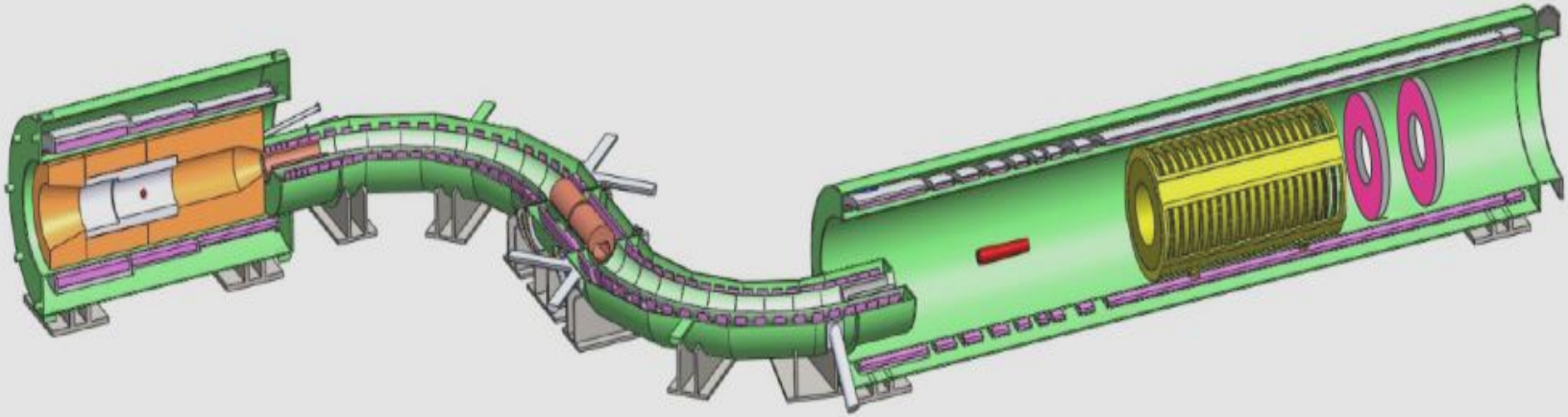
Mu2e Experiment
DESIGN OF TRANSFER LINE CLAMPS



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Outline

Introduction

- Transfer line functions
- Transfer line pipe structure

Clamp modeling – Insulation scheme

Thermal Contact Conductance

- Theory of TCC
- Factors influencing TCC
- Models
- Results

Simulation Results

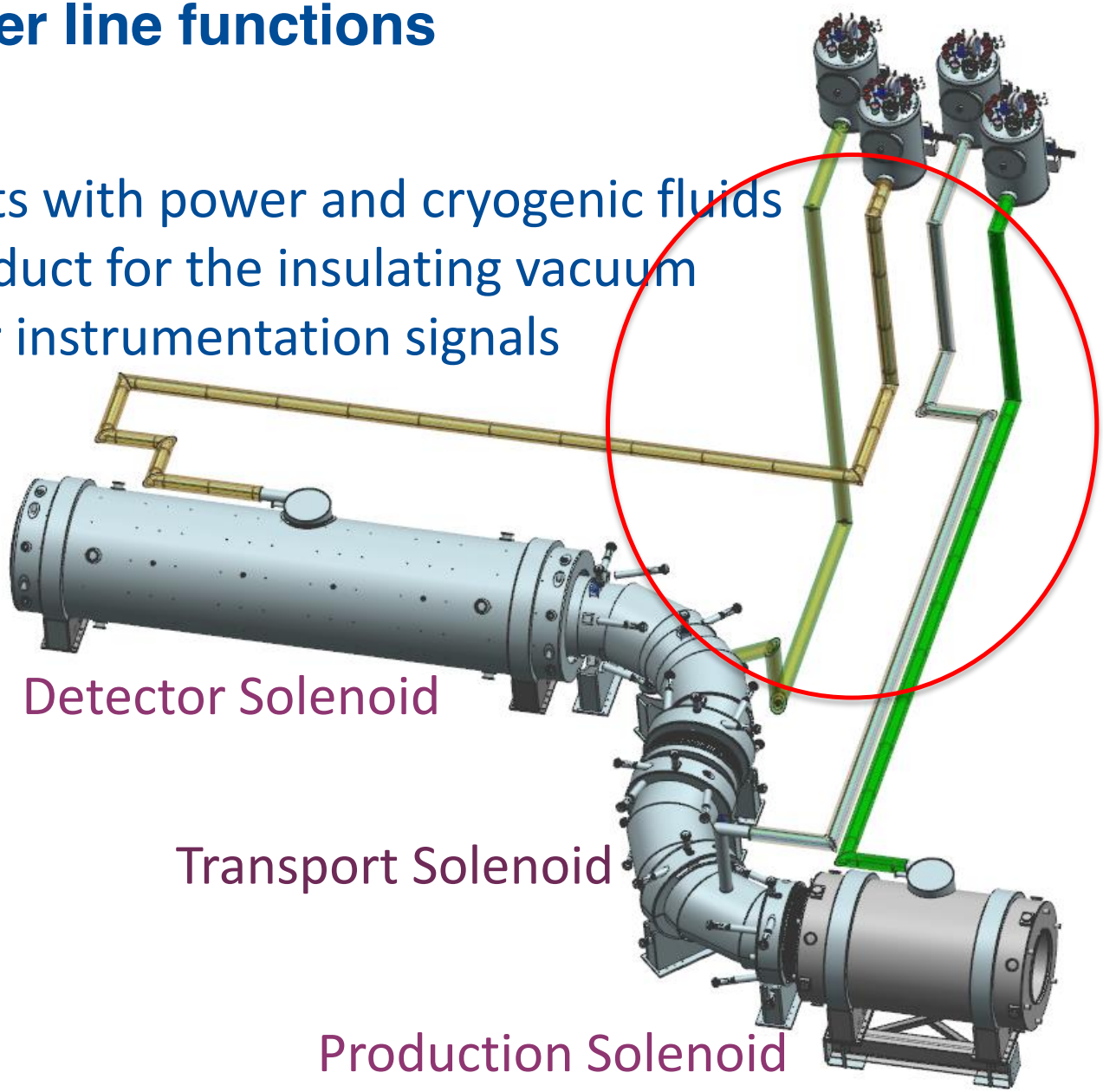
- Stress analysis
- Steady-State Thermal analysis

Clamp Test

Summary and Next Steps

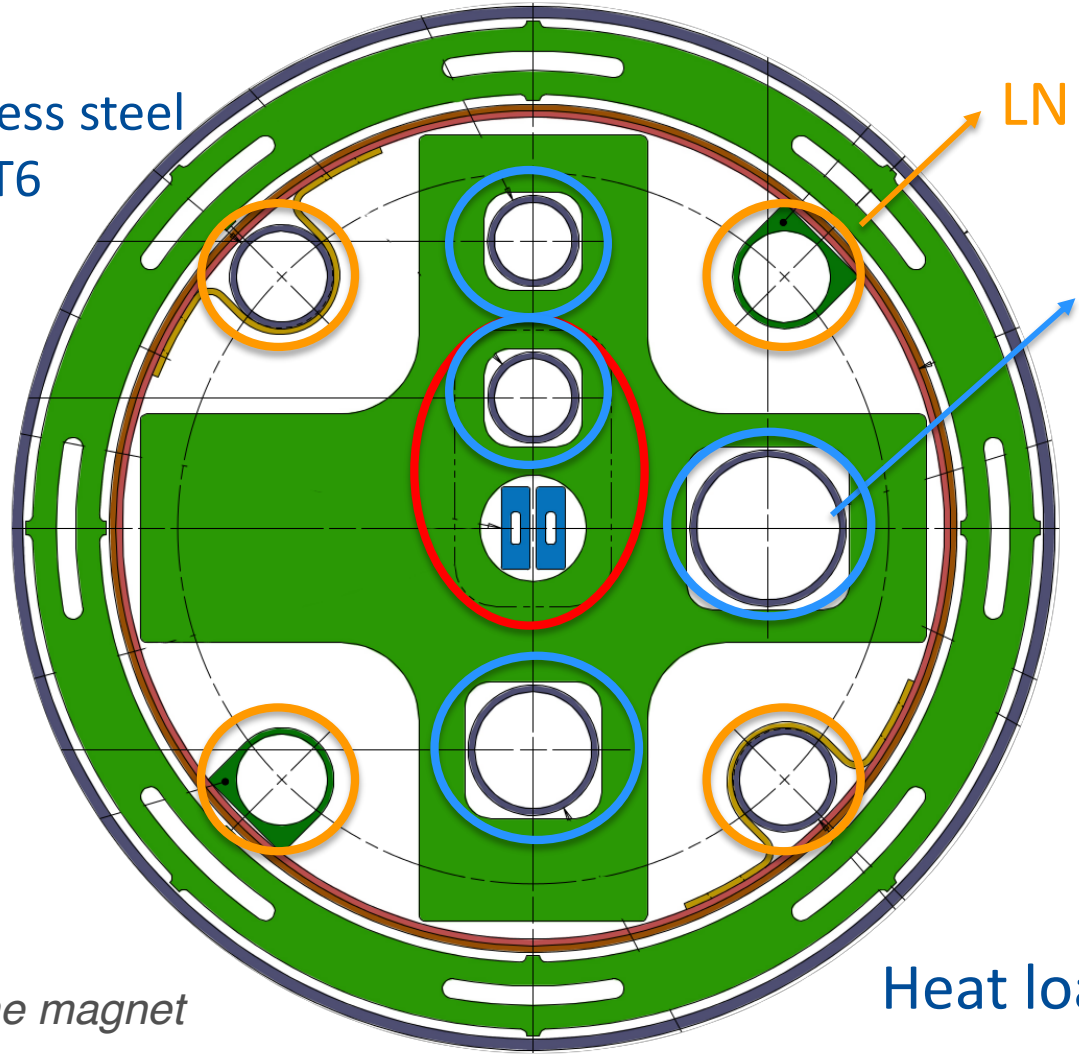
Introduction - Transfer line functions

- Supplies the magnets with power and cryogenic fluids
- Provides pump-out duct for the insulating vacuum
- Acts as a conduit for instrumentation signals



Introduction – Transfer line pipe structure

Pipes: Al 6061 T6
Vacuum tube: stainless steel
Box shield: Al 6061 T6



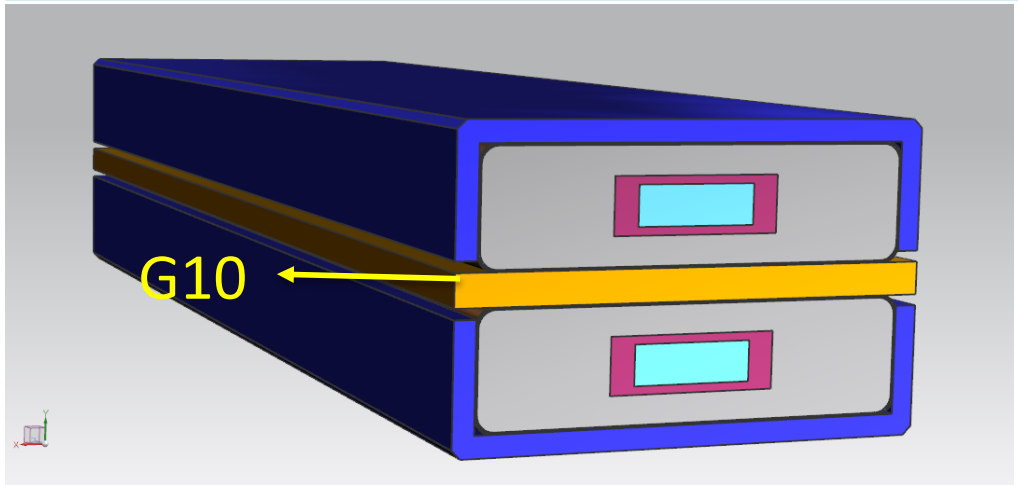
80 K

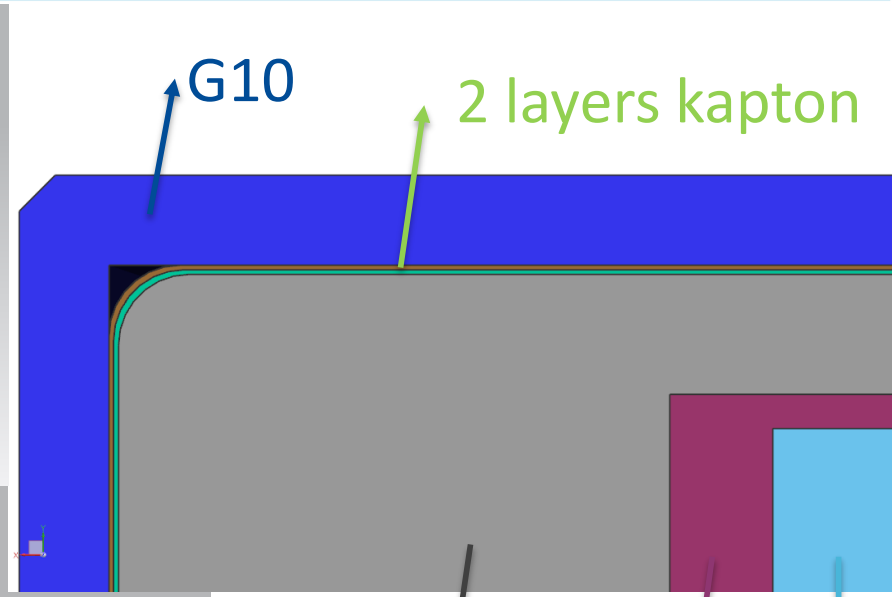
4.7 K

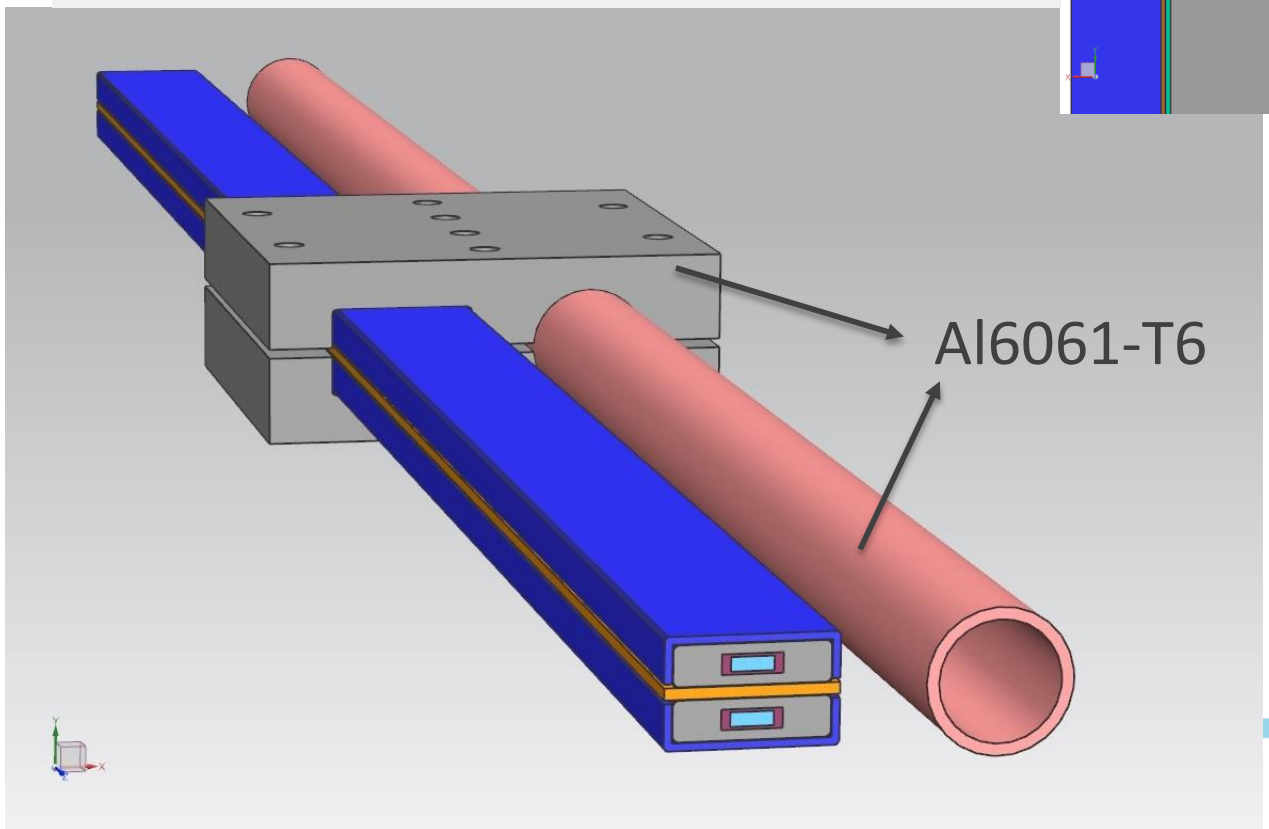
DS Transfer Line
View looking towards the magnet
(Image by Don Arnold)

Heat load: 0.2 W/m

Clamp modeling – Insulation scheme







Al RRR 800

Cu RRR 80

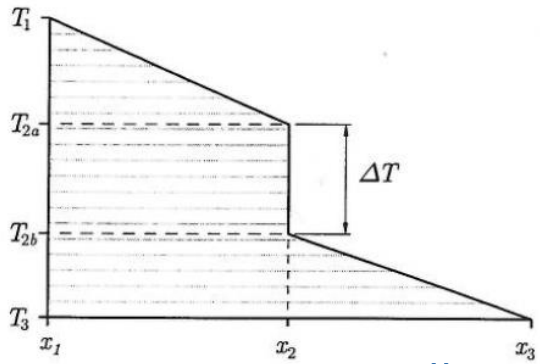
NbTi

Theory of Thermal Contact Conductance

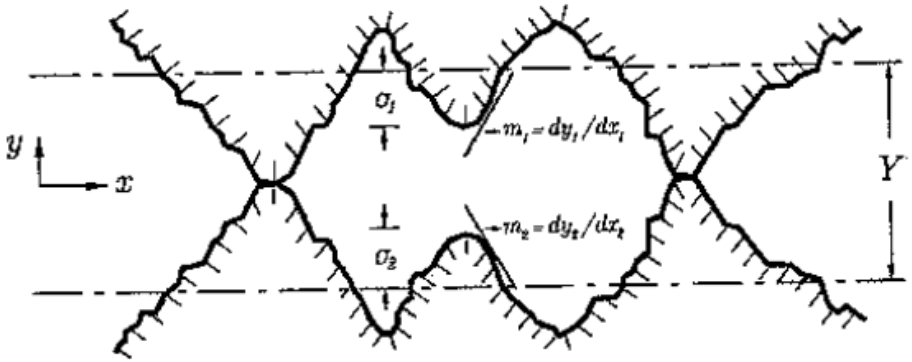
Heat flux over an interface between two surfaces in contact is subjected to a thermal contact resistance:

$$R_j = \frac{\Delta T}{qA} = \frac{1}{h_j A}$$

which causes a drop in temperature over the interface.



The main reason for this resistance is that the real contact area is just a small fraction of the apparent one.

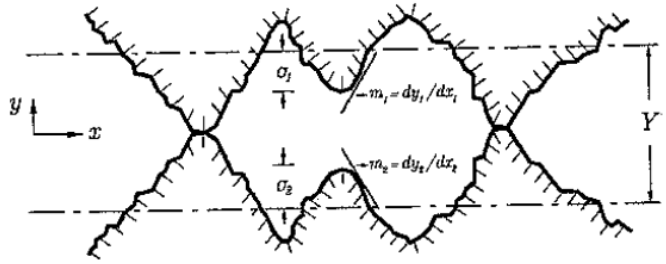


Factors influencing Thermal Contact Conductance

- Geometry of the contacting solids (roughness, flatness deviation, asperity slope)
- Contact pressure
- Gap Thickness
- Thermal conductivity of the materials
- Surface hardness
- Modulus of elasticity
- Average temperature of the interface

Thermal Contact Conductance - Models

- $$k_s = \frac{2k_1k_2}{k_1 + k_2}$$ Effective thermal conductivity



- $$R_a = \frac{1}{L}\int_0^L |y(x)|dx$$ Arithmetic average of roughness

$$\xrightarrow{Gaussian-distribution} \sigma = \sqrt{\frac{\pi}{2}}R_a \approx 1.25R_a$$

$$\sigma = \sqrt{\frac{1}{L}\int_0^L y^2(x)dx}$$ Root Mean Square roughness

- $$m' = \sqrt{\frac{\pi}{2}}m \approx 1.25m$$ m'=Root Mean Square asperity slope
m=Absolute average asperity slope

$$\sigma_s = \sqrt{(\sigma_1^2 + \sigma_2^2)}$$ Effective RMS surface roughness

$$m_s = \sqrt{(m_1^2 + m_2^2)}$$ Effective absolute mean asperity slope

Thermal Contact Conductance - Models

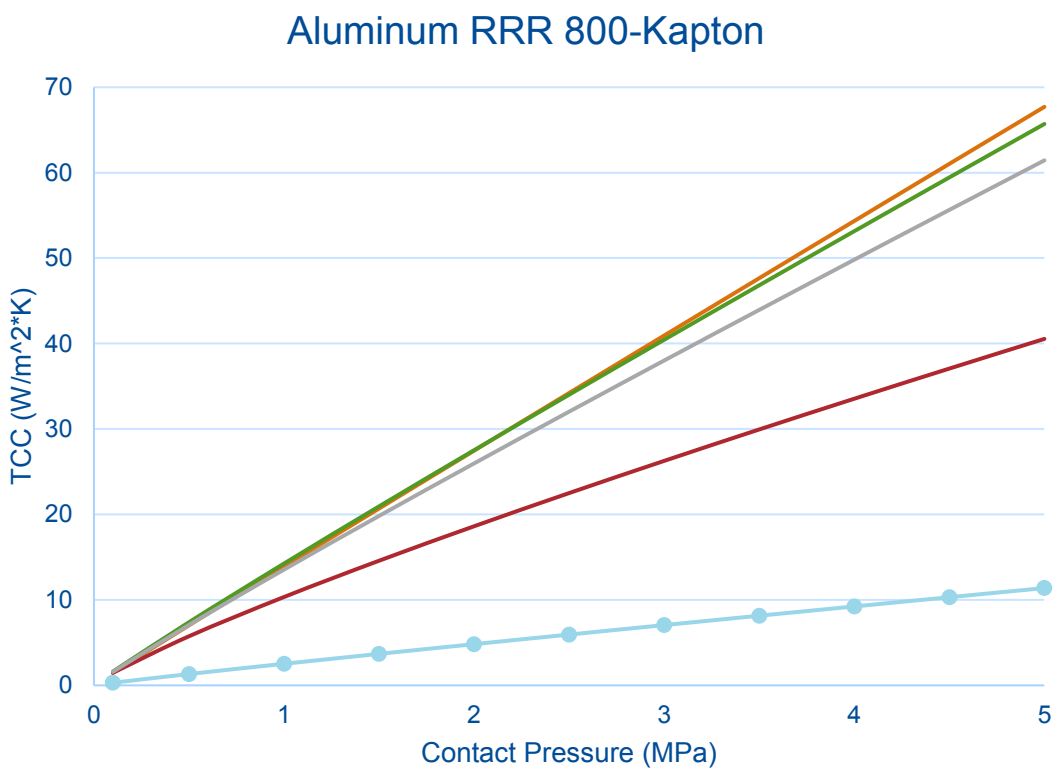
Elastic Models: → $h_c \propto \frac{k_s m_s}{\sigma_s}\left(\frac{P}{E'}\right)^{\alpha}$

- Mikic, 1974: $h_c = 1.55\frac{k_s m_s}{\sigma_s}\left(\frac{P\sqrt{2}}{E' m_s}\right)^{0.94}$ with $E' = \frac{E_1 E_2}{E_2(1-\nu_1^2)+E_1(1-\nu_2^2)}$

Plastic Models: → $h_c \propto \frac{k_s m_s}{\sigma_s}\left(\frac{P}{H_c}\right)^{\alpha}$

- Tien, 1968: $h_c = 0.55\frac{k_s m_s}{\sigma_s}\left(\frac{P}{H_c}\right)^{0.85}$
- Cooper, Mikic and Yovanovich, 1969: $h_c = 1.45\frac{k_s m_s}{\sigma_s}\left(\frac{P}{H_c}\right)^{0.985}$
- Mikic, 1974: $h_c = 1.13\frac{k_s m_s}{\sigma_s}\left(\frac{P}{H_c}\right)^{0.94}$
- Yovanovich, 1982: $h_c = 1.25\frac{k_s m_s}{\sigma_s}\left(\frac{P}{H_c}\right)^{0.95}$

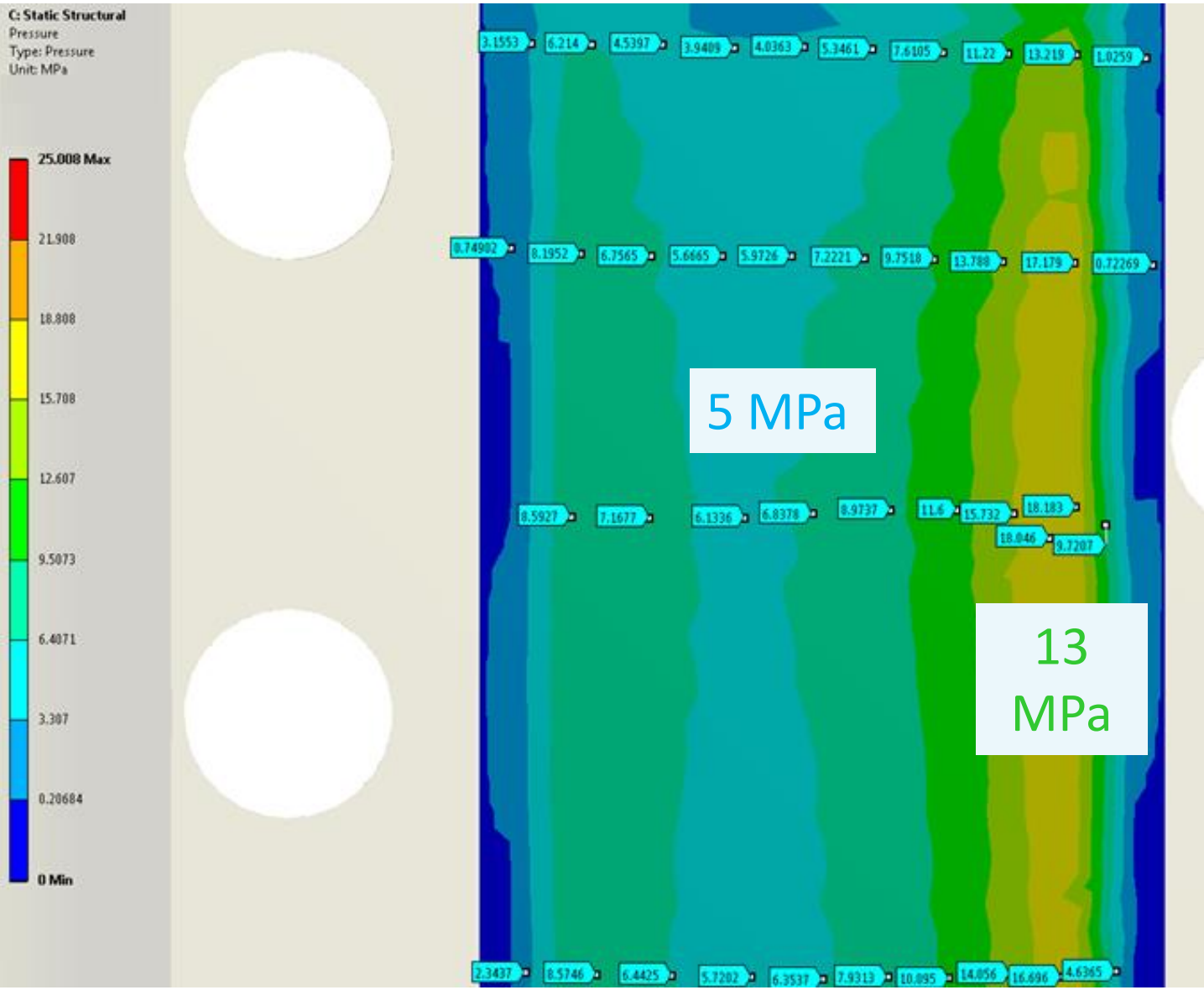
Thermal Contact Conductance vs Contact Pressure - Results



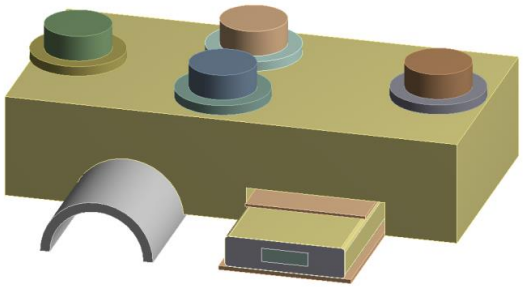
- h_c Tien (W/m^2K)
- h_c Cooper, Mikic, Yovanovich (W/m^2K)
- h_c Mikic (W/m^2K)
- h_c Yovanovich (W/m^2K)
- h_c elastic (W/m^2K)

- Elastic model gives lower values of TCC
- Significant differences in TCC values between plastic and elastic behavior
- Plastic behavior: Tien's model is the most conservative

Simulation results - Stress analysis on clamp contact surface

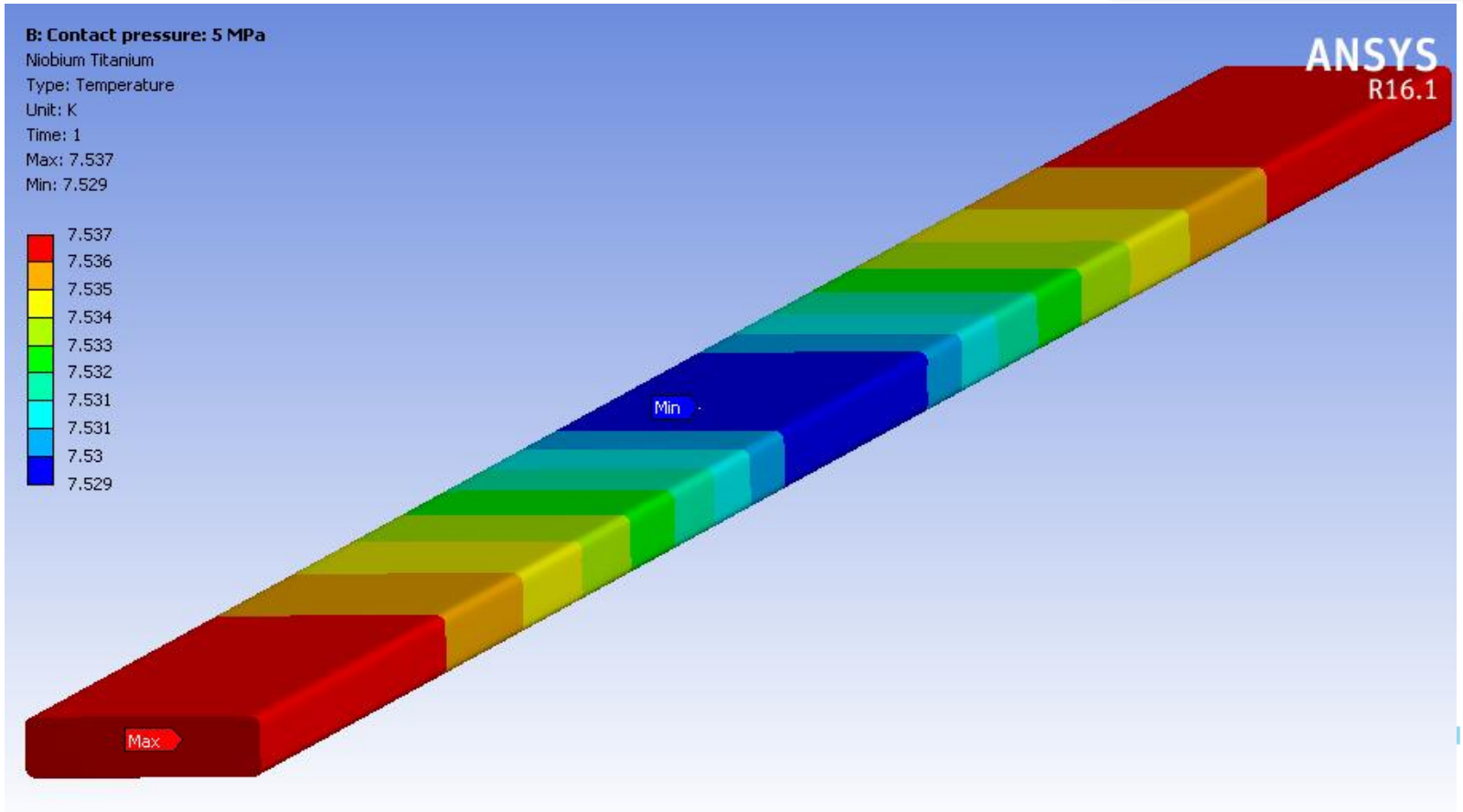


1 mm G10
800lb preload



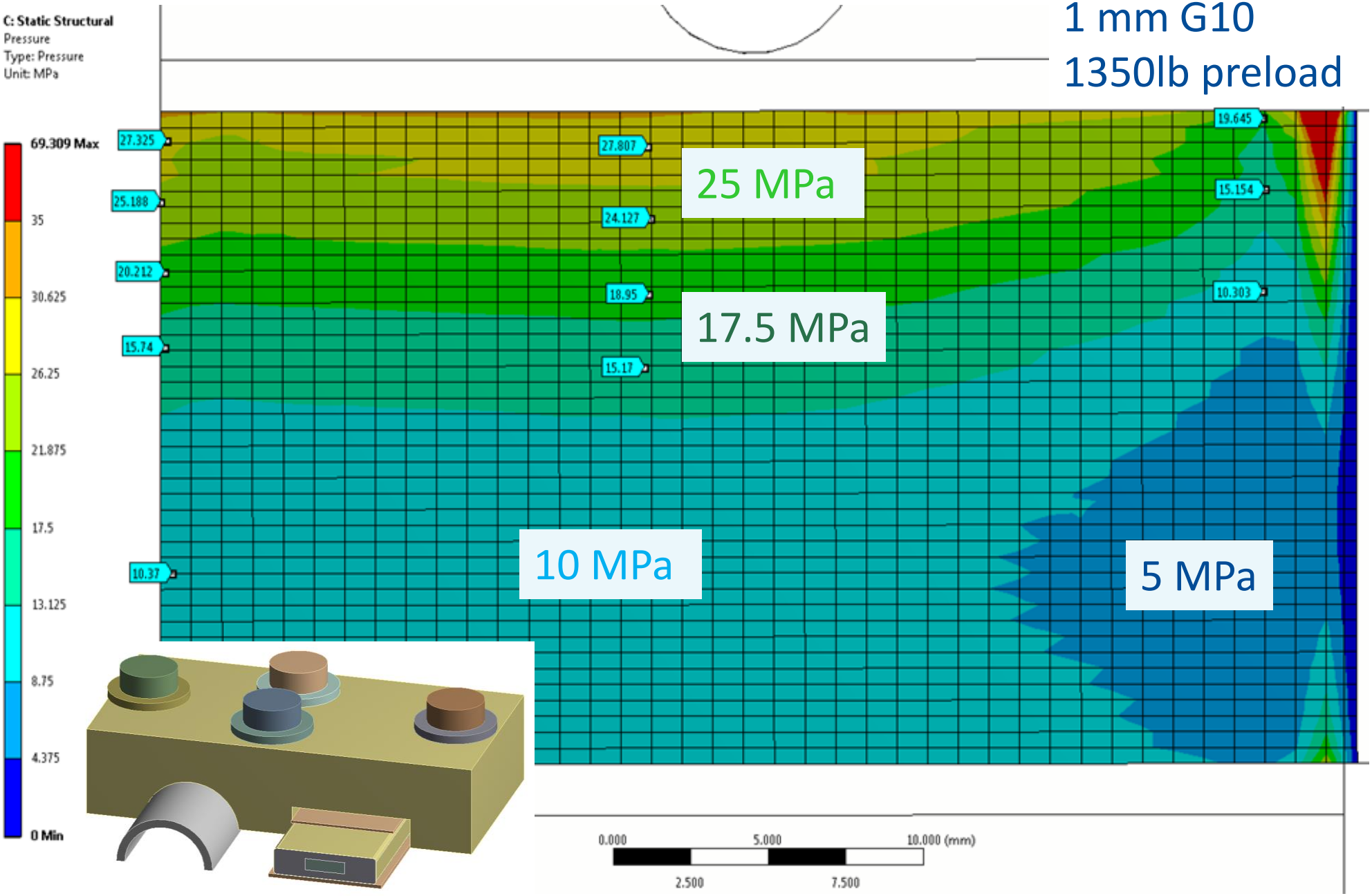
Simulation results – Steady State Thermal Analysis

	Elastic model		Plastic model	
Contact pressure (MPa)	T_{min} (K)	T_{max} (K)	T_{min} (K)	T_{max} (K)
3	9.227	9.234	8.666	8.673
5	7.637	7.645	7.529	7.537



Fermilab

Simulation results - Stress analysis on clamp contact surface

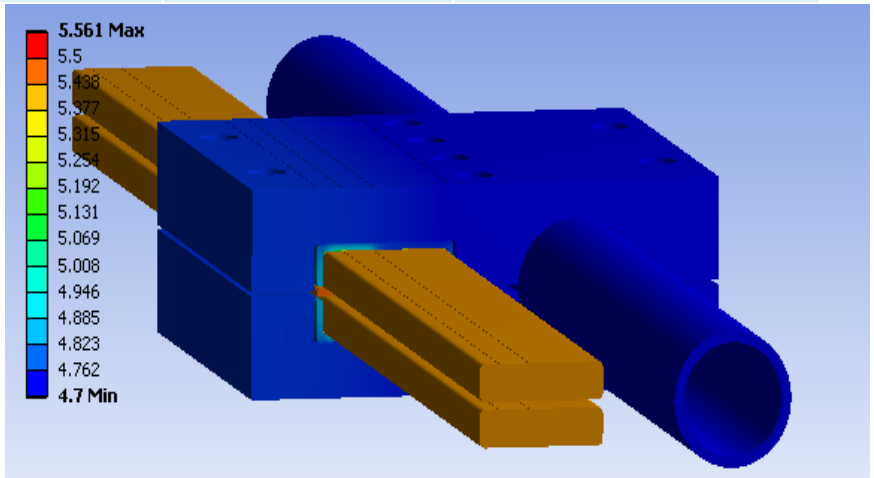


1 mm G10
1350lb preload

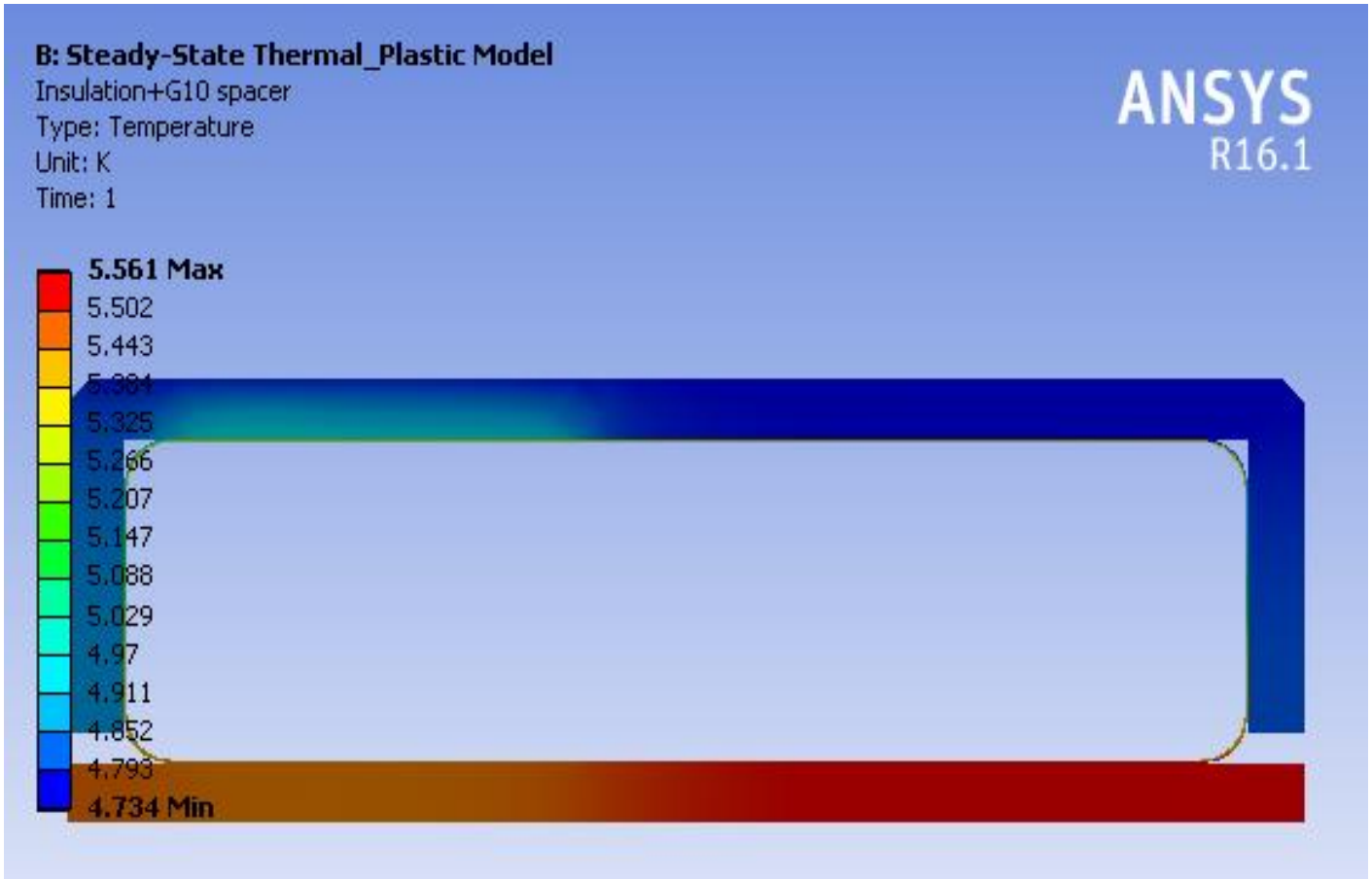
Simulation results – Steady State Thermal Analysis

		0.5 mm G10		1 mm G10	
		T_{max} (K)	T_{max} in superconductor (K)	T_{max} (K)	T_{max} in superconductor (K)
250 mm distance	elastic	5.96	5.84	6.06	5.94
	plastic	5.47	5.35	5.56	5.43
500 mm distance	elastic	7.64	7.51	7.89	7.77
	plastic	6.41	6.29	6.63	6.51

- Distance between clamps: 250 mm
- 1 mm G10 (recommended by magnet designers) is enough to keep the superconductor below 6 K

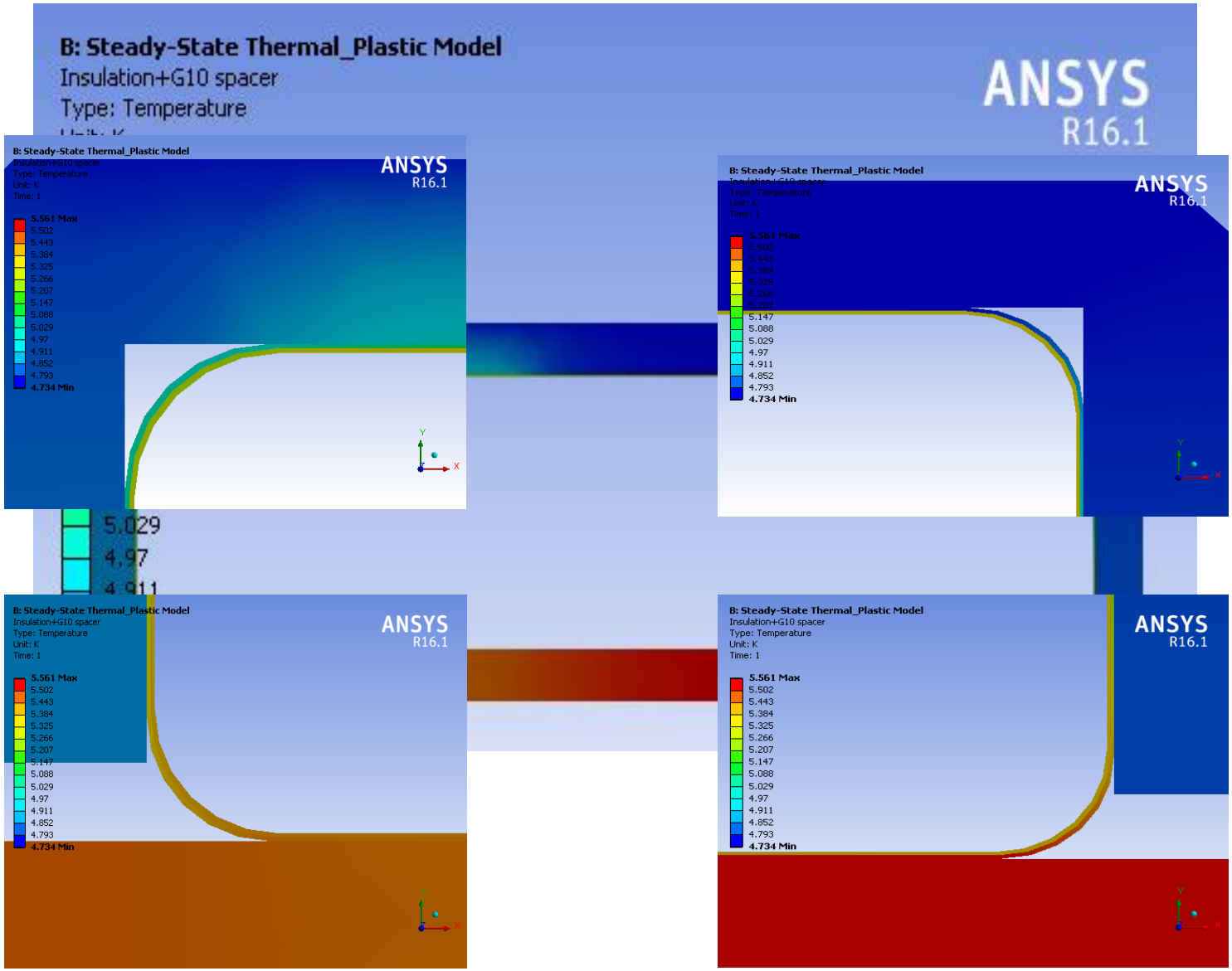


Temperature Distribution across Insulation



- The higher temperatures in G10 insulator
- The uneven pressure distribution is reflected on temperature distribution

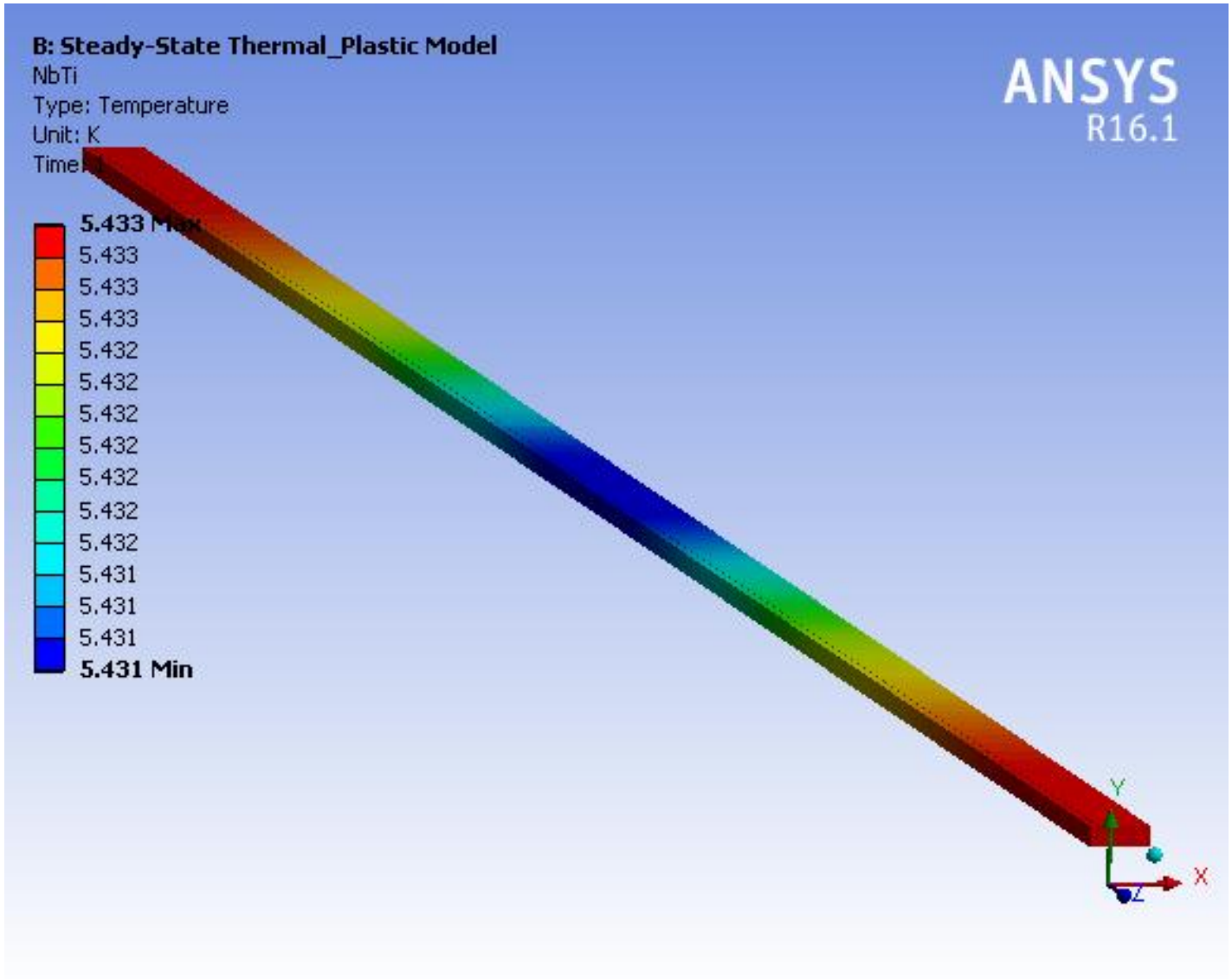
Temperature Distribution across Insulation



The higher temperatures in G10 insulator

The uneven pressure distribution is reflected on temperature distribution

Temperature Distribution in Superconductor

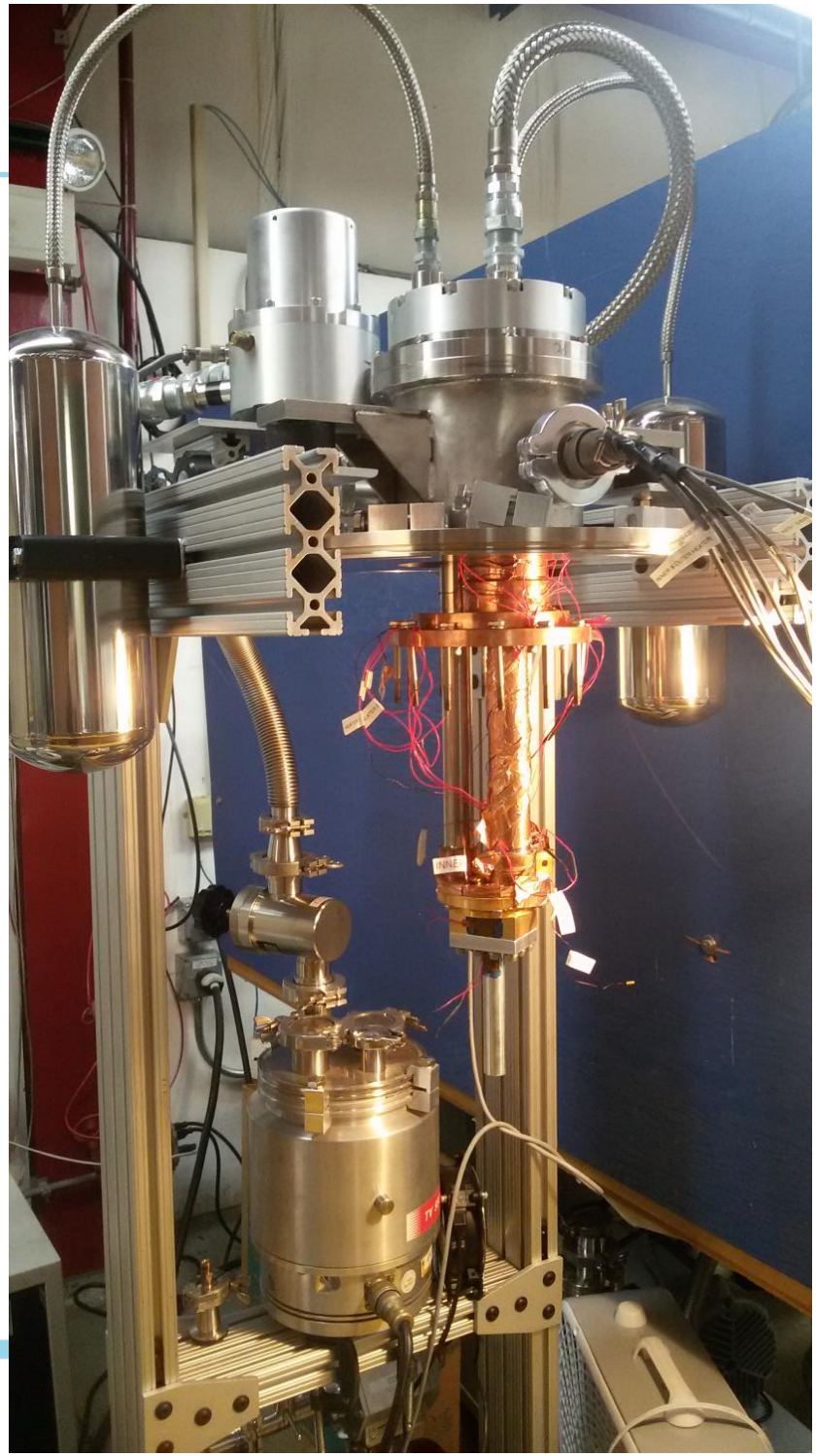


Non relevant temperature difference along the conductor (2 mK)

Test Setup - Components

- Cernox RTD
- 2 Sylicon Diodes
- 3x35 Ohm kapton film heaters
- LakeShore readout
- Detector Solenoid sample conductors

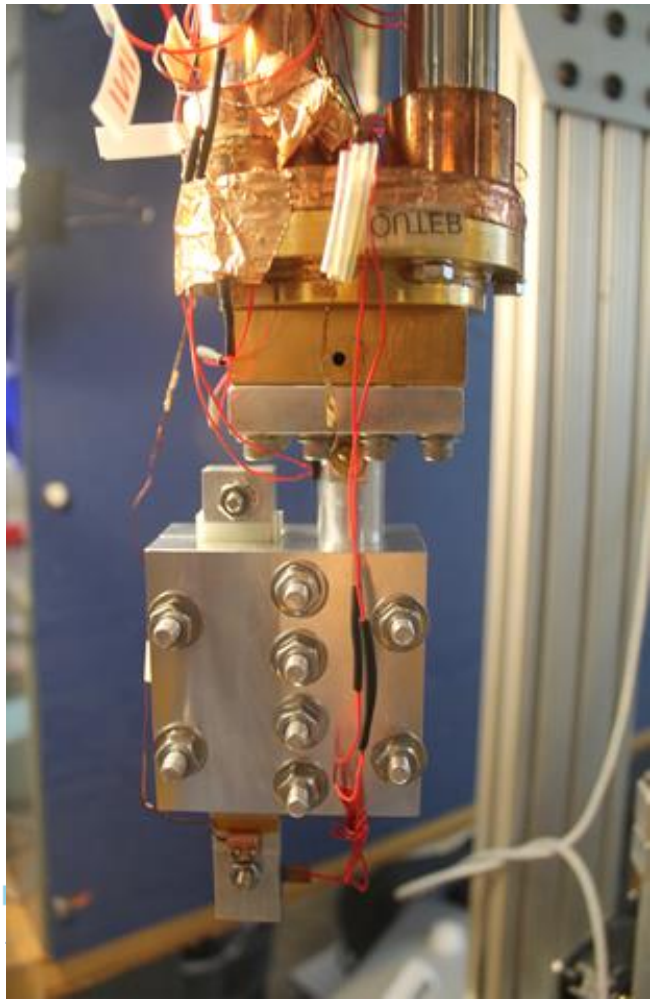
- Cryocooler (Helium Compressor Model)
  Cooling capacity: 40 W at 45K (1st stage)
  1.5 W at 4.2K (2nd stage)
  Base temperature: 2.8K with no load

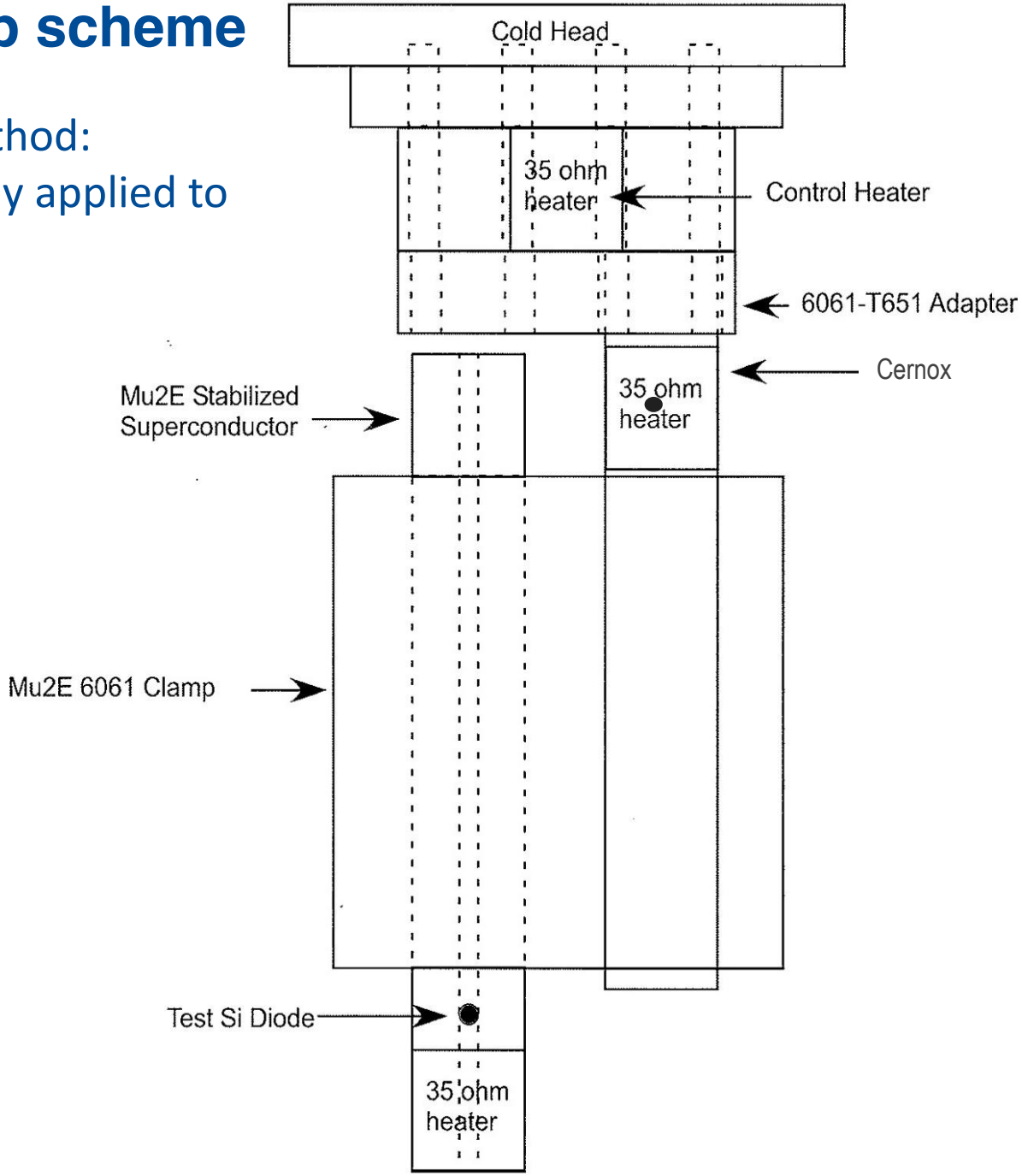


Clamp test-Test setup scheme

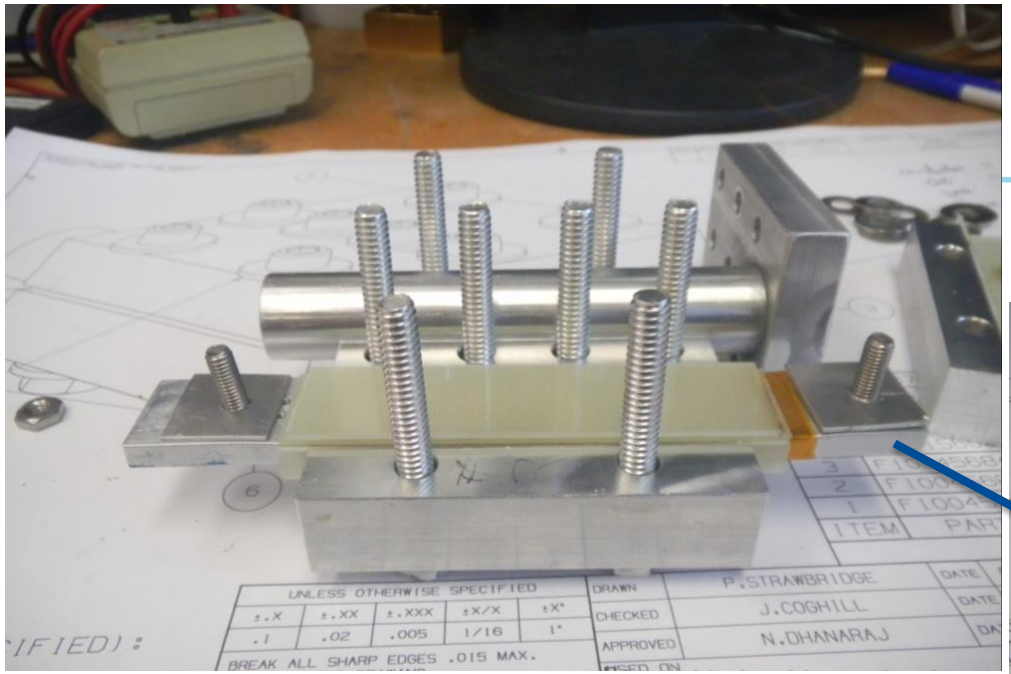
"Two heater-one sensor" method:

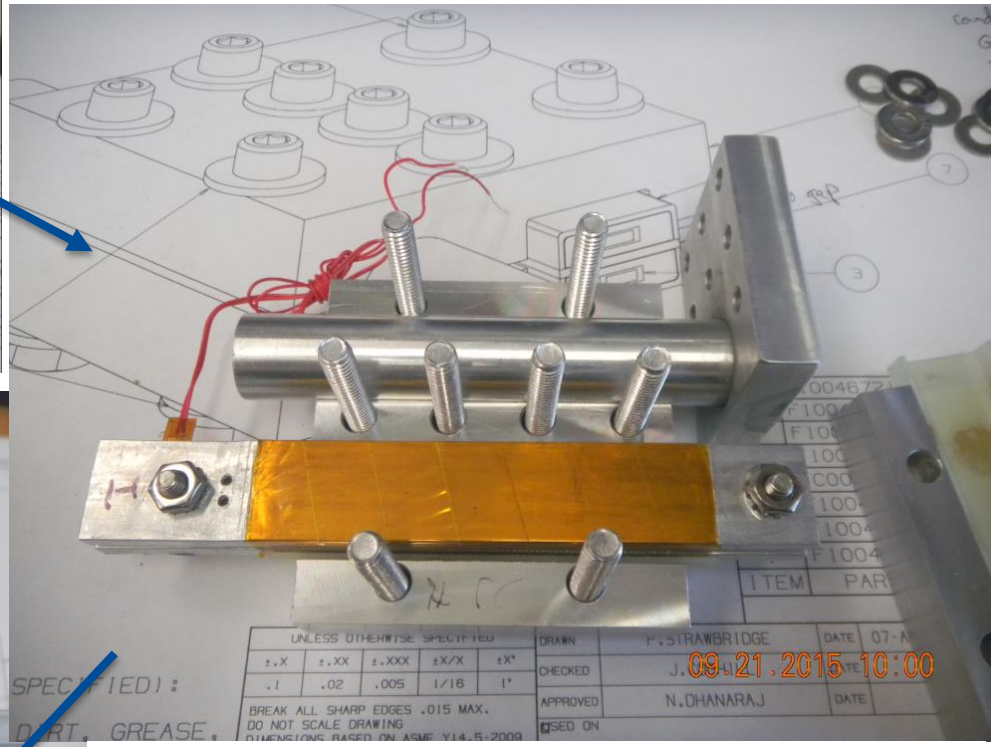
- Heat can be very accurately applied to both ends
- Fewer calibration errors

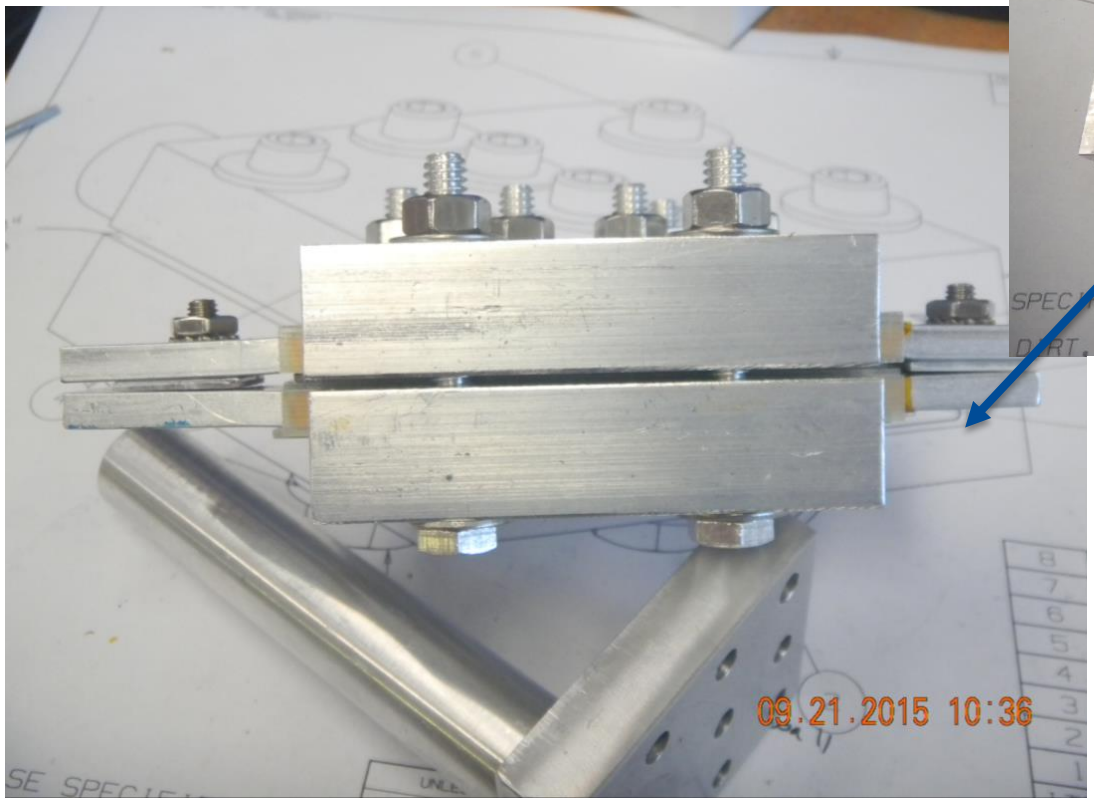




Clamp test – Assembling

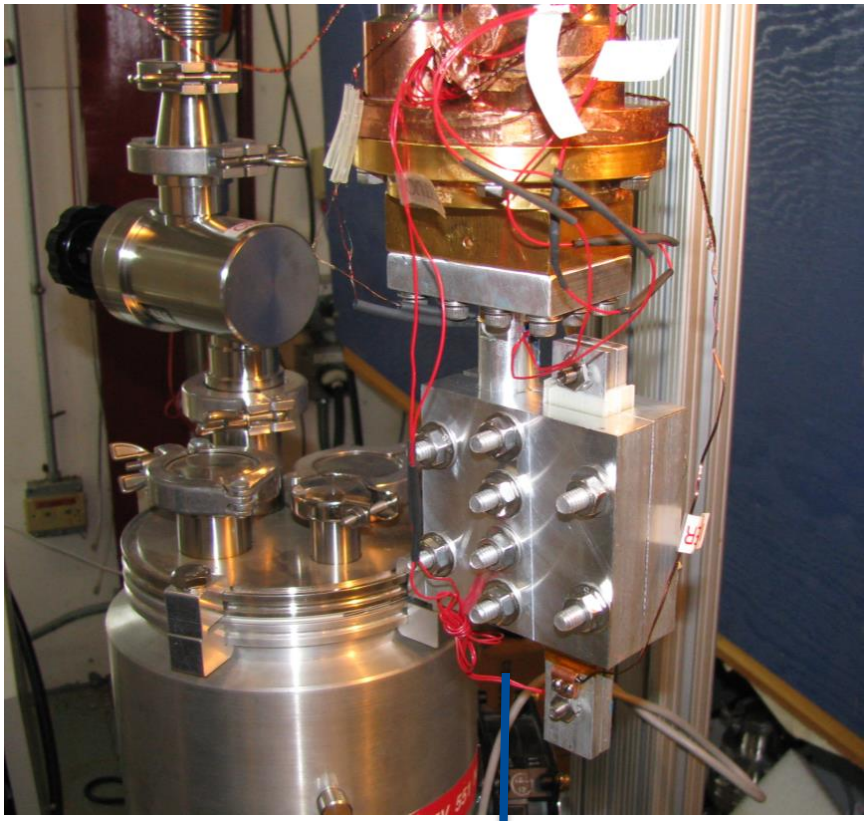


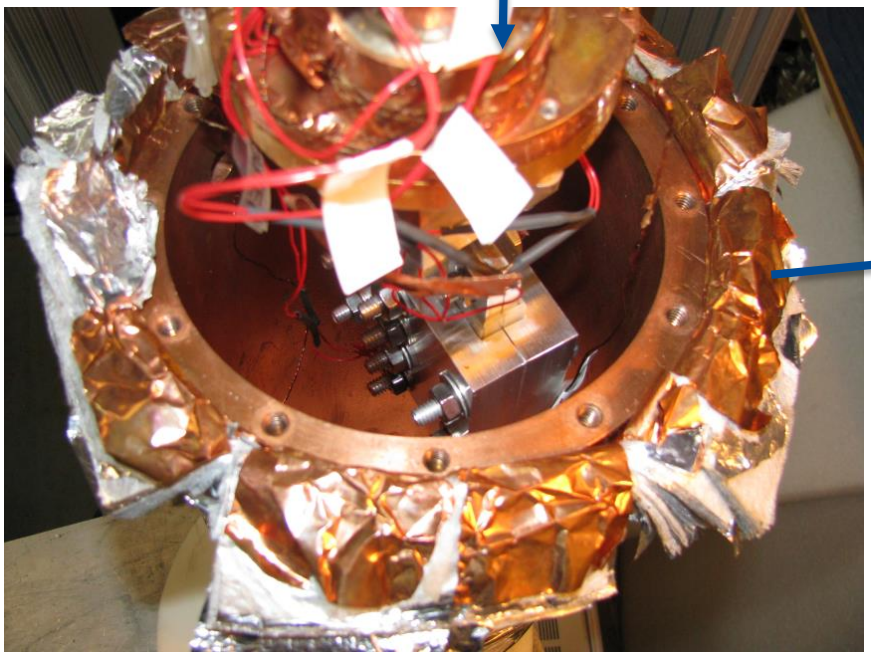




- G10: 1 mm thick
- G10 spacer: 2 mm thick
- 2 layers of kapton 25.4 µm each

- 2024-T4 Aluminum bolts, 0.25”
  Torque: 80 in-lb
  Clamping force=524 lb (2.33 KN)





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Clamp Test – Experimental Results

Conductor1 Temperature (K)	Conductor2 Temperature (K)	Power (W)	Heater status
6.559	7.731	-	Setpoint to 4.7K
6.685	7.843	0.012	Inner heater on
6.872	8.036		Outer heater on
6.691	7.847	0.021	Inner heater on
7.008	8.175		Outer heater on
6.705	7.859	0.032	Inner heater on
7.190	8.361		Outer heater on
6.701	7.852	0.041	Inner heater on
7.556	8.728		Outer heater on
6.794	7.937	0.051	Inner heater on
7.797	8.965		Outer heater on

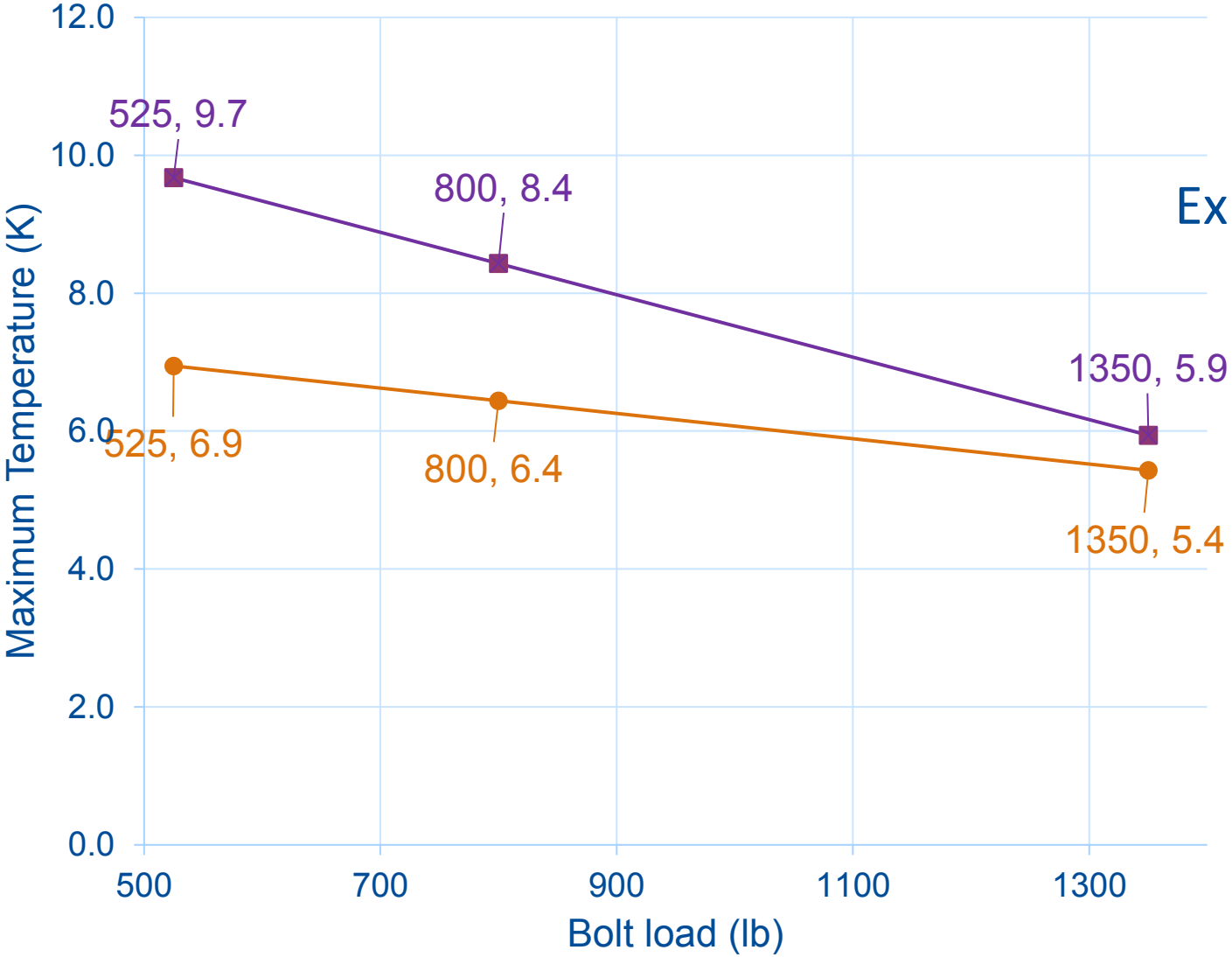
Control temperature=4.7 K

Cold head temperature=4.9 K

Shield temperature=22.7 K

We have worked out the cold testing of the clamp setup, sadly we have run into some issues with the setup and we are working on debugging the system

Estimated Results



Experimental data:
6.7-8.2 K

elastic model
plastic model

Summary

- Designed the clamp
- Optimized insulation scheme (1 mm G10 – 25.4 μm kapton)
- Set the distance between the two clamps (250 mm)
- 800 lb of clamping force is not enough → increased at least to 1350 lb
- Manifactured the clamp and assembly the test

  Currently applied: 524 lb load, using 2024 T4 Aluminum Bolts

What comes next?

- Use high strength bolts (7075 Aluminum bolts)
- Repeat the cold test

Ackowledgment

- Mu2e Experiment
- Computing Division
- TD-Design & Drafting
- Summer Student Organizers

Thank you for your attention!