Superconducting Undulator Development Status

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on behalf of

Superconducting Undulator Project Team

APS User Meeting, December 16, 2009

Superconducting undulator project team

APS:

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

Visitors from

Budker Institute, Russia:

- Nikolay Mezentsev
- Vasily Syrovatin

Collaborators:

- Sasha Makarov,
  Technical Division, FNAL

Scope

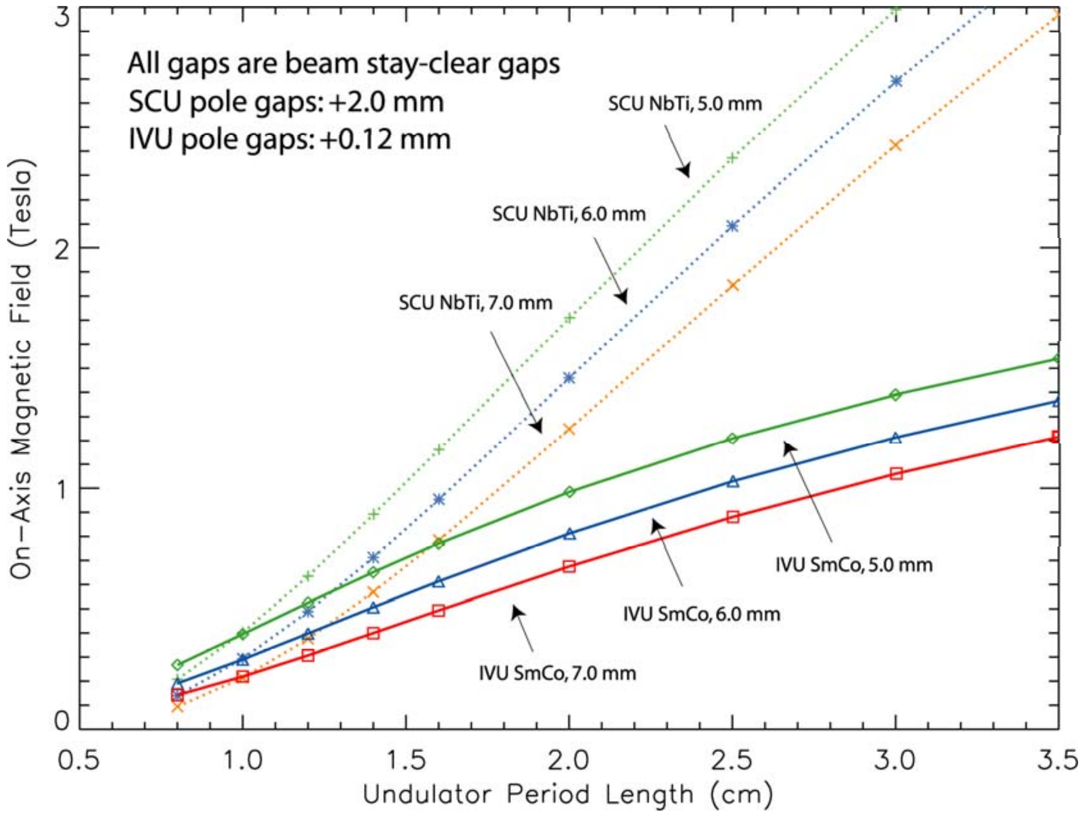
- Why a superconducting technology-based undulator ?
- R&D program on superconducting undulator (SCU) for the APS
- Superconducting undulator road map
- Superconducting test undulator (SCU0)
- Development of SCU measurement facility
- A new concept – a quasi-periodic superconducting undulator
- Conclusions

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

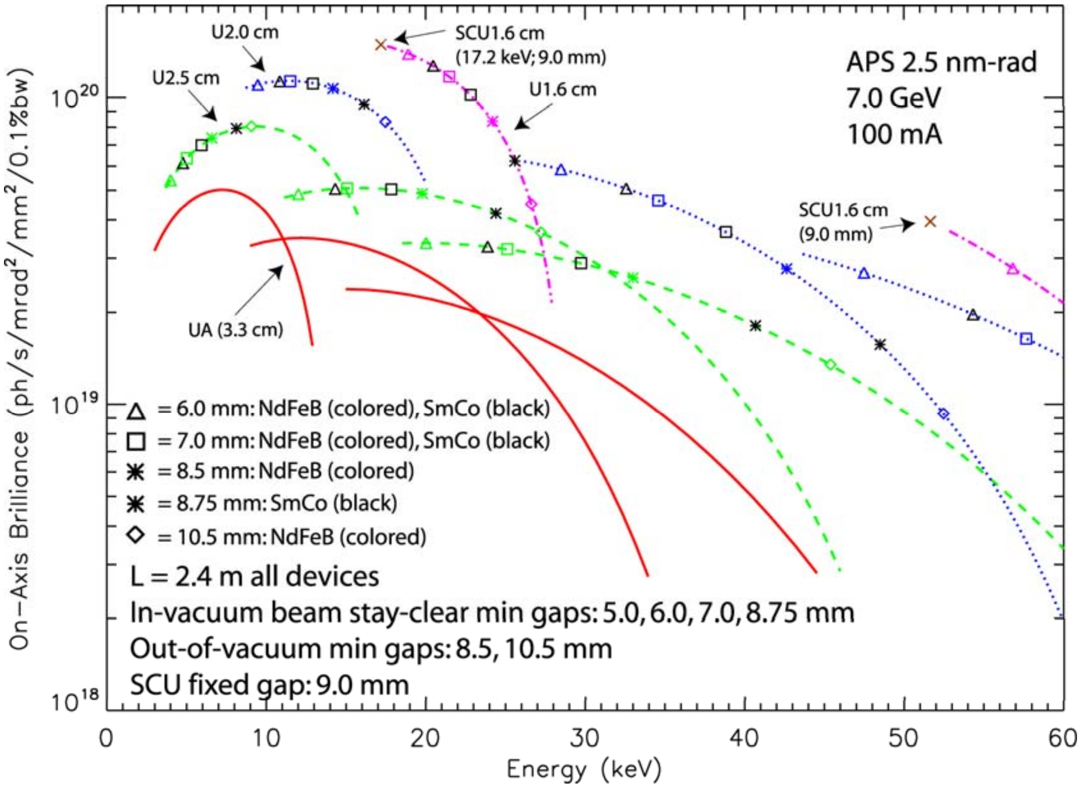
Peak field for various ID technologies



Comparison of the magnetic field in the undulator midplane for in-vacuum SmCo undulators (B_{eff}) and NbTi superconducting undulators (B_0) versus undulator period length for three beam stay-clear gaps. The actual undulator pole gaps were assumed to be 0.12 mm larger for the IVUs and 2.0 mm larger for the SCUs. Under these assumptions, an SCU can achieve the same field at about 2 mm larger gap than an IVU.

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

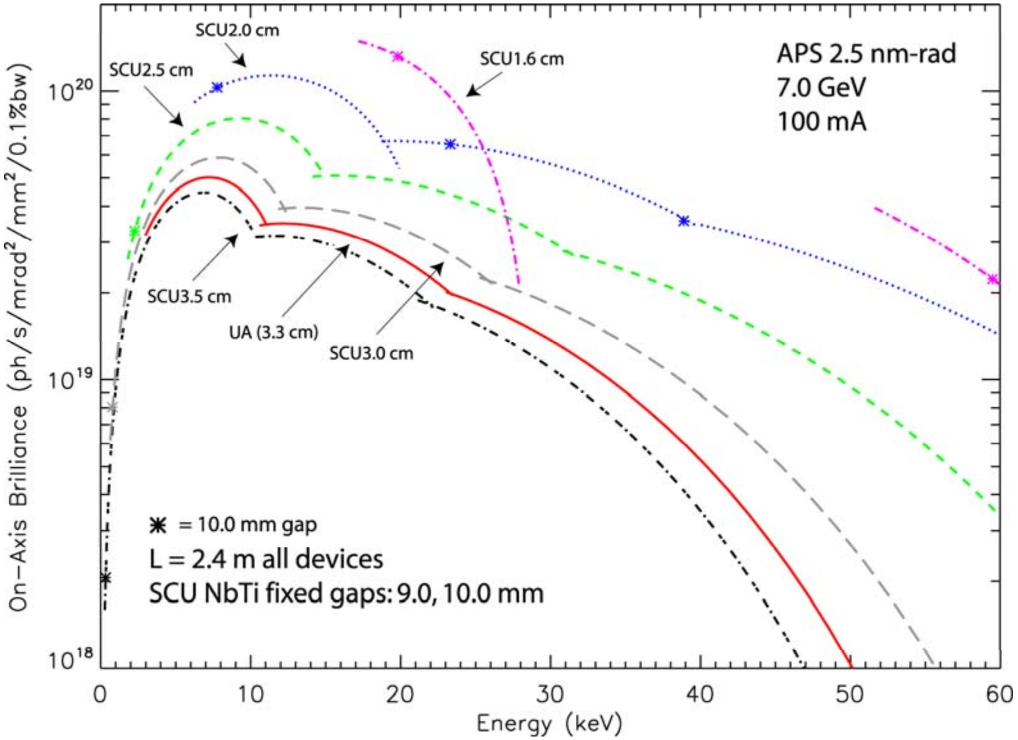
Brilliance tuning curves for various ID technologies



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

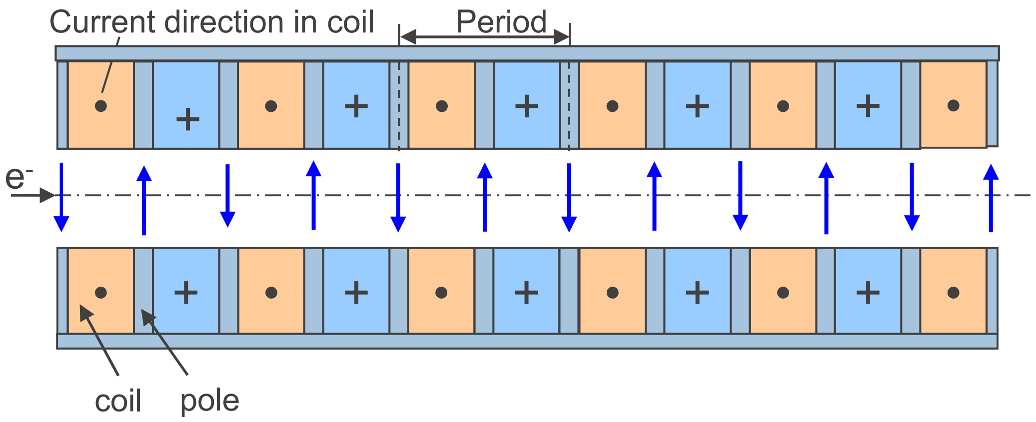
Why a superconducting technology-based undulator ?

- Superconducting technology-based undulators outperform all other technologies in terms of peak field and, hence, energy tunability of the radiation.

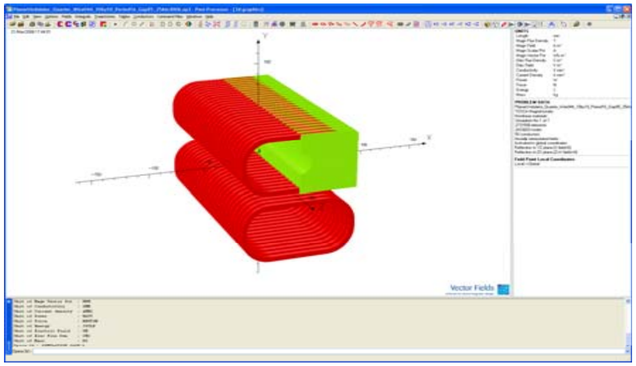
- Superconducting technology opens a new avenue for IDs.

Superconducting planar undulator topology

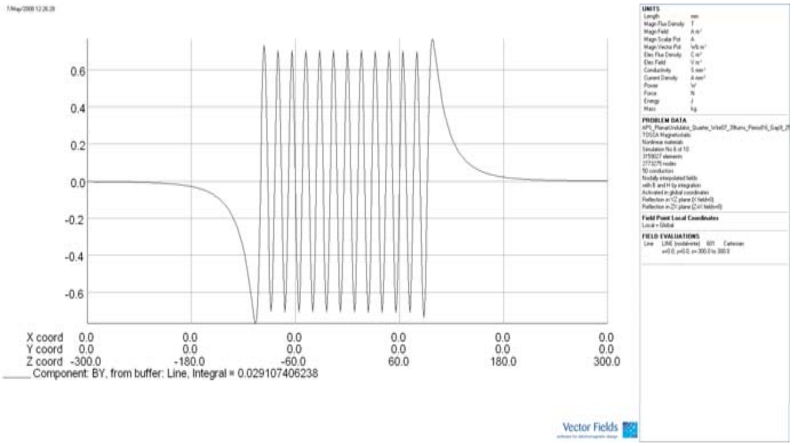
Current directions in a planar undulator



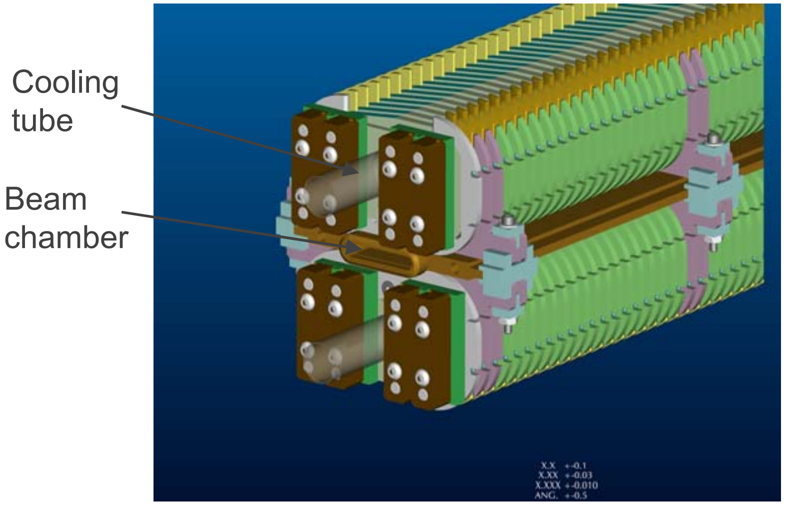
Planar undulator winding scheme



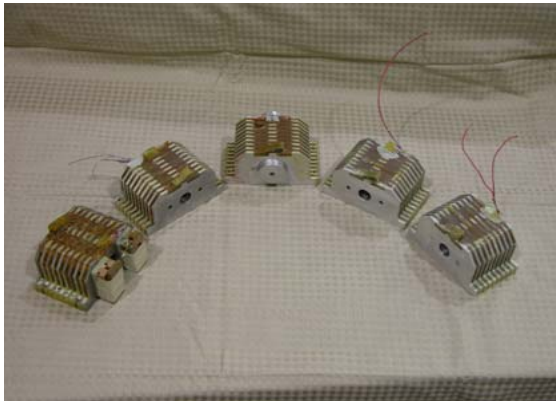
On-axis field in a planar undulator



Magnetic structure layout

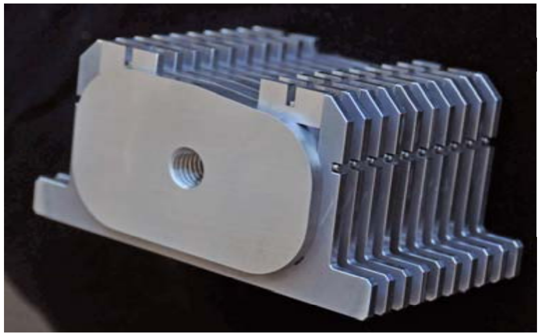


Coil fabrication R&D



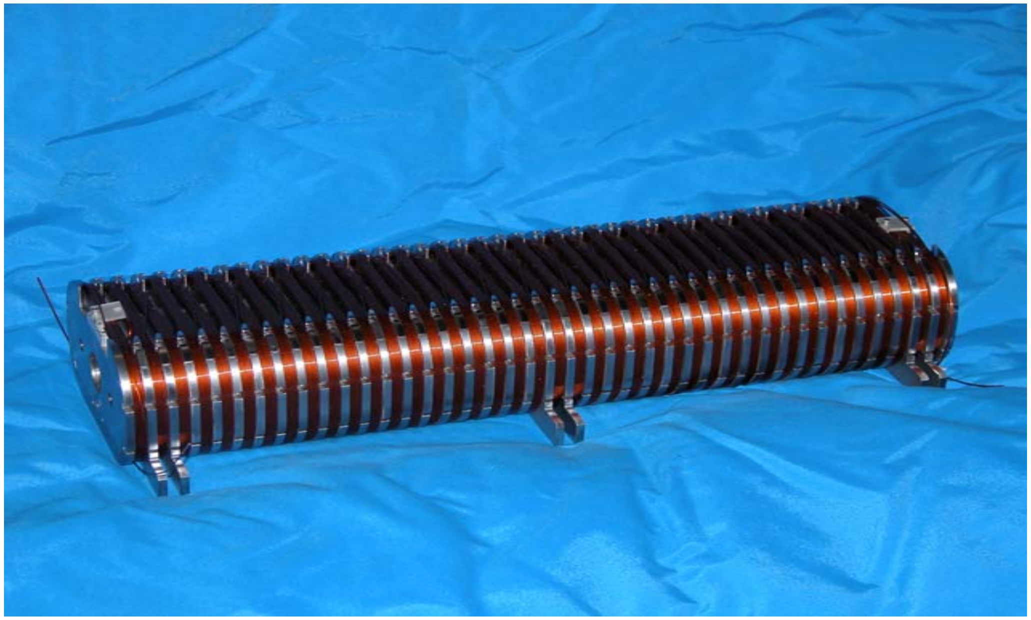
First five 10-pole test coils

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 assembly 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

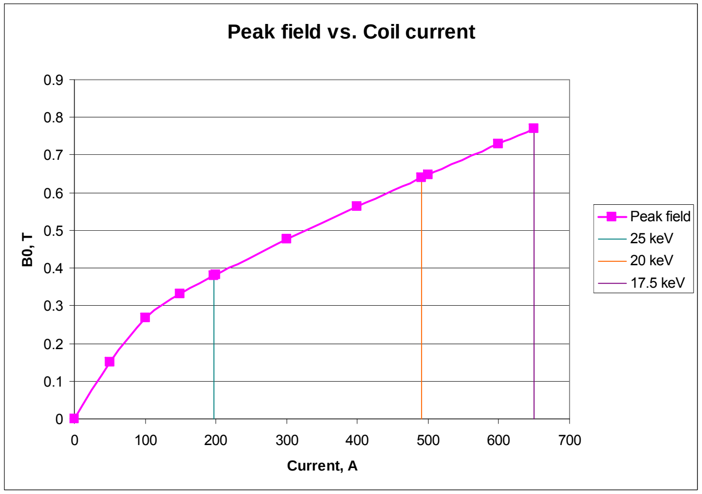
  core material – steel 1006-1008; pole material – steel 1006-1008;

  SC wire – NbTi round wire, 0.74 mm diameter.

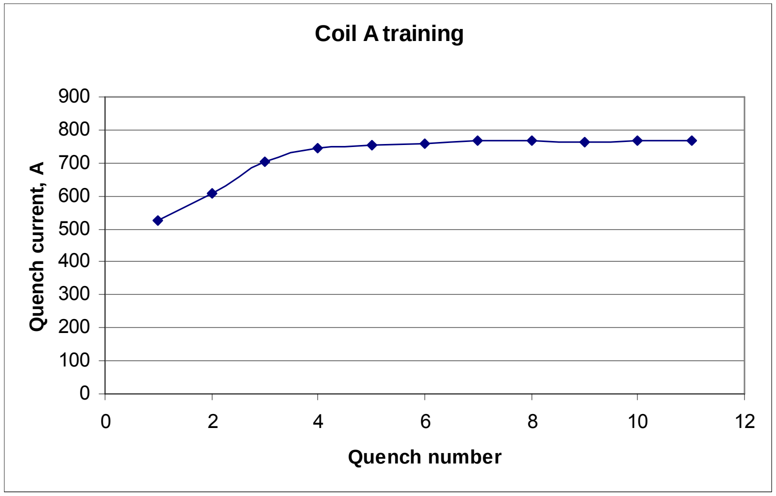
- Assembly immersed into liquid helium (LHe) in the vertical cryostat.
- Level of LHe in the cryostat bore is measured with level sensor, LHe is topped up when required.
- Hall probe is driven by a mechanical stage that is equipped with a position encoder outside the cryostat.
- LabView is employed to 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).

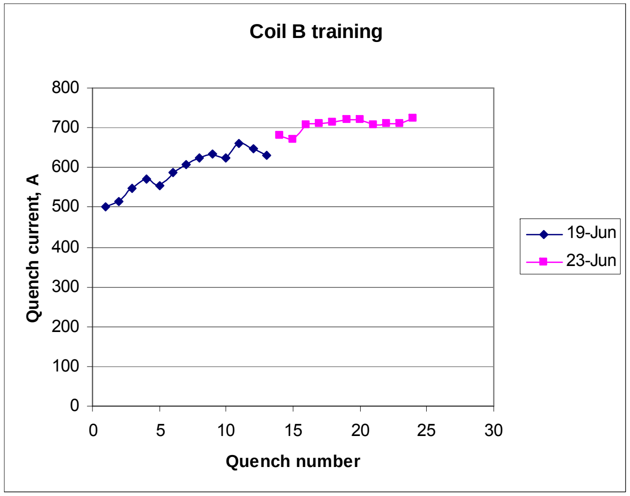
42-pole magnetic assembly →

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)

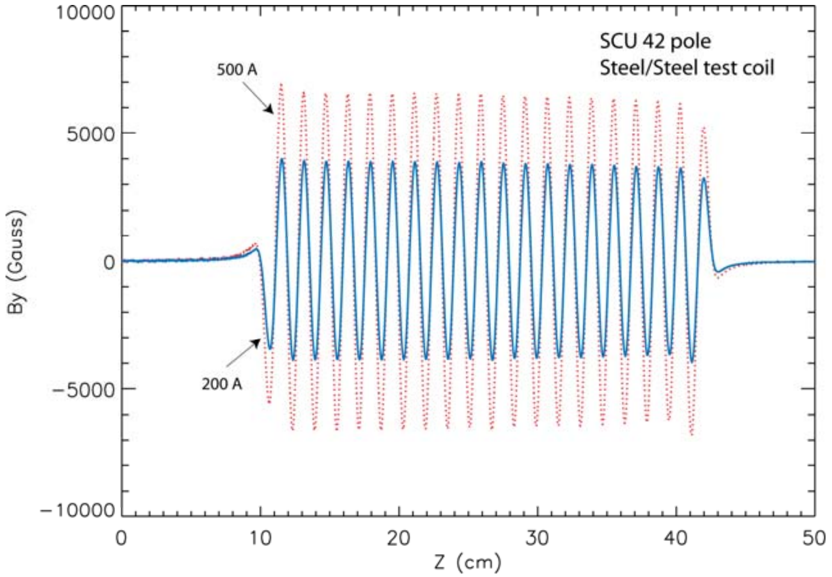




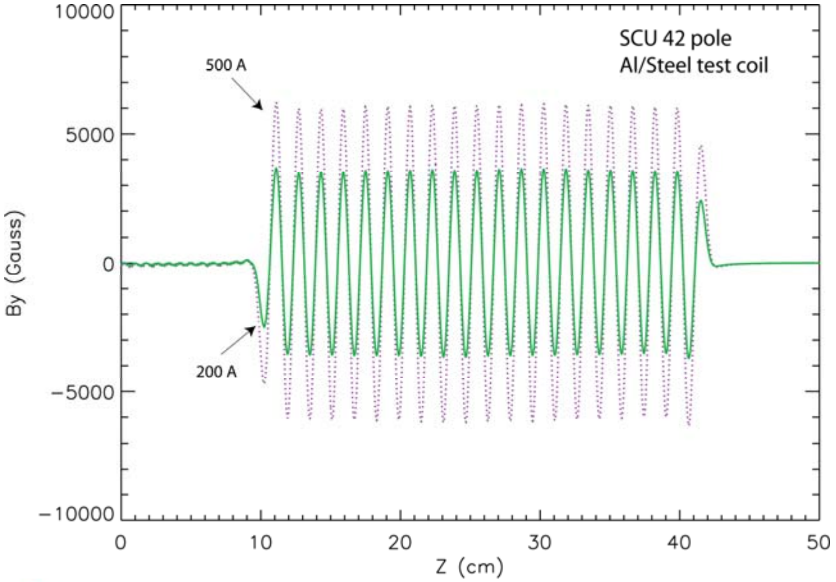
Coil A max current: 760 A, max current reached after 5 quenches

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

Measured magnetic field profiles

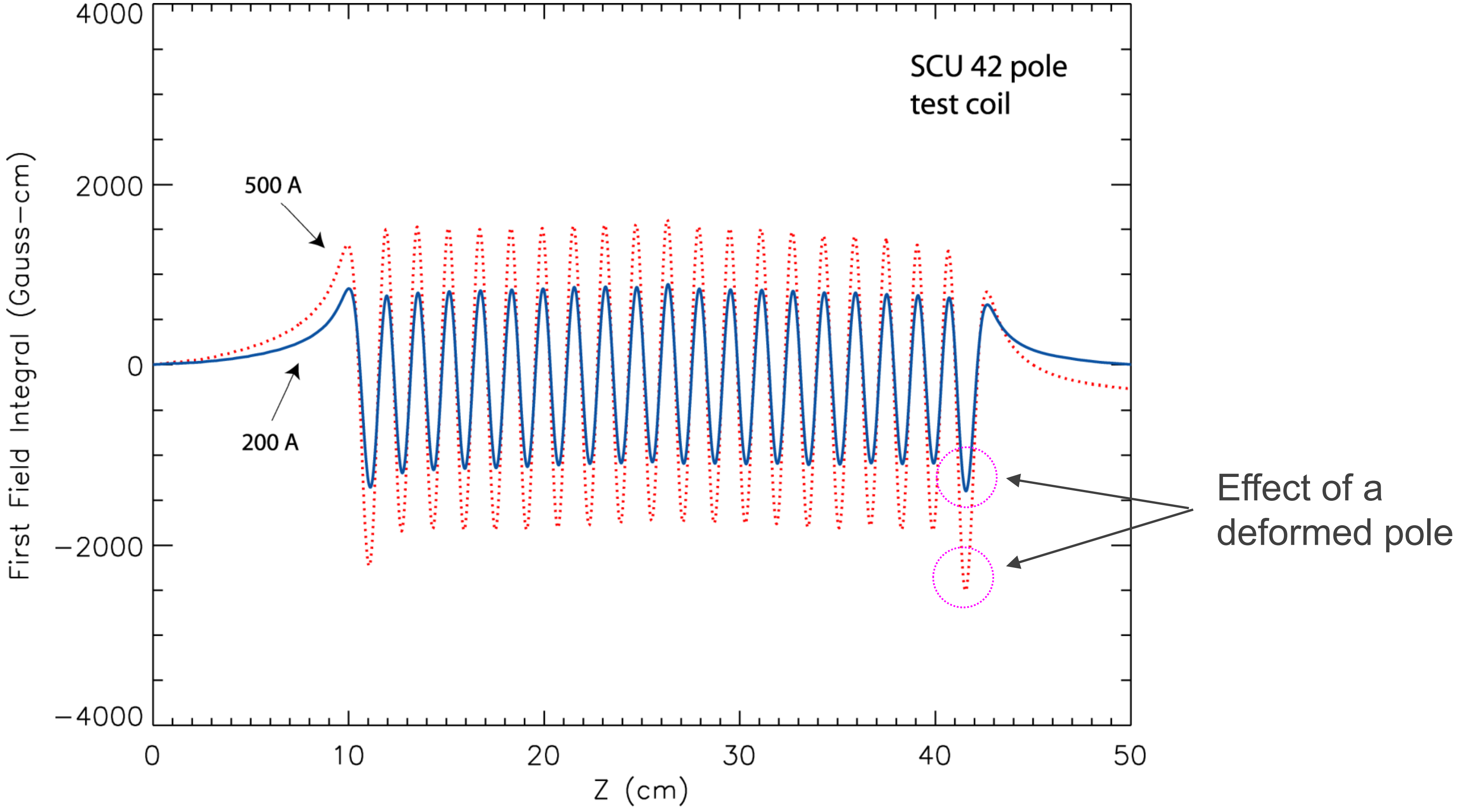


- 42-pole assembly #1 with Steel core / Steel poles
- Magnetic fields were measured for currents of 200 A and 500 A at a nominal gap of 9.50 mm (from July, 2009).
- The effective magnetic fields are 3815 Gauss (200 A) and 6482 Gauss (500 A).



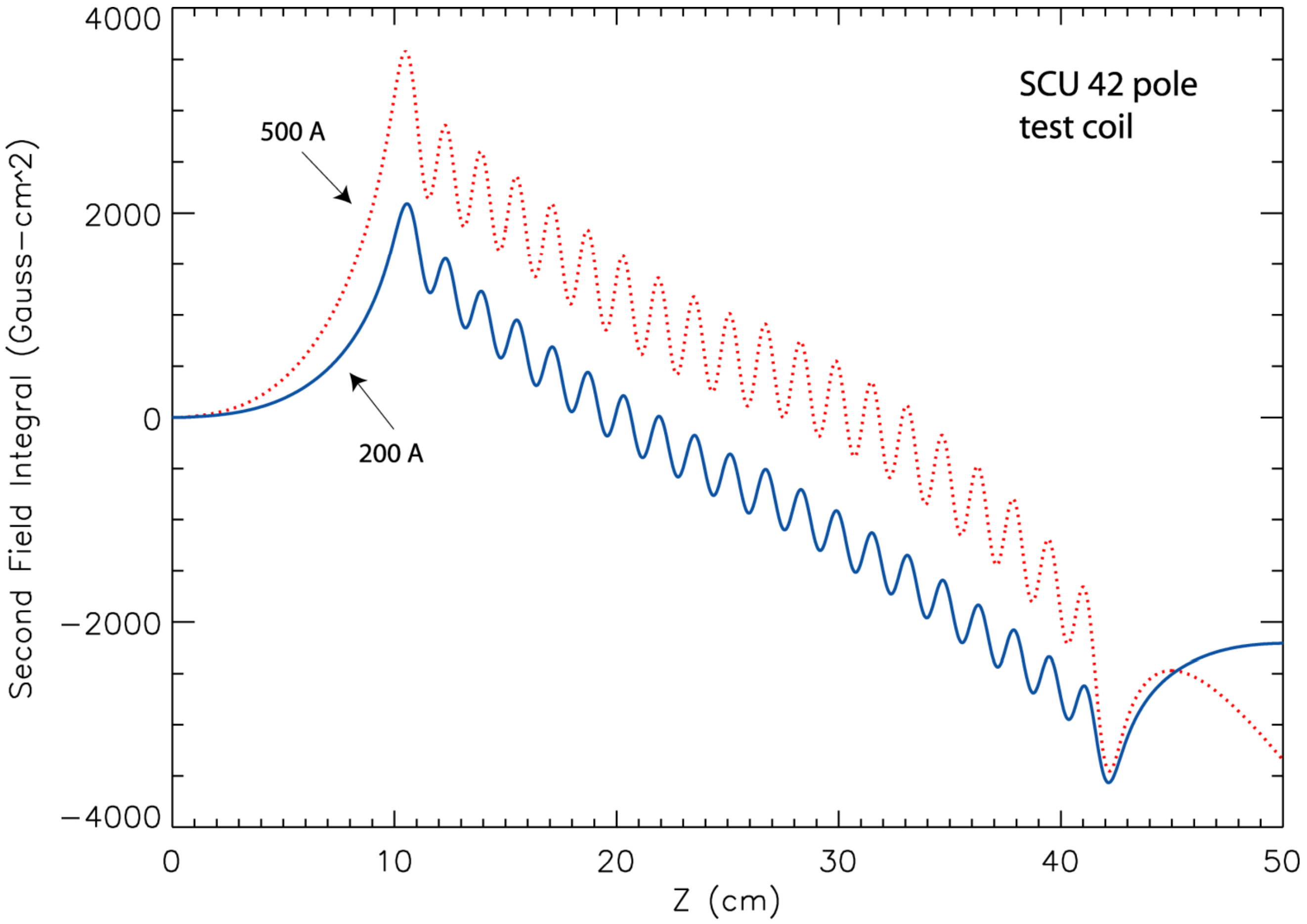
- 42-pole assembly # 2 with Al core / Steel poles
- Magnetic fields were measured for currents of 200 A and 500 A at a nominal gap of 9.50 mm (from October, 2009).
- The effective magnetic fields are 3620 Gauss (200 A) and 6140 Gauss (500 A).

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



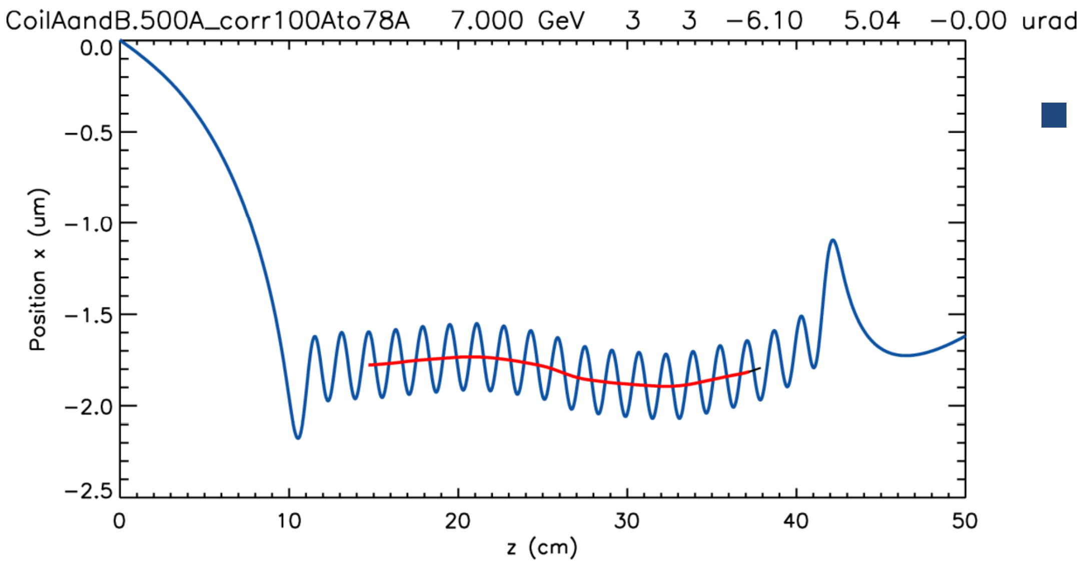
- The measured first field integrals are 2 G-cm (200 A) and -261 G-cm (500 A) (because of deformed pole).
- Storage ring requirement is < 50 G-cm

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

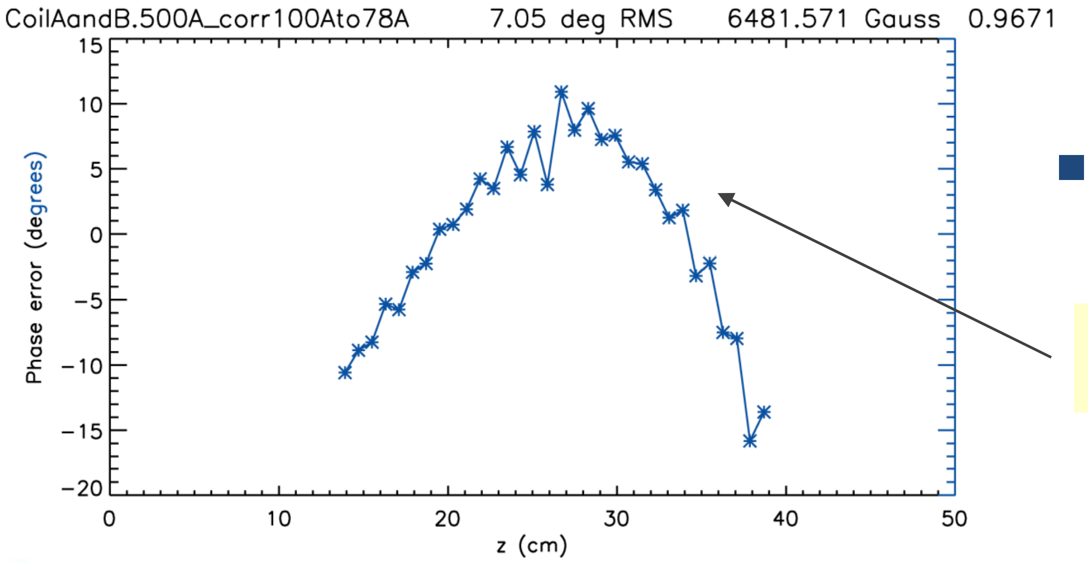


- The measured second field integrals are -2208 G-cm^2 (200 A) and -3345 G-cm^2 (500 A).
- Storage ring requirement is < 100,000 G-cm^2

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



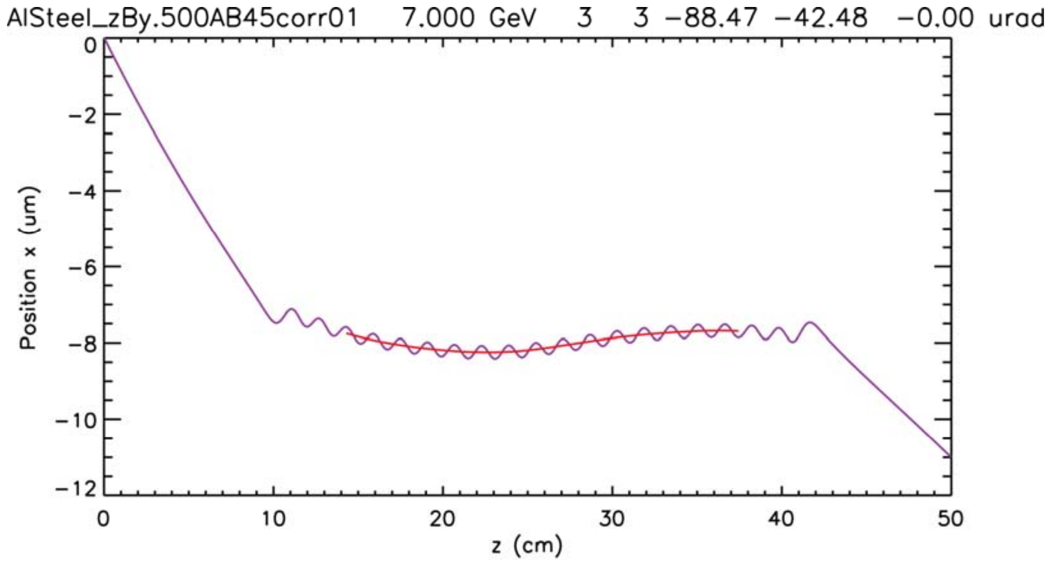
- Calculated electron trajectory and average trajectory for 7.0 GeV beam energy.



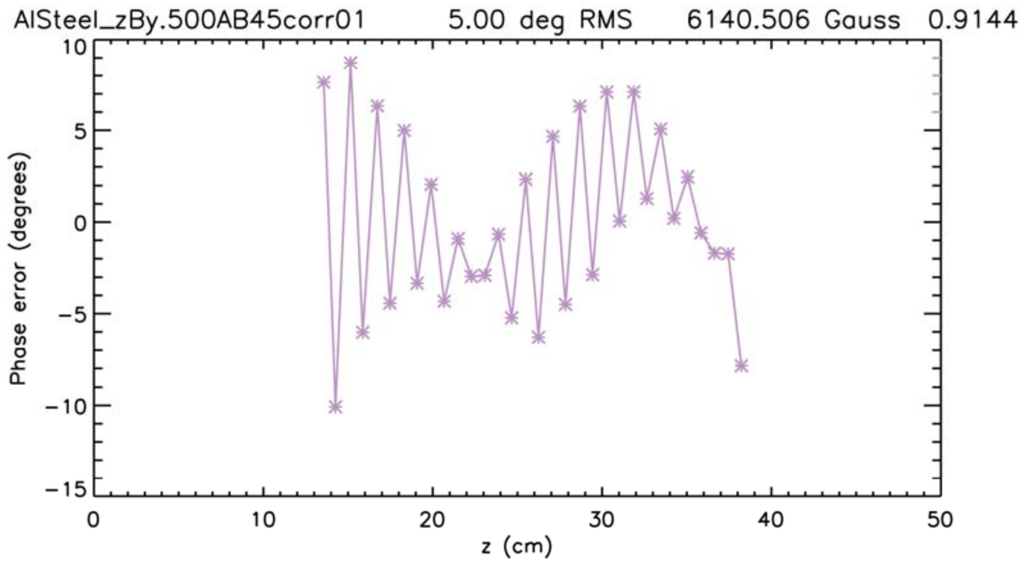
- The measured rms phase error is 7.1 degrees for 500 A current.

This shape is typical for an undulator with a tapered gap

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).

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°

Superconducting undulator road map

"Believe you CAN, because you can, whatever anyone else said to you " Henry Ford

Feasibility study → Superconducting undulator technology development → Ultimate superconducting undulator

2008-2009	2009-2011	2011-2012	2012-2013

SCU0
Period length 1.6 cm
Poles 42
Magnetic length 0.33 m

SCU1
Period length 1.6 cm
Poles 144
Magnetic length 1.15 m

SCU2
Period length 1.6 cm
Poles ≈250
Magnetic length ≈ 2.0 m

SCU+
Period length ≈1.2 cm
Peak field ≈ 1 T

SCU++
Period length ≈1.0 cm
Peak field >1 T

Short prototype R&D

R&D
Shorter period -> Magnetic design, new superconductors
Longer length-> Core fabrication and SC wire winding techniques
Cooling system -> lower temperatures, cryogen-free system
Field errors correction techniques
Field measurement techniques

Quasi-periodic SCU

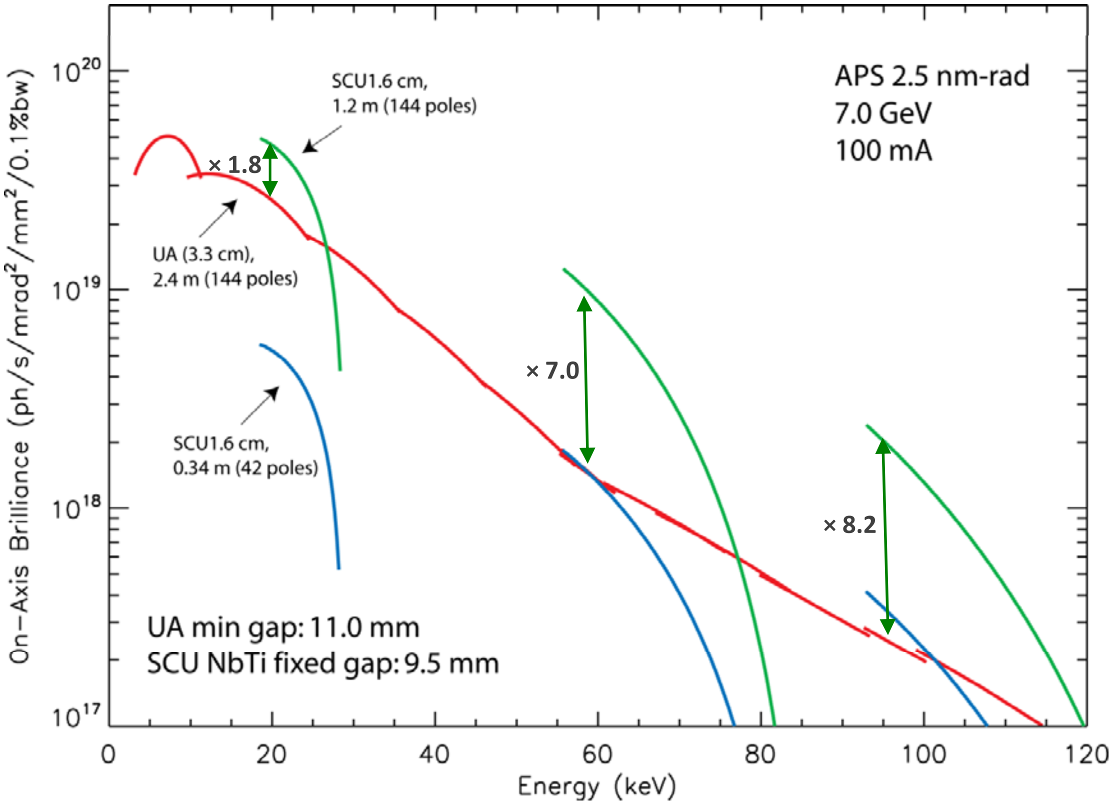
Helical SCU

First two superconducting undulators for the APS

- APS superconducting undulator specifications

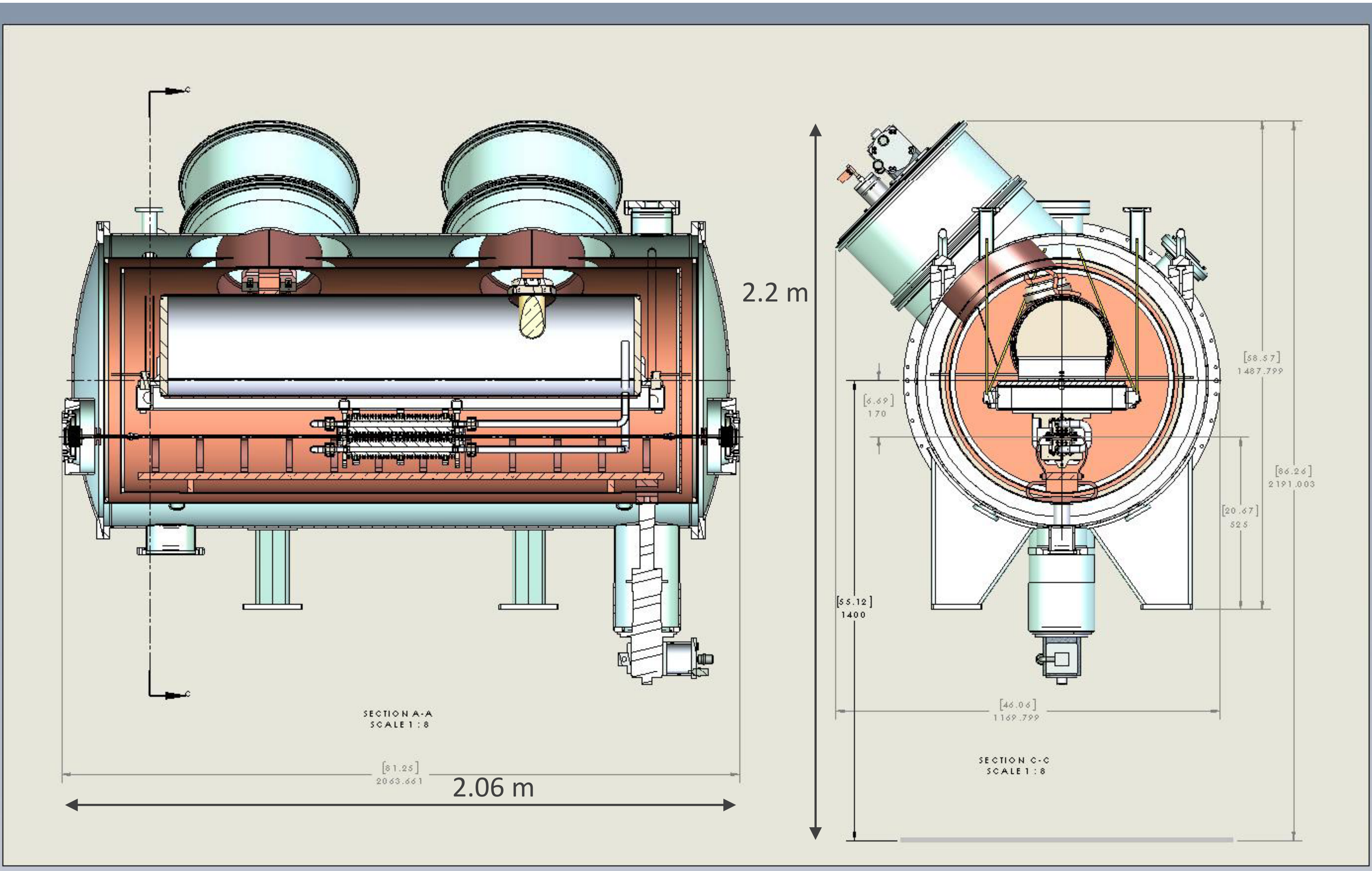
	SCU0	SCU1
Photon energy at 1st harmonic	**20-25 keV**	**20-25 keV**
Undulator period	**16 mm**	**16 mm**
Magnetic length	**0.33 m**	**1.15 m**
Cryostat length	**≈ 2.0 m**	**≈ 2.0 m**
Beam stay-clear dimensions	**7.0 mm vertical × 36 mm horizontal**	**7.0 mm vertical × 36 mm horizontal**
Magnetic gap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

Expected performance of SCU0 and SCU1

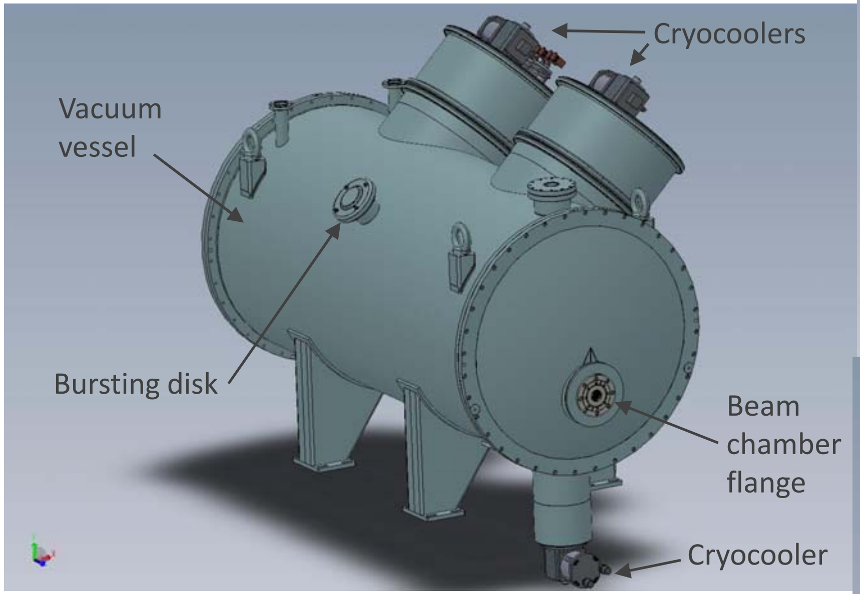


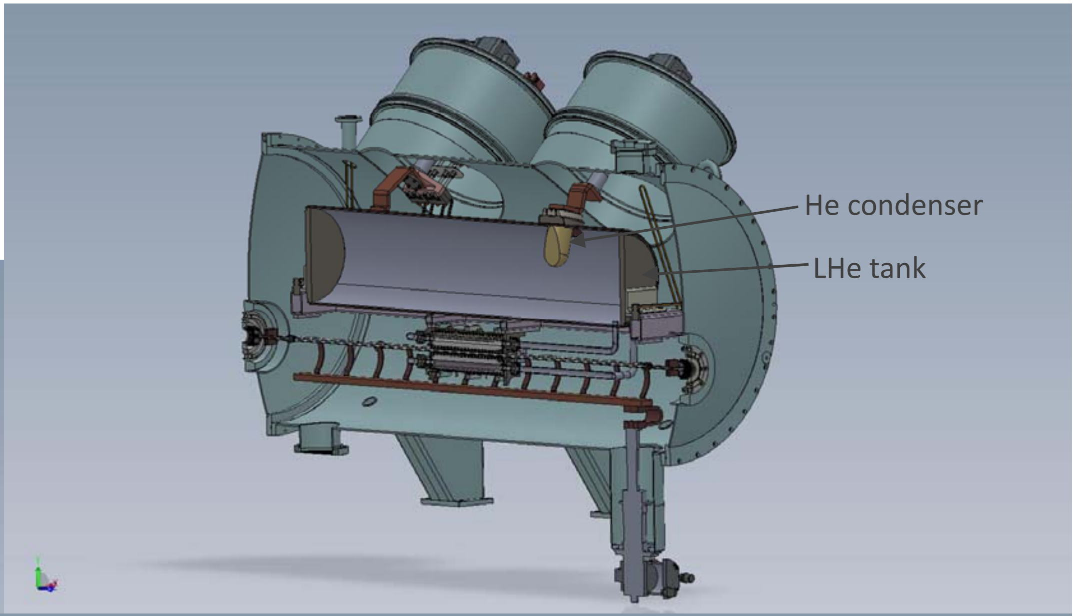
- Tuning curves for odd harmonics for two planar 1.6-cm-period NbTi superconducting undulators (42 poles, 0.34 m long and 144 poles, 1.2 m long) versus the planar NdFeB permanent magnet hybrid undulator A (144 poles, 3.3 cm period and 2.4 m long). Reductions due to magnetic field error were applied the 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.

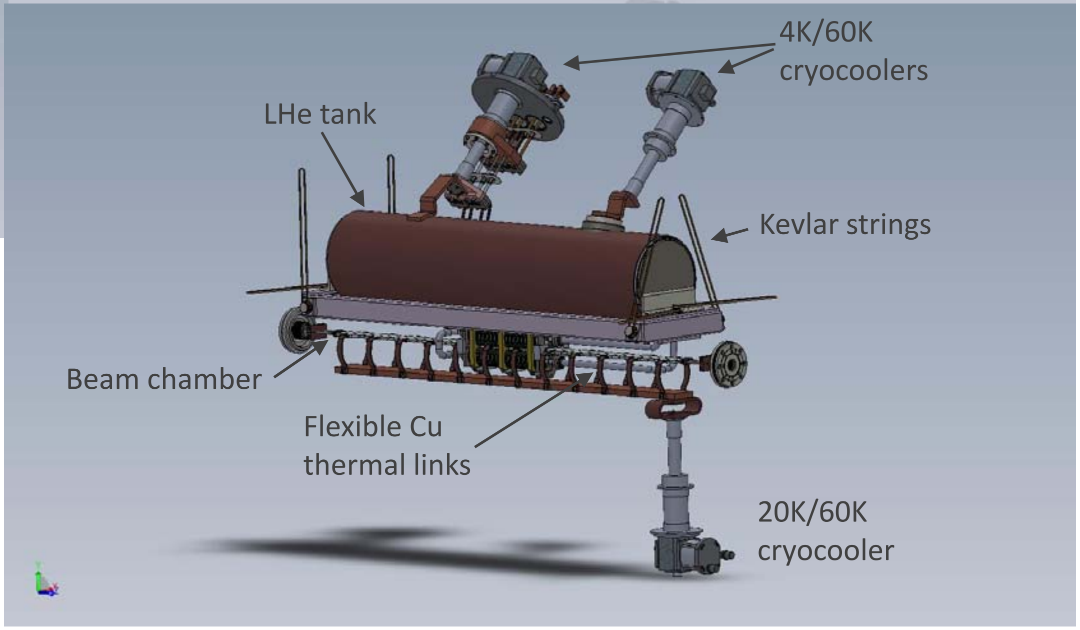
SCU0 layout


2.2 m
[58.57]
1487.799
[6.69]
170
[86.26]
2191.003
[20.67]
525
[55.12]
1400
[46.06]
1169.799
SECTION A-A
SCALE 1 : 8
[81.25]
2063.661
2.06 m
SECTION C-C
SCALE 1 : 8

SCU0 design details



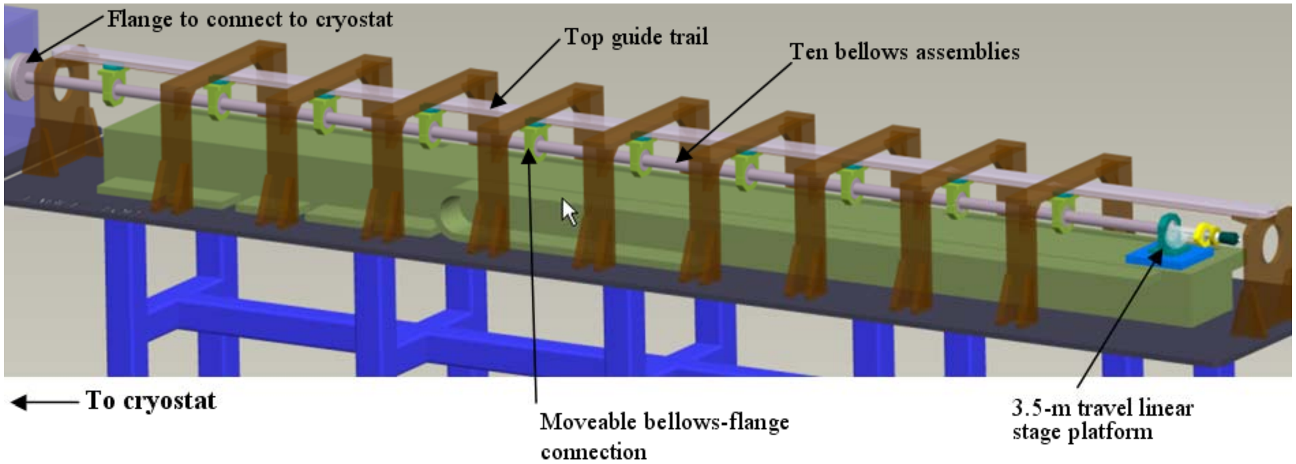




Development of SCU measurement facility

- After fabrication, SC coils are characterized in the vertical LHe cryostat

- Once the undulator is assembled, the magnetic field will be measured with a horizontal Hall probe. The position of the Hall probe in the undulator beam chamber bore will be precisely measured with a laser interferometer.



Hall probe calibration facility at the Advanced Photon Source

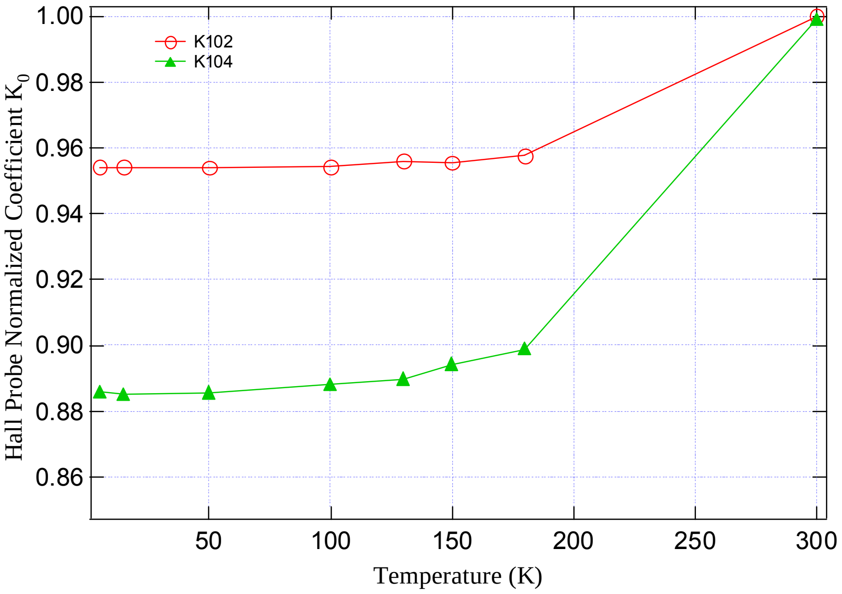
- The reference magnetic field of the calibration electromagnet is measured with NMR probes.
- A small research liquid helium cryostat by Janis is employed to calibrate Hall sensors at temperatures between 5 K and 300 K.

Electromagnet with a set of NMR probes

Janis cryostat with vacuum jacket removed

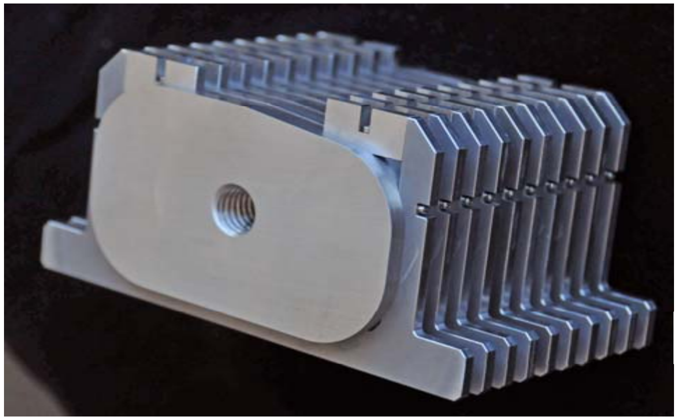
A custom-made Hall probe holder attached to a cold finger

Two Hall sensors response normalized to room temperature

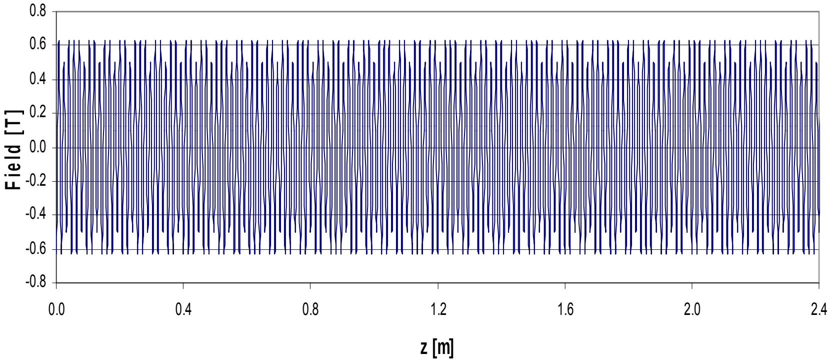


A new concept - superconducting quasi-periodic undulator (SCQPU)

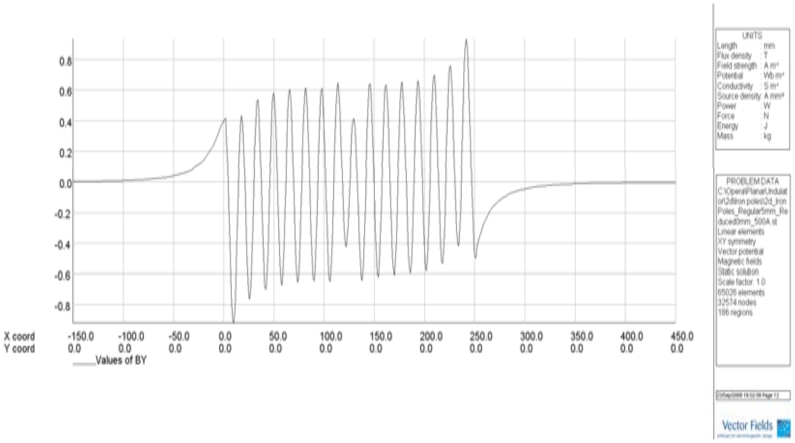
A 10-pole test Al core manufactured in assembled technique.



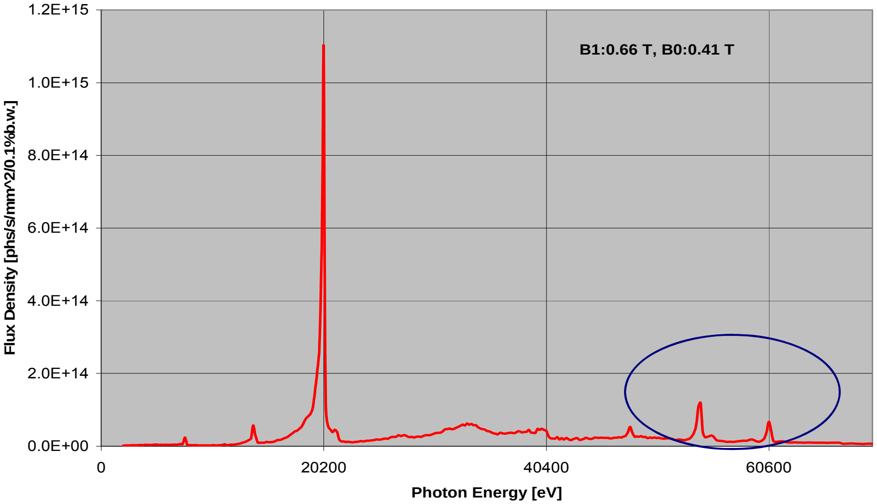
Magnetic field distribution along the undulator axis used in calculation of photon flux density.



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.



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 combined with increased margin in operation temperature. HTS superconductors operating at temperatures around and above 77 K will allow the use of simpler (less costly) cooling systems.

Conclusions

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

And one more thing

The success of this project heavily depends on our joint efforts.

“Coming together is a beginning; keeping together is progress;
working together is success.”
“If everyone is moving forward together, then success takes care
of itself.”
Henry Ford