High Luminosity LHC

Thermal and Outer Magnetic Shields

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The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Content

Warm Magnetic Shield

- Design Approach
- Design Features
- Concept options
- Double Layer Shielding Analysis
- Conclusions and further work

Thermal Shield

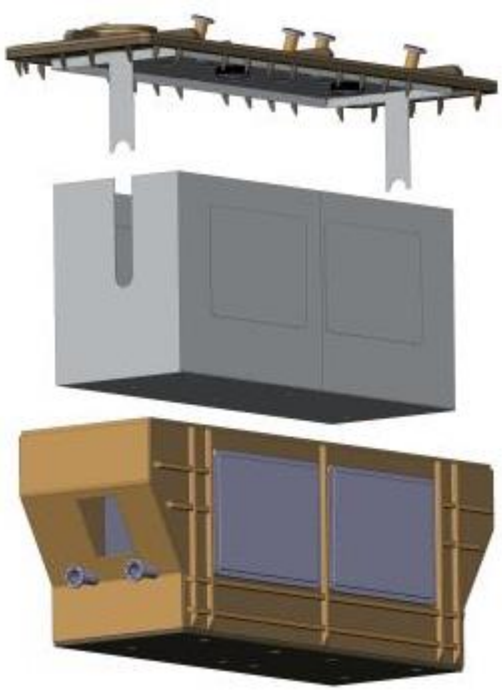
- Specification
- Literature Review
- Material Selection
- Assembly
- Design Challenges

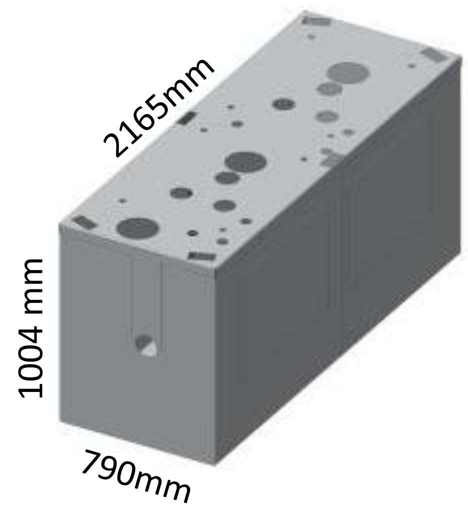
Designs are conceptual at this stage. Both shields are impacted by OVC and cold-warm systems (HOM, Tuner, Supports, etc.) and should be designed in parallel. The objective of this talk is to address the key design challenges and outline the baseline concept for progression.

Warm Magnetic shield

Design Approach

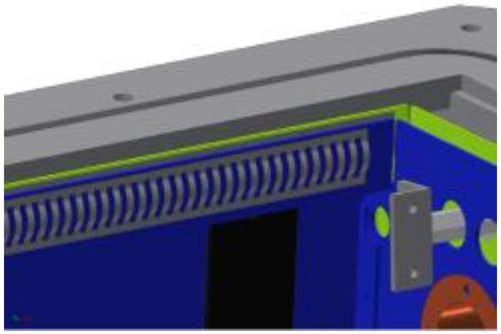
- Fabricated from 3mm MuMetal for shielding performance and stability
- Fitted to OVC (at Room Temperature)
- Compatible with Top loaded Cryomodule design
- Function without connection between top lid and body
- Optimised for minimal connections and maximum stability
- Designed in parallel to Thermal Shield
- Minimise parts for ease of manufacture and assembly (cost)
- Parts small enough for heat treatment furnace (~1.4 x 1 x 1 m)
- Maximise shape and dimensional accuracy with minimal parts and minimal welding
- Ensure any potential field leaks at joints or penetrations are as far away from cavities as possible





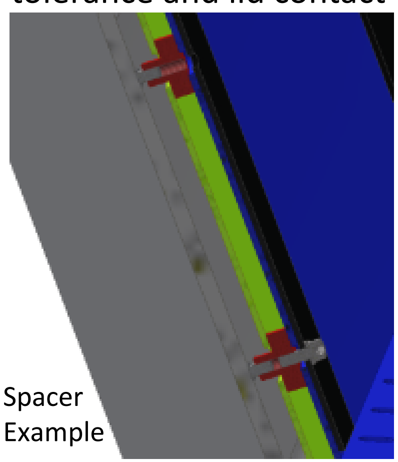
Budget Cost: 1 Shield £45k (+tax), 2 Shields £90k ≈ €125k

Design Features



EM gasket not required

Connects through joints to studs on OVC allows adjustment for tolerance and lid contact



Recommended Material: TUFNOL or AL6082T6

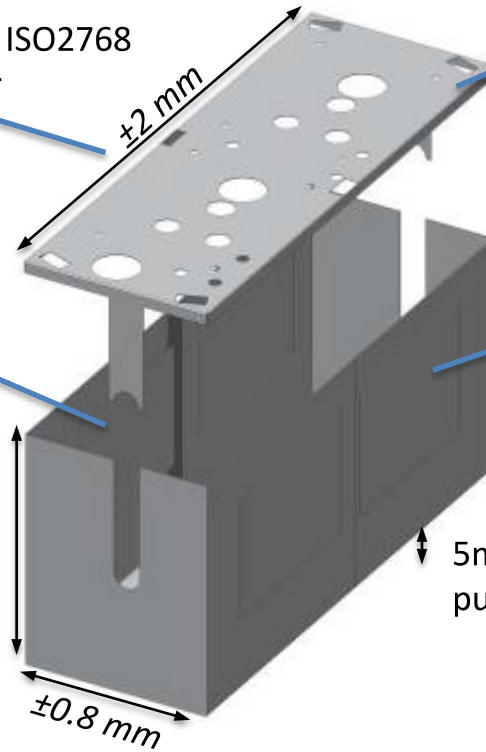
No fixed connection between lid and body

Tolerance to ISO2768 mK or better

Oversized lid with overlaps for attenuation

Slots for cold mass assembly

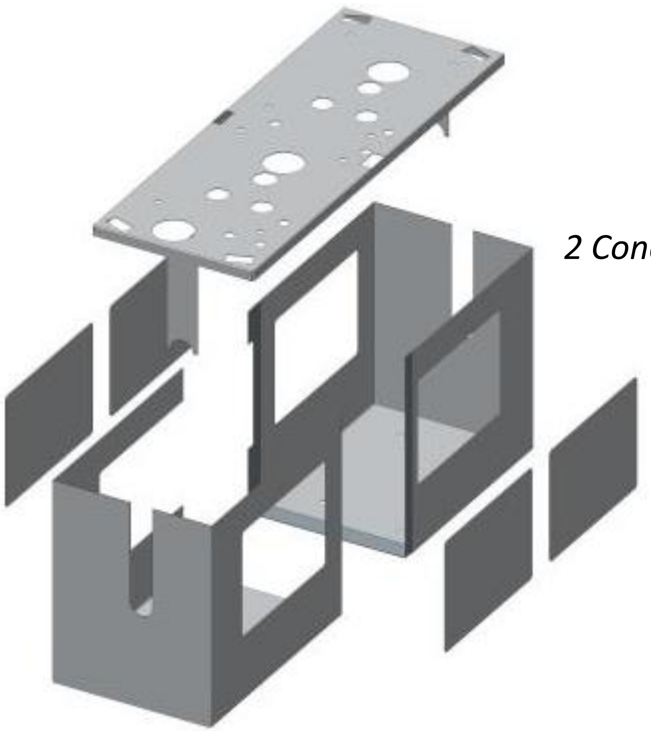
Windows for inspection & maintenance



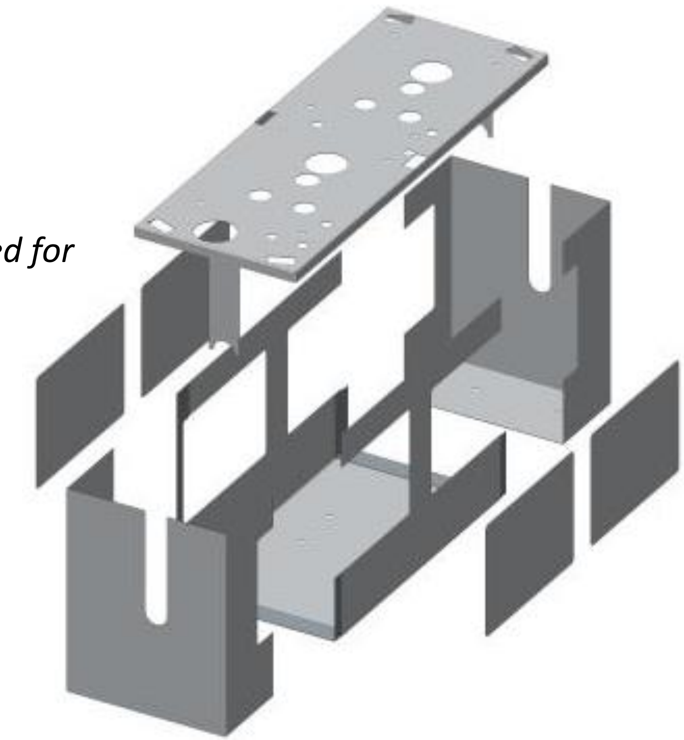
5mm spacing from OVC for pump down and tolerance

Design Options

Joints locations can present potential field leaks, ideally located as far away from the sensitive areas (cavities) as possible.



2 Concepts to be analysed for comparison



Concept 1
Body split into 2 parts
Joint located between the cavities
Less parts

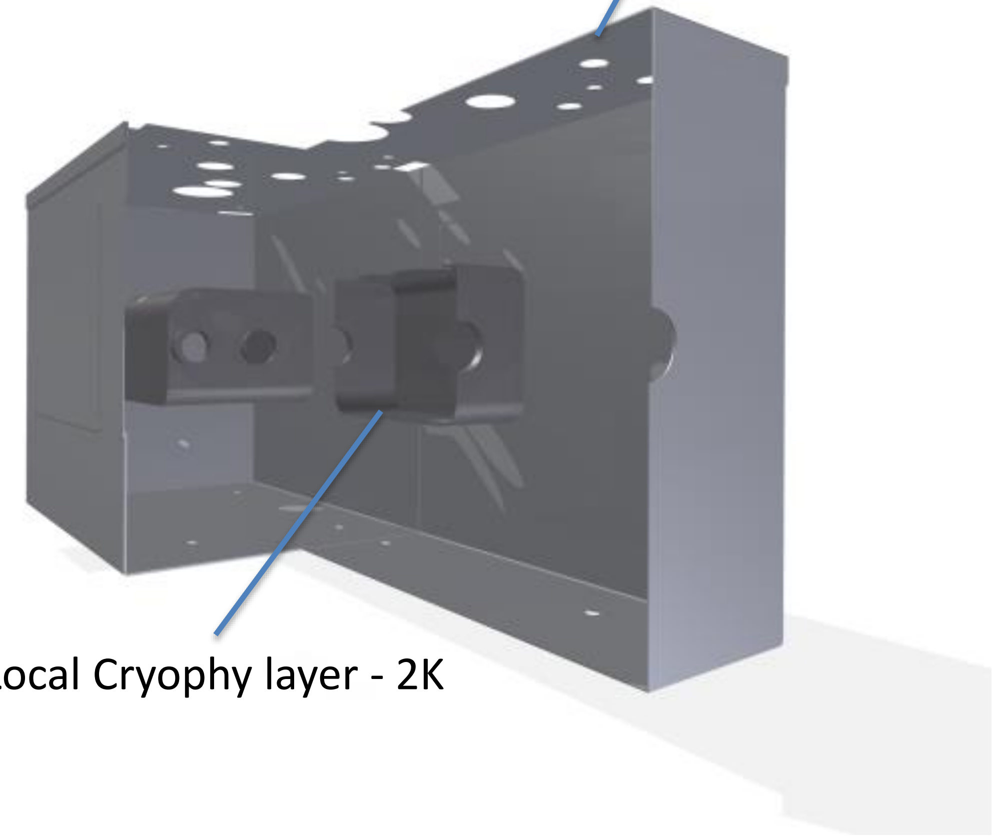
Concept 2
Body split into 3 parts
Joint located towards ends
More parts

Shielding Analysis

- Double layer analysis
  - 3mm MuMetal
  - 1mm Cryophy

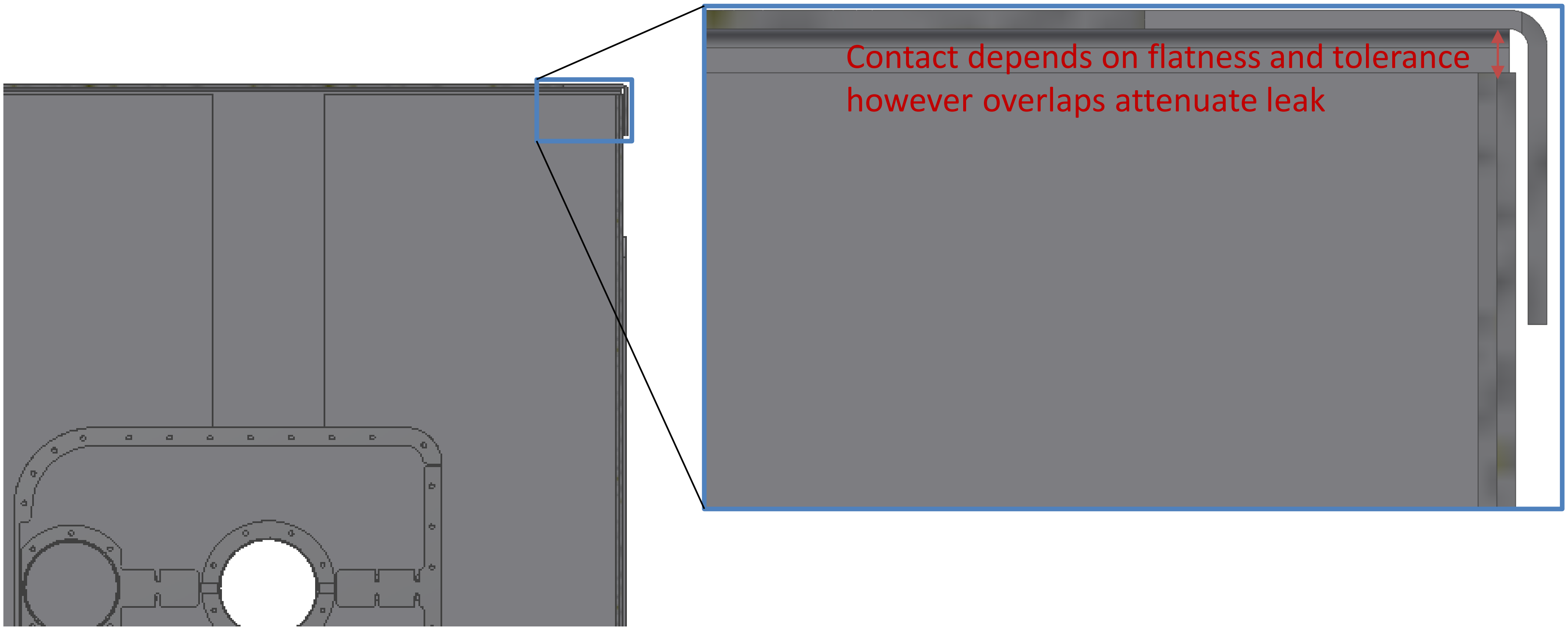
- Local layer finalised
- Global layer conceptual – size and position of penetrations subject to change

- Specification: <1µT on cavity Surface



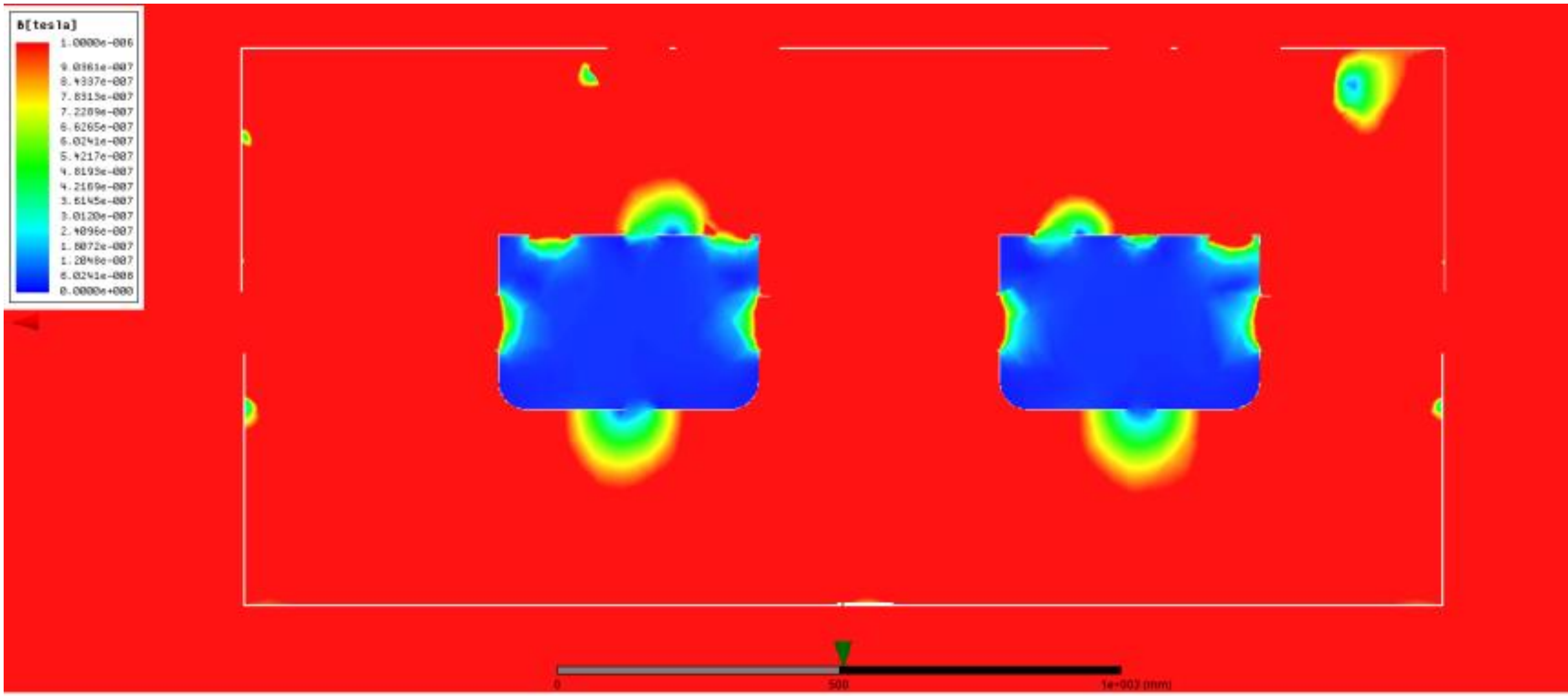
Assumptions

- Perfect joint connections
- Ideal contact between lid and body



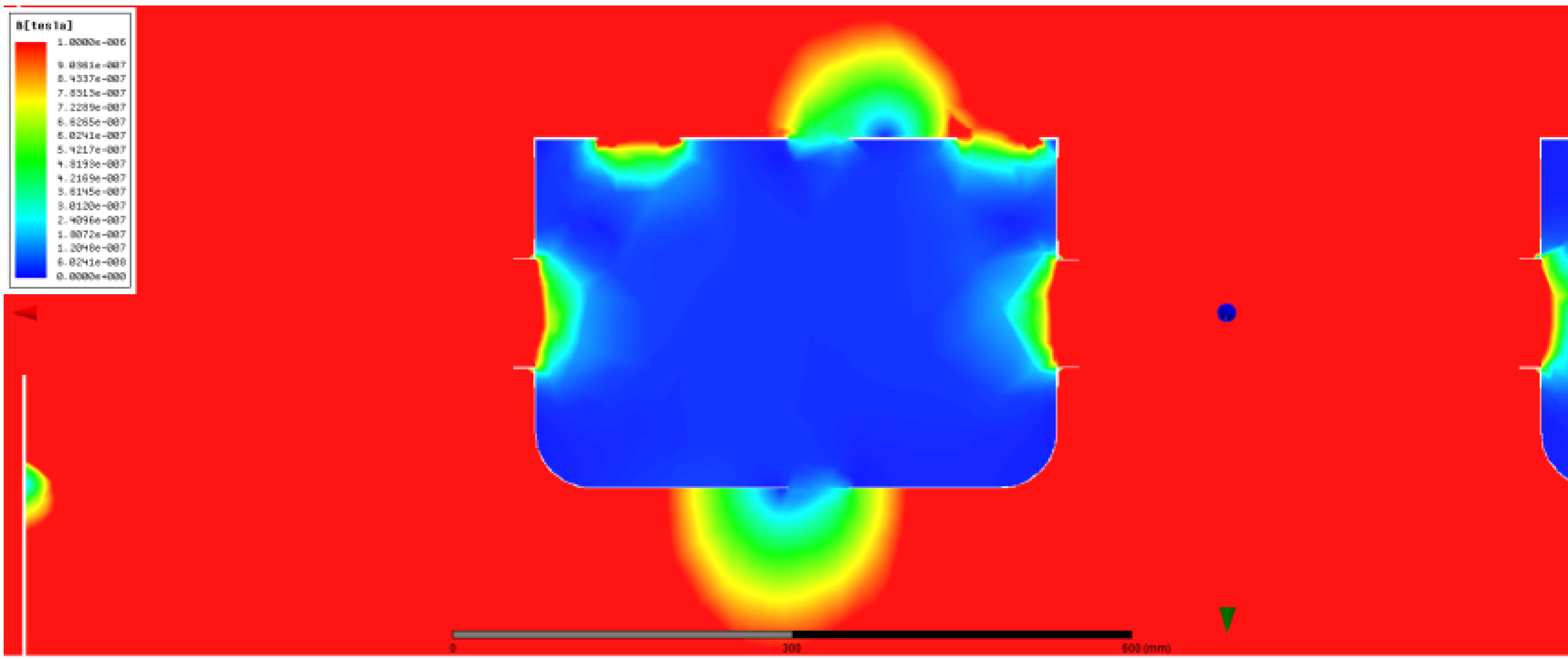
200 µT longitudinal field (along beam axis)

Red > 1 µT



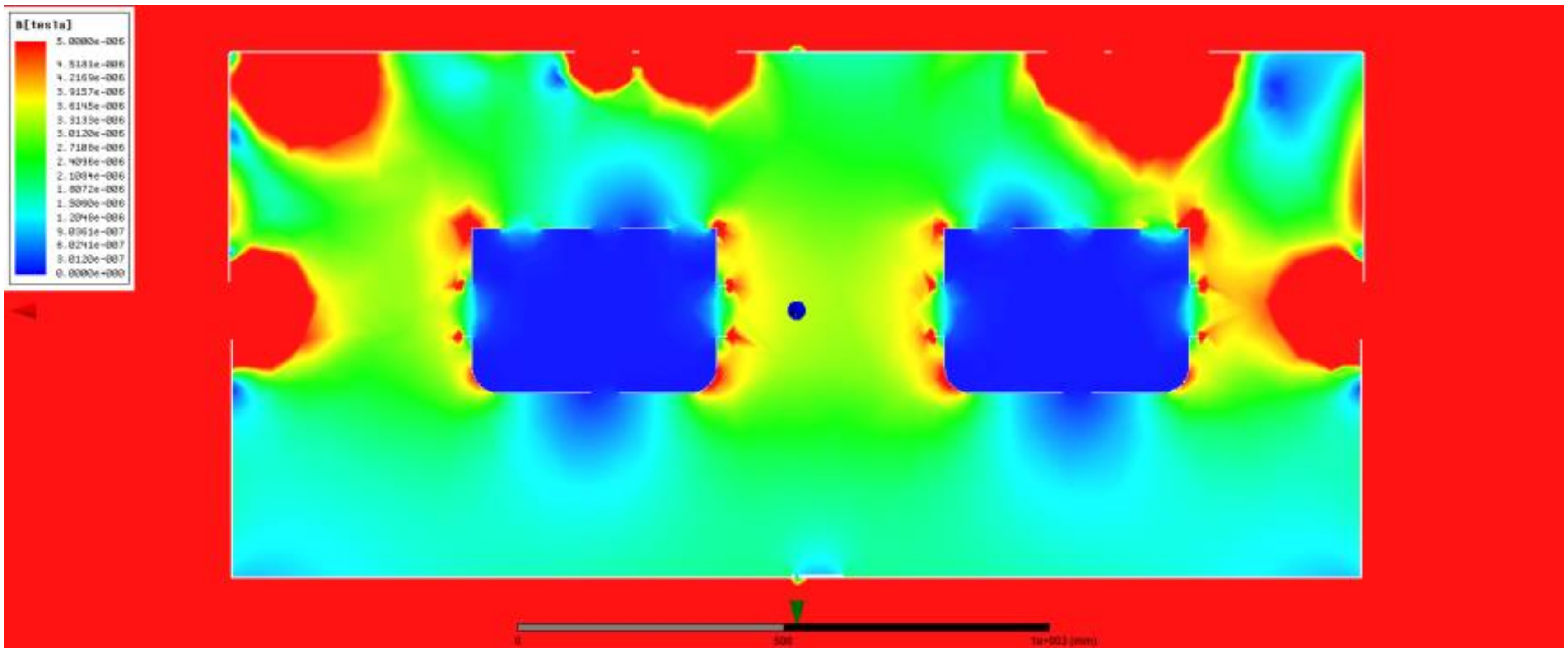
200 µT longitudinal field (along beam axis)

Red > 1 µT



200 µT longitudinal field (along beam axis)

Red > 5 µT



Conclusions

- Field inside cold shield compliant with requirement
- Field outside cold shield higher than requirement, but just by a factor 2x or 3x (longitudinal field)
- Penetrations and gaps make the magnetic field leaking inside the shield when field lines are vertical
- 60 uT vertical field determines a field in the top HOM volumes equivalent to the longitudinal 200 uT

Simulations to be repeated with experimental material data

Thermal Shield Design

Function:

To provide thermal intercept for cold-warm components and shield cold mass from thermal radiation.

Specification:

- See heat load talk (F. Carra)
- Operate with Gaseous Helium 50-80 K, 2-3g/s
- Coated with 20-30 layers of Multi-Layer Insulation
- Global cooling circuit for homogenous cool-down
- Cooling pipes close to intercept points

Thermal Shield Review

Aluminum	Copper
• Lighter & Stronger	• Heavier
• Less expensive	• More expensive
• Difficult to connect to other piping	• Easily soldered or brazed

Common Grades 1050 & 1061-T6

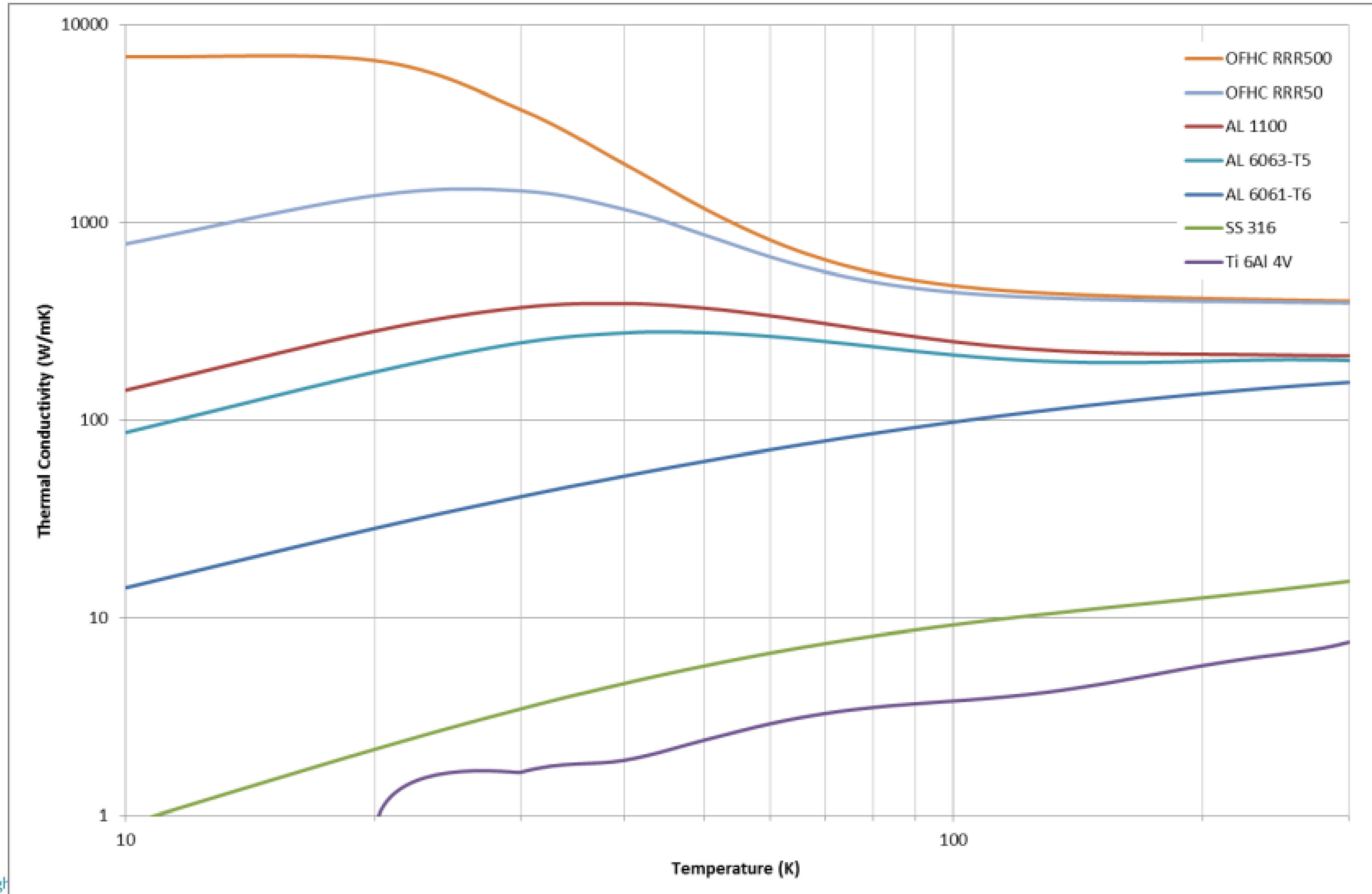
ISAC II Medium Beta Cryomodule at TRIUMF
Riveted Cu Panels
LN2 Circuit
10 mm ID Cu tubing
Tubing soldered to panels
Panels nickel plated to improve emissivity

First generation TTF cryostat
Aluminium Panels
Copper braided Stainless Steel pipes
Panels connected by hundreds of threaded fasteners
Fast cool down

Second generation TTF cryostat
Aluminium panels
Welded Aluminium pipes
"Finger" welding to relieve stresses in the long shield during cool-down
Slow cool down

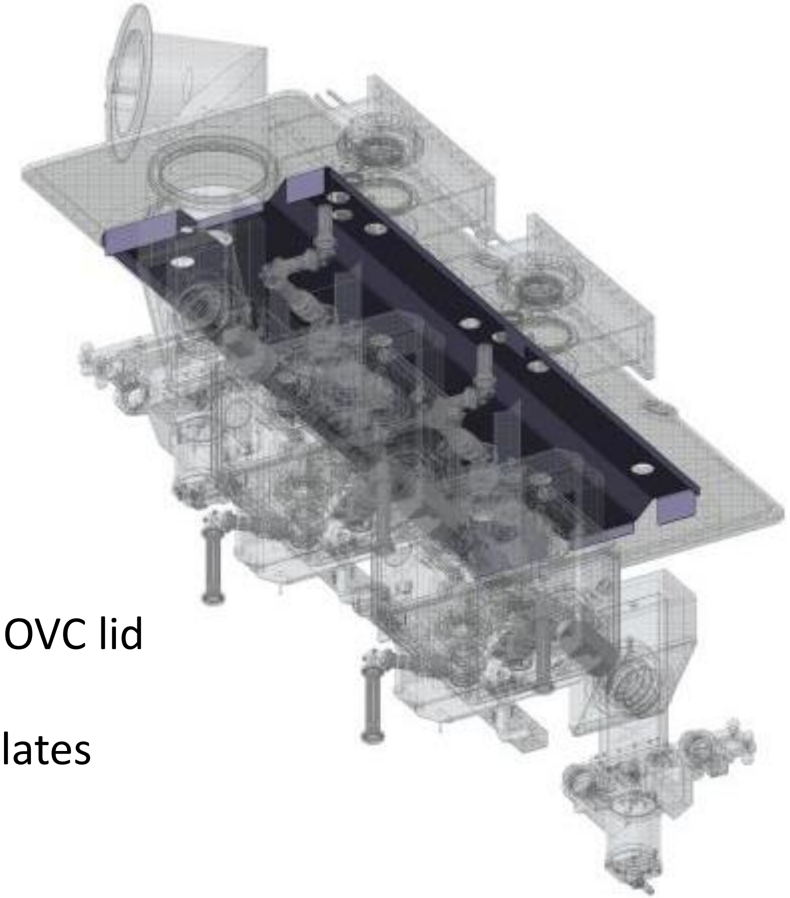
FRIB Cryomodule
Al 1100-O panels with parallel welded cooling tubes
12.7 mm ID
3 bar Helium gas

Cryogenic Thermal Conductivity



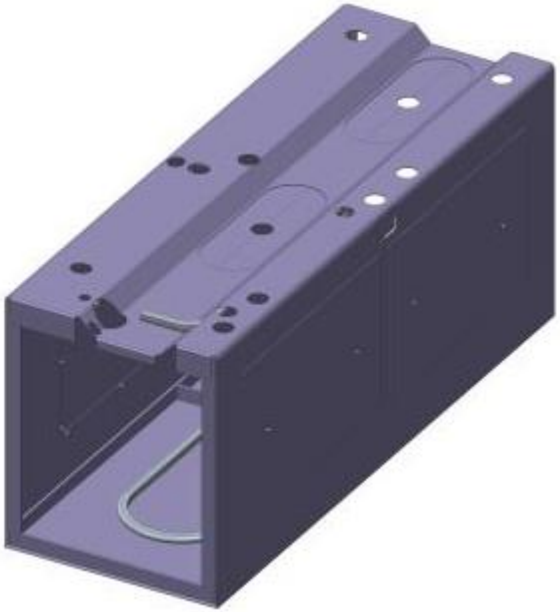
Data from http://www.cryogenics.nist.gov/

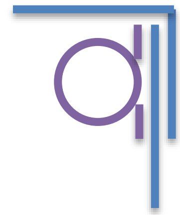
Configuration – Top Plate Assembly



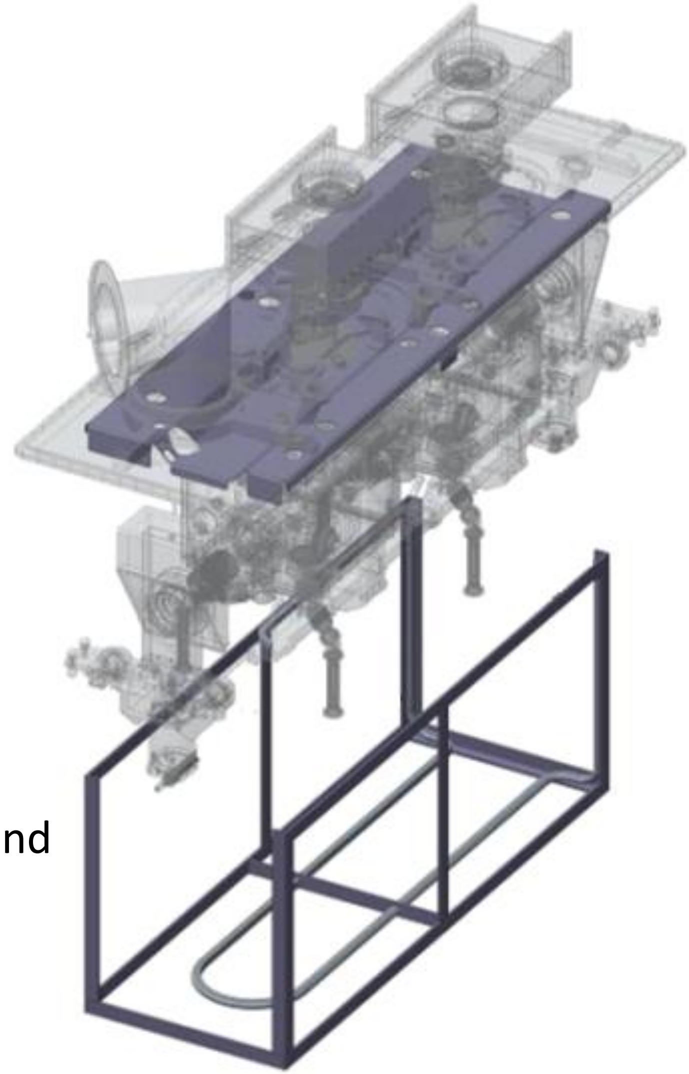
Shield top plate (with cooling pipes) assembled to OVC lid
Cold mass assembled
Top plate is closed around FPC & tuner with split plates

Configuration – Frame Assembly





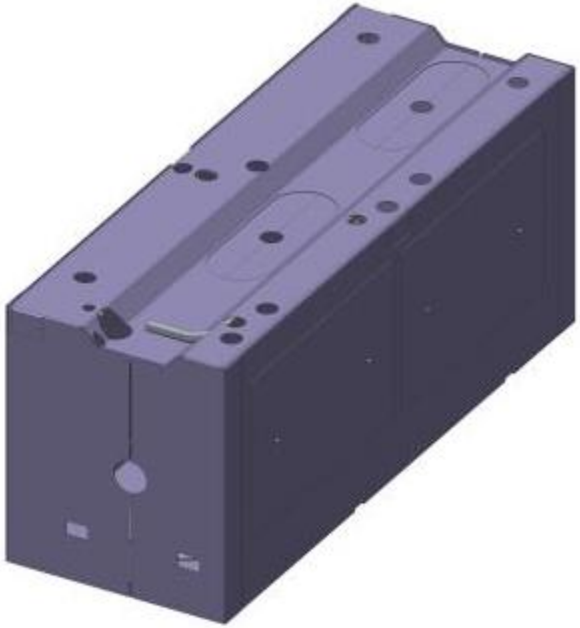
Connection Schematic
Skeleton, **Panels**



Thermal Shield Skeleton
U panel hidden for clarity

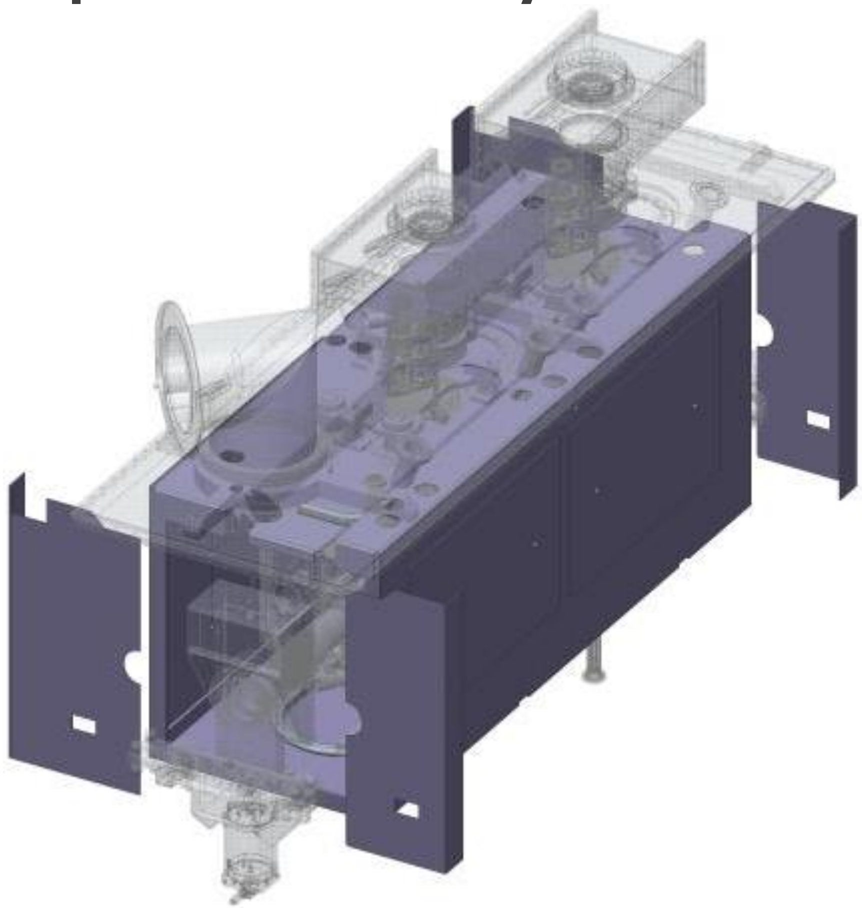
Shield section consisting of skeleton (cooling circuit + frame) and U panel is assembled form underneath or end
Cooling pipe connections made
Cooling circuit to be optimised

Configuration – End Cap Assembly



Material Proposal:
- Skeleton AL 6061-T6
- Panels AL 1050 or 1100 – 2mm thick

Design Features:
- Pipes and panels pre-welded
- Minimal fastener connections (6 edges)
- Minimal conduction cooling



End Caps Complete Assembly

Panel & Frame Connections

Permanent

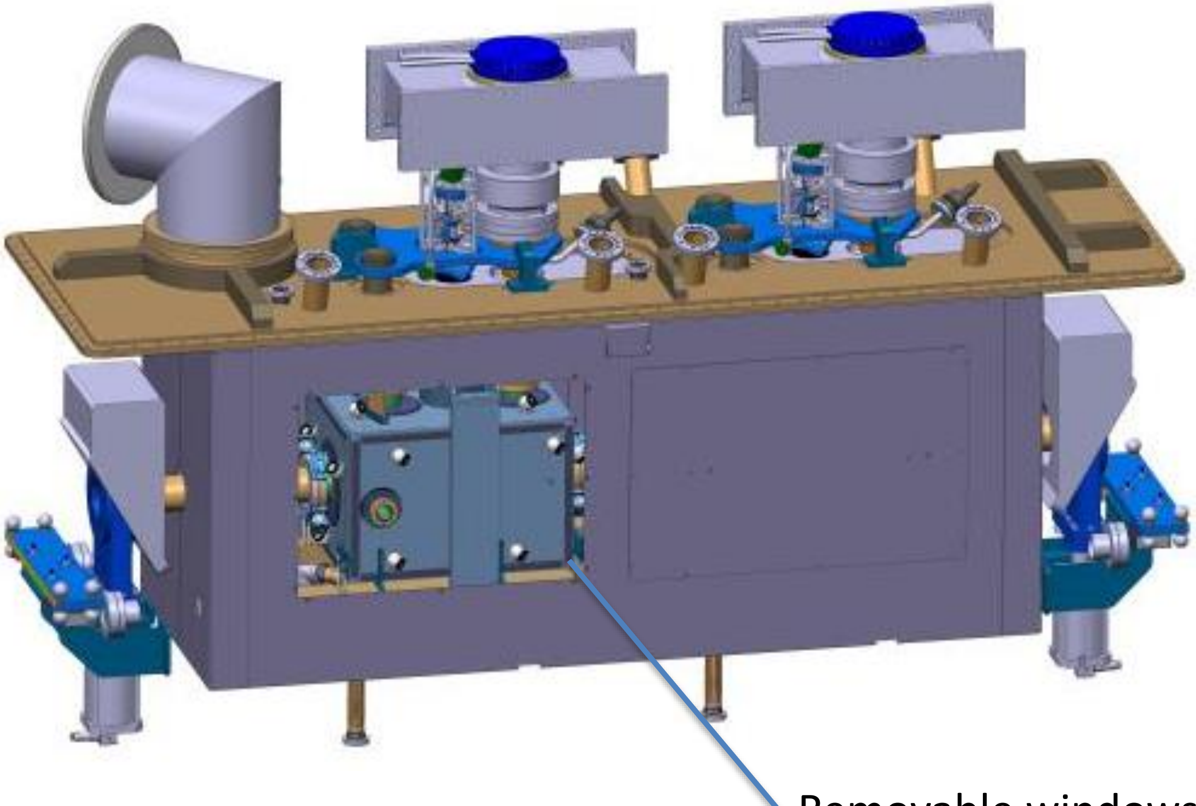
- Rivets
- Weld
- Braze/solder

Non-Permanent

- Screws
  - Bushes
  - Inserts
  - Washers???

Criteria:

- Pressure & Contact Conductance
- Access requirements for inspection & maintenance
- Cost (components & assembly time)



Removable windows

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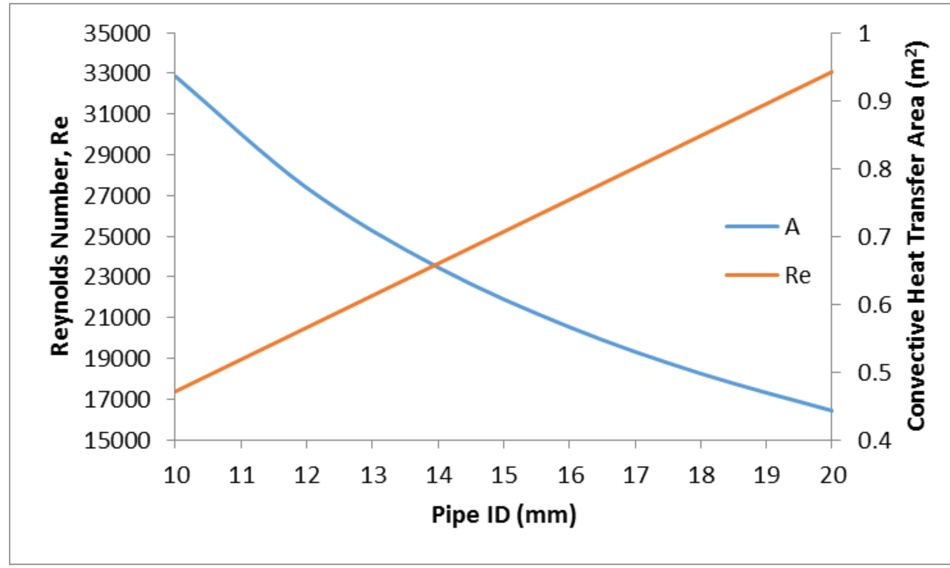
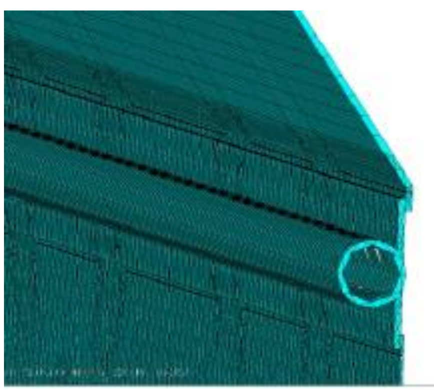
Pipes & Cooling

- Global contraflow circuit to limit conduction cooling requirement
- Pressure Specification: Up to 12 bar
- Suggested ID: 15 mm
- Cooling circuit to optimised for homogenous cool-down to minimise thermal stress
- Pipe pre welded to panels - weld strategy TBD

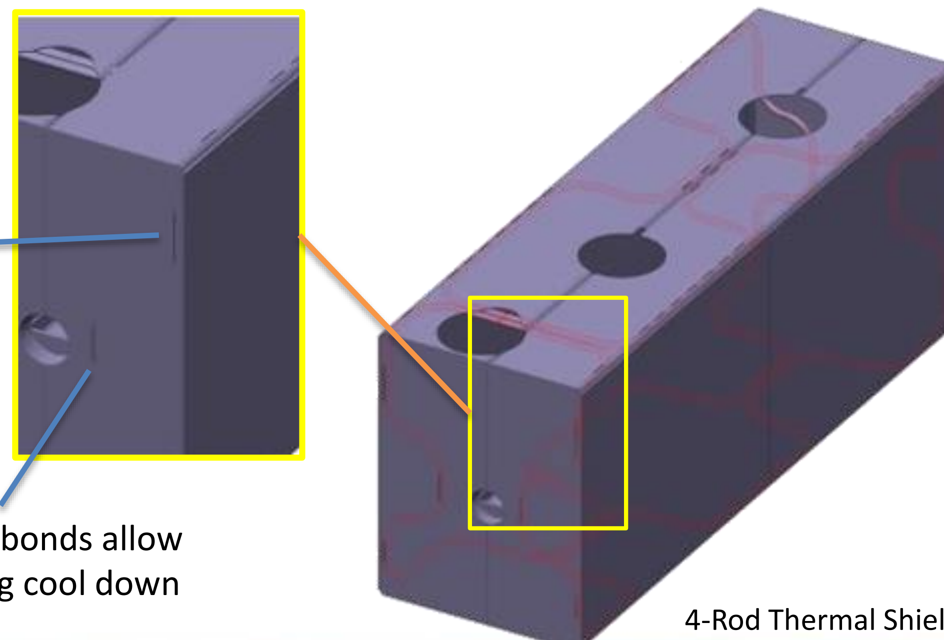
Optimal Pipe ID for convective heat transfer (*Nu* & *A*) and pressure loss for a given flow rate $Nu = 0.026Re^{0.8}Pr^{0.4}$





TTF Shield Pipe - Ω profile
With finger welds

Panel slots allow external bonding



Longitudinal bonds allow flexure during cool down

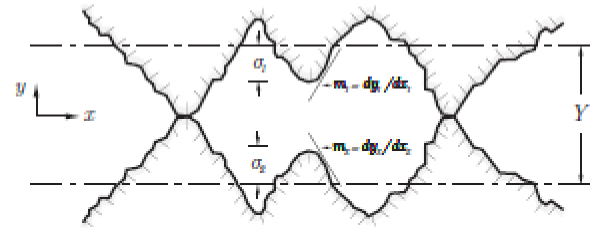
4-Rod Thermal Shield

Thermal Contact Conductance

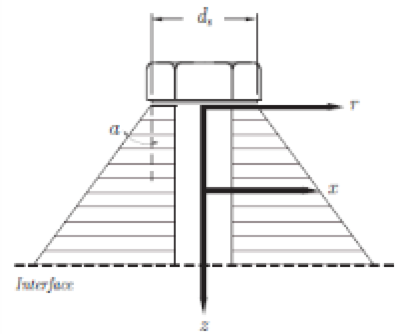
Influencing factors include:

- **Finish** - surface roughness (Ra), flatness deviation (FD)
- **Contact Pressure**
  - Number of fasteners / spacing
  - Fastener Torque
- Surface hardness (Hc) or yield strength (SY) of the contacting materials
- Interstitial material, such as Indium foil, placed between the two surfaces

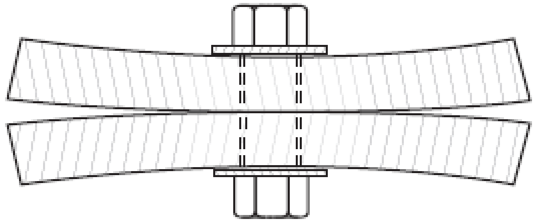
- *Thermal Cycling - Improves interface but reduces fastener torque (pressure)*



Two contacting surfaces, showing surface slope m and the RMS surface roughness



Pressure cone model



Contact of bolted joint

Thermal Contact Conductance in Bolted Joints , A Hasselstrom 2012

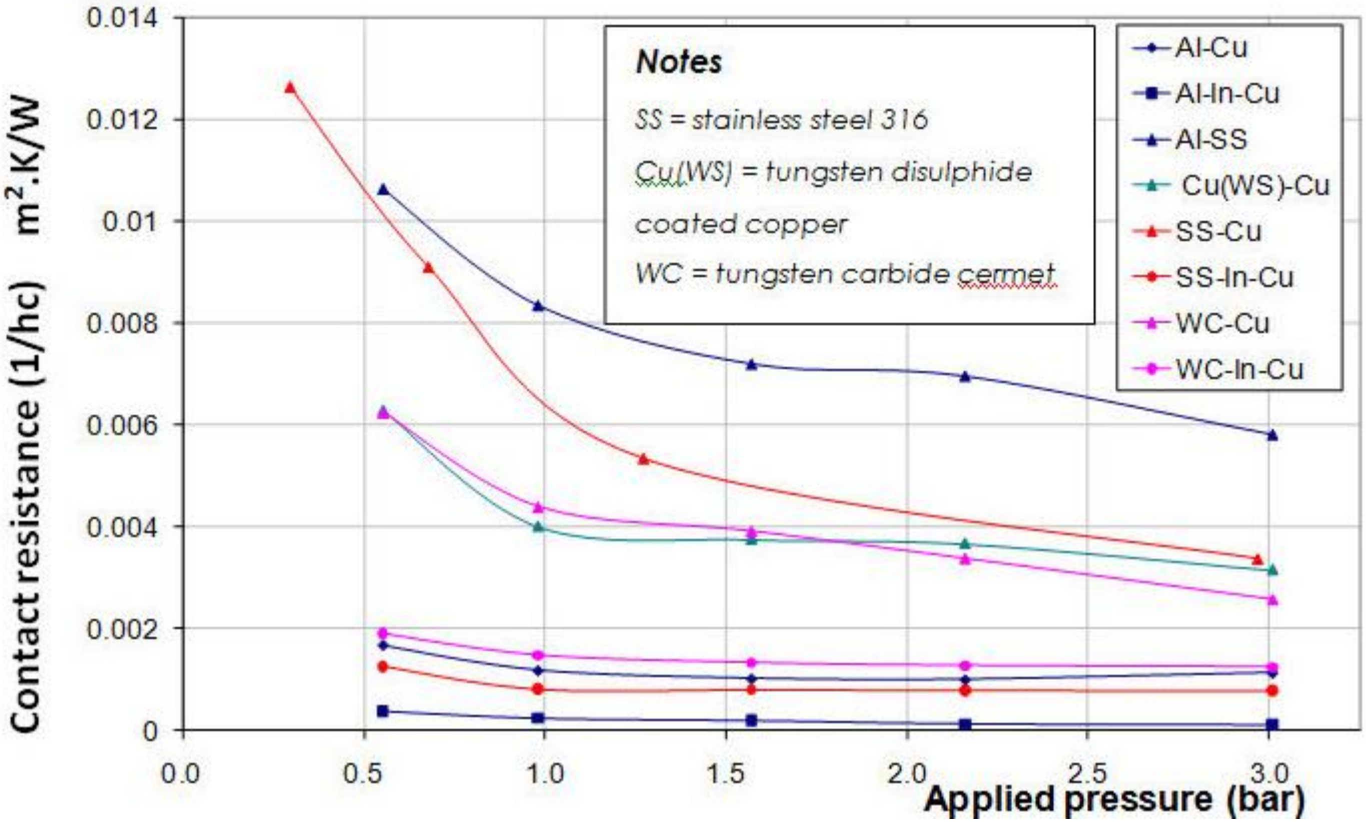
Thermal Contact Conductance

*The accordance of the **analytical models** to the empirically achieved results of thermal contact conductance in the cylinder joint experiment **varied strongly** among the models. The model of Cooper et al. showed the highest overall accordance to experimental results.*

*Depending on application, a certain model can be several hundred percent off, in estimation of true thermal contact conductance. Therefore, it is **strongly advised to perform practical experiments** for each specific application, to avoid significant errors due to arbitrary choice of theoretical model.*

Thermal Contact Conductance in Bolted Joints A Hasselstrom , U. Nilsson 2012

Thermal Contact Conductance



125 W/m2K

167 W/m2K

250 W/m2K

500 W/m2K

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Thermal Contact Resistance Measurements for indirectly cooled SR Optics, B Fell & K Fayz, Daresbury Laboratory 2013

Thermal Contact Conductance Analysis

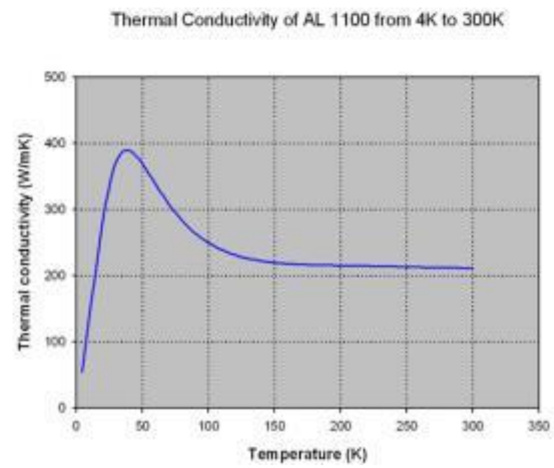
Steady State Thermal Analysis

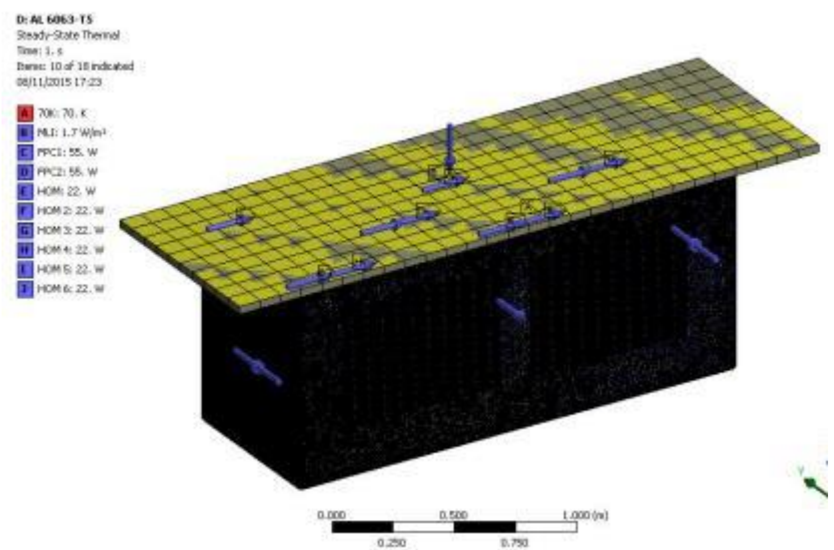
- Comparison of 3 Thermal Contact Conductance Values:
  - 100 W/m^2K – Unlikely Worst Case
  - 200 W/m^2K – Reasonable
  - 300 W/m^2K – Good

- Simplified analysis with panel parts only
- Top plate cooling only & additional connections for conservative results
- Accurate heat loads
- Al1100 Panels

- To observe conductance cooling of (un-cooled) bottom plate

For Contact Conductance comparison only - results do not indicate actual shield temperatures.





Conductivity data from http://www.cryogenics.nist.gov/

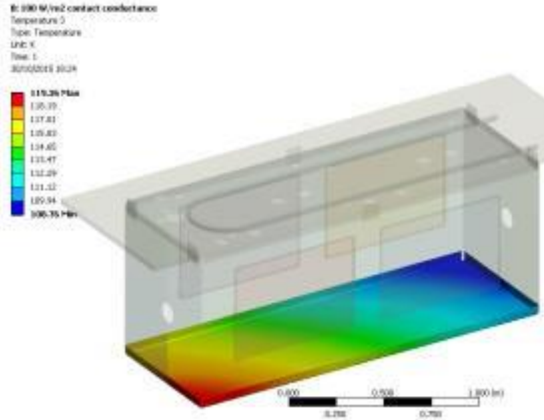
Thermal Contact Conductance Analysis

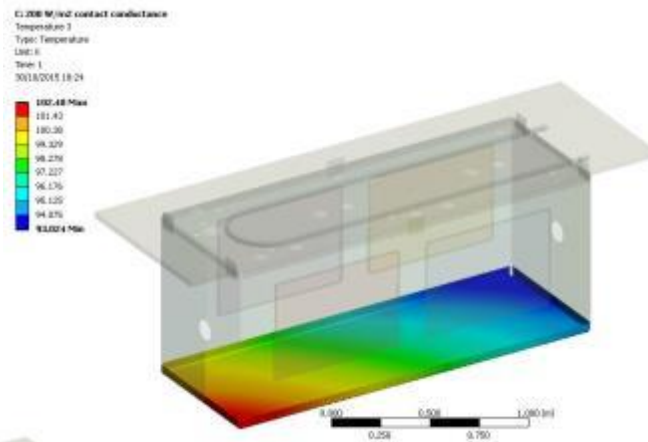
Results

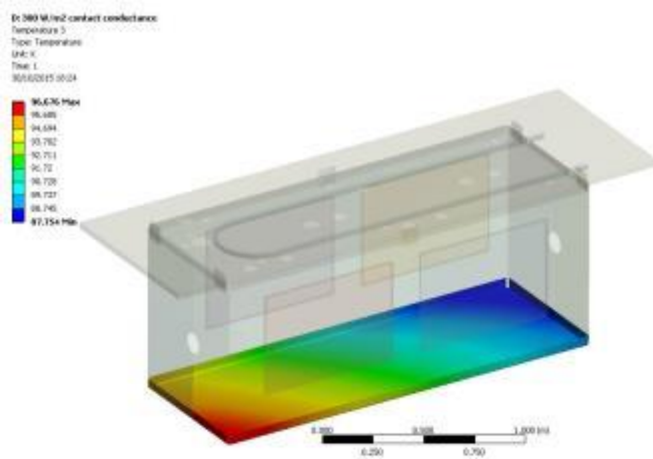
TCC (W/m^2K)	Max T (K)	Min T (K)
100	*119.4*	*108.8*
200	*102.4*	*93.0*
300	*96.7*	*87.8*
Ideal	*84.4*	*77.2*

Conclusion

- Results seem high due to very conservative thermal path
- TCC >200 W/m^2K achievable without ‘filler’ material and should give good results in optimally cooled shield.







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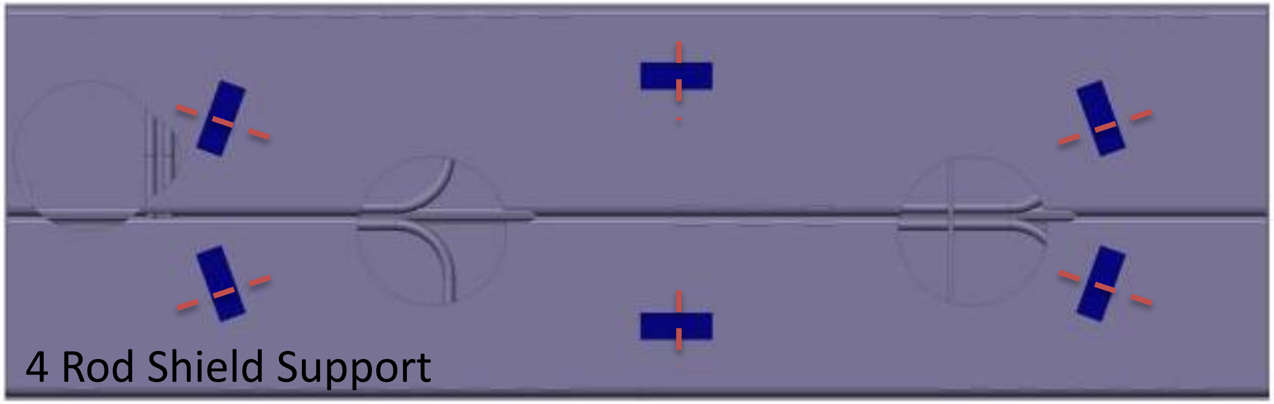
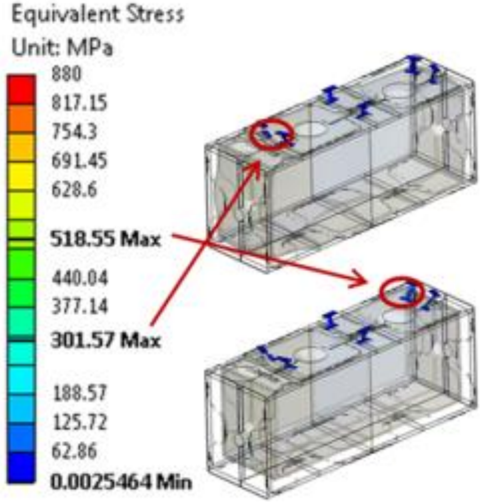
Thermal Stress

- All Aluminium shield eliminates stress sue to differential expansion
- Thermal gradient stress still applicable
  - Minimised by slow cool down and global contraflow cooling circuit
- Flexure support mounts compensate thermal stress between cold shield and warm OVC
  - Blades to be optimised, 1-2mm thickness depending on final length, heat leak ≤ 1 W per blade
- Common design features such as slots and bends for flexibility to be utilized where possible.





Thermal Shields Summary

- Material Selection
  - AL 6061 Skeleton & Pipes
  - AL 1050/11000 panels
- Configuration
  - Split skeleton-panel assembly to suit top loaded configuration, minimal fastener connections (6 edges)
- Connections
  - Pre-welded pipe-panels, fastened edges to ensure good TCC and allow removal
- Thermal Stress
  - Optimise cooling circuit for homogeneity
  - Preferably slow cool-down
  - Use features such as blades, slots & bends for flexibility

To be analysed in transient cool-down with fluid gradient

High Luminosity LHC

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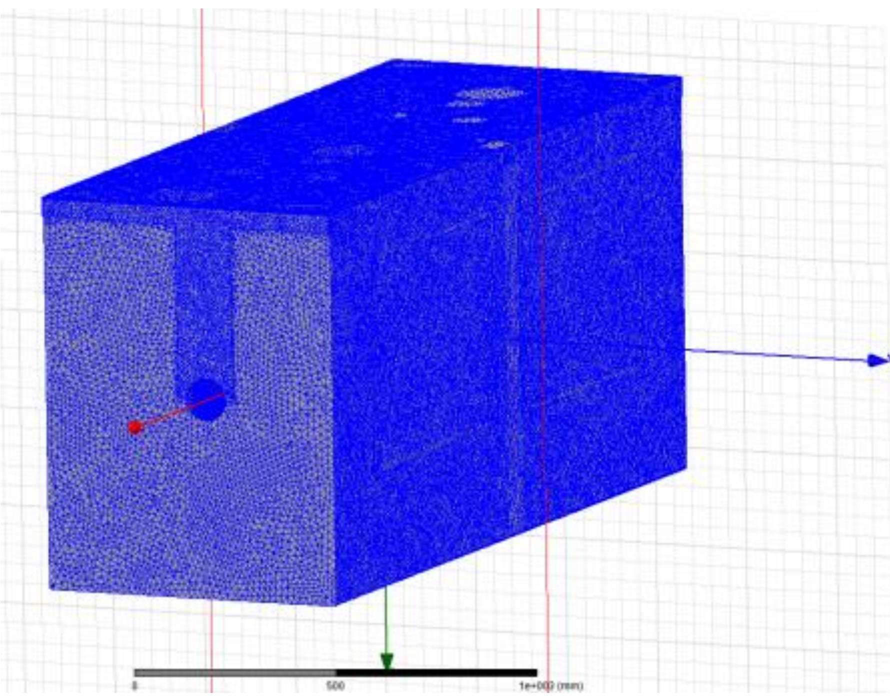
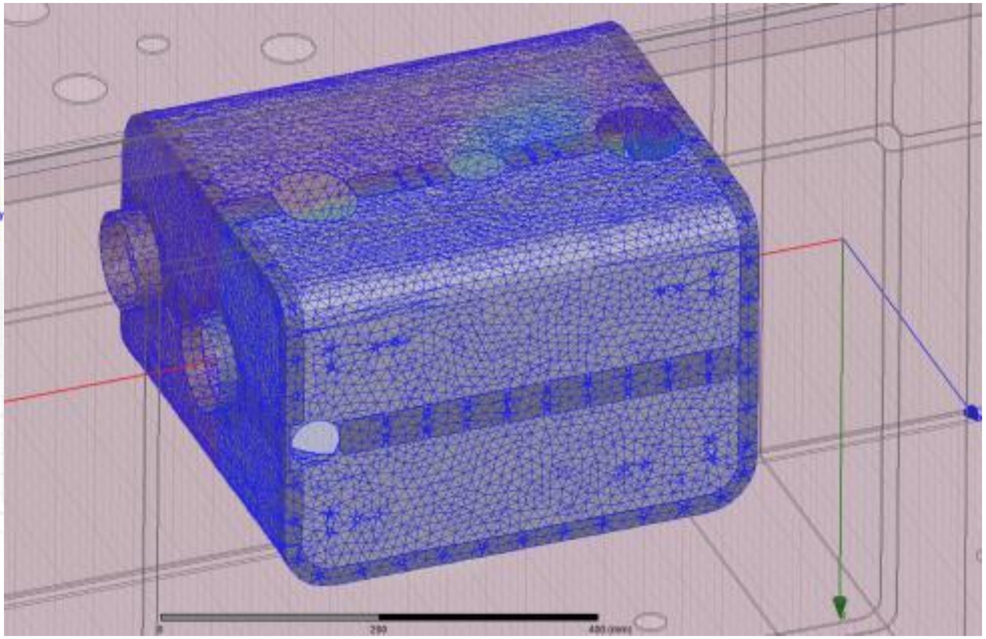
Mesh

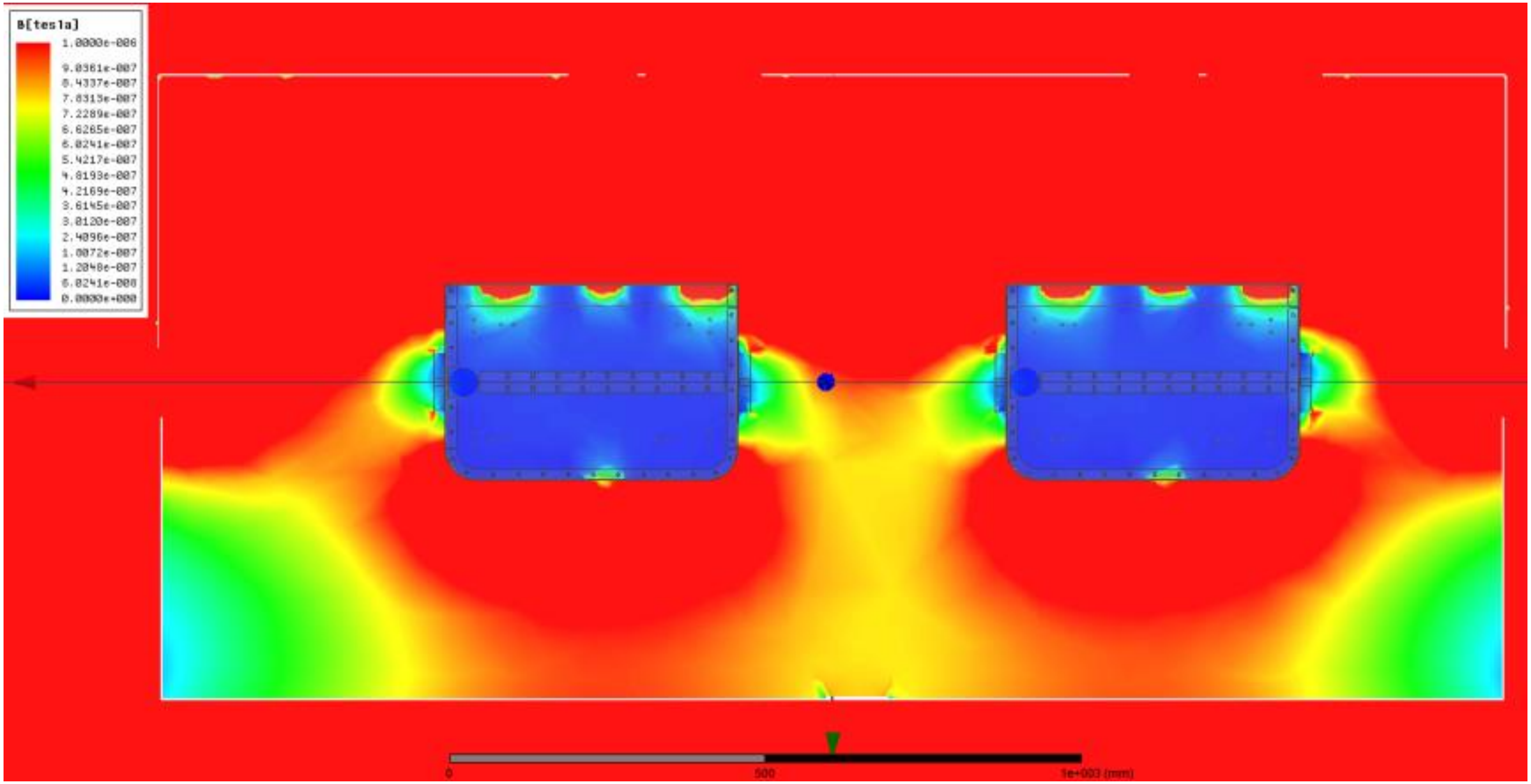
- Adaptive mesh as fine as possible (in the limits of computational power): ~1.5e6 elements with convergence analysis





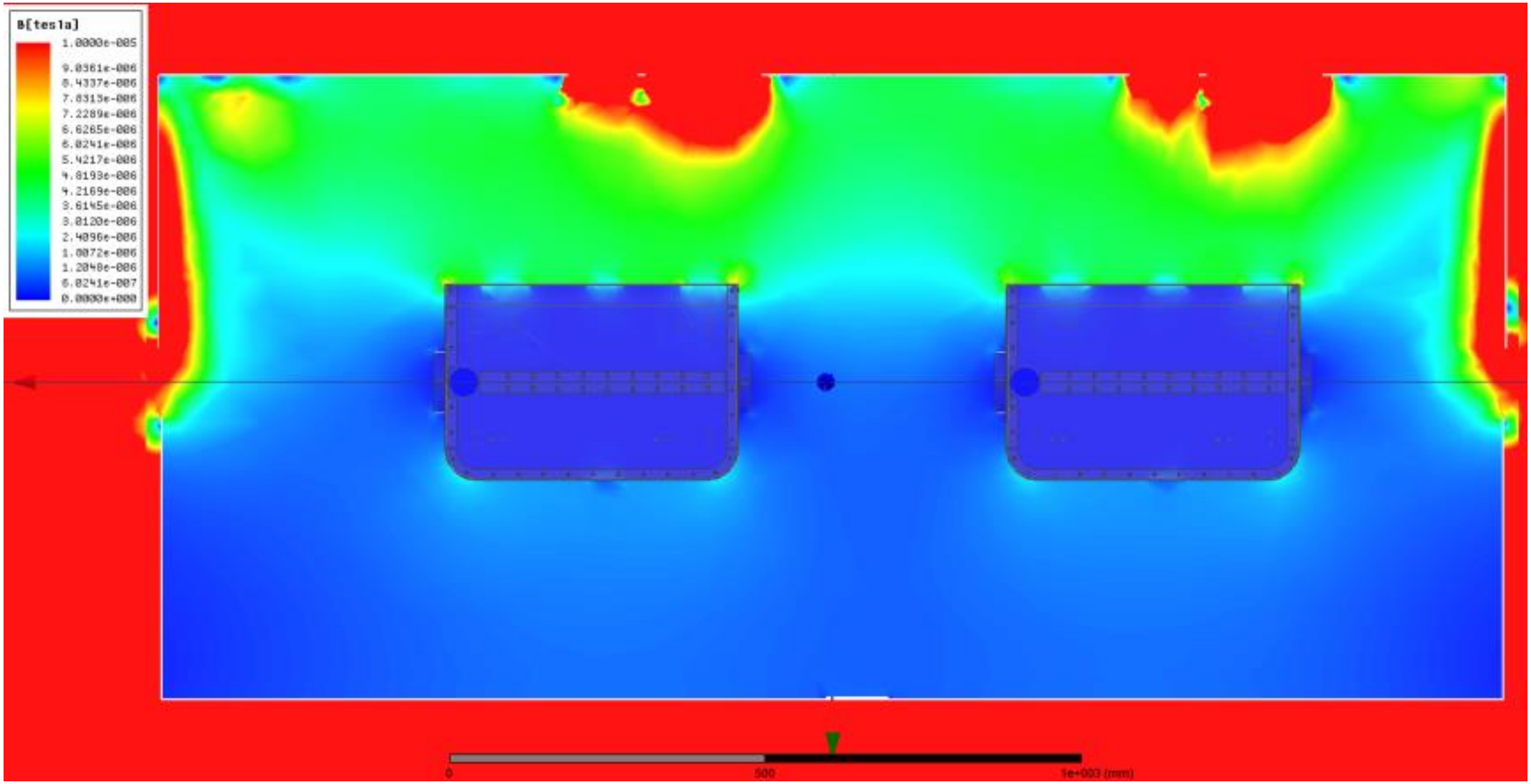
60 µT vertical field

Red > 1 µT



60 µT vertical field

Red > 10 µT



Loads and Boundary Conditions

Loads in *W*	DQW		RFD	
	2K	70K	2K	70K
Static				
Radiation	~~3~~	~~35*~~	~~3~~	~~35*~~
CWT	0.2	2	0.2	2
Supports	0.8	30	0.8	30
FPC	4	100	4	100
Instrumentation	1	0	1	0
HOM/Pickup	2.5	10	1.7	10
Tuner	0.3	10	0.3	10
Total static	11.8	187	11	187
Dynamic				
Cavity	6	0	6	0
FPC	5.6	10	5.6	20
HOM/Pickup	7.2	120	5.5	80
Beam	0.5	0	0.5	0
Total Dynamic	19.3	130	17.6	100
TOTAL	28.2	282	25.6	252

*see MLI

Aluminium Panels – Grade Comparison

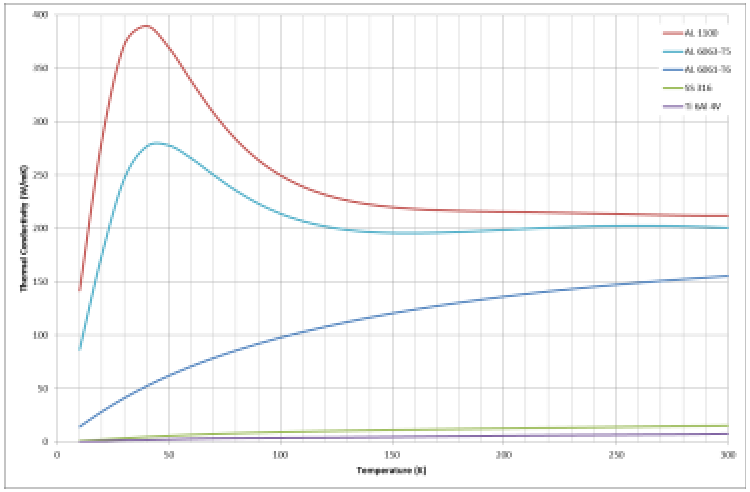
Steady State Thermal Analysis

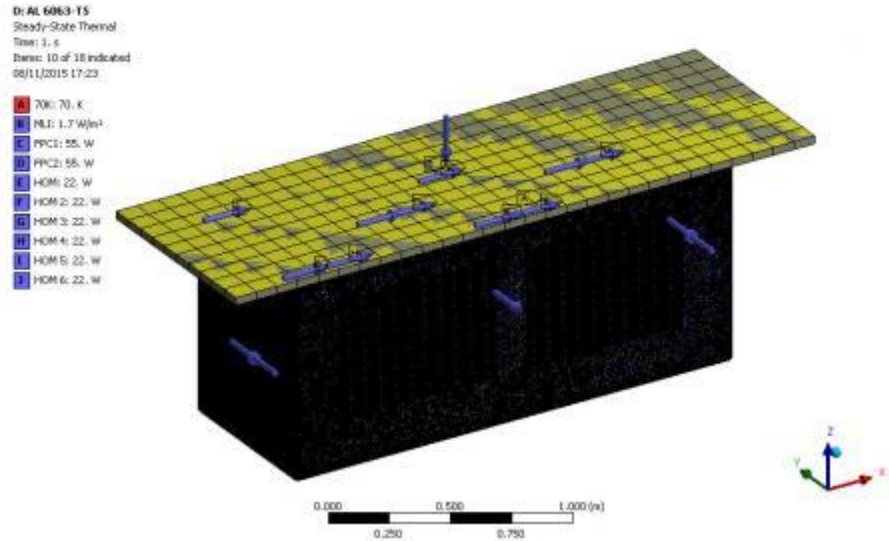
- Comparison of 3 Aluminium grades:
  - 1100 – Pure Aluminium
  - 6063 - good mechanical properties and weldable
  - 6061
- Conductivity, Formability & Weldability are key characteristics for material selection

- Simplified analysis with panel parts only
- Top plate cooling only
- Accurate heat loads
- Assuming perfect contact connections

- To observe conductance cooling of (un-cooled) bottom plate

*For material comparison only - results do not indicate actual shield temperatures



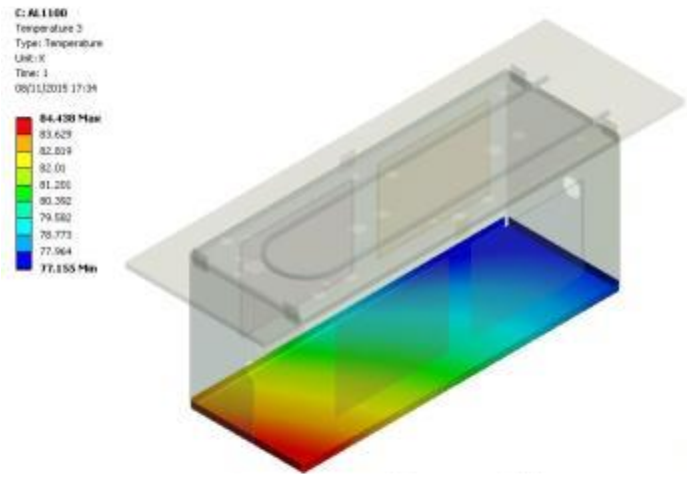


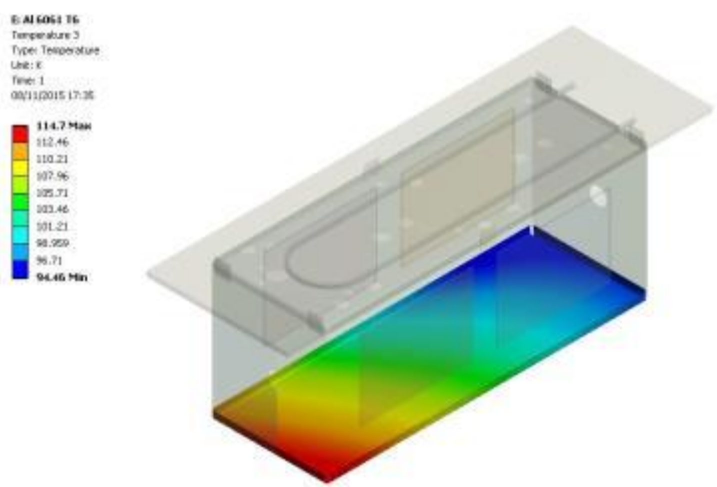
Conductivity data from http://www.cryogenics.nist.gov/

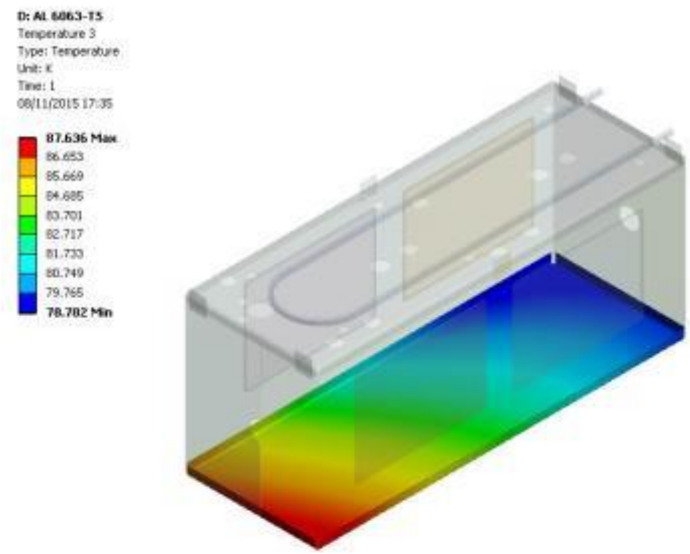
Aluminium Panels – Grade Comparison

Results

Grade	Max T (K)	Min T (K)
Al 1100	*84.4*	*77.2*
Al 6063	*87.6*	*78.8*
Al 6061	*114.7*	*94.5*







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