Magnetic Measurements of the First Superconducting Undulator (SCU) at the Advanced Photon Source

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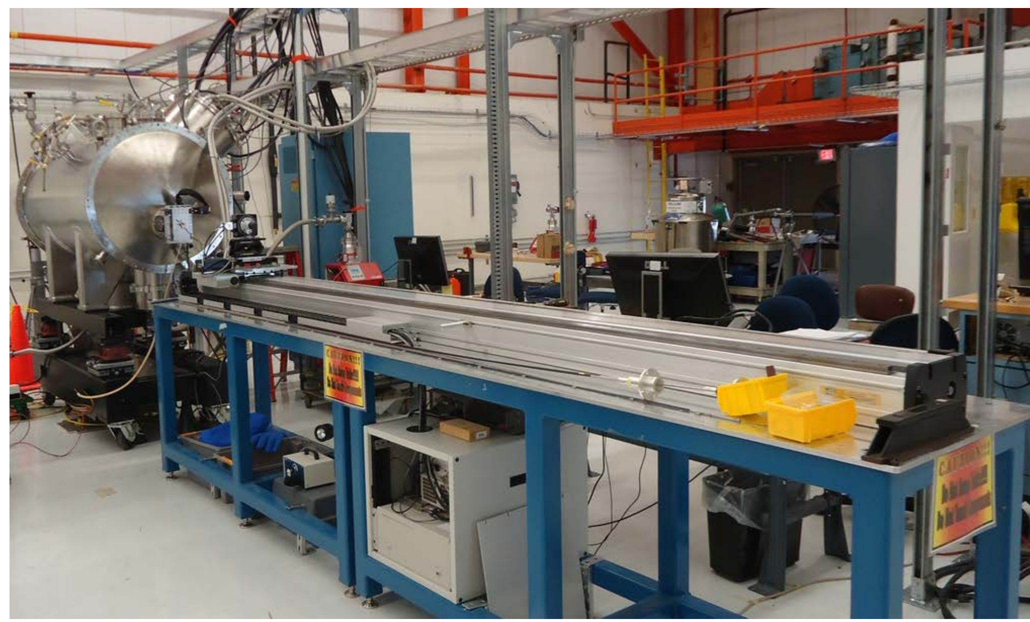

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Scope

- Acknowledgment of the SCU0 project contributors
- SCU0 magnet design and correction coil operation
- Brief description of the SCU horizontal measurement system
- Rotating coil measurement results
- Dynamic integrated fields during magnet quench measured with fixed coil
- Hall probe measurement results
- Typical trajectory and phase errors of SCU0
- SCU0 calculated and measured flux curves at 85 keV
- Conclusion
- References

Thanks to Some of the Contributors to the SCU0 Project

APS:

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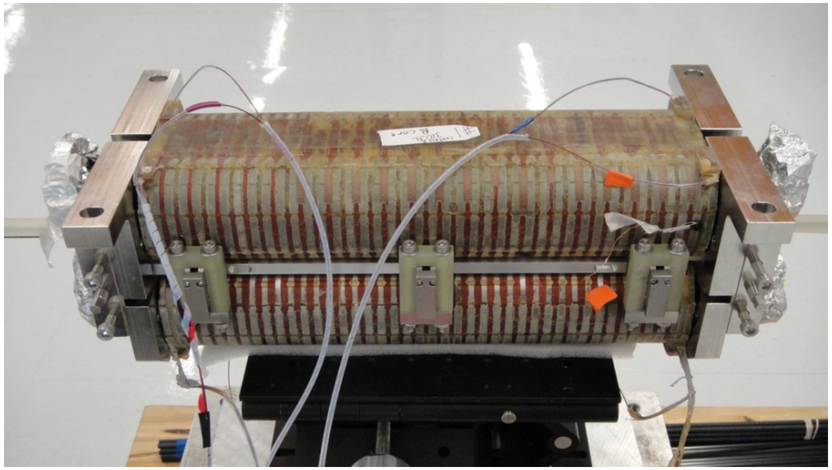
- V. Lev
- V. Tsukahov

Collaborators:

- Sasha Makarov, Technical Division, FNAL
- John Pfotenhauer, UW Madison

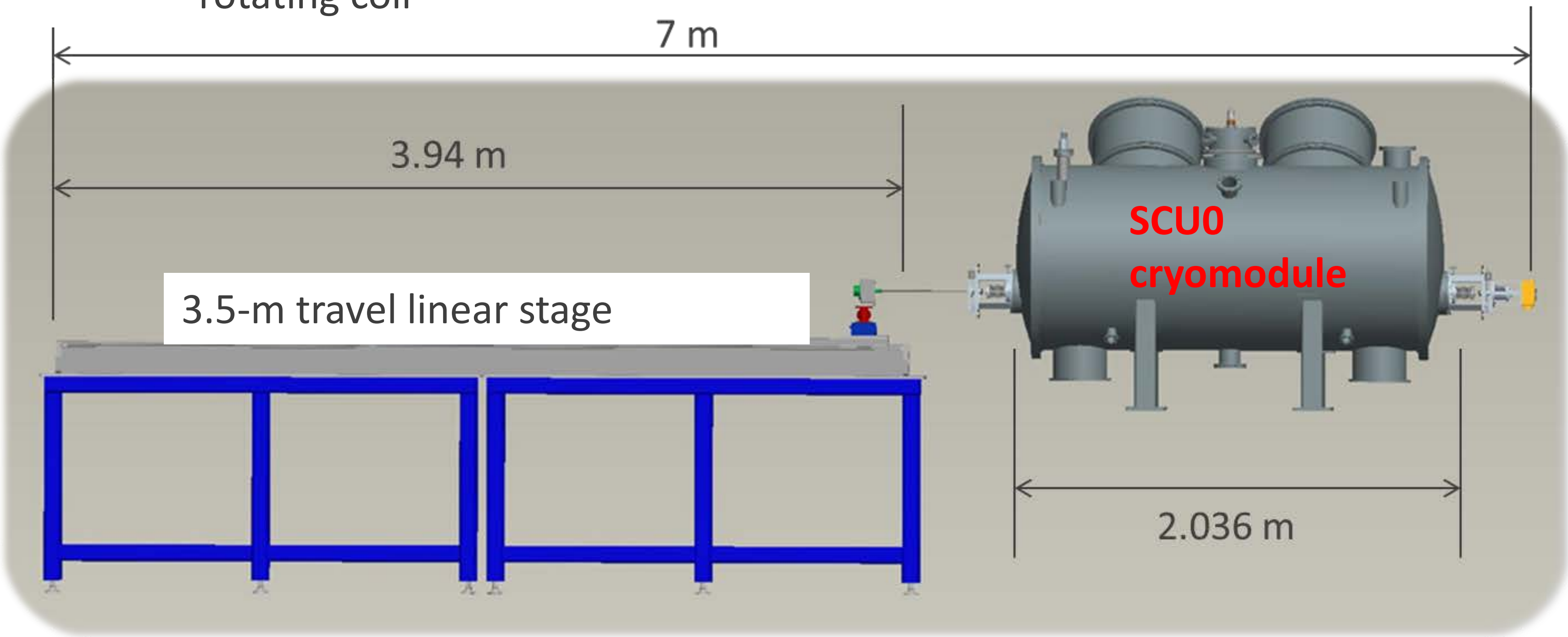
Review of SCU0 Magnet Design

- SCU0 is the first SCU at the Advanced Photon Source and consists of two 42-pole SC magnet cores with a 9.5-mm gap between cores; operating temperature is 4.2 K
- Each core is wound with a continuous SC for the 41 main coils
- 11-turn correction coils are wound on the last two main coils of each end of the cores
- The correction coils are used to adjust the 2nd field integral
- One main power supply energizes the main coils in series
- One corrector coil supply is used to energize all four corrector coils in series
- The ideal correction current is a function of the main current
- Adjustment of the correction coil current affects the photon beam angle, but has very little effect on the e-beam exit angle (final 1st field integral) [1,2,3,4]



SCU Horizontal Magnetic Measurement System Dimensional Overview

- 3.5-m travel linear stage for Hall probe linear motion in z
- Three ±1-cm travel transverse linear stages
- Three manual vertical stages
- Two rotary stages
- Warm Ti tubing installed inside cold beam chamber used as guide for carbon fiber Hall probe assembly or warm area for rotating coil

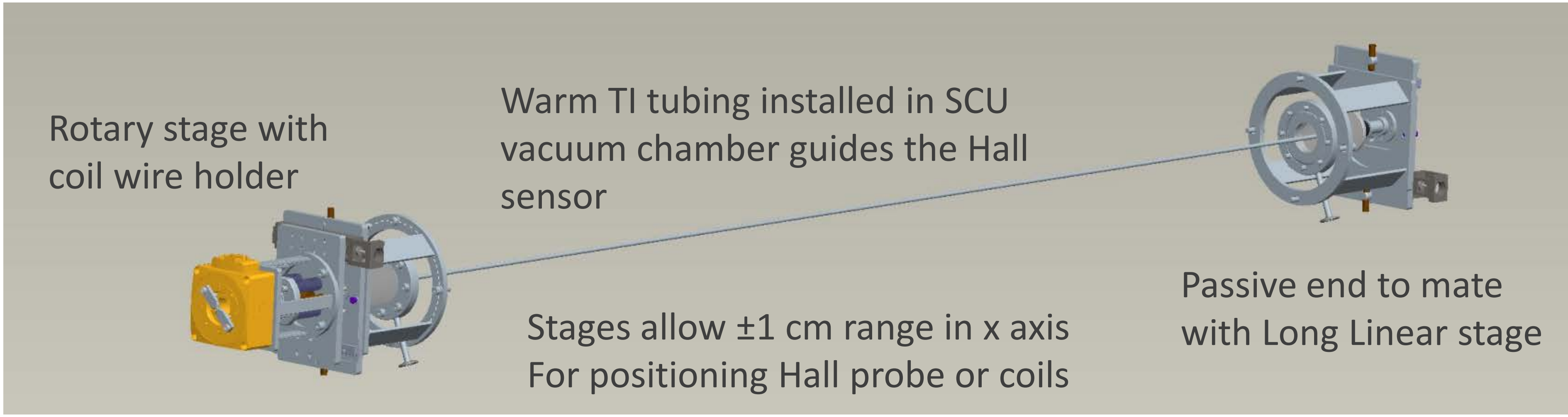


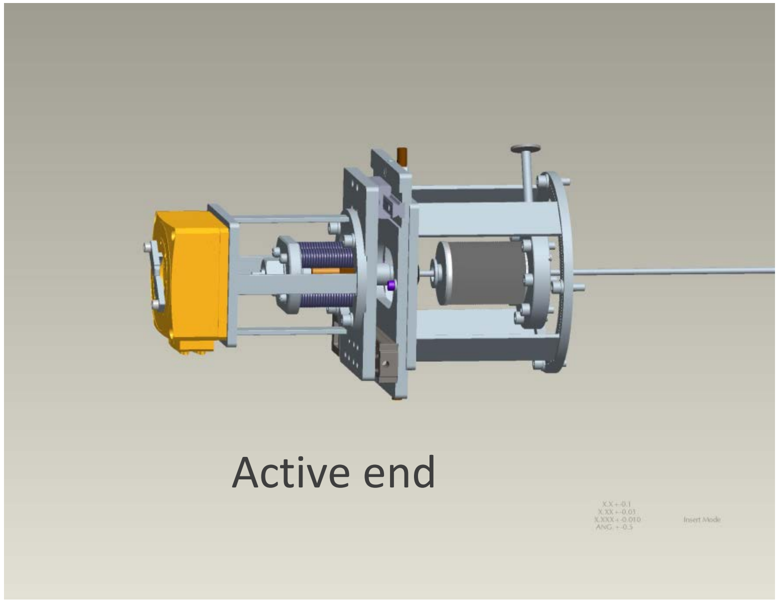
SCU Horizontal Measurement System Capabilities

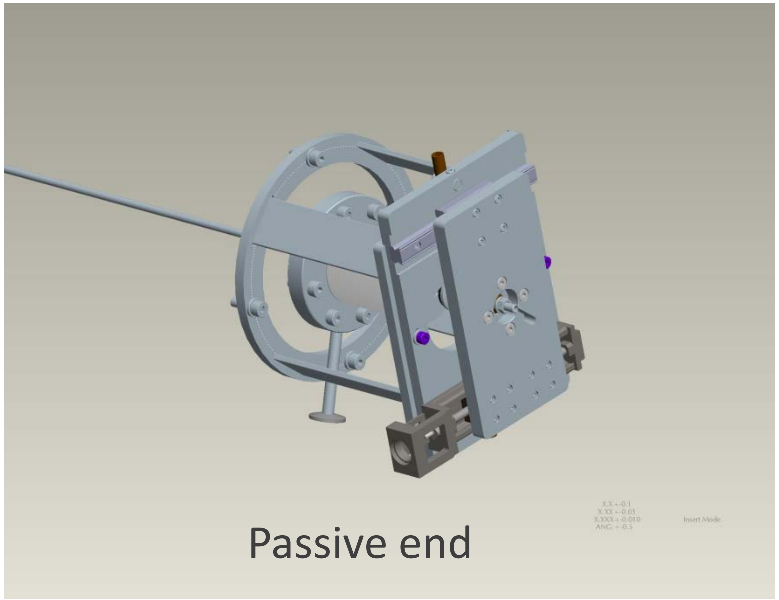
- Warm bore system based on Budker Institute's wiggler measurement system. Allows configuring for Hall probe or coil measurements without affecting the SCU magnet or cryomodule [5,6]

- Scanning Hall Probe
  - On-the-fly Hall probe measurements (2 cm/s, Δz 0.2 mm, typical z range ±35 cm) to determine local field errors and phase errors.
  - Three-sensor Hall probe (attached to carbon fiber tubing and driven by linear stage) to measure B_y and B_x simultaneously and determine the mid-plane field regardless of sensor vertical offset from magnetic mid-plane. [7]
  - Hall probes can be rotated to any fixed angle with 0.01 degree absolute accuracy. The probes can also be rotated through 360 degrees at a fixed z location.
- Stretched Wire Coil
  - Stretched wire rectangular, delta, and figure-eight coils to determine static and dynamic 1st and 2nd field integrals. [8] Wire diameter is 100 µm, coil width is 4 mm, and coil length is 3.5 m.
  - Rotary stages on downstream end of cryostat as well as on the z-axis linear stage to provide synchronized rotary motion for stretch coils.
  - Integral coil measurements performed by continuously rotating and using a software-based lock-in amplifier to determine the integrated B_y and B_x field components. [9]
  - Coils can be translated along x-axis approximately ±1 cm to measure integrated multipole components.
- Miscellaneous
  - Ability to measure dynamic 1st and 2nd field integrals, magnet coil voltages, and current during a quench.
  - Control main and corrector power supplies with accurate current read-back.
  - Ability to measure the LHe level, and temperature sensors.
  - Perform excitation measurements with fixed Hall probe position.

TI Guide Tube and Cryomodule End Stages Concept

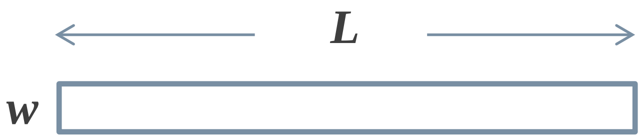






Integral Coil Measurement Concept

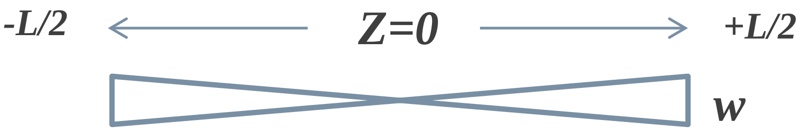
- The integral coil system utilizes a single-turn beryllium-copper wire with a width of 4 mm that is determined by a fixture mounted to the rotary stages.
- The coil is aligned to the mid-plane of the SCU inside the TI tubing and the plane of the coil is referenced to gravity.
- The peak dipole B_y 1st field integral is simply:



$$I_{y1} = \int_0^L B_y dz = \frac{\phi}{w}$$

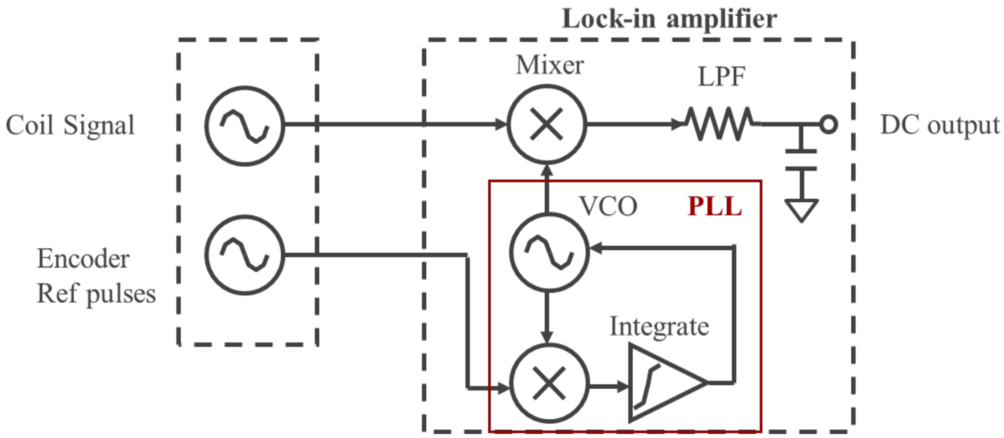
- The 2nd field integral is measured by rotating one end of the rectangular coil by 180 degrees forming a figure-eight coil [8]. The 2nd field integral can then be found by:

$$I_{y2} = \int_{\frac{-L}{2}}^{\frac{L}{2}} I_{y1} dz = \frac{\phi}{\theta} \pm \frac{L}{2} I_1 \qquad \theta = \frac{2w}{L}$$

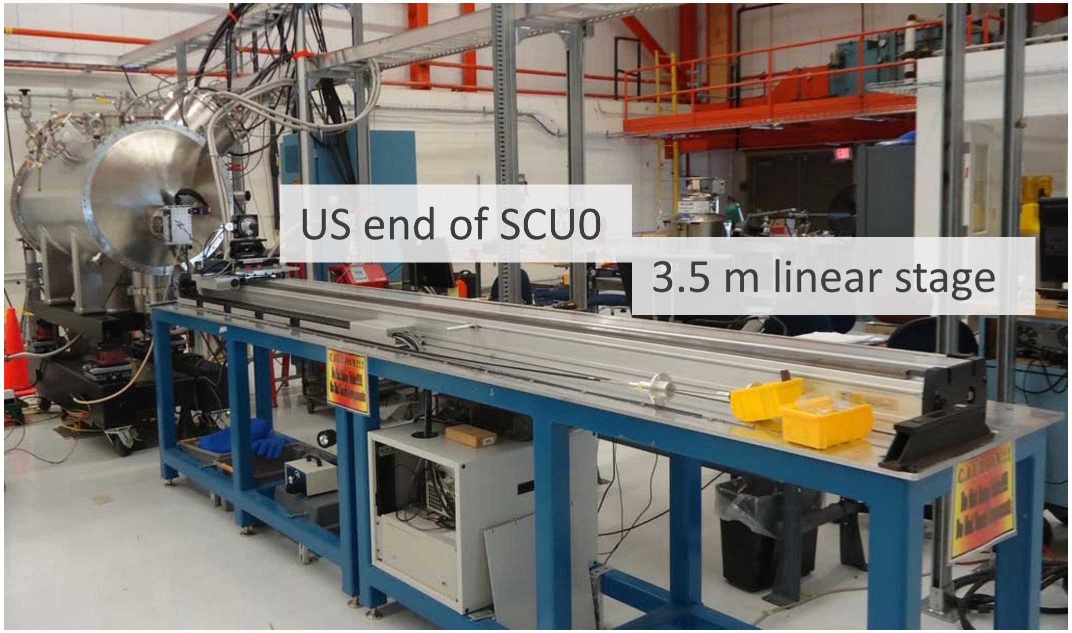


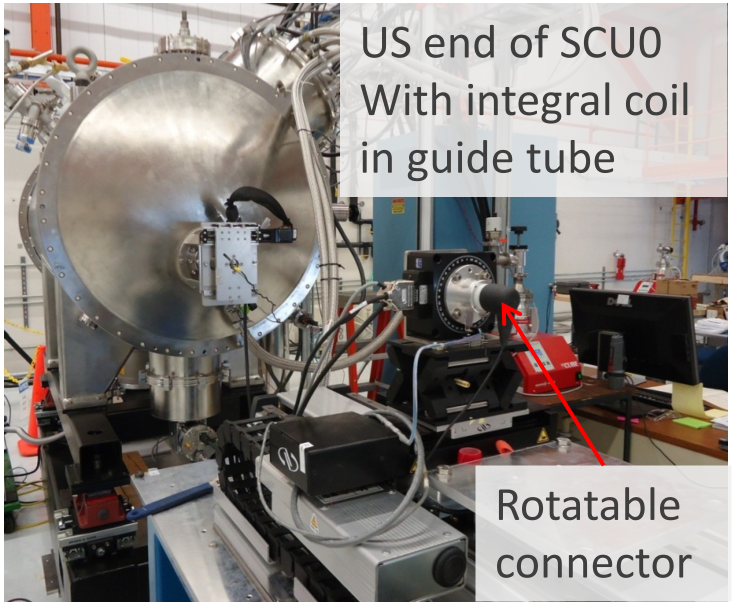
Integral Coil Signal Options

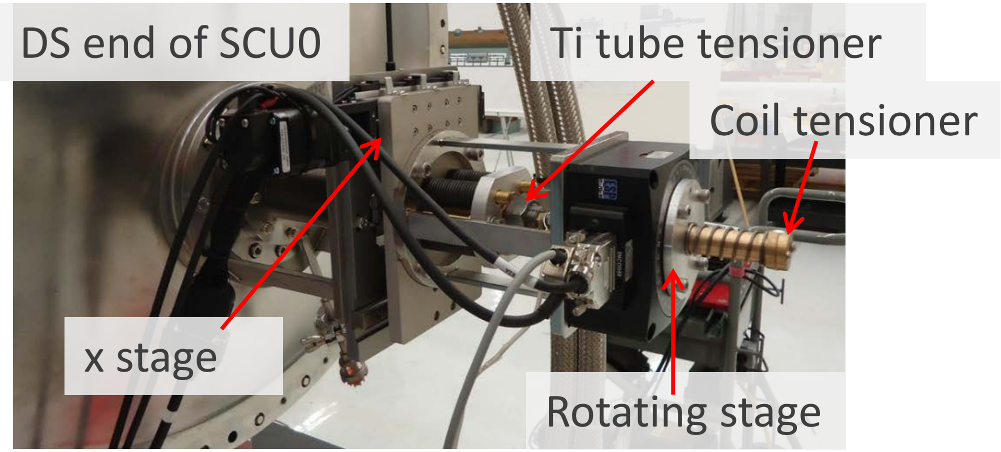
- The rotary stages allow continuous rotation of up to 2 Hz, or rotating through ±360 degrees and triggering on the rotary encoder pulses as a standard flip-coil.
- By using a rotatable signal connector it is possible to do continuous coil rotations and use the National Instruments software-based lock-in amplifier.
- The lock-in amplifier is a technique whereby a reference signal (which is phase locked to the measured signal) is multiplied by the measured signal. This produces a DC output that is proportional to ½ the product of the reference and measured signal amplitudes and the cosine of the phase angle. Virtually all noise and higher harmonics of the reference signal are rejected using this measurement technique. The reference signal in this case would be from the rotary stage encoder position.

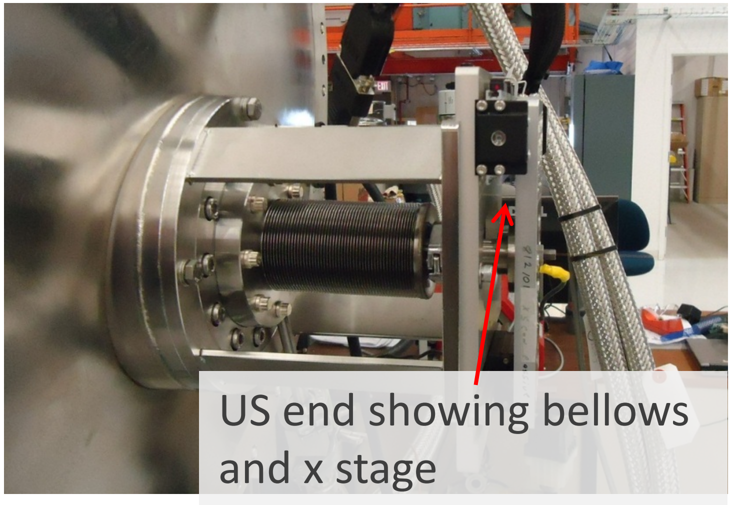


SCU Magnetic Measurement System Photos



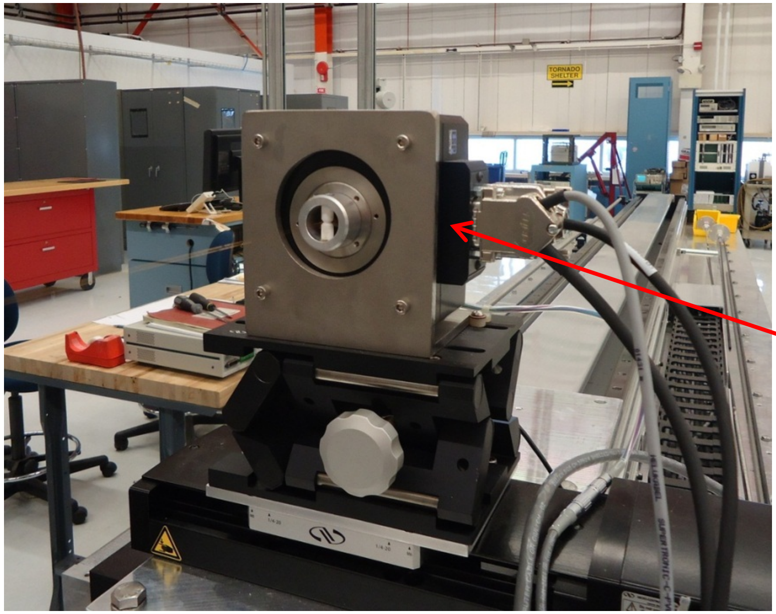




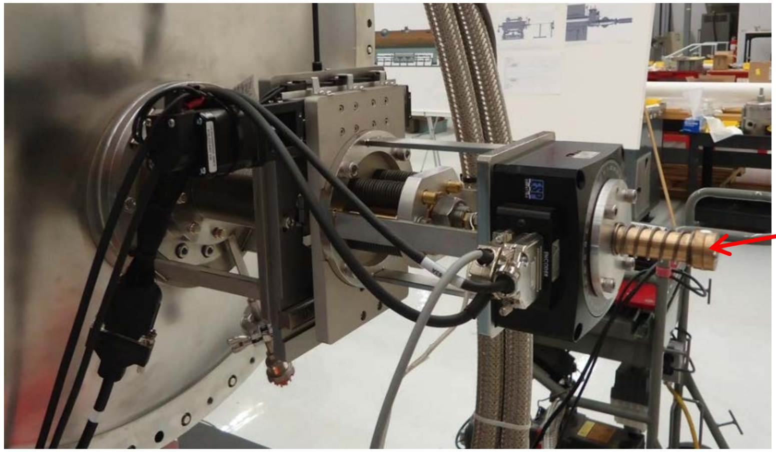


SCU Integral Coil System

One turn integral coil is supported at each end by ceramic pins with 4-mm V cut mounted to rotating stages.
Coil can be configured at rectangular, delta, or figure-eight.



Upstream end rotating stage with ceramic pin to define coil width and position.

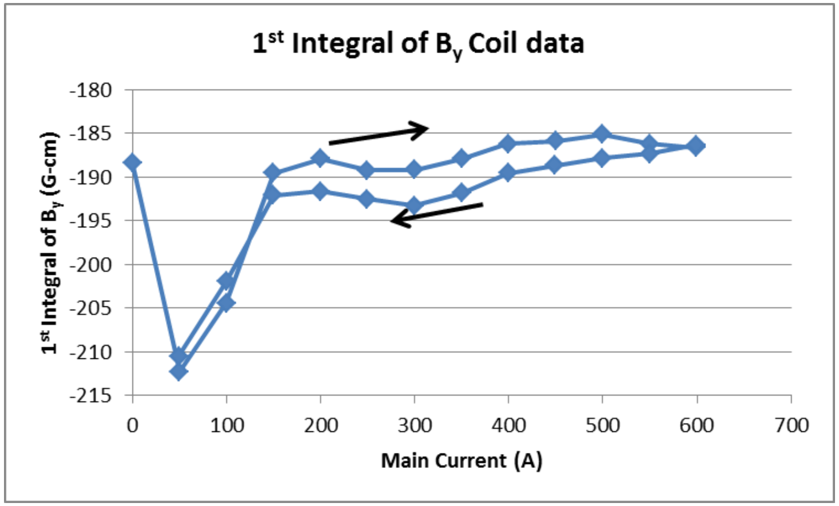


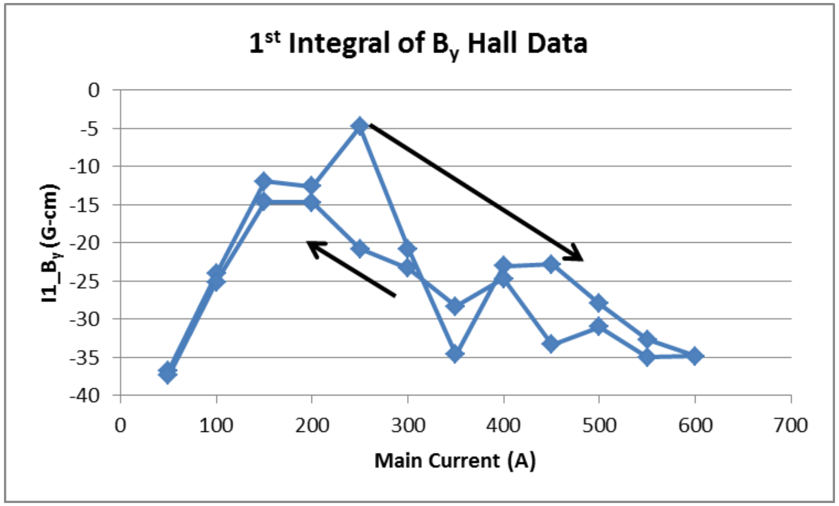
Downstream end rotating stage with ceramic pin and brass tensioning fixture.

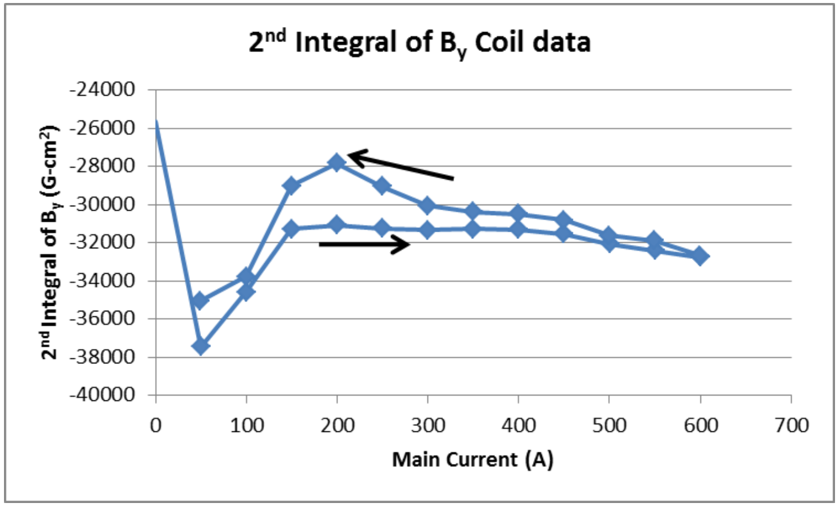
Rotating Coil Data

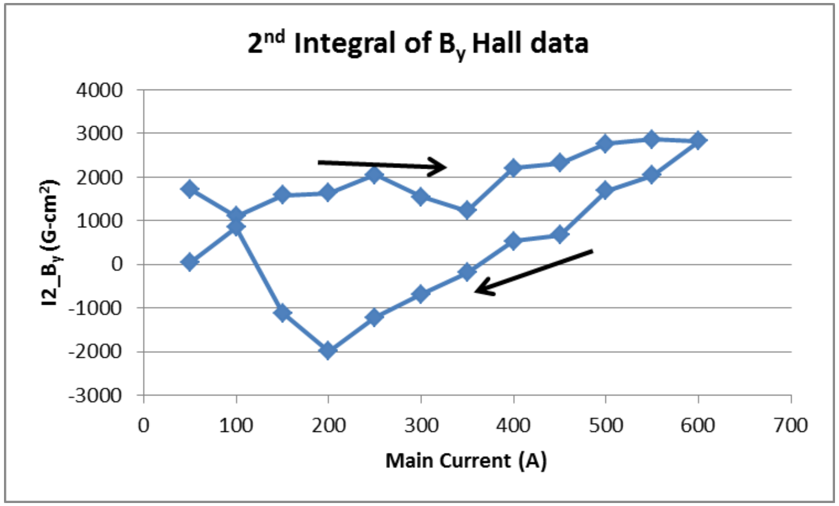
- Measurements were performed to measure the 1st and 2nd field integrals as a function of current (slide 13) and horizontal position (slide 14) using a continuously rotating coil and a software-based lock-in amplifier technique. [9]
- The SCU was first conditioned 4 times from 0 to 600 A then measurements were done from 0 to 600 A and back to 0 A at 50-A increments.
- The measured field integrals include the Earth's field, which is the dominant component and is approximately 175 G-cm, i.e., 0.5 G integrated over the 3.5-m coil length.
- Slide-13 compares the rotating coil and Hall probe measurements at x = 0 as a function of current.
- The coil data includes the Earth's field, whereas the Hall data does not.
- Slide-14 compares the rotating coil and Hall probe measurements along the x-axis for both B_y and B_x.

1st and 2nd B_y Field Integrals as a Function of Current

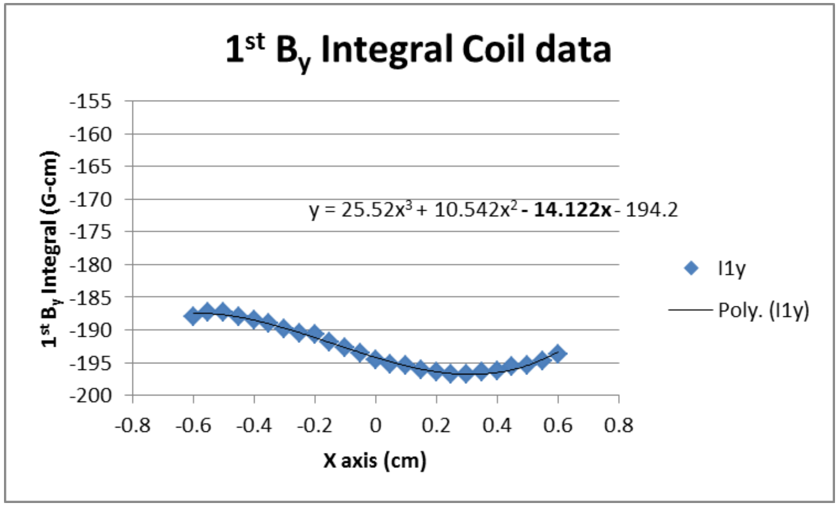


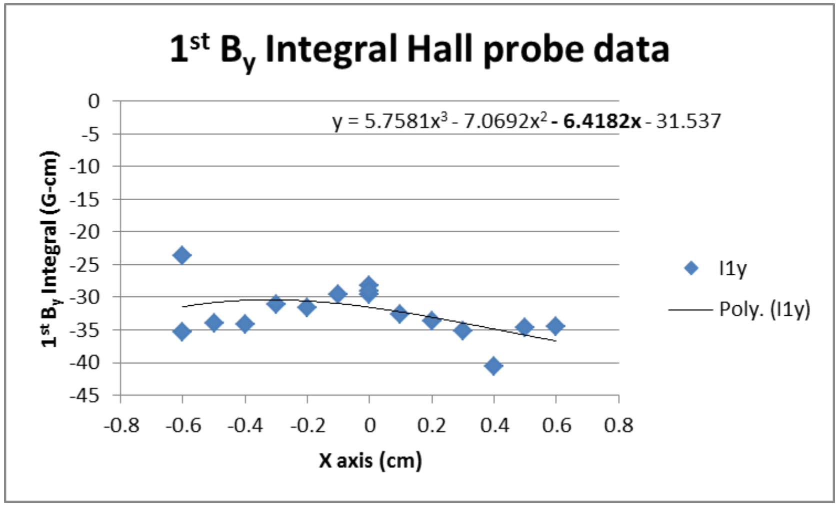


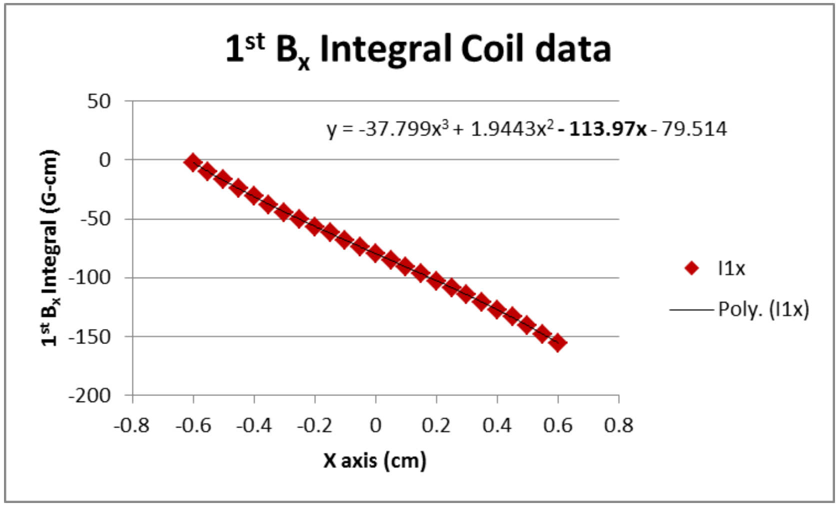


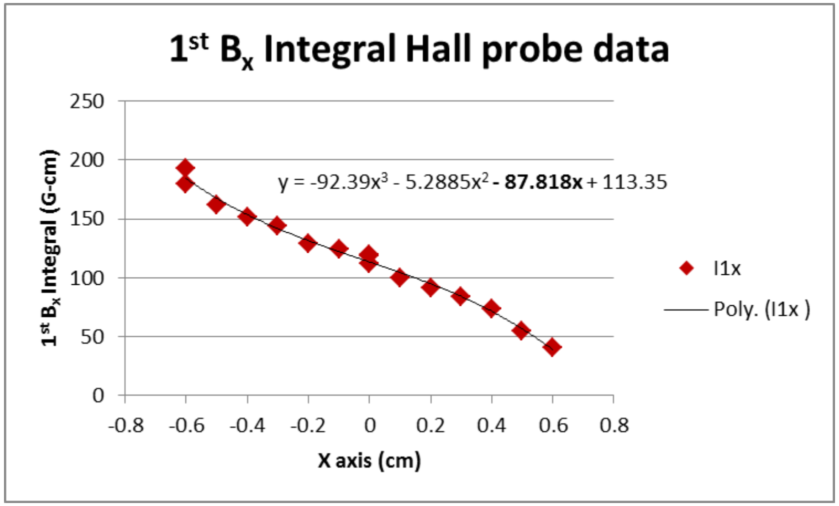


1^{st} Integrals of B_y and B_x as Function of x Position Main I = 500 A and Correction I = 51.5A

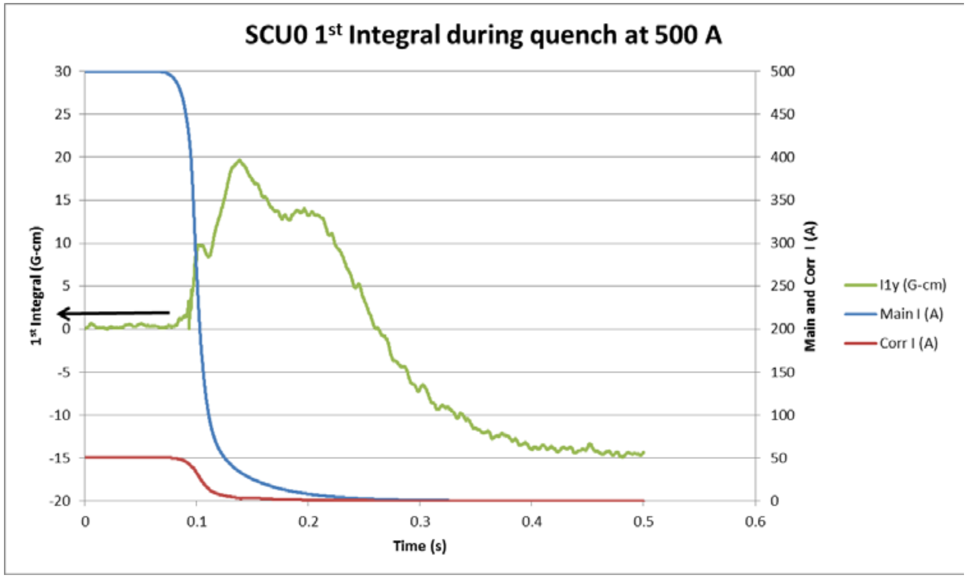




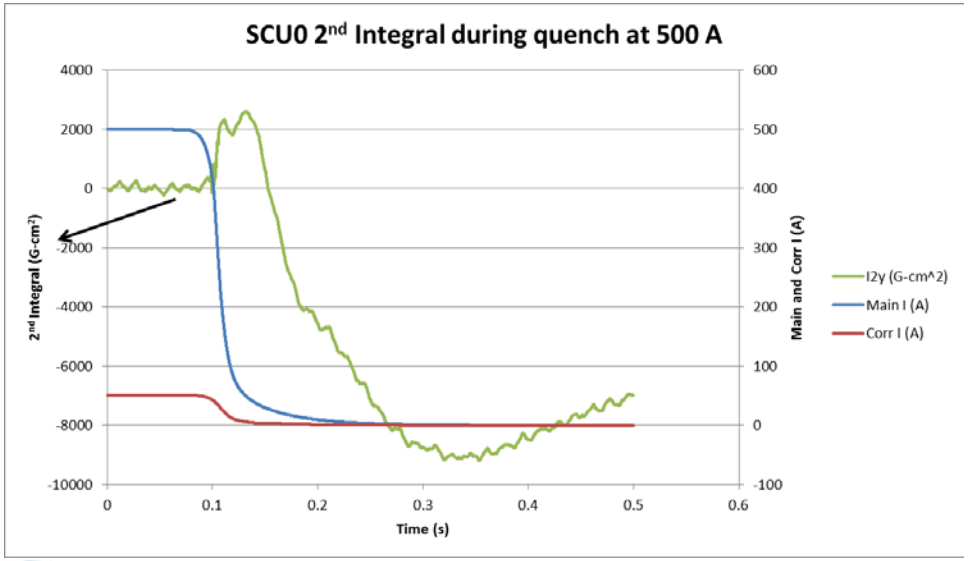




Integrated B_y Field during Magnet Quench (Fixed Coil)



Heater induced quench,
Corrector current slaved to main current
23 G-cm = 1 μRad
2300 G-cm^2 = 1 μm offset



During a quench of the main coil, the corrector PS current will follow the main according to a lookup table. This will minimize disruption of the e-beam.

Change of exit angle ~1.5 μRad in 50 ms
Change of exit offset ~4 μm

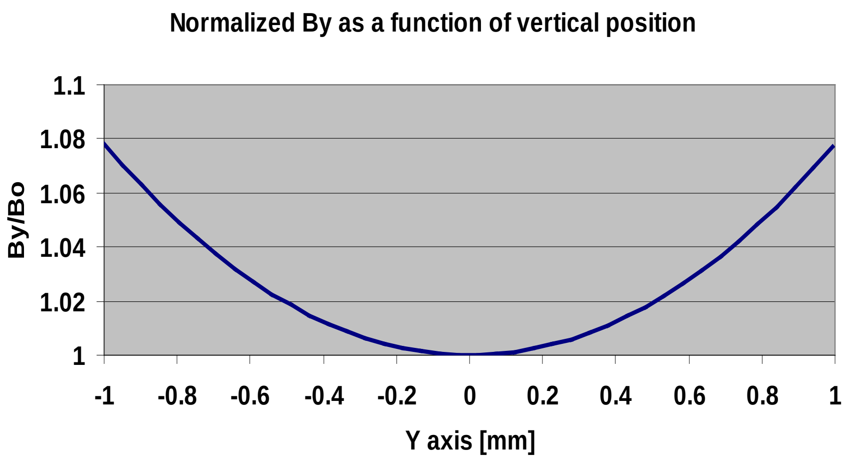
Details of quench properties presented in [10, 11]

Dual Hall Probe Measurements for Undulators

- Since a self-supporting Hall probe assembly is not possible, the stretched TI guide tube inside the beam vacuum chamber defines the path of the Hall probes.
- The straightness tolerance of the Hall probe path cannot be exactly determined but is estimated to be ±100 μm.
- If only one Hall probe is used, a measurement error due to the vertical position uncertainty will be introduced
- By using two Hall probes spaced a known distance apart in the vertical plane, the actual vertical position and mid-plane field can be calculated.

Dual Hall Probe Measurements for Undulators

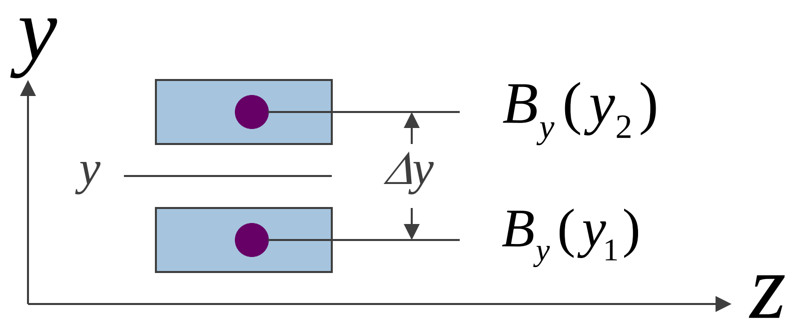
- The mid-plane field B_0 and average vertical position y can be determined using two Hall probes separated by a known distance Δy, which in this case is ~1 mm
- The vertical field B_y of an undulator as a function of vertical position and z position can be described by:



$$B_y = B_0 Cosh(ky) Sin(kz)$$

$$k = 2\pi / \lambda$$

$$\Delta y = y2 - y1 = 1.0mm$$



And at the field peaks by:

$$B_y(y_1) = B_0 Cosh(ky_1)$$

$$B_y(y_2) = B_0 Cosh(ky_2)$$

Dual Hall Probe Measurements for Undulators

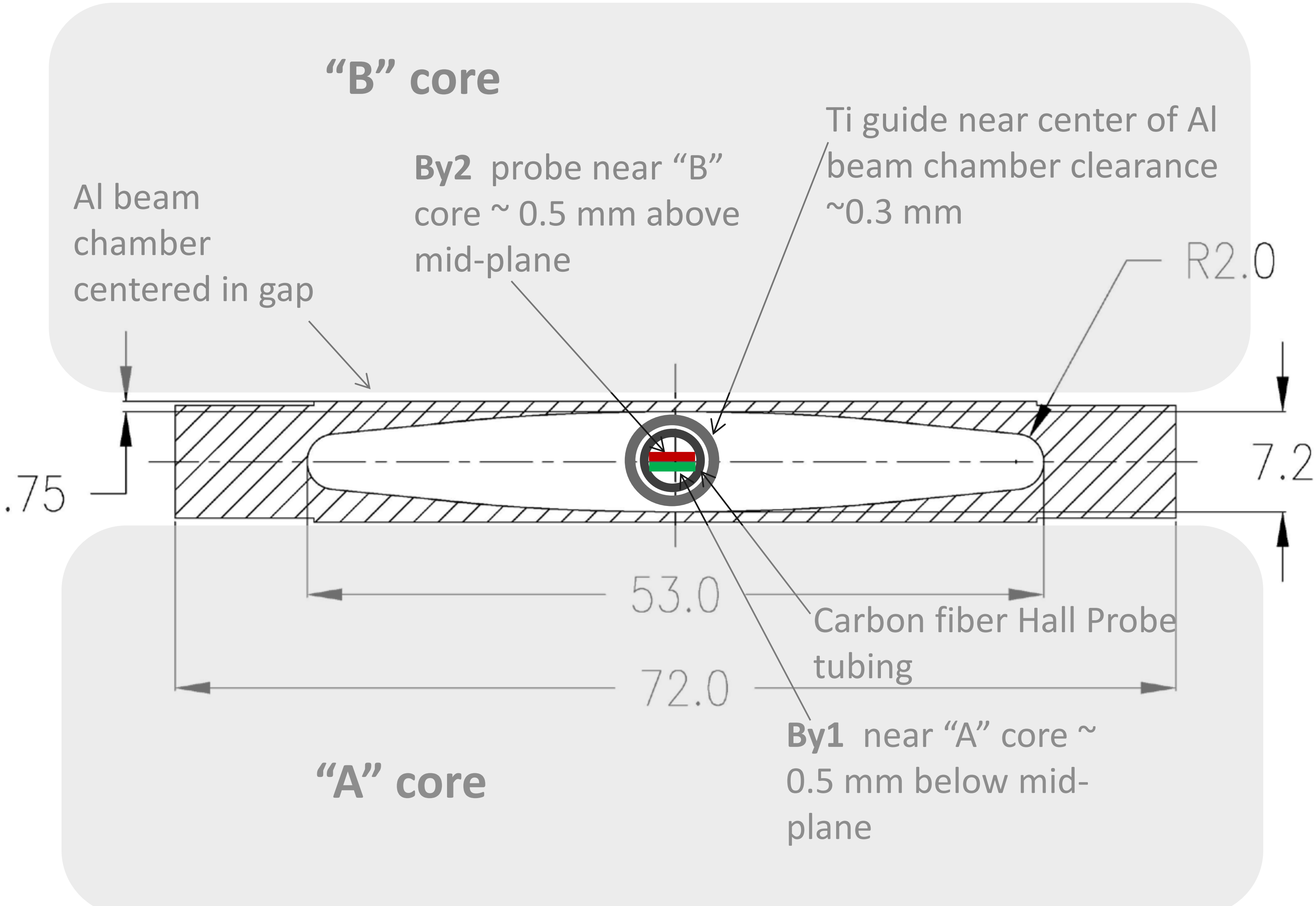
- Knowing the field values at $B_y(y_1)$ and $B_y(y_2)$ and the distance between probes Δy, the mid-plane field B_{yo} and average vertical position y of the probes can be determined by the following expression:

$$\Delta B_y = B_y(y_2) - B_y(y_1) \quad B_{sum} = B_y(y_2) + B_y(y_1) \quad \frac{\Delta y}{2} = 0.5mm$$

$$y = \frac{1}{k}\tanh^{-1}\left[\frac{\Delta B_y}{B_{Sum}}\frac{1}{(\tanh(k\frac{\Delta y}{2}))}\right]$$

$$B_{yo} = \frac{B_y(y_1)}{Cosh(ky_1)} = \frac{B_y(y - \frac{\Delta y}{2})}{Cosh(ky_1)} = \frac{B_y(y_2)}{Cosh(ky_2)} = \frac{B_y(y + \frac{\Delta y}{2})}{Cosh(ky_2)}$$

Al Beam Chamber Cross Section with Ti Guide Tube and CF Hall Probe



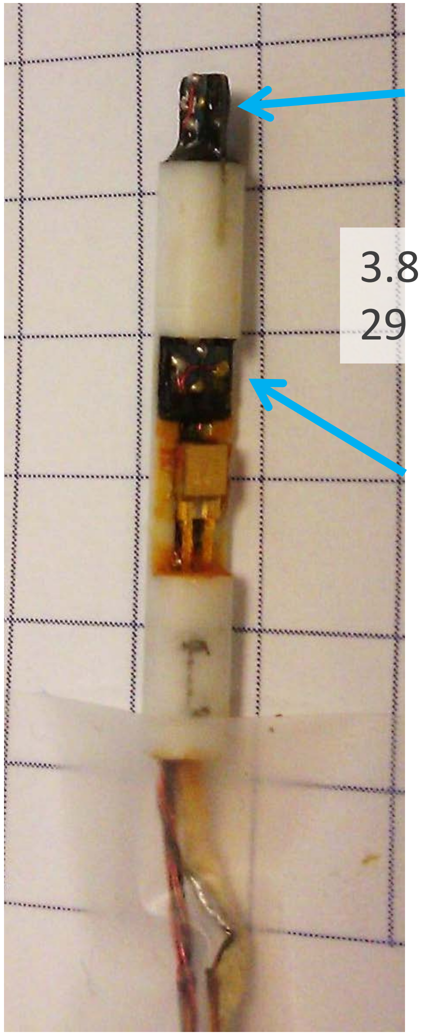
Custom 3-sensor Hall Probe Assembly

Three Arepoc Hall sensors and one temperature sensor are mounted to a ceramic holder, which is then installed in a carbon fiber tube.

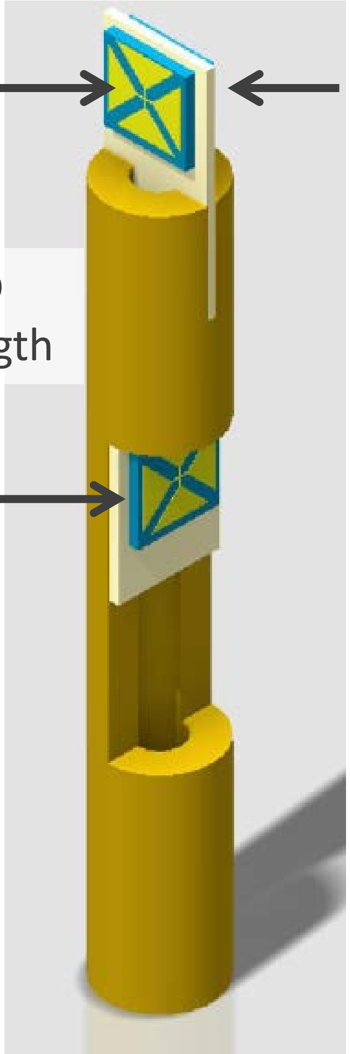
Two sensors measure B_y above and below the mid-plane separated by ~1 mm (suggested by I. Vasserman) [7]
These sensors were calibrated by M. Abliz [12]

Third sensor measures B_x

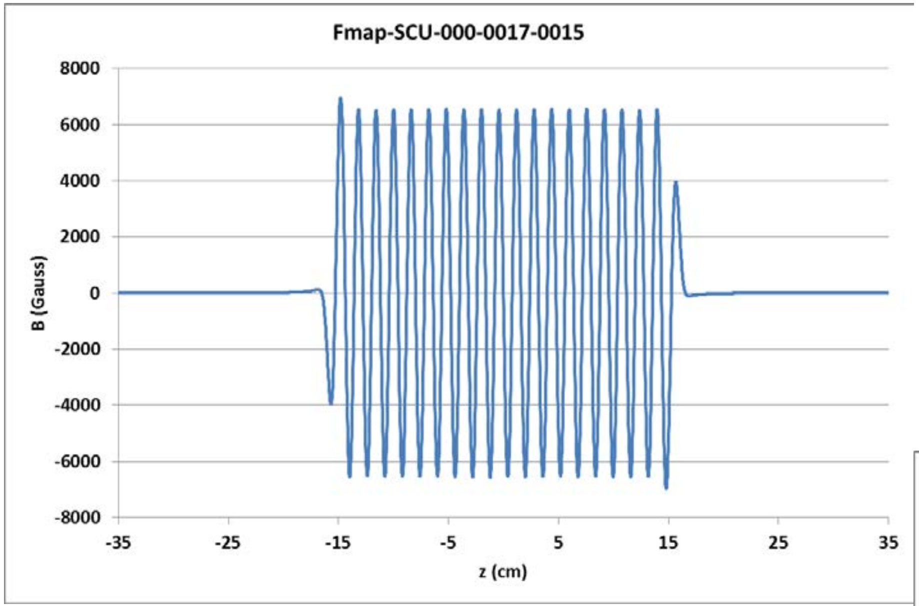
Nominal K1 scale factor 14 T/V



3.8 mm OD
29 mm length

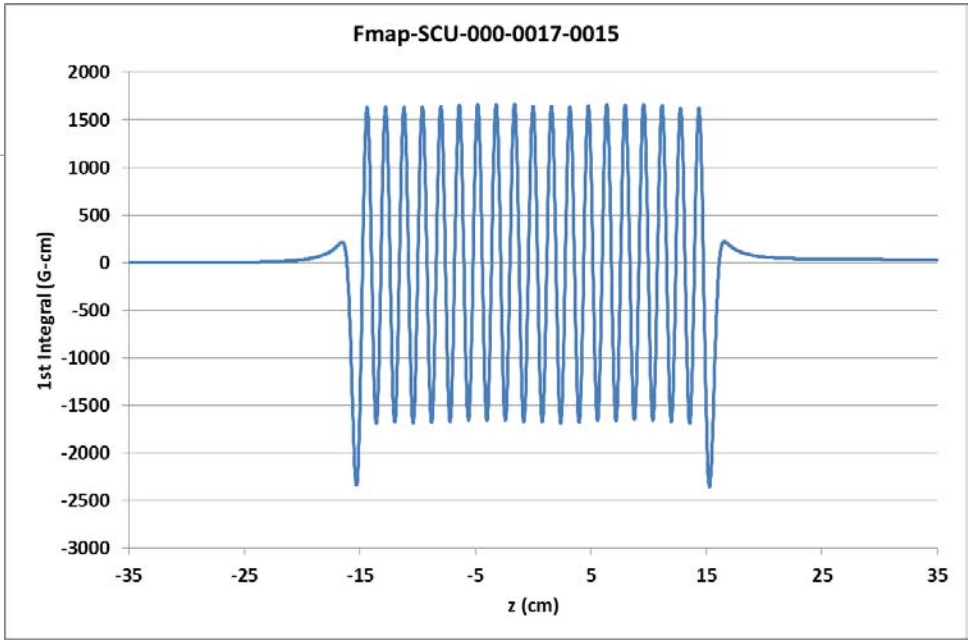


Typical Hall Probe Measurement Results at 500 A



Typical B_y field with main coil current of 500 A and correction current of 51.7 A

1st field integral of above data

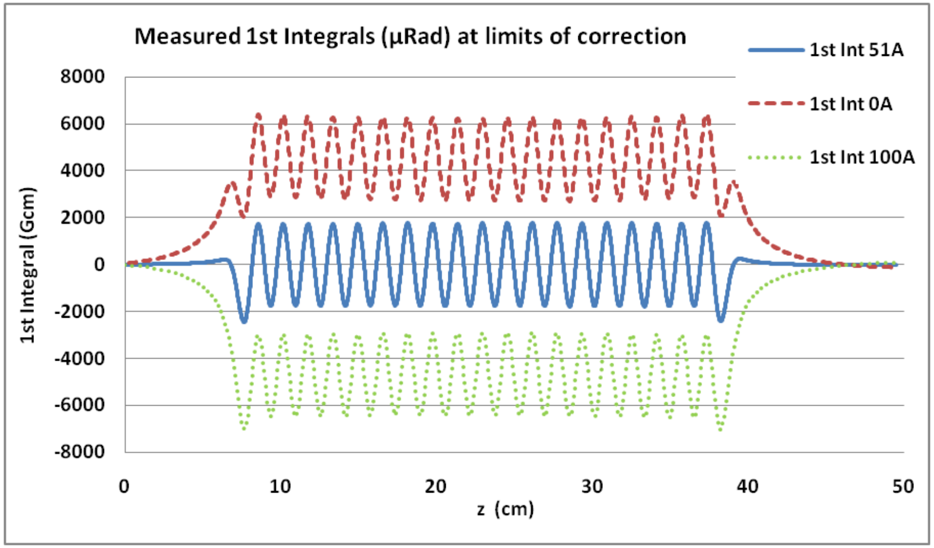


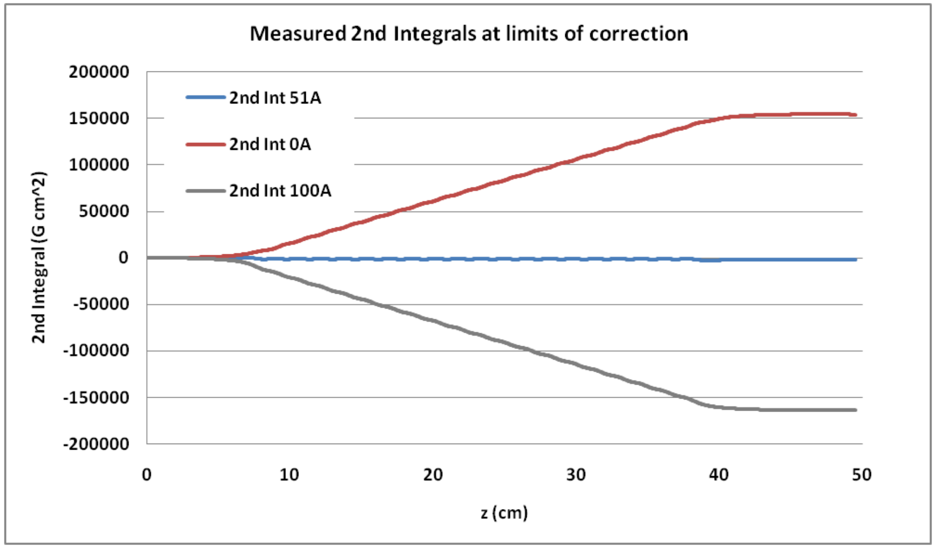
Range of Correction with Main Current at 500 A [13]

The plot to the right shows typical 1st field integrals (measured with Hall probes) with maximum, minimum, and ideal correction current with 500 A main current.
5000 G-cm ~ 200 μRad angle @ 7GeV

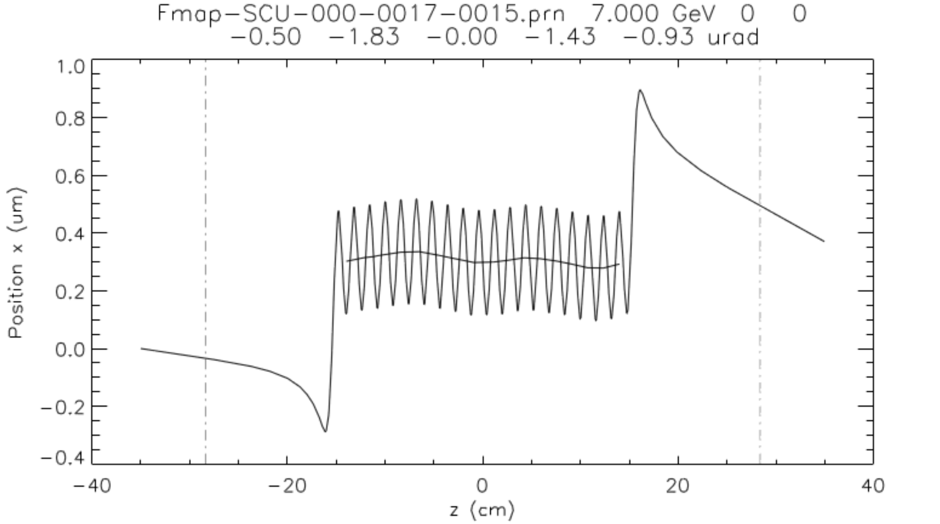
The average photon beam angle can be adjusted ±200 μRad relative to the incoming e-beam.

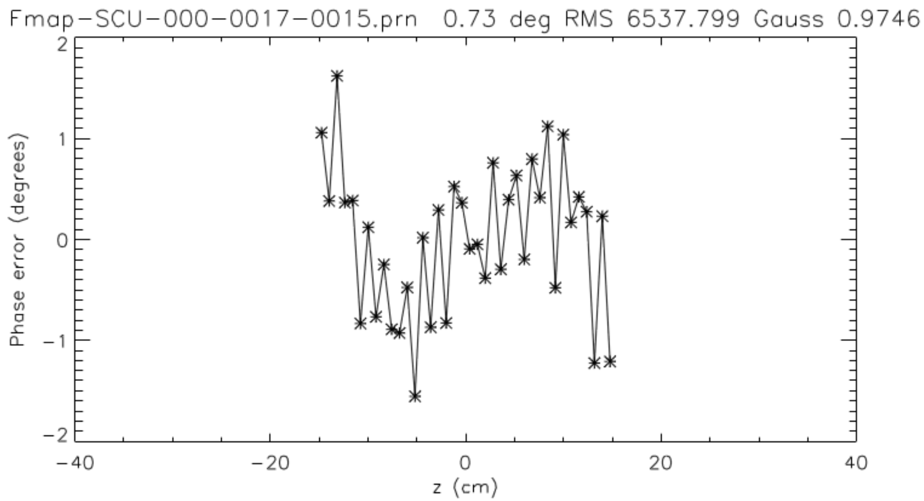
The plot to the right shows the range of the 2nd field Integrals, equivalent to an exit offset of ~ ±70 μm.





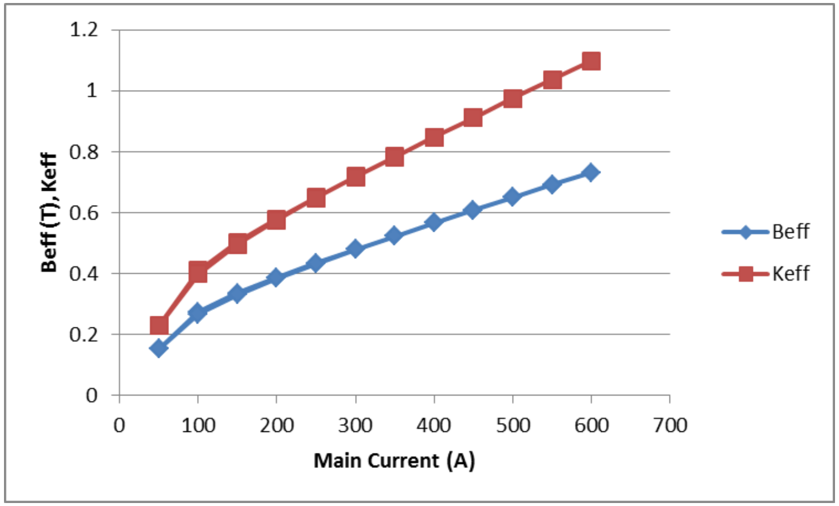
SCU0 Trajectory and Phase Errors
Main Current, 500 A, Corrector Current, 51.6 A

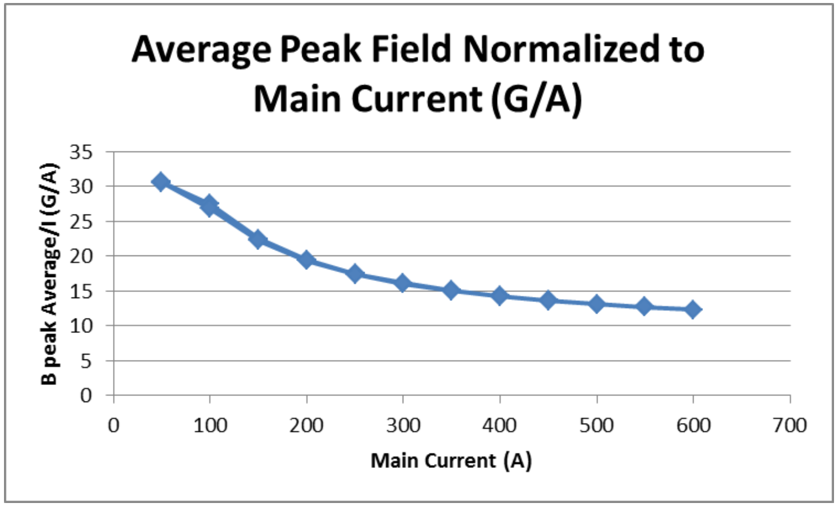


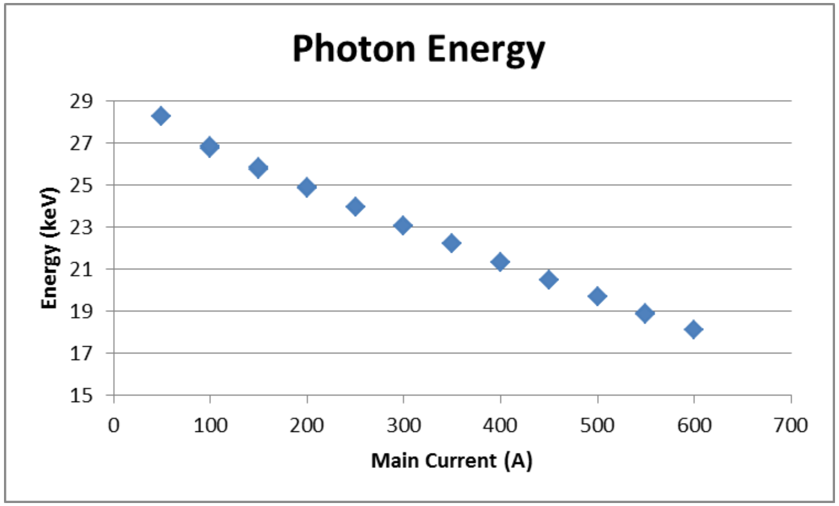


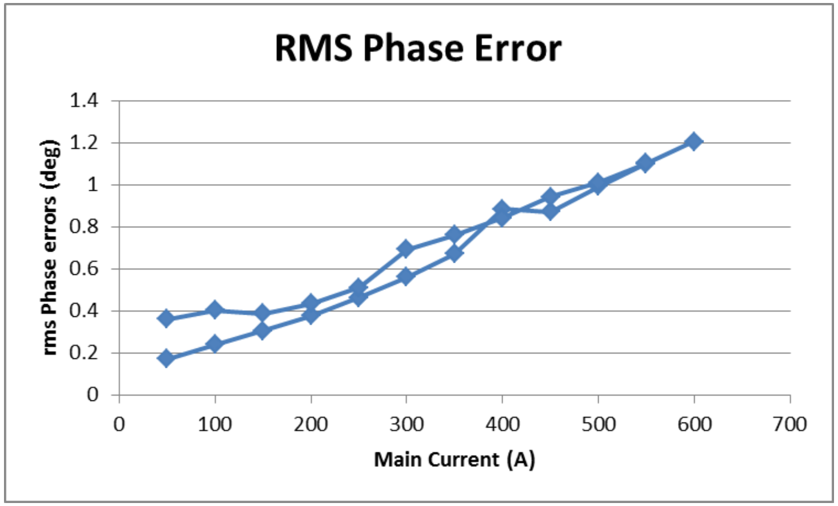
Some Current-Dependent Parameters based on Hall Probe Measurements

Fmap-SCU-000-0017-0002 to 0024

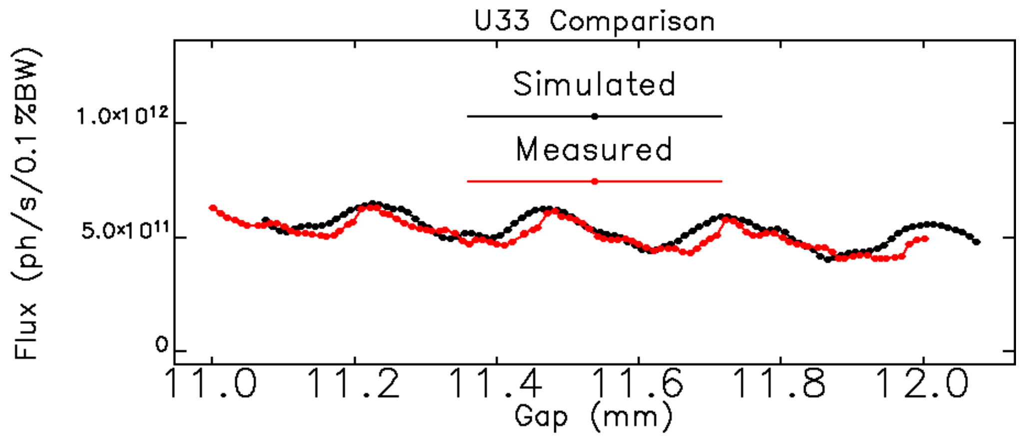


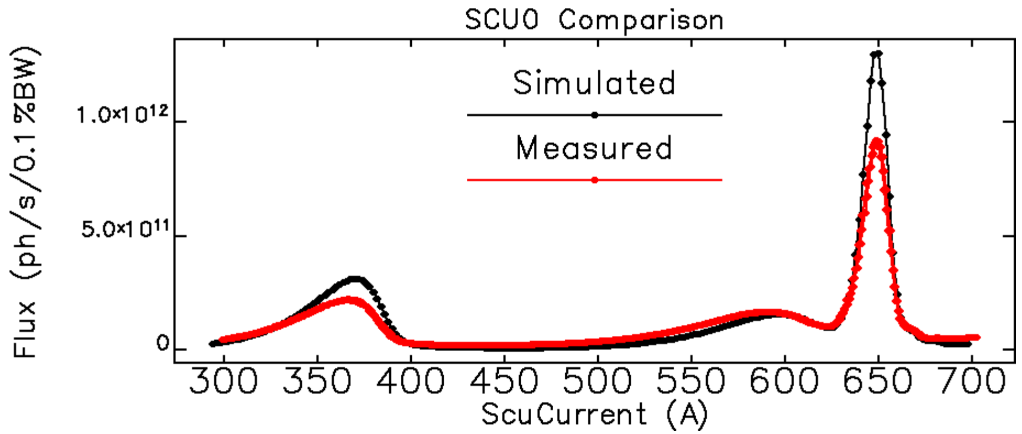






SCU0 and U33#25C Flux in 0.5 x 0.5 mm at 40.5 m at 85.3 keV

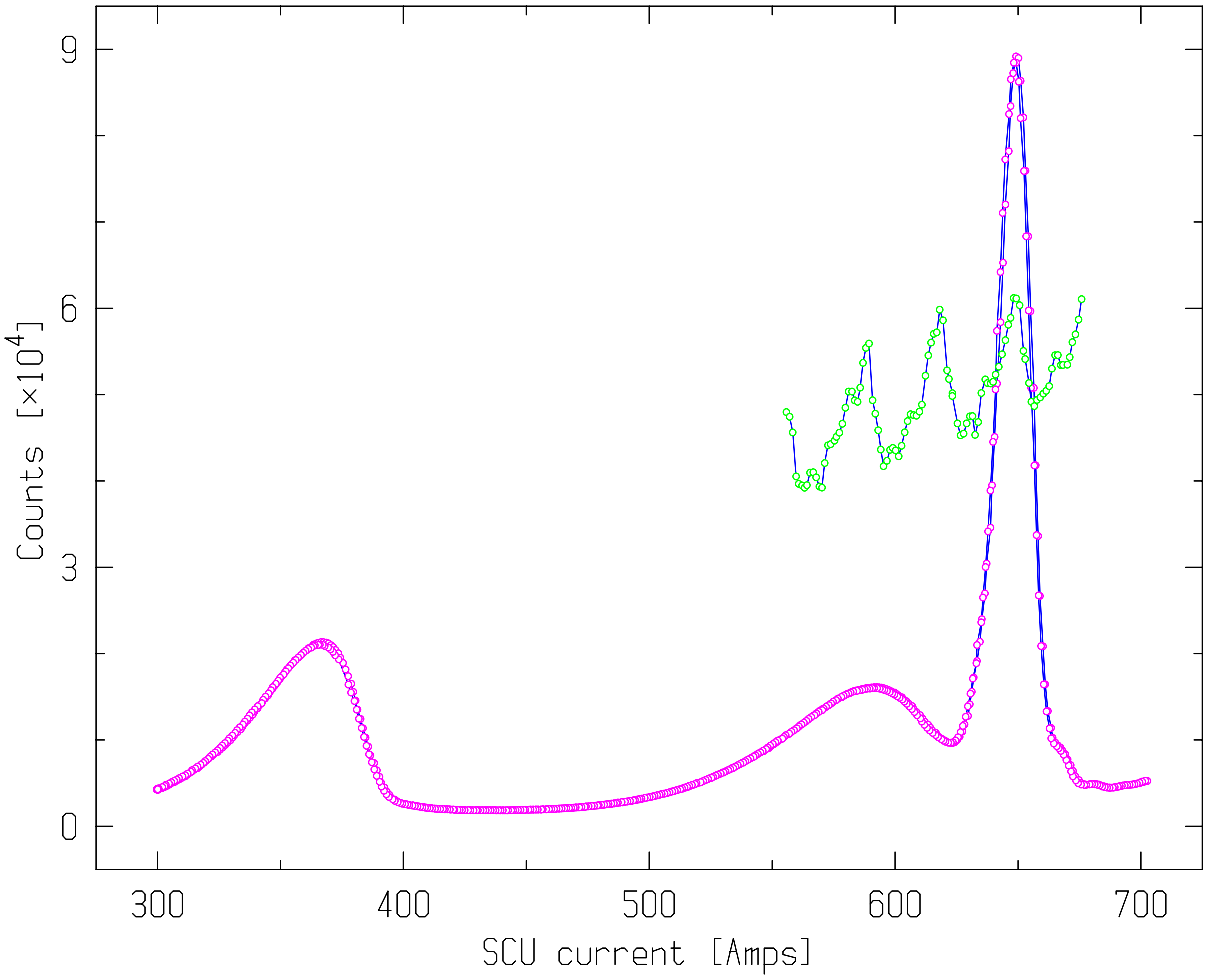




Courtesy
R. Dejus, APS
(2013)

- The measured flux of the U33#25C (3.3 cm period, 70 periods) was scaled to coincide with the simulated flux (top figure). The same scale factor was then applied to the measured flux of the SCU0.
- The SCU0 (1.6 cm period, 21 periods) shows a measured flux of about 70% of the simulated flux for the 5th harmonic at 85.3 keV (bottom figure). It shows about 45% higher flux than that of the U33#25C. (The rms phase error of the SCU0 is about 2.3 degrees at 650 A and about 3.9 degrees for the U33#25C over the range gap 11 – 12 mm).

SCU0 5th Harmonic and Undulator A at 85 keV



Courtesy
J. Lang, APS
(2013)

SCU0 flux at 85 keV is 1.4x higher than Undulator A

Conclusions

- The SCU horizontal magnetic measurement system performed very well for both the Hall probe and coil measurements. Overall design worked very well. We have plans to do some small modifications to ease guide tube alignment.
- Hall probe calibrations of the Arepoc sensors were confirmed by M. Abliz, J. Xu, and I. Vasserman to be adequate for the SCU measurements. [14]
- The SCU0 magnet performs better for all design parameters except the integrated skew quadrupole component. The design specification is 50 G and the measured value was 120 G at 500 A. Methods to correct for this in longer devices are being explored.
- Measured phase errors are typically 1 degree rms or less from 100 to 600 A.
- The normal 1st field integrals typically change less than 30 G-cm from 100 to 600 A for both fixed currents and dynamic changes in current.
- The skew 1st field integral changes by less than 40 G-cm from 100 to 600 A.
- The normal and skew 2nd field integrals change by less than 8000 G-cm^2 from 100 to 600 A dependent on the corrector current lookup table.
- A magnet coil quench will not cause an excessive stored e-beam perturbation.

References

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