnetic Measurement System

- Warm sensor concept:
  - 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 the room temperature
- Hall probe:
  - 3-axis commercial Hall sensor measures B_y, B_x, B_z components
  - Attached to fiber tube and driven by precise 3.5-m linear stage
  - B_z- 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



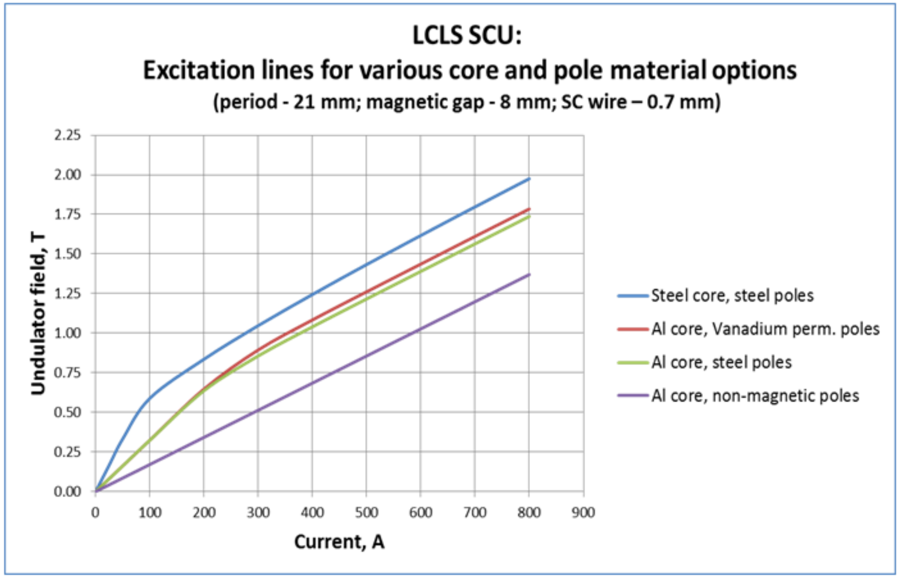
Warm-sensor concept

SCU horizontal measurement system

Magnetic Simulation

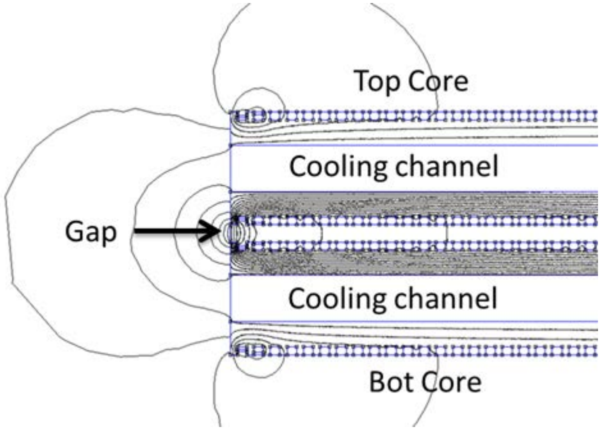
- Magnetic simulation was performed in Opera 3D (S. Kim), Radia 3D (Y. Ivanyushenkov) and FEMM 2D (M. Kasa)
- A useful field parametrization was worked out by Suk Kim:
  - Predicted field is 1.72 T at 80% of short sample I_c

Simulation in Radia



Steel core-steel poles configuration was chosen

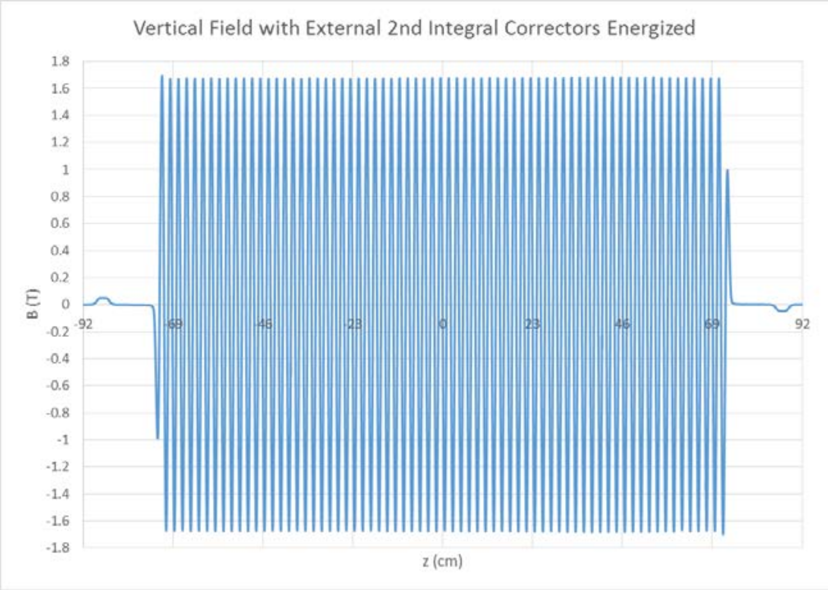
2D Model in FEMM



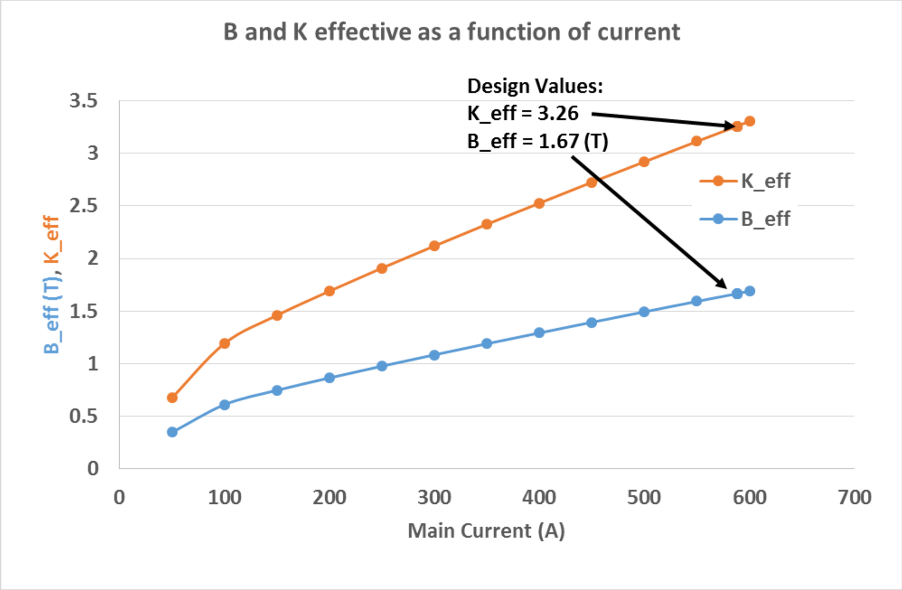
- FEMM predicts 1.67 T at 600 A
- Radia predicts 1.67 T at 620 A

Achieving Undulator Field

Measured field profile



Measured excitation curve



Achieved field

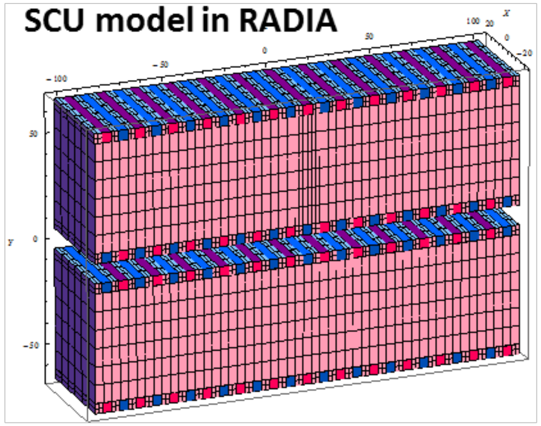
Parameter	Symbol	Design	Measured	Units
Nominal on-axis, peak field (at 80% short-sample limit)	$\lvert B_0 \rvert$	1.67	1.6657	T
Nominal peak undulator parameter (at 80% short-sample limit)	K_0	3.26	3.260	-
Nominal excitation current (at 80% short-sample limit)	I_0	~600	588	A

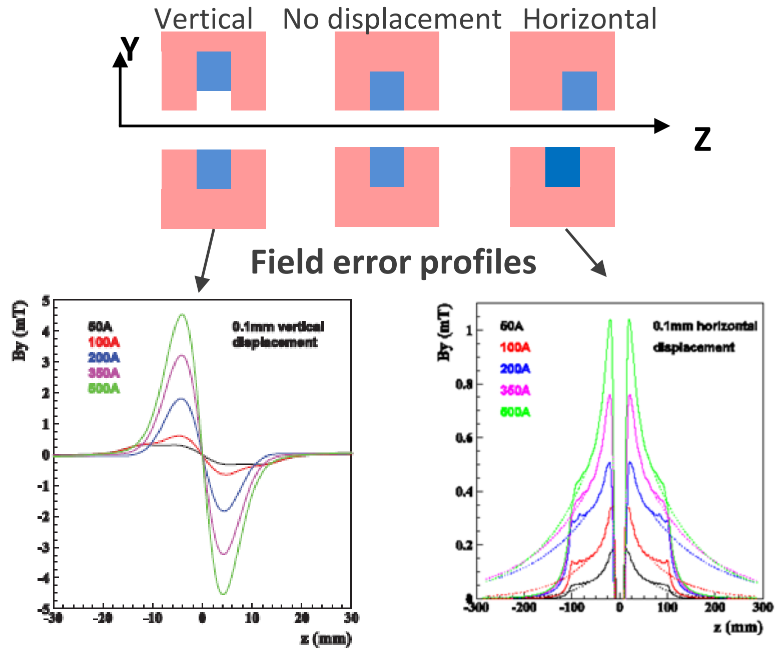
Winding Errors Analysis

- Phase errors due to winding errors
- Results of simulation [1];
- Vertical winding pack displacement has a local effect on the field while the horizontal displacement generates a long-range field error
- Phase error due to horizontal winding pack displacement is larger than the one due to vertical displacement
- Effect of random winding pack displacements on phase error scales as √Length

- Expected phase errors:
- 0.33-m long SCU0 magnet:
  measured 1-2 deg rms (at 200-500 A)
- 1.5-m long LCLS-II prototype magnet:
  estimated 4-5 deg rms when cores are manufactured with the precision better than 50 µm.

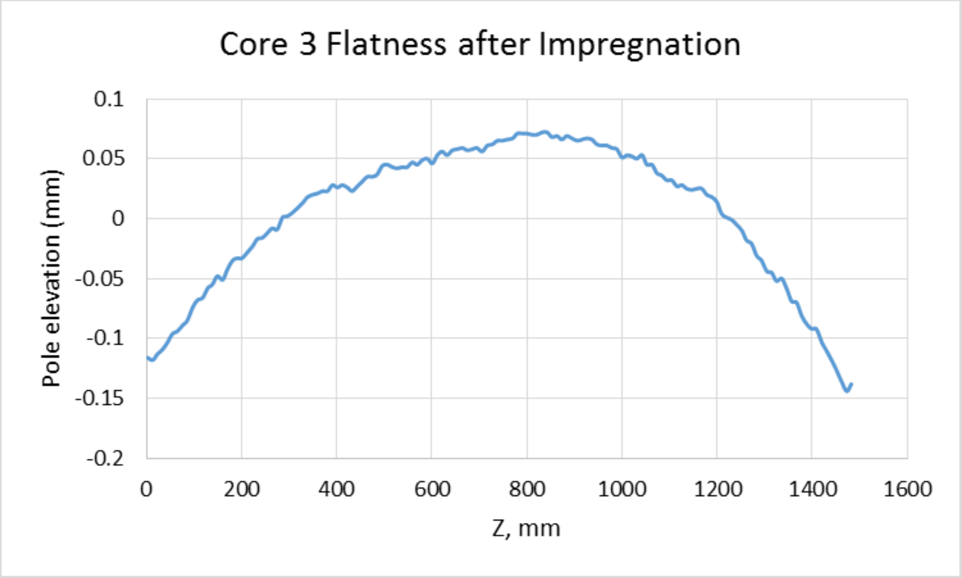
[1] J. Bahrdt and Y. Ivanyushenkov, MOPP065, Proc. of IPAC2012.





Achieved Precision

- Cores machined to high precision
- Resin impregnation process causes cores to bow
- Gap correction is therefore required



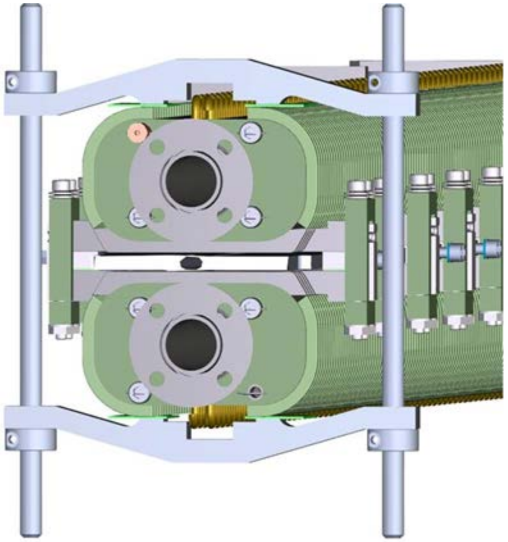
Core flatness after machining

	Core 1	Core 2	Core 3
Elevation AVERAGE (mm)	-0.010	-0.015	-0.001
Elevation RMS (mm)	0.009	0.008	0.008
Elevation MAX (mm)	0.008	0.008	0.008
Elevation MIN (mm)	-0.025	-0.025	-0.010
MAX – MIN (mm)	0.033	0.033	0.018

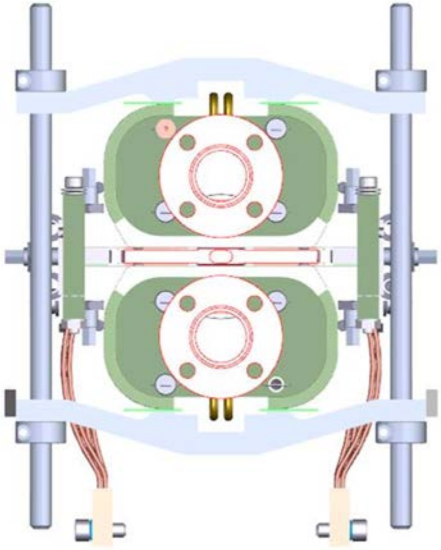
Core groove dimensions after machining

	Core 1	Core 2	Core 3
Half period AVERAGE (mm)	10.500	10.500	10.500
Half period RMS (mm)	0.007	0.008	0.006
Half period MIN (mm)	10.483	10.483	10.483
Half period MAX (mm)	10.516	10.513	10.513
MAX-MIN (mm)	0.033	0.030	0.030
Groove width AVERAGE (mm)	6.118	6.118	6.117
Groove width RMS (mm)	0.012	0.012	0.011
Groove width MIN (mm)	6.101	6.086	6.086
Groove width MAX (mm)	6.152	6.137	6.152
MAX-MIN (mm)	0.051	0.051	0.066
Groove depth AVERAGE (mm)	4.894	4.900	4.898
Groove depth RMS (mm)	0.009	0.018	0.008
Groove depth MIN (mm)	4.869	4.735	4.887
Groove depth MAX (mm)	4.905	4.920	4.920
MAX-MIN (mm)	0.036	0.185	0.033

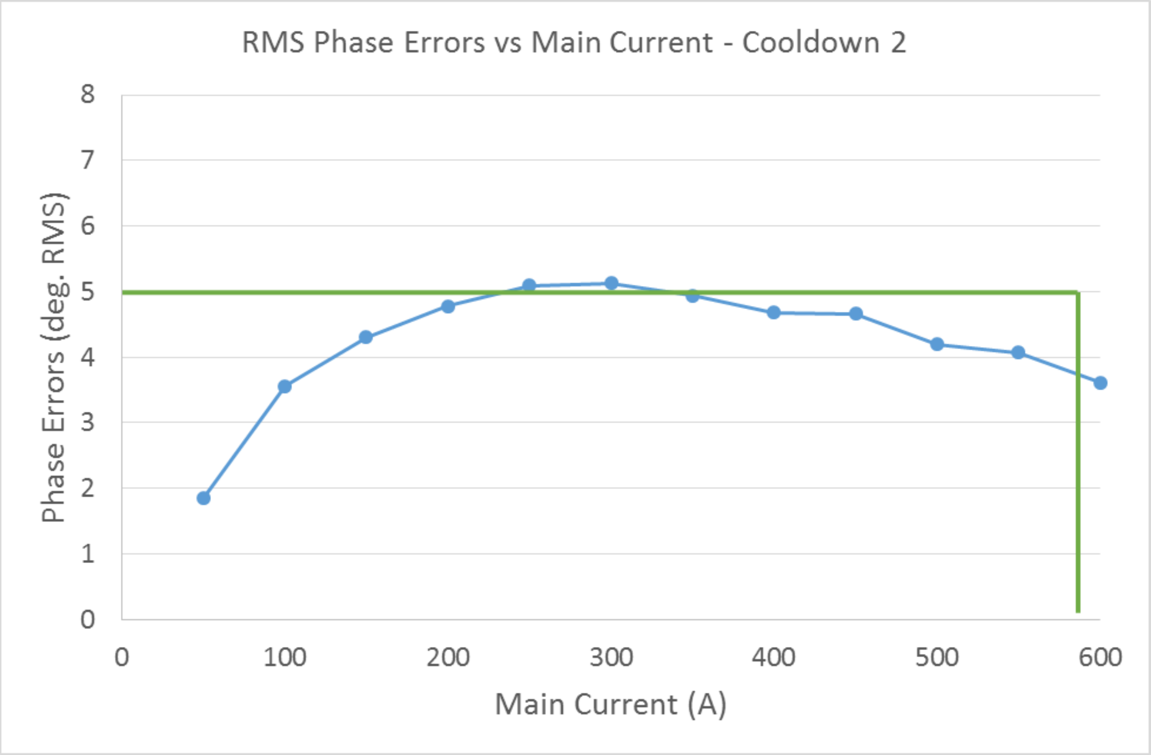
Magnetic Gap Correction



- Mechanical correction of the gap:
  - A system of clamps to compress the cores
  - A clamp in the middle to adjust vertical position of the gap
  - Gap is defined by the precise spacers
- Clamps were added in situ sequentially - partial disassembly of the cryostat and 3 cool downs
- For future implementation - complete clamping system requires a clamp in each spacer position



Measured Phase Errors

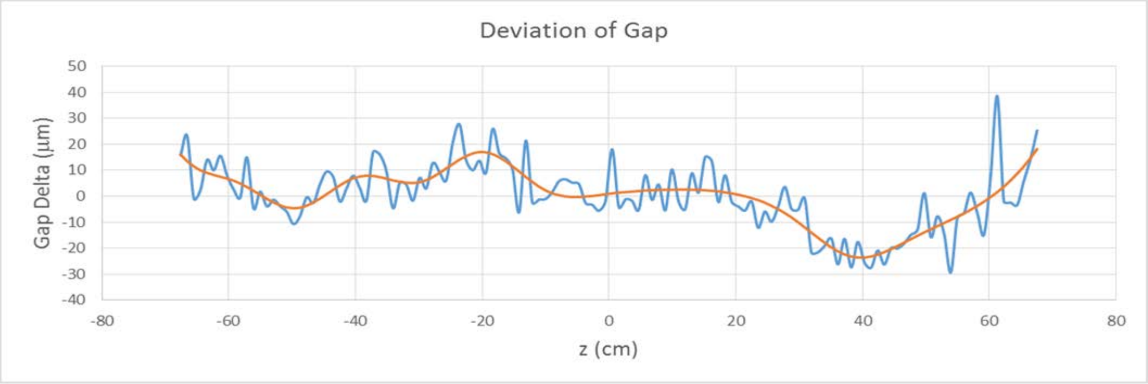


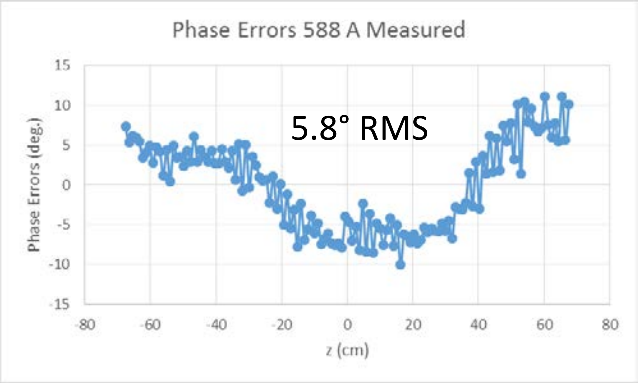
Parameter	Symbol	Design	Measured	Units
Phase shake error over undulator (rms)	Δj_{rms}	5	3.8±0.3	deg

The most challenging tolerance is achieved without magnetic 'shimming' !

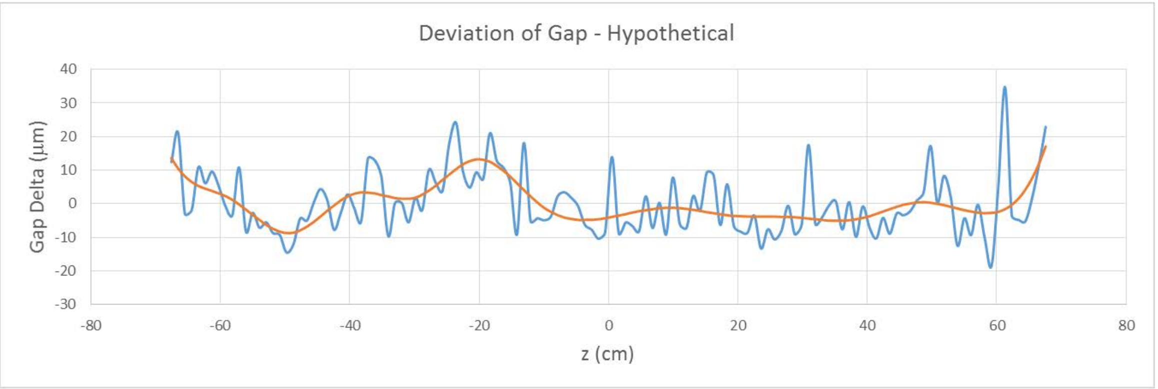
Phase Errors can be Further Improved

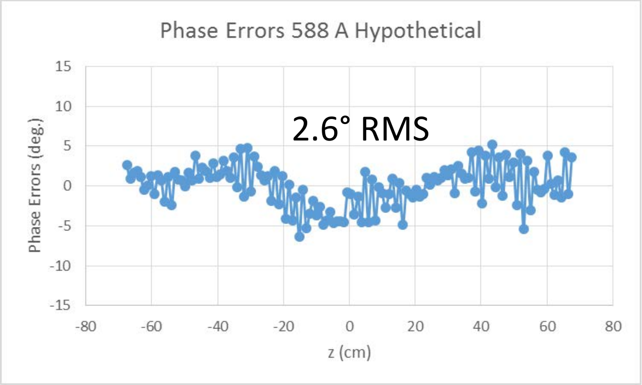
Measured gap and corresponding phase errors.



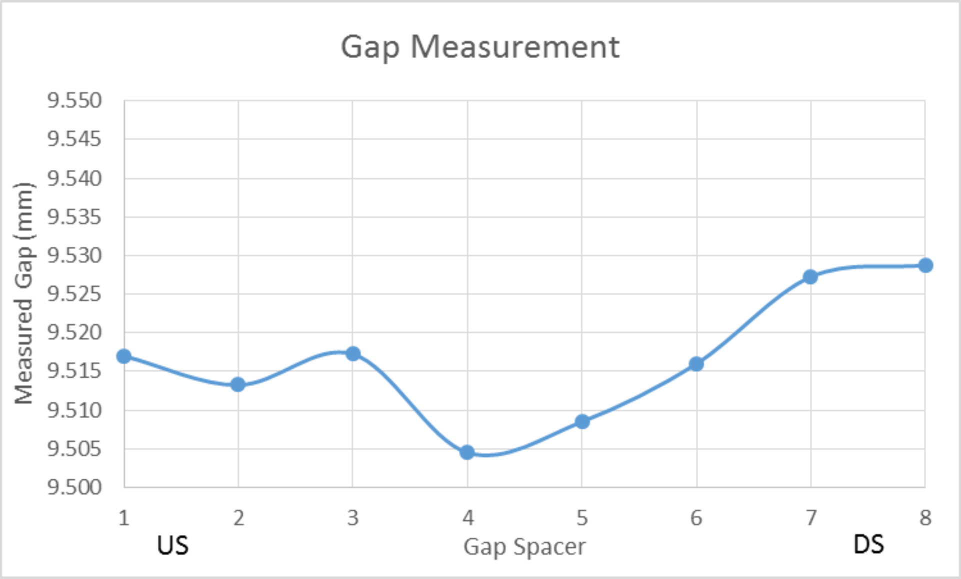


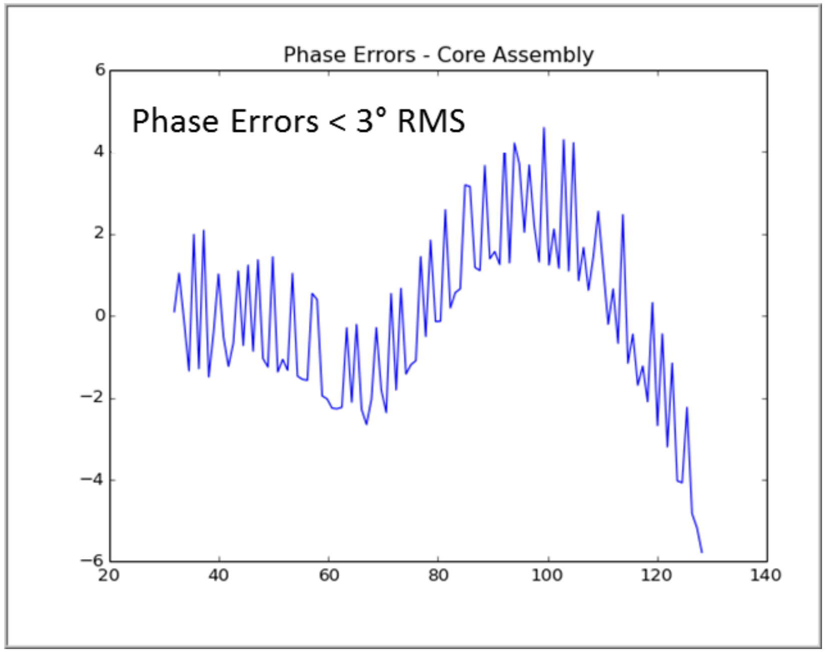
Corrected the largest gap error in software by scaling the field in the region between 30 cm and 60 cm.





Expected Phase Errors in SCU18-2

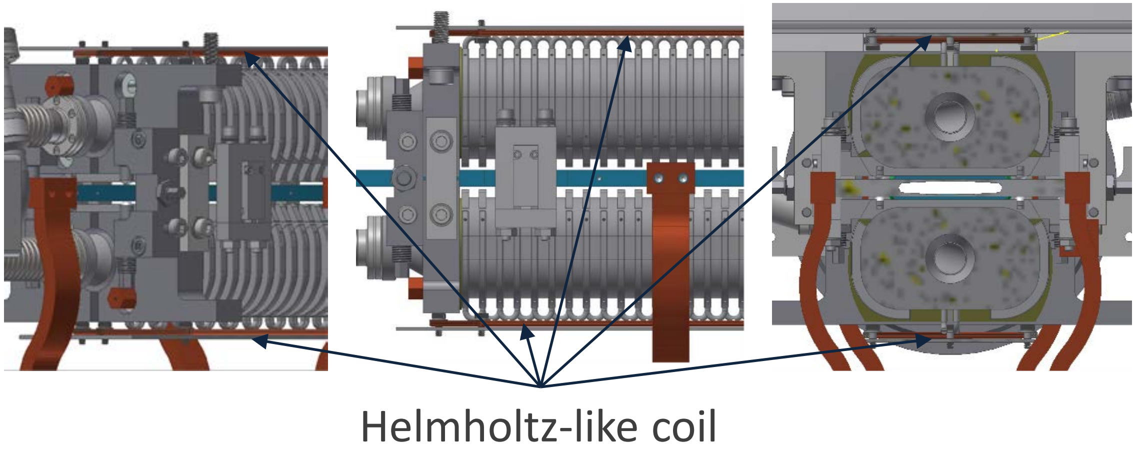


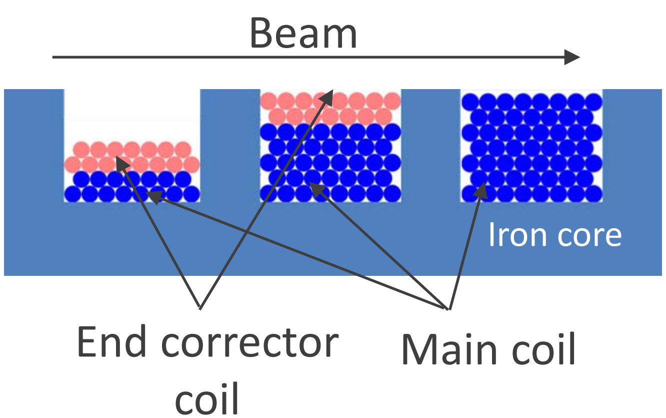


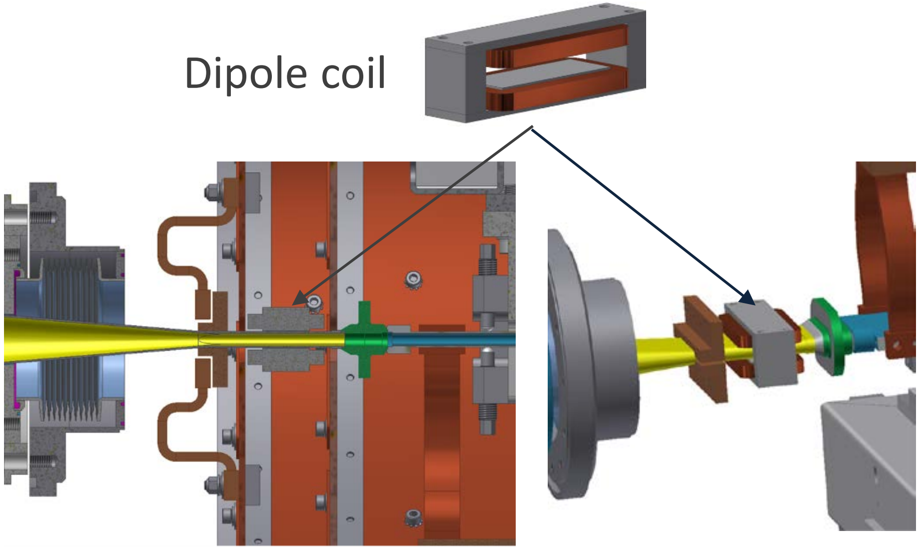
Phase errors determined by applying measured gap dimensions to a simulated undulator field of 1T.

Field Integral Correction

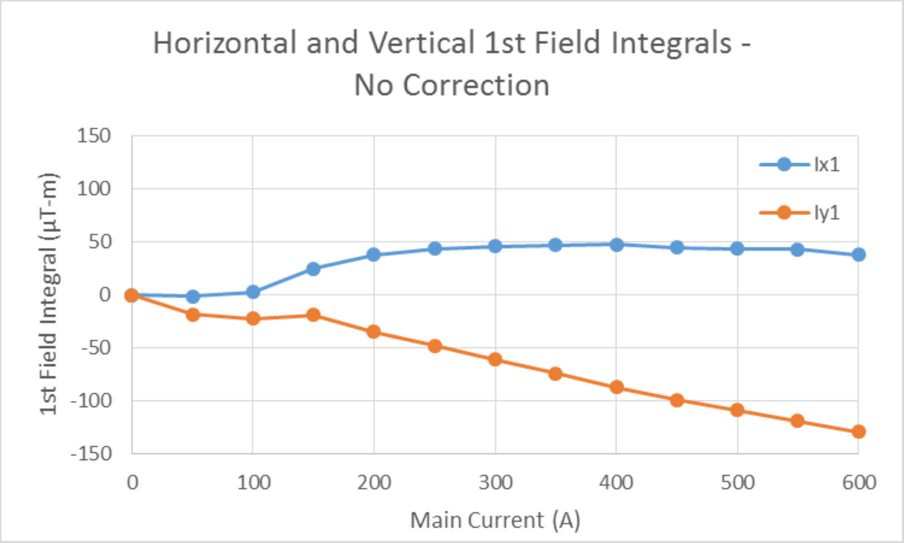
- 1st field integral is corrected with Helmholtz-like coil
- 2nd field integral is corrected with end corrector coils and with a pair of external dipole coils.

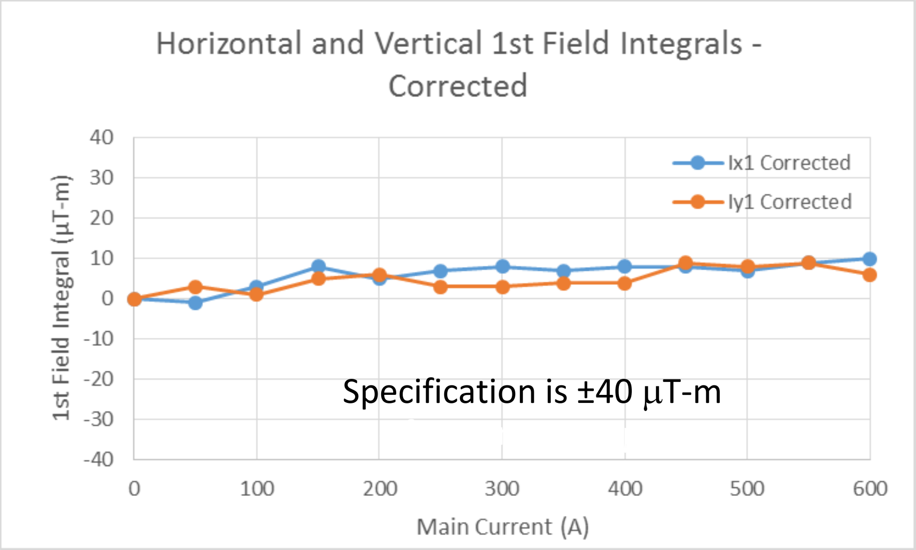






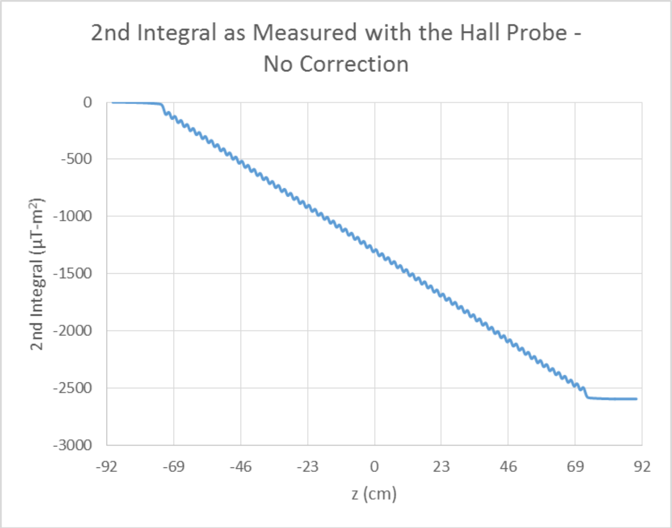
1^{st} Integral Correction

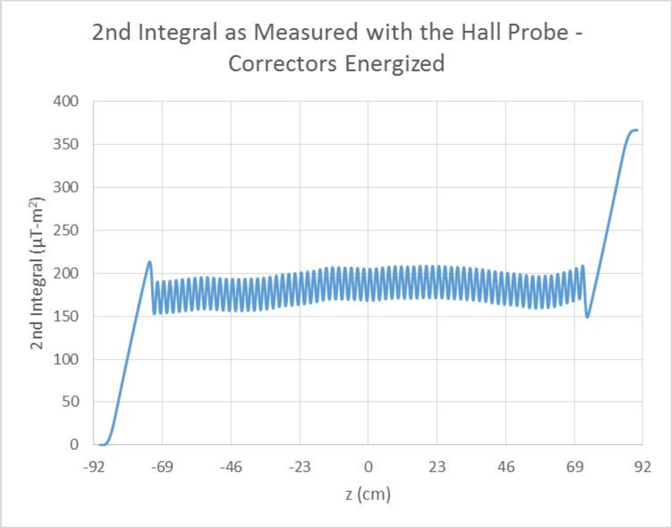


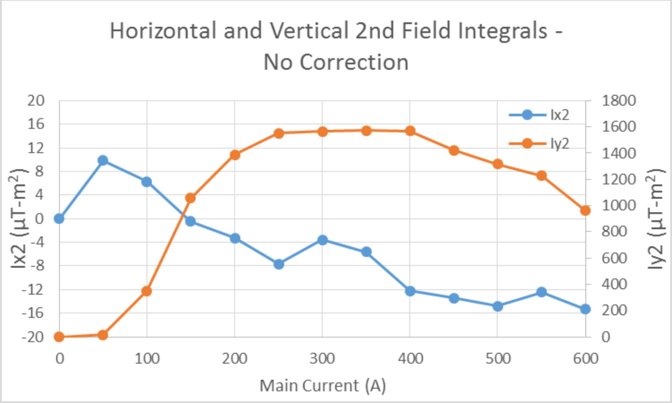


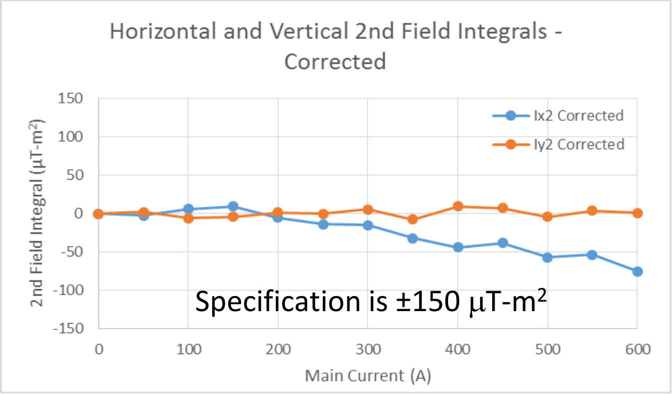
Parameter	Symbol	Design	Measured	Units
Max. 1^{st} field integral (x and y)	$I_{1x,y}$	±40	I_{1x} = 10 ±3 I_{1y} = 10 ±3	µT-m

2^{nd} Integral Correction









Parameter	Symbol	Design	Measured	Units
Max. 2^{nd} field integral (x and y)	$I_{2x,y}$	±150	I_{2x} = 75 ±10 I_{2y} = 10 ±10	$\mu T\text{-}m^2$

Y.Ivanyushenkov, "Superconducting Undulators-Magnetic Performance and Universality", April 20, 2016

NbTi Magnet Performance

Table 1: Main design parameters of the NbTi undulator.

Parameter	Symbol	Design	Measured	Units
Undulator period (at 300 K)	l_u	21	21	mm
Undulator length (approx. magnetic)	L_u	1.5	1.5	m
Full-height magnetic gap	g_m	8.0	8.0	mm
Full-height vacuum chamber stay-clear gap	g_v	5.7	5.7	mm
Nominal on-axis, peak field (at 80% short-sample limit)	$\|B_0\|$	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

Table 2: Tolerances and quality of the NbTi undulator magnet.

Parameter	Symbol	Design	Measured	Units
Measurement resolution of mean K (rms)	$\langle \Delta K/K \rangle_{rms}$	0.02	0.008	%
Reproducibility of mean K (after on/off)	$\langle \Delta K/K \rangle_{err}$	±0.03	0.008	%
Phase shake error over undulator (rms)	Δj_{rms}	5	3.8±0.3	deg
Max. field roll-off over pole width	$\|\Delta K/K\|$ @ $\Delta x = \pm 0.4$ mm	0.05	0.02	%
Max. 1st field integral (x and y)	$I_{1x,y}$	±40	I_{1x} = 10 ±3 I_{1y} = 10 ±3	µT-m
Max. 2nd field integral (x and y)	$I_{2x,y}$	±150	I_{2x} = 75 ±10 I_{2y} = 10 ±10	µT-m^2

All tolerances and specifications are met.

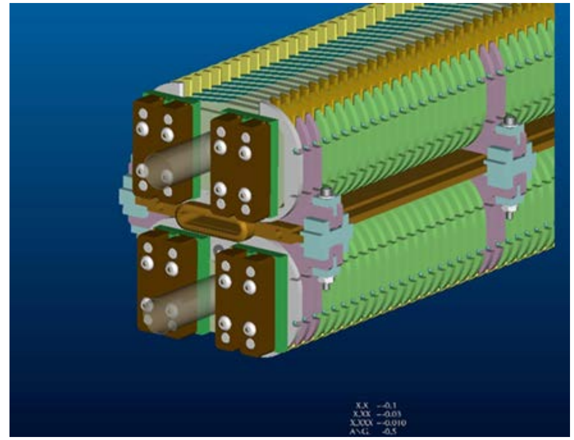
Magnetic Performance - Summary

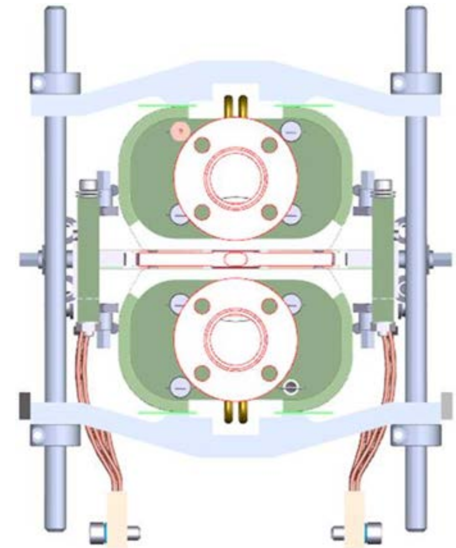
- 1.5-m long NbTi magnet was built and tested in the 2-m cryostat
- Performance of the magnet was measured with SCU magnetic measurement system
- The NbTi magnet achieved all the specs
- Superconducting undulator magnet is able to deliver high quality field without any magnetic shimming !

SCU Technology Versatility

Planar SCUs

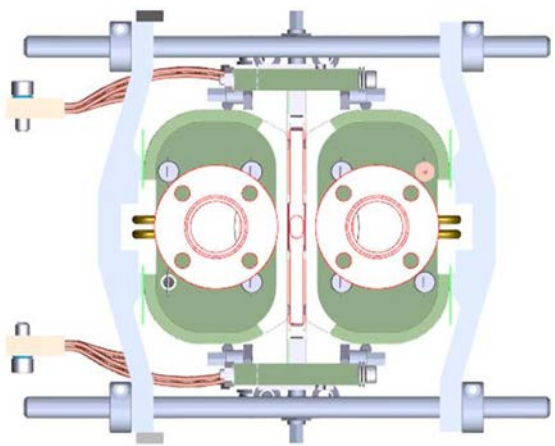
- Planar SCU:
  - Magnetic forces are reacted by spacers
  - Two jaws with clamps and spacer form a rigid structure
  - All structure can be rotated by 90 deg

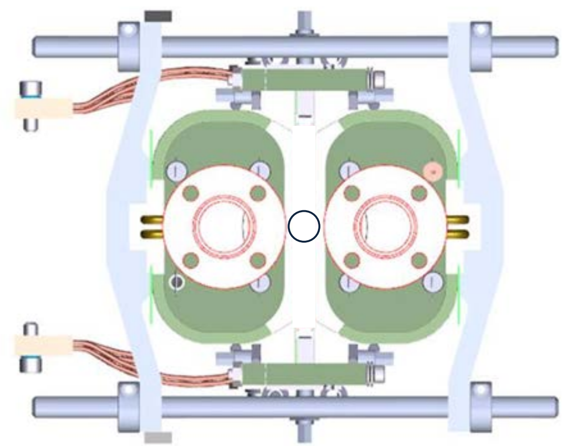




- Planar SCUs:

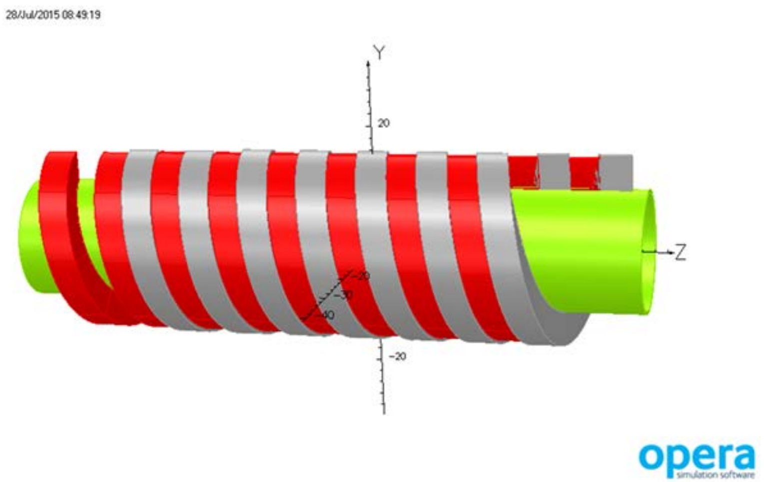
Both vertical field orientation (horizontal polarization) and horizontal field orientation (vertical polarization) is possible





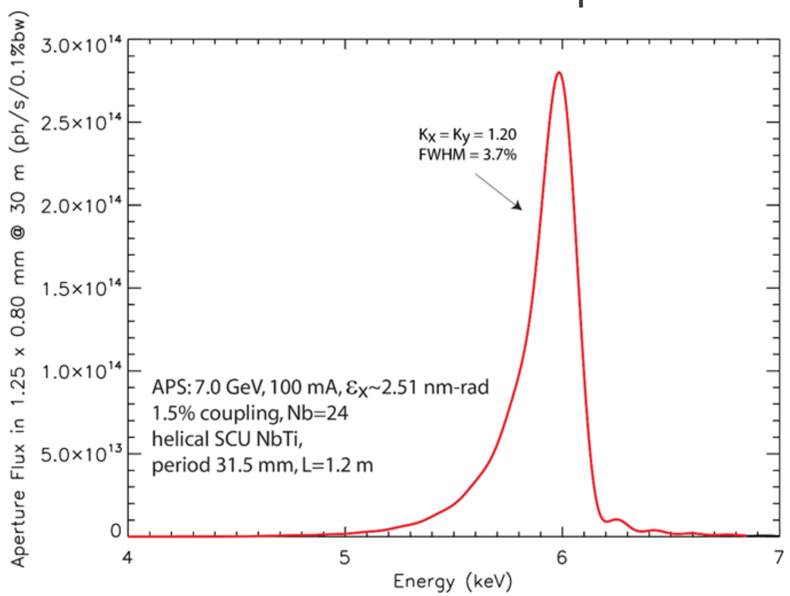
Helical SCUs

- Helical SCU:
  - Double helical winding
  - Helical magnetic field
  - Single harmonic on axis



- Helical SCUs are possible

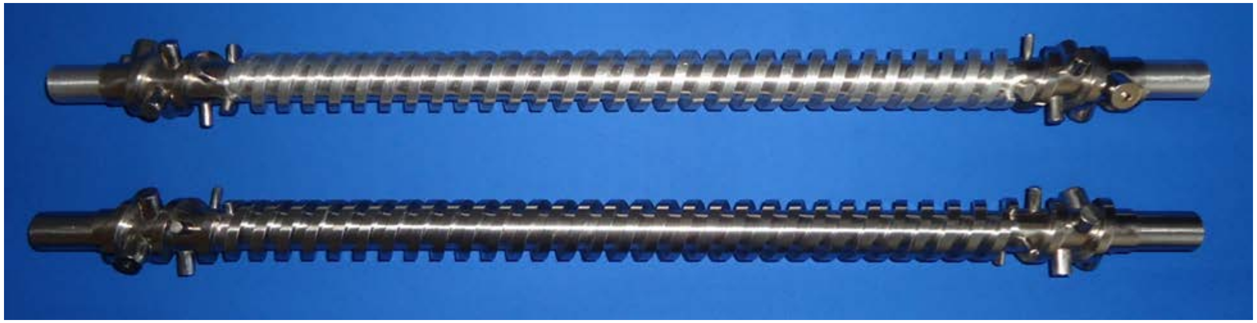
Helical SCU Radiation Spectrum

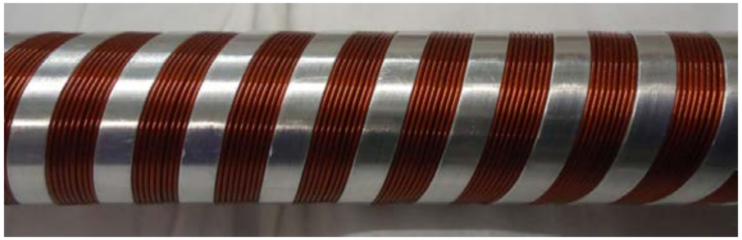


APS HSCU parameters

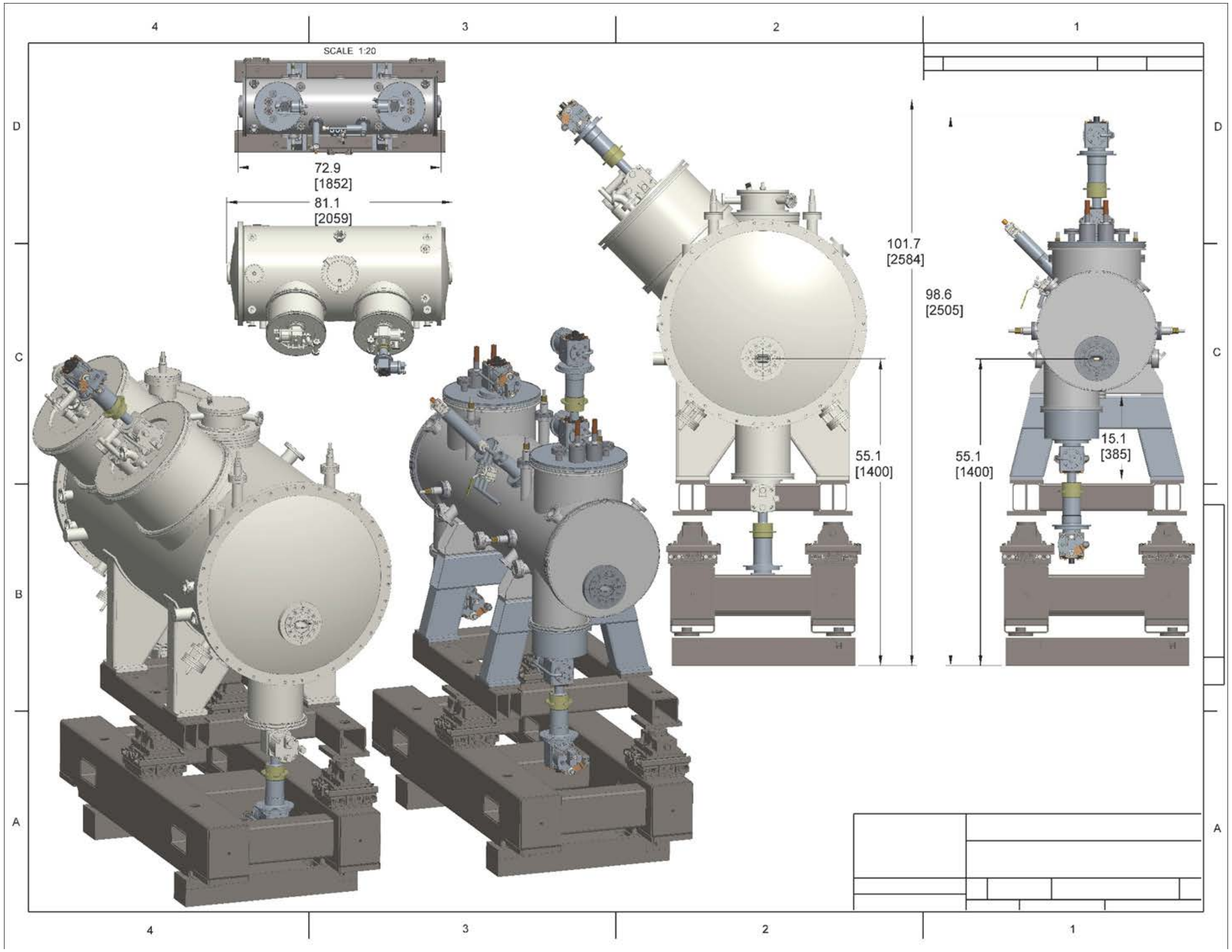
- APS sector: 7
- Photon energy range: 6-12 keV
  - Desirable FWHM: ≤ 3%
- Period length: 31.5 mm
- Magnetic length: ≈1.2 m
- Beam stay clear: 7 mm vertical, 26 mm horizontal
- Winding bore diameter: 31 mm
- Conductor: NbTi
- Field on axis: 0.41 T

HSCU Magnet R&D





HSCU Cryostat vs. SCU0/SCU1 Cryostat

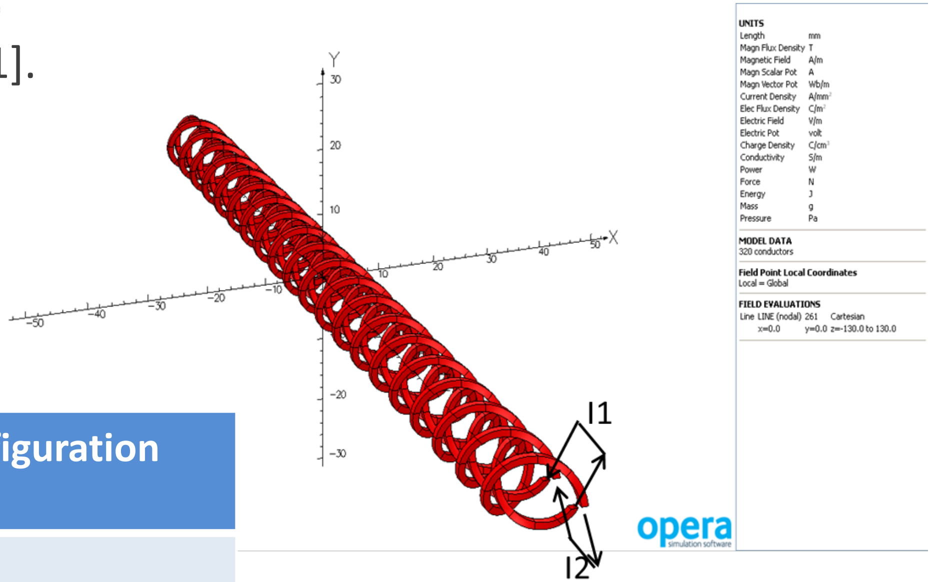


SCU0/SCU1 cryostat,
designed by V. Syrovatin, BINP

HSCU cryostat,
designed by J. Fuerst, APS

Universal Helical SCU

Universal SCU concept is based on old idea [1].
It requires one helical SCU structure to be inserted into the other with the opposite helicity.
Such a device can generate both planar and vertical fields.



Inner Coil Current	Outer Coil Current	Field Configuration
+ I_1	0	Helical
0	+ I_2	Helical (opposite helicity)
+ I_1	+ I_2	Vertical
- I_1	+ I_2	Horizontal

[1] D. Alferov, Yu. Bashamkov, and E. Bessonov "Generation of circularly polarized electromagnetic radiation," Zh. Tekh. Fiz **46**, 2392-2397, November 1976.

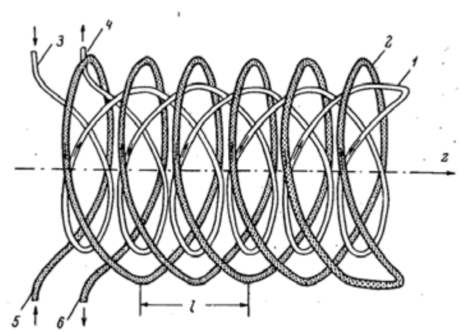
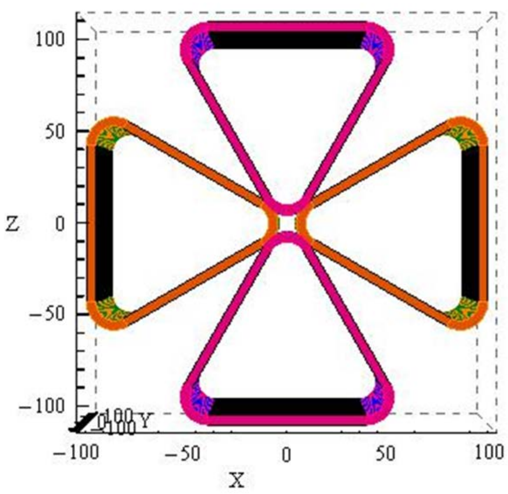
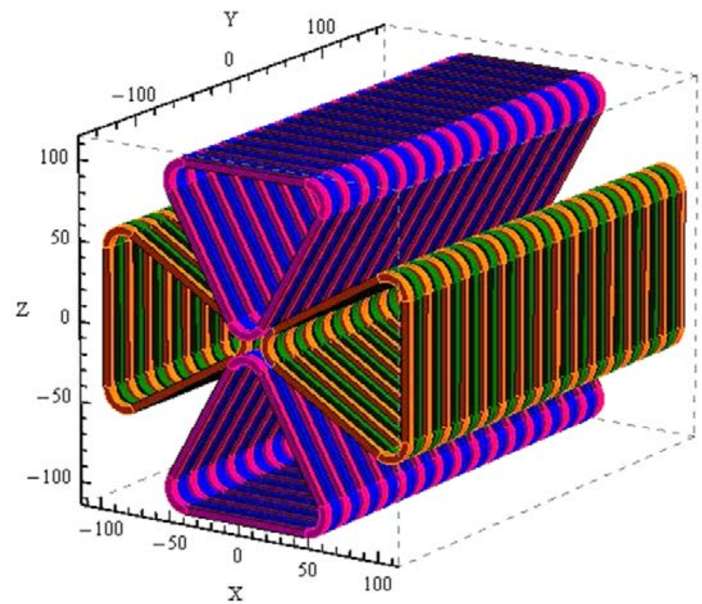


FIG. 2. Schematic diagram of a helical undulator.

Universal Planar SCU

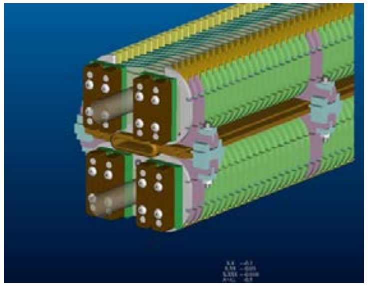
- New idea by Efim Gluskin.
- Magnetic structure consists of two pairs of planar-like jaws.
- Can generate both planar and helical fields (confirmed by simulation).



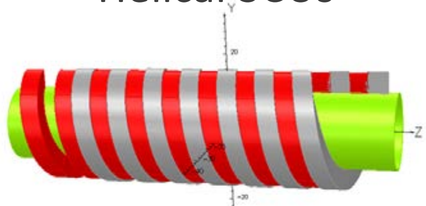


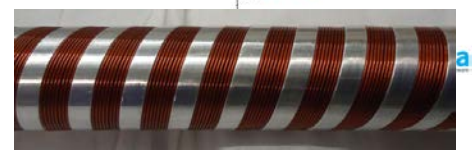
SCU Technology Versatility - Summary

Planar SCUs



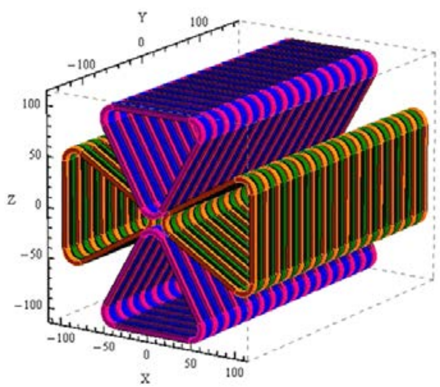
Helical SCUs



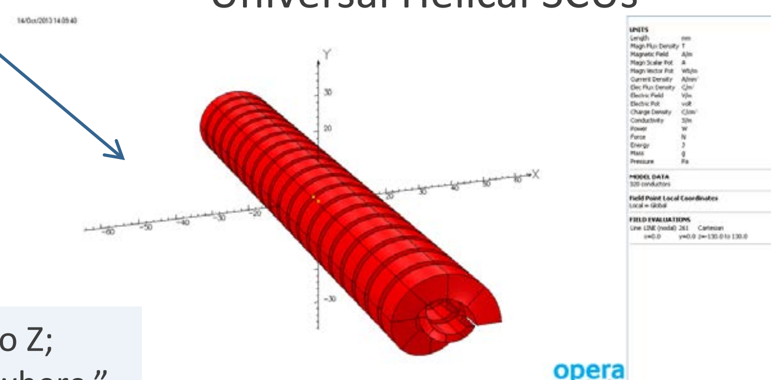


SCU Technology

Universal Planar SCUs



Universal Helical SCUs



"Logic will get you from A to Z;
imagination will get you everywhere."
Albert Einstein

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