Development Status of a Superconducting Undulator for APS

Yury Ivanyushenkov

on behalf of

the APS Superconducting Undulator Project Team

Workshop on Superconducting undulators, APS, September 20-21, 2010

Superconducting undulator project team

APS:

- Melike Abliz
- Kurt Boerste
- Tom Buffington
- Dana Capatina
- Jeff Collins
- Roger Dejus
- Chuck Doose
- Joel Fuerst
- Quentin Hasse
- Yury Ivanyushenkov
- Mark Jaski
- Matt Kasa
- Suk Kim
- Bob Kustom
- Liz Moog
- Denise Skiadopoulos
- Emil Trakhtenberg
- Isaac Vasserman
- Joseph Xu
- Marion White

Visitors from

Budker Institute, Russia:

- Nikolay Mezentsev
- Vasily Syrovatin
- Valeriy Tsukanov
- Vladimir Lev

Collaborators:

- Sasha Makarov,
  FNAL
- John Pfotenhauer,
  Daniel Potratz
  University of Wisconsin-Madison

Scope

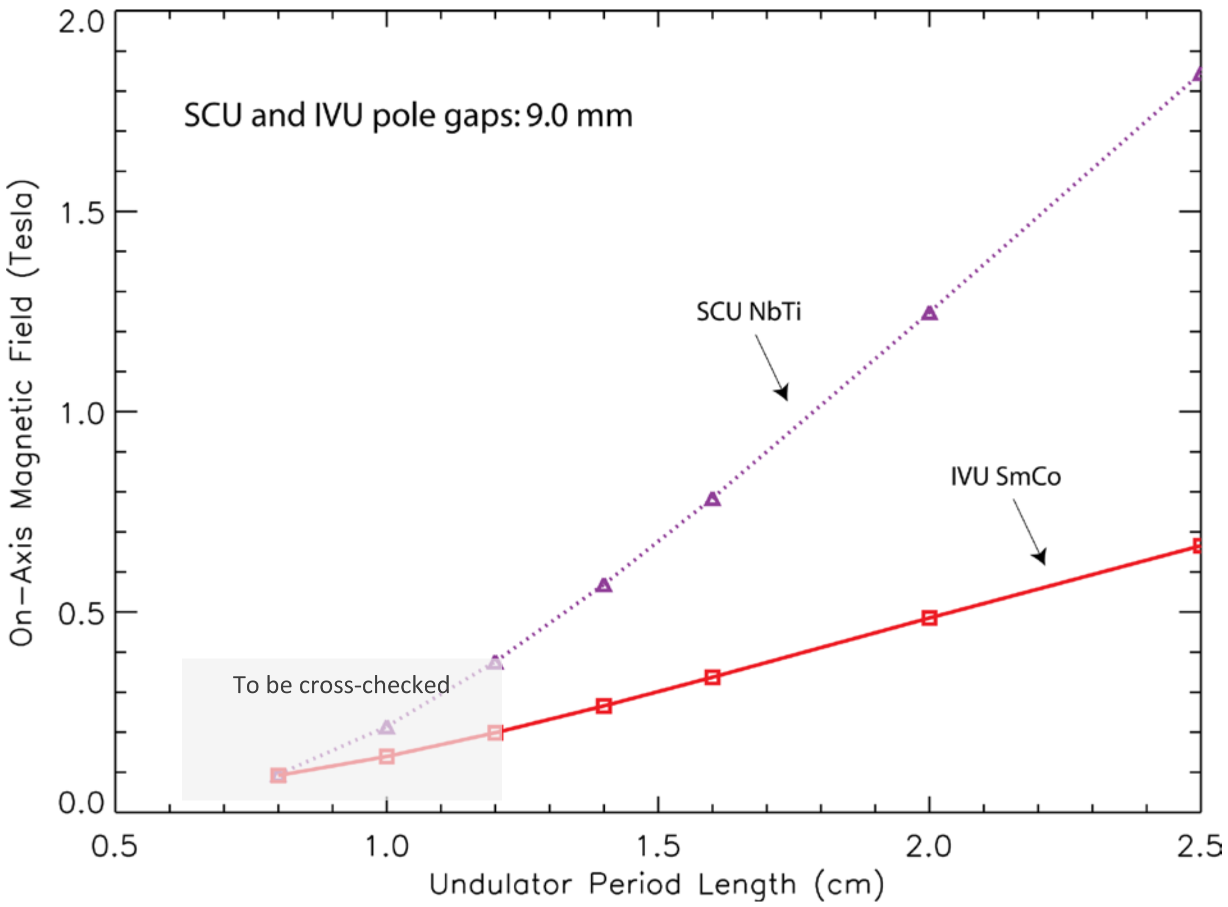
- Why a superconducting technology-based undulator ?
- Results of R&D program on superconducting undulator (SCU) for the APS
- Superconducting undulators in the APS upgrade program
- The first two superconducting undulators (SCU0 and SCU1)
- SCU cooling system concept
- SCU0 cryomodule details
- Development of SCU measurement facility
- Status of the SCU0
- Conclusions

Why a superconducting technology-based undulator ?

- A superconducting undulator is an electromagnetic undulator that employs high-current superconducting windings for magnetic field generation -
    - total current in winding block is up to 10-20 kA -> high peak field
    - poles made of magnetic material enhance field further -> coil-pole structure (“super-ferric” undulator)
- Superconducting technology compared to conventional pure permanent magnet or hybrid IDs offers:
    - **higher peak field for the same period length**
    - **or smaller period for the same peak field**

- Superconducting technology-based undulators outperform all other technologies in terms of peak field and, hence, energy tunability of the radiation.
- Superconducting technology opens a new avenue for IDs.

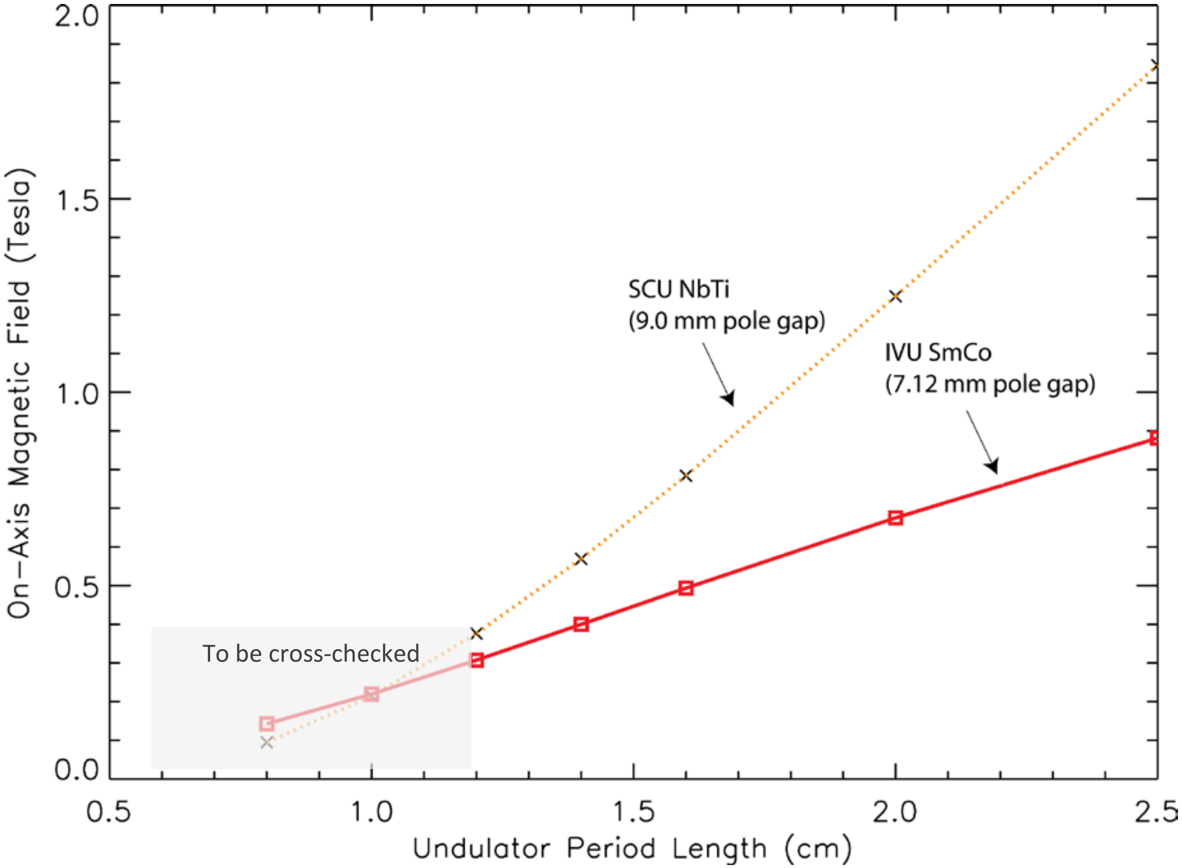
Peak Fields of Various ID Technologies



- Comparison of the magnetic fields in the undulator midplane for an in-vacuum SmCo undulator and a NbTi superconducting undulator versus the undulator period length at 9.0 mm pole gap.
- At 1.6 cm period length the fields are 0.34 Tesla (IVU) and 0.78 Tesla (SCU) – more than 2 times higher than that of the IVU.

Y. Ivanyushenkov, Workshop on superconducting undulators, APS, September 20-21, 2010

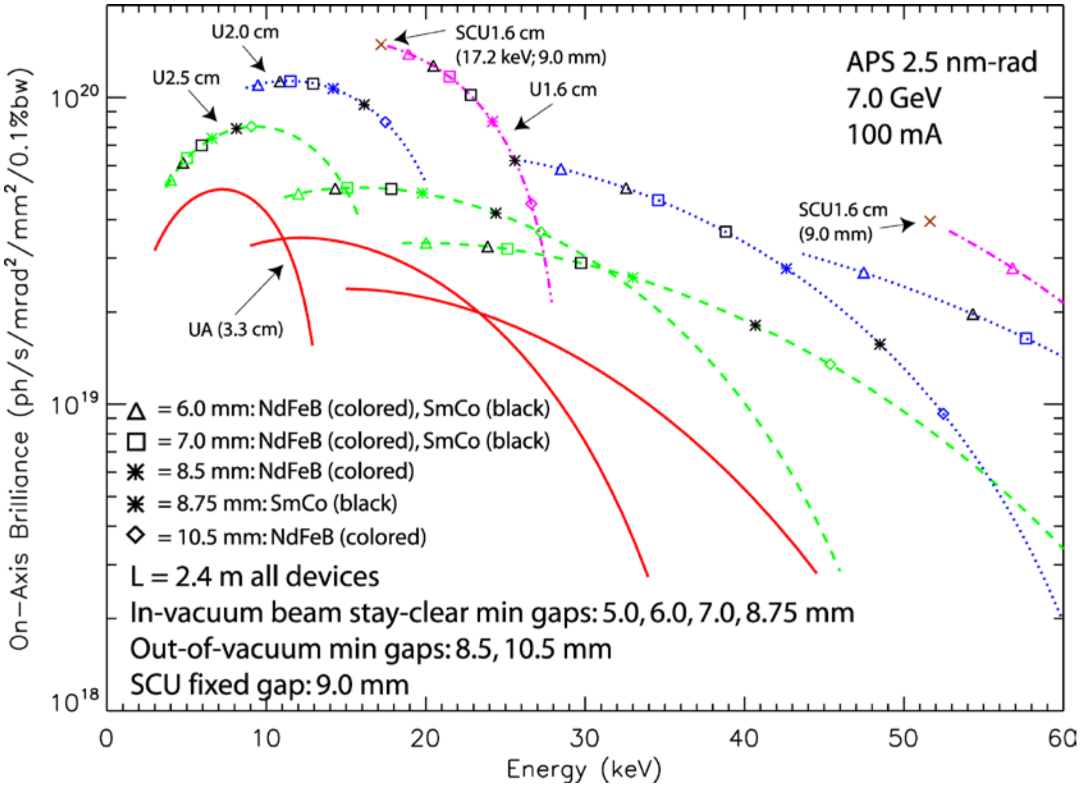
Peak Fields of Various ID Technologies (2)



- Comparison of the magnetic fields in the undulator midplane for a SmCo in-vacuum undulator (IVU) and a NbTi superconducting undulator (SCU) versus the undulator period length at 7.0 mm beam stay-clear gap.
- At 1.6 cm period length the fields are 0.49 Tesla (IVU) and 0.78 Tesla (SCU) – about 1.6 times higher than that of the IVU.
- The impact on the reachable minimum first harmonic energy is large: 17.3 keV (SCU) vs. 22.9 keV (IVU).

Y. Ivanyushenkov, Workshop on superconducting undulators, APS, September 20-21, 2010

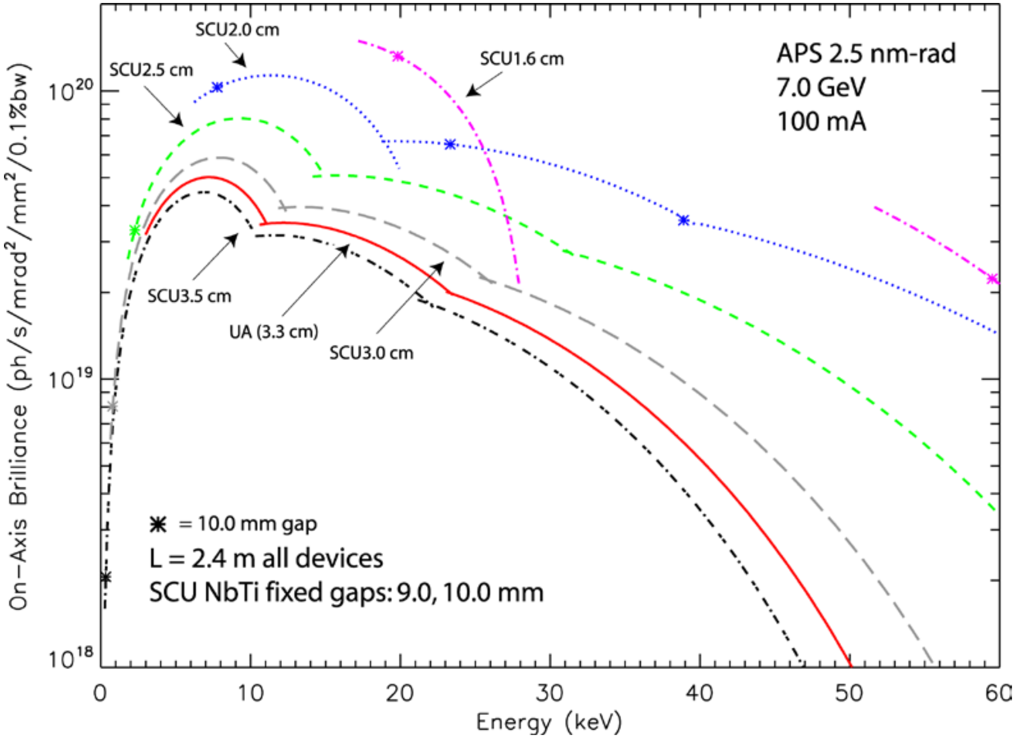
Tuning curves for various IDs



On-axis brilliance tuning curves for three in-vacuum undulators (1.6-cm, 2.0-cm, and 2.5-cm periods, each 2.4-m long) compared to undulator A for harmonics 1, 3, and 5 in linear horizontal polarization mode for 7.0-GeV beam energy and 100-mA beam current. The minimum reachable harmonic energies were calculated assuming SmCo magnets and a 5.0-mm beam stay-clear gap. The current design values for the superconducting undulator (SCU) at 9.0-mm pole gap have been marked separately by the two Xs. The SCU at the first harmonic energy of 17.2 keV nearly overlaps with the SmCo undulator at 5.0 mm gap. Ideal magnetic fields were assumed.

R. Dejus, M. Jaski, and S.H. Kim, “On-Axis Brilliance and Power of In-Vacuum Undulators for The Advanced Photon Source,” MD-TN-2009-004

Brilliance tuning curves for superconducting IDs

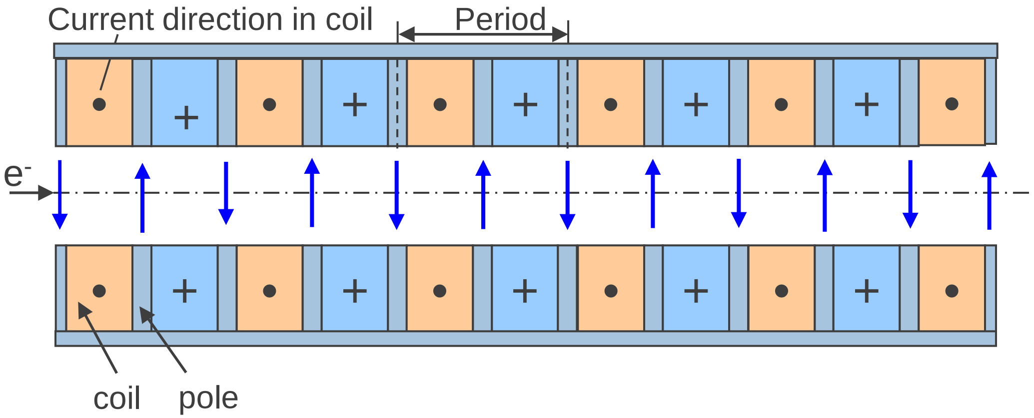


On-axis brilliance tuning curves with the overlaps between harmonics removed for five superconducting undulators (1.6-cm, 2.0-cm, 2.5-cm, 3.0-cm, and 3.5-cm periods, each 2.4-m long) compared to undulator A for harmonics 1, 3, and 5 in linear horizontal polarization mode for 7.0-GeV beam energy and 100-mA beam current. The minimum reachable harmonic energies were calculated assuming a 9.0 mm magnetic pole gap. The markers (*) indicate the beginning of each harmonic tuning curve for 10.0-mm pole gap. Ideal magnetic fields were assumed.

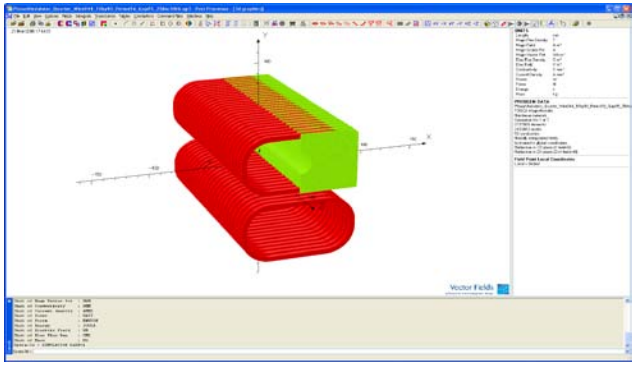
R. Dejus, M. Jaski, and S.H. Kim, "On-Axis Brilliance and Power of In-Vacuum Undulators for The Advanced Photon Source," MD-TN-2009-004

Superconducting planar undulator topology

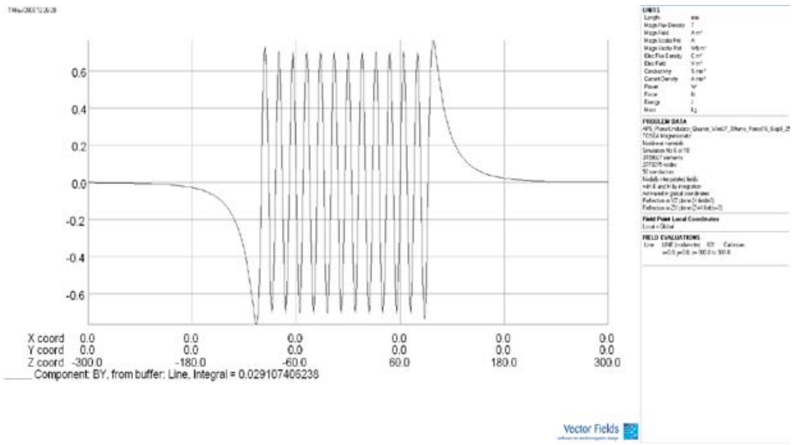
Current directions in a planar undulator



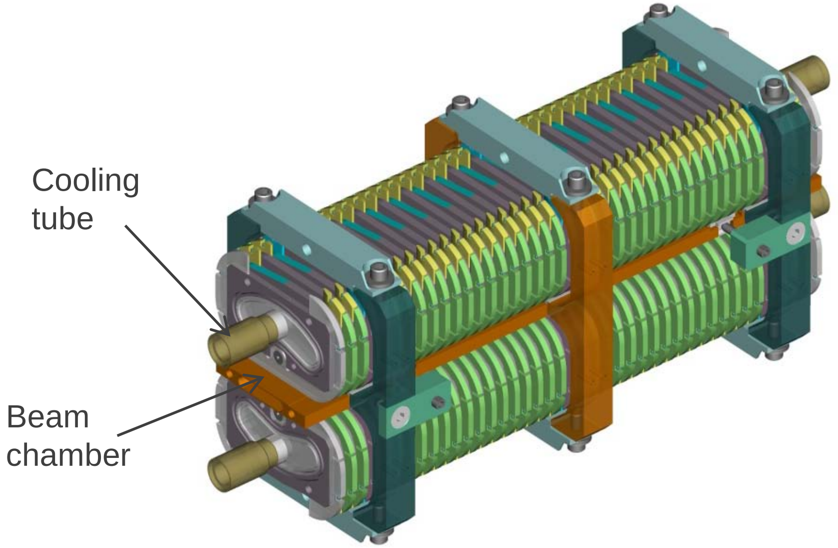
Planar undulator winding scheme



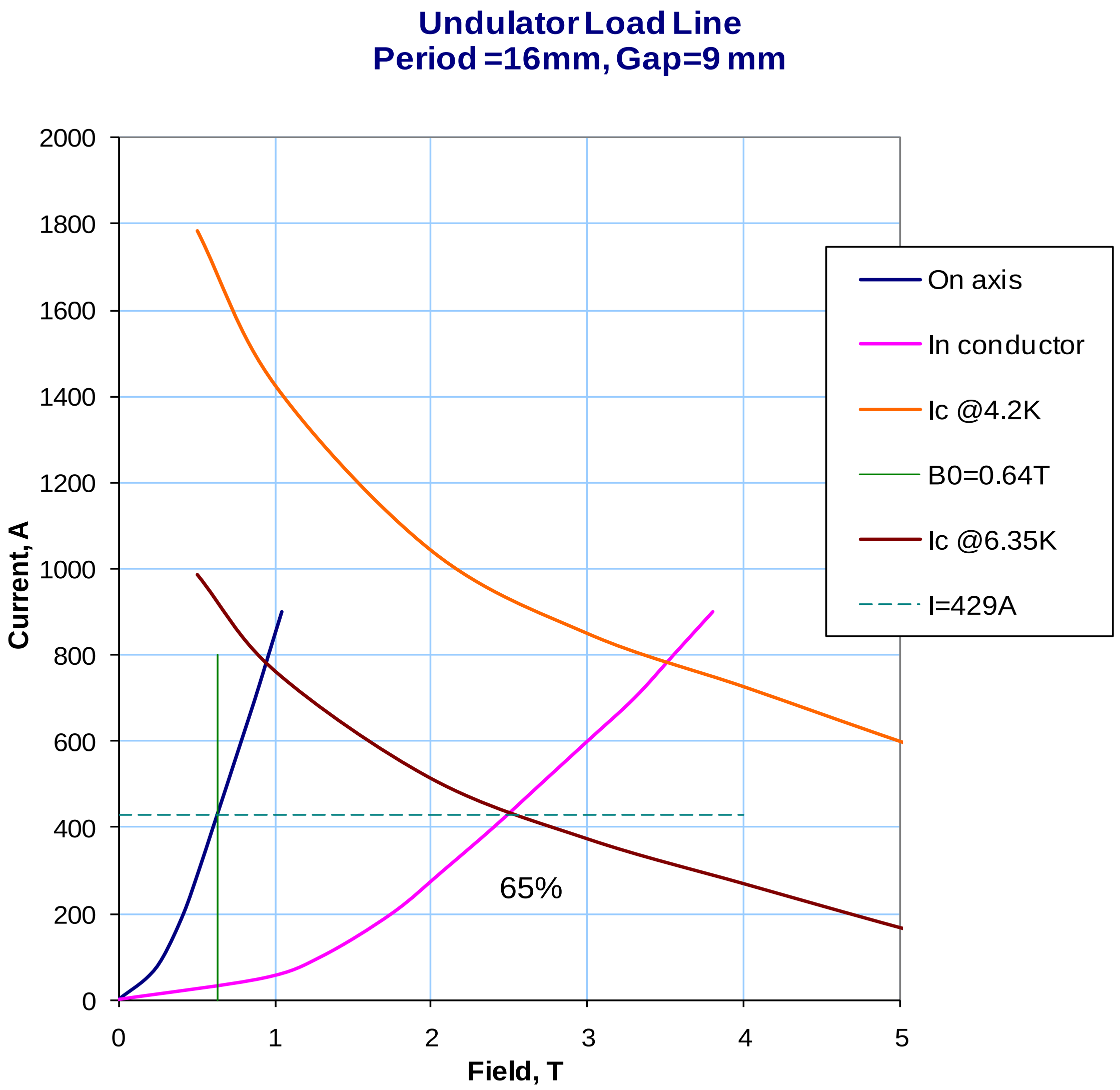
On-axis field in a planar undulator



Magnetic structure layout

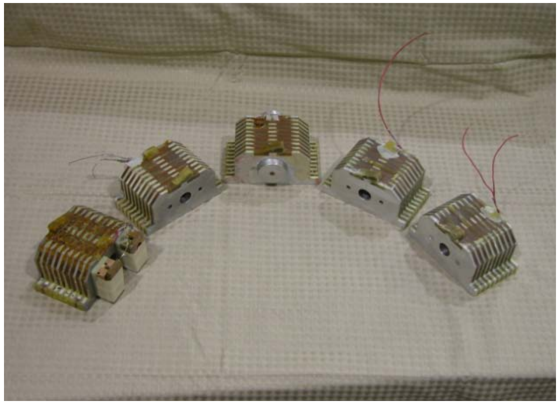


Superconductor load line



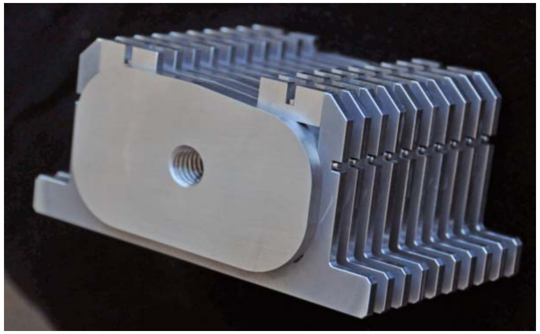
At 9 mm magnetic gap:
peak field 0.64 T is achieved at 429 A

Coil fabrication R&D



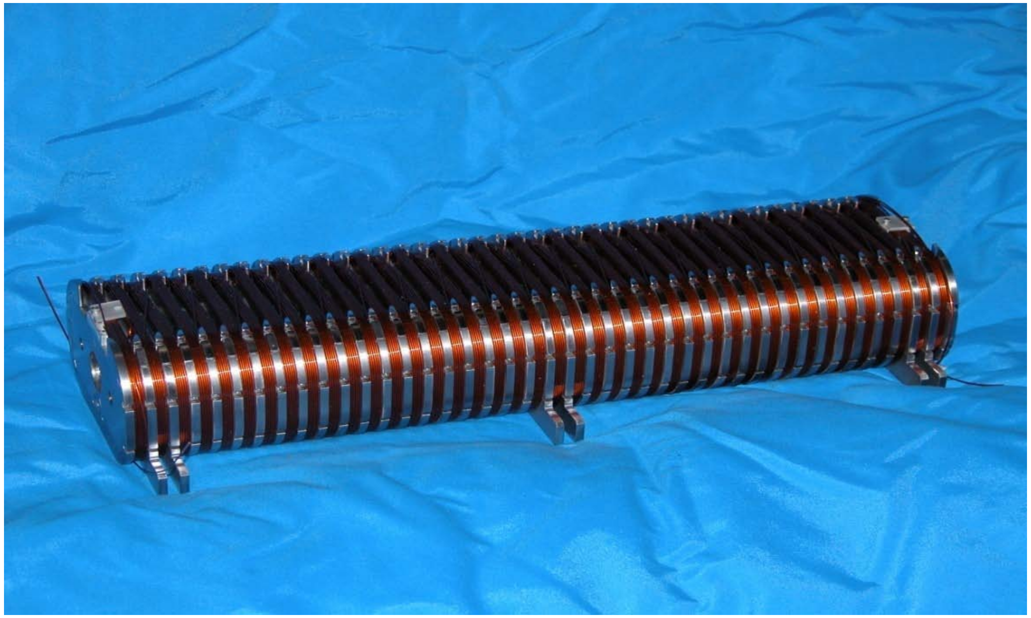
First five 10-pole test coils

A 10-pole test Al core manufactured in assembled technique.



- Coil fabrication process:
  - Core manufacture (10 µm precision achieved)
  - Coil winding (high quality achieved)
  - Coil impregnation (good results achieved)

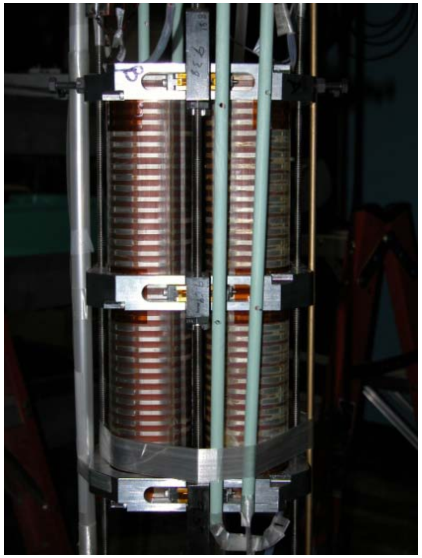
First wound 42-pole test coil



Test of 42-pole magnetic assemblies in the vertical cryostat

- Assembly includes two identical magnetic structures – Coils "A" and "B", each with a main coil and a pair of correction coils
- Parameters of the coils:
  - period length – 16.0 mm;
  - magnetic gap - 9.5 mm
  - core material – steel 1006-1008 or Al alloy;
  - pole material – steel 1006-1008;
  - SC wire – NbTi round wire, 0.74 mm diameter.

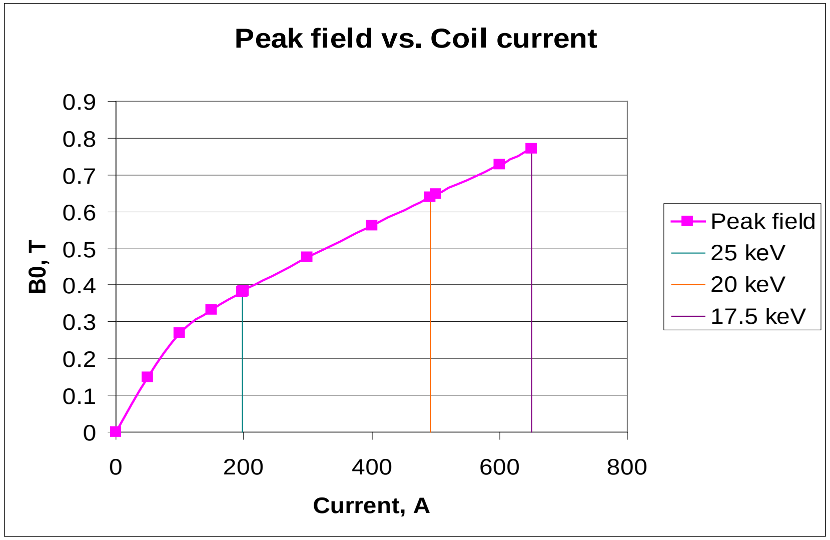
- Assembly immersed into liquid helium (LHe) in the vertical cryostat.
- Level of LHe in the cryostat bore is measured with level sensor, LHe is topped up when required.
- Hall probe is driven by a mechanical stage that is equipped with a position encoder outside the cryostat.
- LabView is employed to control movement of the Hall probe as well as to control the two main power supplies .
- Field profile is measured by the Hall probe every 0.1 mm (according to the encoder).
- Hall probe calibrated at room temperature (a facility for calibration Hall probes at cryogenic temperatures has been set up).



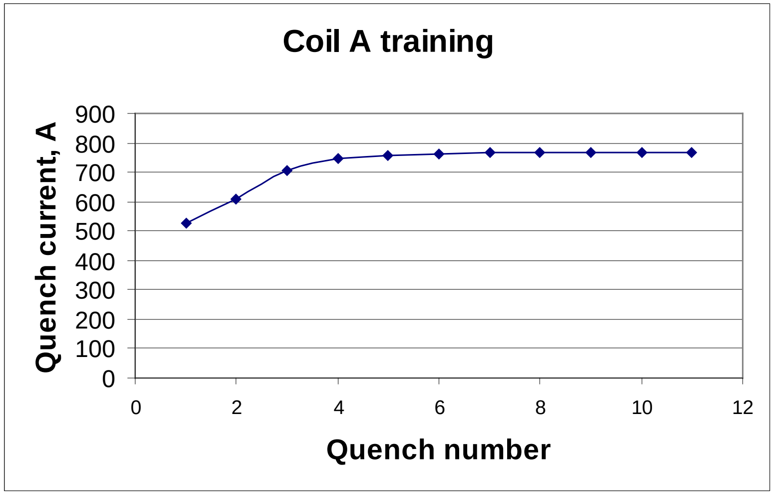
42-pole magnetic assembly →

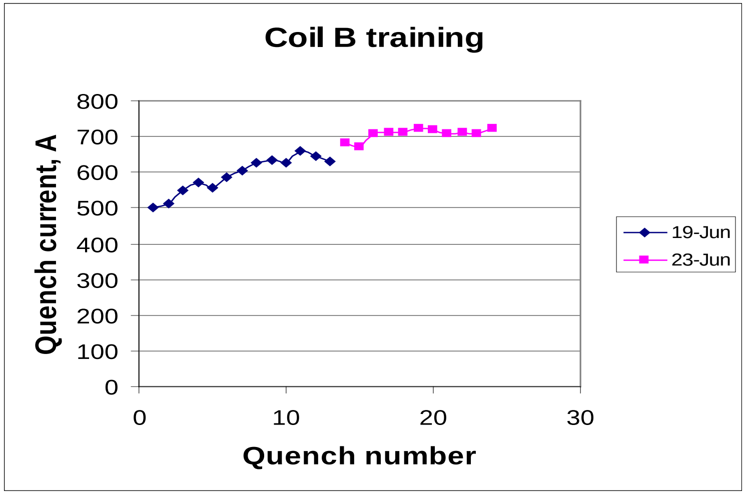
Y. Ivanyushenkov, Workshop on superconducting undulators, APS, September 20-21, 2010

Superconducting coil excitation and training



- Iron is already saturated at about 150 A
- Iron adds about 0.2 T to the peak field
- Operating current for 25 keV – 200 A; for 20 keV – 500 A (max current 720 A)

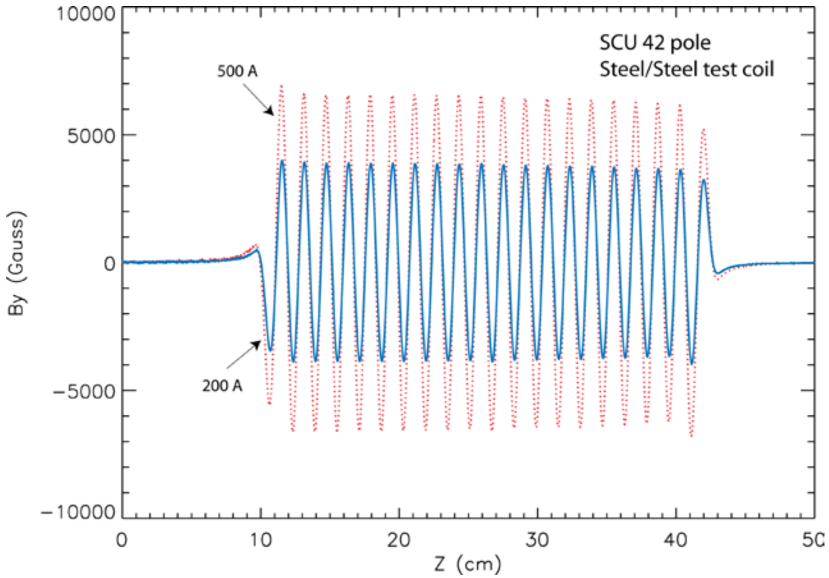




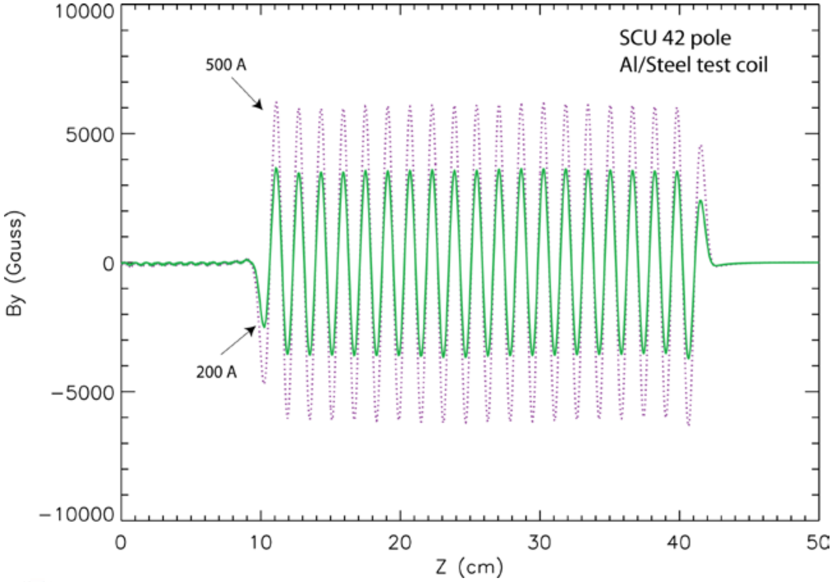
Coil A max current: 760 A, max current reached after 5 quenches

Coil B max current: 720 A, required many quenches to reach its max current

Measured magnetic field profiles



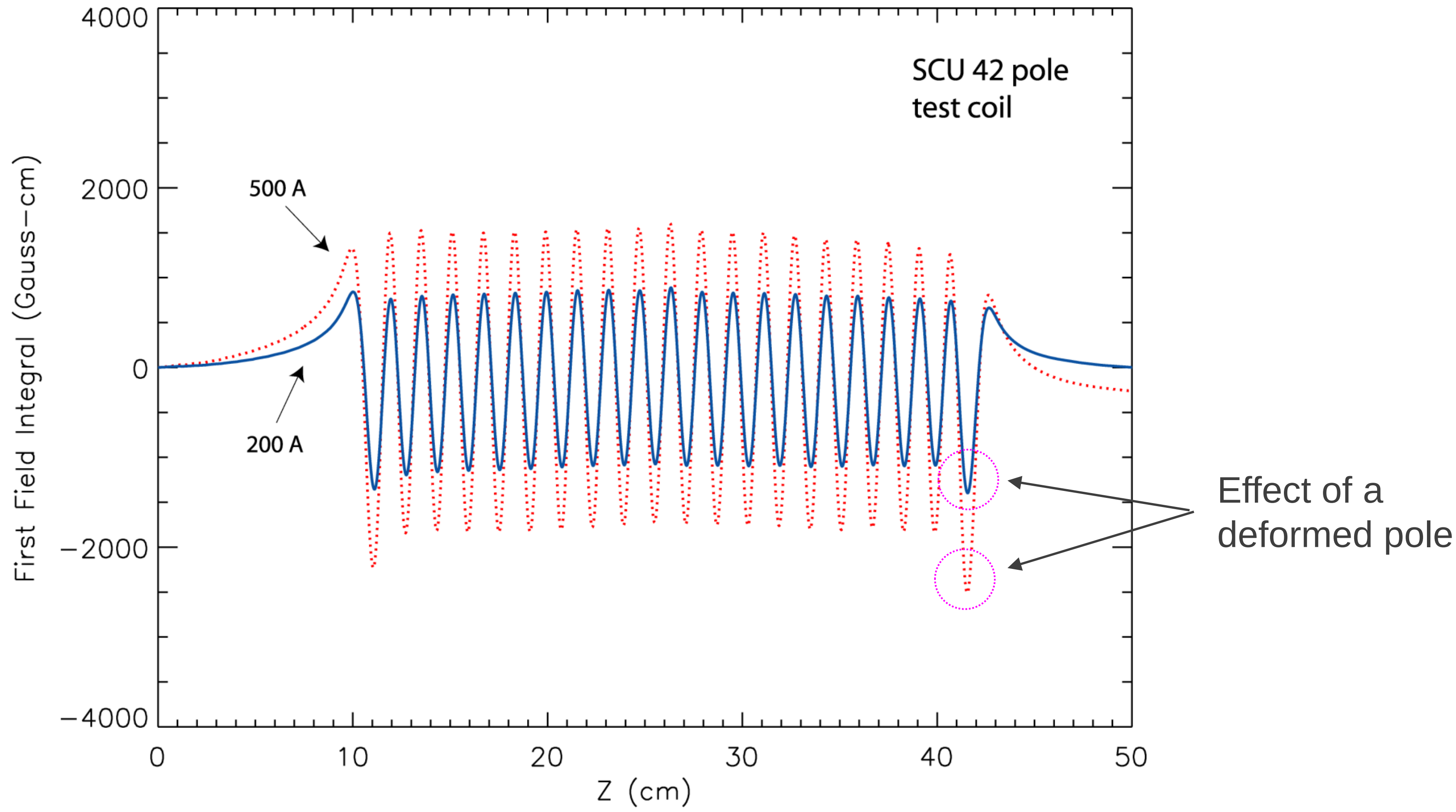
- 42-pole assembly #1 with Steel core / Steel poles
- Magnetic fields were measured for currents of 200 A and 500 A at a nominal gap of 9.50 mm (from July, 2009).
- The effective magnetic fields are 3815 Gauss (200 A) and 6482 Gauss (500 A).



- 42-pole assembly # 2 with Al core / Steel poles
- Magnetic fields were measured for currents of 200 A and 500 A at a nominal gap of 9.50 mm (from October, 2009).
- The effective magnetic fields are 3620 Gauss (200 A) and 6140 Gauss (500 A).

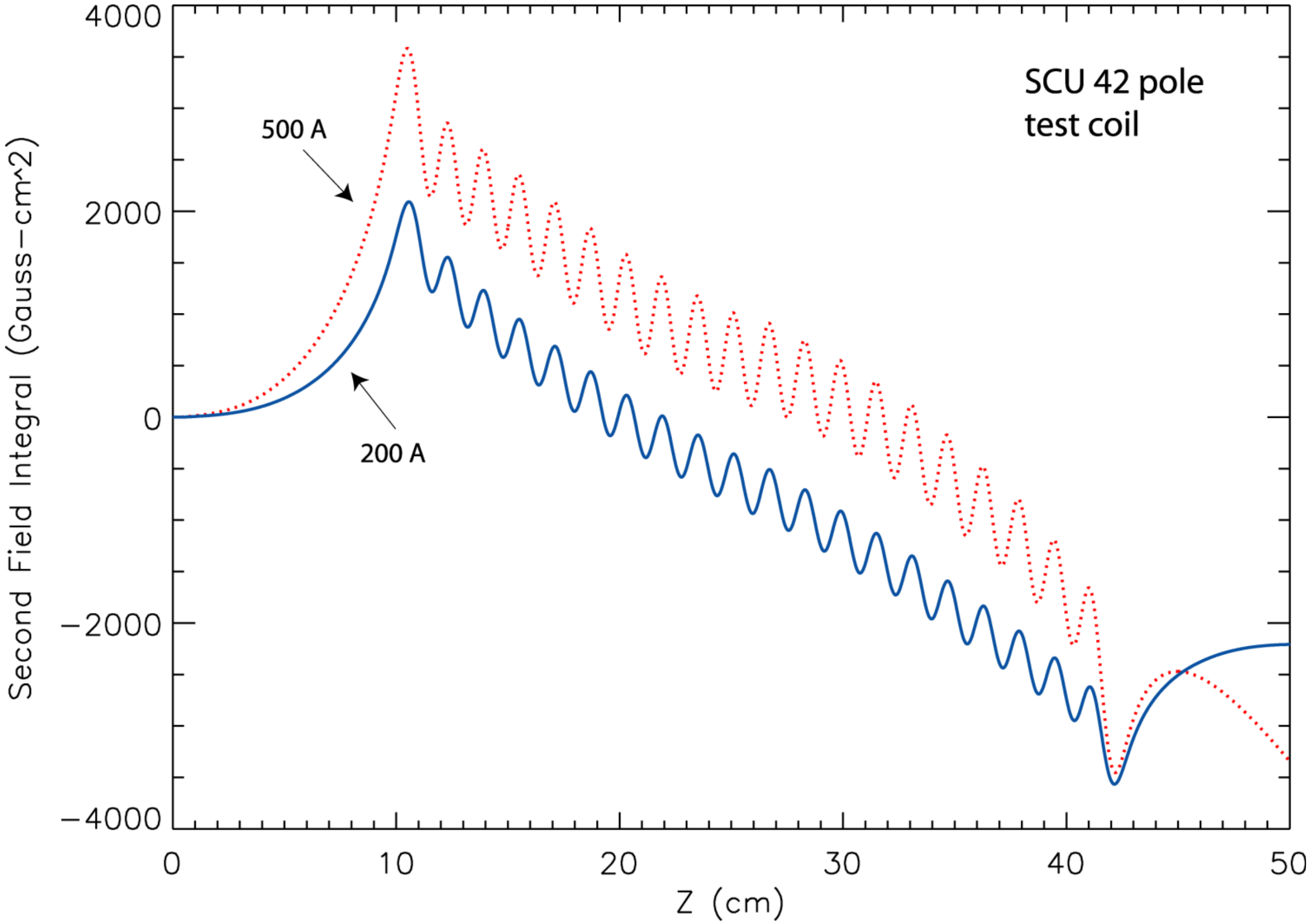
Y. Ivanyushenkov, Workshop on superconducting undulators, APS, September 20-21, 2010

First field integrals for 42-pole Steel/Steel assembly #1



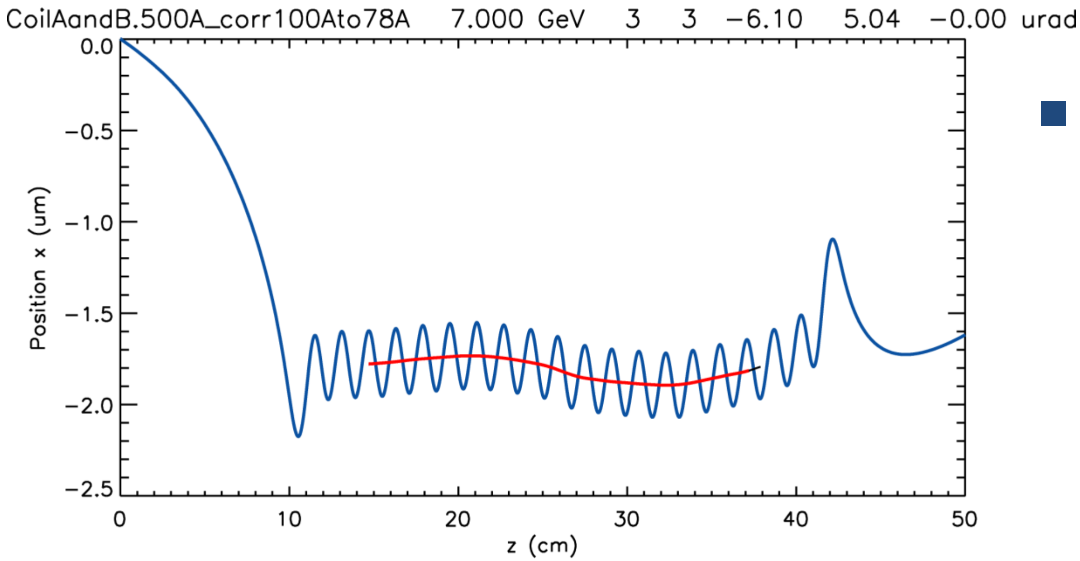
- The measured first field integrals are 2 G-cm (200 A) and -261 G-cm (500 A) (because of deformed pole).
- Storage ring requirement is < 50 G-cm

Second field integrals for 42-pole Steel/Steel assembly #1

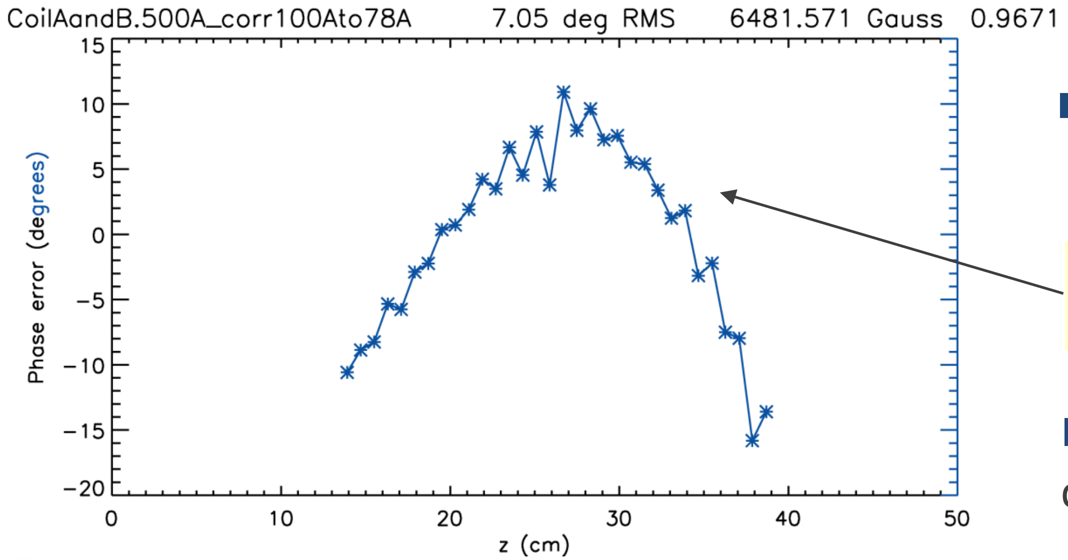


- The measured second field integrals are -2208 G-cm^2 (200 A) and -3345 G-cm^2 (500 A).
- Storage ring requirement is < 100,000 G-cm^2

Trajectory and phase errors at 500 A for Steel/Steel assembly #1 (first harmonic at 20 keV)



- Calculated electron trajectory and average trajectory for 7.0 GeV beam energy.

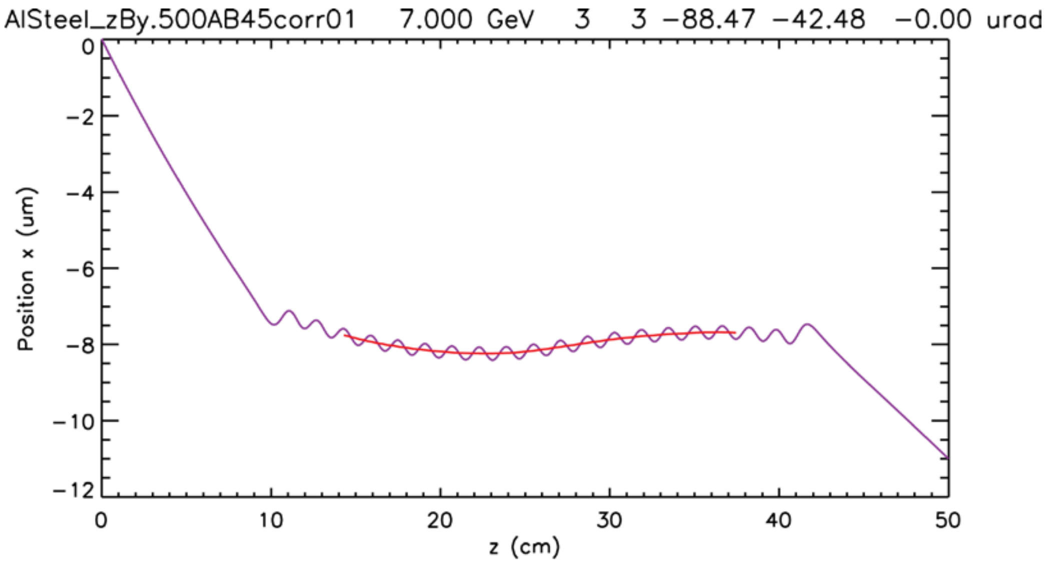


- The measured rms phase error is 7.1 degrees for 500 A current.

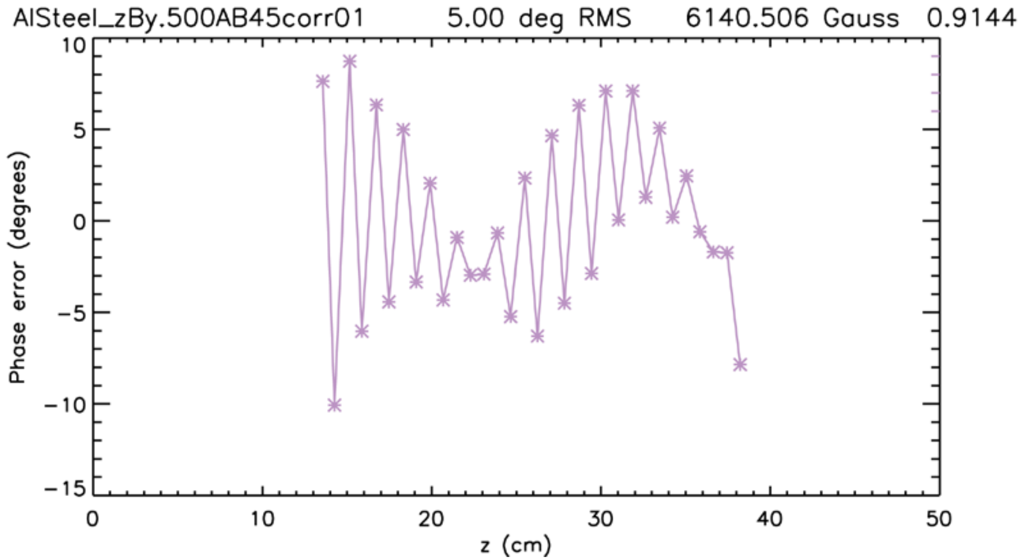
This shape is typical for an undulator with a tapered gap.

- Storage ring requirement is < 8 degrees

Trajectory and phase errors at 500 A for Al/Steel assembly #2 (first harmonic at 20 keV)



- Calculated electron trajectory and average trajectory for 7.0 GeV beam energy (the large slopes at the entrance/exit are due to uncorrected ends).



- The measured rms phase error is 5.0 degrees for 500 A current (no taper is visible and the rms phase is reduced).

- Storage ring requirement is < 8 degrees

Short prototype R&D summary table

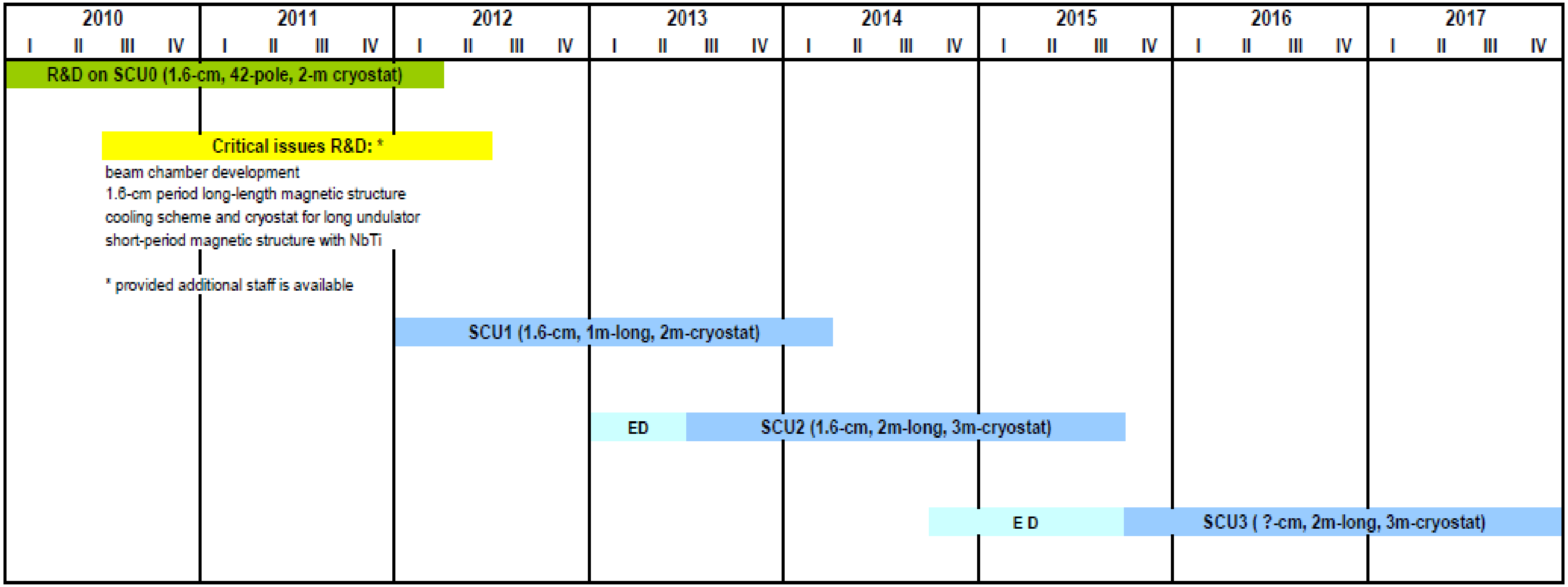
Prototype Parameter	1	2	3	4	5	Assembly 1	Assembly 2
No of poles	10	10	10	10	10	42	42
Core/ pole material	Al/Al	Iron/Iron	Al/Al	Al/Al	Al/Al	Iron /Iron	Al/Iron
LHe test status	Tested	Tested	Used for impregnation study	Used for impregnation study	Used for impregnation study	Tested	Tested
Peak field						0.65 T @ 500 A	0.61 T @ 500 A
Phase error*						7.1 @ 500 A 3.3 @ 200 A	5.0 @ 500 A 3.0 @ 200 A
Spectral performance (phase errors included)						>75% of ideal in 3rd harmonic (60 keV); >55% of ideal in 5th harmonic (100 keV)	

* Original specification for Undulator A was ≤ 8

More details on quench studies are in the talk by Chuck Doose this afternoon.

Superconducting undulators in the APS upgrade program

SCU Road Map



R&D on SCU0 (1.6-cm, 42-pole, 2-m cryostat)

Critical issues R&D: *

beam chamber development
1.6-cm period long-length magnetic structure
cooling scheme and cryostat for long undulator
short-period magnetic structure with NbTi

* provided additional staff is available

SCU1 (1.6-cm, 1m-long, 2m-cryostat)

SCU2 (1.6-cm, 2m-long, 3m-cryostat)

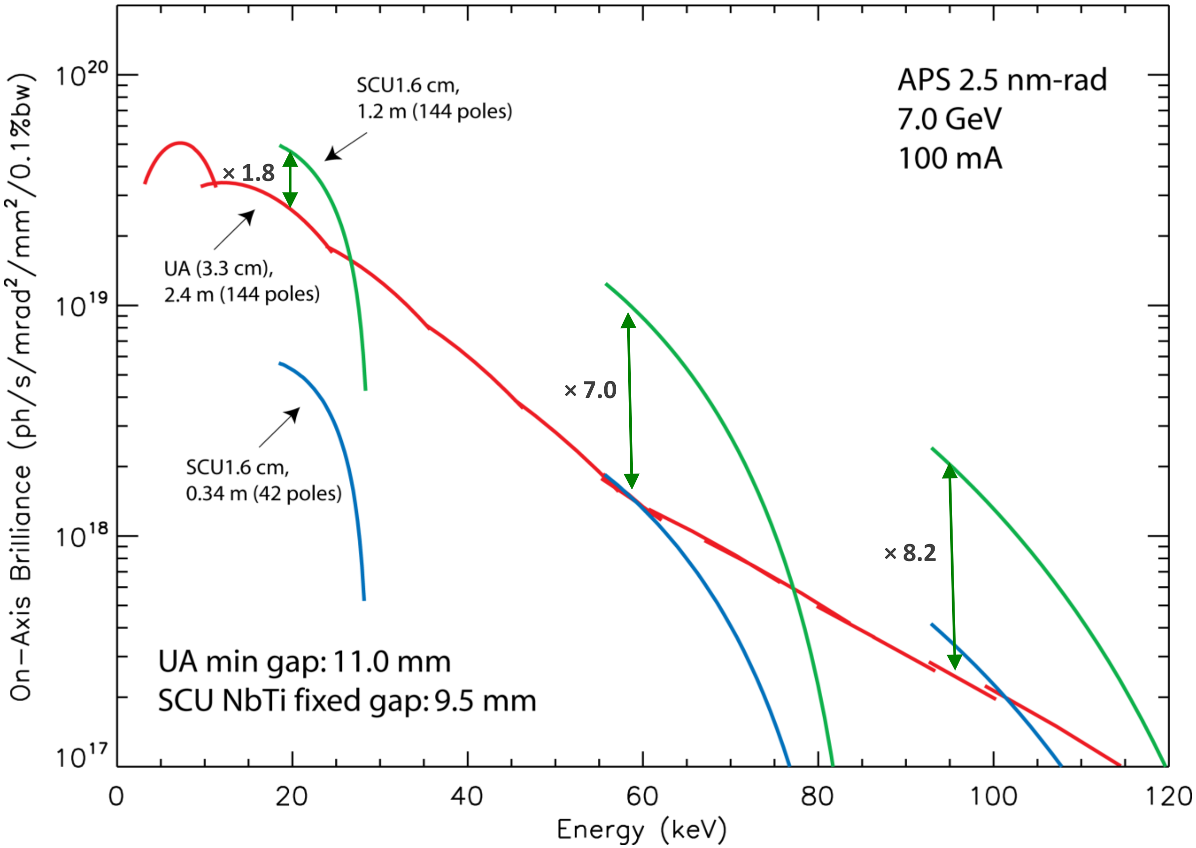
SCU3 (?-cm, 2m-long, 3m-cryostat)

First two superconducting undulators for the APS

- APS superconducting undulator specifications

	SCU0	SCU1
Photon energy at 1st harmonic	**20-25 keV**	**20-25 keV**
Undulator period	**16 mm**	**16 mm**
Magnetic length	**0.33 m**	**1.15 m**
Cryostat length	**≈ 2.0 m**	**≈ 2.0 m**
Beam stay-clear dimensions	**7.0 mm vertical × 36 mm horizontal**	**7.0 mm vertical × 36 mm horizontal**
Magnetic gap	**9.5 mm**	**9.5 mm**

Expected performance of SCU0 and SCU1



- Tuning curves for odd harmonics for two planar 1.6-cm-period NbTi superconducting undulators (42 poles, 0.34 m long and 144 poles, 1.2 m long) versus the planar NdFeB permanent magnet hybrid undulator A (144 poles, 3.3 cm period and 2.4 m long). Reductions due to magnetic field error were applied the same to all undulators (estimated from one measured undulator A at the APS). The tuning curve ranges were conservatively estimated for the SCUs.
- The minimum energies are 3.2 keV for the UA and 18.6 keV for the SCUs.
- The short 42-pole 1.6-cm-period SCU surpasses undulator A at ~ 60 keV and ~ 95 keV. The 144-pole SCU brilliance exceeds that of undulator A by factors of 1.8 at 20 keV, 7.0 at 60 keV, and 8.2 at 95 keV.

Heat loads and cooling system concept

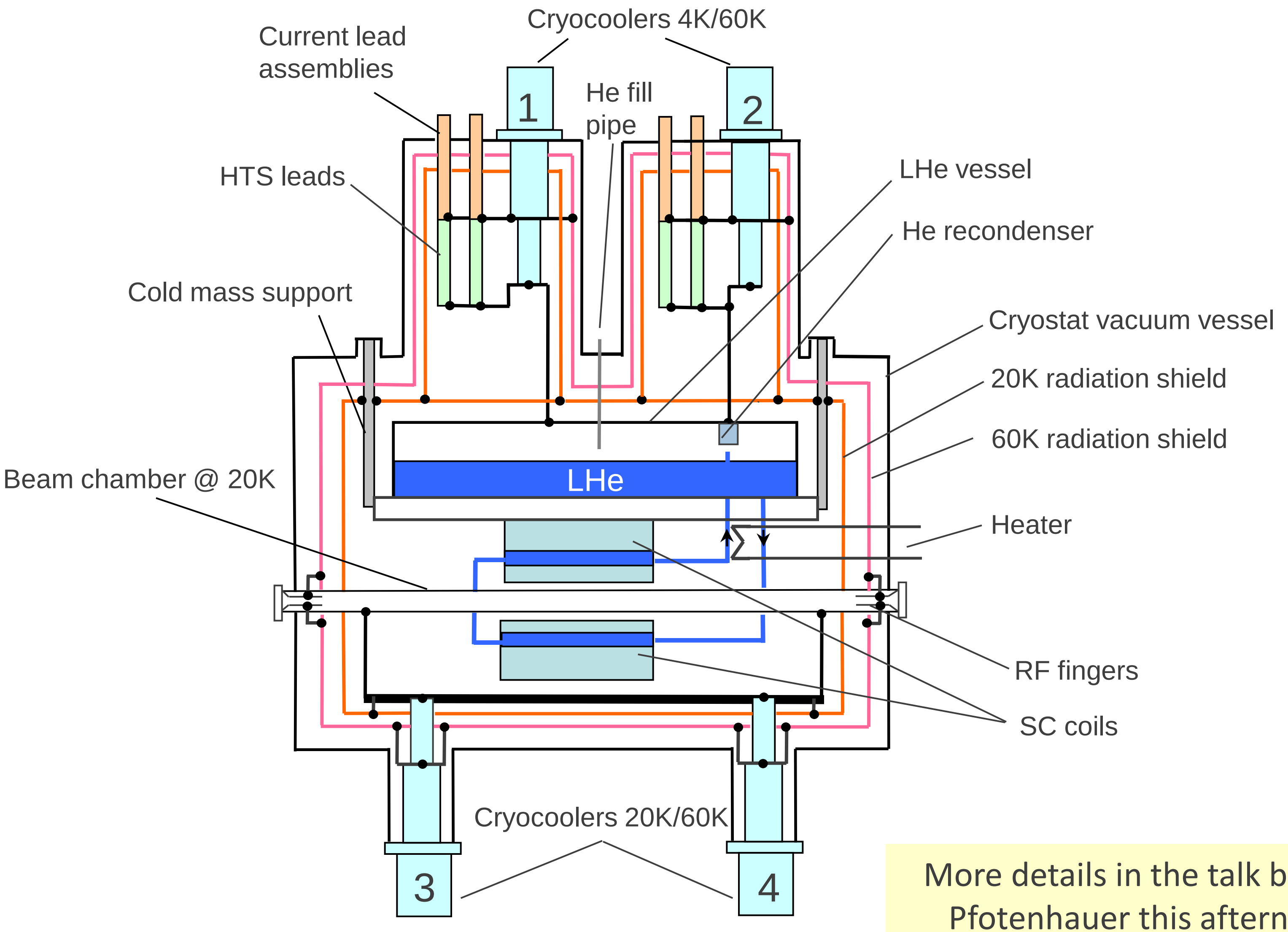
Heat source	Heat load @ 4K, W	Heat load @ 20K, W	Heat Load @ 60 K, W
Beam		6.6 (nominal) 45 (injection accident)	
Radiation	0.0116	1.21	4.2
Conduction through:			
beam chamber bellows			1.4
beam chamber supports	0.08		
He vent bellows	0.006	0.07	0.9
He fill pipe	0.012		
cold mass support	0.005		
radiation shields supports		1.2	5.6
Current leads at:			
I = 0 A	0		44
I = 100 A	0.12		22
I = 500 A	0.45		52
Total at I = 500 A:	0.685	up to 45	86.1

Conceptual points:

- Thermally insulate beam chamber from the rest of the system.
- Cool the beam chamber separately from the superconducting coils.

In this approach beam heats the beam chamber but not the SC coils !

SCU cooling scheme



More details in the talk by John Pfotenhauer this afternoon.

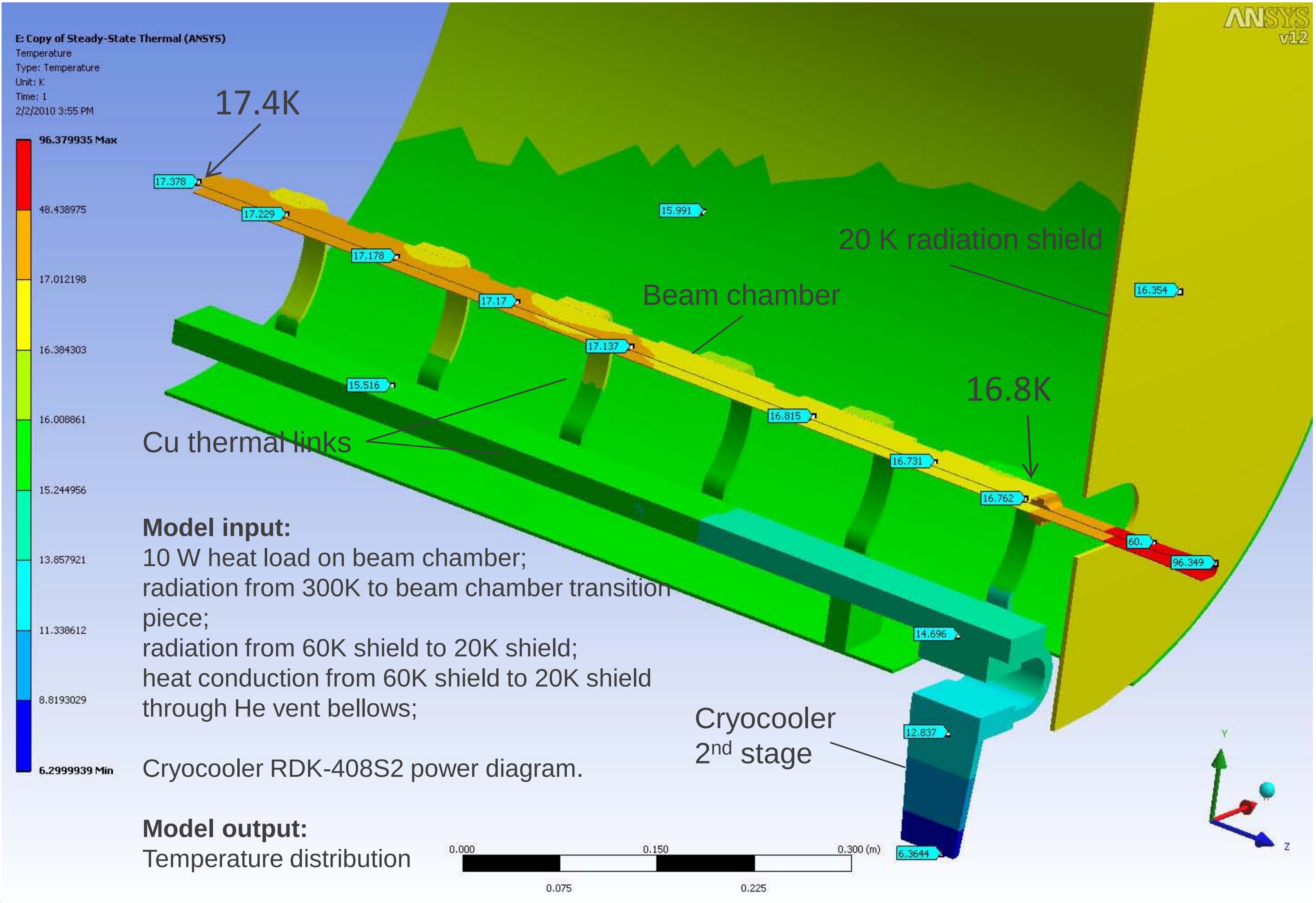
Cooling system budget

	4 K	20 K	60 K
Heat load, W	0.69	12.5	86.1
Cooling capacity, W	3	40	224

Cryocooler cooling power

	4.2 K	19 K	60 K
RDK-415D (60Hz)	1.5 W	–	57 W
RDK-408S (60Hz)	–	20 W	55 W

Thermal modeling. Beam chamber temperature distribution



17.4K

20 K radiation shield

Beam chamber

16.8K

Cu thermal links

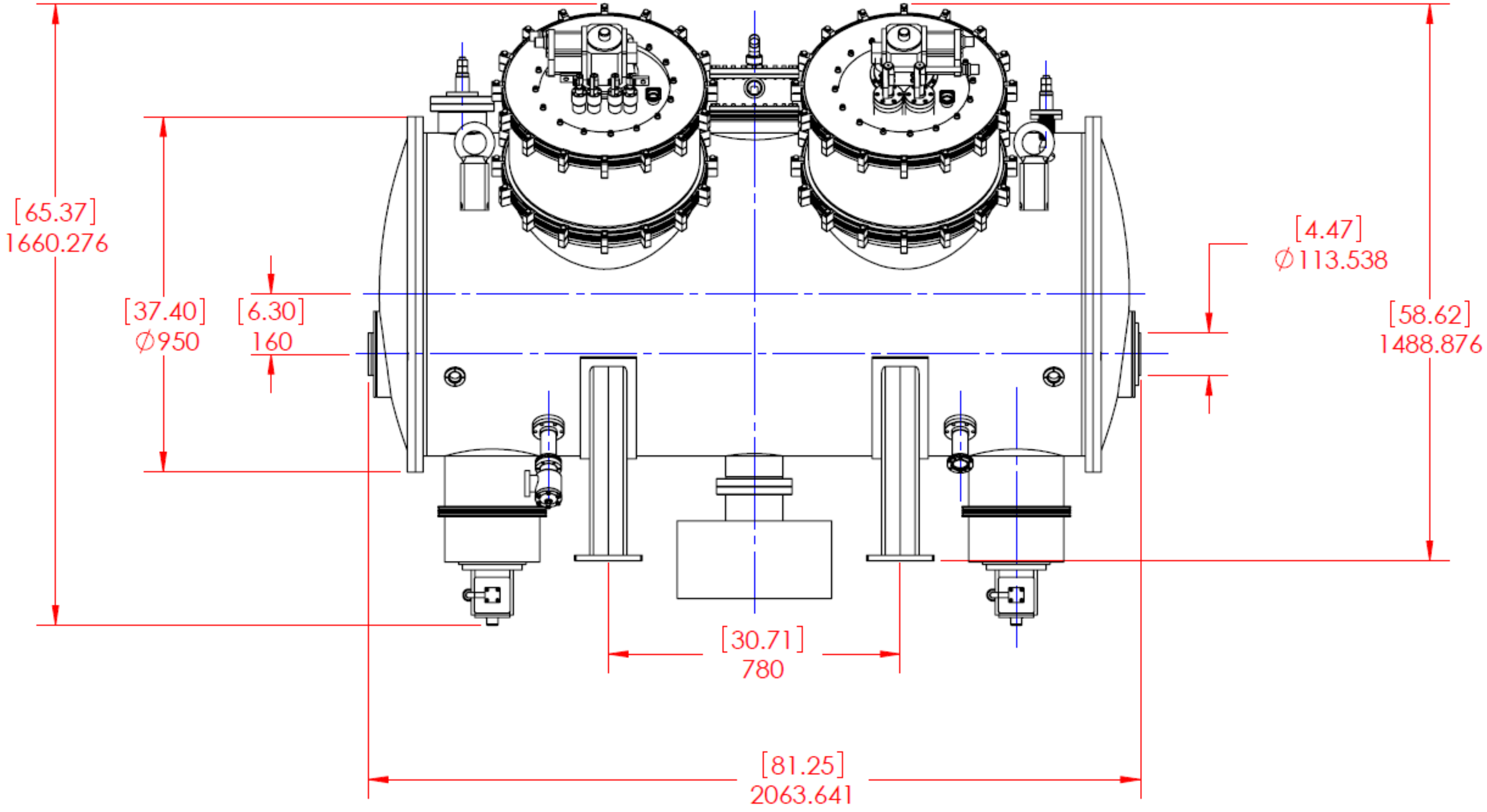
Cryocooler 2nd stage

Model input:
10 W heat load on beam chamber;
radiation from 300K to beam chamber transition piece;
radiation from 60K shield to 20K shield;
heat conduction from 60K shield to 20K shield through He vent bellows;

Cryocooler RDK-408S2 power diagram.

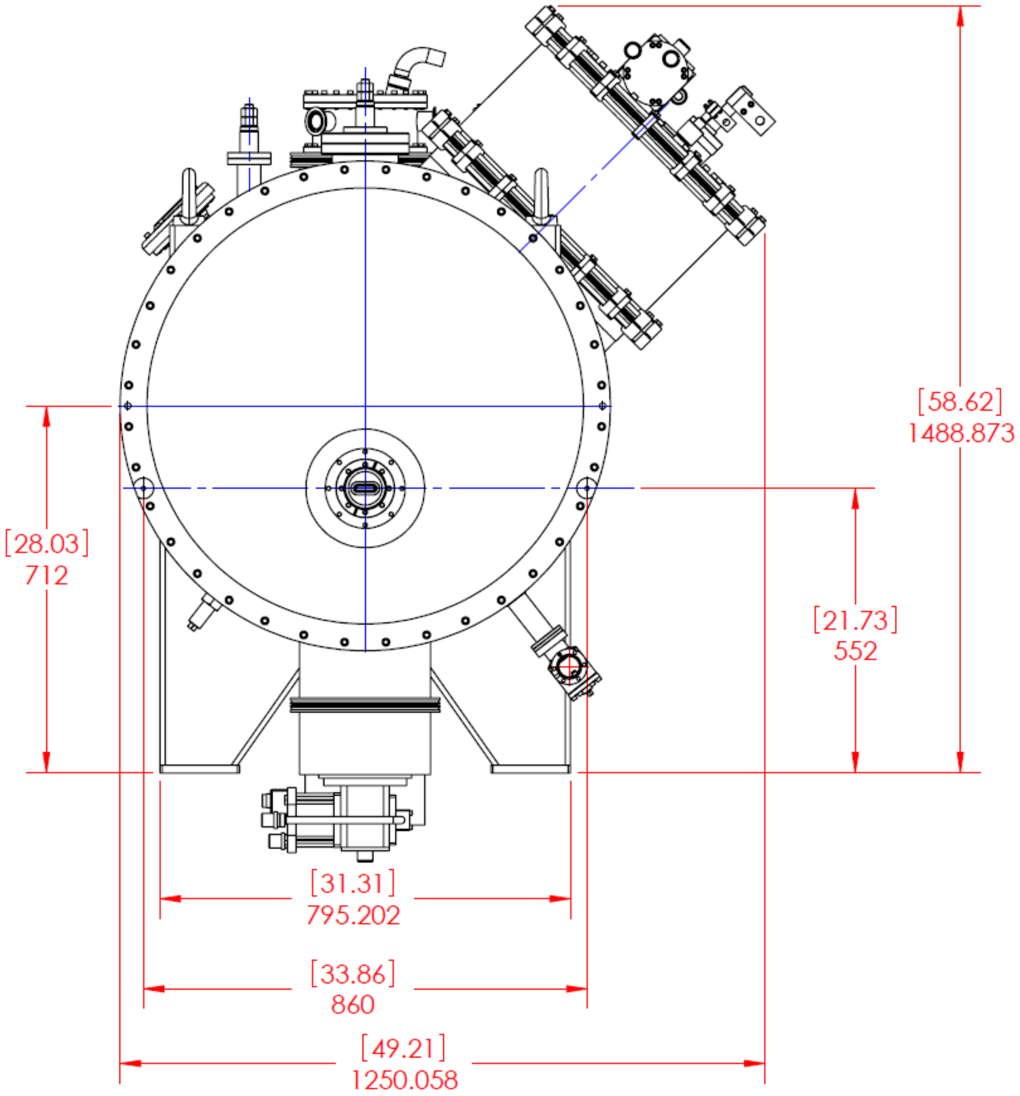
Model output:
Temperature distribution

Cryostat dimensions

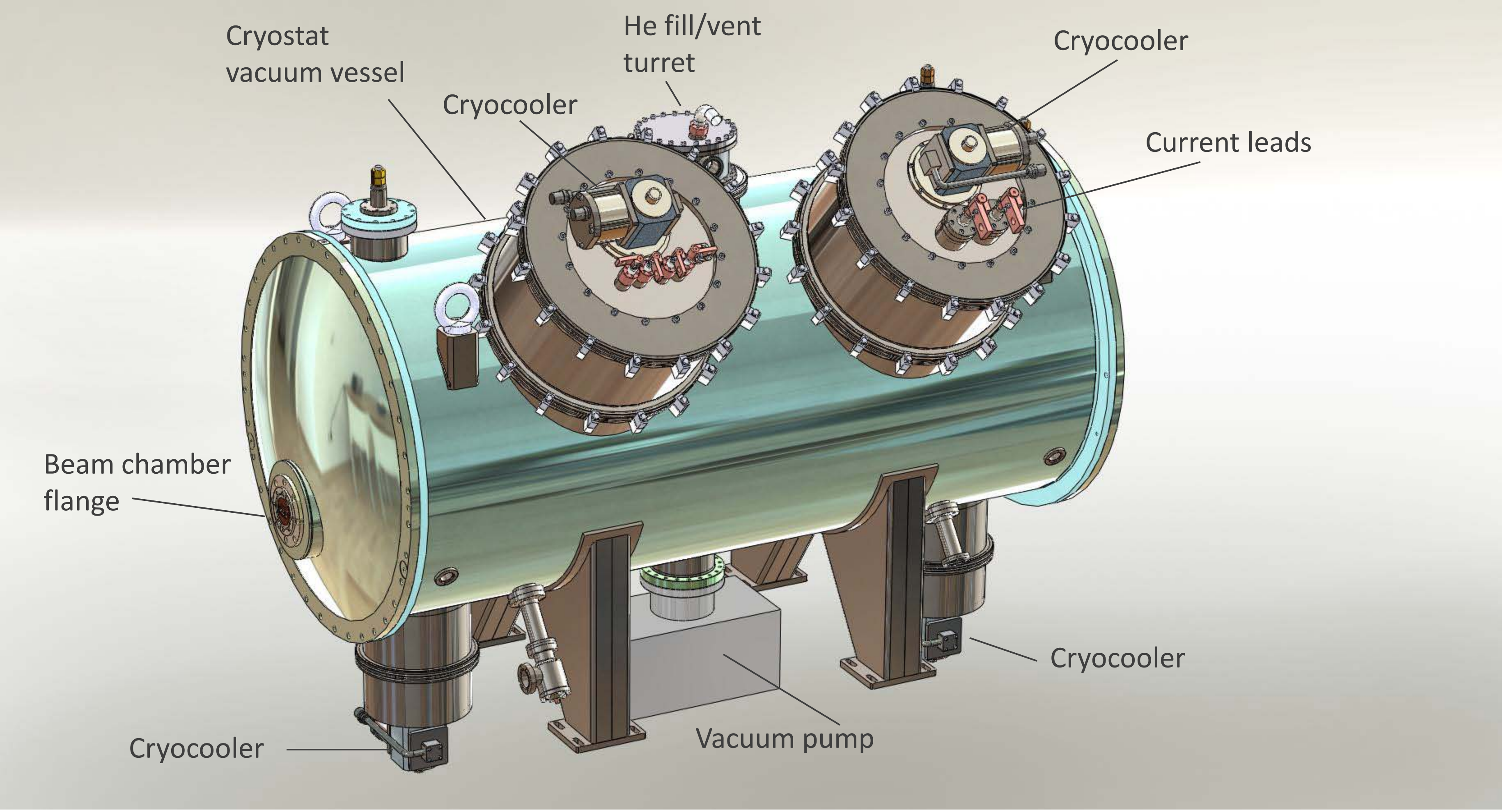


Y. Ivanyushenkov, Workshop on superconducting undulators, APS, September 20-21, 2010

Cryostat dimensions (2)

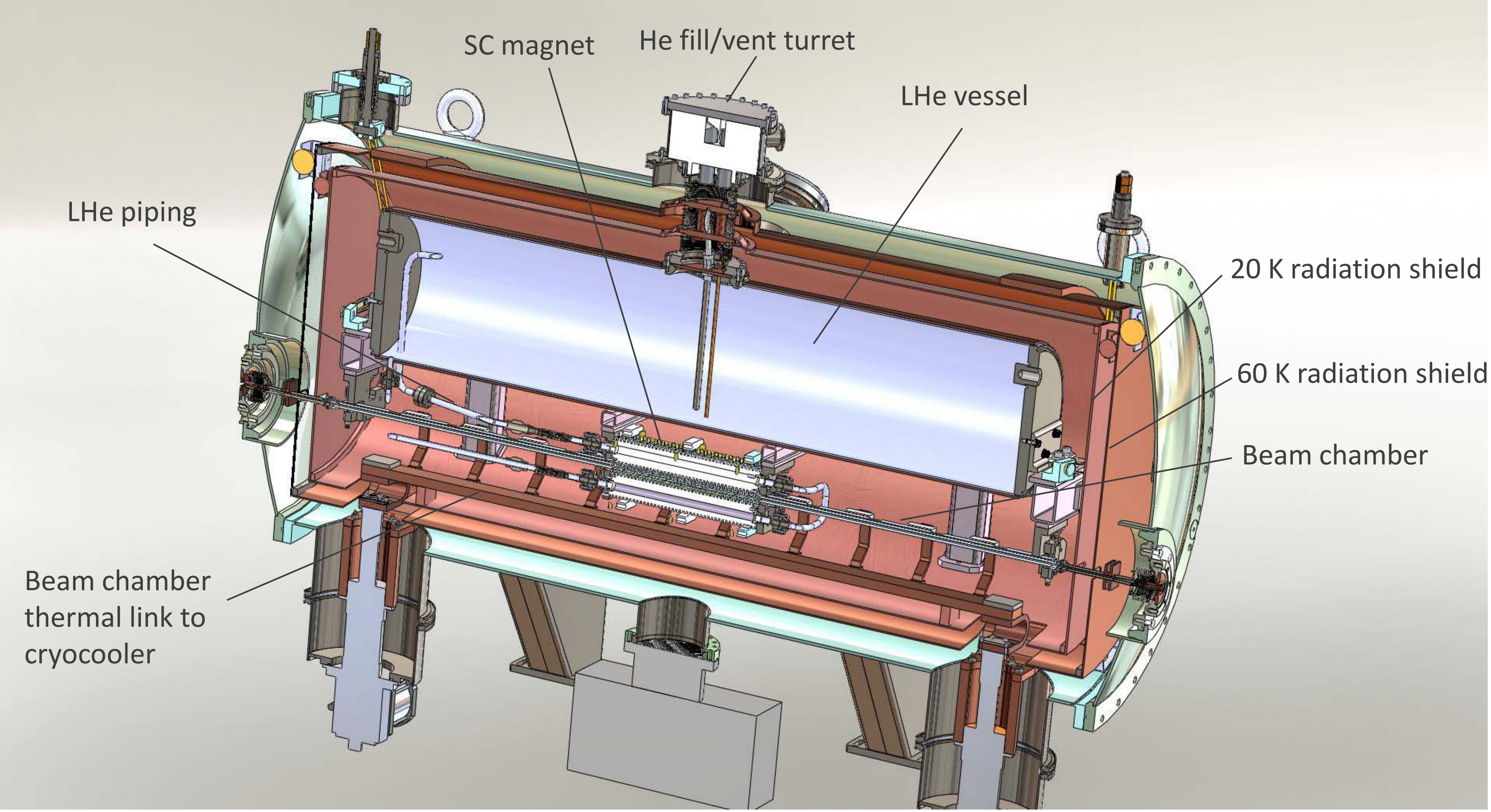


SCU0 cryostat layout



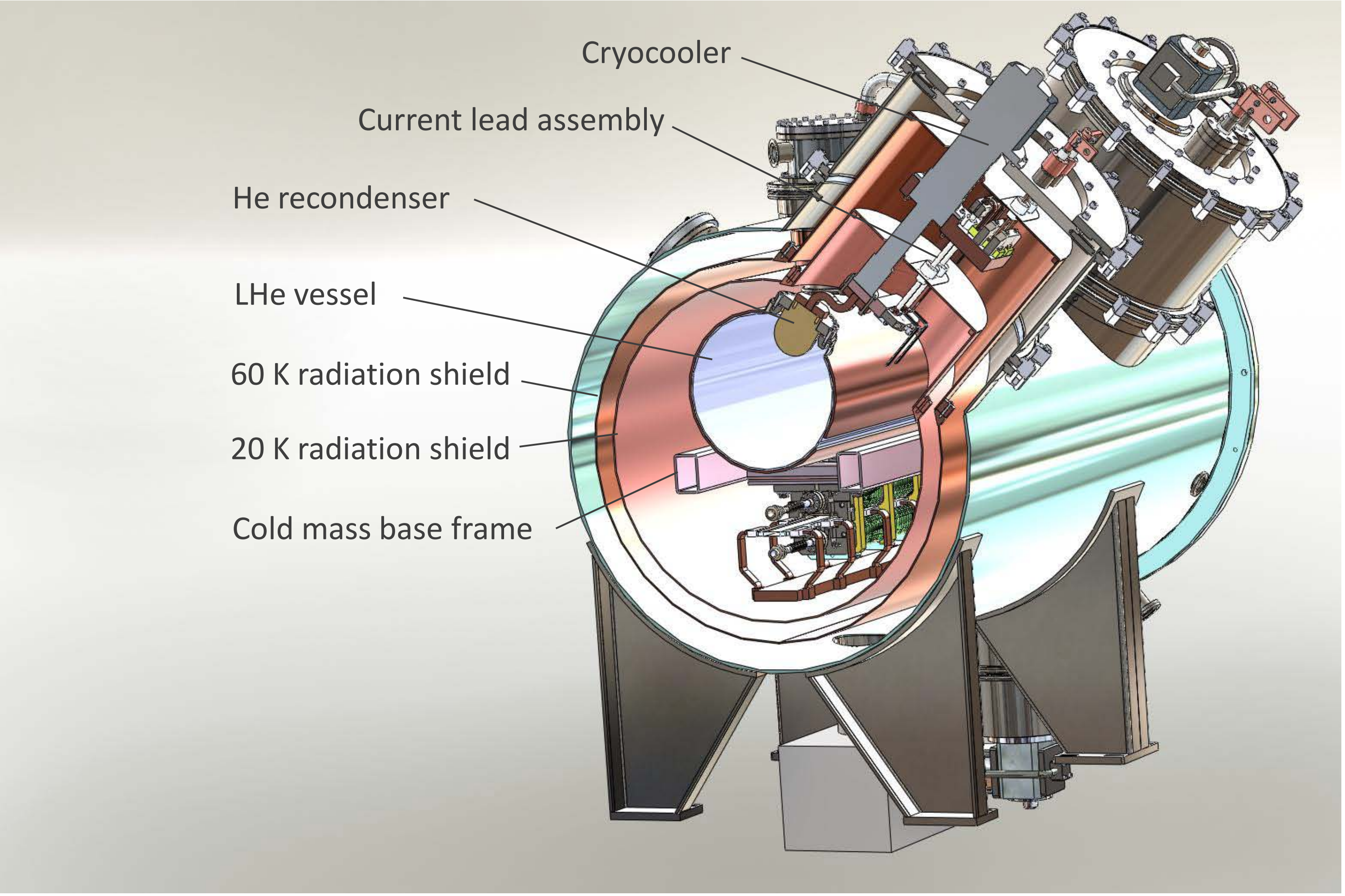
Cryostat structure

Cryostat contains cold mass with support structure, radiation shields, cryocoolers, and current lead assemblies.



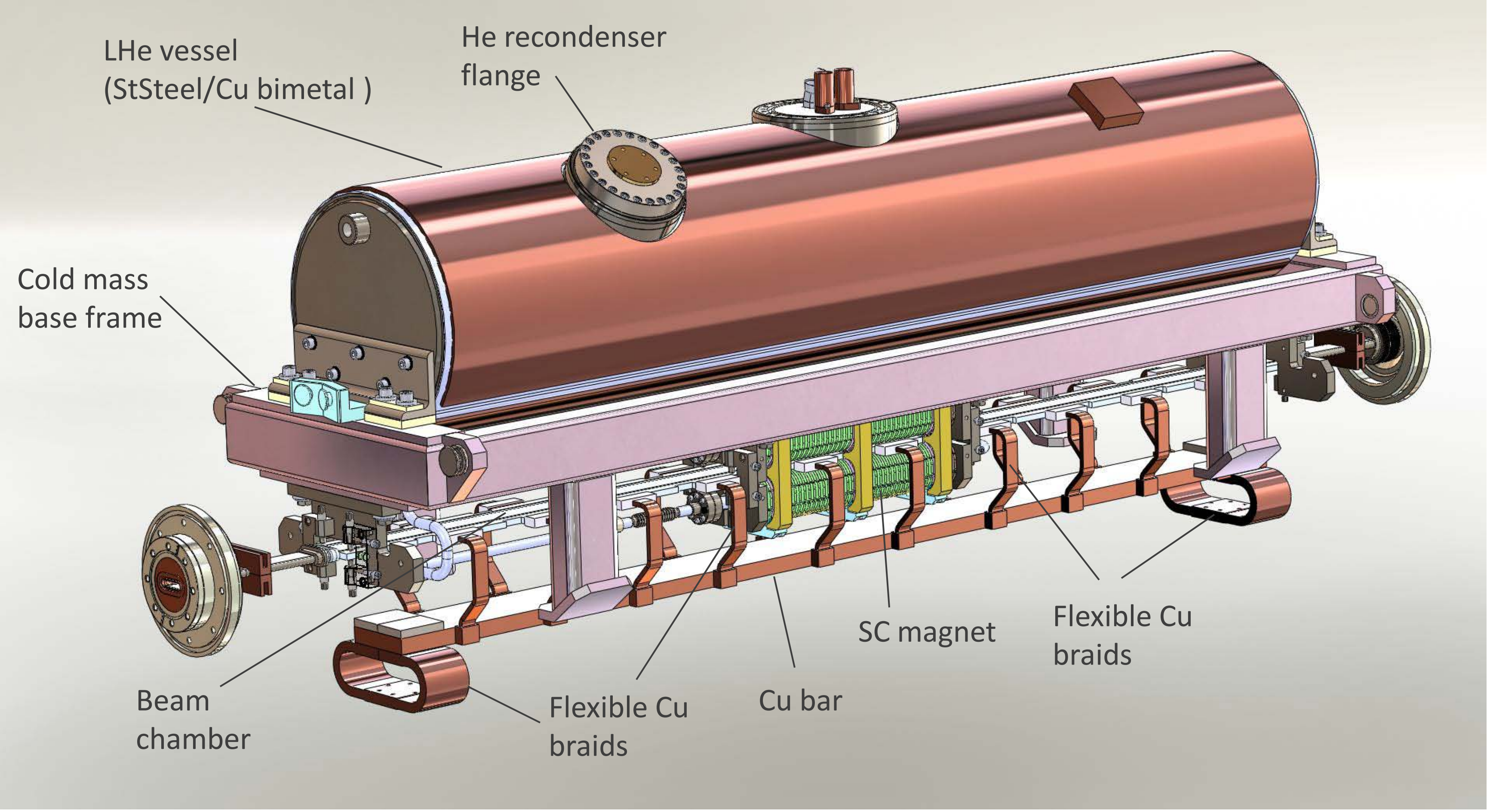
Y. Ivanyushenkov, Workshop on superconducting undulators, APS, September 20-21, 2010

Cryostat structure (2)

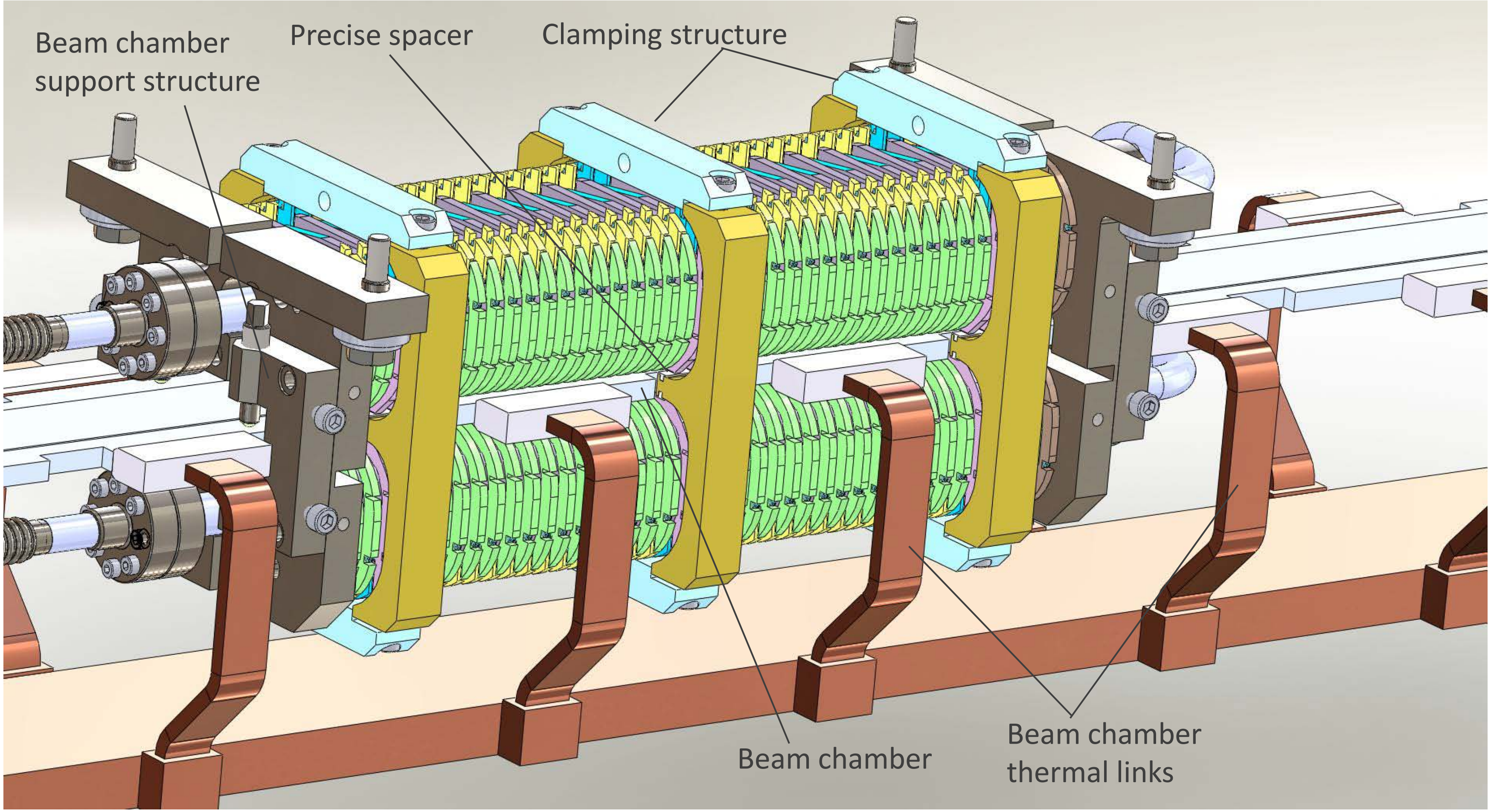


Cold mass

Cold mass includes SC magnet, LHe vessel with piping, and cold beam chamber with thermal links to cryocoolers. Cold mass is structurally supported by base frame.

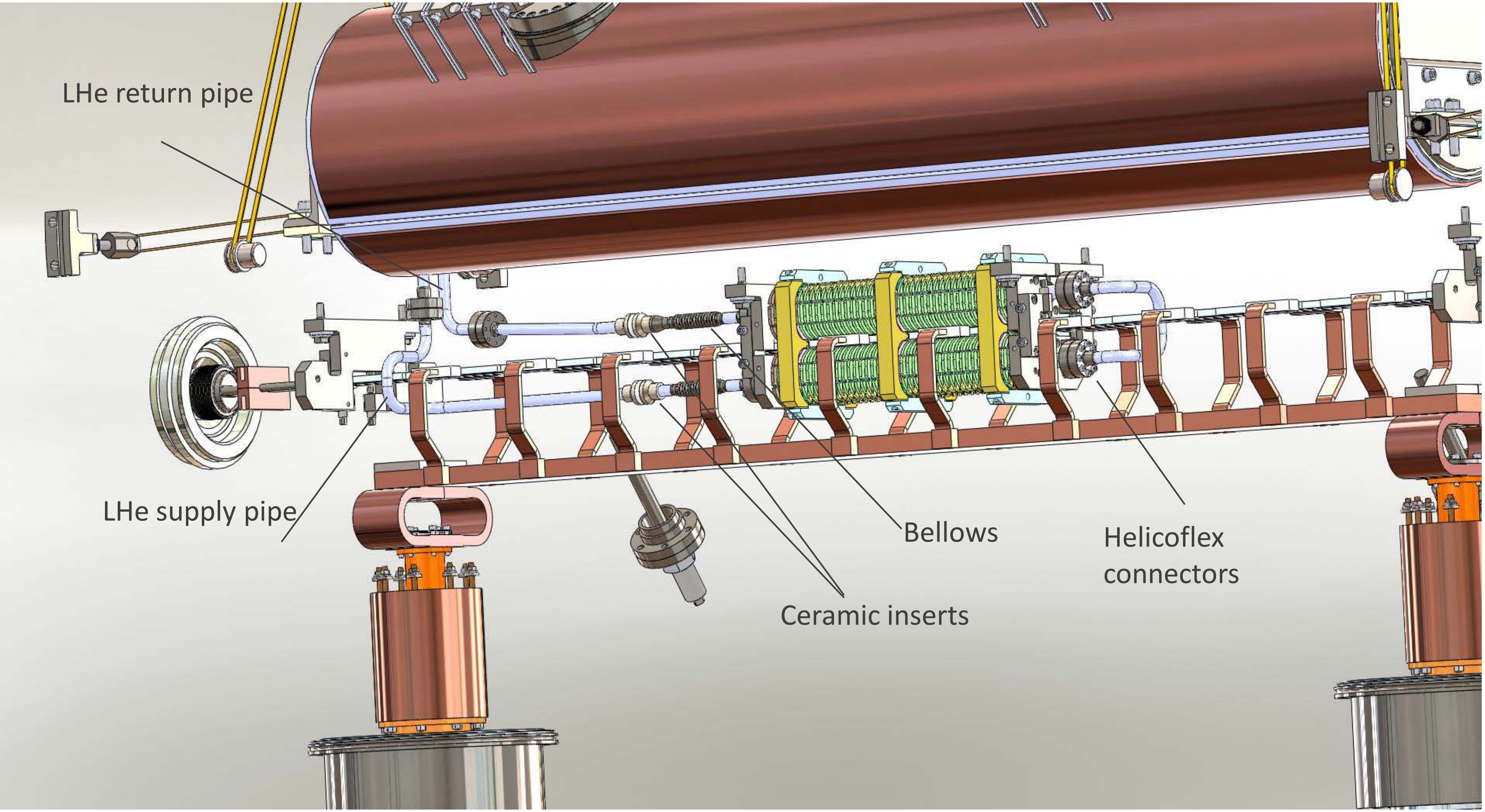


Superconducting magnet

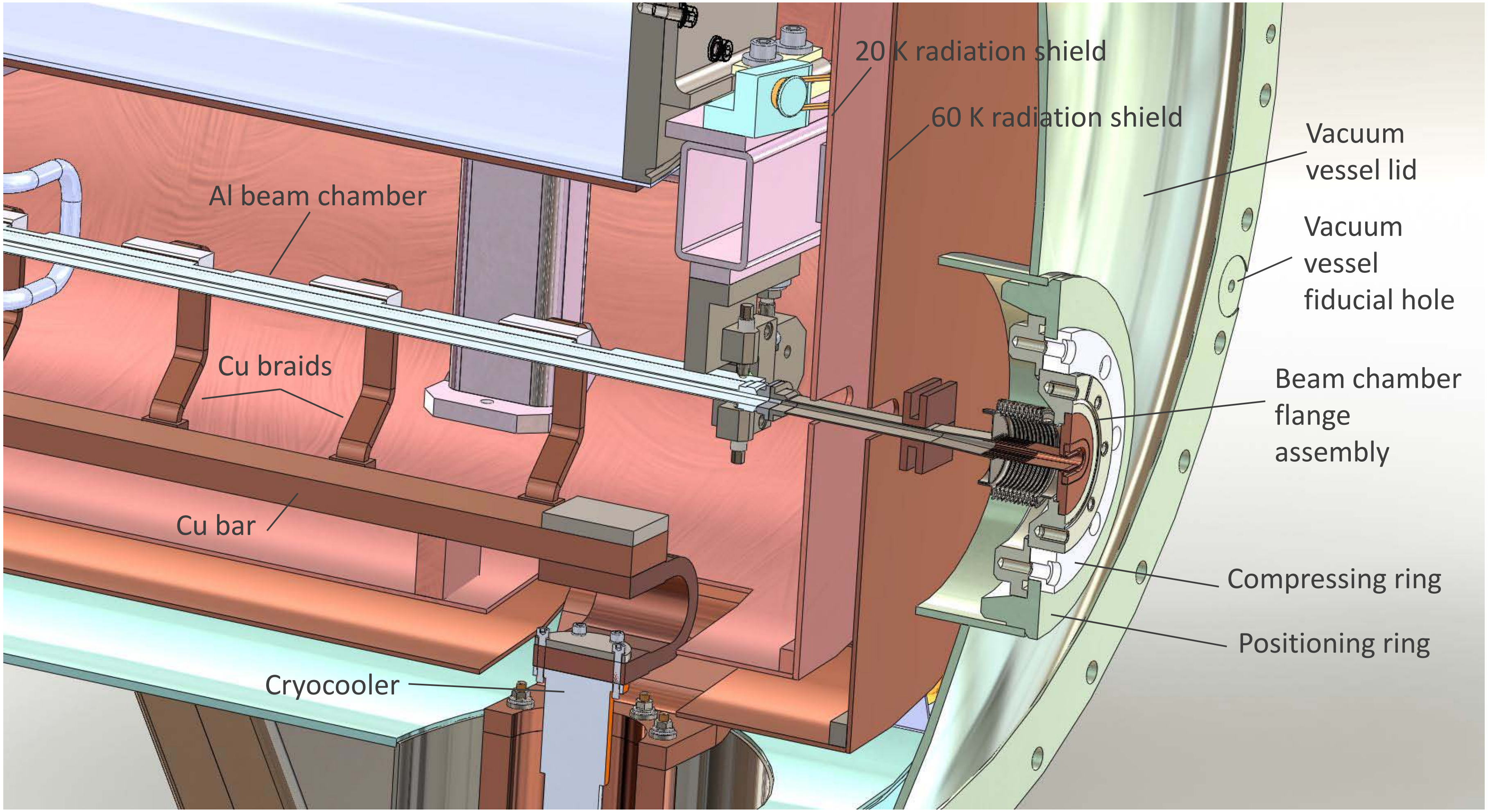


LHe system piping

LHe flows from the LHe vessel into SC magnet cores and returns into the LHe vessel.
He vapor is then recondensed into liquid in the LHe vessel.



Beam chamber connections

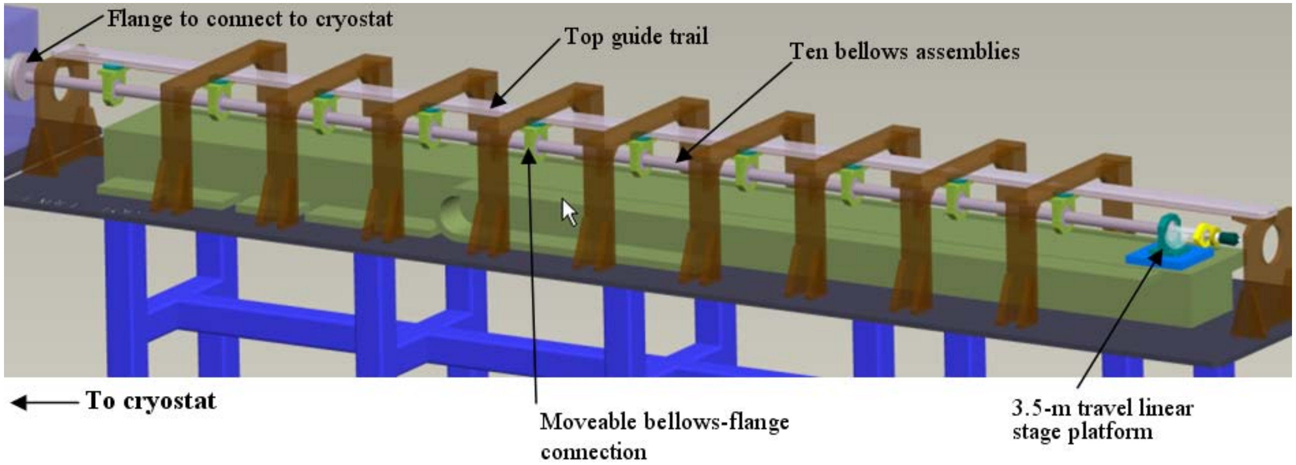


Development of SCU measurement facility

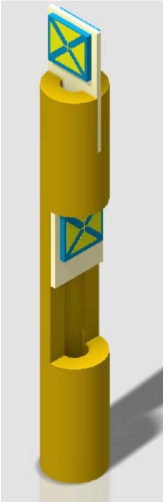
- After fabrication, SC coils are characterized in the vertical LHe bath cryostat. A 2-m and 3-m cryostats are available.

- Once the undulator is assembled, the magnetic field will be measured with a horizontal measurement system containing a Hall probe assembly and a rotating coil.
- Measurement system spec is done.
- A design concept is being developed.
- A novel 3-sensor cryogenic Hall probe is being developed.

Design concept for Hall probe linear drive



3-sensor cryogenic Hall probe



Y. Ivanyushenkov, Workshop on superconducting undulators, APS, September 20-21, 2010

Hall probe calibration facility at the Advanced Photon Source

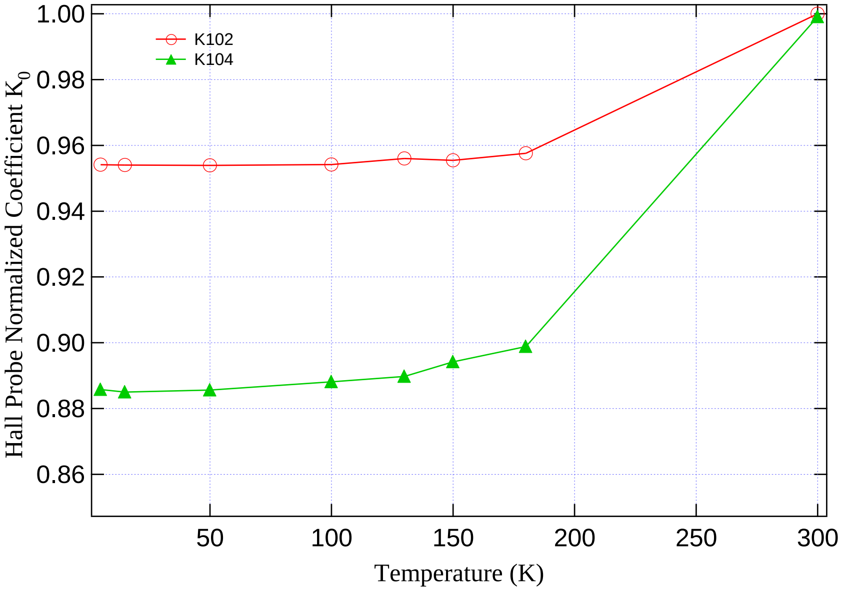
- The reference magnetic field of the calibration electromagnet is measured with NMR probes.
- A small research liquid helium cryostat by Janis is employed to calibrate Hall sensors at temperatures between 5 K and 300 K.

Electromagnet with a set of NMR probes

Janis cryostat with vacuum jacket removed

A custom-made Hall probe holder attached to a cold finger

Two Hall sensors response normalized to room temperature



More details in the talk by Melike Abliz this afternoon.

SCU0 project status and schedule

Task	Status and schedule
Initial R&D phase	Complete
Conceptual design	Complete
Conceptual design review	Passed in February, 2010
Detail design	In progress
Cryostat pressure safety review	Passed in July, 2010
Cryostat production review	September 2010
Cryostat manufacture	November 2010 – Spring 2011
Undulator assembly	Summer 2011
Measurement system design and manufacture	Summer 2010- Summer 2011
Undulator tests	Fall 2011
SCU installation into the ring	Winter 2011-12
SCU beam test	Spring 2012

Why a superconducting technology-based undulator? (2)

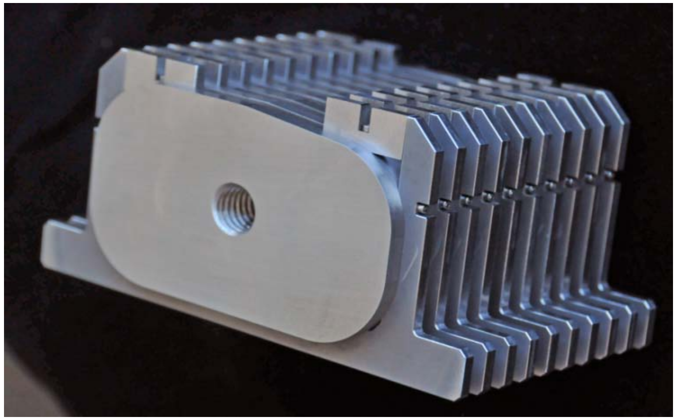
- Superconducting technology-based undulators outperform all other technologies in terms of peak field and, hence, energy tunability of the radiation.
- Superconducting technology allows various types of insertion devices to be made – planar, helical, quasi-periodic undulators, and devices with variable polarization.
- We are starting with a relatively simple technology based on NbTi superconductor. A Nb_3Sn superconductor will offer higher current densities and, therefore, higher peak fields at shorter period lengths.

Conclusions

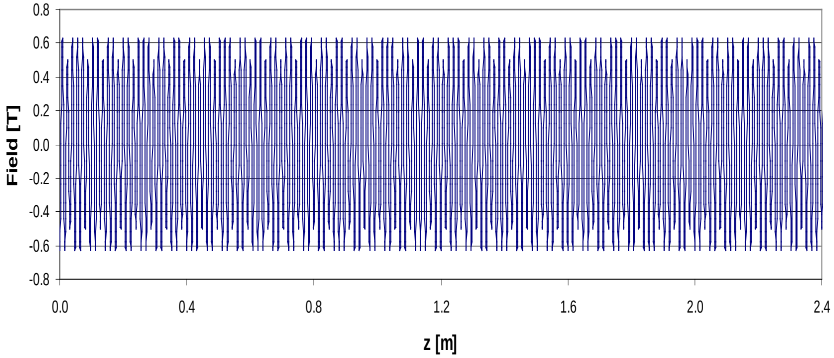
- Superconducting technology opens a new avenue for IDs.
- We are designing and building the first short superconducting test undulator – SCU0.

A new concept - superconducting quasi-periodic undulator (SCQPU)

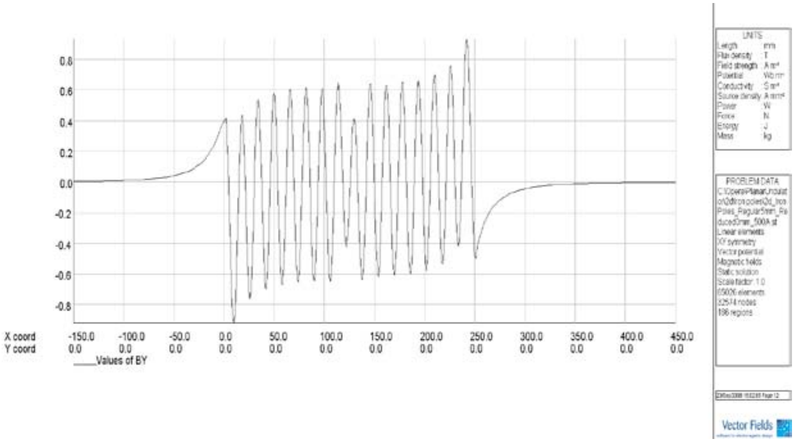
A 10-pole test Al core manufactured in assembled technique.



Magnetic field distribution along the undulator axis used in calculation of photon flux density.



Simulated field profile for a magnetic structure with two non-magnetic poles in the middle.



Calculated on-axis photon spatial flux density from SCQPU. The quasi-periodicity shifts the higher harmonic peak to an energy that will not pass through the monochromator.