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Status of R&D on superconducting undulator for the APS

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on behalf of SCU Project Team

U.S. Department of Energy

UChicago ▸ Argonne LLC

Office of Science
U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

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Scope

- Why a superconducting technology-based undulator ?
- Calculated performance of superconducting ID
- Examples of superconducting undulators and wigglers
- R&D program on superconducting undulator
- Planar undulator topology
- Short 42-pole prototype test results:
  - Coil training
  - Coil excitation
  - Field profile
  - Magnetic field phase errors and spectral performance
- Quasi-periodic superconducting undulator
- Next steps
- Conclusions

Why a superconducting technology-based undulator ?

- A superconducting undulator is

  an electromagnetic undulator which employs high current superconducting windings for magnetic field generation -

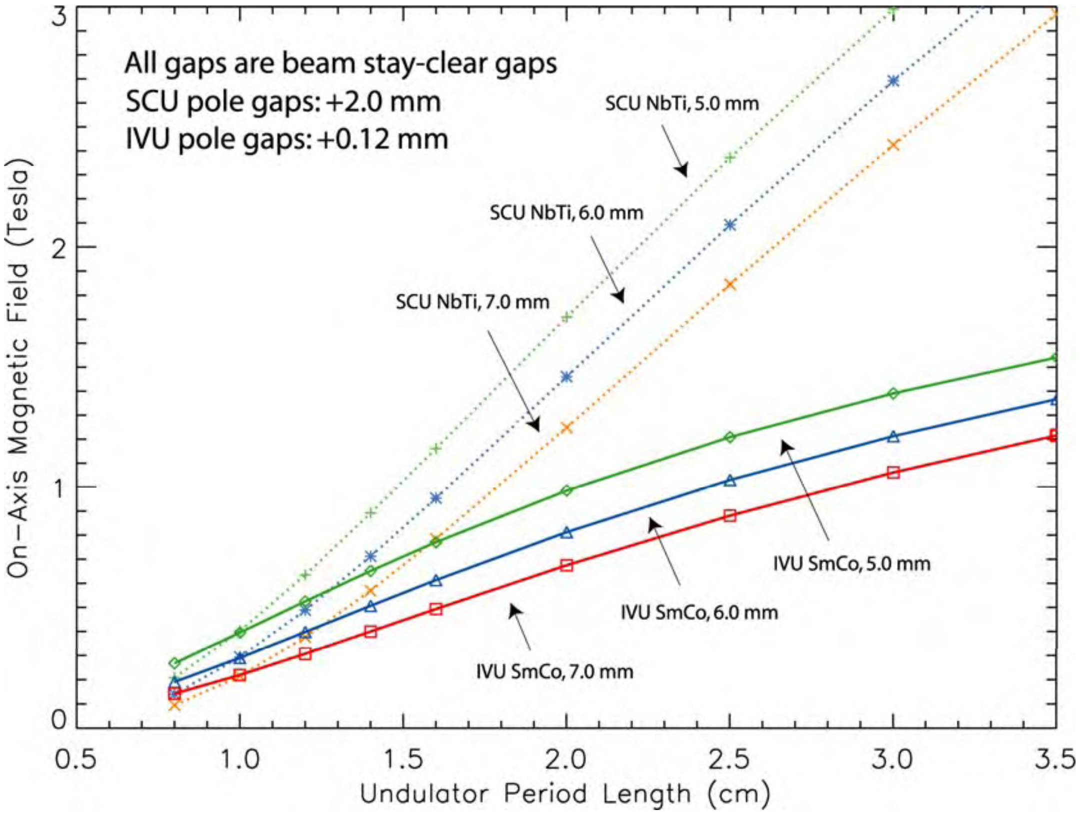
  total current in winding block is up to 10-20 kA -> high peak field

  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

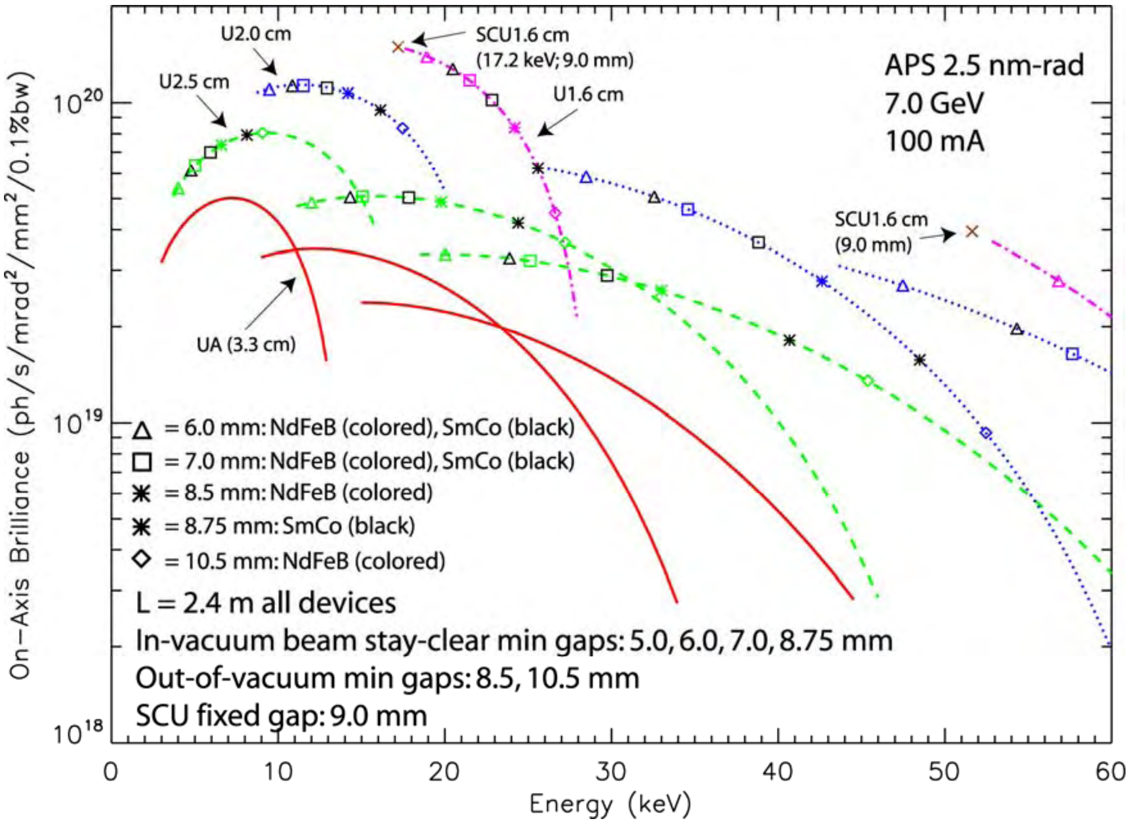
Peak field for various ID technologies



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, about 2 mm is gained in beam stay-clear gap for a 1.6 cm period undulator.

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

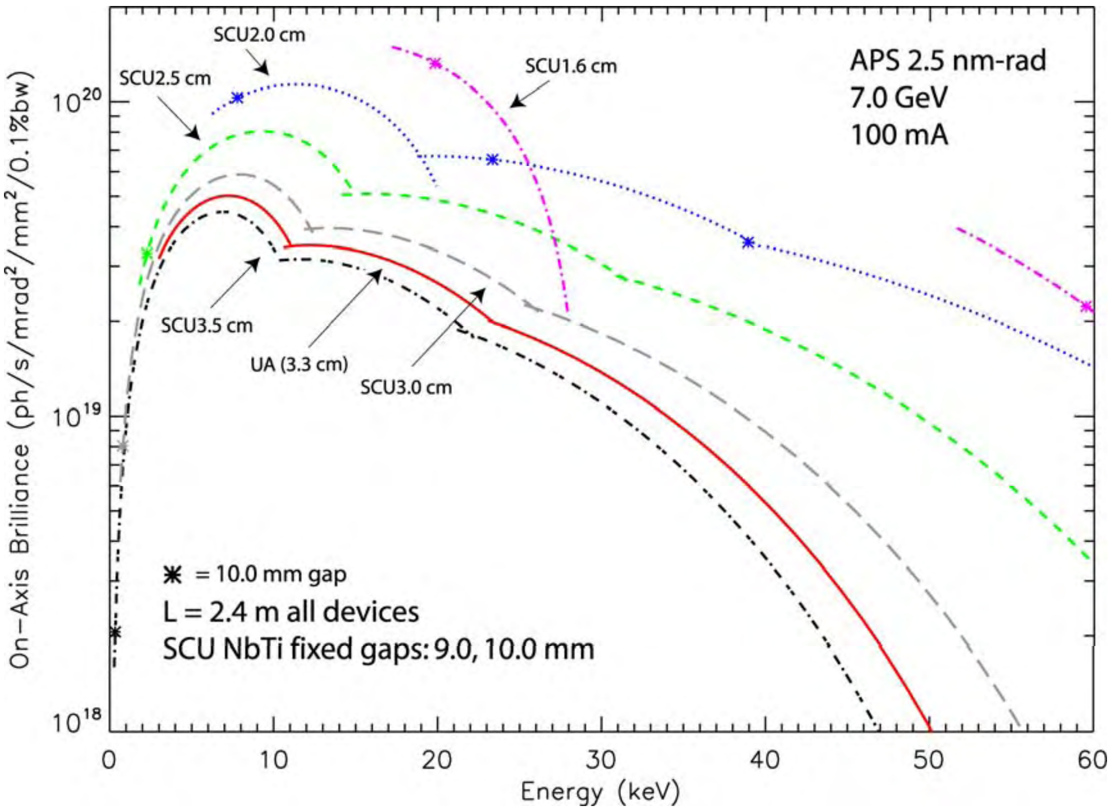
Brilliance tuning curves for various ID technologies



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.

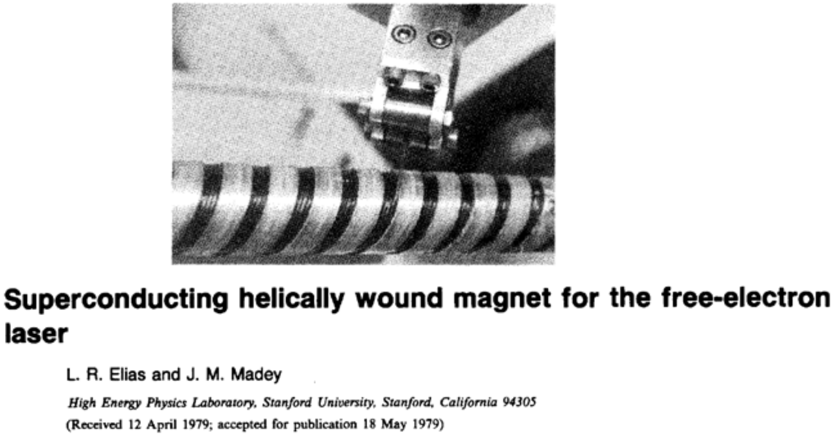
R. Dejus, M. Jaski, and S.H. Kim, "On-Axis Brilliance and Power of In-Vacuum Undulators for The Advanced Photon Source**",** MD-TN-2009-004

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 yet somewhat unexplored avenue for IDs

Examples of superconducting IDs



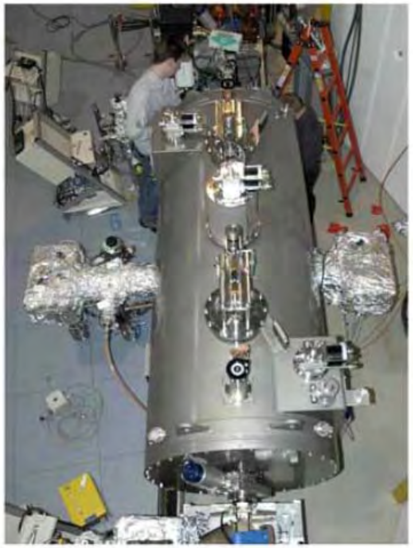
Superconducting helically wound magnet for the free-electron laser

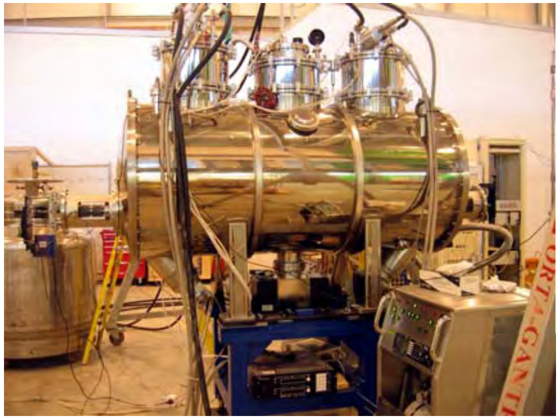
L. R. Elias and J. M. Madey

High Energy Physics Laboratory, Stanford University, Stanford, California 94305

(Received 12 April 1979; accepted for publication 18 May 1979)

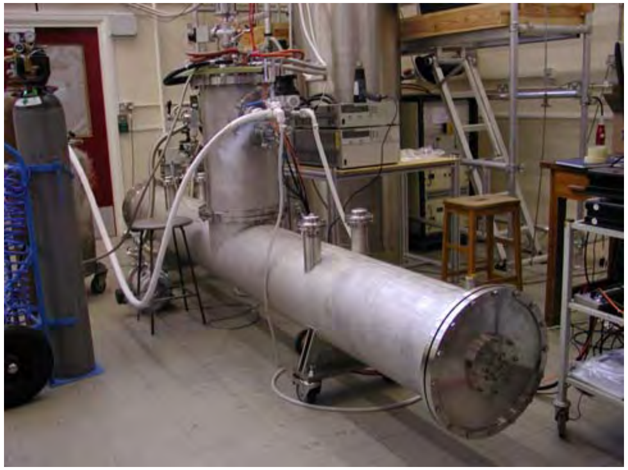
SC planar undulator built by ACCEL for ANKA





49 pole SC wiggler for Diamond Light Source by Budker Institute

4-m long SC helical undulator built by RAL for ILC positron source project



R&D on superconducting undulator for the APS

- APS superconducting undulator specifications

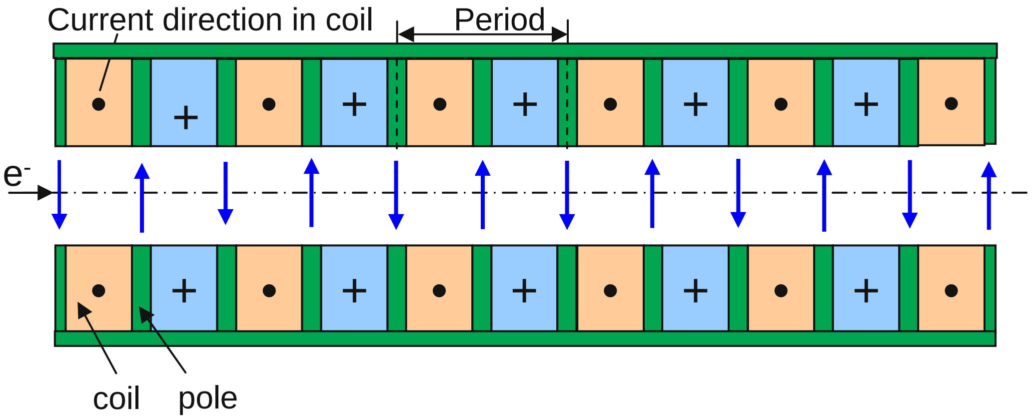
Electron beam energy	**7.0 GeV**
Photon energy at 1st harmonic	**20-25 keV**
Undulator period	**16 mm**
Magnetic length	**1.2 m or 2.4 m**
Maximum cryostat length	**3.5 m**
Beam stay-clear dimensions	**7.0 mm vertical × 36 mm horizontal**
Magnetic gap	**9.0 mm**

- R&D phase of the project

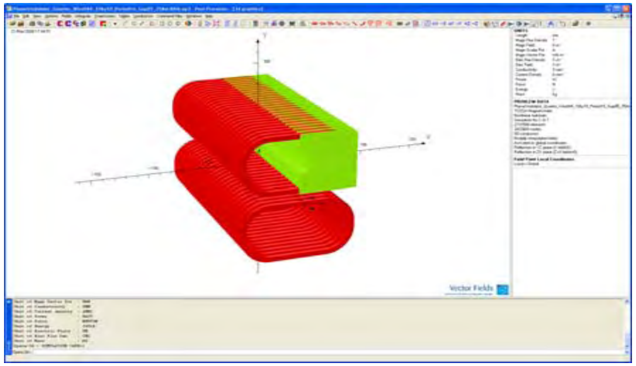
The R&D effort aimed at developing construction techniques for superconducting planar undulators up to 2.4 meters long intensified in 2008. This program involves:
 - magnetic modeling,
 - developing manufacturing techniques,
 - building and testing short prototype magnets,
- and thermal tests of possible cooling schemes.

Superconducting planar undulator topology

Current directions in a planar undulator

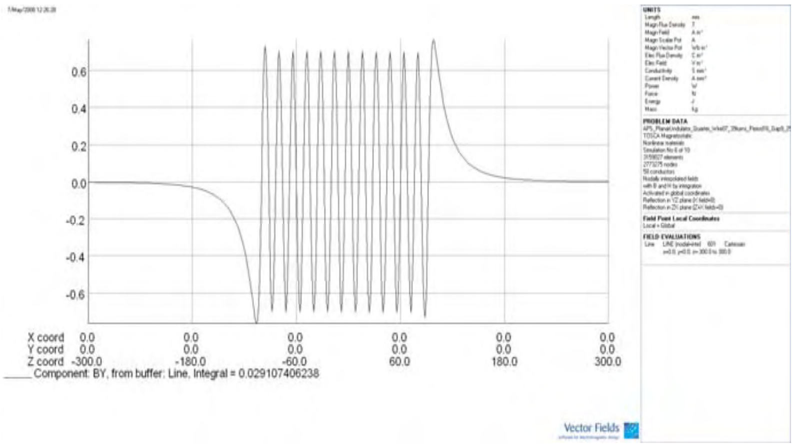


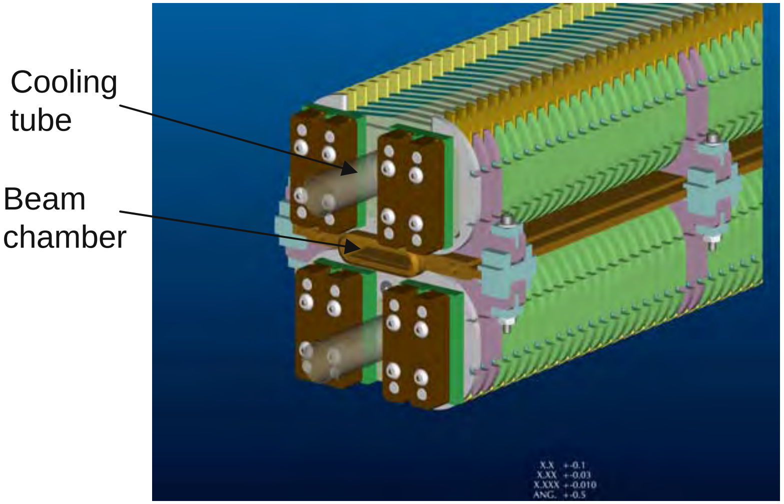
Planar undulator winding scheme



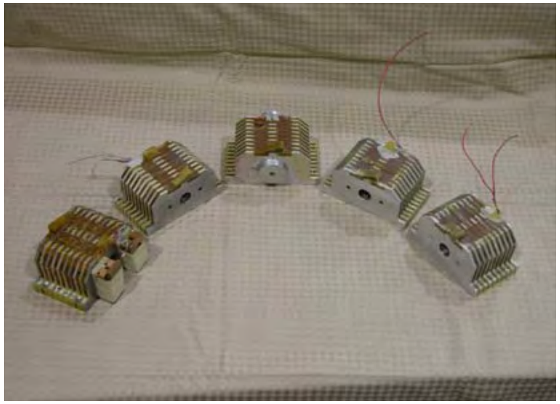
Magnetic structure layout

On-axis field in a planar undulator





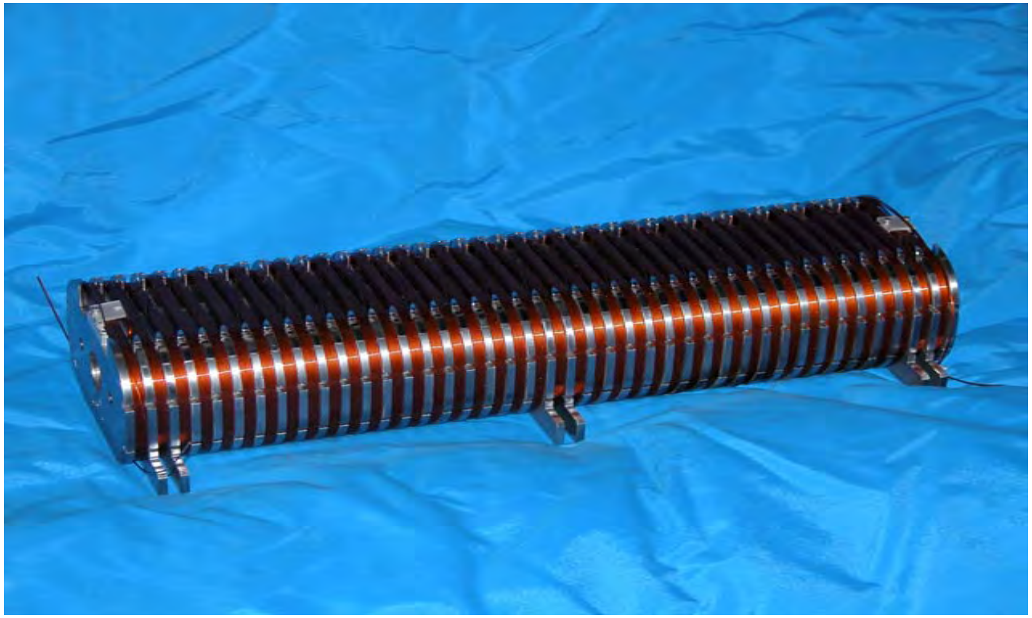
Coil fabrication R&D



First five 10-pole test coils

- 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



42-pole test assembly

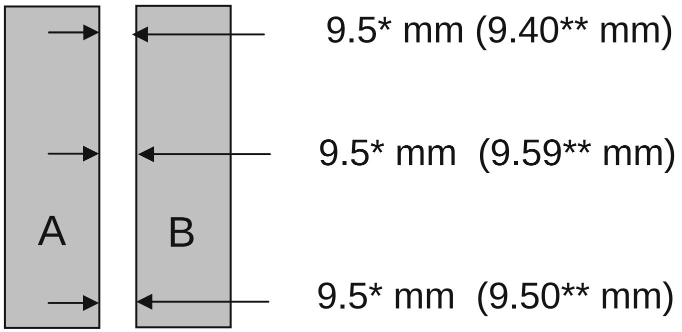
- Assembly includes two identical magnetic structures – Coils “A” and “B”, each with a main coil and a pair of correction coils
- Parameters of the coils:

  period length – 16.0 mm;

  design gap 9.0 mm, actual gap - 9.5 mm (see layout below);

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

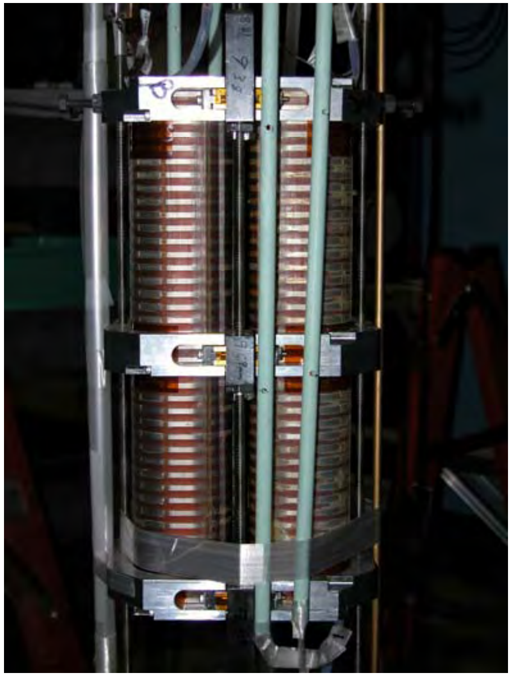
  SC wire – NbTi round wire, 0.74 mm diameter.



* - expected after gap tuning, ** - measured initially

Test set up in vertical cryostat

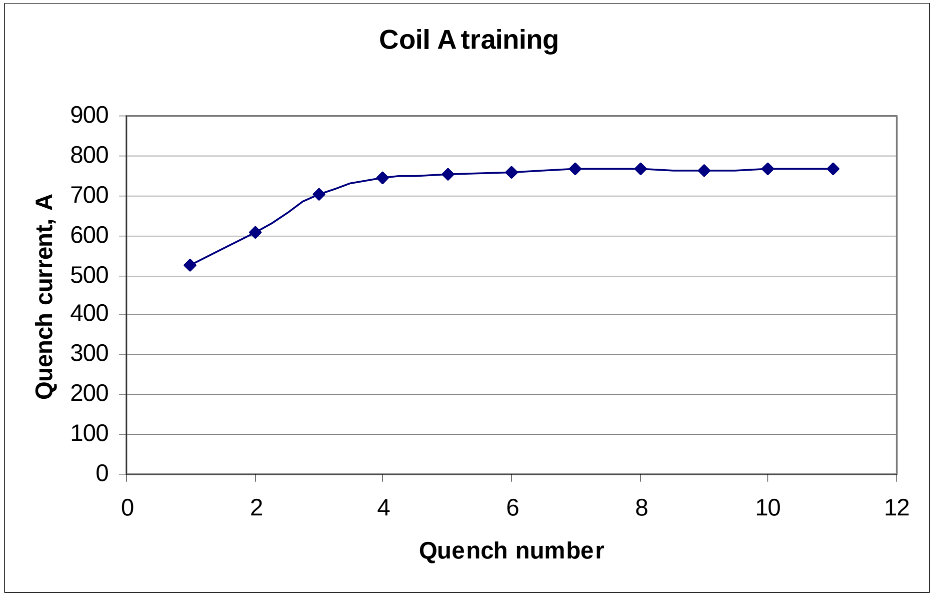
42-pole magnetic structure

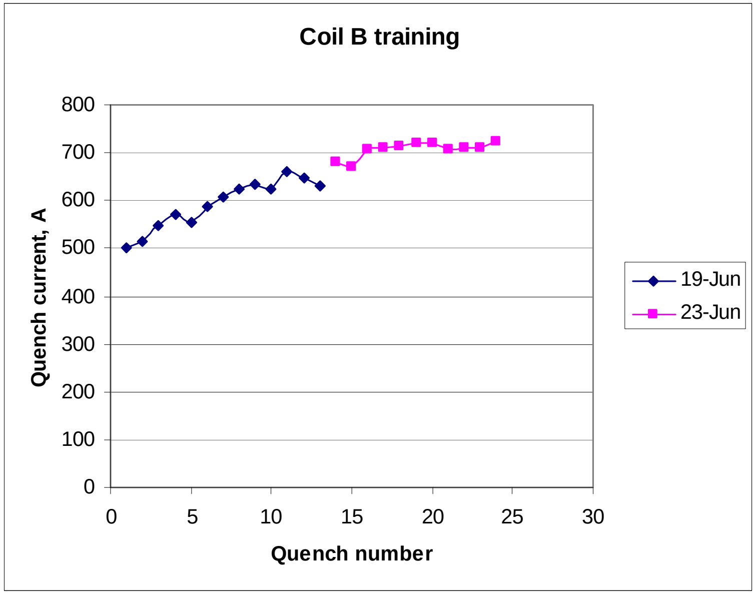


Test set up in vertical cryostat (2)

- 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 which is equipped with a position encoder outside the cryostat
- LabView is employed to control movement of the Hall probe as well as 2 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 is under development)

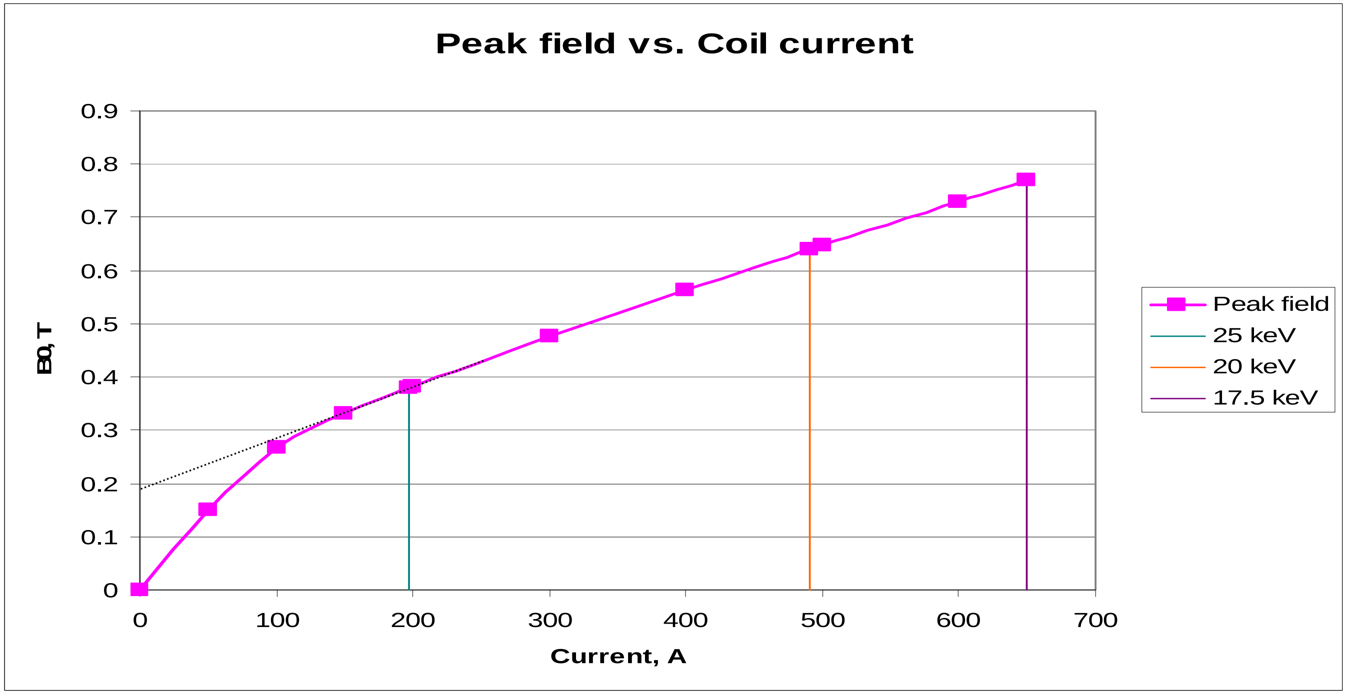
Coil training





- 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

Coil excitation

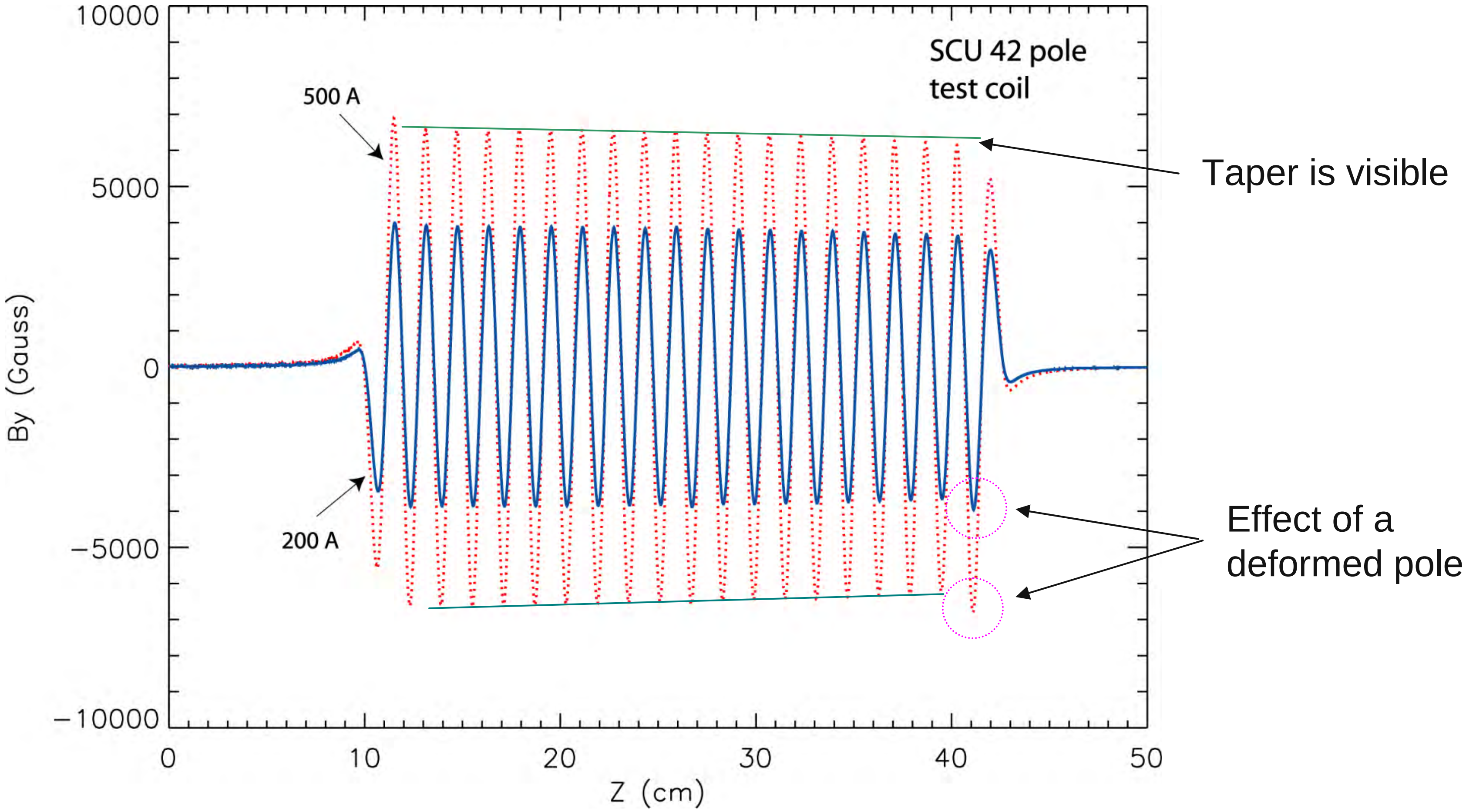


- Iron is already saturated at about 150 A
- Iron adds about 0.2 T to the peak field
- Operating current for 25 keV – 200 A; for 20 keV – 500 A (max current 720 A)

❑ Lessons learned:

- we may use a 9.5 mm design gap instead of 9.0 mm

Measured magnetic field profile

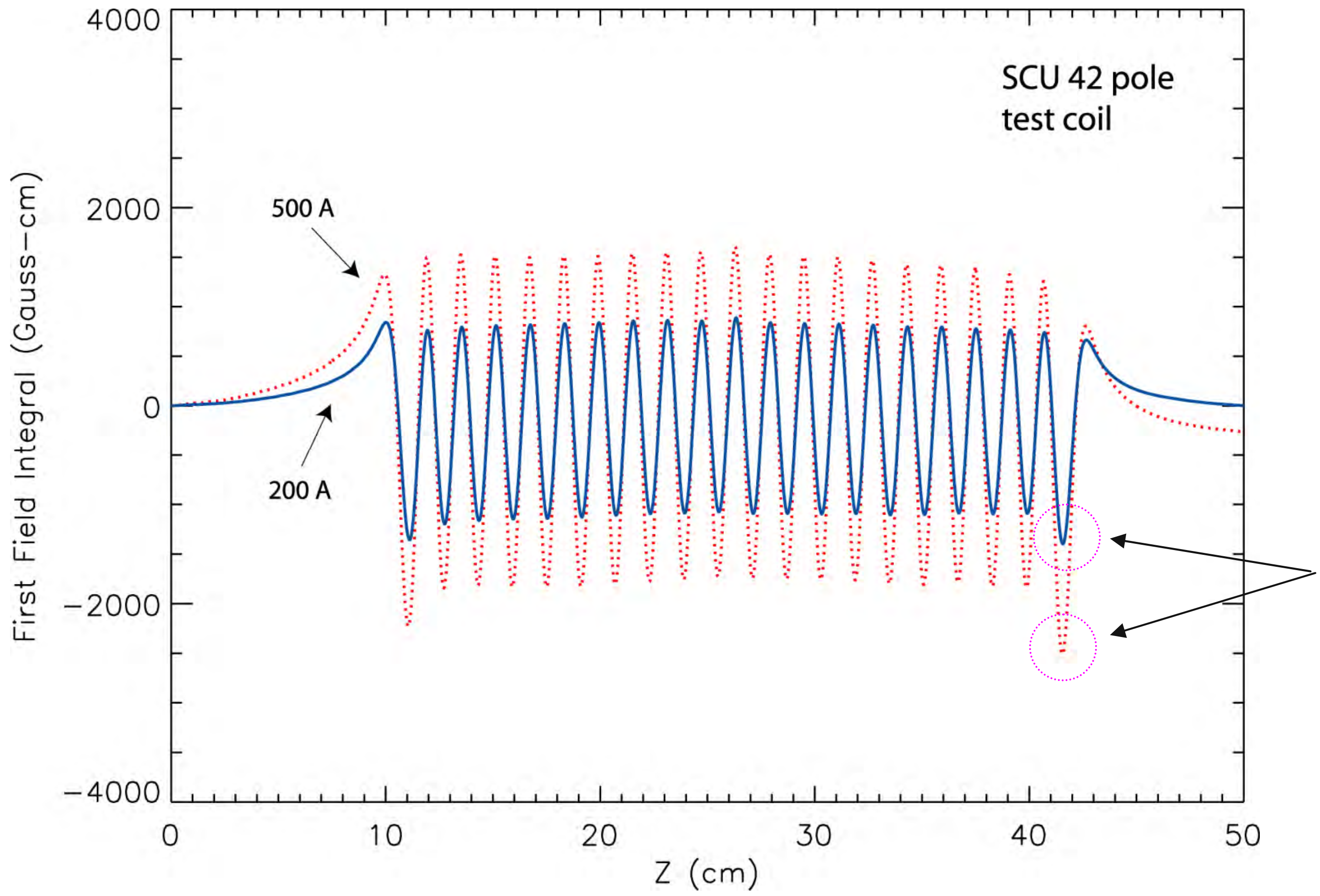


Taper is visible

Effect of a deformed pole

- Magnetic fields were measured for currents of 200 A and 500 A at a nominal gap of 9.50 mm.
- The effective magnetic fields are 3815 Gauss (200 A) and 6482 Gauss (500 A).

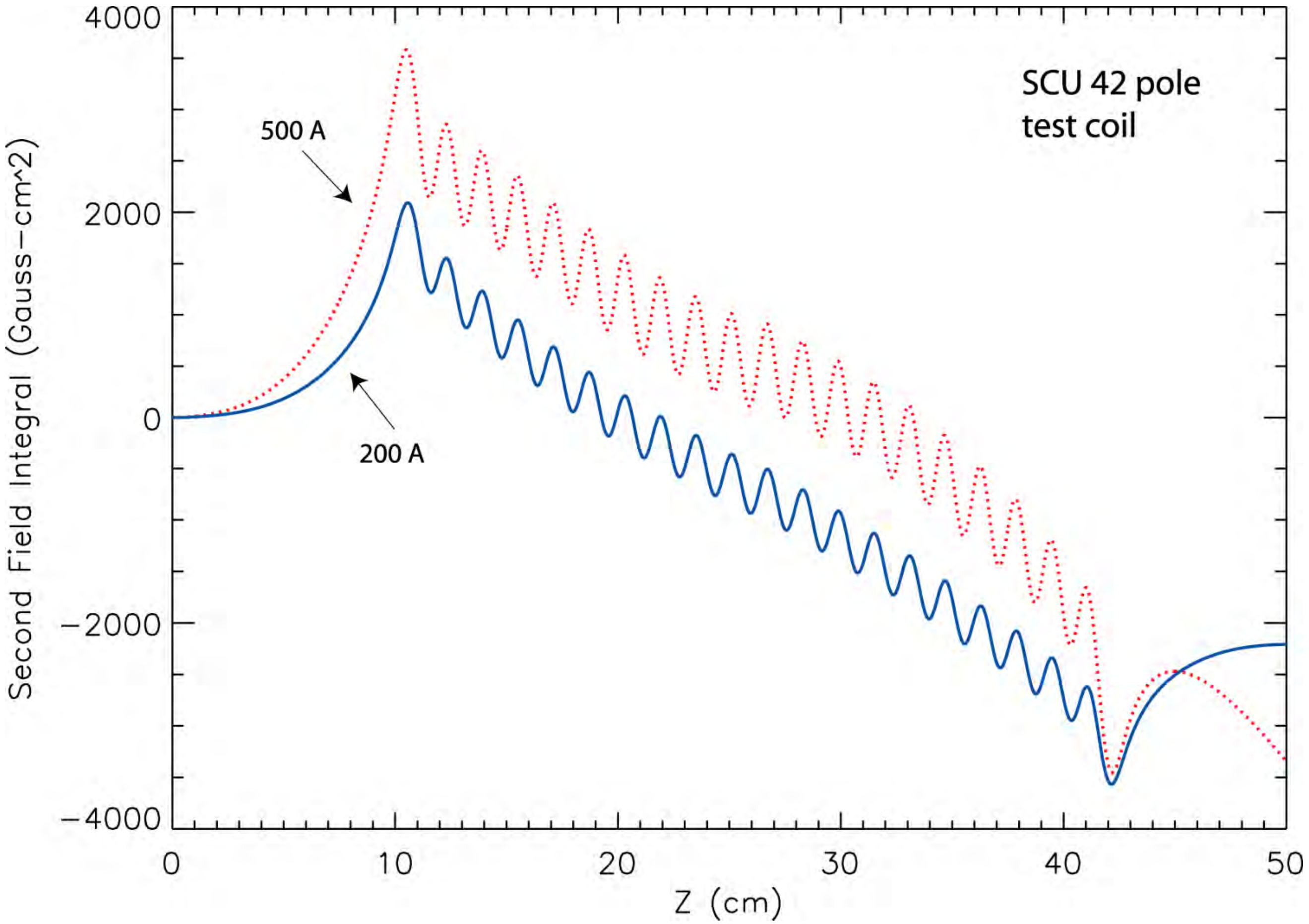
First field integrals



Effect of a deformed pole

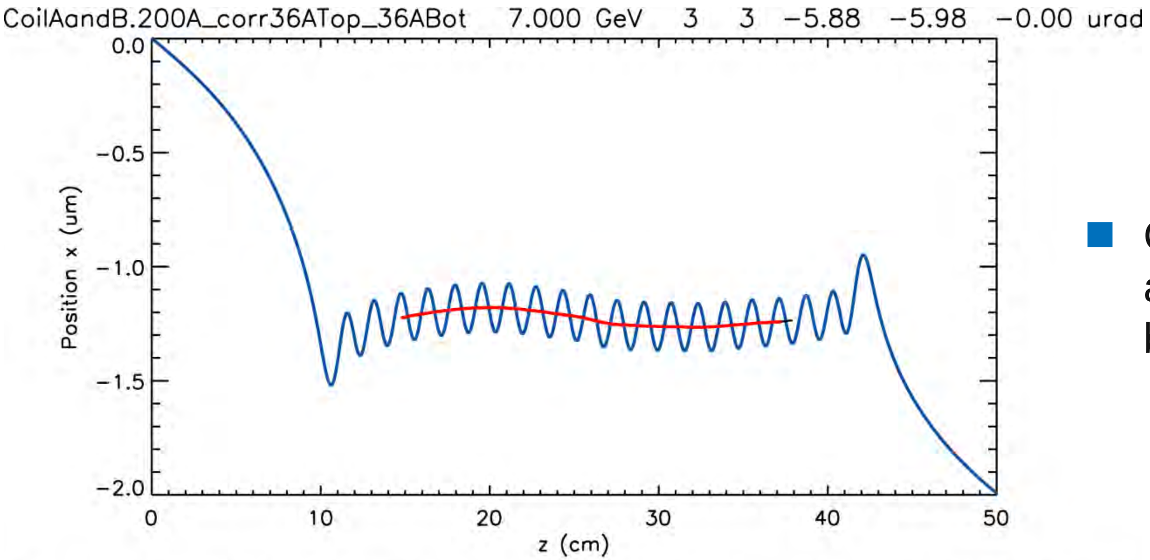
- The measured first field integrals are 2 G-cm (200 A) and -261 G-cm (500 A) .
- Storage ring requirement is < 50 G-cm

Second field integrals

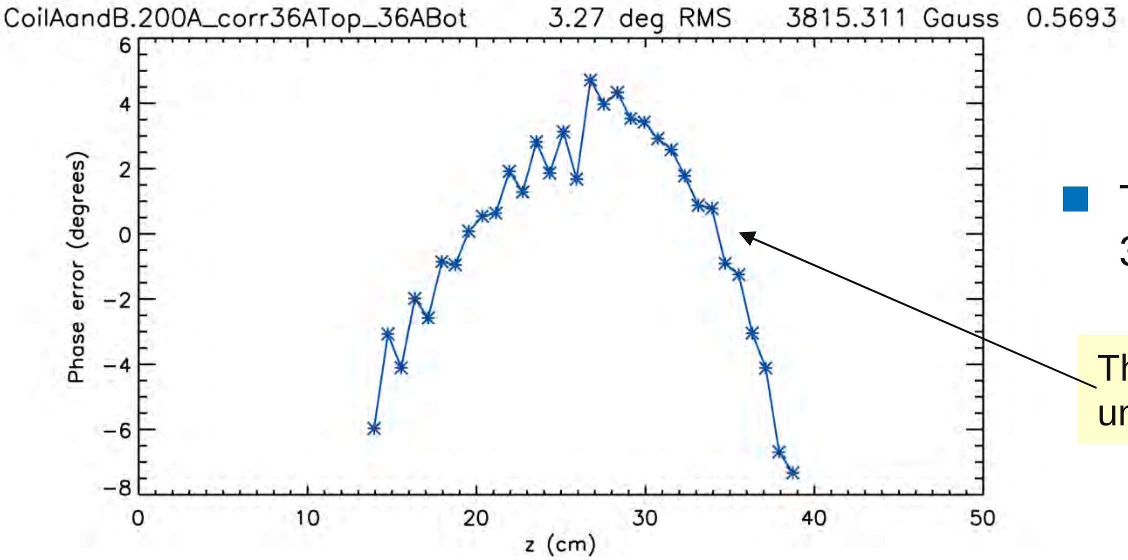


- The measured second field integrals are -2208 G-cm^2 (200 A) and -3345 G-cm^2 (500 A)
- Storage ring requirement is < 100,000 G-cm^2

Trajectory and phase errors at 200 A (first harmonic at 25 keV)



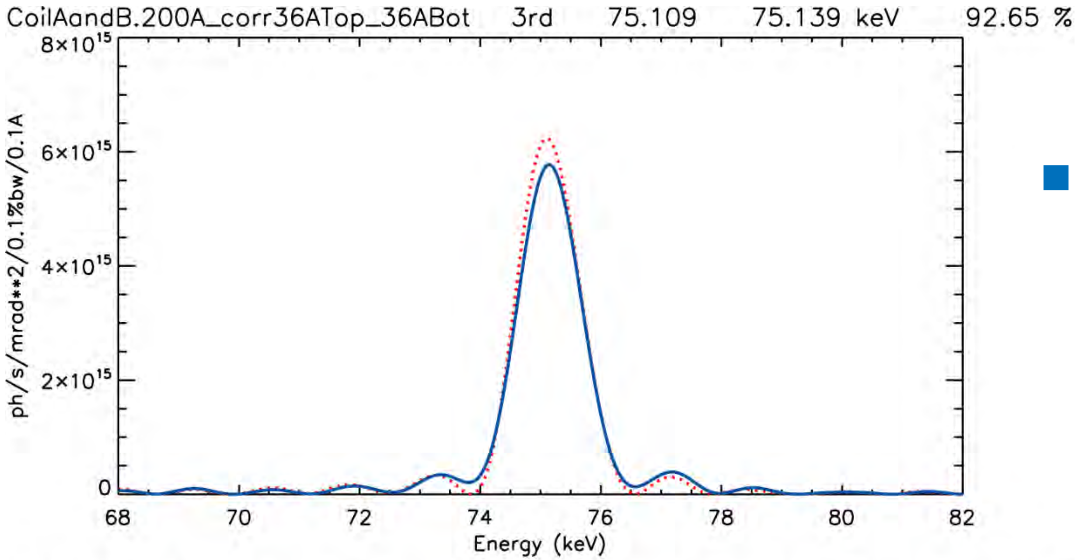
- Calculated electron trajectory and average trajectory for 7.0 GeV beam energy.



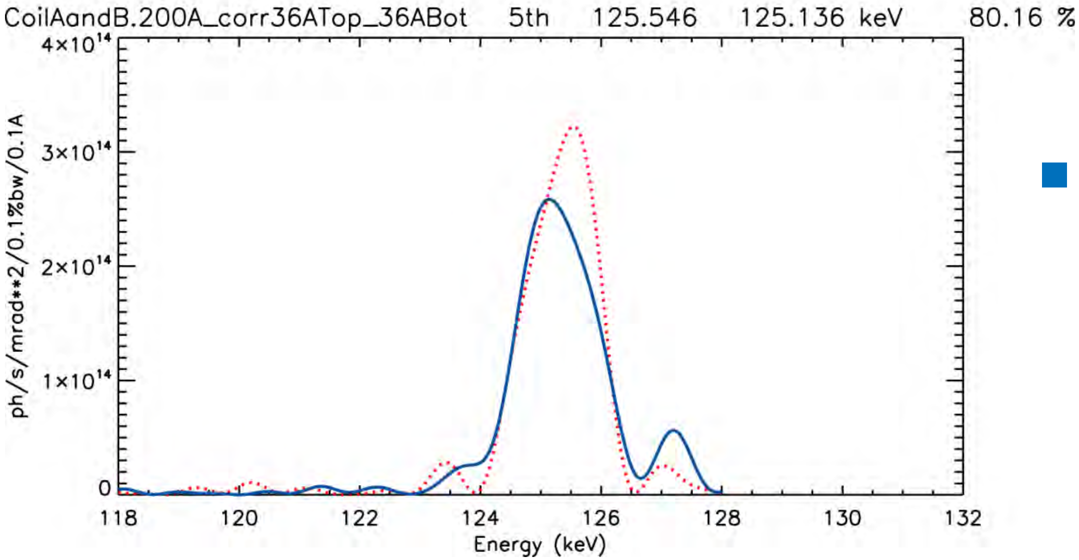
- The measured rms phase error is 3.3 degrees for 200 A current.

This shape is typical for an undulator with a tapered gap

Spectral performance at 200 A (first harmonic energy at 25 keV)

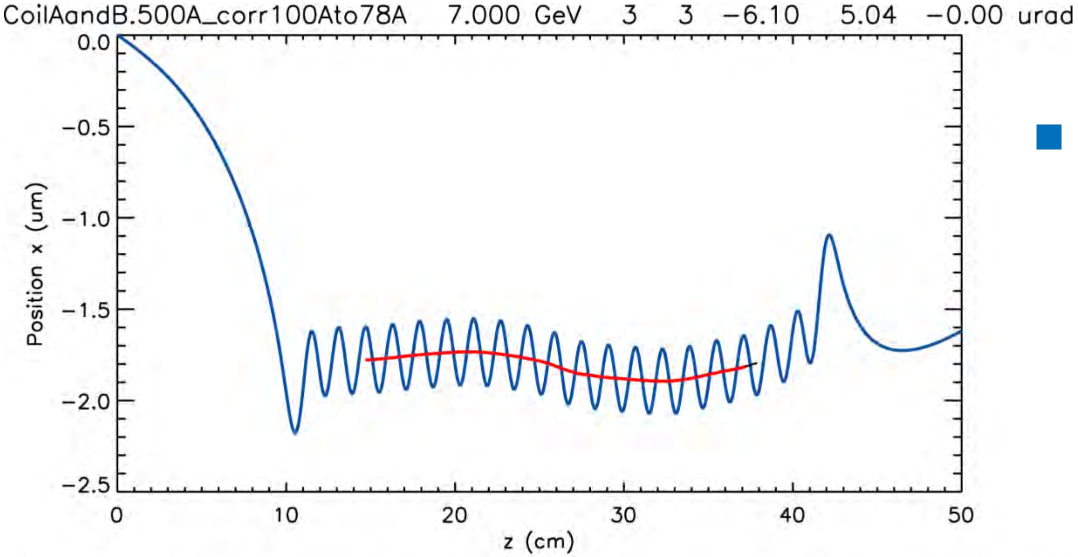


- The estimated reduction of the third harmonic intensity at 75 keV is less than 8% compared to an ideal magnetic field (first harmonic reduction less than 2%).

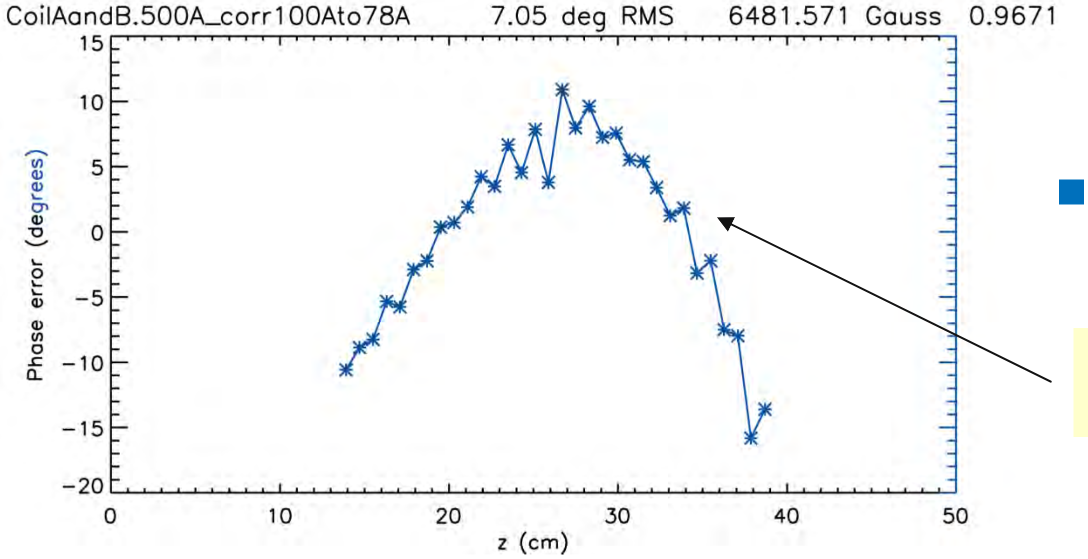


- The estimated reduction of the fifth harmonic intensity at 125 keV is less than 20%.

Trajectory and phase errors at 500 A (first harmonic at 20 keV)



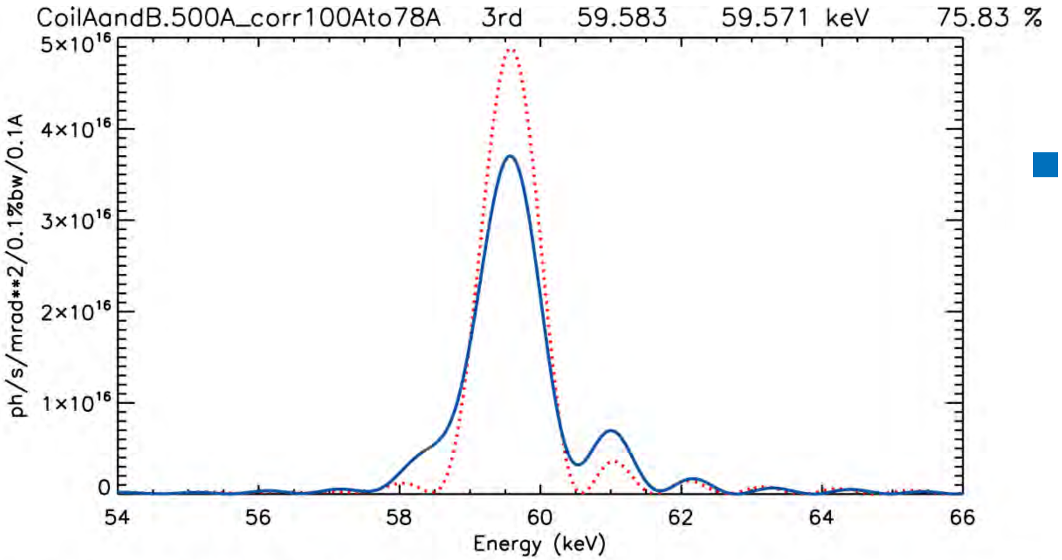
- Calculated electron trajectory and average trajectory for 7.0 GeV beam energy.



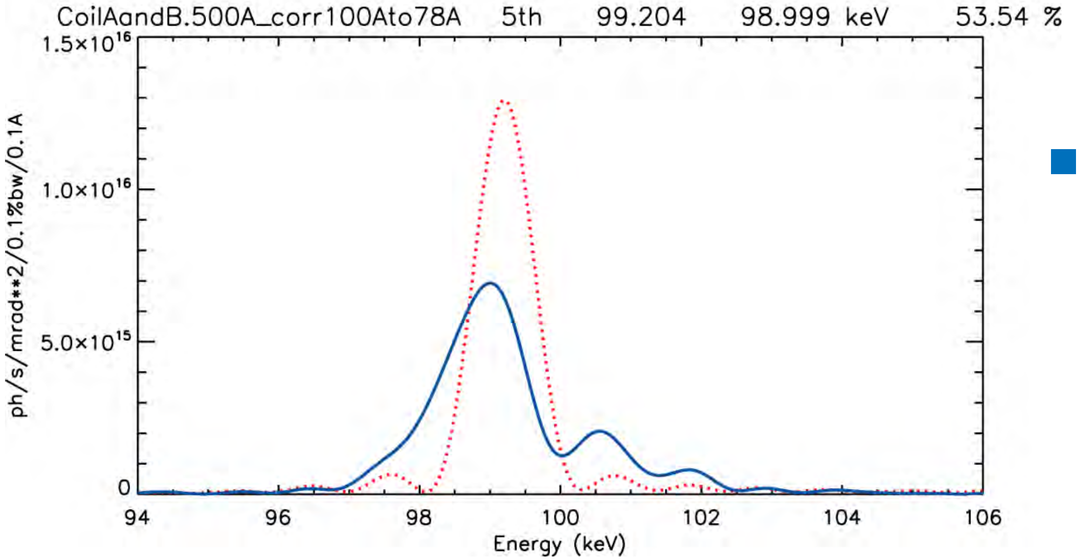
- The measured rms phase error is 7.1 degrees for 500 A current.

This shape is typical for an undulator with a tapered gap

Spectral performance at 500 A (first harmonic energy at 20 keV)



- The estimated reduction of the third harmonic intensity at 60 keV is less than 25% compared to an ideal magnetic field (first harmonic reduction less than 5%).



- The estimated reduction of the fifth harmonic intensity at 100 keV is less than 50%.

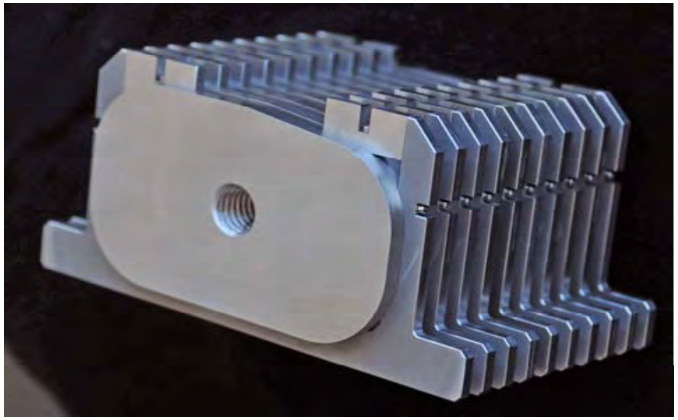
Field analysis summary

- Magnetic measurements of the first 42-pole assembly show encouraging results:
  - ☐ The effective magnetic fields are 3815 Gauss (200 A), K = 0.57, and 6482 Gauss (500 A), K = 0.97.
  - ☐ The measured first field integrals are 2 G-cm (200 A) and -261 G-cm (500 A) .
  - ☐ The measured second field integrals are -2208 G-cm^2 (200 A) and -3345 G-cm^2 (500 A) .
  - ☐ The measured rms phase errors range from 3.3 degrees to 7.1 degrees for currents from 200 A to 500 A.
  - ☐ The first harmonic reductions are expected to be less than 2% and 5%, at 25 keV and 20 keV, respectively.

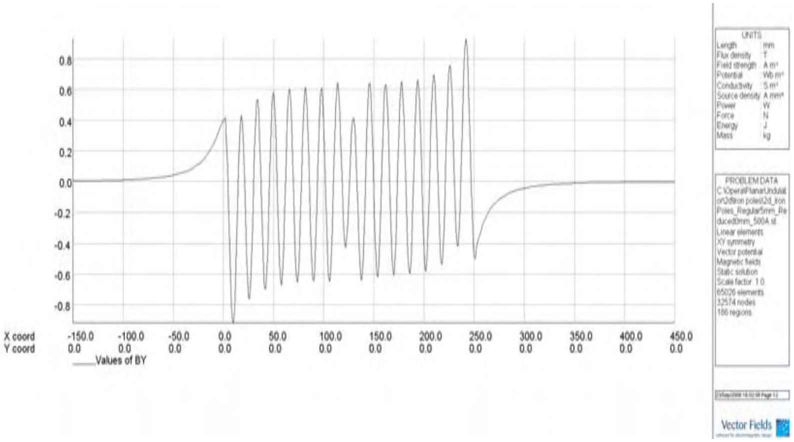
- Correction system (with end coils) works well

Superconducting quasi-periodic undulator (SCQPU)

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



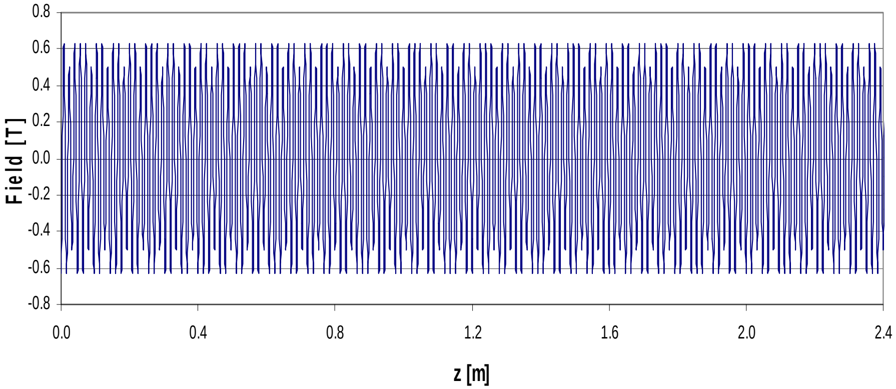
Simulated field profile for a magnetic structure with two non-magnetic poles in the middle.



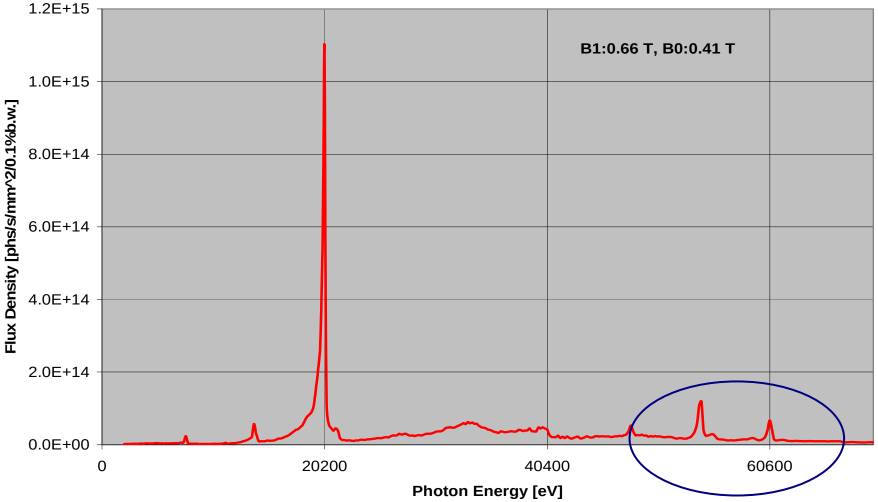
UNITS	
Length	mm
Flux density	T
Field strength	A m⁻¹
Potential	Wb m⁻¹
Conductivity	S m⁻¹
Source density	A mm⁻²
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA
C:\Opera\PlanarUndulator\2d\Iron poles\2d_Iron Poles_Regular5mm_Reduced0mm_500A.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor: 1.0
65026 elements
32574 nodes
186 regions

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



Calculated on-axis photon spatial flux density from SCQPU.



Next steps

☐ Short-term:

- Complete and test 42-pole Al-core/ iron-poles assembly (second 42-pole assembly)
- Complete design of 42-pole assembly with new support structure and with cooling system connectors

☐ Long-term:

- Make plan to manufacture SCU0 – a complete SC undulator based on a 42-pole structure
- Convert this project from an R&D-type activity into a formal working project
- Start conceptual design of SCU0
- Continue R&D on thermal tests
- In collaboration with UW make conceptual design of the cooling system
- In collaboration with visitors from Budker Institute complete conceptual design of SCU0 and start detailed design
- Prepare and pass conceptual design review (winter 2009-10)

- Build
  - SCU0 (42-pole device, 1.6 cm period) in 2010 – 11
  - SCU1 (1.2-m long, 1.6 cm period) in 2011 – 12
  - SCU2 (2.4-m long, 1.6 cm period) in 2012 – 13

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 opens a new yet avenue for IDs

- Superconducting technology allows to make various types of insertion devices – planar, helical, quasi-periodic undulators, 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 to use simpler (less costly) cooling systems.

Conclusions

- Superconducting technology opens a new avenue for IDs.
- With the successful test of the 42-pole assembly, the R&D on short SCU prototypes is completed.
- We are ready to start designing and building the first short superconducting undulator – SCU0.
- We a looking for a potential user of the first superconducting undulator SCU0.