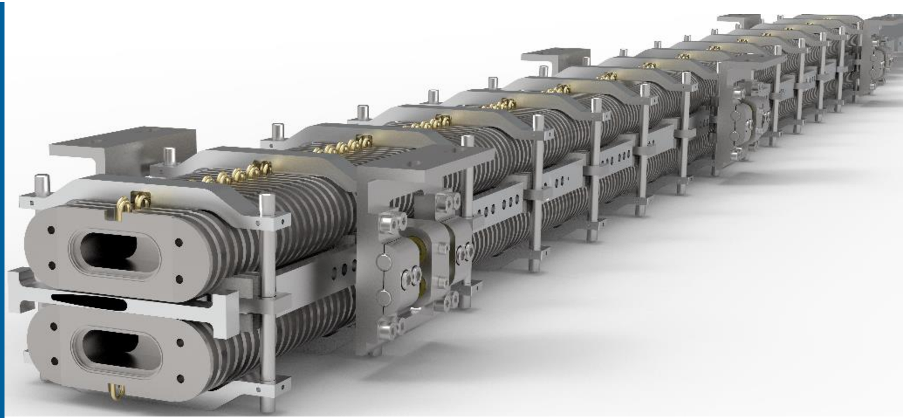
MAGNETIC MEASUREMENT SYSTEM BEING DEVELOPED FOR THE SCU PROGRAM AT THE APS



Matt Kasa and Yury Ivanyushenkov

IMMW 21 Grenoble, France June 24th – 28th

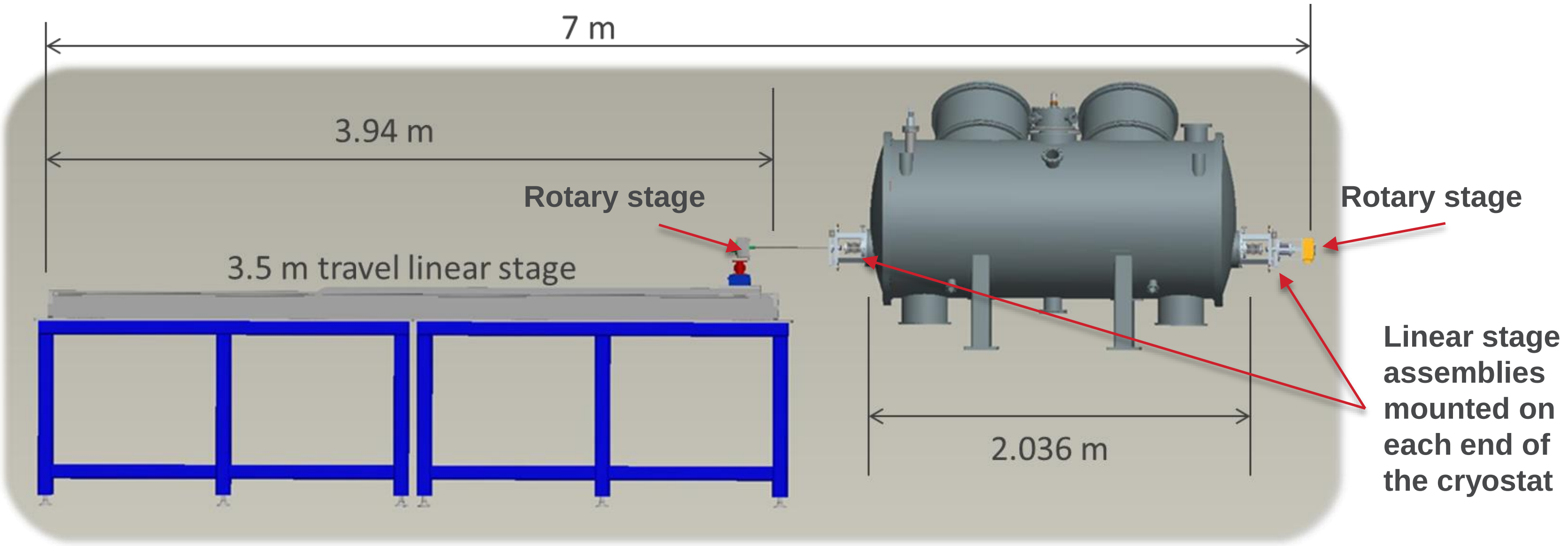
Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.

OUTLINE

- Existing measurement system
- New measurement system guide tube
- New Hall probe drive system
- Wire based measurement system
- Commissioning and initial measurement results

- Thank you
  - Ethan Anliker for design work and providing rendered images
  - Yuko Shiroyanagi for Ansys analysis
  - Isaac Vasserman
  - Roger Dejus

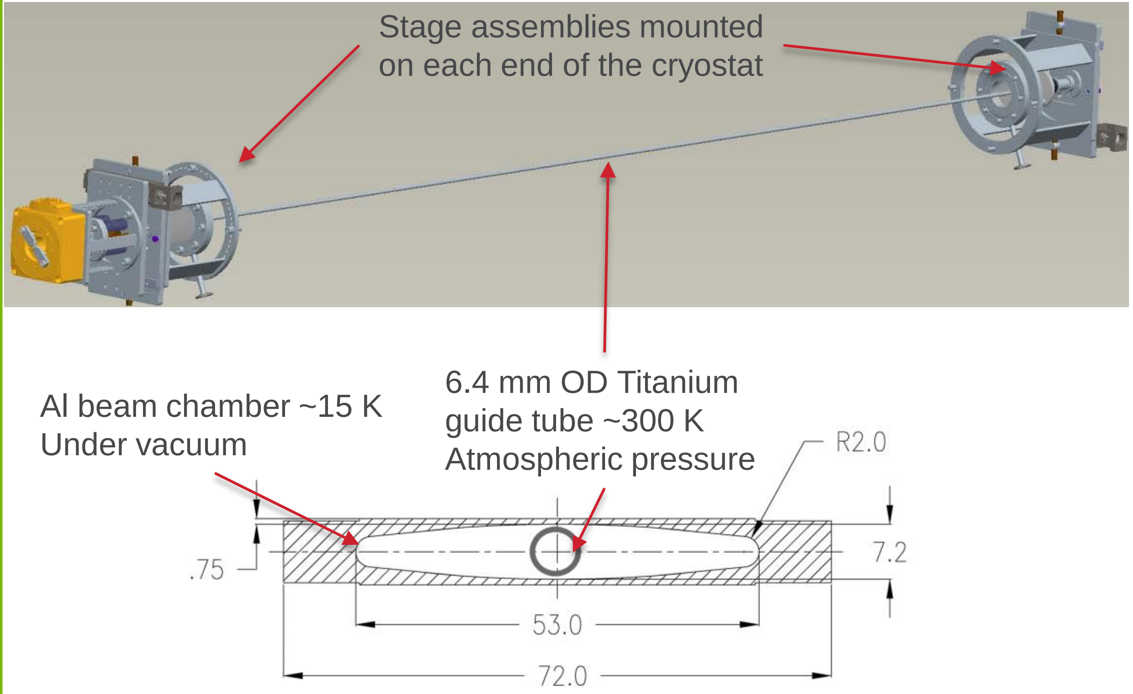
EXISTING SCU MEASUREMENT SYSTEM



- Adapted from Budker Institute by C. Doose
- Hall probe mounted inside a long carbon fiber tube and scanned through the device using the 3.5 m linear stage
- Wire based measurements performed using rotary stages

C. L. Doose and M. Kasa, *NAPAC'13*, Pasadena, CA, USA, Sep.-Oct. 2013, paper THPBA06

EXISTING SCU MEASUREMENT SYSTEM

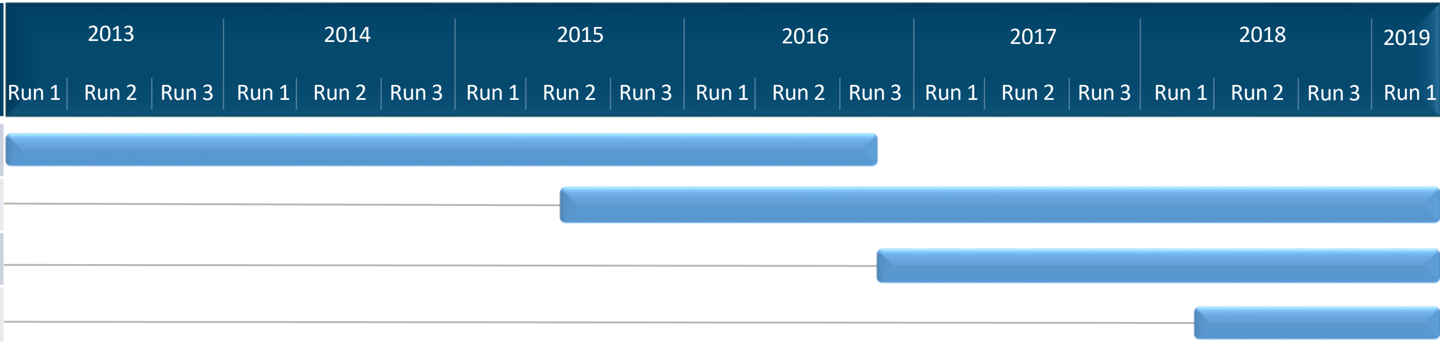


- Ti guide tube is isolated from the beam chamber with spiral wrapped Kevlar string
  - Tube is tensioned to reduce sag
  - Heated to room temperature with current
  - Translated horizontally using stages on the cryostat

- Successfully used to measure all of the SCUs currently in operation at the APS
  - Main challenge was to maintain a uniform temperature along the length of the guide tube

SCUS IN OPERATION AT THE APS

	λ (mm)	# of periods	B (T)
SCU0	16	20.5	0.8
SCU18-1	18	59.5	0.97
SCU18-2	18	59.5	0.97
HSCU	31.5	38.5	0.41



		SCU0 and SCU18-2				SCU18-1				HSCU			
Year	APS delivered	Oper.	Down	quench	avail. %	Oper.	Down	quench	avail. %	Oper.	Down	quench	avail. %
2013	4871 h	4189 h	20 h	*34* + 3	99.5	-	-	-	-	-	-	-	-
2014	4926 h	4391 h	174 h [1]	*32* + 2	96.2	-	-	-	-	-	-	-	-
2015	4940 h	4834 h	0 h	*26* + 1	100	3059 h [2]	0.1 h	*5* + 0	99.997	-	-	-	-
2016	4941 h	4647 h [3]	0 h	*9* + 0	100	4585 h	0.3 h	*11* + 1	99.990	-	-	-	-
2017	4840 h	4756 h	0 h	*8* + 1	100	4818 h	0.75 h	*13* + 2	99.984	-	-	-	-
2018	4853 h	4755 h	5 h	*14* + 1	99.89	4710 h	0.59 h	*14* + 2	99.987	751 h	0 h	*0* + 0	100
2019 [4]	1691 h	1562 h	4.3 h	*7* + 1	99.68	1671 h	0 h	*4* + 0	100	144 h	0 h	*0* + 0	**100**
Total	31062 h	29134 h	203.3 h	*122* + 8	**99.31**	18843 h	1.74 h	*40* + 5	**99.991**	895 h	0 h	*0* + 0	**100**

- e-beam has never been lost due to self-quenches
- *Red = beam dump-induced quench*
- Blue = non-beam dump, possible self-induced quench

[1] November: Partial loss of one cryocooler capacity
[2] Installed in May; operated May – Dec. 2015
[3] SCU18-2 replaced SCU0 in Sep.
SCU0 3310 h, SCU18-2 1337 h
[4] January 2019 through April 22, 2019

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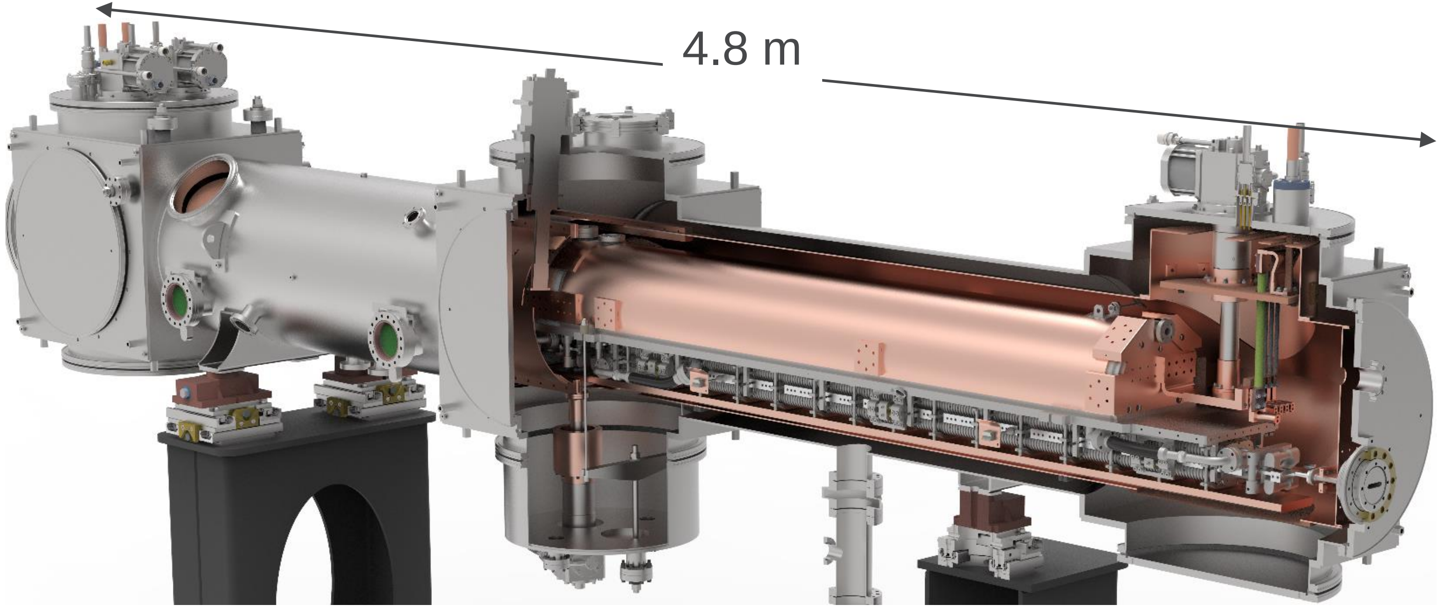
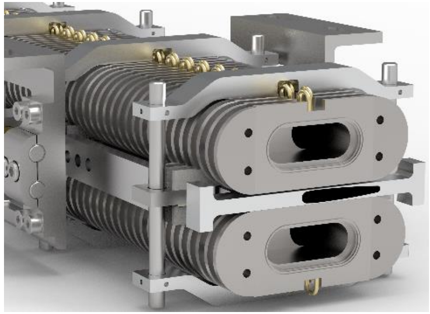
APSU CRYOSTAT LAYOUT





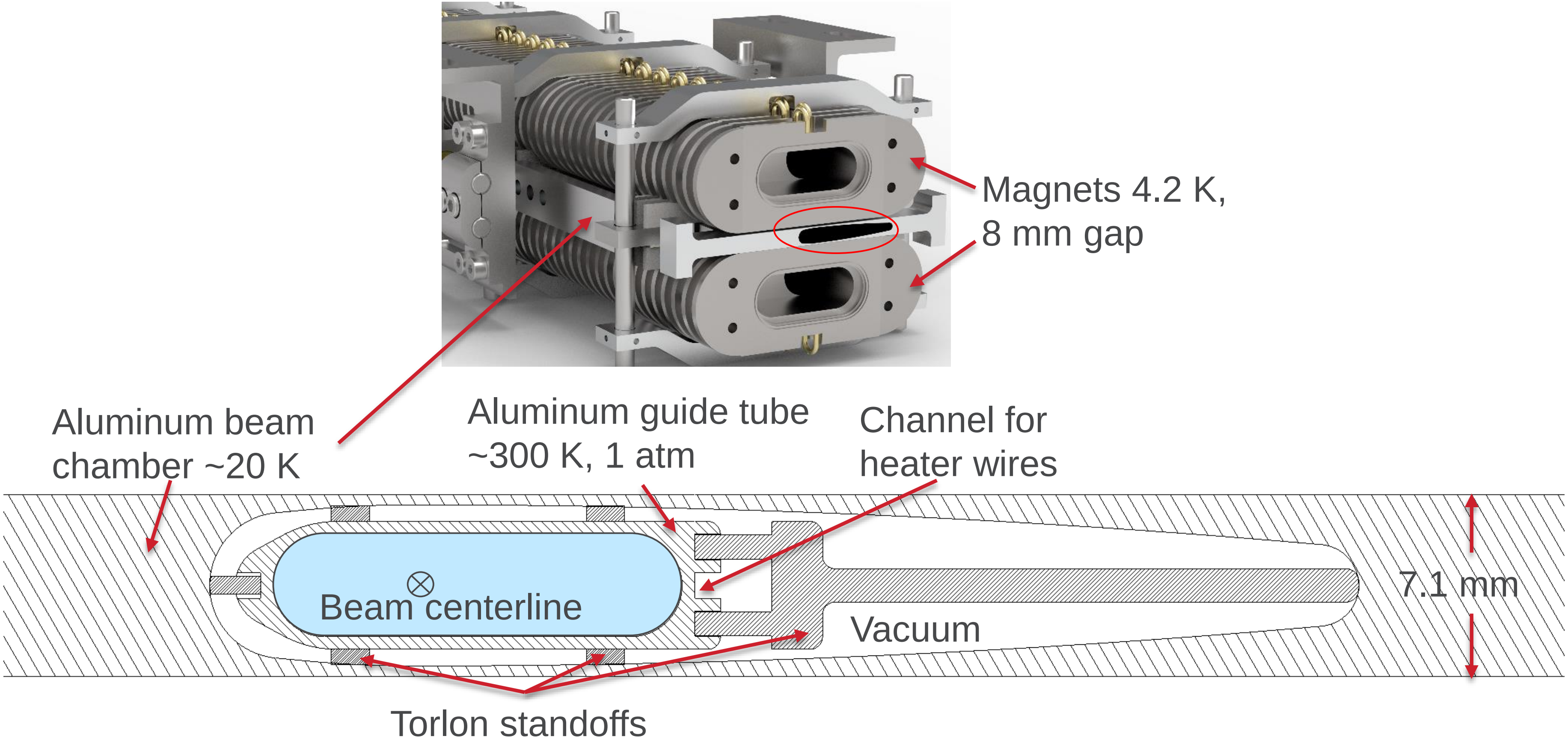
- Four long SCU cryostats
  - 2 in-line and 2 canted
  - 16.5 mm or 18.5 mm period wound with NbTi superconductor
- Two ~1.9 m long magnetic structures
- Magnetic gap is 8 mm
- Vertical beam stay clear is 6.3 mm

SCU MEASUREMENT SYSTEM UPGRADE

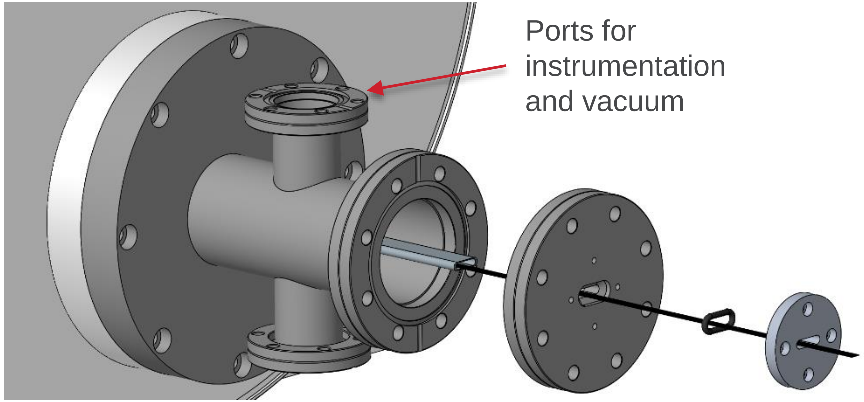
- Retain features of the current measurement system
  - Capability to measure the SCUs in the production cryostat under normal operating conditions
  - All measurement components at room temperature and atmospheric pressure

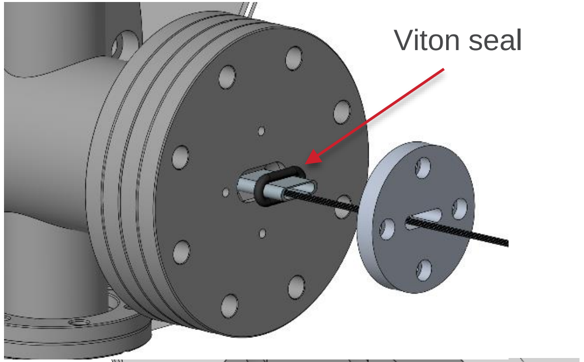
- Issues to address
  - Maintain uniform temperature along the guide tube
    - Affects the straightness of the guide tube
    - Caused the carbon fiber tube of the Hall probe to twist during a scan
  - Upgrade the drive system to accommodate Hall probe scan length ~4.8 m
    - Not easily achieved with the current system and methods
  - Decouple the drive system from the cryostat

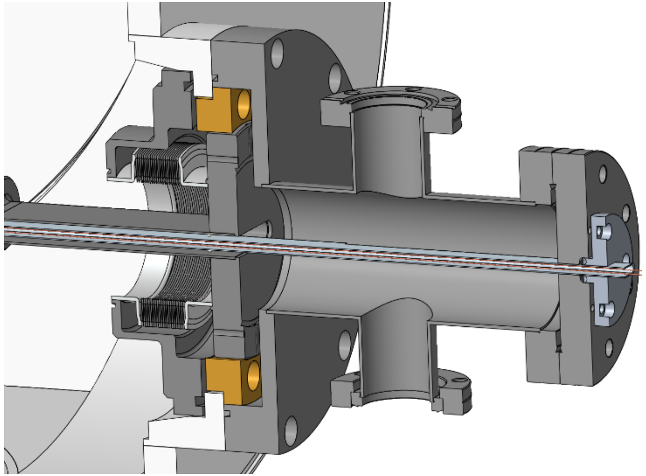
EXTRUDED AND MACHINED GUIDE TUBE

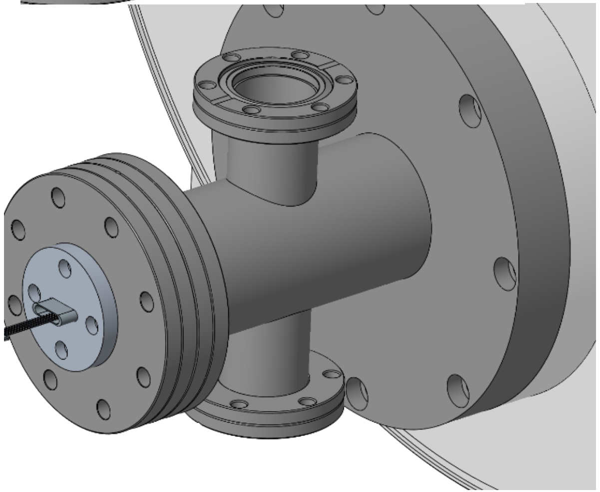


MACHINED GUIDE TUBE

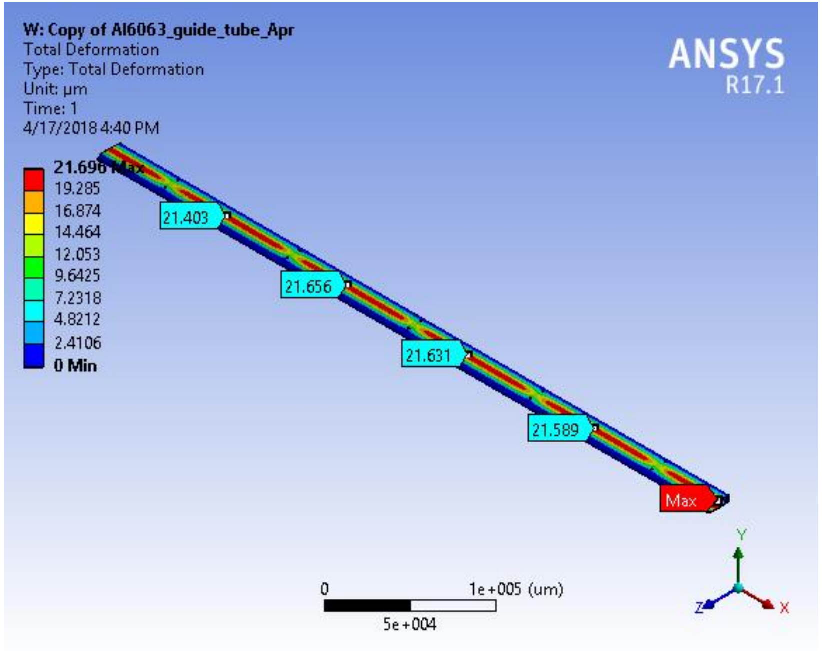




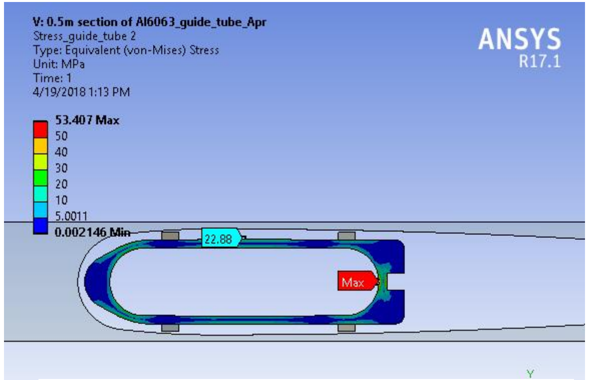




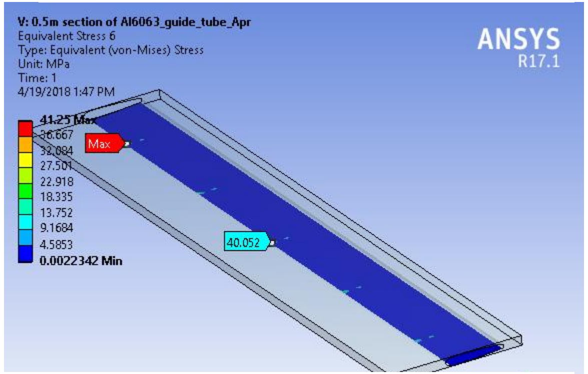
DEFORMATION AND STRESS



Maximum deformation of guide tube = 22 μm
Beam chamber deformation = 4 μm



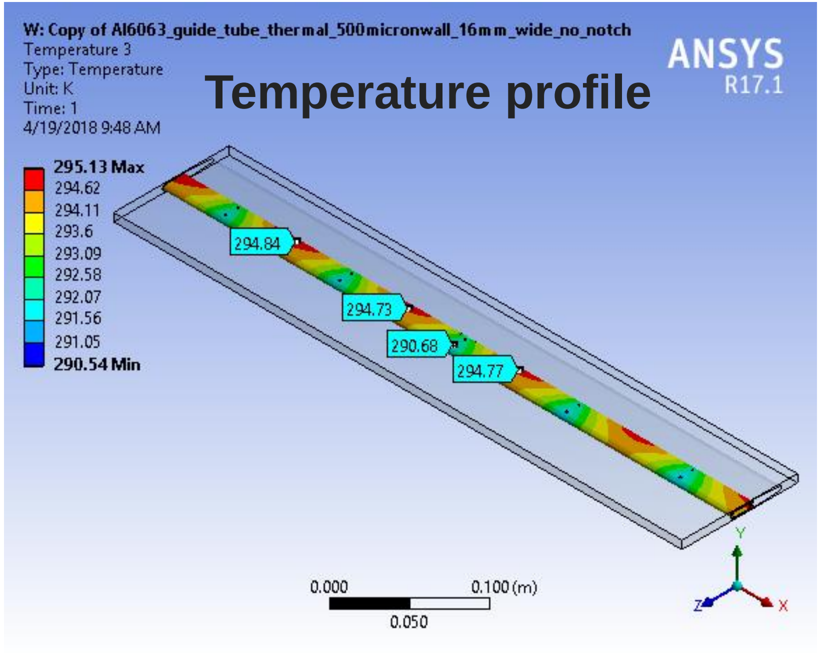
Maximum stress on guide tube = 53 MPa < 145 MPa (yield strength)



Maximum stress on beam chamber = 41 MPa < 145 MPa (yield strength)

Provided by Y. Shiroyanagi

HEATER POWER REQUIREMENTS



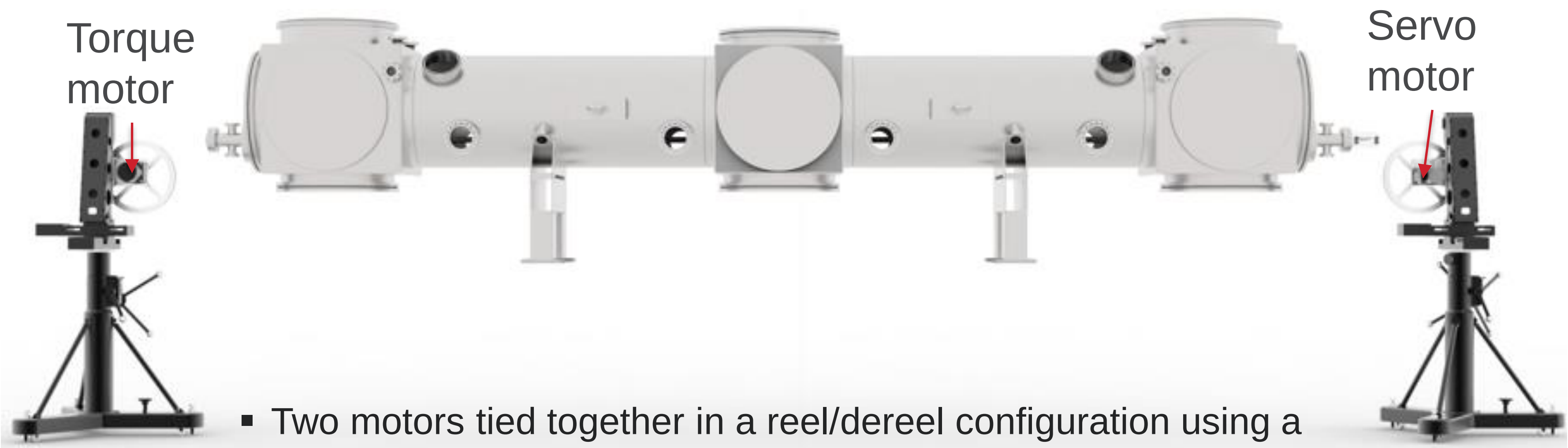
Location	Heat (W)
Q_{total}	2.7
$Q_{conduction}$	1.78
$Q_{radiation}$	0.92

- Model: 2.7 W/0.5 m = 5.4 W/m
- Length of the beam chamber = 4.8 m
- Total heater power = 5.4 W/m x 4.8 m = 25.9 W
- 9.6 m long 32 AWG phosphor bronze wire = 38.4 Ω
- Power supply requirements: ~0.8 A at 32.4 V

	AWG	Resistance (Ω/m)			Diameter (mm)	Fuse current air (A)	Fuse current vacuum (A)	Number of leads	Name	Insulated diameter (mm)	Insulation type	Insulation thermal rating (K)	Insulation breakdown voltage (VDC)
		4.2 K	77 K	305 K									
Phosphor bronze	**32**	3.34	3.45	4.02	0.203	4.2	3.1	1	SL-32	0.241	Polyimide	500	400
								2	DT-32	0.241	Polyimide		
								4	QT-32	0.241	Polyimide		
									QL-32	0.241	Polyimide		
	36	8.56	8.83	10.3	0.127	2.6	1.4	1	SL-36	0.152	Formvar®	378	250
								2	DT-36	0.152	Polyimide	500	400
								4	QT-36	0.152	Formvar®	378	250
									QL-36	0.152	Polyimide	500	400

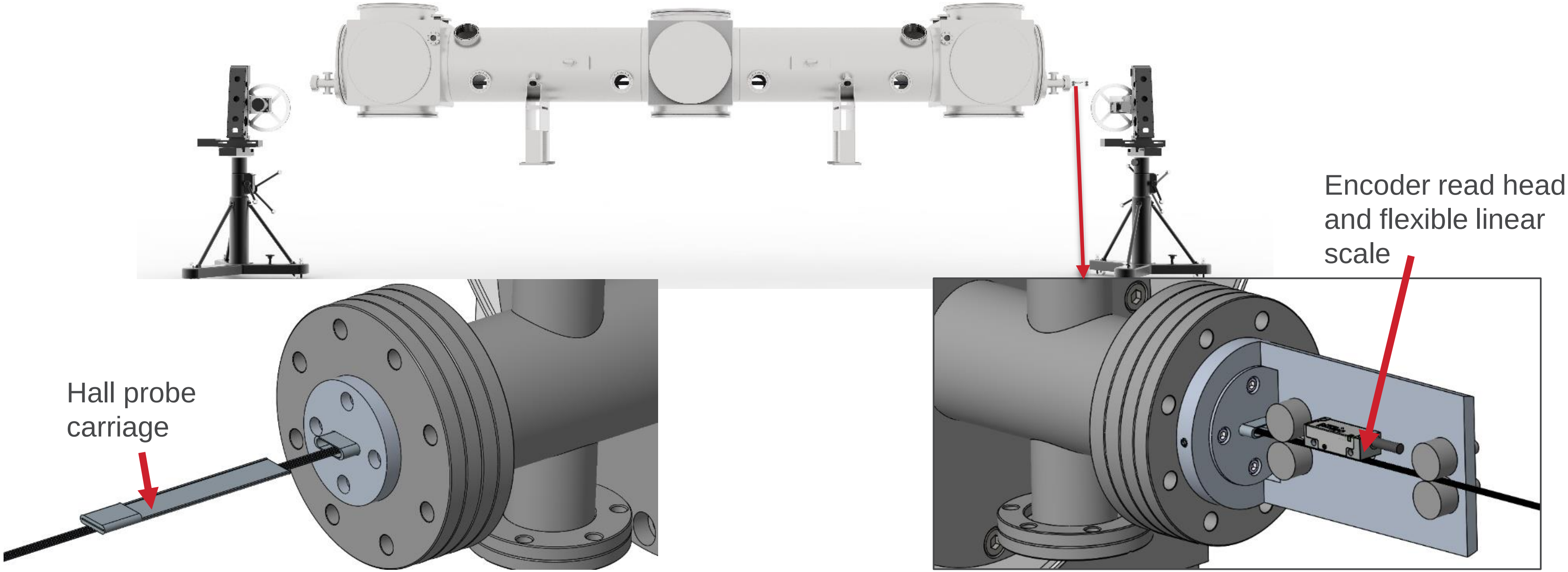
Provided by Y. Shiroyanagi

HALL PROBE DRIVE SYSTEM



- Two motors tied together in a reel/dereel configuration using a flexible linear encoder scale, Hall probe carriage, and wire
- Hall probe carriage driven through the guide tube
- Servo motor position control through feedback from linear encoder
- Torque motor maintains tension
- System eliminates the need for a long linear stage

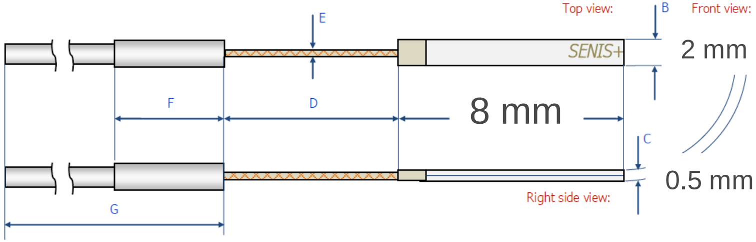
HALL PROBE DRIVE SYSTEM



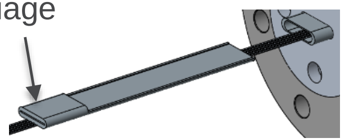
- Veratus series encoder from Celera Motion
  - Flexible scale
    - Inconel 625 – non-magnetic
    - 6 mm x 0.2 mm
  - 1 µm resolution
  - Up to 20 m lengths

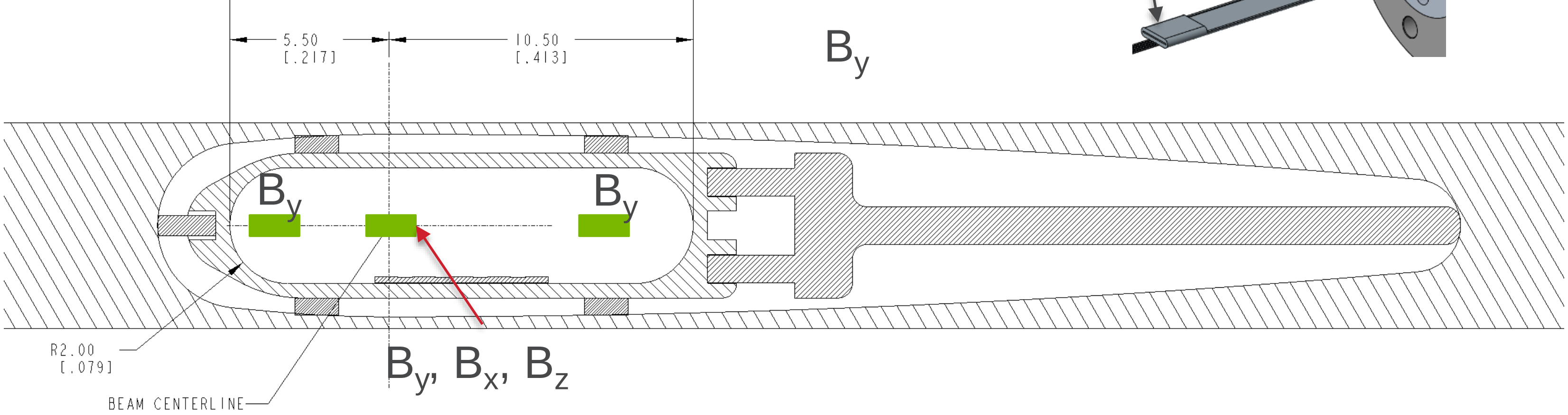
SENIS HALL PROBES

- Type H probe, similar to probes we currently use
  - Orthogonality error 3-axis probe < 0.1°
  - Offset and drift error < 1 G
  - Total measurement accuracy better than 0.1%
  - Integrated temperature sensor
- B_z is used to measure longitudinal field and determine vertical position of sensor in the magnetic gap



Hall probe carriage



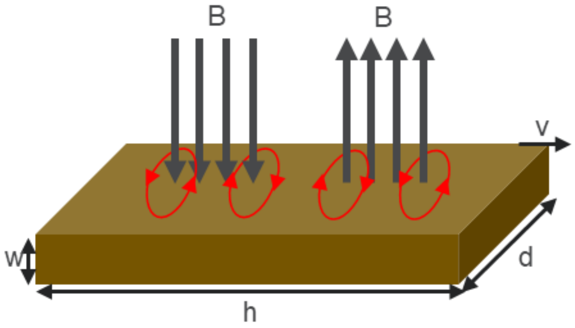


EDDY CURRENT HEATING AND BRAKING FORCE IN THE ENCODER SCALE

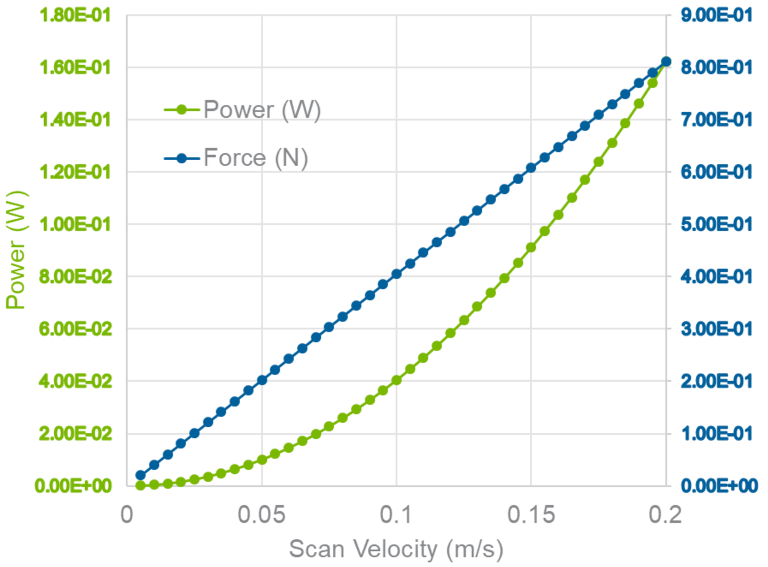
$$P_{EC} = N\frac{v^2 B^2 dhw}{\rho}$$

$$F_{Brake} = N\frac{vB^2 dhw}{\rho}$$

P is power (W)
B is peak magnetic field (T)
d is the width of the encoder (m)
v is the scan velocity (m/s)
ρ is resistivity of the material (Ω-m)
w is the thickness of the encoder (m)
h is the length of one period (m)
N is the number of periods



- Eddy currents penetrate the full thickness of the scale at all reasonable scan rates.
- Inconel 625 scale properties:
  - D = 8440 kg/m^3
  - ρ = 1.29E-6 Ω-m
  - d = 0.006 m
  - w = 0.0002 m
  - μ = 1.26E-6 H/m
  - μ_r = 1.0006



- Two 1.8 m long, 16.5 mm period devices, B = 1.1 T
- Anticipated scan velocity is <0.1 m/s

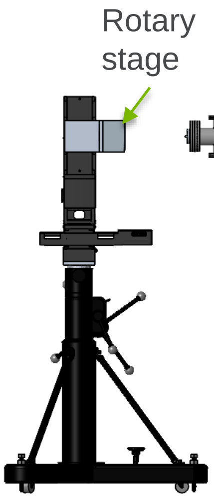
EFFECTS OF EDDY CURRENT HEATING AND BRAKING FORCE

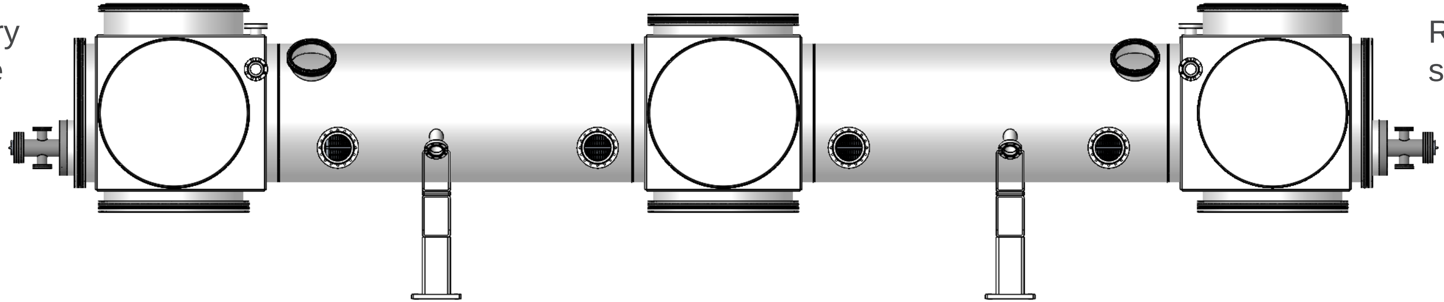
- Temperature rise during a scan due to Eddy current power dissipation
  - Scan 3.6 m long device at 0.1 m/s deposits 1.44 J into the scale
  - Specific heat capacity 0.41 J/g-°C
  - $\Delta T = \frac{1.44}{0.41 \times 36} = 0.098\ ℃$

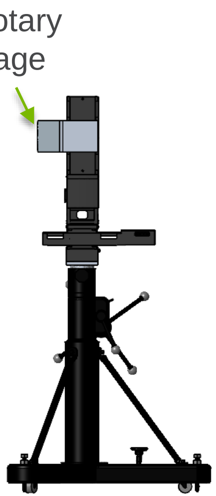
- Change in scale length due to temperature rise
  - CTE is 12.8 μm/m- °C
  - $\Delta L = 12.8 \times 3.6 \times 0.098 = 4.4\ \mu m$

- Tension limits
  - Applied braking force is < 1 N
  - Yield strength of Inconel 625 is 460 Mpa
  - 0.006 m x 0.0002 m gives a yield strength of 552 N (124 lbf)
    - Max tension from torque motor is 65 N (14.7 lbf)

WIRE BASED MEASUREMENTS

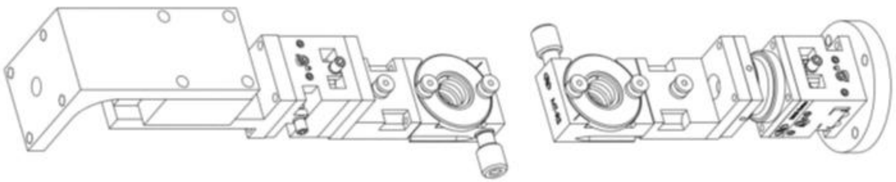


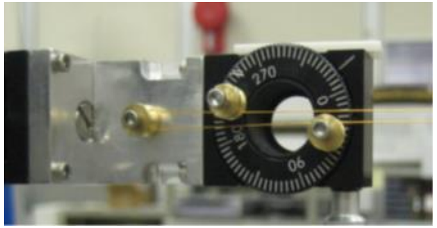


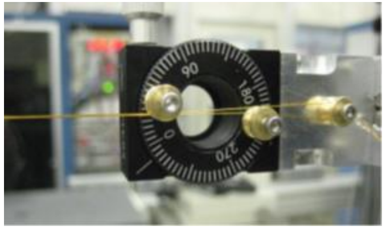


- Easily switch to/from the Hall probe measurements by replacing the torque and servo motor with Newport rotary stages that we currently use
- Very similar to the system in MM1
- Can also be used for pulsed wire measurements by moving one stage assembly further from the cryostat

WIRE BASED MEASUREMENTS

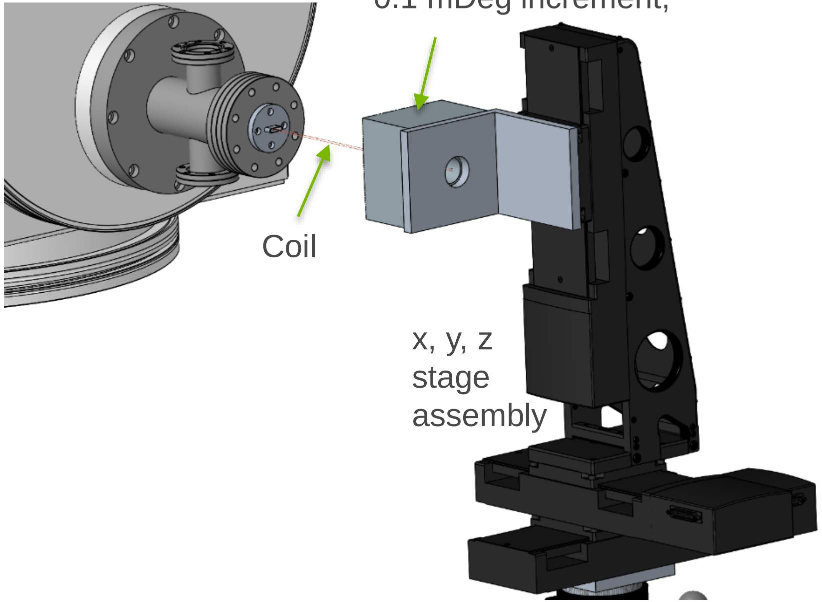






- Implement the same coil holder system developed in MM1
  - Easily adjust the geometry of the coil
- Coil is positioned using the x, y, and z stages
  - Guide tube position remains constant

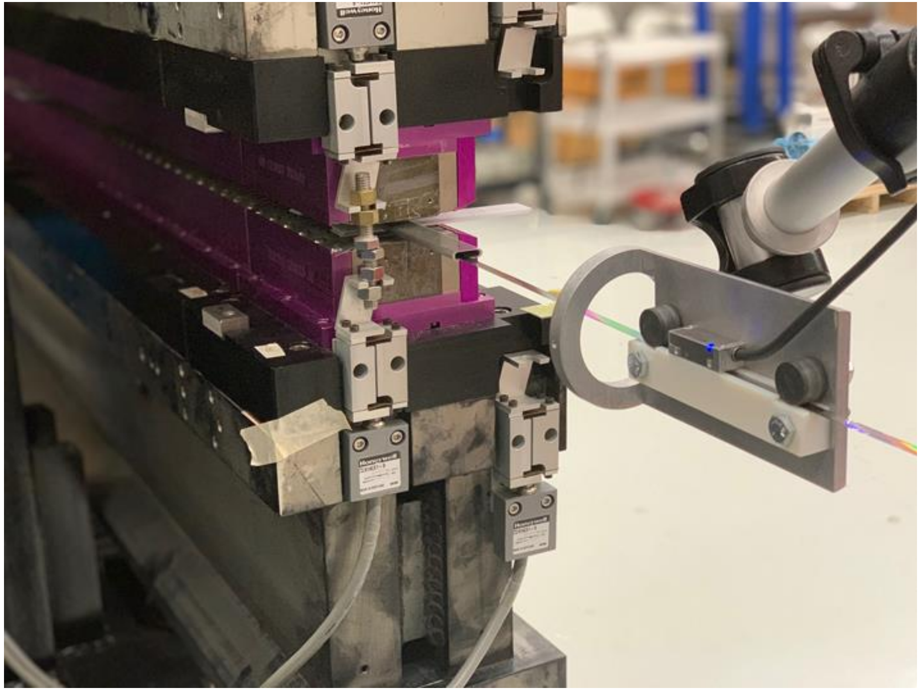
Rotary stage:
RGV100
0.1 mDeg increment,



ILS100CC stages:
100 mm travel (±3 mm spec)
1µm resolution

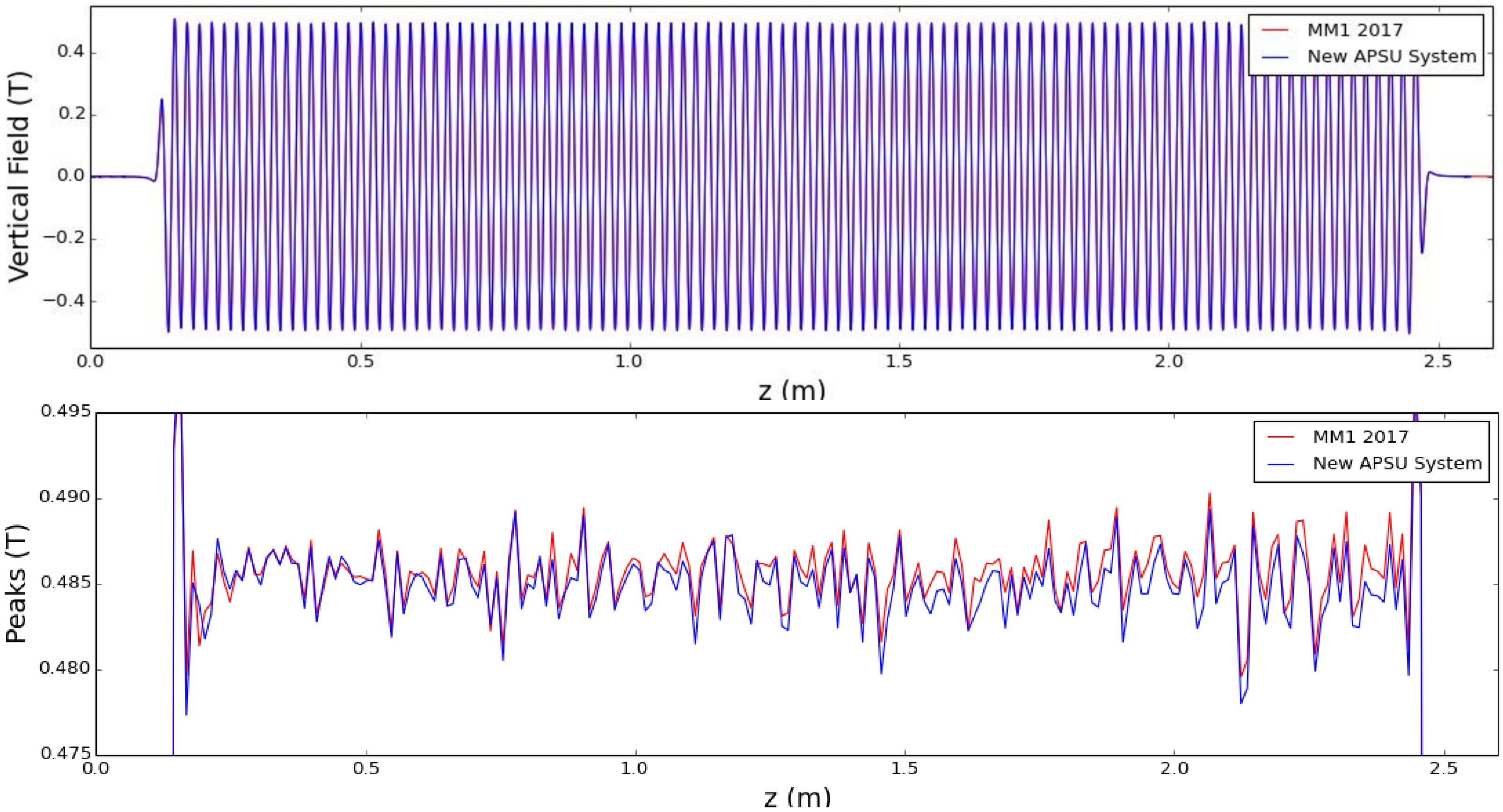
J. Xu and I. Vasserman, "New Upgrade to the APS Magnetic Field Integral Measurement System," Presentation at the 19th International Magnetic Measurement Workshop, Taiwan, Oct. 2015.

COMMISSIONING



- Measurement system was setup to measure a 2.3 cm period hybrid permanent magnet undulator that was last characterized in MM1 in 2017 by I. Vasserman
- Guide tube was shimmed to be near the center of the gap (11.5 mm)

FIELD SCAN AND FIELD PEAKS



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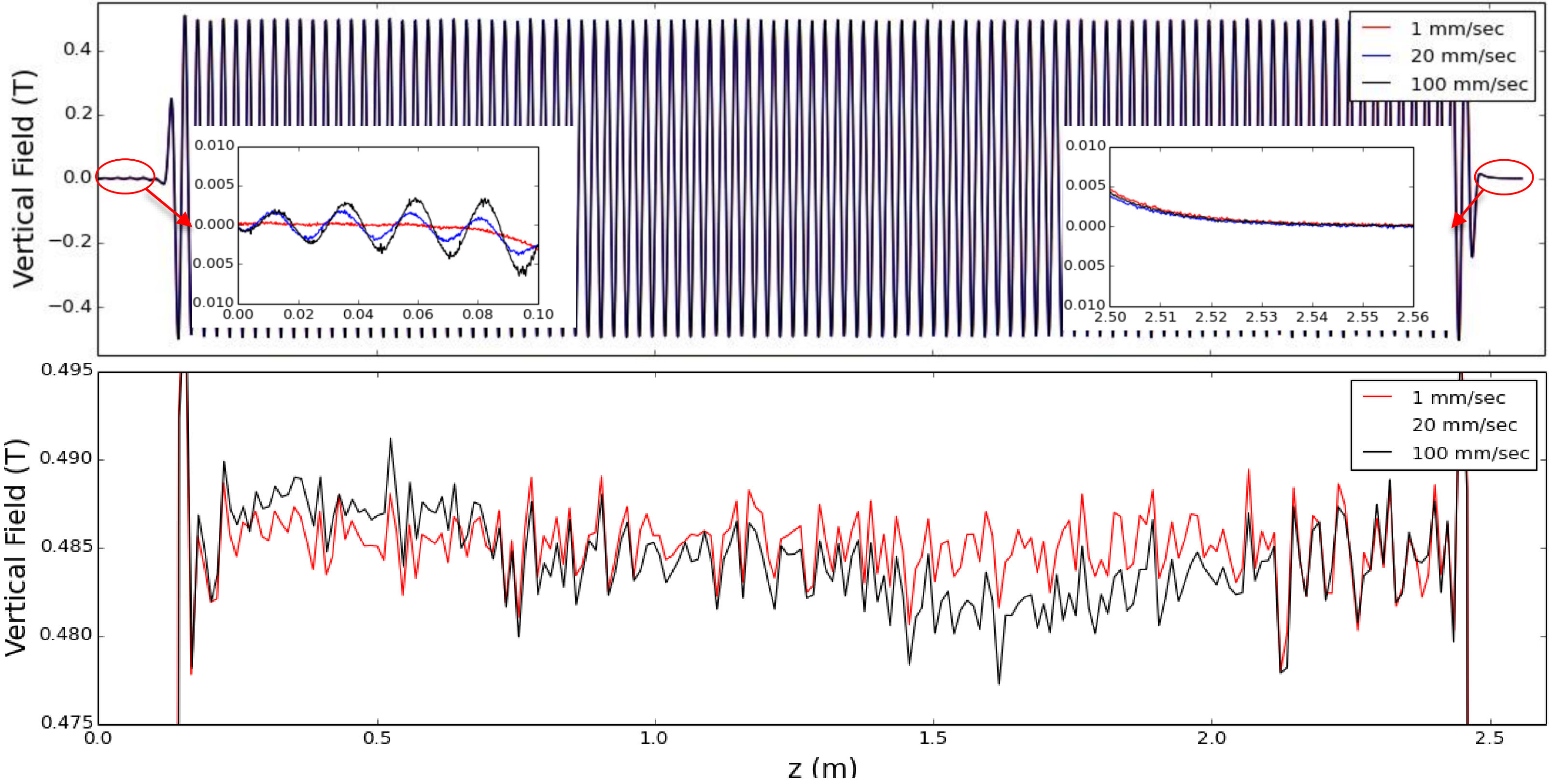
SCANNING SPEED

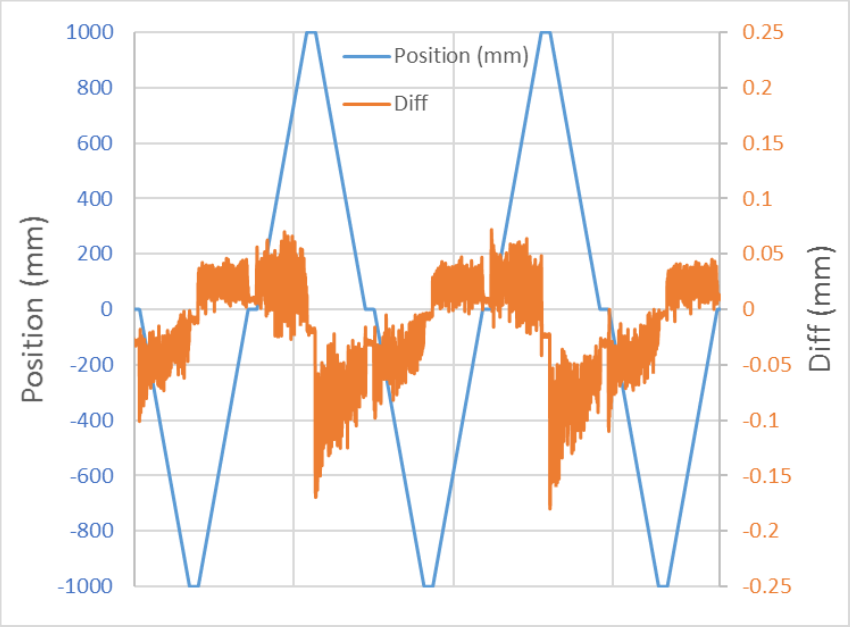
- Data is currently acquired on-the-fly and scanning speeds below 10 mm/sec are required to get reasonable agreement with data from 2017
- Noise increases with scanning speed due to induced voltage on Hall sensor signal cables



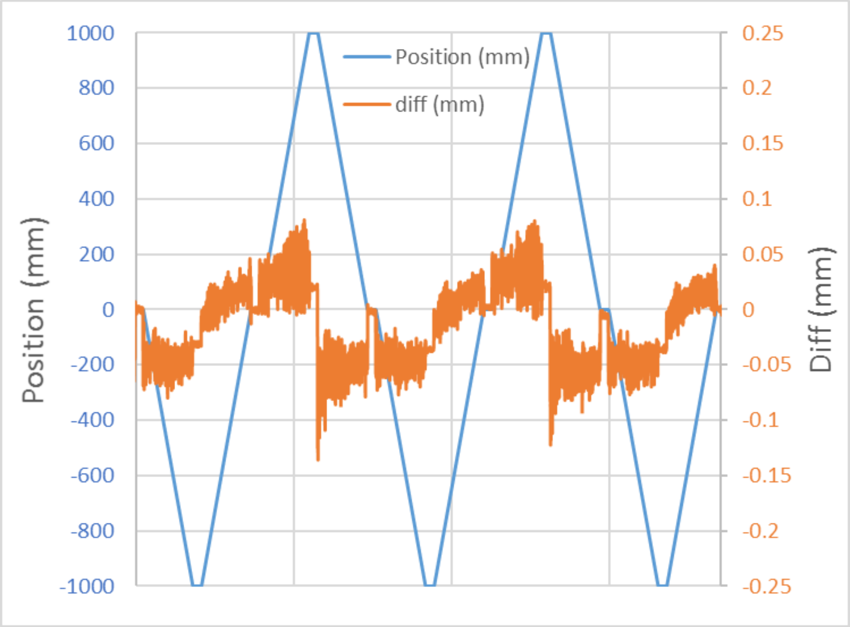
20 mm/sec peaks were suppressed to declutter the plot

TENSION

- Tension affects position accuracy
  - Different tension is needed depending on scan direction
- Plots show the scale position and difference between the scale and interferometer positions

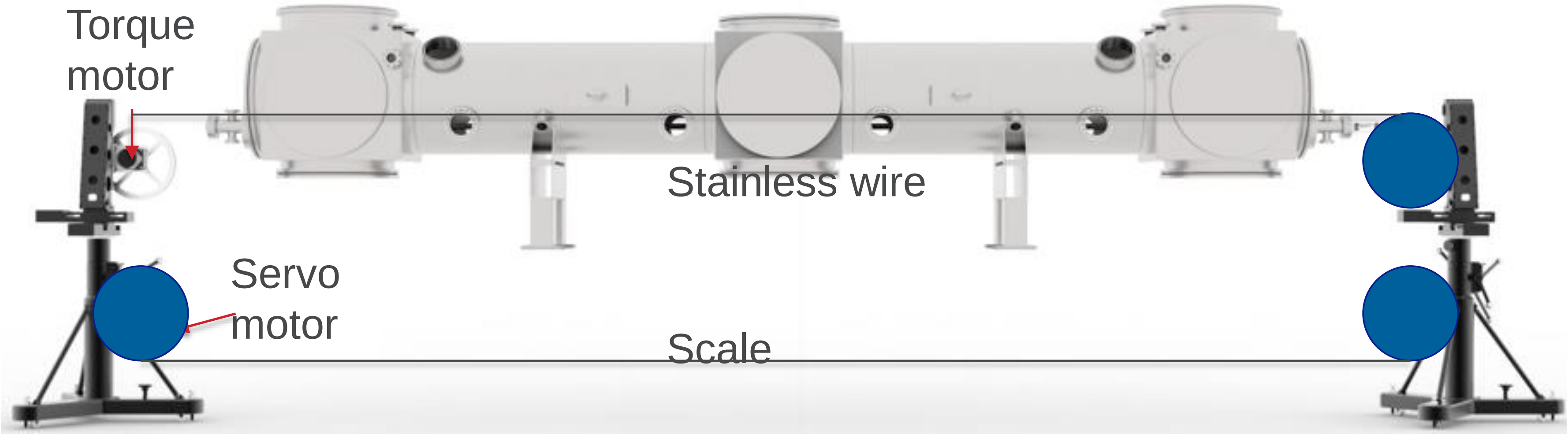


1 V applied to torque motor



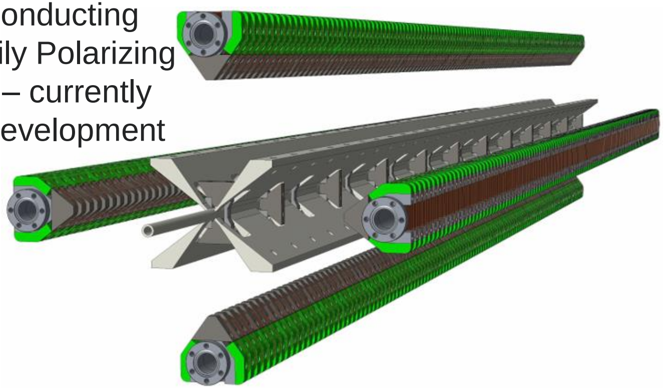
0.85 V applied to torque motor

DRIVE SYSTEM – ALTERNATIVE SETUP



- Move the scale outside of the measurement aperture – space constraint or scale material
- Modification of the guide tube extrusion can be made to accommodate measurement of a permanent magnet undulator with side access to the gap

SuperConducting Arbitrarily Polarizing Emitter – currently under development



CONCLUSION

- A new magnetic measurement system has been developed for the SCU program in preparation for the APS upgrade
- Novel idea for a Hall probe drive system has been developed and initial results look promising
- Wire based measurement system being implemented is similar to the system in MM1
- The system is compact and portable
  - Could be transported to measure IDs outside of the magnetic measurement lab using a different guide tube design

Thank you!

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