SCU Horizontal Magnetic Measurement System Design

Chuck Doose

August 1, 2011

Thank you to the following people for making significant contributions to the measurement system specification and design

- N. Bartkowiak (AES-DD)
- T. Buffington (AES-DD)
- D. Skiadopoulos (AES-DD)
- J. Liu (AES-MD)
- E. Trakhtenberg (AES-MD)
- M. Abliz (ASD-MD)
- I. Vasserman (ASD-MD)
- J. Zu (AES-C)
- K. Boerste (ASD-MD)
- M. Kasa (ASD-MD)
- S. Kim (ASD-MD)
- E. Gluskin (ASD-MD)
- R. Kustom (ASD-RF)
- E. Moog (ASD-MD)
- Y. Ivanyushenkov (ASD-MD)
- N. Mezentsev (Budker)
- V. Syrovatin (Budker)
- V. Tsukanov (Budker)
- V. Lev (Budker)

Scope

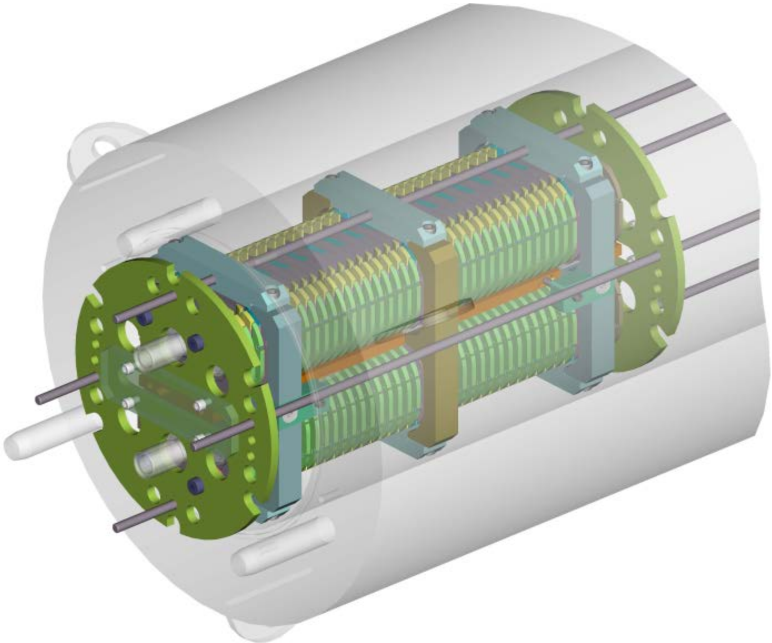
- Brief description of the SCU0 magnet specifications and cryomodule
- Existing vertical LHe bath magnetic measurement system
- Measurement results using vertical system
- Magnetic measurement challenges and solutions
- Horizontal measurement system requirements
- Magnetic measurement capabilities
- Hall probe system description
- Integral coil system description
- System Costs

SCU0 Specifications	
Electron beam energy	7 GeV
Photon energy at 1st harmonic	19-25 keV
Undulator period	16 mm
Magnetic length	0.33 m
Cryostat length	~2.0 m
Beam stay-clear dimensions	7.0 mm vert. x 36 mm horz.
Magnetic gap	9.5 mm
Beam chamber vertical aperture	7.2 mm
1st field integral	100 G-cm vertical, 50 G-cm horizontal
2nd field integral	105 G-cm2

SCU0 Specification and Concept
Author: Yury Ivanyushenkov
Division: ASD Group: MD
APS_1405265

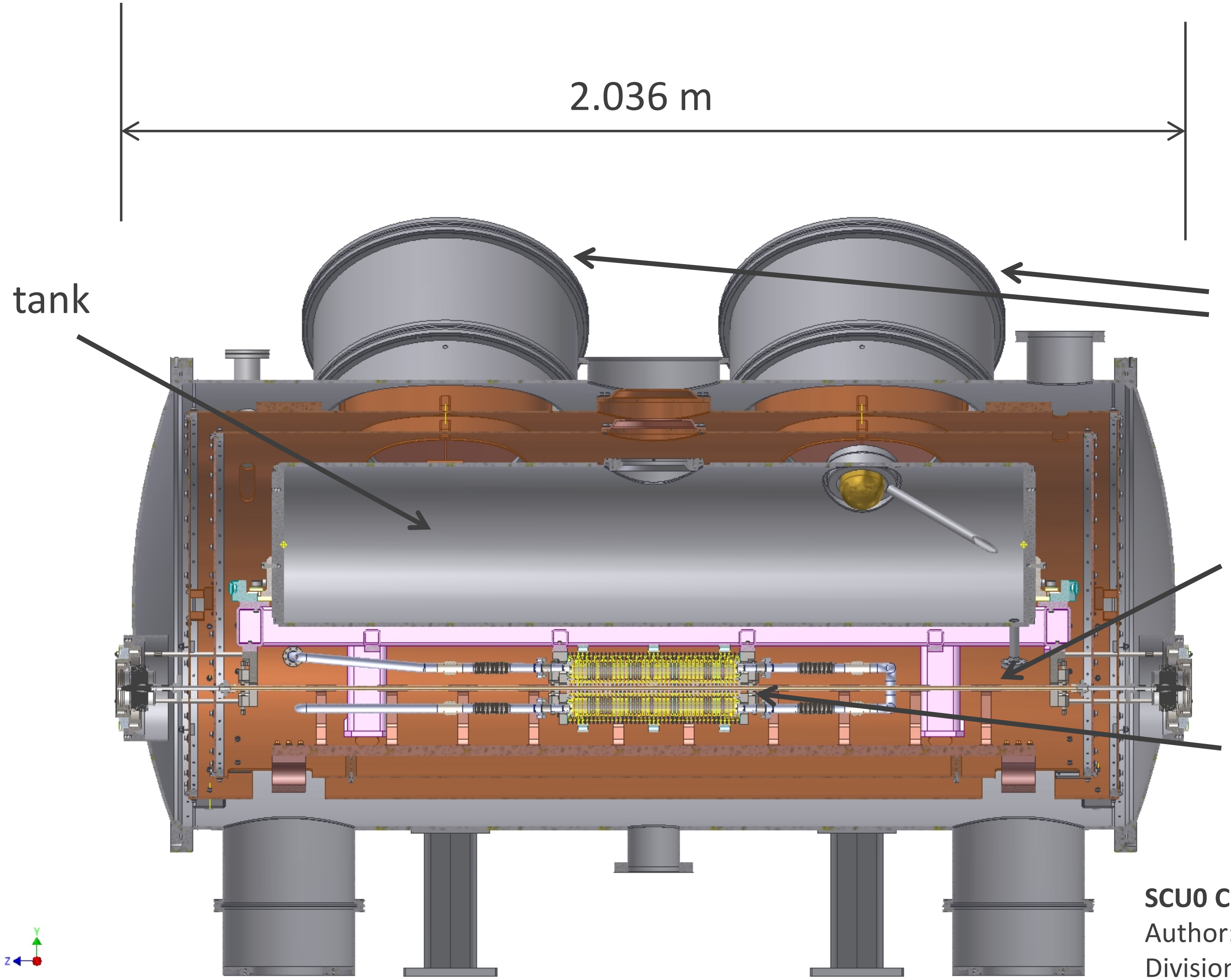
SCU0 magnetic structure

One of two 42 pole epoxy-potted steel cores showing the pole face
Overall length is 331 mm



Two-core SCU0 assembly in LHe vertical cryostat for preliminary magnetic measurements

SCU0 Cryomodule



LHe tank

Cryocoolers

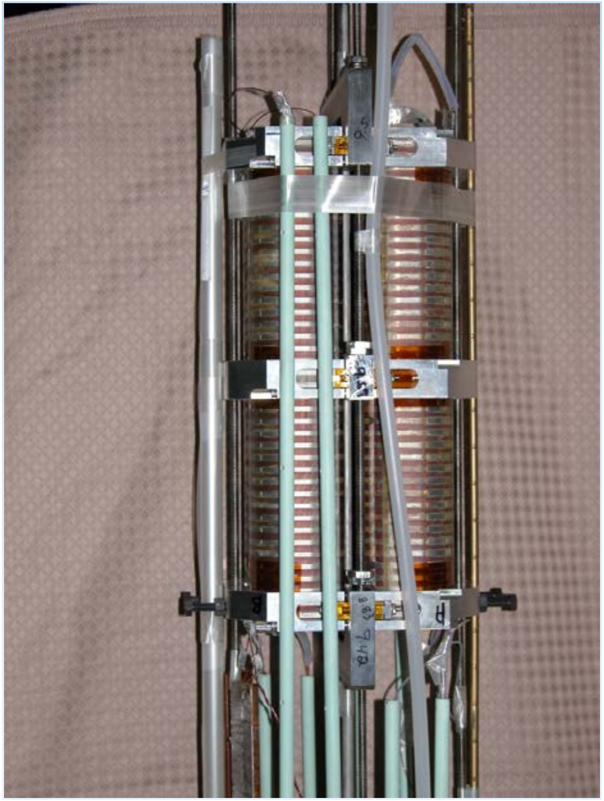
Beam chamber

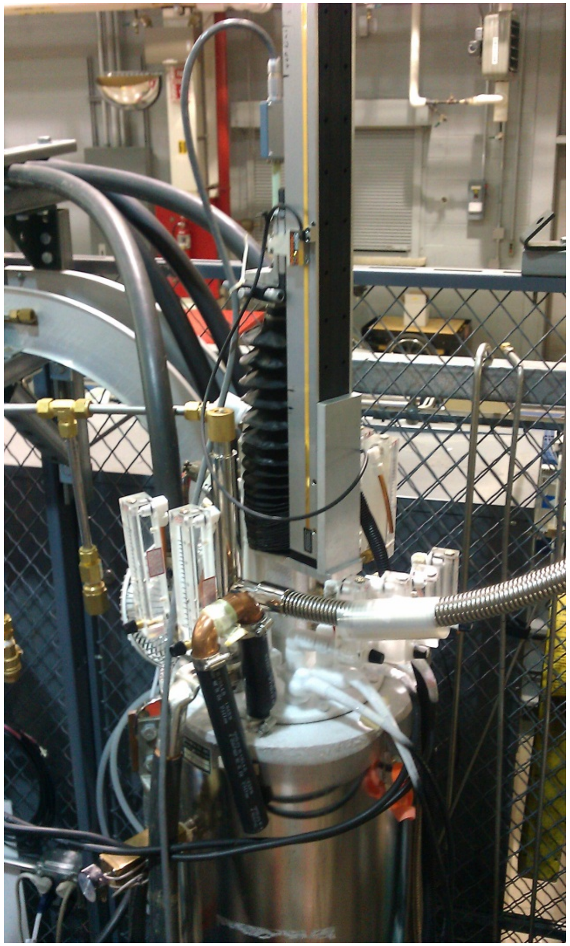
SCU0 magnet

SCU0 Conceptual Design
Author: Yury Ivanyushenkov
Division: ASD Group: MD
APS_1405266

Existing LHe vertical cryostat measurement system

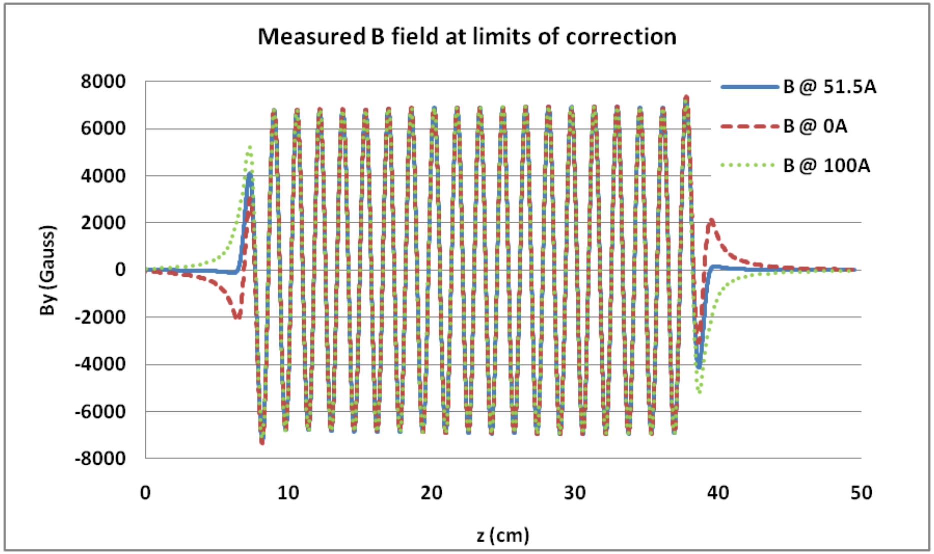
- Presently using to measure the prototype SCU magnet assemblies
- This system used to ensure the field quality prior to cryomodule installation





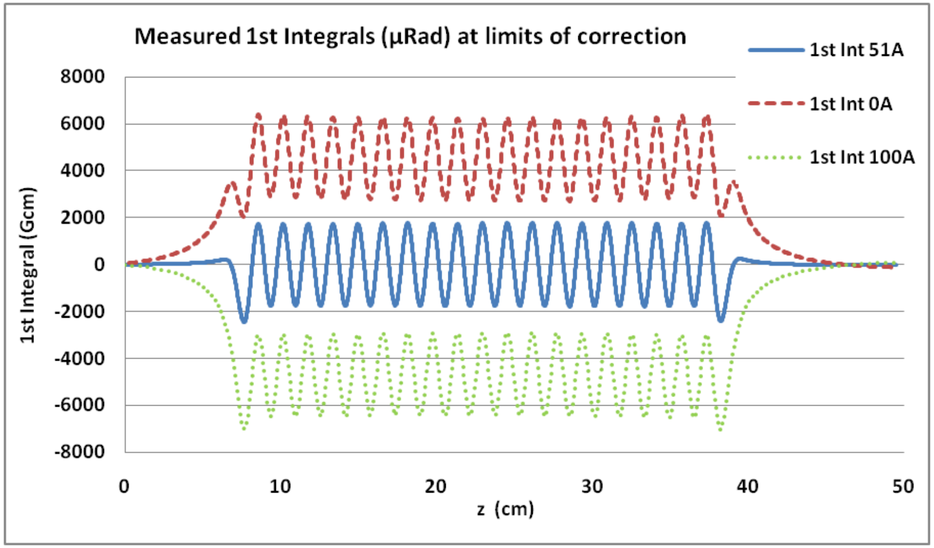
Measured B_y and 1st integral with main coils at 500 A

This plot shows the B field profile with all the correction coils connected in series and energized to 0, 51.5, and 100 A

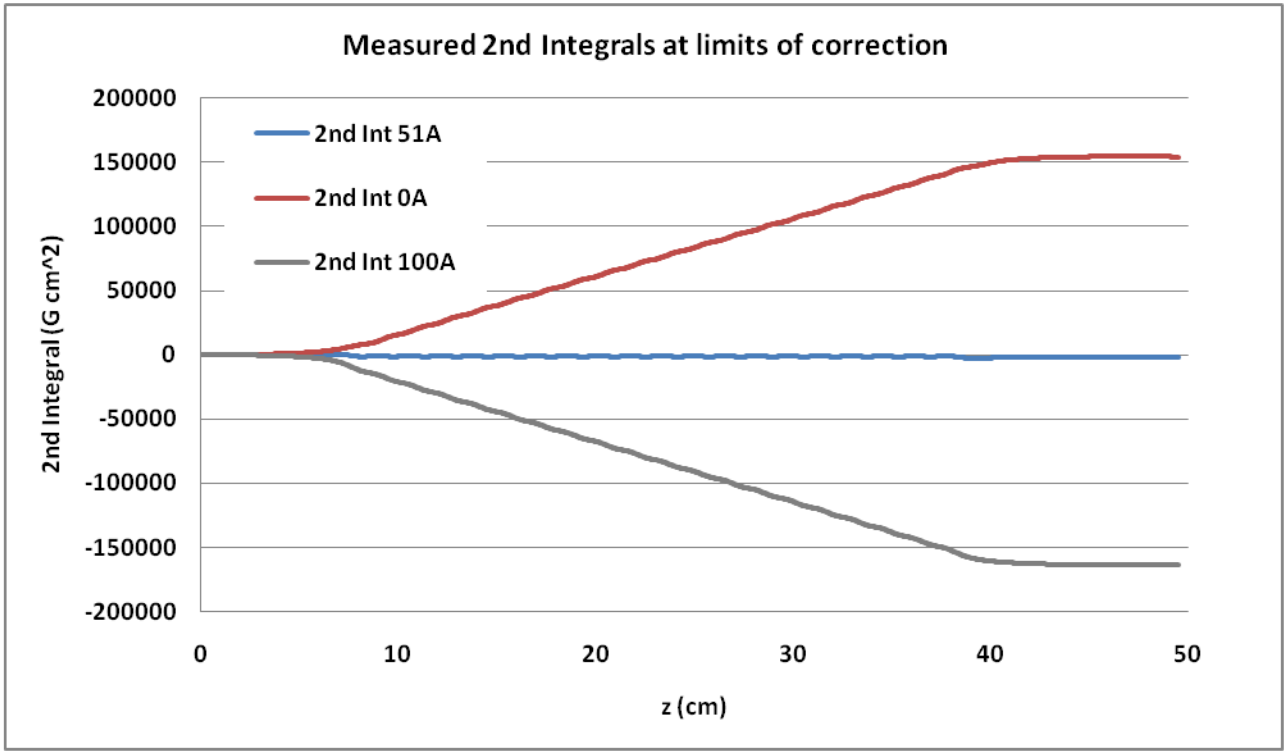


This plot shows the first integrals calculated from the above B field data 5000 Gcm ~ 200 μRad angle @ 7GeV

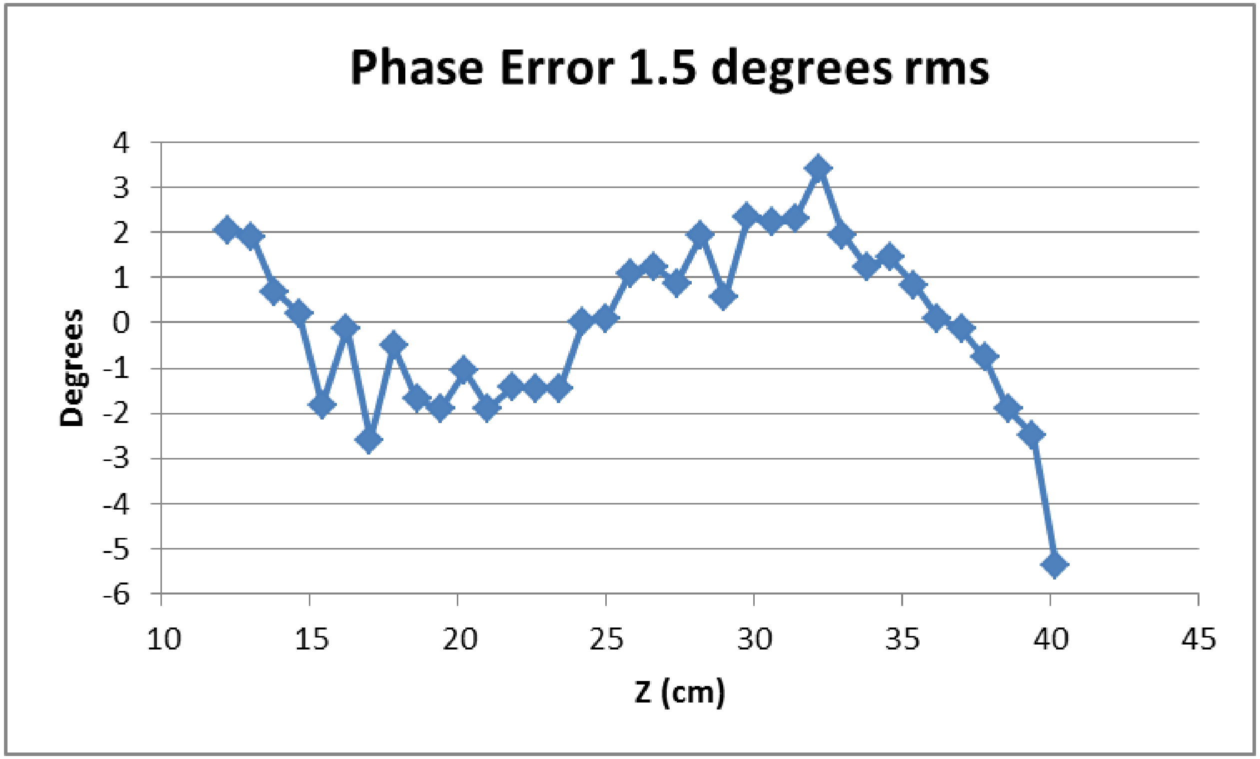
The photon beam angle can be adjusted ±200 μRad relative to the incoming e-beam



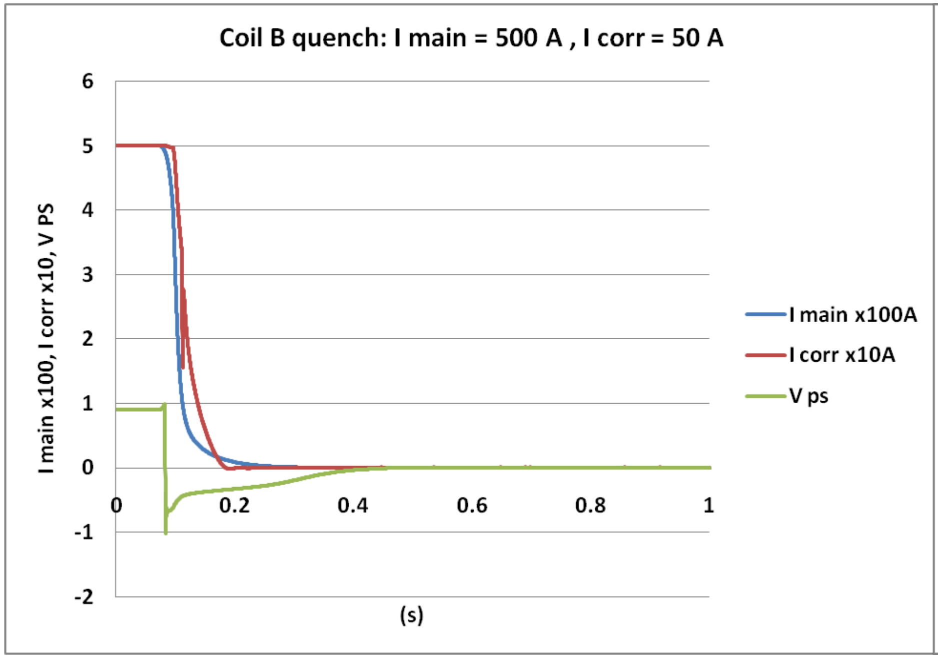
Range of 2nd Integral with correction of 0, 51 and 100 A, beam offset at exit ~ ±70 μm beam angle ~±200 μrad

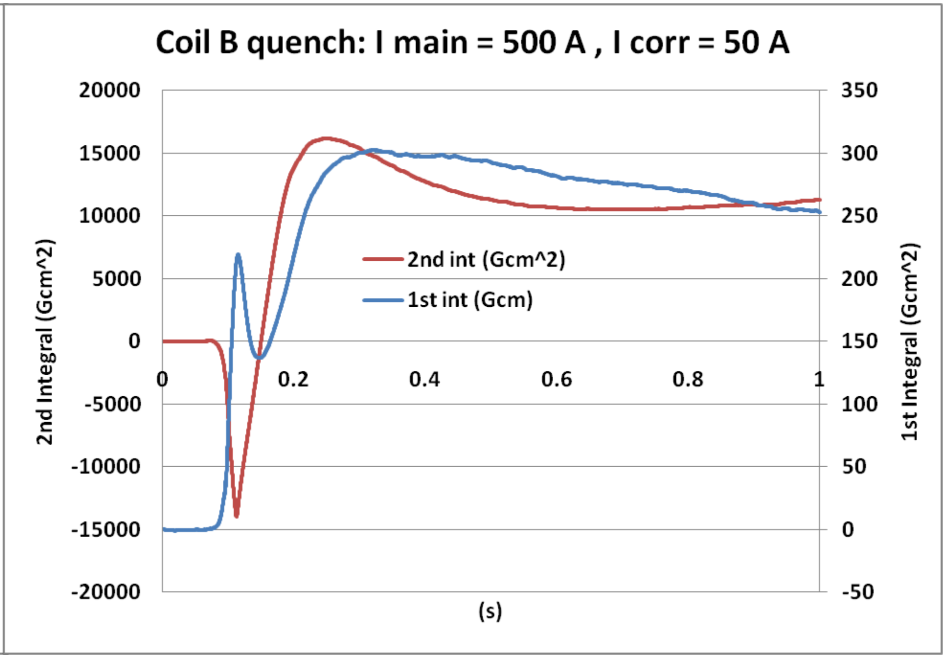


Phase errors prototype SCU
K effective 1.04
B effective 0.698 T
1st Harm E 18.8 keV



1st and 2nd field integrals during a quench

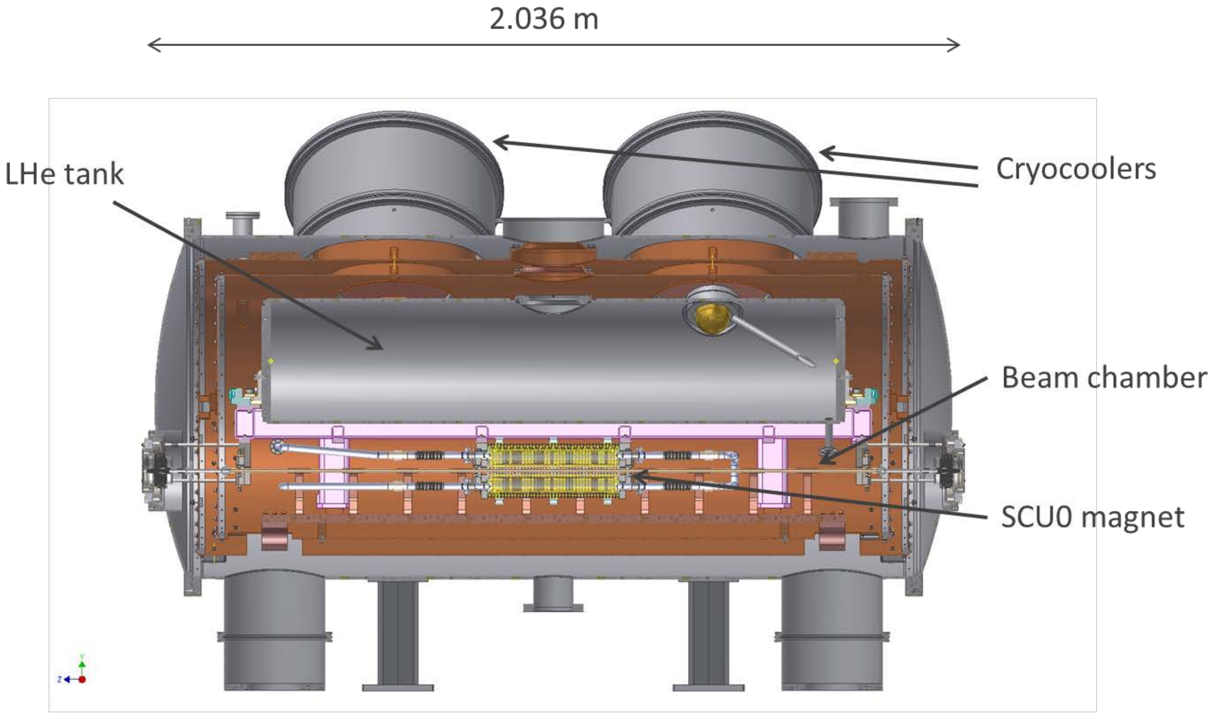




- When the correction current decays at nearly the rate of the main current, the 1st and second integrals are relatively small i.e. 300 Gcm (13 μR) and 12000 Gcm^2 (5.5 μm) respectively.
- During main coil quench, induced current in the correction coils disrupts the PS regulator and the terminal voltage will momentarily rise to compensate.
- Operating the corrector PS with the OVP set-point slightly higher than the operating point will automatically cause the PS to shut down ~ 10 ms after the main current.

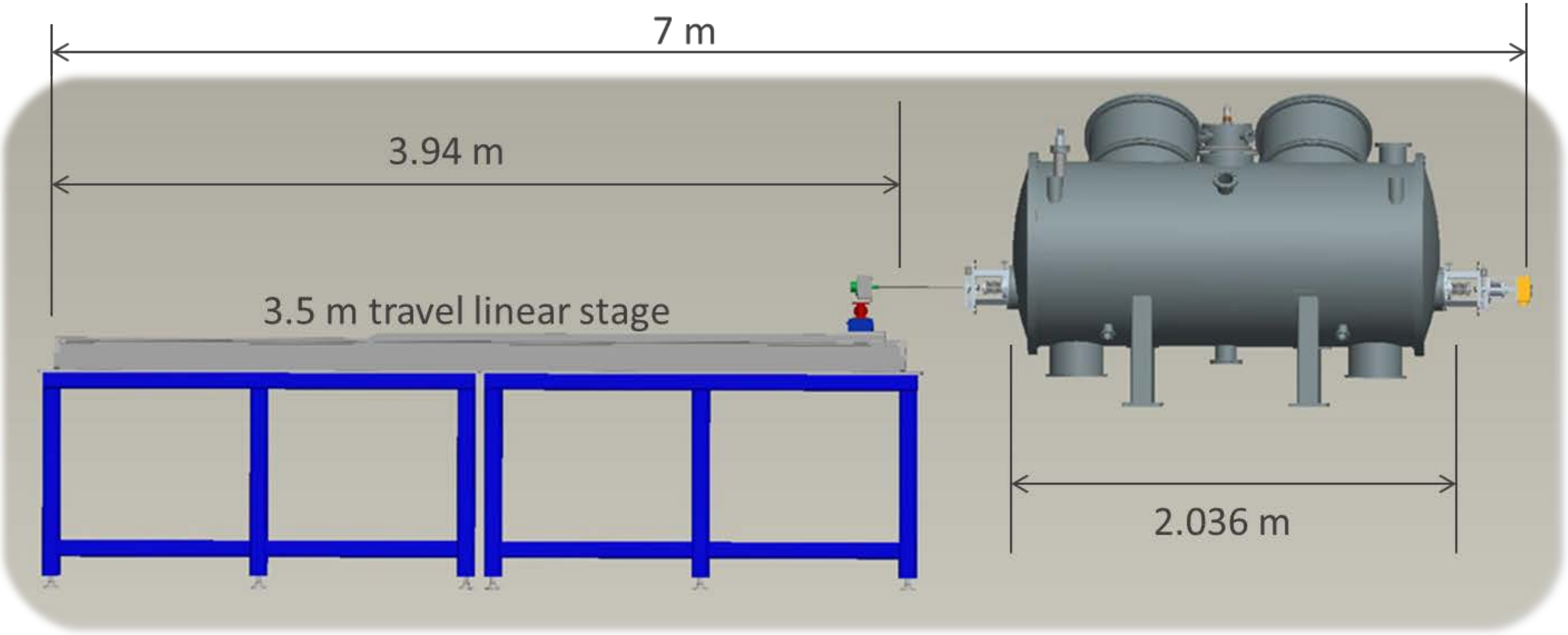
Horizontal magnetic measurement challenges

- Cryogenic undulator magnet beam chamber ~20 K, magnet 4.2 K
- Small vertical aperture 7.2 mm
- Two to Three meter long cryomodule
- Only access to magnetic gap from ends of device
- Need Hall probe scans and integral coil measurements



Horizontal measurement system design features

- Warm bore tube inside cold beam chamber (based on Budker design)
- Warm tube is insulated from beam chamber and serves as a guide for Hall probe scanning and can be positioned ± 1 cm horizontally from the magnet central axis
- 3.5 m stage used for Hall probe scanning
- Rotary stages used for integral coil measurements



Measurement system requirements

Parameter	Required resolution	Peak signal level	Measurement resolution
Hall B field (Gauss)	0.2	10000	0.1 *
1st Field Integral (G-cm)	10	0.5 μV @ 2 Hz	0.1 μV @ 2 Hz
2nd Field Integral (G-cm^2)	2500	2 μV @ 2 Hz	0.1 μV @ 2 Hz

* With Hall probe scan velocity 2 cm/s with measurement Δz = 0.1 mm

The theoretical resolution of the Dynamic Signal Analyzer is 20 nV, but in reality the ultimate resolution is limited by thermal and electrical noise which is expected to be about 0.1 μV.

The above listed resolutions are based on using a rectangular and figure 8 coil with 4 mm width.

Measurement system capabilities

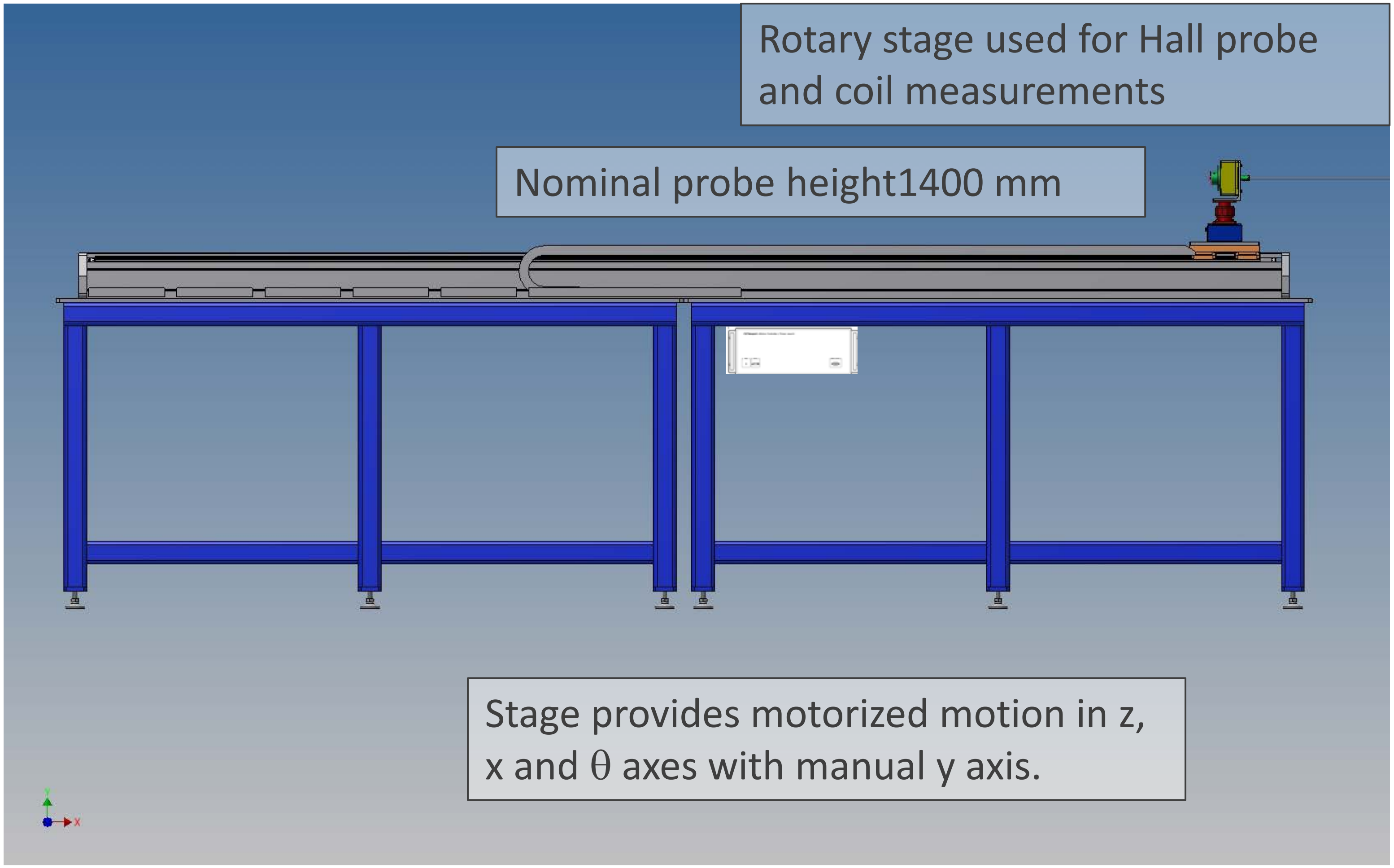
- Warm bore system based on Budker Institute's wiggler measurement system.

- Scanning Hall Probe
  - On-the-fly Hall probe measurements (2 cm/s, Δz 0.1 mm) 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.
  - Hall probes can be rotated to any fixed angle with 0.01 degree absolute accuracy. The probes could also be rotated through 360 degrees at a fixed z location.

- Stretched Wire Coil
  - Stretched wire rectangular and figure 8 coils to determine 1st and 2nd field integrals.
  - Rotary stages on upstream end of cryostat as well as on the Z axis linear stage to provide synchronized rotary motion for stretch coils.
  - Integral coil measurements can be done by rotating through 360 degrees and triggering at fixed angular positions, or can be rotated continuously to provide for lock-in amplifier capability.
  - Coils can be translated along x axis approximately ±1 cm to measure integrated multipoles.

- 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

3.5 m Linear stage used for Hall probe and integral coil measurements



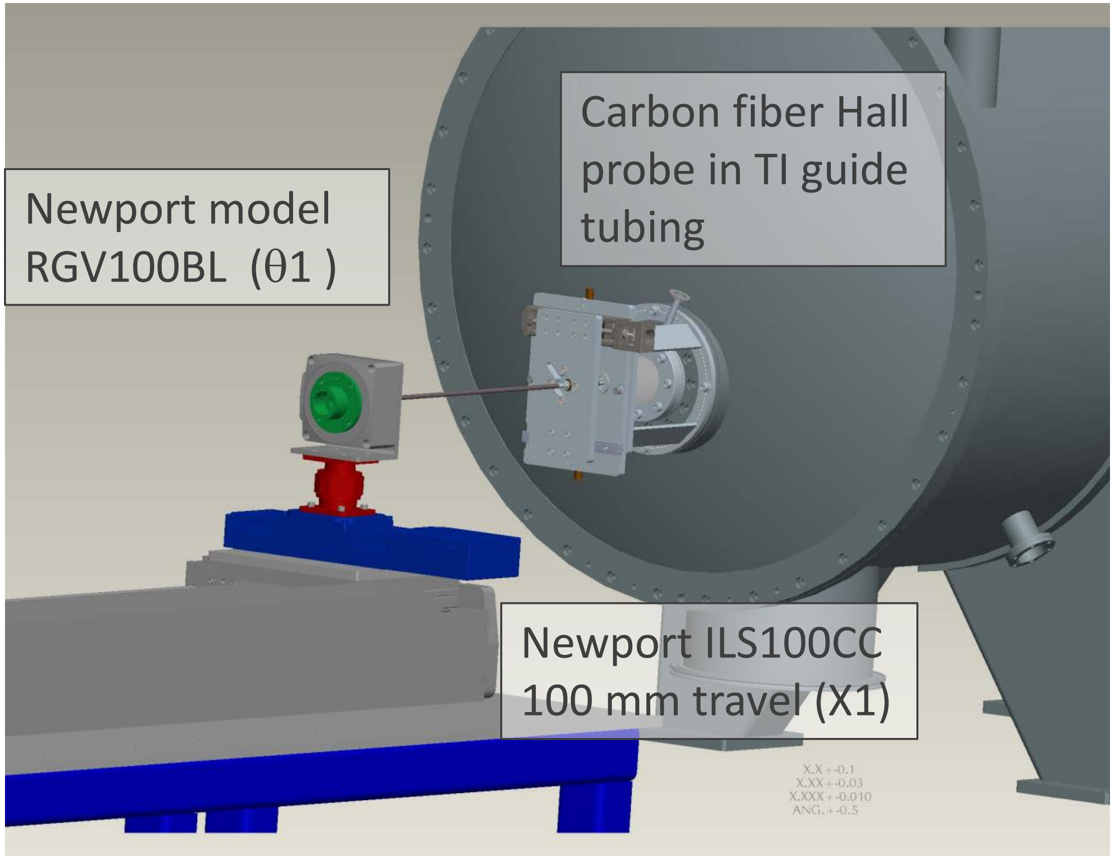
Rotary stage used for Hall probe and coil measurements

Nominal probe height1400 mm

Stage provides motorized motion in z, x and θ axes with manual y axis.

Hall probe scanning system

- Linear stage used to drive a carbon fiber Hall probe inside a heated titanium guide tube in the SCU vacuum chamber
- Guide tube centered vertically and can be moved transversely to measure within ±1 cm from the beam center

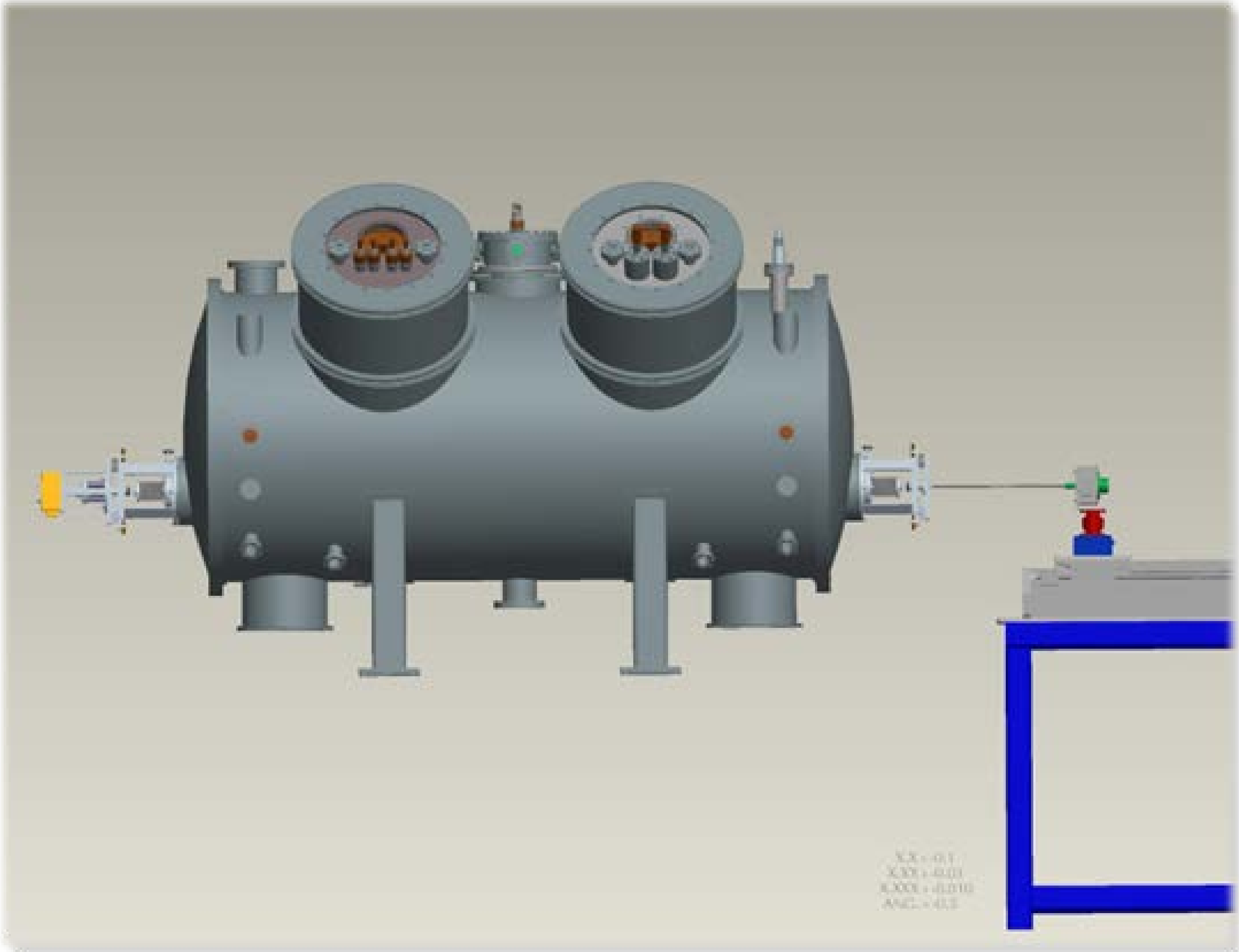


Newport model RGV100BL (θ1)

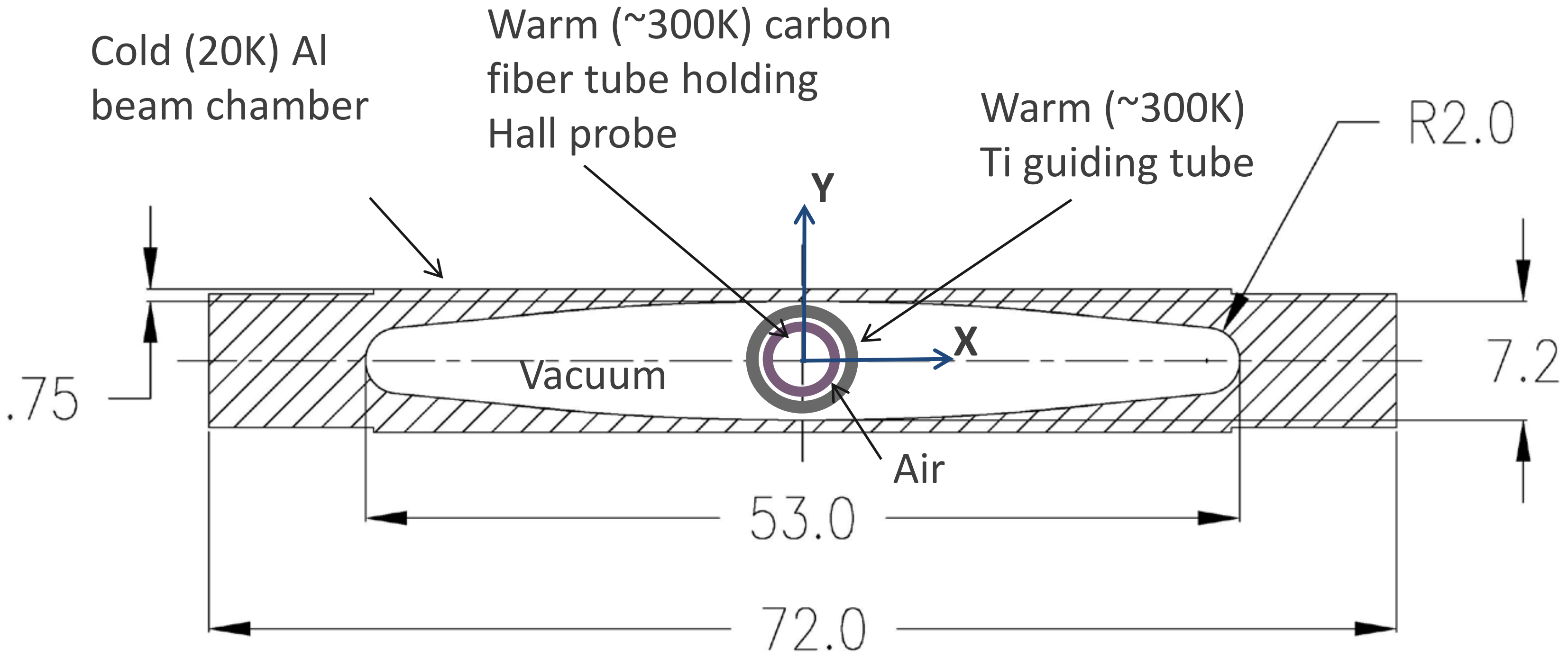
Carbon fiber Hall probe in TI guide tubing

Newport ILS100CC 100 mm travel (X1)

Hall probe scanning system: turret view



Hall probe scanning system
Vacuum chamber cross section inside cryomodule



Hall probe scanning system
Arepoc Hall probe ceramic holder

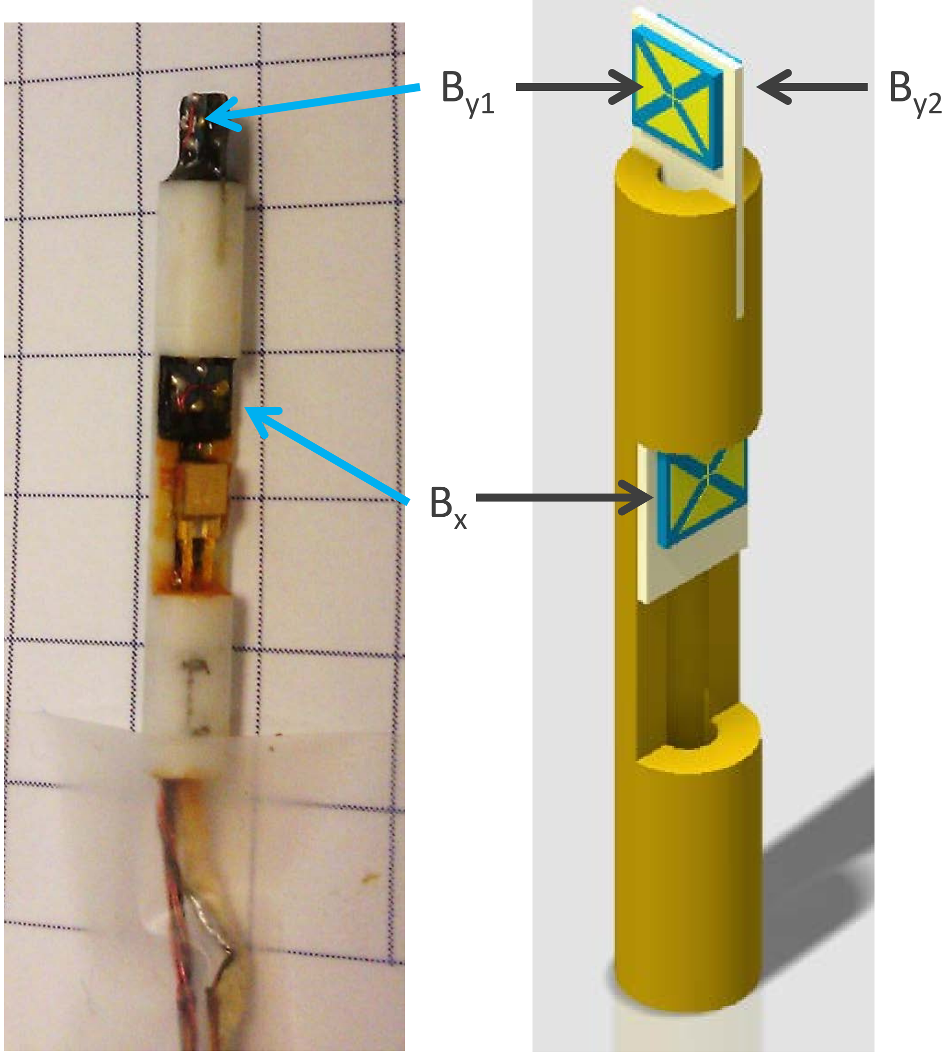
Three Hall sensors mounted to ceramic holder which is then installed in a carbon fiber tube

Two sensors measure *B_y* above and below the mid-plane separated by ~1mm

Third sensor measures *B_x*

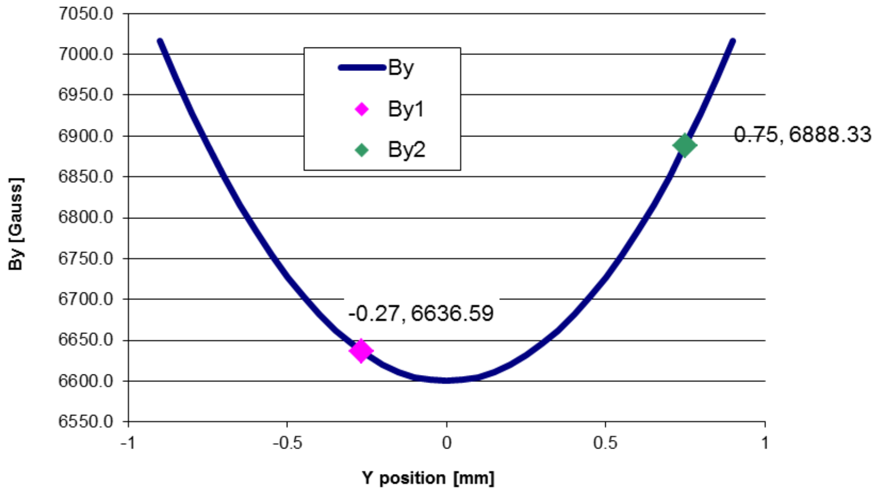
Nominal sensitivity 14.6 T/V

3.8 mm OD
29 mm length



Dual Hall probe measurement technique

- This method was suggested by Isaac Vasserman
- The mid-plane field B_o can be determined using two Hall probes separated by a known distance Δy
- The vertical field B_y of an undulator as a function of vertical position and z position can be described by:



$$B_y(z,y) = B_o Cosh(ky) Sin(kz)$$

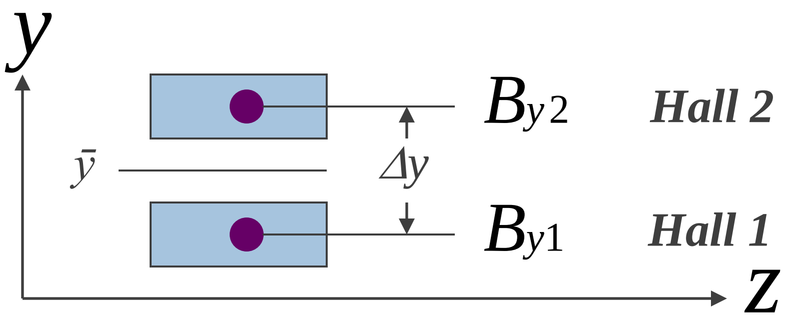
$$k = 2\pi/\lambda = 0.3927 mm^{-1}$$

$$\Delta y = y_2 - y_1 = 1.018 mm$$

- And at the field peaks by:

$$B_{y1} = B_o Cosh(k \cdot y1)$$

$$B_{y2} = B_o Cosh(k \cdot y2)$$



Dual Hall probe measurement technique

- Knowing the field values at B_{y1} and B_{y2} and the distance between probes Δy the mid-plane field B_{yo} and average vertical position $\bar{y}$ of the probes can be determined by the following expression:

$$\Delta B_y = B_{y2} - B_{y1} \qquad B_{sum} = B_{y2} + B_{y1} \qquad \frac{\Delta y}{2} = 0.509mm$$

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

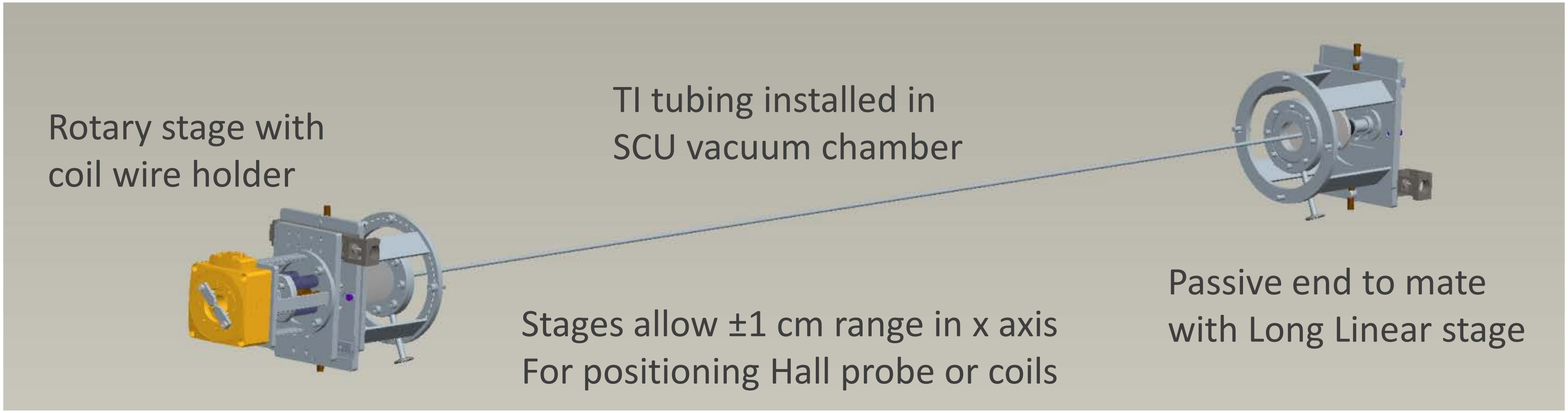
$$B_{yo} = \frac{B_{y1}}{Cosh(k \cdot y_1)} = \frac{B_{y1}}{Cosh\left[k\left(\bar{y} - \frac{\Delta y}{2}\right)\right]} = \frac{B_{y2}}{Cosh(k \cdot y_2)} = \frac{B_{y2}}{Cosh\left[k\left(\bar{y} + \frac{\Delta y}{2}\right)\right]}$$

- The calculation of B_{yo} is most accurate at the field peaks, however if the Hall probe path is parallel to the poles , a single correction factor can be used to determine B_{yo} . If the path is not parallel to the poles, a fit to $\bar{y}$ can be done to calculate $B_{yo}(z)$

Practical challenges with three Hall sensor probe

- The z position of each sensor is not exactly the same which complicates numerical calculations.
- The calculation of B_o, y_1, y_2 and $\bar{y}$ is done at the field peaks. If $\bar{y}$ is relatively constant, then a single factor can be used to calculate $B_o(z)$ for all measured points, if not a fit of $\bar{y}(z)$ can be used.
- Due to these challenges we plan to also have a single sensor probe mounted so the active area is centered on the axis of the CF tubing. In this way field at any angle can be measured near the beam axis as a check to the dual sensor results.

TI Guide tube and cryomodule end stages

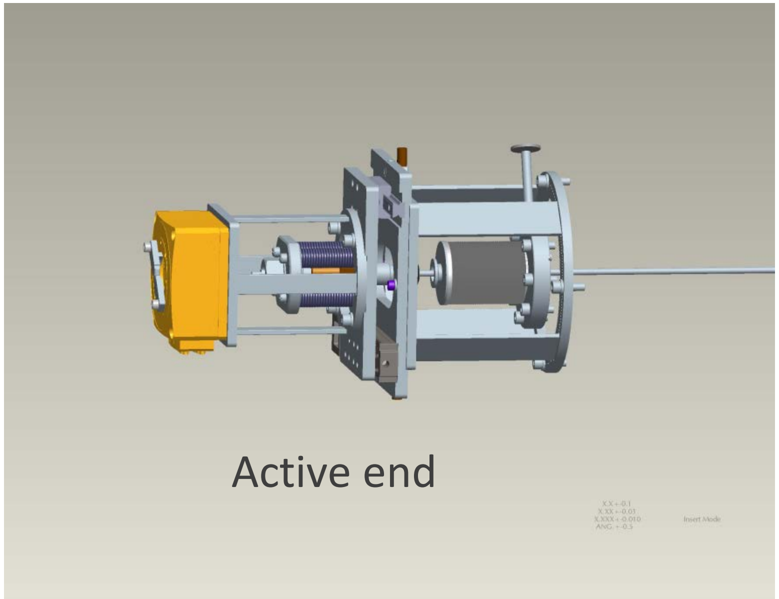


Rotary stage with coil wire holder

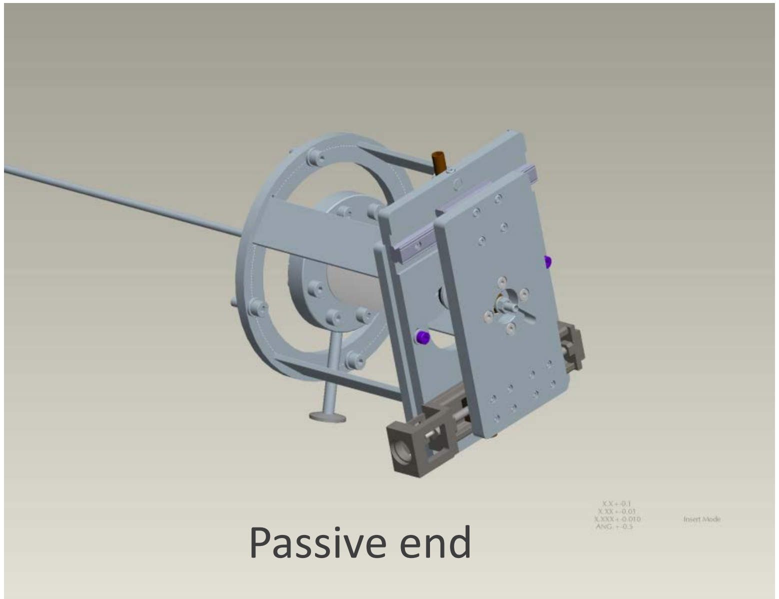
TI tubing installed in SCU vacuum chamber

Passive end to mate with Long Linear stage

Stages allow ±1 cm range in x axis
For positioning Hall probe or coils

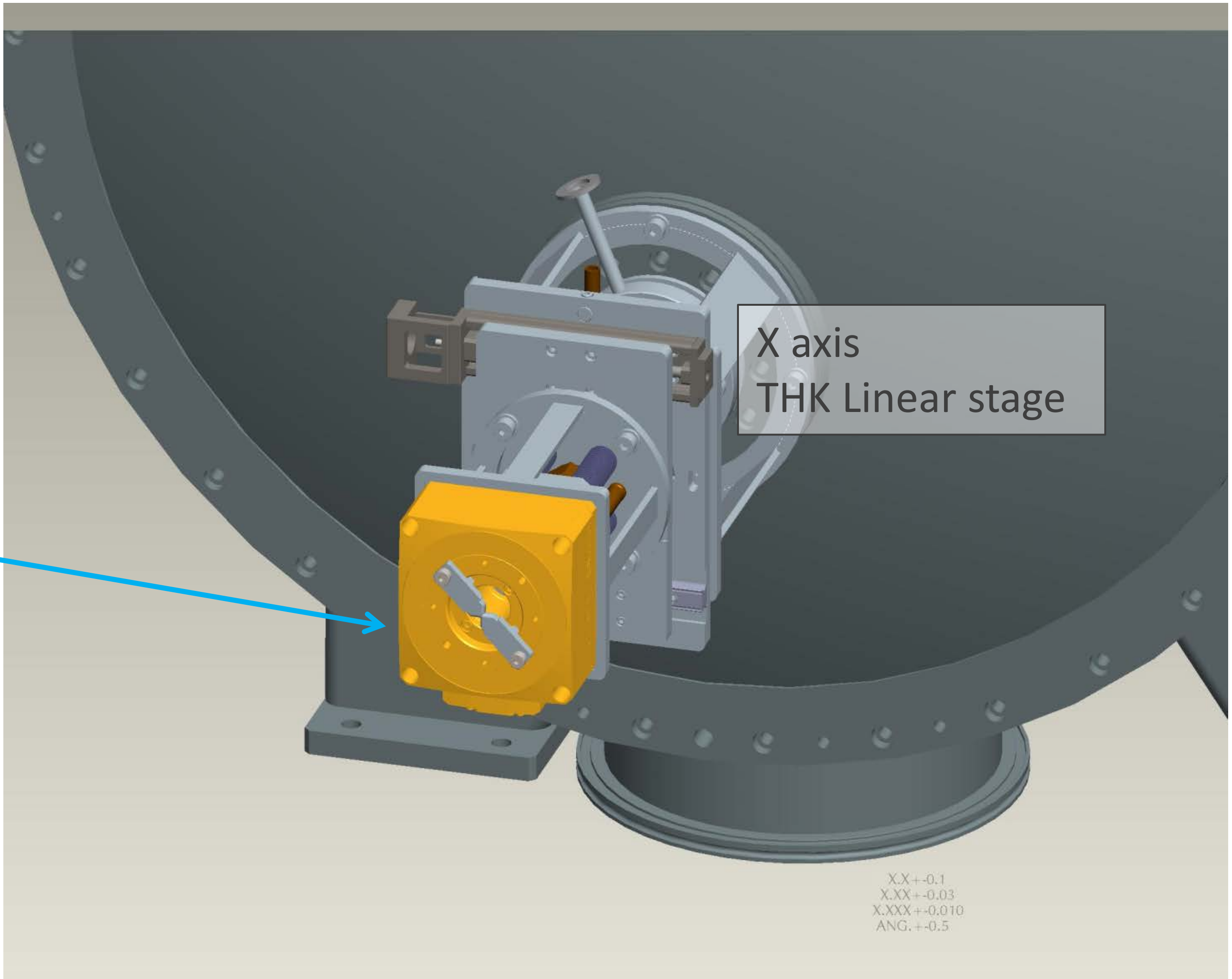


Active end



Passive end

Integral coil measurement system active end stages



X axis
THK Linear stage

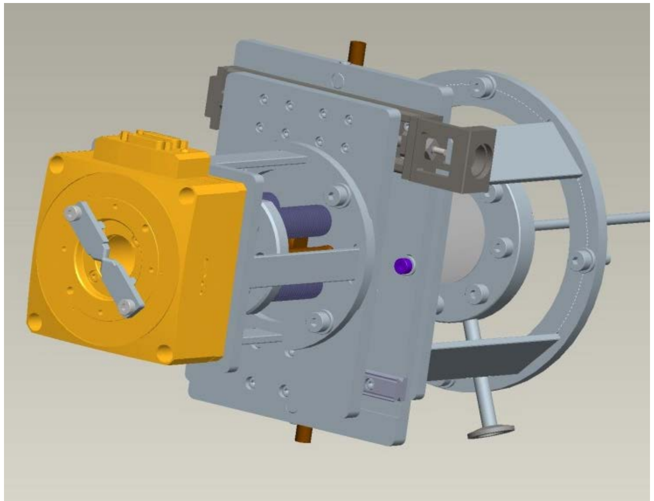
Newport Rotary stage
with coil wire holder
Identical stage on 3.5 m
x stage

Single turn coil will be
Rotated inside the guide
tube to measure 1st and
2nd integrals

Integral coil measurement system

- The integral coil system will utilize a single-turn beryllium-copper wire 4 mm wide (plus the wire diameter) determined by a fixture mounted to the rotary stages.
- The coil will be aligned to the mid-plane of the SCU inside the TI tubing and the plane of the coil will be referenced to gravity.
- The peak B_y 1st field integral is simply:

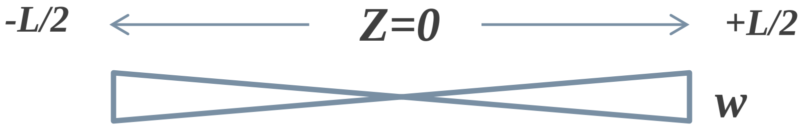
$$I_{y1} = \int_0^L B_y dz = \frac{\phi}{w}$$ [1]



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

$$I_{y2} = \int_{\frac{-L}{2}}^{\frac{L}{2}} I_{y1} dz = \frac{\phi}{\theta} \pm \frac{L}{2} I_1$$ [1]

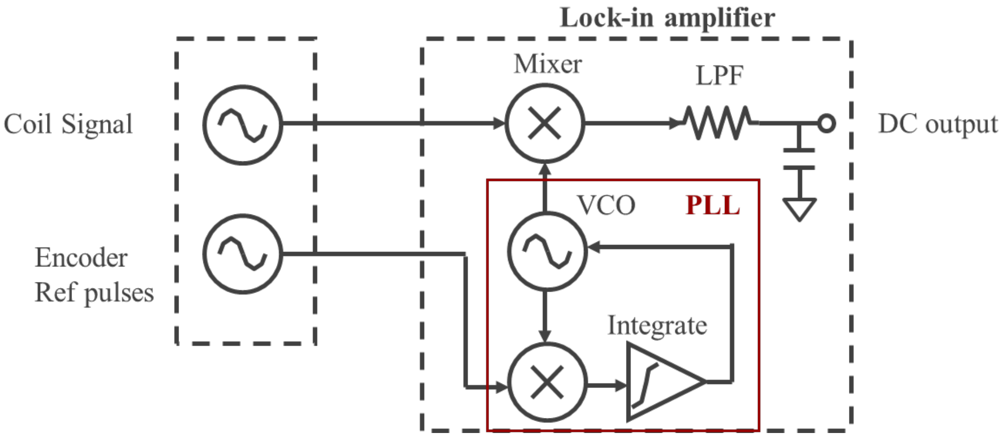
$$\theta = \frac{2w}{L}$$



[1] ANL/APS/TB-49 I. Vasserman, J. Xu

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 should be possible to do continuous coil rotations and use 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 which 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.

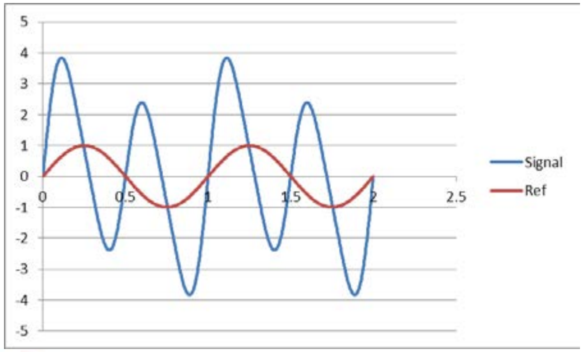


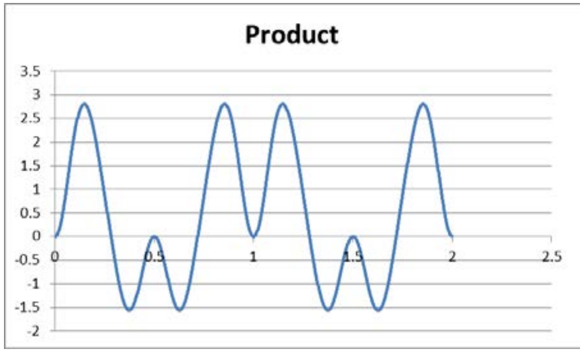
Lock-in Amplifier description

Lock-in measurements require a frequency reference. Typically an experiment is excited at a fixed frequency (from an oscillator or function generator) and the lock-in amplifier detects the response from the experiment at the reference frequency. Suppose the reference signal is a square wave at frequency ω_r generated by the Z channel of the rotary stage. The signal from the integral coil is $A_c \sin(\omega_r t+\theta_c)$ where A_c is the signal amplitude. The lock-in amplifier multiplies the signal by the reference $A_r \sin(\omega_r t+\theta_r)$ using a mixer. The mixer generates the product of its two inputs as its output V_o.

$$V_o = A_c A_r \sin(\omega_r t+\theta c)\sin(\omega_r t+\theta_c) = ½ A_c A_r \cos(\theta_r - \theta_c) + ½ A_c A_r \sin(2 \omega_r t+\theta_r+\theta_c)$$

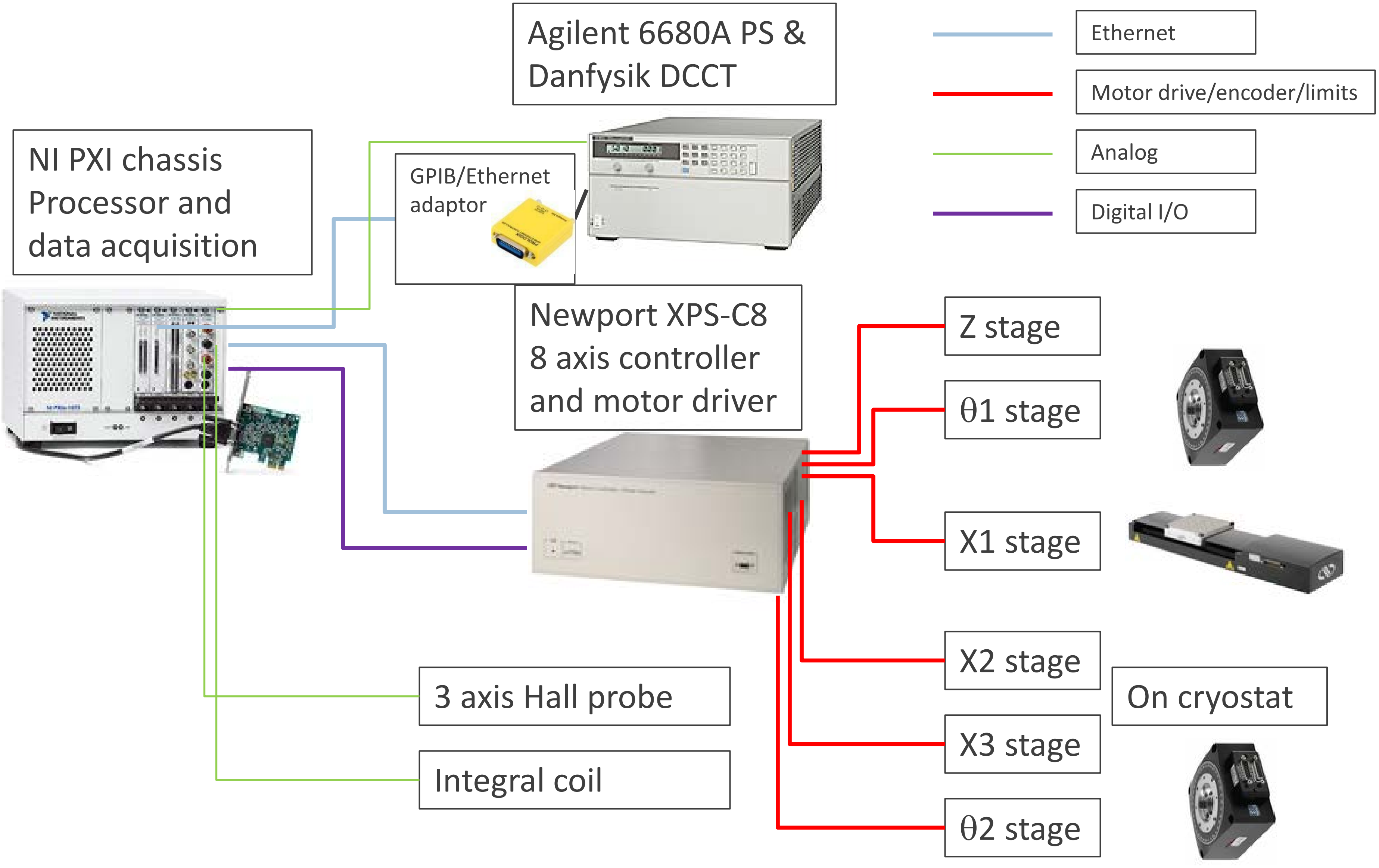
Since the two inputs to the mixer are at *exactly* the same frequency, the first term in the mixer output is at DC. The second term is at a frequency $2 \omega_r$, which is at a high frequency and can be readily removed using a low pass filter. After filtering $V = ½ A_c A_r \cos(\theta_r - \theta_c)$.





In this case the fundamental and ref. signals are 1 V and in phase, so the average DC is 0.5 V.

Overview of electronics



Agilent 6680A PS & Danfysik DCCT

NI PXI chassis Processor and data acquisition

GPIB/Ethernet adaptor

Newport XPS-C8 8 axis controller and motor driver

Z stage

θ1 stage

X1 stage

X2 stage

X3 stage

θ2 stage

On cryostat

3 axis Hall probe

Integral coil

Ethernet

Motor drive/encoder/limits

Analog

Digital I/O

Hardware specifications: National Instruments Dynamic Signal Analyzer NI-4462

- 4 simultaneously sampled analog inputs
- 118 dB dynamic range, 24-bit resolution
- 204.8 kS/s maximum sampling rate
- 92 kHz alias-free bandwidth
- Input range from ±316 mV to 42.4 V
- 6 gain settings
- AC/DC coupling
- Antialiasing and anti-imaging protection
- Multimodule synchronization

Magnet power supplies

- **HP 6680A** 5V 895 A powers the main coils and provides the required regulation, drift and current ripple of ≤ 1000 ppm. [2]
- **TDK Lambda Genesys** 6V 100 A energizes the correction coils

[2] Requirements on current stability for SCU power supply
Y. Ivanyushenkov April 15, 2011

Component list and cost

SCU Horizontal Magnetic Measurement system parts

Item	Quantity	Manufacturer	Part No.	Description	UM	Price	Total
1	1	Newport	ILS100CC	100 mm linear stage	ea.	$3,538.00	$3,538.00
2	1	Newport	9204	Big Lab Jack	ea.	$348.88	$348.88
3	2	Newport	RGV100BL	Rotary stage	ea.	$6,540.00	$13,080.00
4	1	Newport	XPS C-8	8 axis motor controller	ea.	$7,652.00	$7,652.00
5	3	Newport	MMCABLE-7	7 meter DB-25 cable	ea.	$263.00	$789.00
6	3	Newport	MMCABLE-REG	Inline 5 V regulator	ea.	$136.00	$408.00
7	3	Newport	XPS-DRV01	Motor Driver for ILS100CC	ea.	$571.00	$1,713.00
8	2	Newport	XPS-DRV02	Motor Driver for RGV100BL	ea.	$850.00	$1,700.00
9	1	Newport	XPS-DRV00	Pass through module for Z axis	ea.	$140.00	$140.00
10	1	Belden	03F4137	Newark # 8PR 100' shielded cable	Reel	$441.67	$441.67
11	2	Mcmaster Carr	86825K35	24" x 72" AL tooling plate	ea.	$563.00	$1,126.00
12	12	Mcmaster Carr	6111K58	Leveling feet 5/8"x11 x 2 1/2" base	ea.	$15.09	$181.08
13	1	Prologix	gpib-eth	GPIB to Ethernet adaptor	ea.	$199.95	$199.95
14	2	Local shops		Steel support tables	ea.	$1,600.00	$3,200.00
15	1	Hi Tech		Cryomodule end stages	ea.	$14,750.00	$14,750.00
16	2	THK	KR2001B+150LP1-1700	THK 150 mm linear stages	ea.	$1,200.00	$2,400.00
17	1	Local Shops		Long stage base and Hall probe fixture	ea.	$2,000.00	$2,000.00
18	1			Misc Hardware cables etc.	ea.	$5,000.00	$5,000.00
19	1	National Instruments	PXI chassi and modules	Additional NI hardware	ea.	$10,000.00	$10,000.00
						Total	**$68,667.58**

Closing Comments

- Design is complete due to Jie Liu’s and Emil’s fast work in completing the drawing package for the cryomodule components.
- We are presently procuring the components
- Assembly can begin as soon as parts are delivered and building 314 is ready for occupancy which should be mid September 2011.
- Much of the core software is done, the additional software to be written will be for motion of the rotary and x axis linear stages. When the Newport motion control hardware is delivered, the new software can be developed.
- First tests of the system to begin March 2012

Additional options:

- Calibration dipole magnet to be used to determine Hall probe and integral coil angles.
- Use a test PM ID to characterize the accuracy and repeatability of the system
- Additional short linear stage on the end opposite the long stage to enable motion of the coils in the z axis.

Thank you!