Calculations and FEA simulations for MICE/Muool Coupling Magnet Cryostat Design

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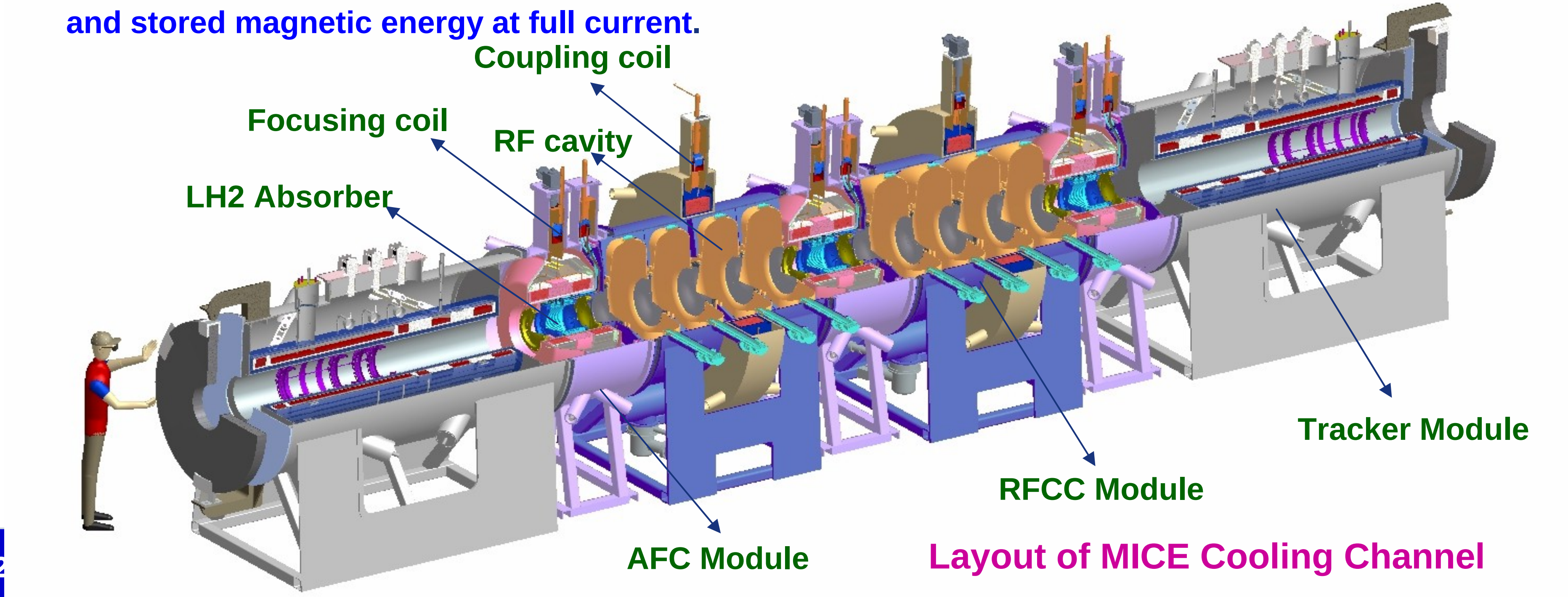
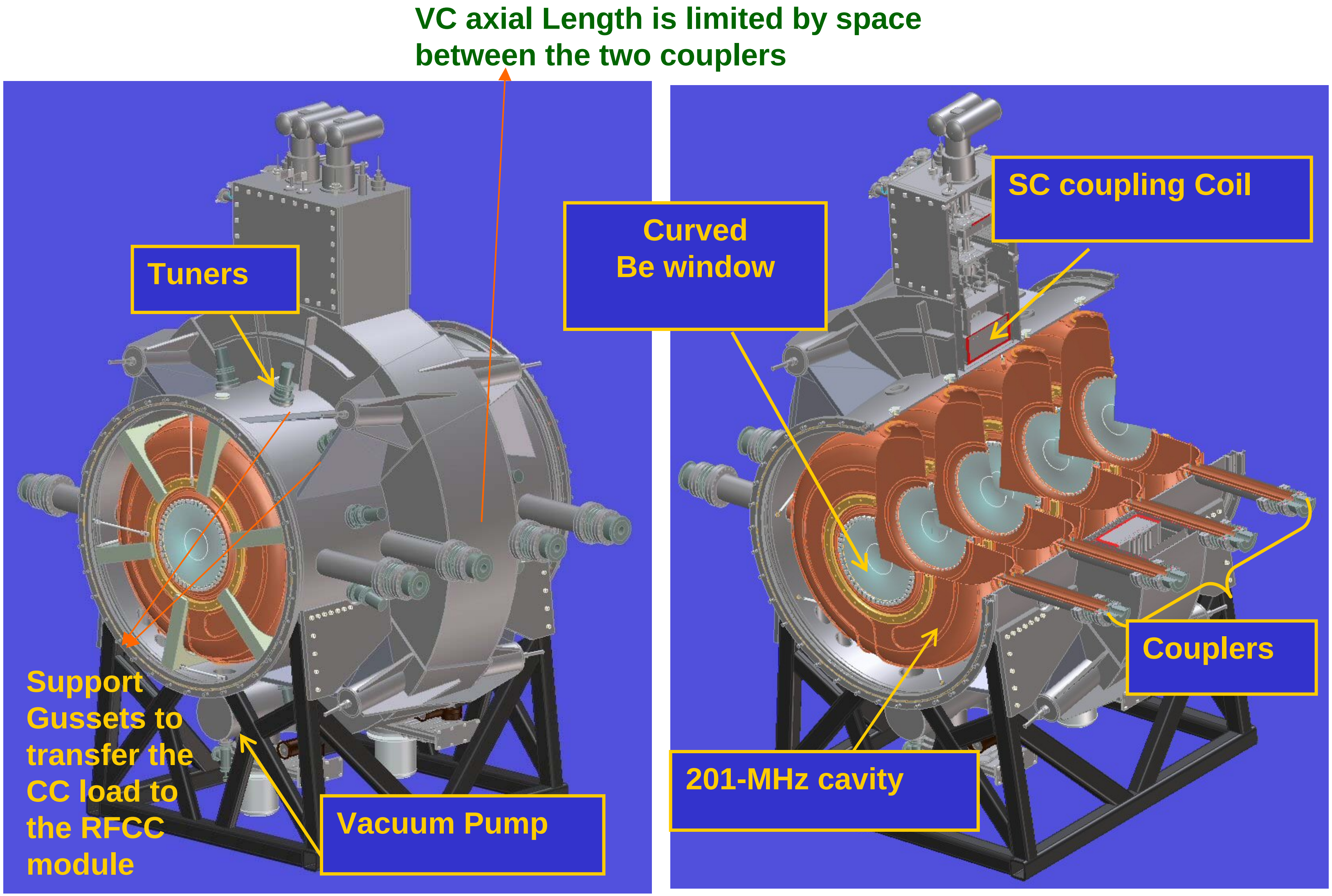
Brief Introduction to Coupling Magnet

Muon Ionization Cooling Experiment (MICE)

- **A demonstration of muon cooling in a configuration of superconducting solenoids and absorbers that may be useful for a neutrino factory. Ionization cooling occurs when there is a net loss of transverse muon momentum when the muons pass through the absorber material in the AFC module. The longitudinal momentum of muon beam is then recovered by accelerating the beam with the adjacent four cell 201.25 MHz RF cavity that is in a 2.6T magnetic field generated by the coupling magnet.**
- **A function of the coupling coil magnetic field is to produce a low muon beam beta function in order to keep the beam from expanding beyond the edge of the RF cavity thin windows.**
- **The coupling magnet is the largest of the three types of magnets in MICE both in terms of diameter and stored magnetic energy at full current.**



Layout of MICE Cooling Channel


VC axial Length is limited by space between the two couplers
Tuners
Curved Be window
SC coupling Coil
Couplers
201-MHz cavity
Vacuum Pump
Support Gussets to transfer the CC load to the RFCC module

RFCC module

The engineering design were carried out mainly according to the "A Technical Agreement on the MICE and MuCool Coupling Solenoid Magnet Fabrication, Assembly, Test and Shipping" issued in September, 2007 in collaboration with Lawrence Berkeley National Laboratory. The design principle:

- **A coupling magnet assembly consists of a single coil that fits into a cryostat vacuum vessel.**
- **The coupling magnet is designed to operate in a channel where the fields from other magnets can interact with the magnet.**
- **The size and shape of the coupling magnet is determined by the RF cavities.** The size diameter of the coupling magnet is determined by the diameter of the 201.25 MHz RF cavities and the vacuum vessel that must go around the cavities. The length of the coupling magnet is determined by the space needed for the cavity RF couplers and the cavity tuners.
- **The coupling magnet is to be cooled by using cryocoolers that produce up to 1.5 W at 4.2 K each.** The connection of the cooler to the magnet is designed to maximize the coupling magnet operating temperature margin.

- **The coupling solenoid will be powered by using a single 300 A, 0-20V unipolar power supply** that is connected to the magnet **through a single pair of binary leads** that are designed to carry a maximum current of 250 A. The high temperature superconducting (HTS) leads are to be applied between the first stage of the cooler and the magnet in order to reduce the heat leak, which operates at around 4.2 K.
- **The coupling magnet is to be passively protected by cold diodes and resistors across sections of coil and by quench back from the 6061 aluminum mandrel.** Sub–division of the coupling magnet using cold diodes and resistors will result in lower quench voltages and a lower hot spot temperature.
- **The coupling magnet cold mass support is to be a self-centering support system consisting of eight tension bands so that the magnet center does not change as the magnet is cooled down.** The support system is designed to carry a sustained **longitudinal force up to 500 kN (50 tons) in either direction** during the anticipated operating and failure modes of the experiment and **to withstand a 2.5g shipping load** at any direction during warm transportation.

Basic design parameters for coupling coil (updated)

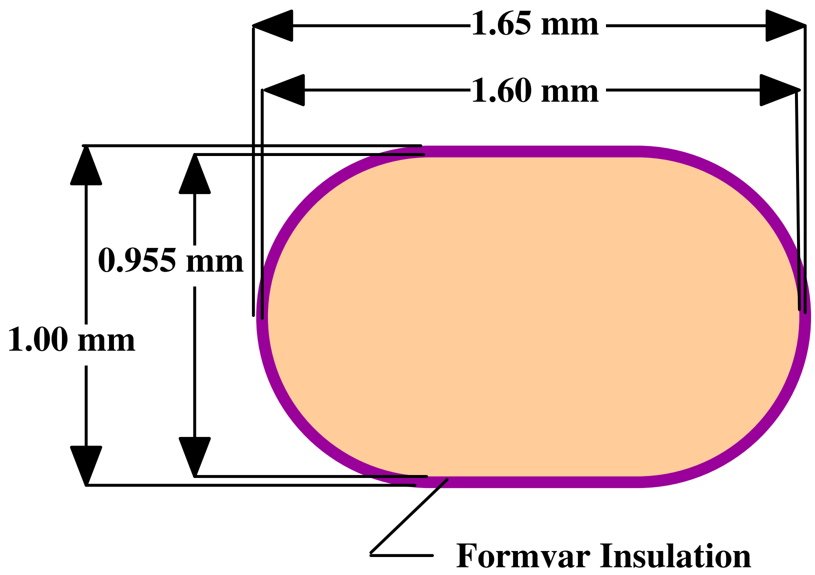
	p = 240 MeV/c and *b*= 420 mm		p = 200 MeV/c and *b*= 400 mm	
Parameter	Flip	Non-flip	Flip	Non-flip
Coil Length (mm)	281		281	
Coil Inner Radius (mm)	750.5		750.5	
Coil Thickness (mm)	104		104	
Number of Layers	96		96	
No. Turns per Layer	166		166	
Magnet Self Inductance (H)	595.590		595.590	
Magnet J (A mm^{-2})*	114.6	108.1	95.5	90.1
Magnet Current (A)*	210.1	198.2	175.1	165.2
Magnet Stored Energy (MJ)**	13.145	11.698	9.130	8.127
Peak Induction in Coil (T)*	7.477	7.054	6.231	5.879
Coil Temperature Margin (K)	~0.77	~1.1	~1.6	~1.8

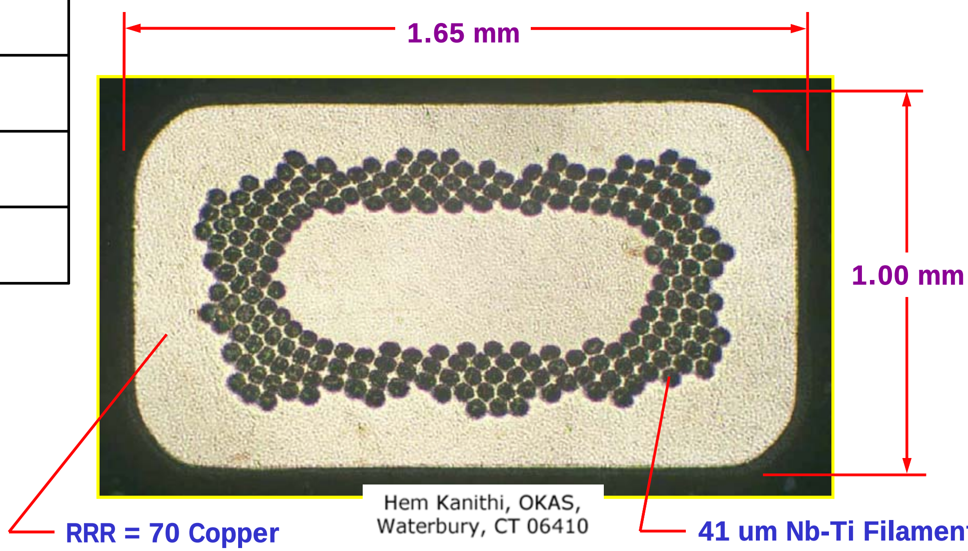
- Two modes due to the polarity change of two focusing coils in the AFC module: Gradient mode (flip mode) and Solenoid mode (non-flip mode).
- For each mode, two cases: at standard case with p = 200 MeV/c (average momentum of the muons traveling along the channel) and beta = 420 mm (beam beta at the center of the absorbers) or at the worse case with p = 240 MeV/c and beta = 420 mm.

Superconductors

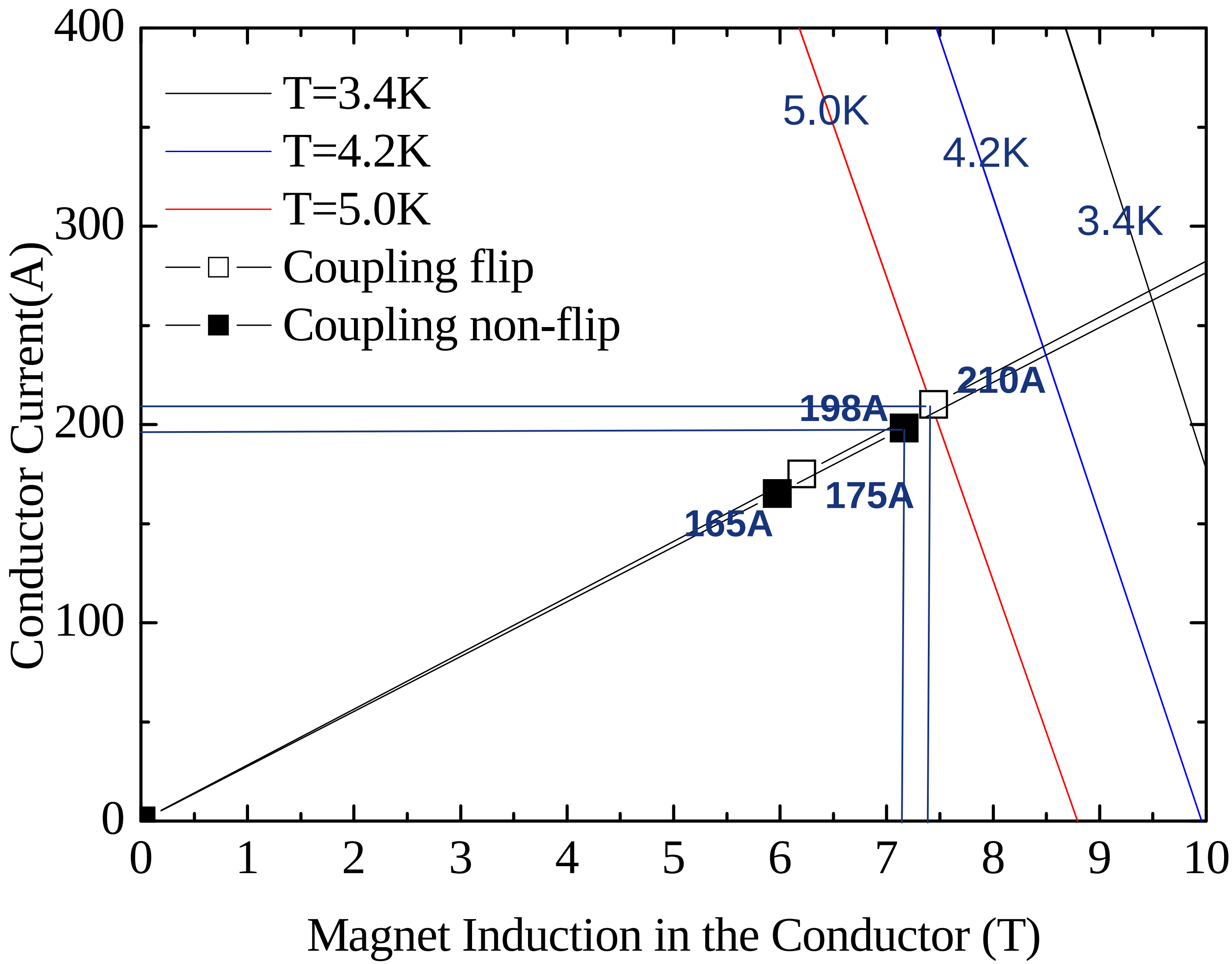
Insulated dimension	1.00mm x 1.65mm
Cu to S/C Ratio	4.0 ± 0.5
Cu RRR	>70
No. Filaments	222
Filament Diameter	~41 μm
Filament twist Pitch	19 mm ± 6
Ic(4.2K, 5T)	> 760 A
n	> 35 @ 5T
Length	~260 km

Parameters for superconductors

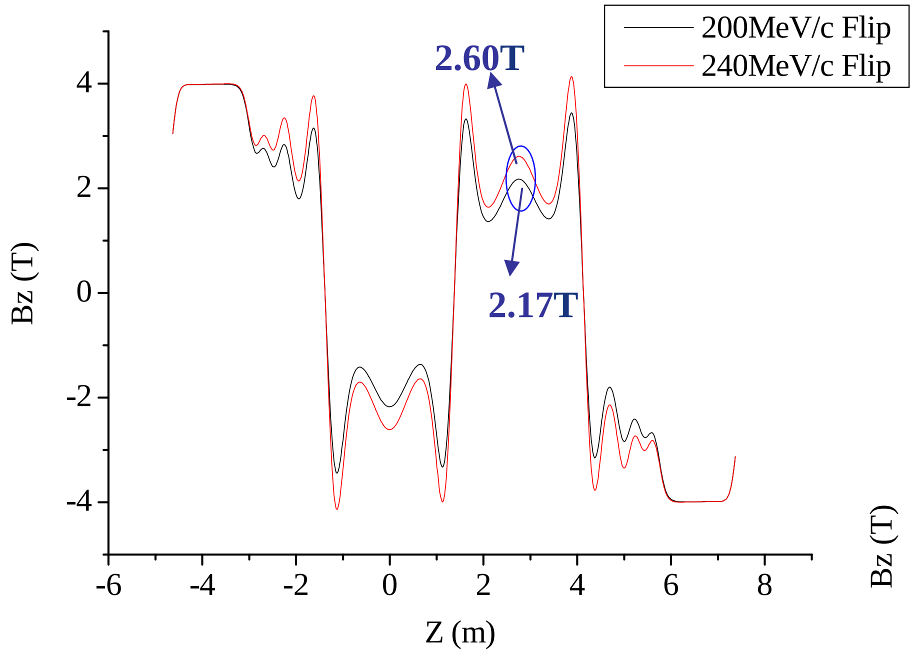


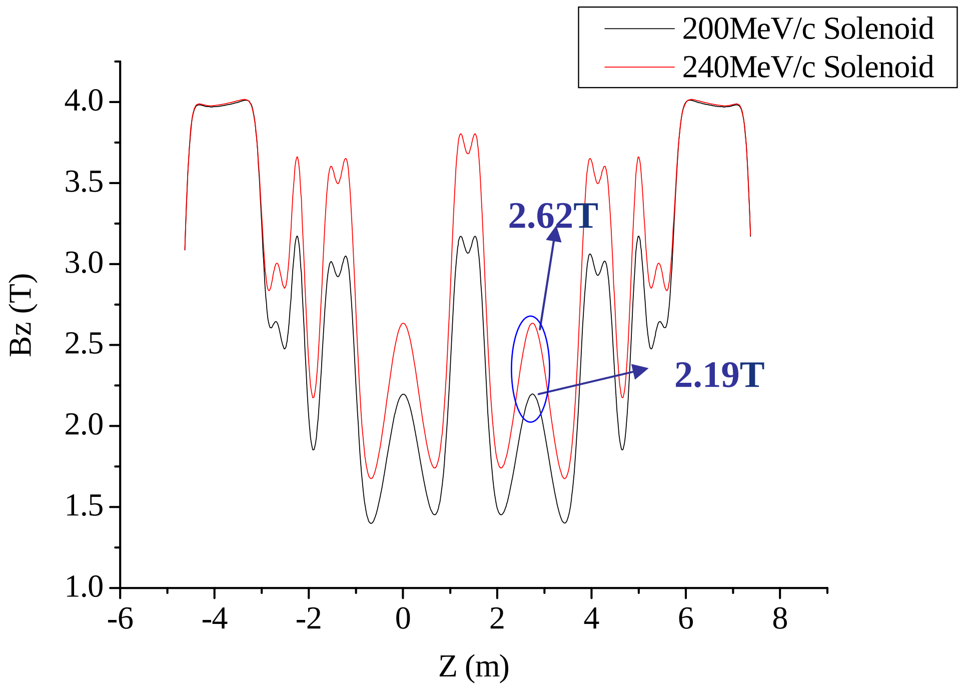


Load line of coils (updated)

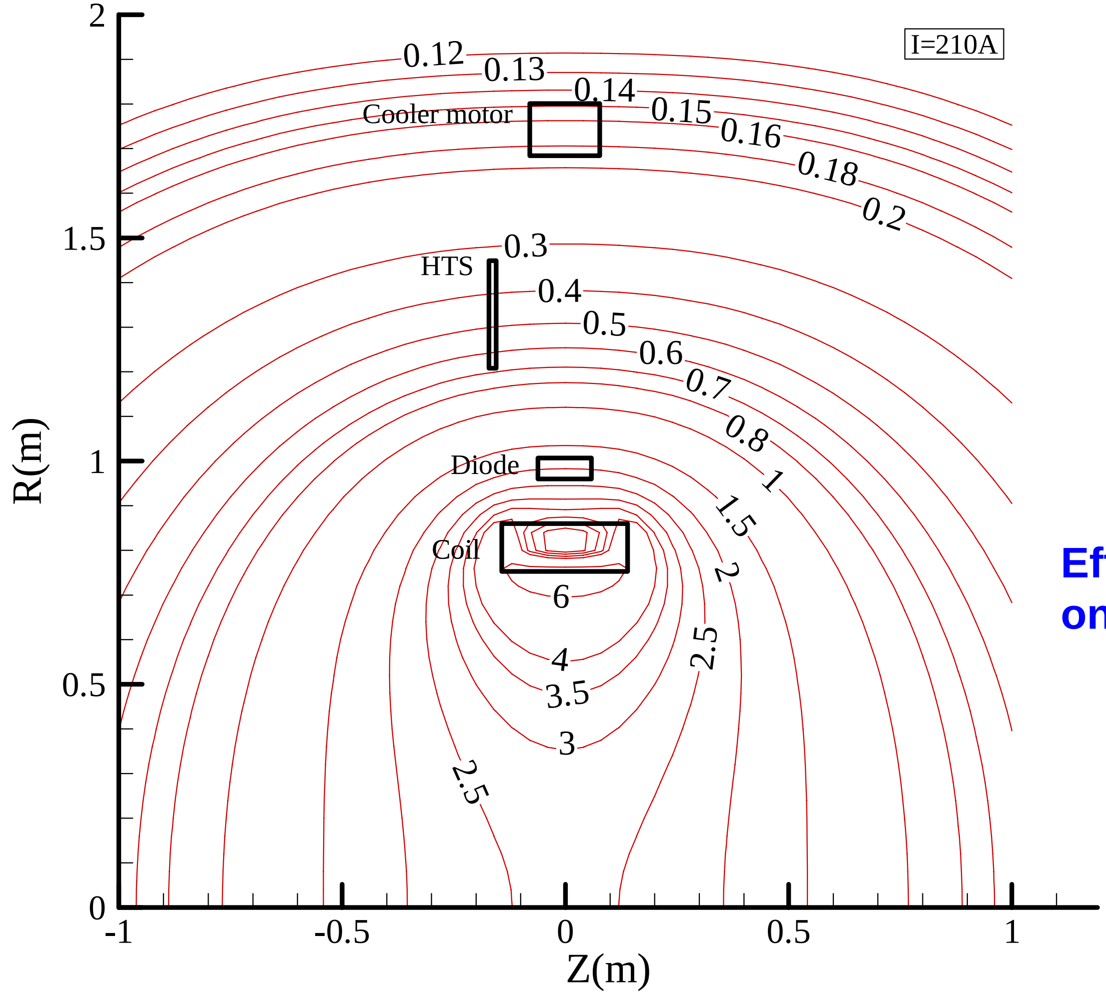


Magnetic fields





Magnetic field on the axis of the MICE cooling channel



Magnet field around the coupling coil in the channel

- **Cold diodes is in a field from 1.5 to 2.5T**
- **The warm end of HTS leads is in a field from 0.3T to 0.4T and the cold end is 0.6 to 0.7T,**
- **The valve motor of the cooler is in a field from 0.15 to 0.20T which should be shielded, and the PTR cooler second stage cold head is in a field from 0.5 to 0.6T.**

Effects of the other coils in the channel on magnetic field of coupling coil:

- **The other coils in the channel can increase or decrease the magnitude of magnetic field generated by only coupling coil and the effect is less than 1.0 percent at the peak field point and the minimum surface field point.**
- **The effects of the other coils on the magnetic field of the coupling coil are small so that they can be neglected in design analysis.**

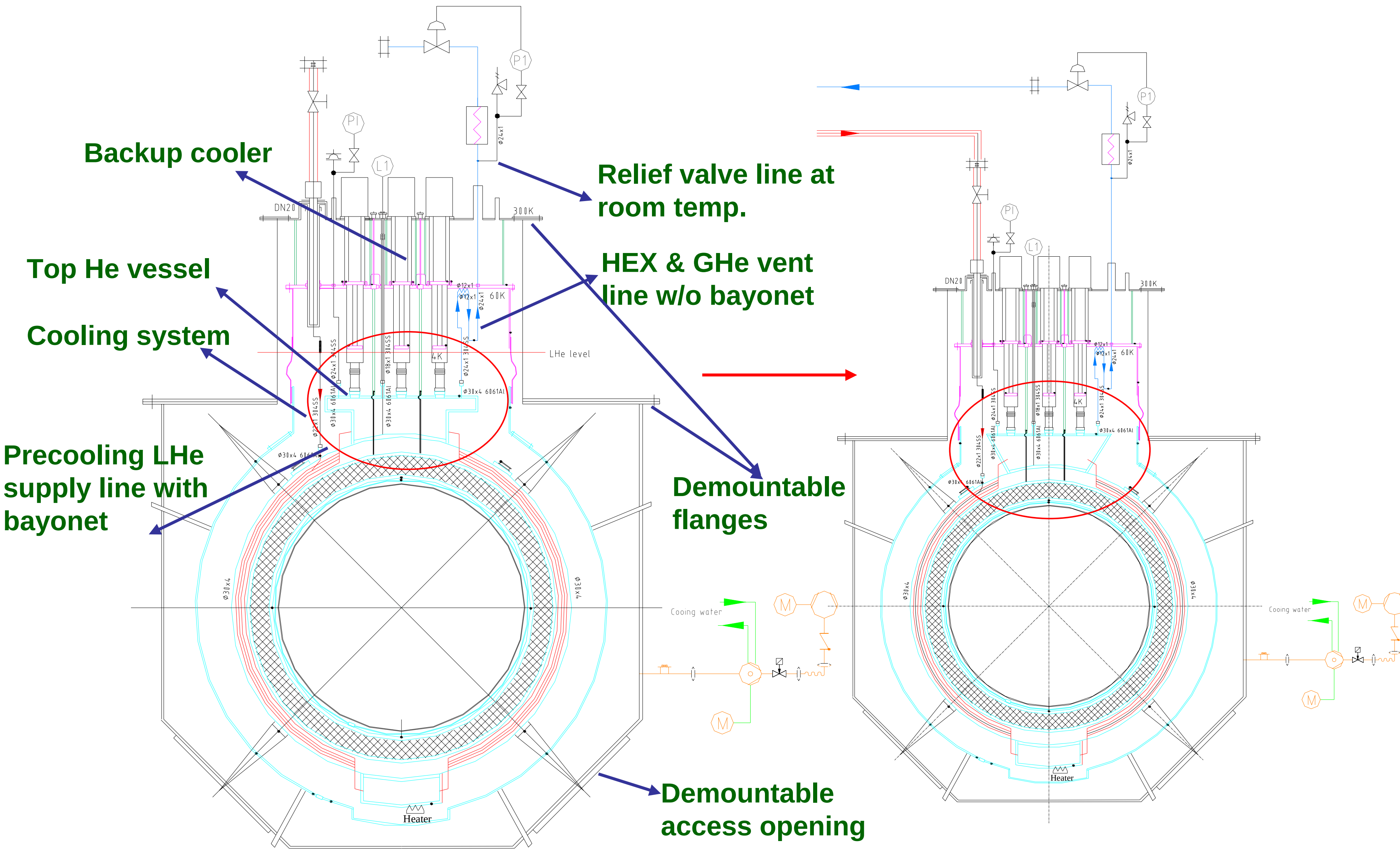
Technical Requirement and Current Design for Coupling Magnet Cryostat

Inner diameter of inner vacuum vessel (mm)	1389±3 (1388.8)
Length of vacuum vessel (mm)	489±2 (501, axial length of lower vessel body)
Inner radius of coil (mm)	750 (750.5)
Coil to ground insulation (mm)	≥1 (1.626)
Thickness of coil (mm)	102.5 (104~106)
Length of coil (mm)	285 (281)
Layers of coil	96
Turns per layer	166±3 (166)
Space between 4.2K cold mass and heat shields (mm)	>5 (min. 10mm between inner shield and coil case locally)
Space between vacuum vessel and heat shields (mm)	>20 (min. 12.5mm around coupler cut-aways)
ΔT between the coil and second-stage cold head	<0.2 K
Intercept temperature for the cold mass support	<70K (For upper 4 supports: ~72K, for lower 4, 75~77 K)
Temperature on the heat shield	<80K
Cooling capacity at the first-stage cold head	55W/60K，45W/50K
Cooling capacity at the second-stage cold head	1.5 W/4.2K
4.2K heat load along the cold mass support	<0.25W (0.478W according to support interception temp.)
Spring constant for the cold mass support	>2x10^8N-m-1
Radial force on the cold mass	<50kN
Longitudinal force on the cold mass	500kN

Design pressure for cooling tubing	20bar (290psig)
Design pressure for helium vessels	4bara (44psig)
Relief pressure for relief valves of cooling tubing	≤3bar (29psig)
Relief pressure for burst disc of cooling tubing	3.3bar (32psig)- 4bar (44psig)
Design outer pressure for vacuum chamber	1bar (15psig)
Design inner pressure for vacuum chamber	0.3bar (4.4psig)
Relief pressure for vacuum chamber	0.14bar (2psig)
Relief pressure for burst disc of vacuum chamber	0.3bar (4.4psig)
Copper leads (A)	optimized design current 220A, maximum operating current 250A
HTS leads	nominal 220A, 500A at 64K, 0.5T
Magnetic field around the warm end of HTS leads	≤0.5T, otherwise, shielding needed
Magnetic field around the cooler drive motor	<0.05T, otherwise, shielding needed

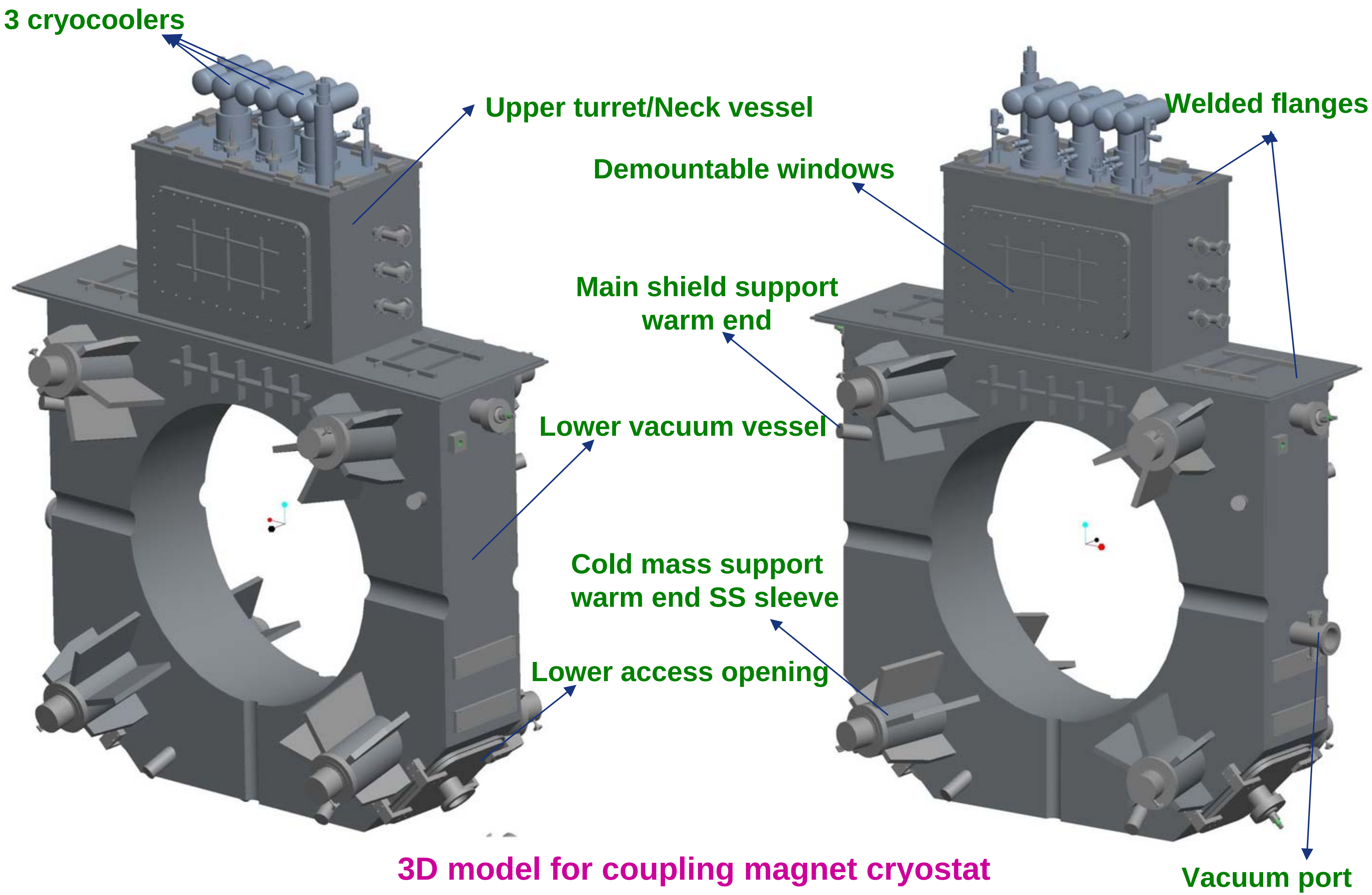
Coupling magnet assembly tolerance	Tolerance range
The longitudinal position of the cryostat center should be the same as the coil center	±0.5-1.0 mm
The coupling solenoid cold mass central axis shall be co-axial with the cryostat vacuum vessel axis	± 0.3-1.0 mm
The maximum allowable tilt of the cold mass axis (the magnetic axis) with respect to the axis of the warm bore tube	±0.057 to ±0.069 degree

MICE/MuCool Coupling Magnet Cryostat Engineering Design

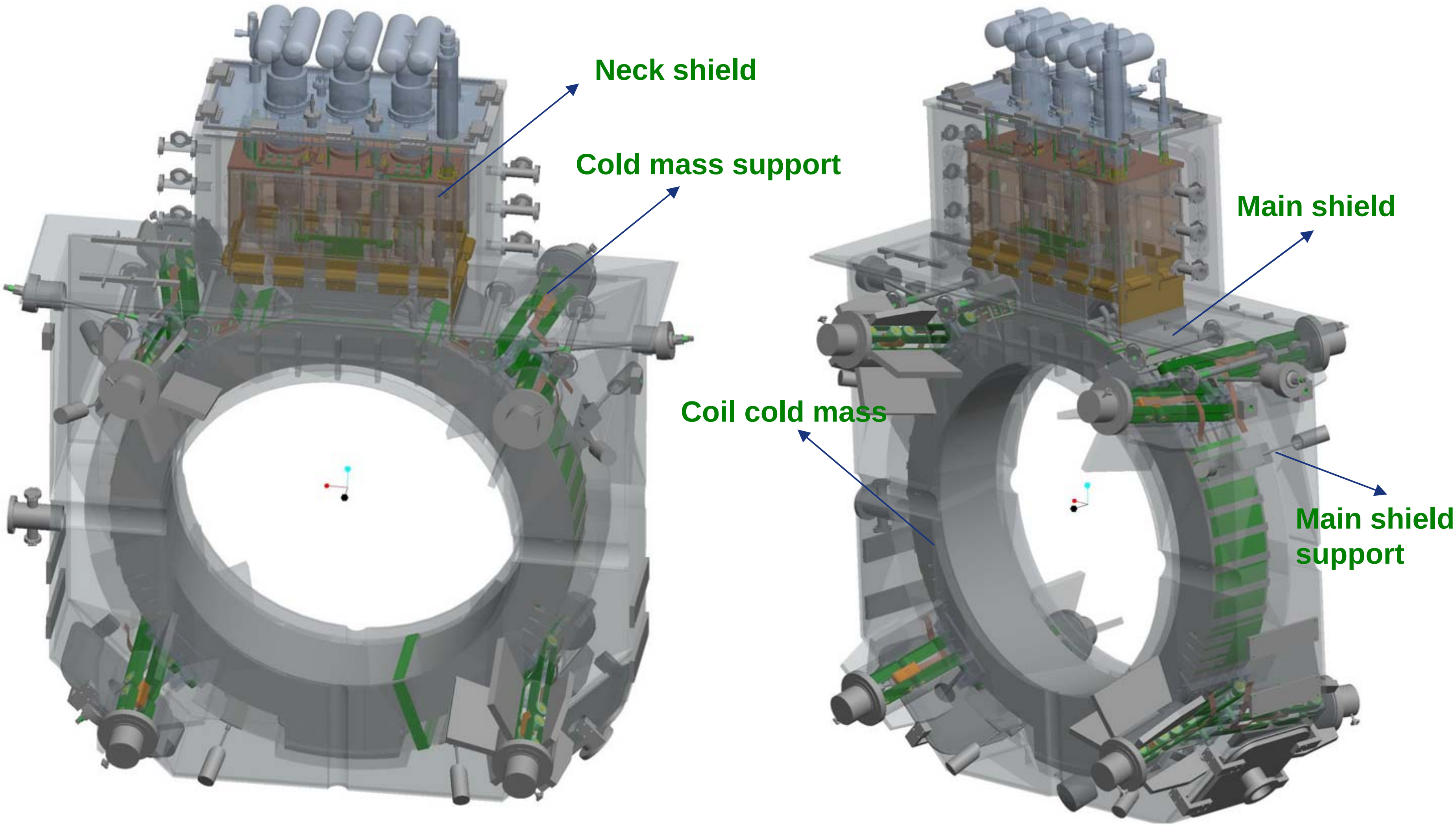


Previous design

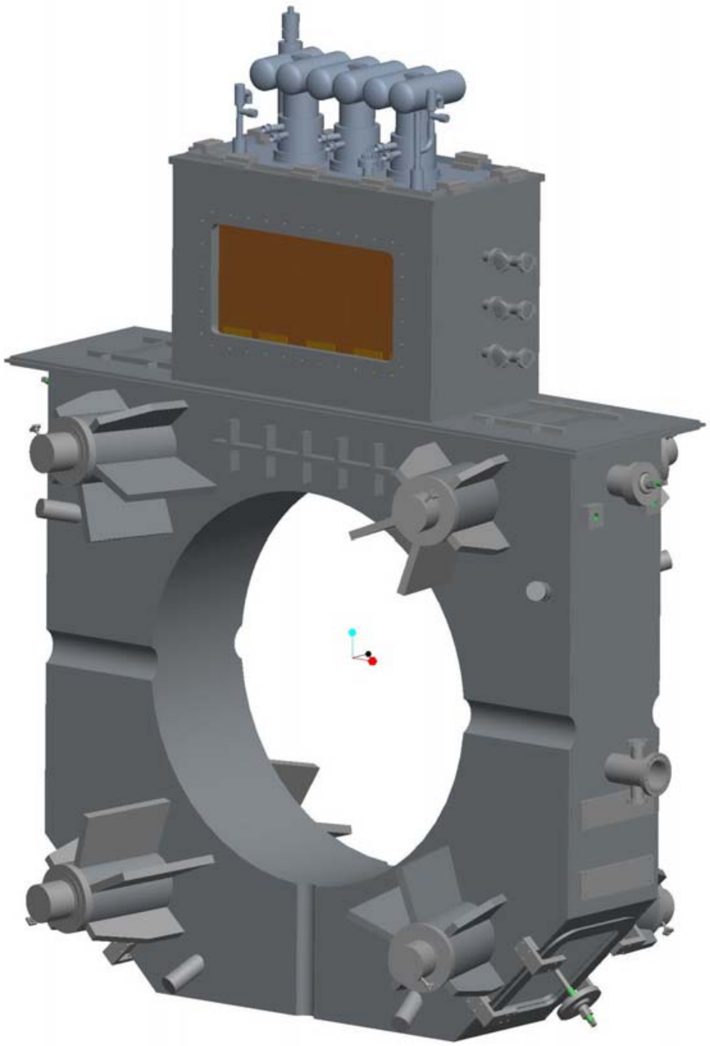
Updated design

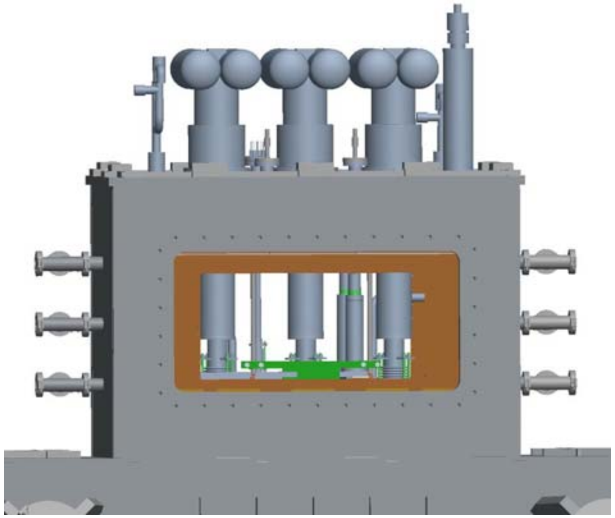


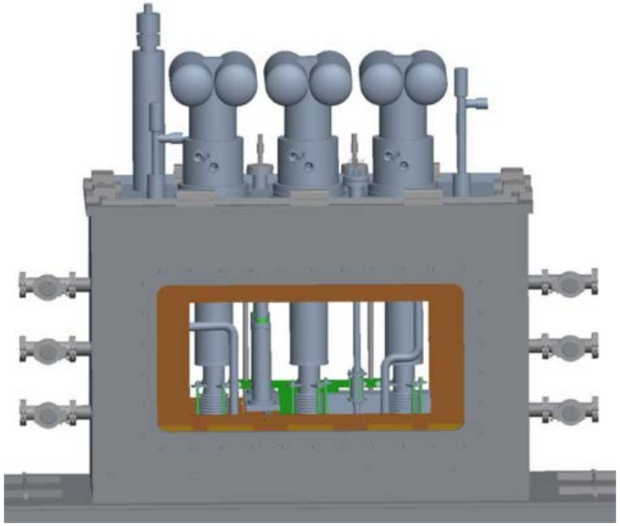
3D model for coupling magnet cryostat

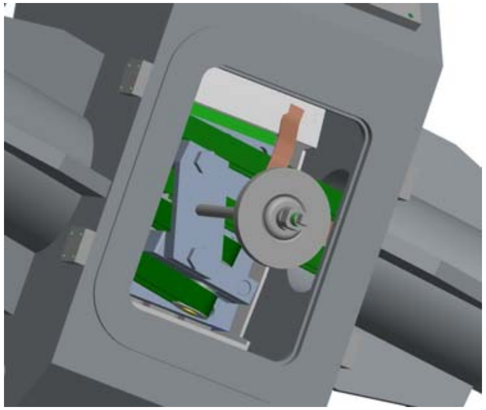


3D model for coupling magnet cryostat



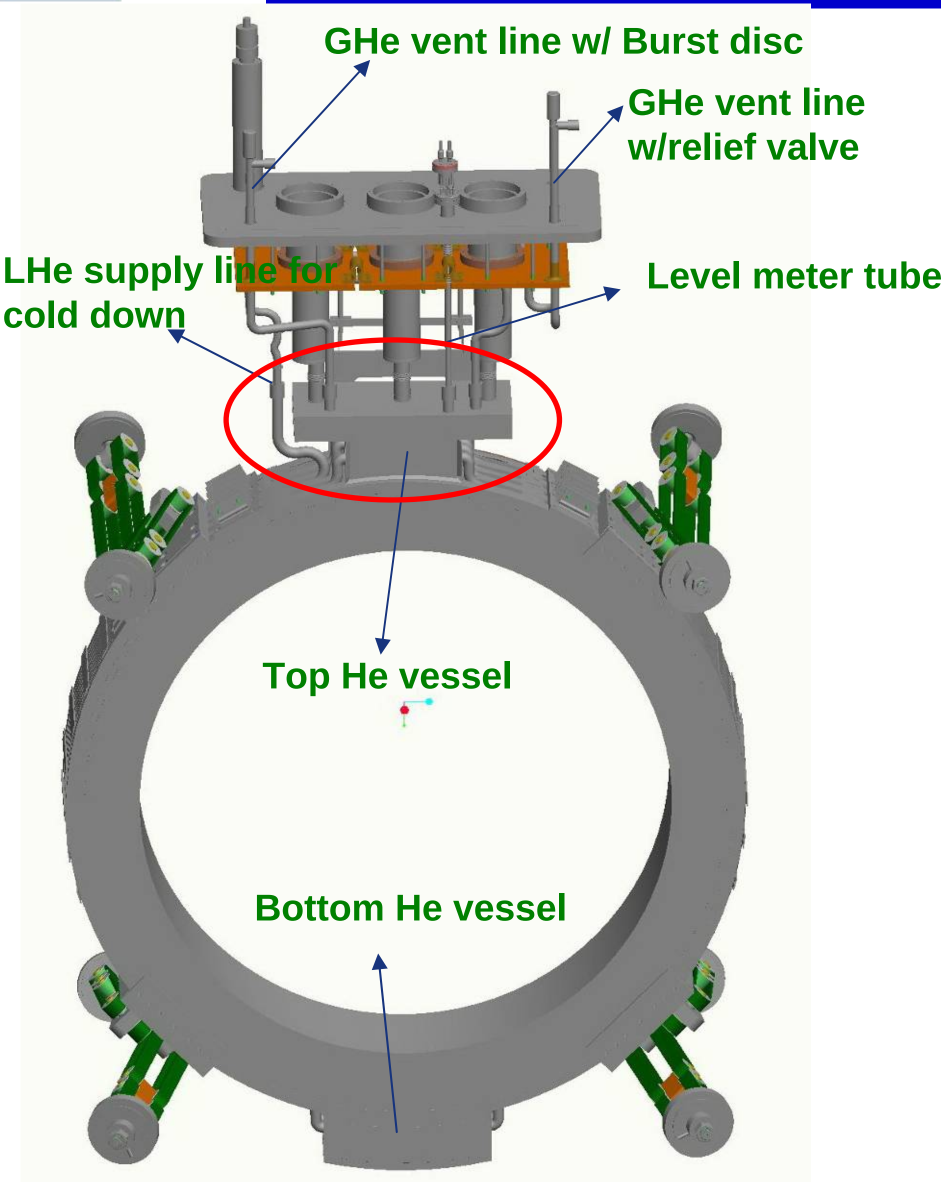






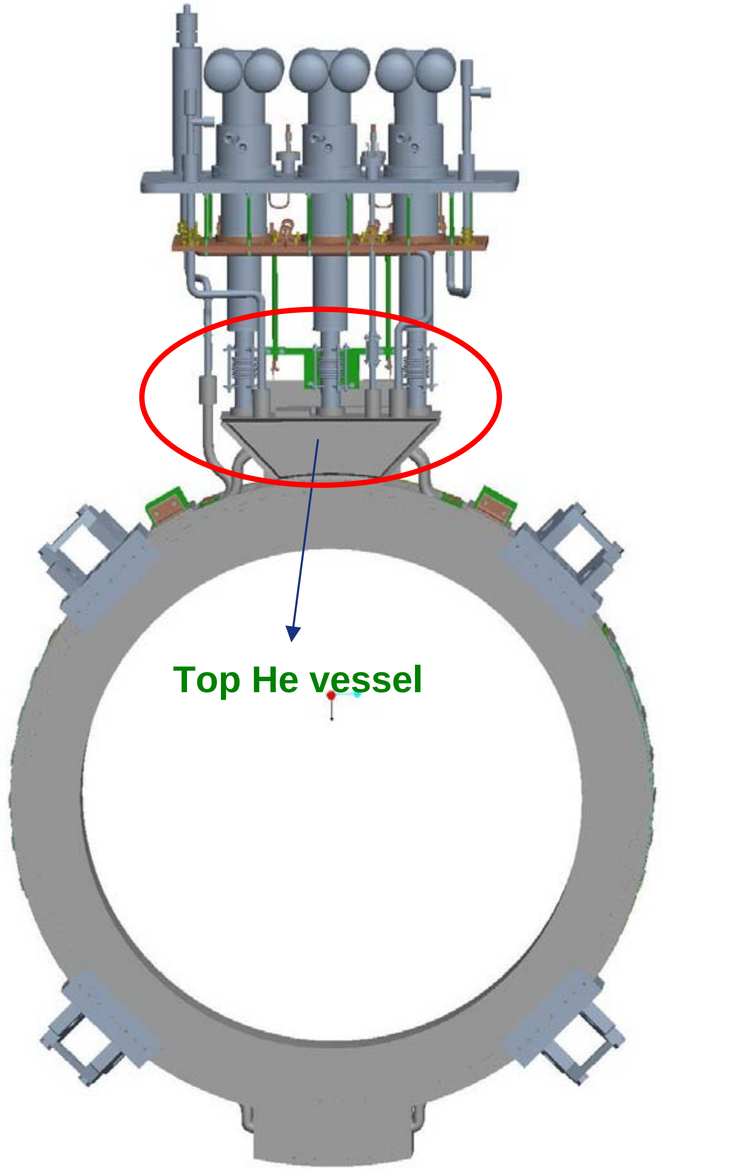
Lower access opening

Demountable windows: two sides' view

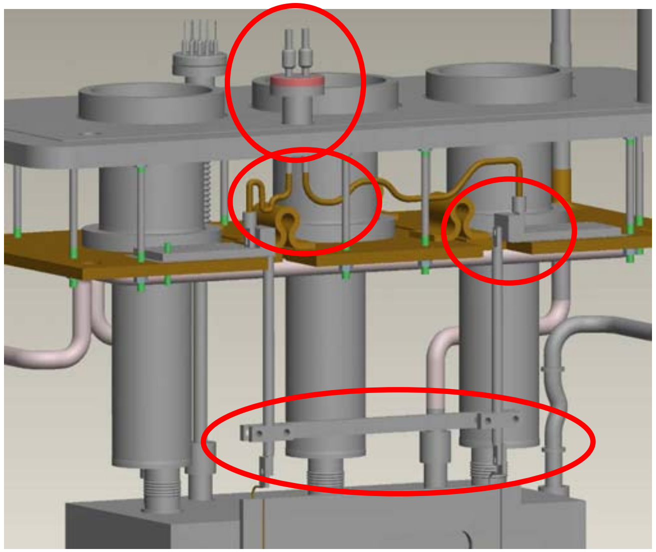


Previous design

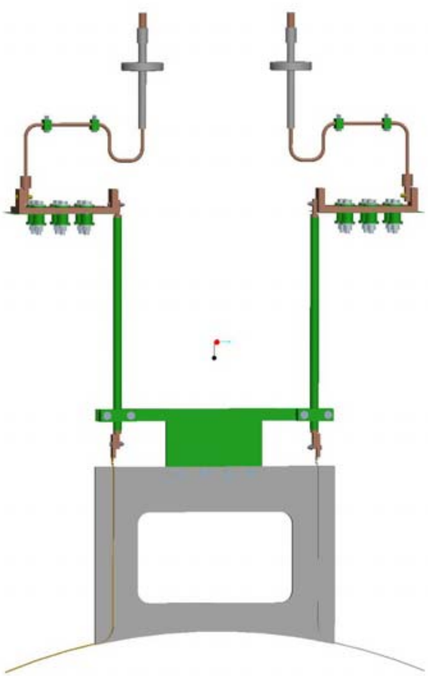
CC Cooling system

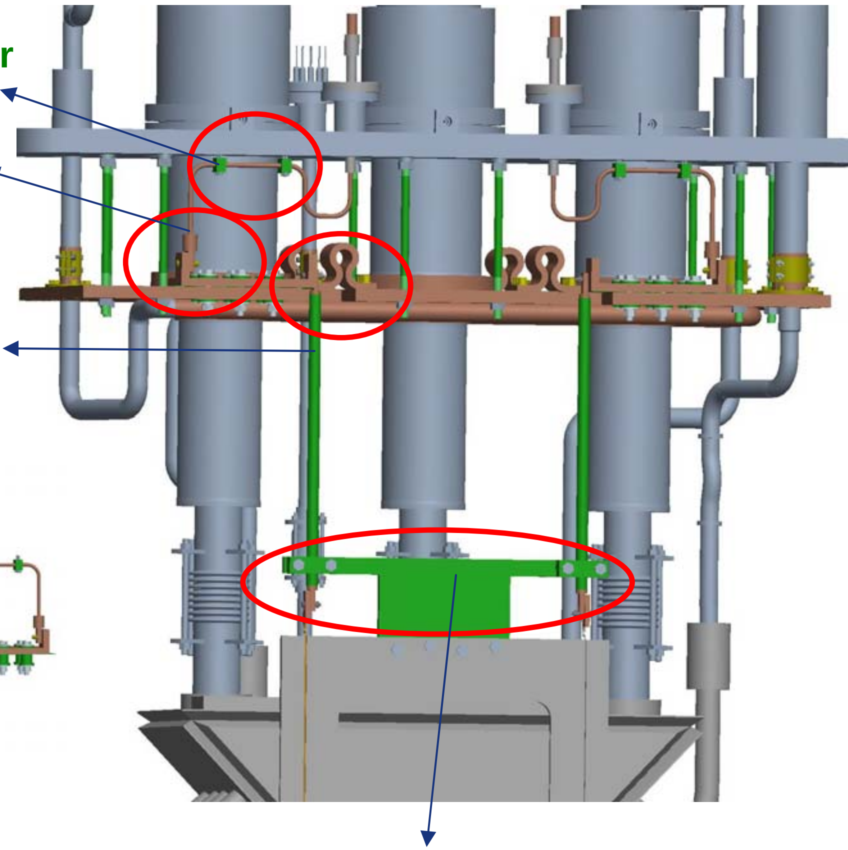


Updated design



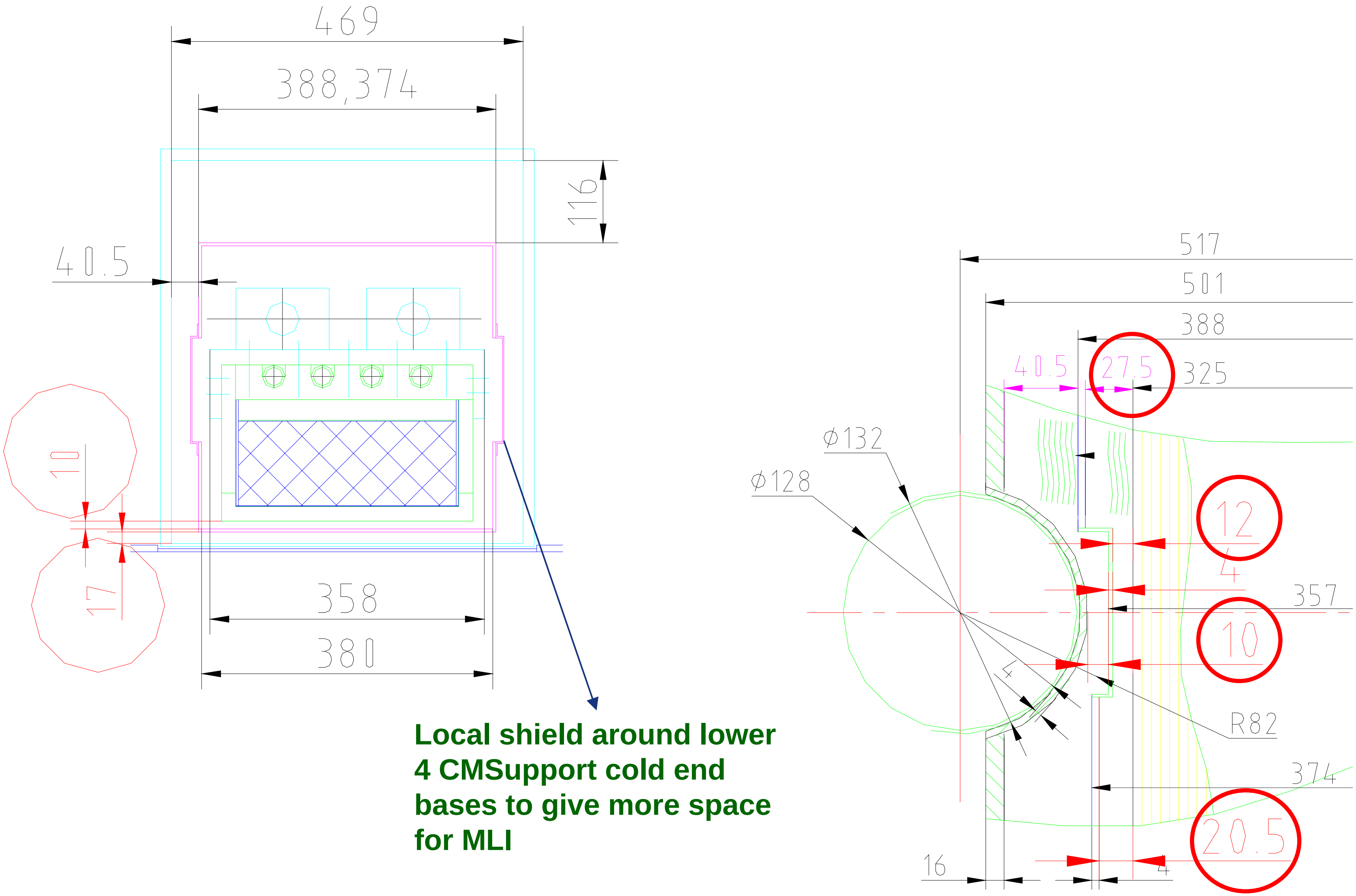
Previous design





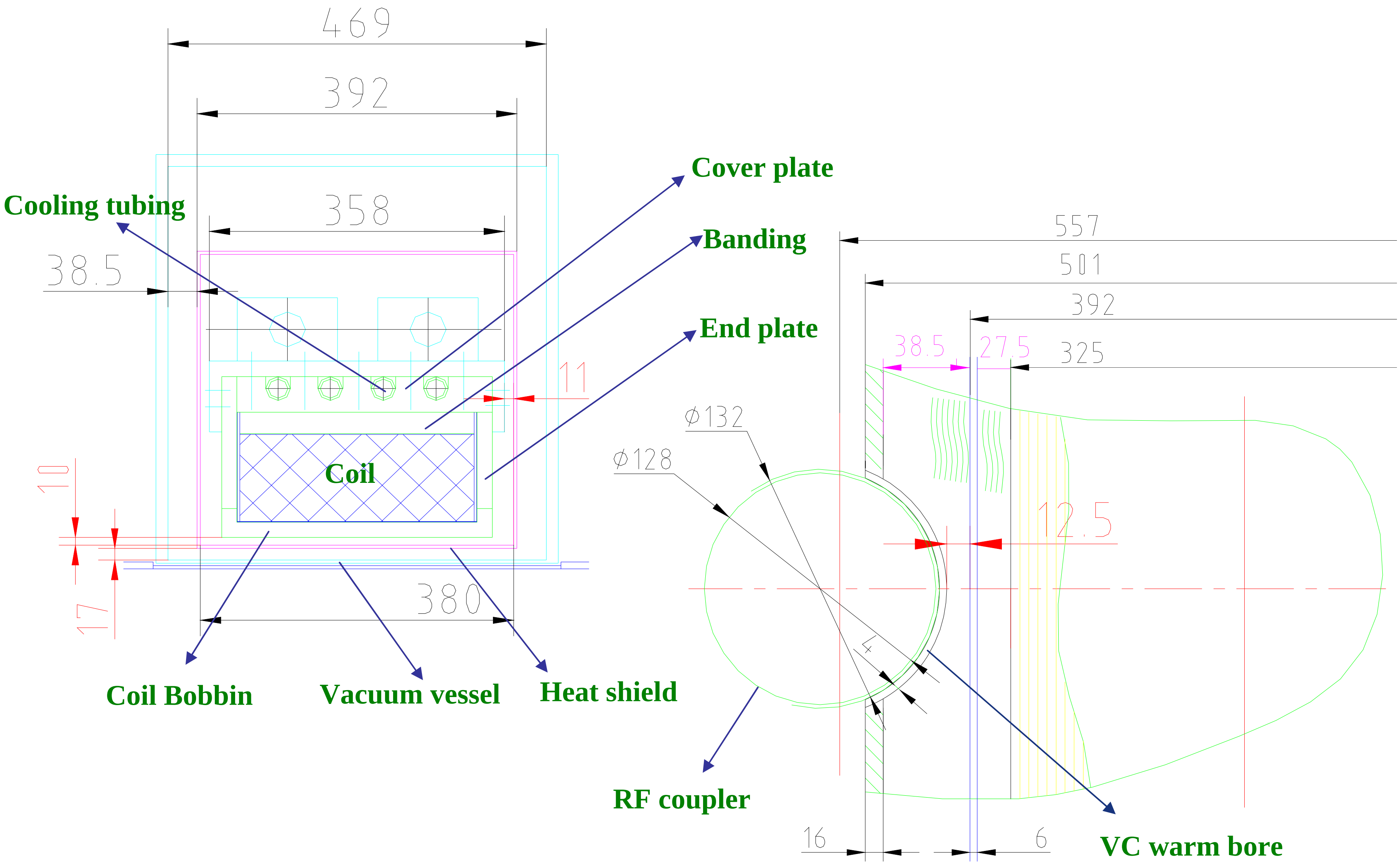
Updated design

Power leads and their cooling



Local shield around lower 4 CMSupport cold end bases to give more space for MLI

Previous design



Updated design

Comments

The proposed engineering design of coupling magnet cryostat is:

- To provide the space available for one more cryocooler
- To update the cryostat design to make assembly, alignment, disassembly and maintenance MUCH EASIER
- To give more room for MLI and lower down possible heat loads at 4.2K
- To provide a complete 3D model

Calculations and FEA simulations for Coupling Magnet Cryostat Design

- Heat loads/Cold surfaces/Cold mass/Helium inventory

  (Response to Does the design provide sufficiently low heat load to the cold mass to allow stable operation with 3 cryo-coolers?)

- Temperature on cold mass assembly at normal operation

  (Response to Is there sufficient temperature margin to operate the coil stably?)

- Temperature on thermal shield assembly

  (Response to Is the thermal shield design/cooling adequate? Is heat from the cold-mass supports appropriately intercepted?)

- Current leads' cooling

  (Response to Is heat from the current leads appropriately intercepted?)

- Pressure vessels and piping
- Vacuum vessel

  (Response to Does the cryostat design support all expected loads?)

- Cooling circuit

  (Response to Does the LHe system effectively separate two phase He gas and re-condense it to form liquid?)

Heat Loads

- Comparison of heat loads for previous design and current design

Heat loads from 300K to 60K (W)	Previous design	Current design
Copper leads from 300 K	19.30	19.30
Cold mass supports (intercept *T*=72-77 K)	11.215	11.215
Radiation Heat to the Shields *	9.756	8.47
Instrumentation wires	0.092	0.092
He Cooling Tubes	3.57	2.91
Level sensor tube	1.03	0.85
Cooler SS sleeves	9.73	9.73
Neck shield supports	0.88	0.88
Heat shield supports	0.69	0.37 (longer support)
Sub-total (calculated)	56.2629	53.817
Total Heat Load with 50% Contingency	84.3944	80.7255
Total Heat Load with 100% Contingency	112.526	107.634

*Radiation heat from 300K to 60K-80K: q=1.0W/m^2; PTR415 cooling capacity at 60K: 55W-60W

Heat load from 60K to 4.2K (W)	Previous design	Current design
HTS current leads (Warm HTS end *T* = 64 K)	0.15	0.15
4.2K Cold mass supports (intercept *T*=73-78K)	0.478	0.478
Radiation heat to 4.2K cold mass (Shield *Tave* = 70K) (W) (MLI layer is 20)*	0.84	0.832
Instrumentation Wires	0.00307	0.00307
He cooling tubes	0.06	0.09
Level sensor tube	0.02	0.03
Cooler SS sleeves**	0.60	0.60
14 Superconducting Splices at 10 nW per splice and 210 A	0.01	0.01
Sub-total (calculated)	2.1611	2.1931
Total with 50% Contingency	3.2416	3.2897
Total with 100% Contingency	4.3221	4.3862

*Radiation heat from 60K-80K to 4.2K: q=0.15W/m^2; PTR415 cooling capacity at 4.2K: 1.5W
** Test data from Michael Green

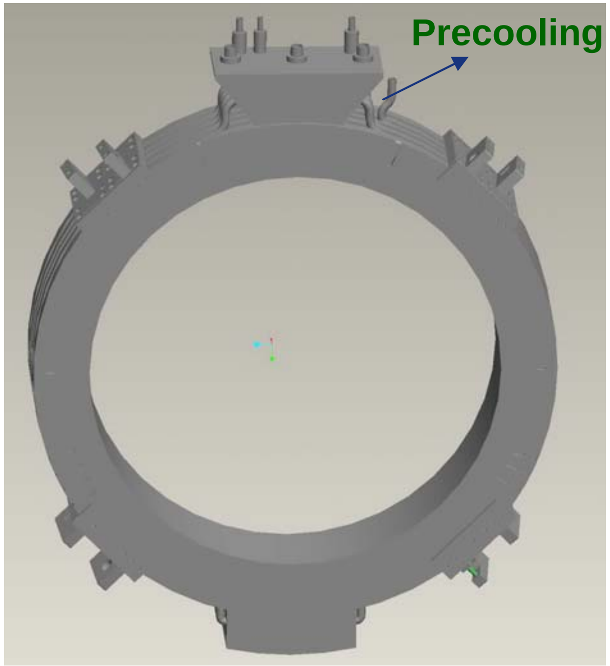
Comparison of cold surface/cold mass/He inventory for different schemes

Design schemes	Cold Surface (m^2)		Cold mass (kg)		Heat inventory (L)	Calculated heat loads (W)	
	60K	4.2K	60K	4.2K	4.2K	60K	4.2K
Previous design	9.756	5.594	189.65	1640.02	37.908	56.263	2.1611
Current design	8.63	5.56	186.00	1639.20	39.053	53.817	2.1931

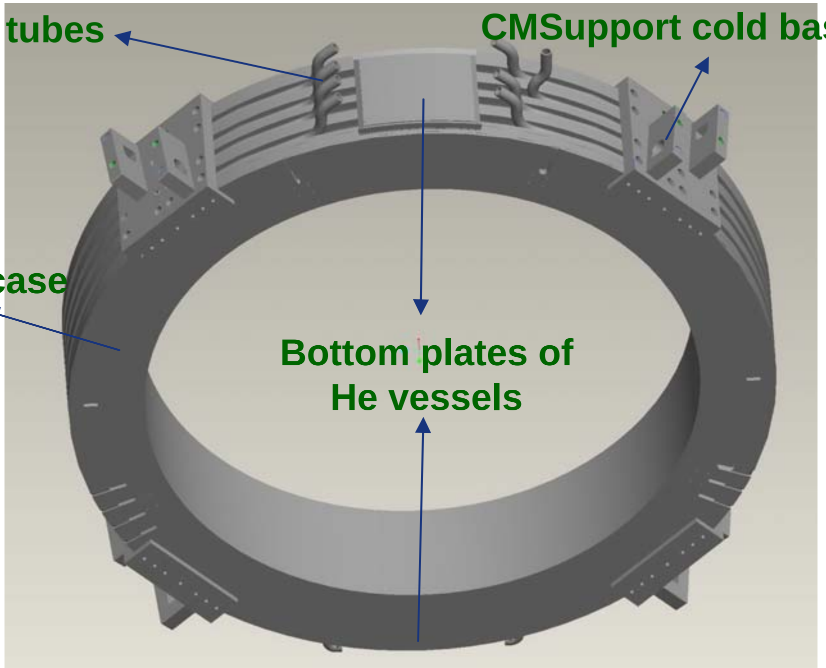
Design schemes	Cold mass of cooling conduction plate and neck shield at 60K (kg)
Previous design	109.27*
Current design	117.45

*Heat capacity deposited in the cold mass at 60K is to be helpful for keep the warm ends of HTS leads cooled during the fast discharge process in case of power failure or other failures

Temperature on cold mass assembly at normal operation



Coil cold mass



FE Model

The FE model includes:

- Coil assembly: superconductor wire (NbTi/Cu=1:4), Al banding (5052Al)、coil case (6061Al)and G-10 insulations
- Cooling tubes (6061Al)
- Cold mass support cold base (304SS)
- Bottom plates of He vessels（6061Al）
- ½ or ¼ model was created according to cooling tube numbers to be used on two sides

Boundary conditions and loads:

- The temperatures on the inner walls of the cooling tubes and on the bottom plates of He vessels are set at 4.27K.
- Radiation heat flux on cold surfaces: 0.225W/m^2.
- Heat conduction through the cold mass supports from 60K to 4.2K is 0.0896W each, and imposed on the clevis round surface.
- Heat leaks from the HTS leads and SC joints is 0.16W and imposed on the coil as volumetric load.
- The side plates of the cold mass support cold base are in good contact with the cover plate of coil case.
- Cooling tubes are in contact with the slots on the cover plate only by welds.

Simulation results:

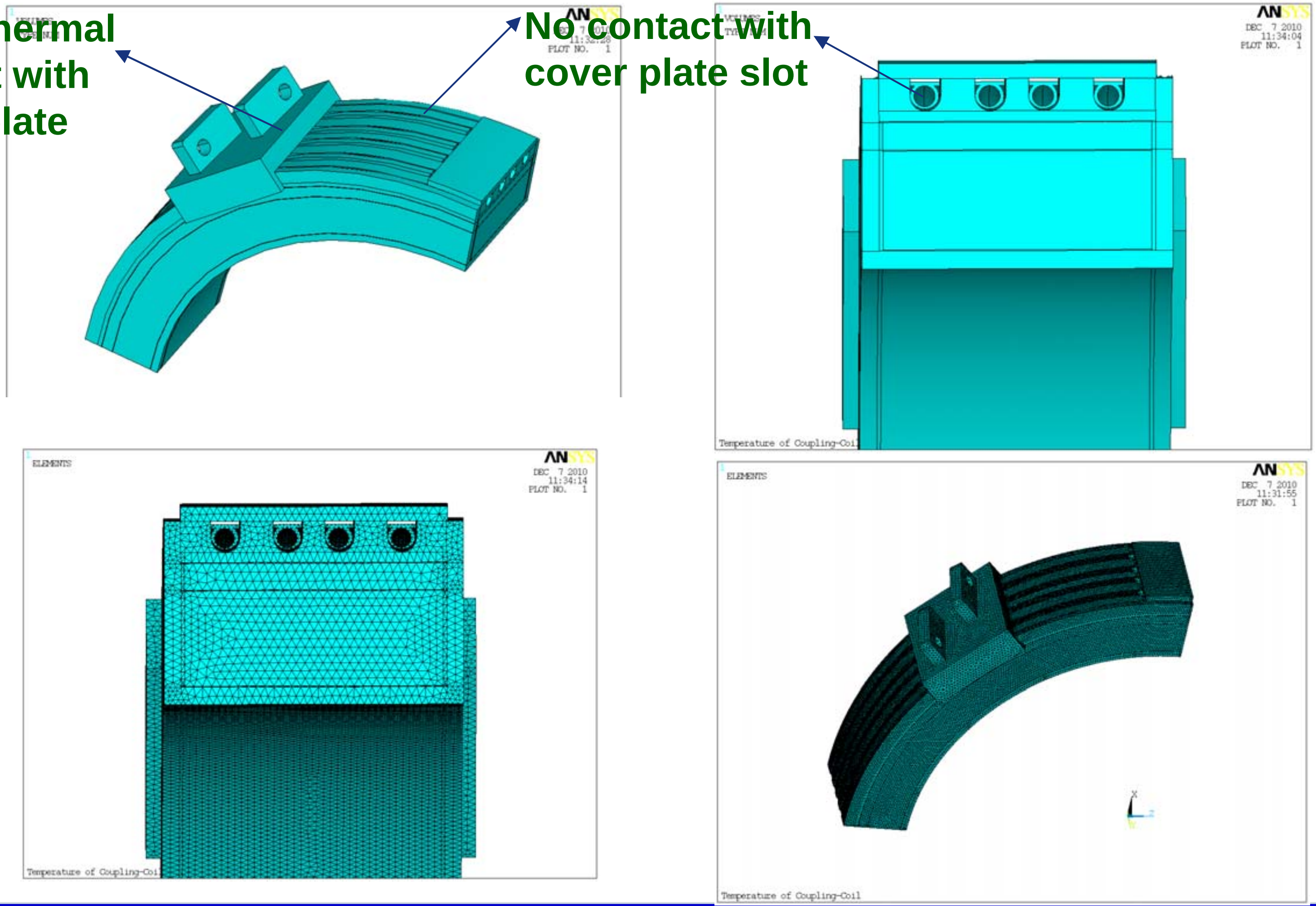
CASE I:

1) **Only 3 cooling tubes on each side, and the bottom plates of the cold mass support cold base are in good contact with the cover plate of coil case.**
2) **The hot spot temperature inside the coil is around 4.31K, and happened at the coil inner layer.**
3) **The hot spot temperature on the coil case is around 4.36K, and at the locations of cold mass support cold base.**
4) **The highest temperature on the CMSupport cold base is around 8.018 K.**

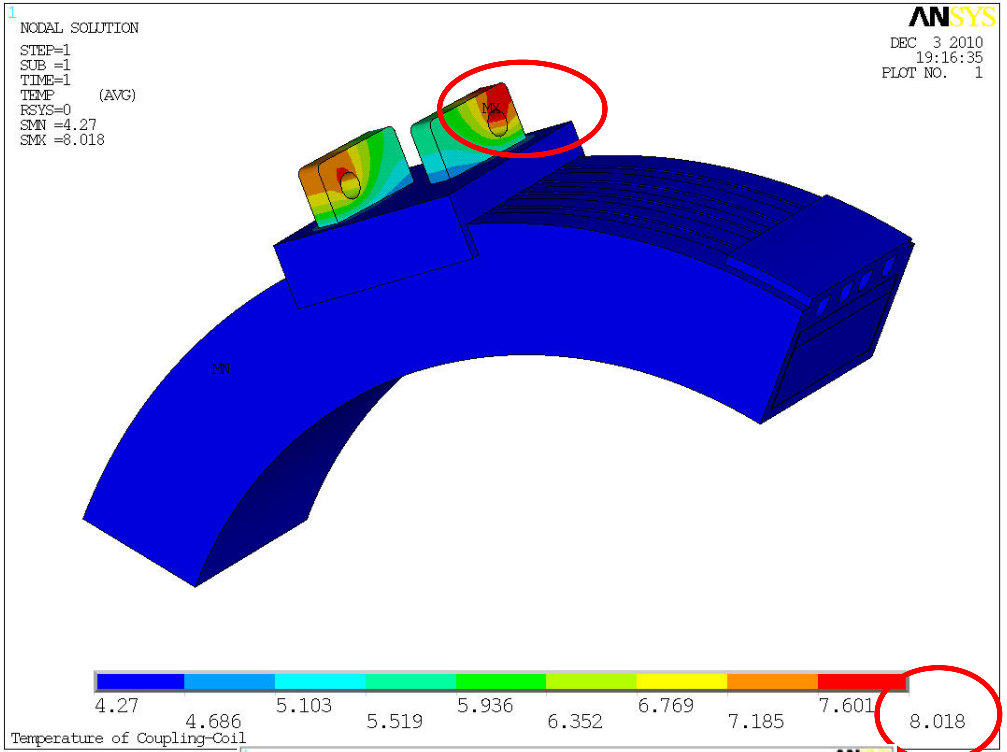
CASE II:

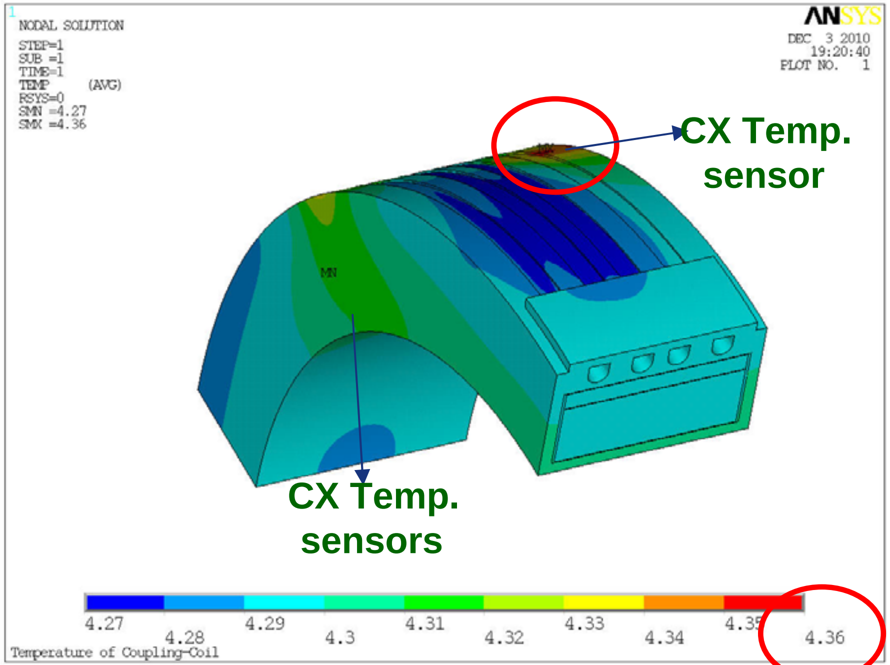
1) **3 cooling tubes on precooling tube side, 4 tubes on the opposite side, and the bottom plates of the cold mass support cold base are in good contact with the cover plate of coil case**
2) **The hot spot temperature inside the coil is around 4.297K, and happened at the coil inner layer**
3) **The hot spot temperature on the coil case is around 4.324 K, and at the locations of cold mass support cold base.**
4) **The highest temperature on the CMSupport cold base is around 8.011 K.**

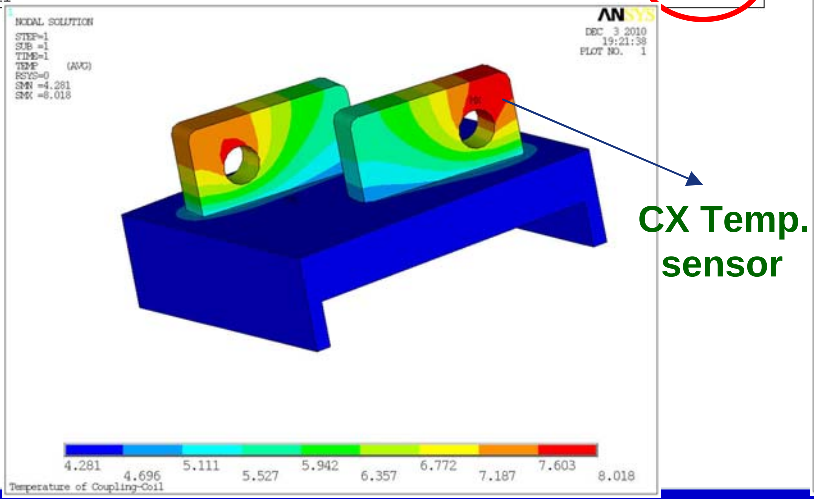
CASE I: **Only 3 tubes on each side to be used for coil cooling, the fourth one on one side is for coil precooling, that on the other side is for delivering LHe directly from top He vessel to bottom He vessel.**

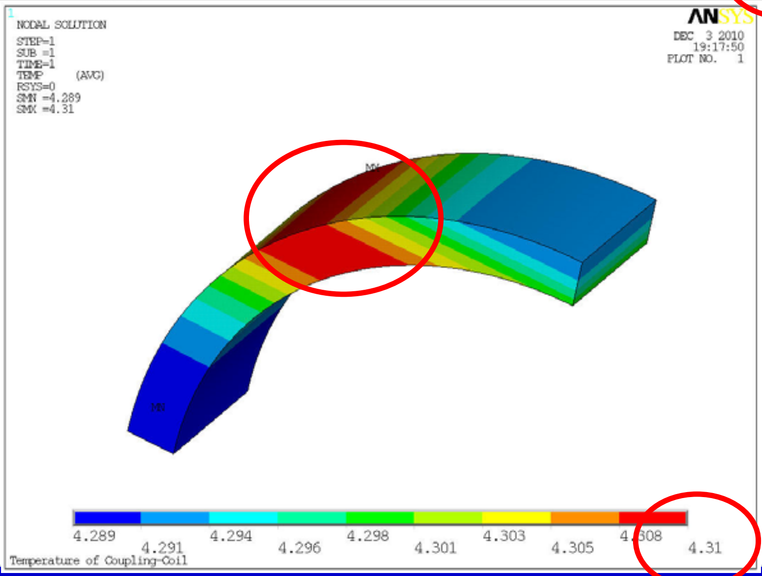


MICE/MuCool Coupling Magnet Cryostat Engineering Design

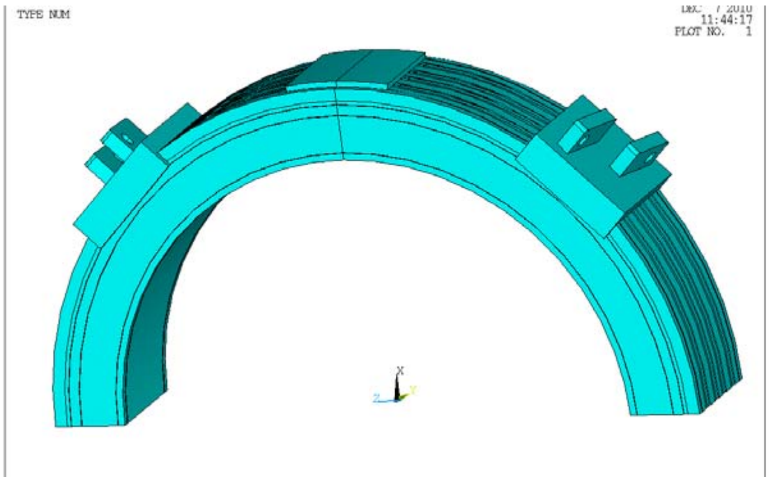


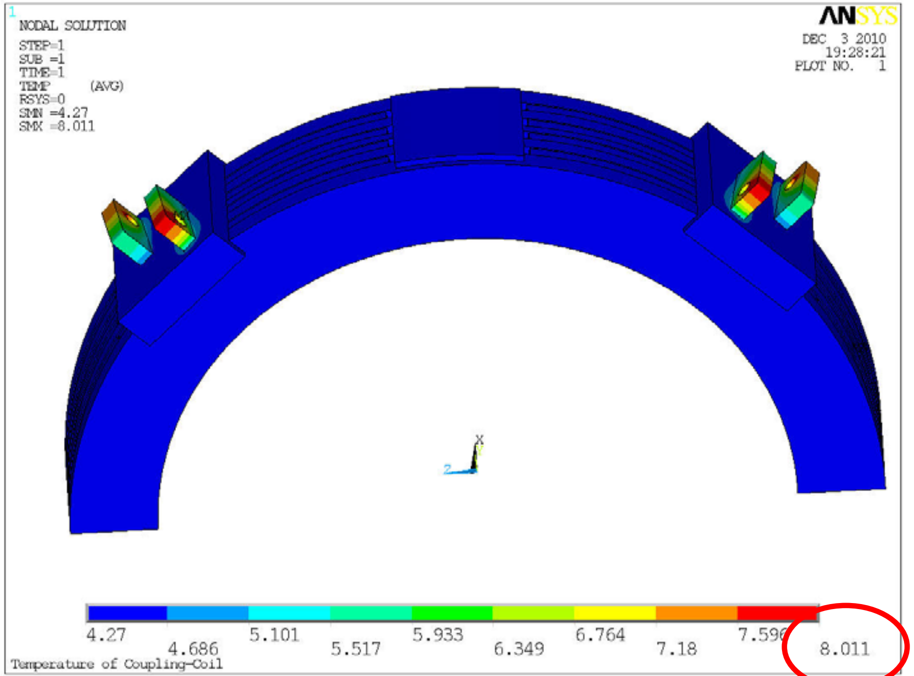


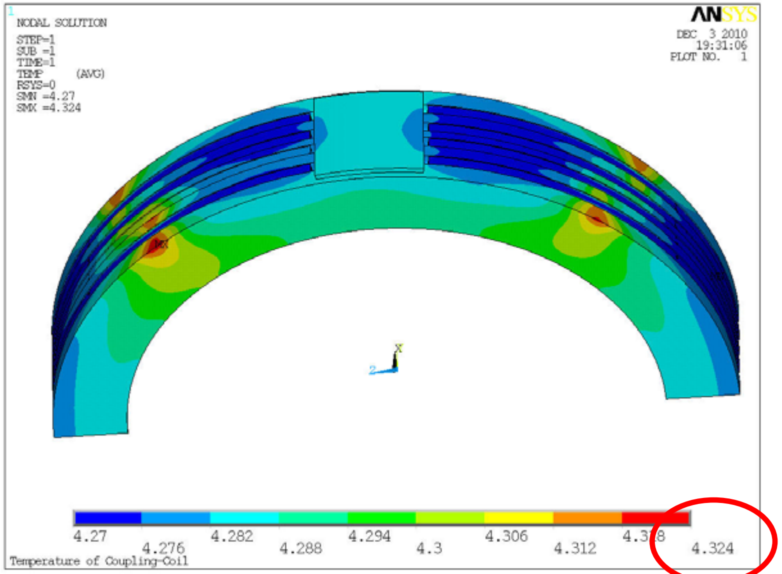


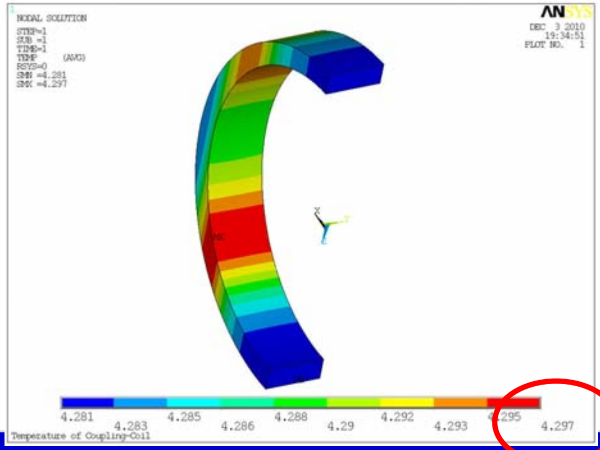


CASE II: **3 cooling tubes on precooling tube side, 4 tubes on the opposite side**



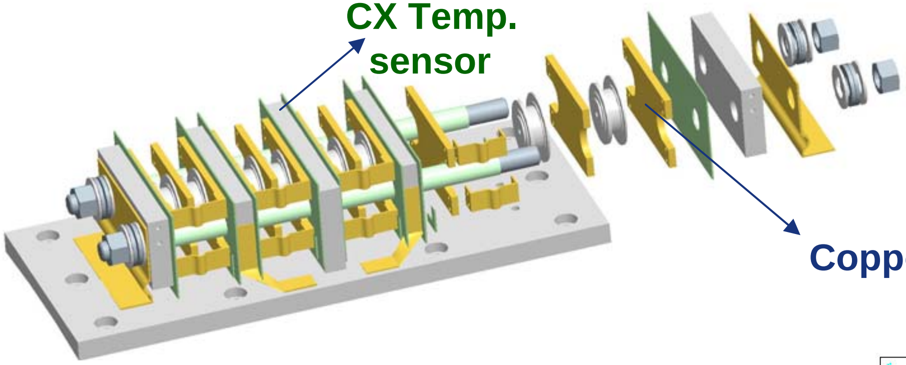






Simulation results on temperature on the cold diode assembly

CX Temp. sensor



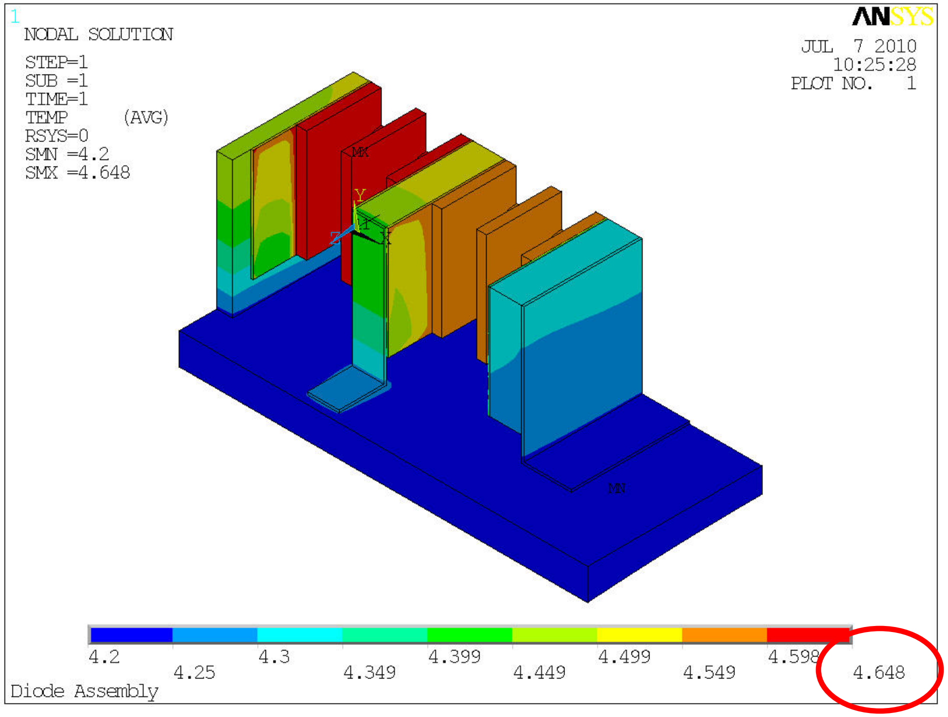
Quench protection diode assembly

Copper block: 40*45mm^2, 4mm thick, mass 0.065kg

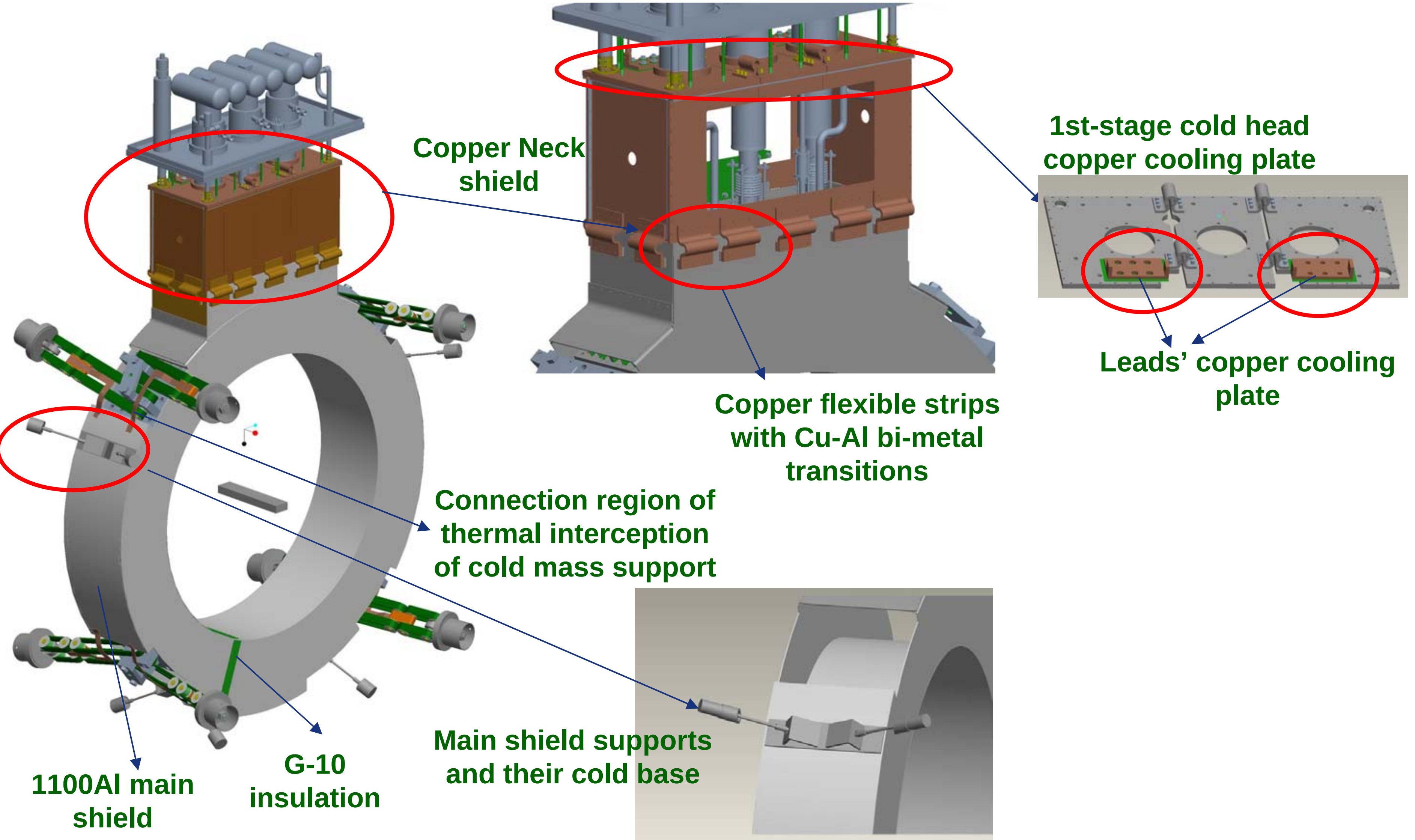
½ model for quench protection diode assembly

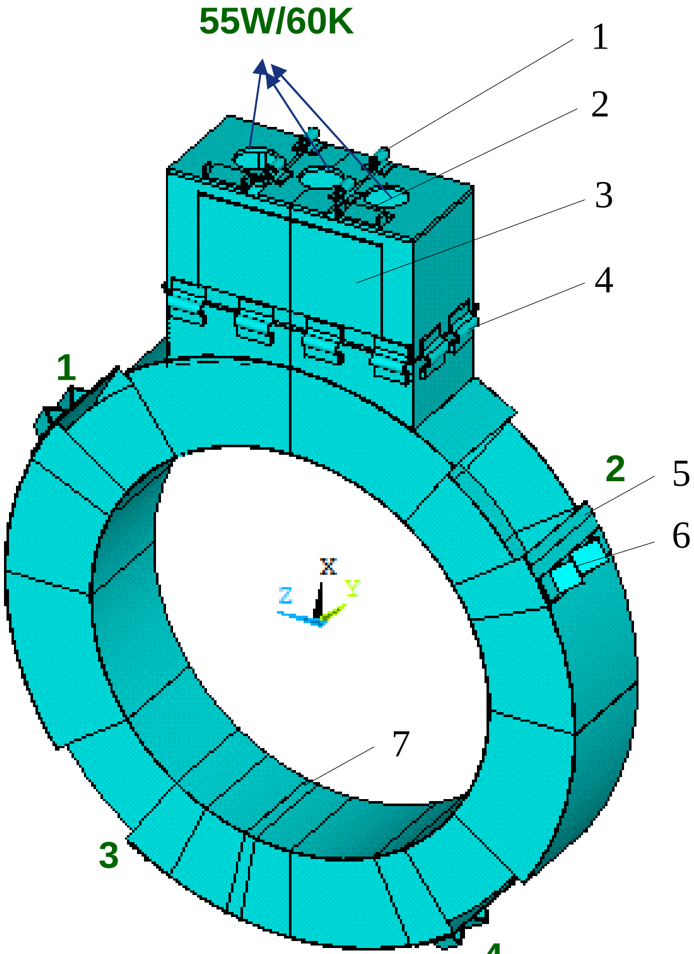
Diode	
Cross-section Area	π*9.5^2 mm^2
Thickness	14mm
Mass	0.056kg
Max.Temp.during quench *	155K

*Assuming: the Joule heat generated during quench process is absorbed totally by the diode itself. Quench time=8s, I=250A, V=1.5v



Temperature on thermal shield assembly





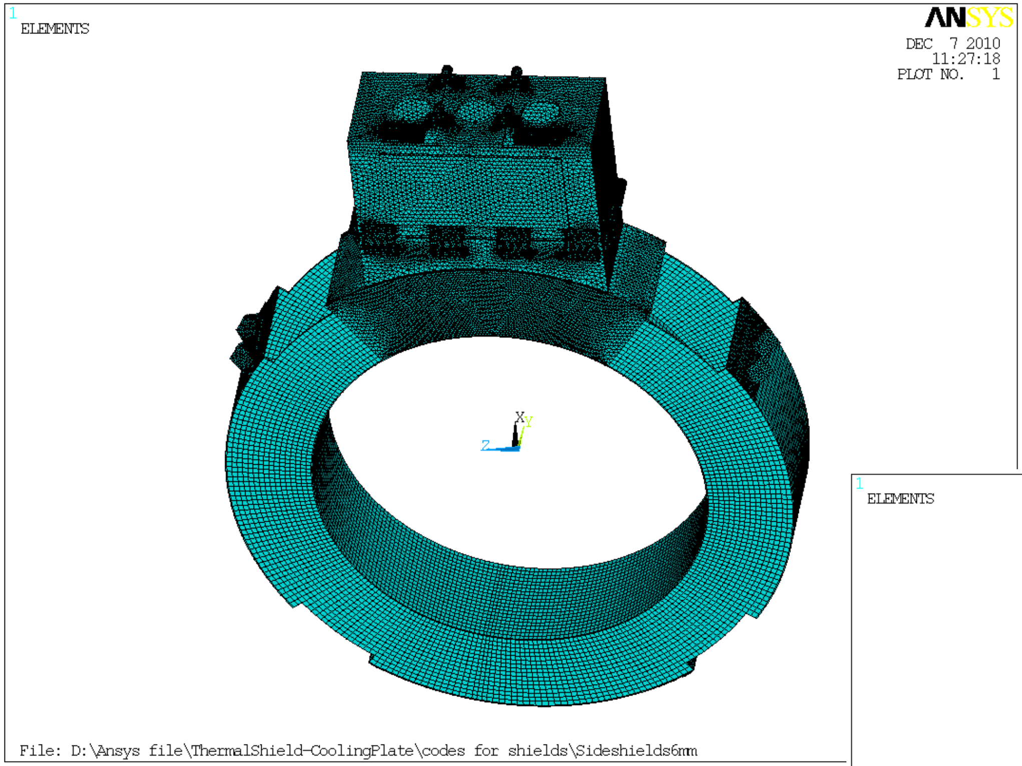
FE Model

The FE model includes:

1. Flexible strips for 1st-stage cold head cooling plates
2. Cooling plates for leads
3. Copper neck shield
4. Copper flexible strips with Cu-Al bi-metal transitions
5. Connection area of thermal interception of cold mass support, no shield for interception
6. Main shield supports' cold base
7. G-10 insulations

Assumption and loads:

- The 1st-stage cold heads and their copper connection flanges are in good contact with the cooling plates, no thermal contact resistance.
- The 1st-stage cold head cooling plates are in good contact with the neck shield, no thermal contact resistance.
- All parts on the neck shield are in good contact, no thermal contact resistance.
- Heat loads with 50% contingence are imposed on the shields, shield support cold bases, CMSupport interception connection area and leads' cooling plates.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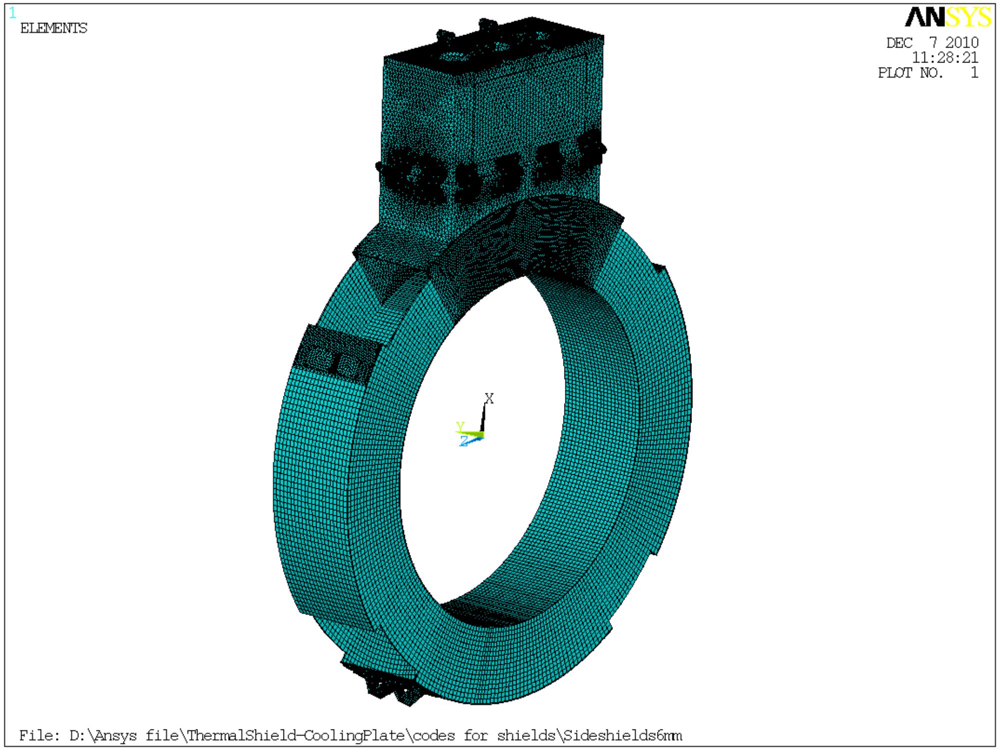
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Meshing

Main structure dimensions:

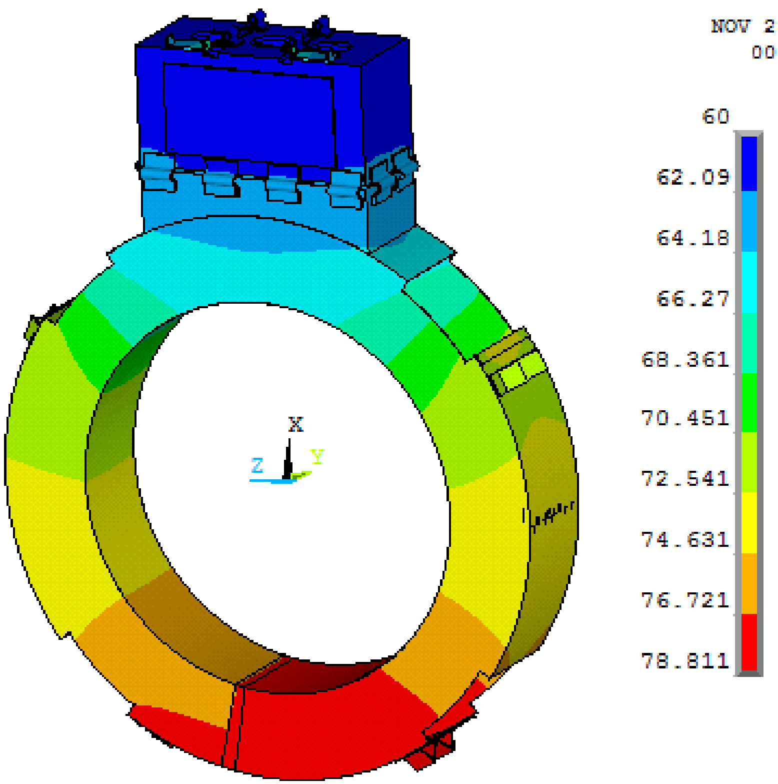
ID of inner cylindrical shield (mm)	1431
OD of outer cylindrical shield	2060
Axial width of main shield	388
Thickness of inner cylindrical shield	4
Thickness of neck shield	4
Thickness of side shield	4, or 6
Thickness of outer cylindrical shield	4, or 6
Neck shield Height/width/length	574/380/884
Flexible strip Length/width/thickness	166/120/8
Flexible strip number	12
Leads' cooling plate Length/width/thickness	145/85/10
Width of G-10 elec-insulation	40

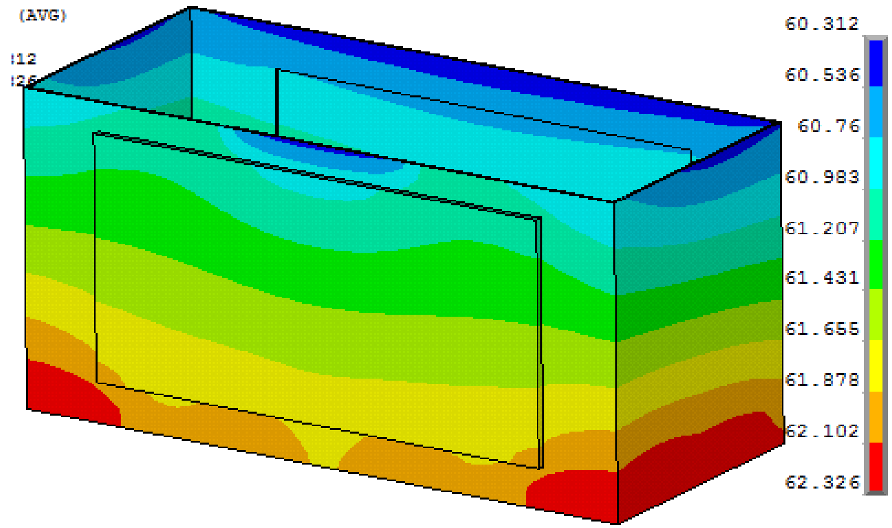
Simulation results:

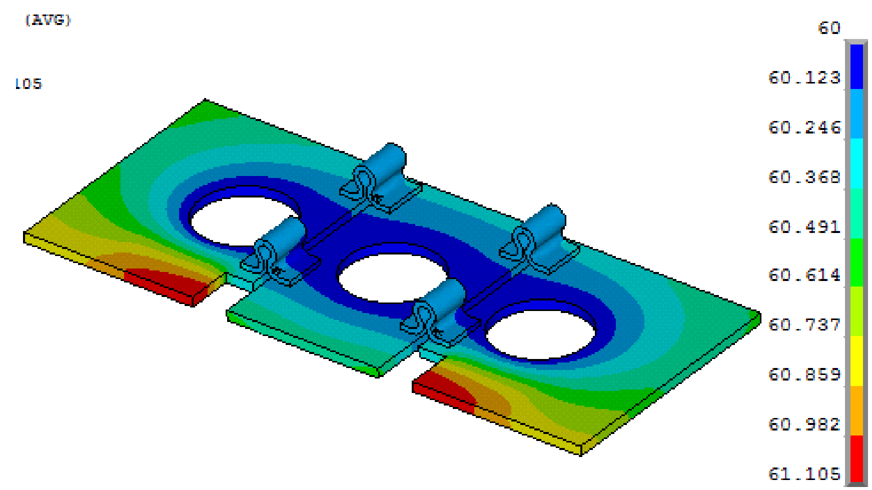
	Tmax/ΔT along the whole shield	ΔT along the neck shield	Interception Tmax of CMSupport	Tmax on main shield support cold bases
Case I: The thickness of all the heat shields is 4mm w/3 coolers running.	18.811	2.014	78.811	78.557
Case II: The thickness of all the heat shields is 6mm w/3 coolers running.	13.654	2.396	73.654	73.466
Case III: The thickness of outer cylindrical shield is 6mm w/3 coolers running.	18.372	2.025	78.372	78.171
Case IV: The thickness of side shields is 6mm w/3 coolers running.	15.117	1.994	75.117	74.879
Case V: The thickness of outer and side shields is 6mm w/3coolers running.	14.767	2.005	74.767	74.578

Conclusions: the thickness of side shields was changed from 4mm to 6mm in order to reduce the hot temperature on the shield.

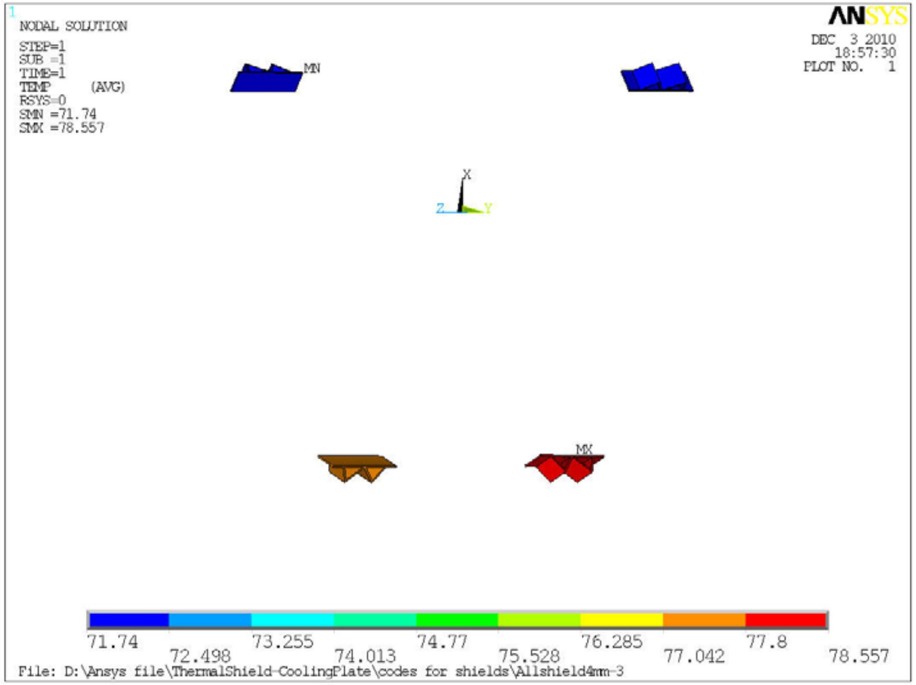
CASE I: The thickness of all the heat shields is 4mm w/3 coolers running

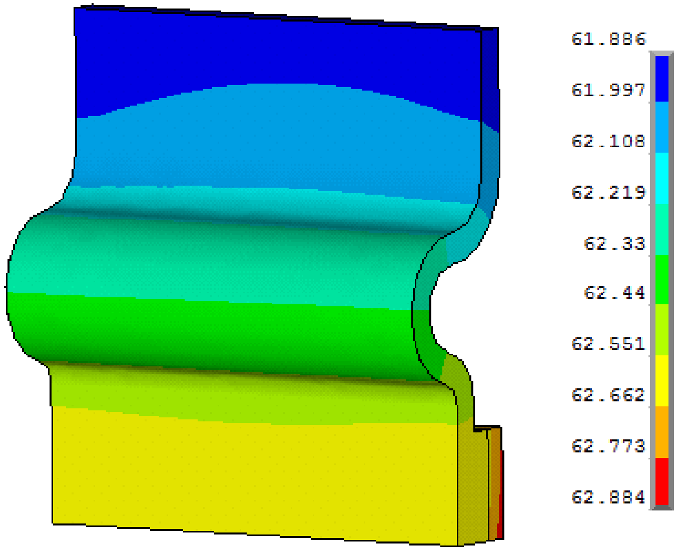




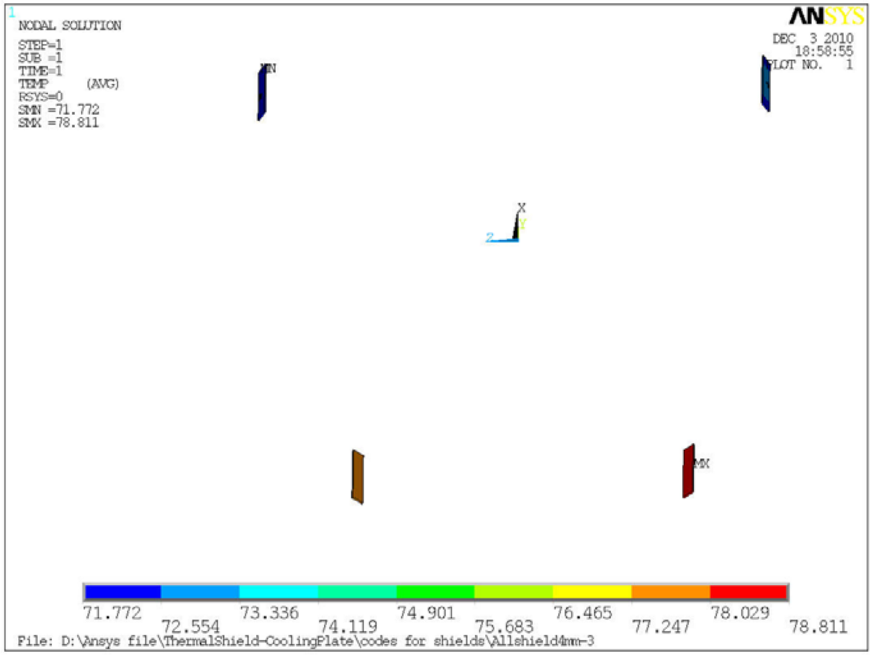


ΔT=18.811 K



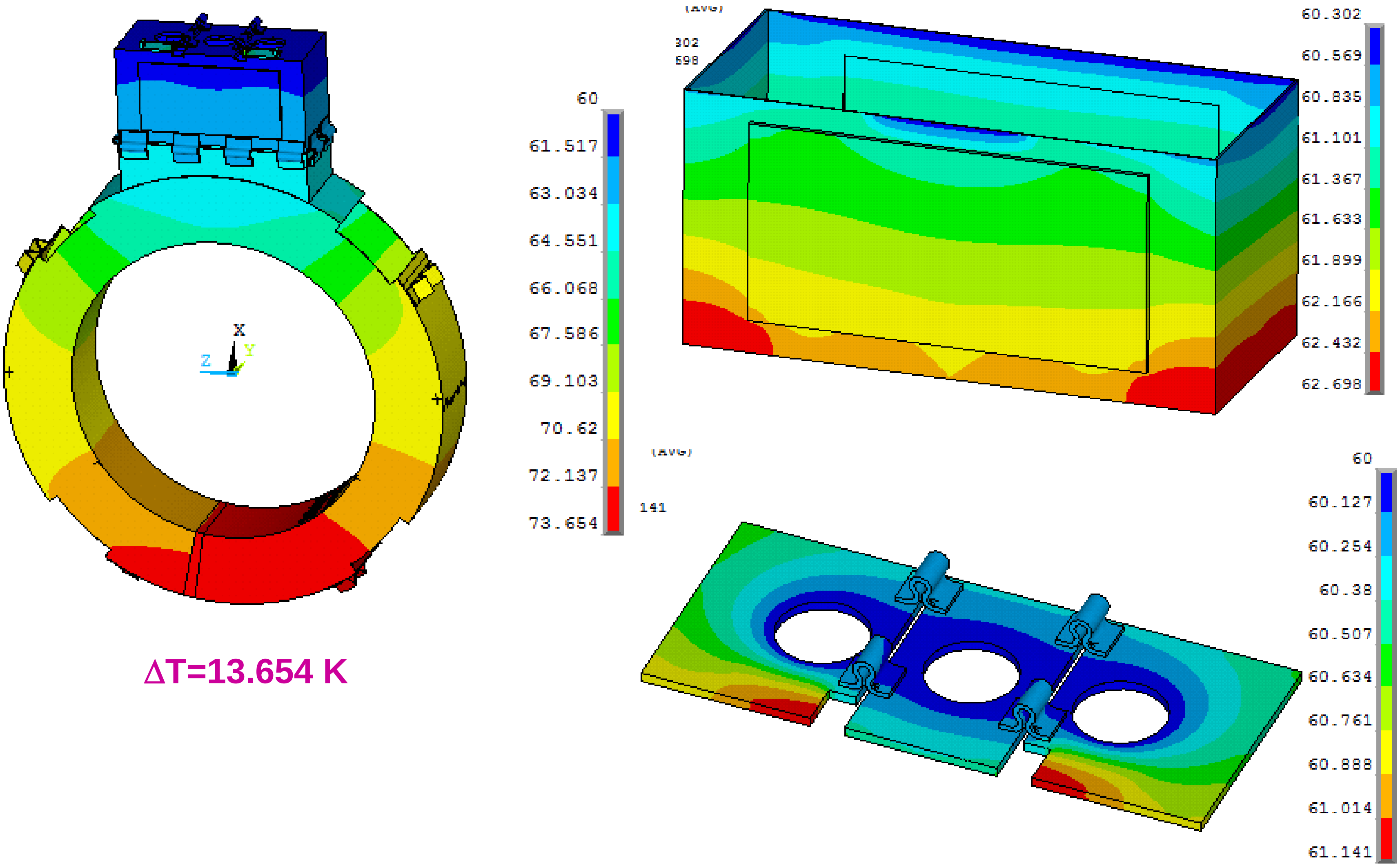


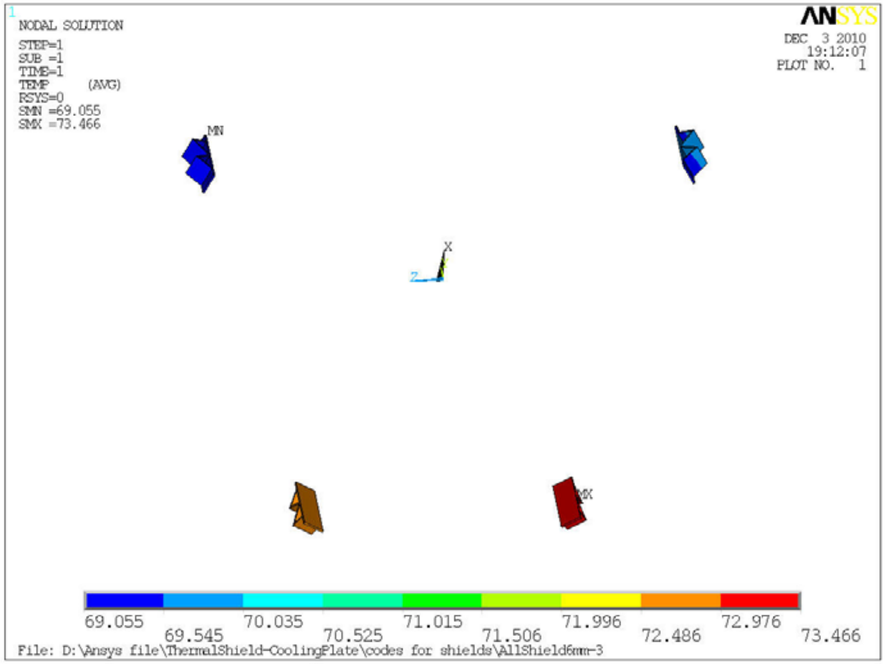
Tmax=78.557 K at main shield support cold base

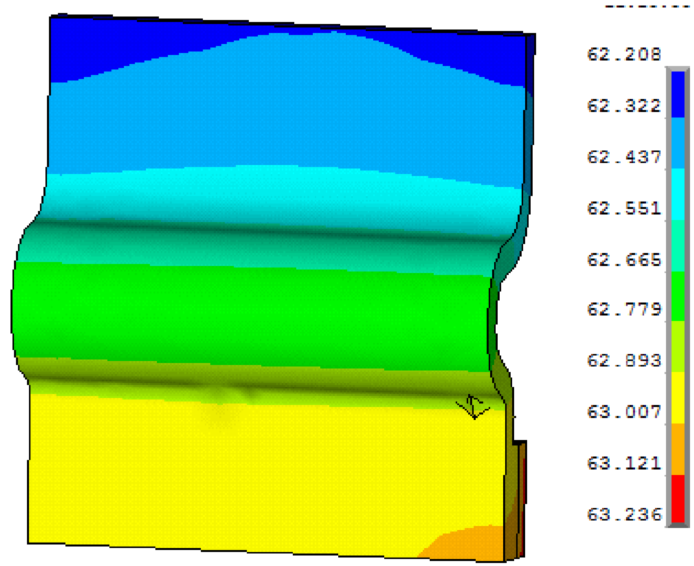


Tmax=78.811 K at connection surface of Cu strips to be connected with cold mass support interception

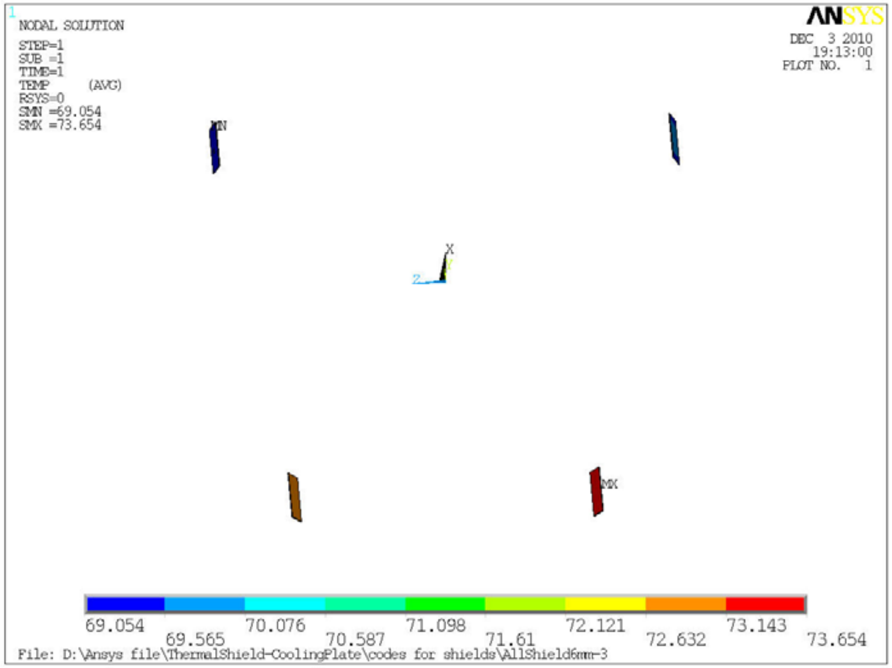
CASE II: The thickness of all the heat shields is 6mm w/3 coolers running





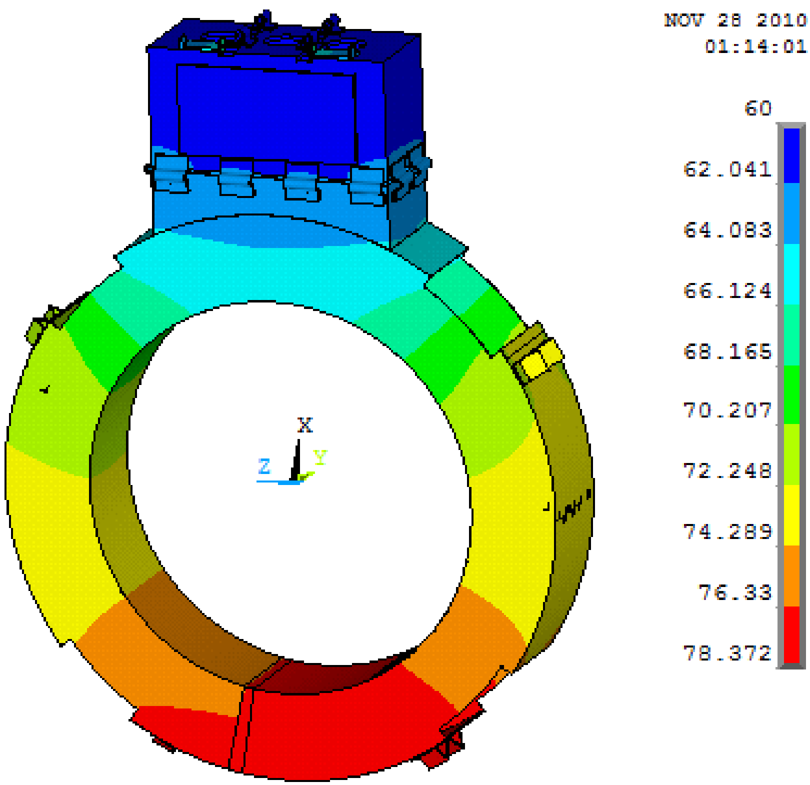


Tmax=73.466 K at main shield support cold base

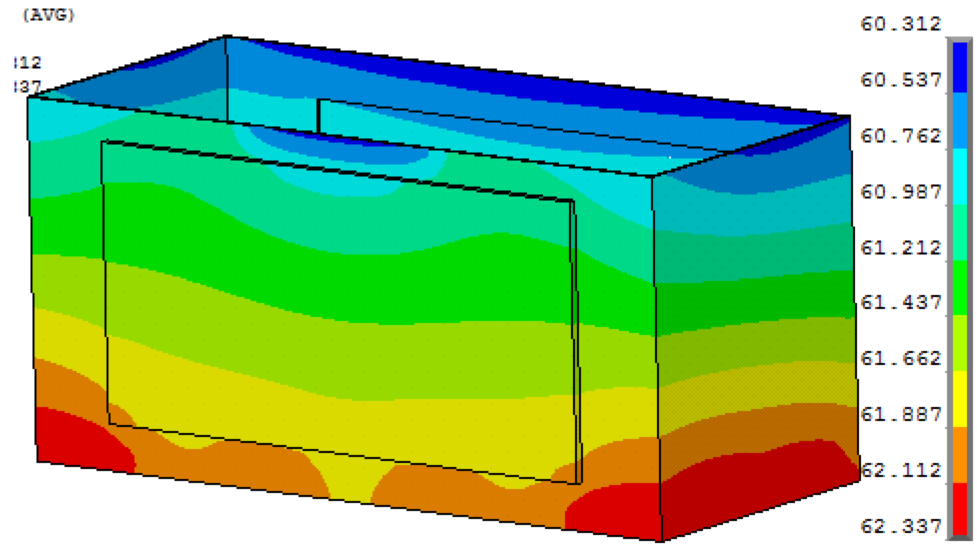


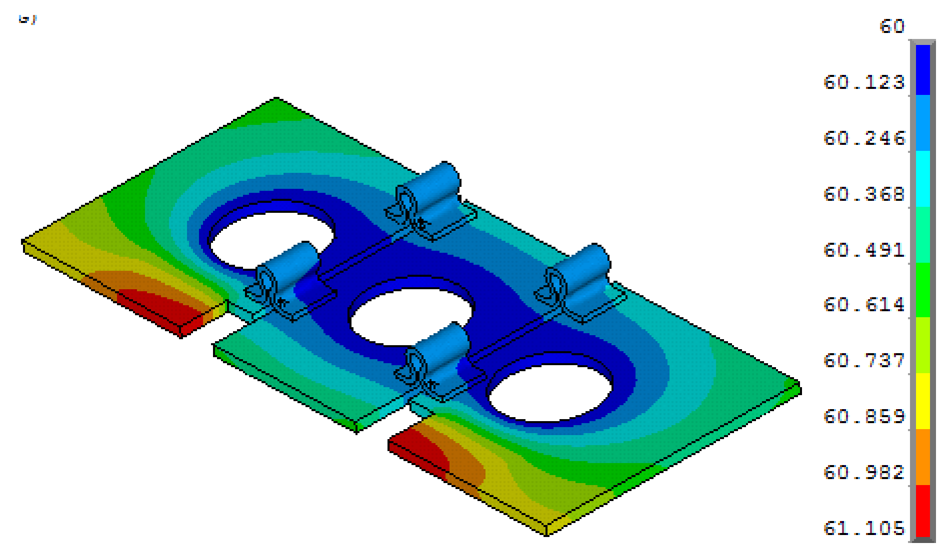
Tmax=73.654 K at connection surface of Cu strips to be connected with cold mass support interception

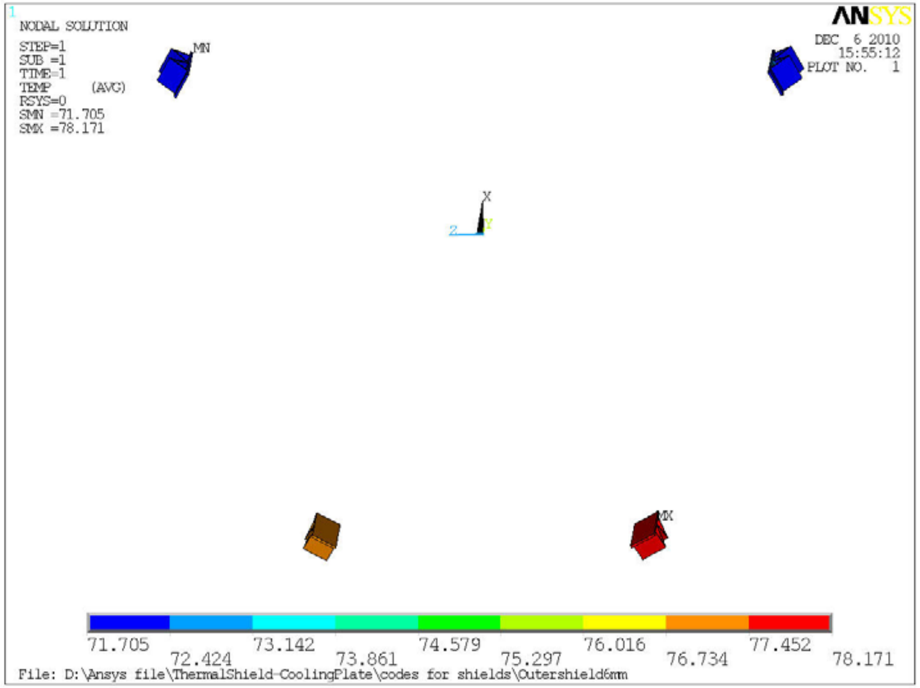
CASE III: The thickness of outer cylindrical shield is 6mm w/3 coolers running



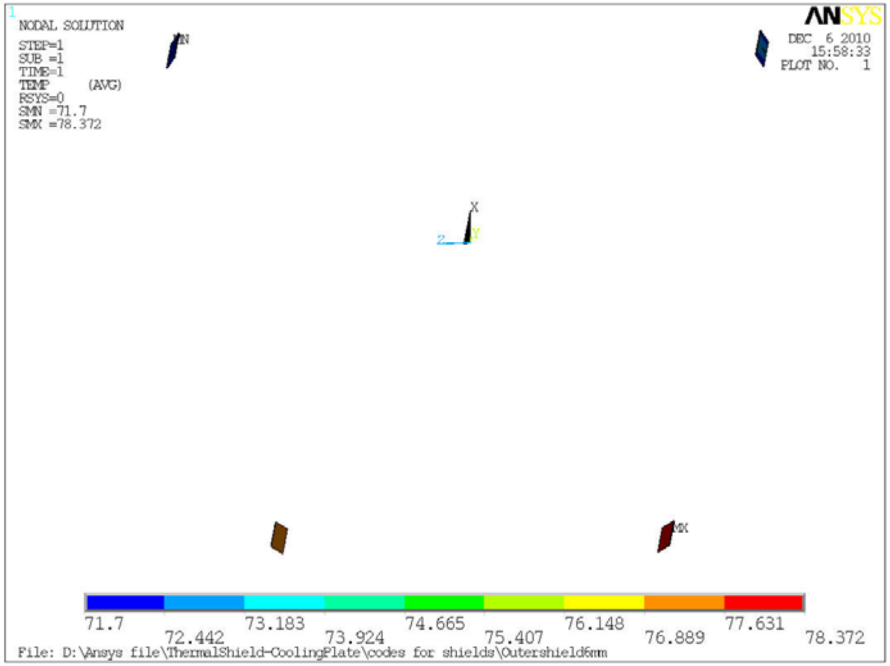
ΔT=18.372 K





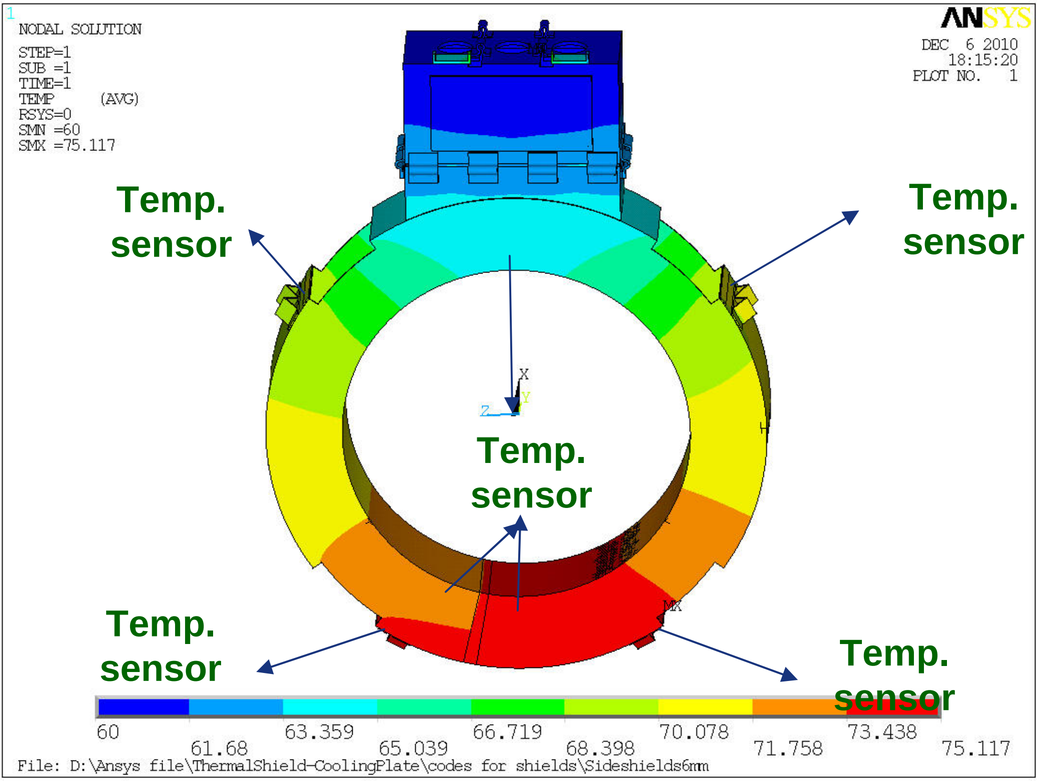


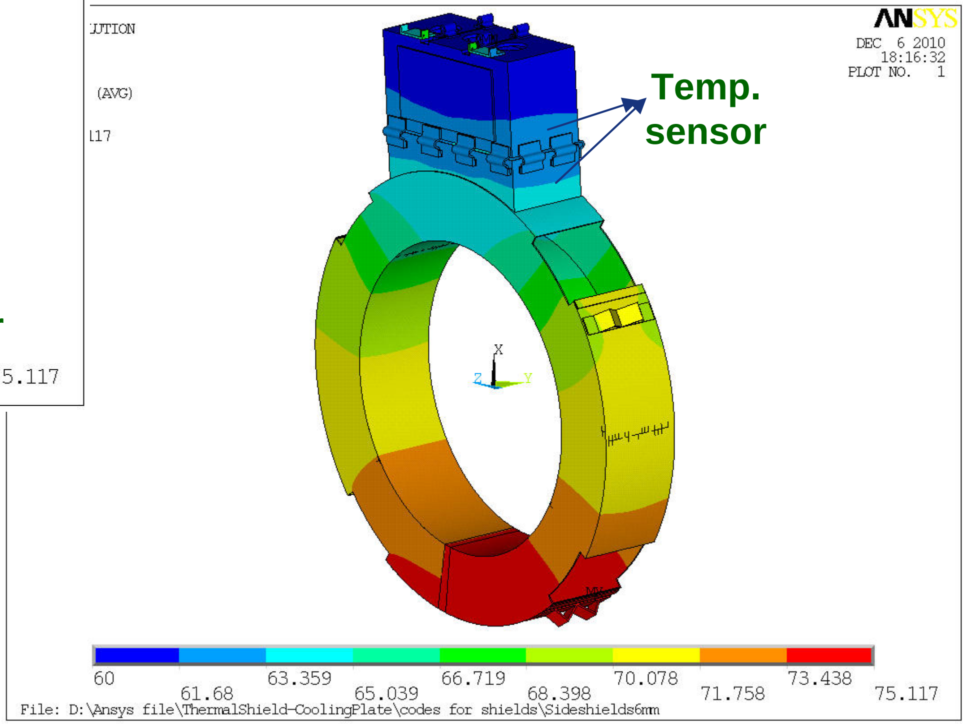
Tmax=78.171 K at main shield support cold base



Tmax=78.372 K at connection surface of Cu strips to be connected with cold mass support interception

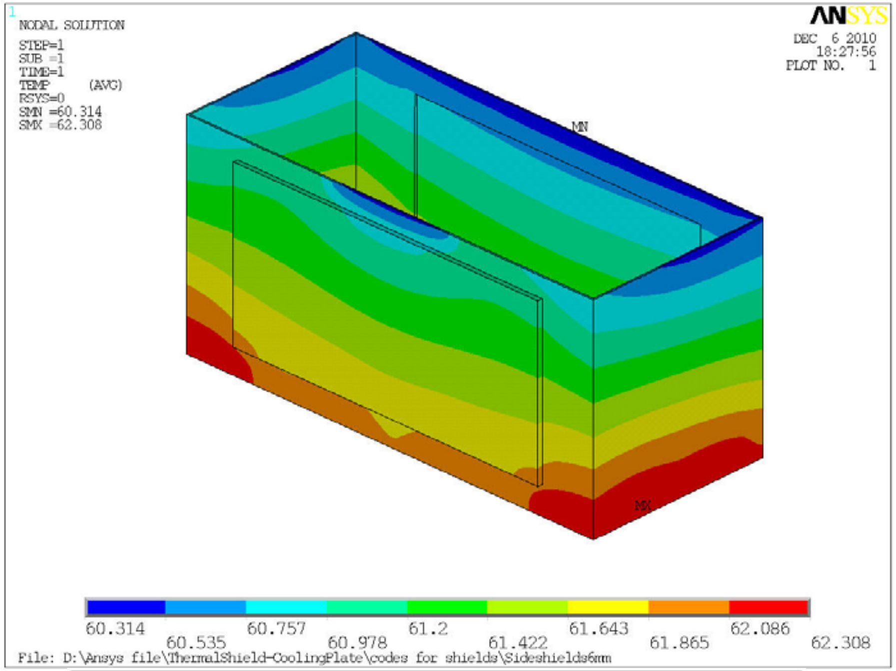
CASE IV: The thickness of side shields is 6mm w/3 coolers running

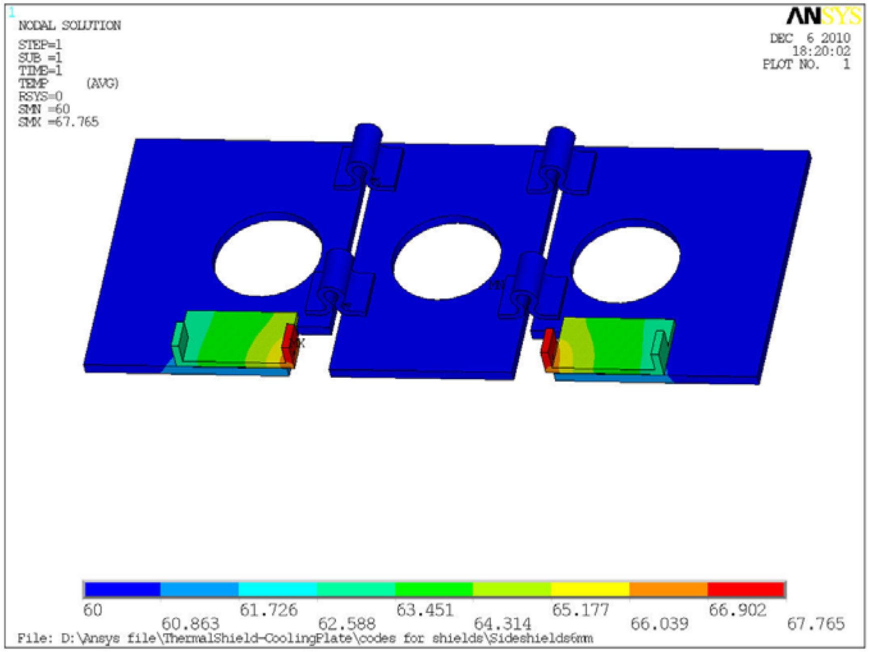


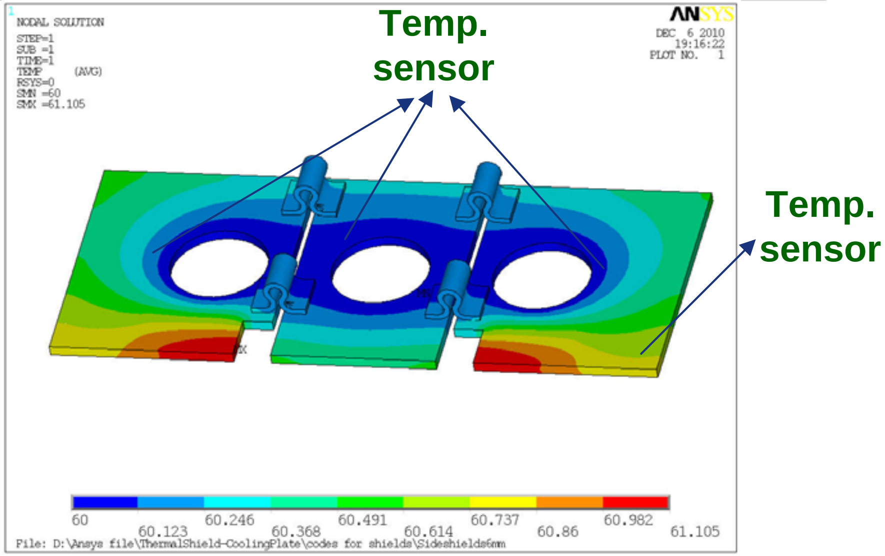


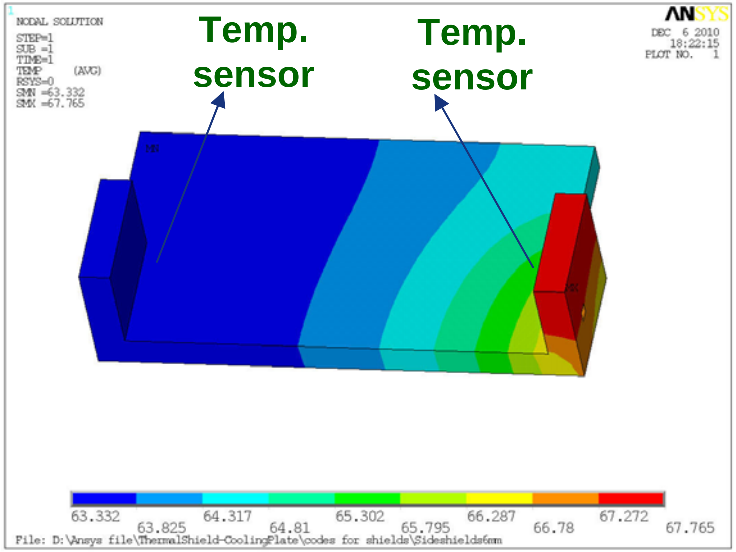
ΔT=15.117 K

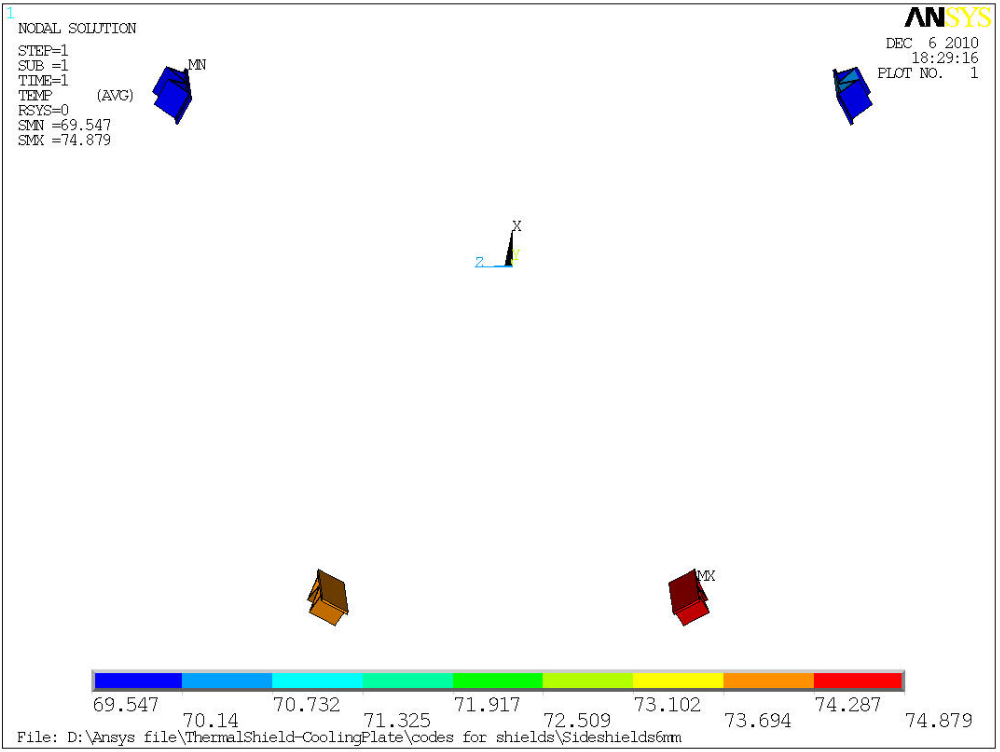
MICE/MuCool Coupling Magnet Cryostat Engineering Design

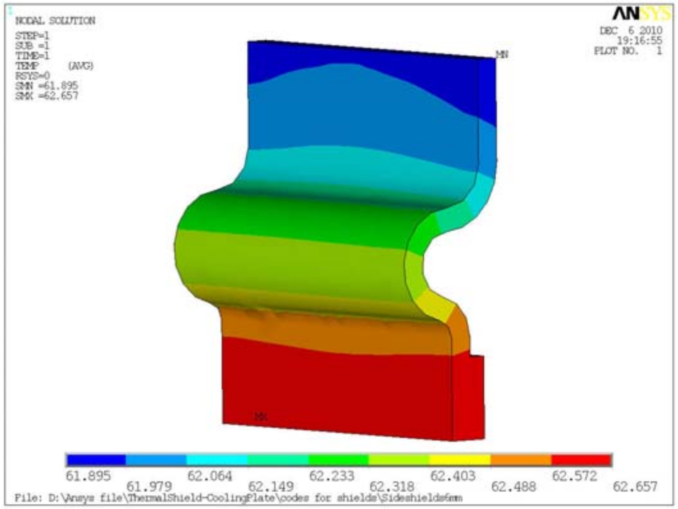




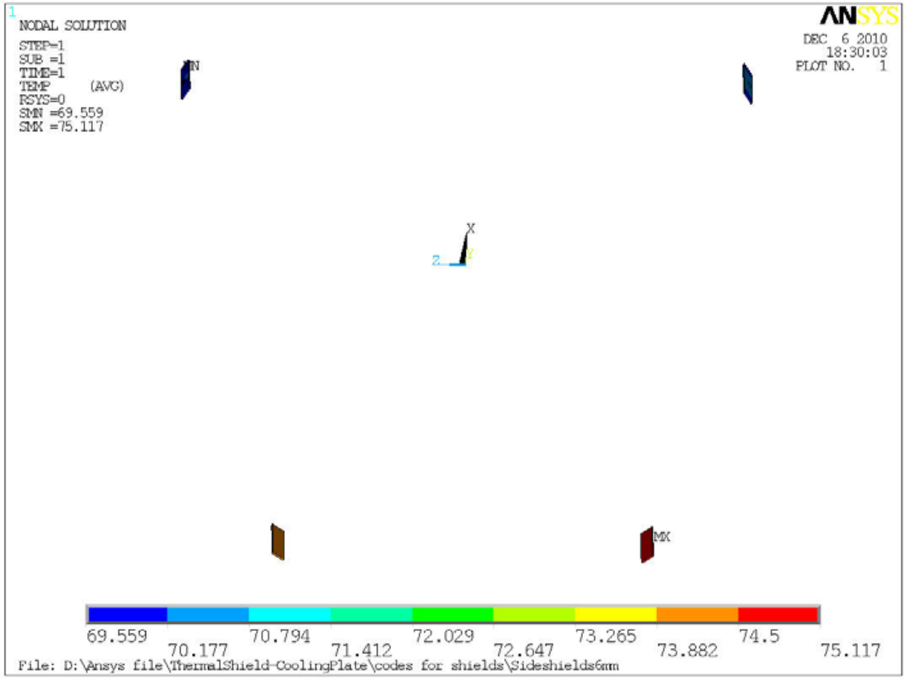






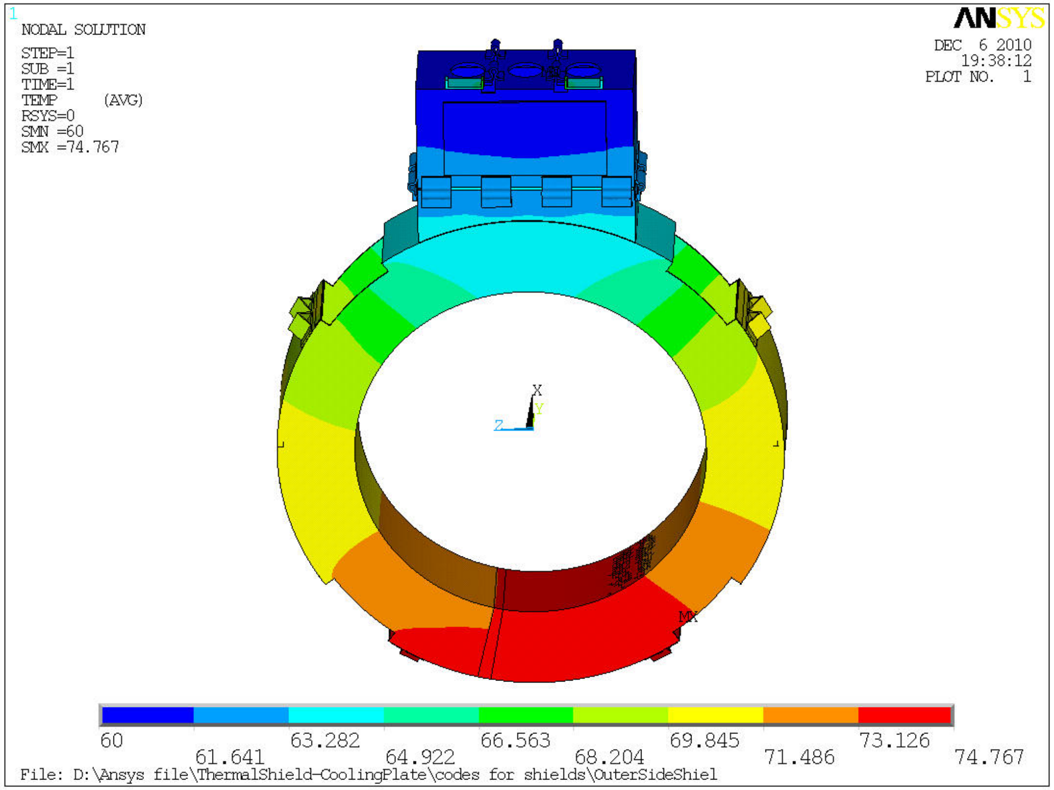


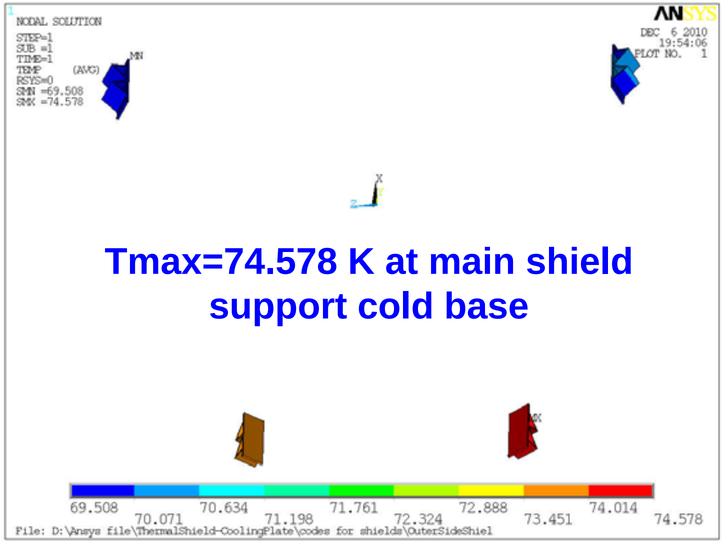
Tmax=74.879 K at main shield support cold base

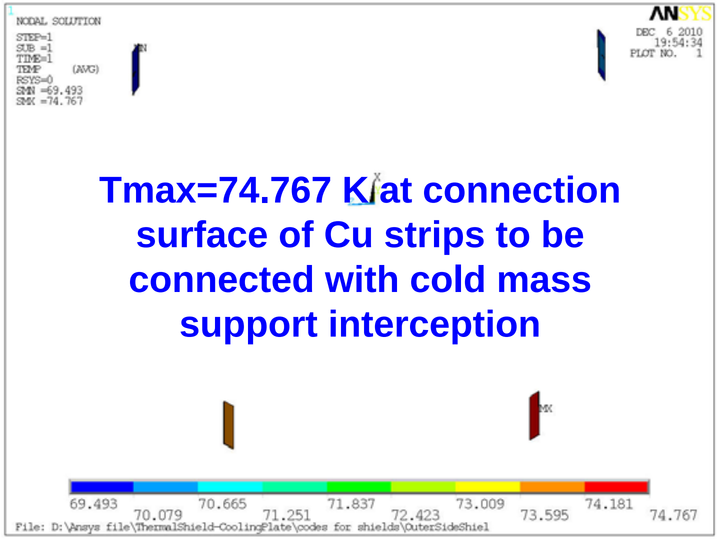


Tmax=75.117 K at connection surface of Cu strips to be connected with cold mass support interception

CASE V: The thickness of side and outer cylindrical shield is 6mm w/3 coolers running

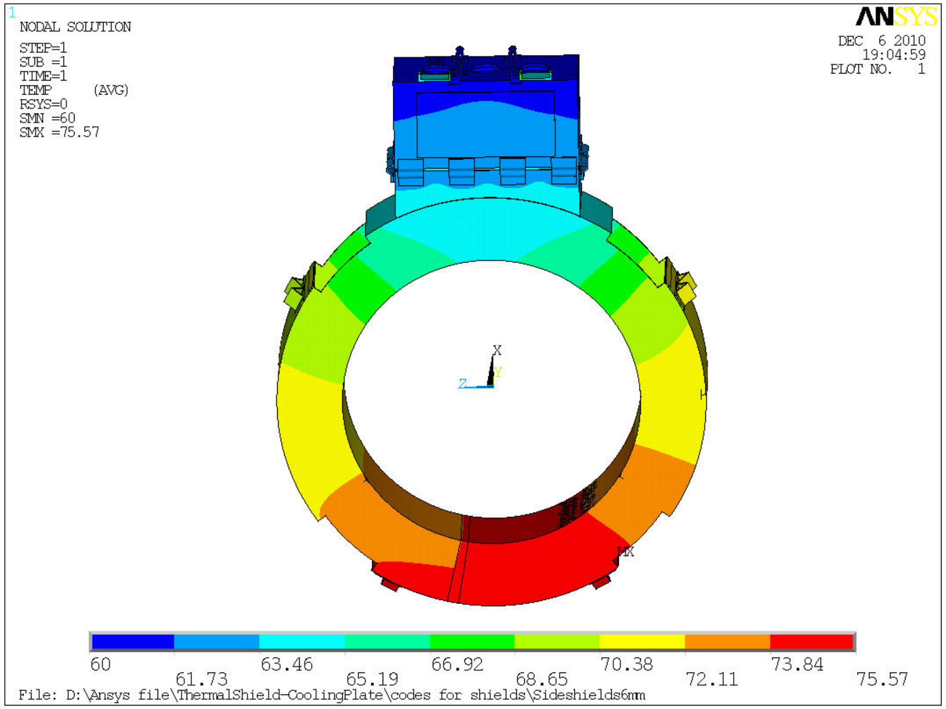


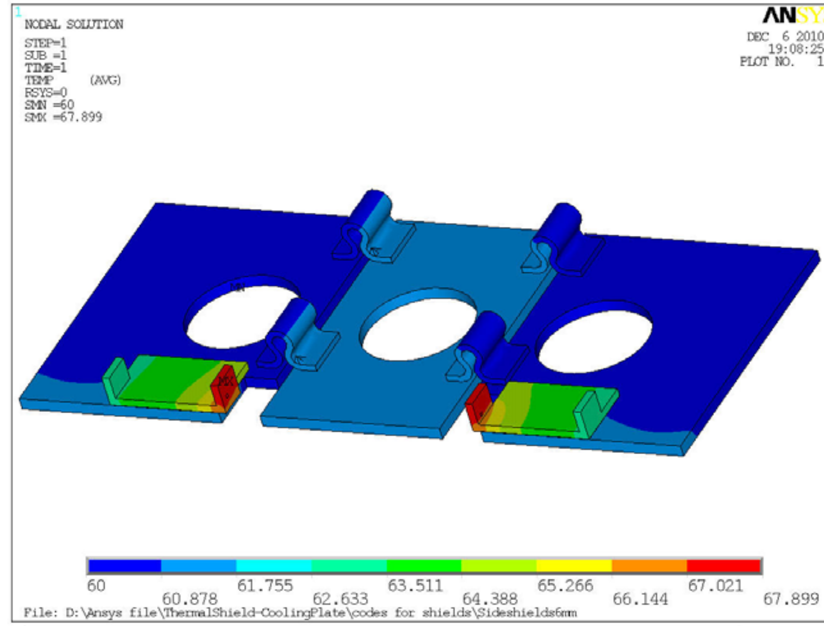




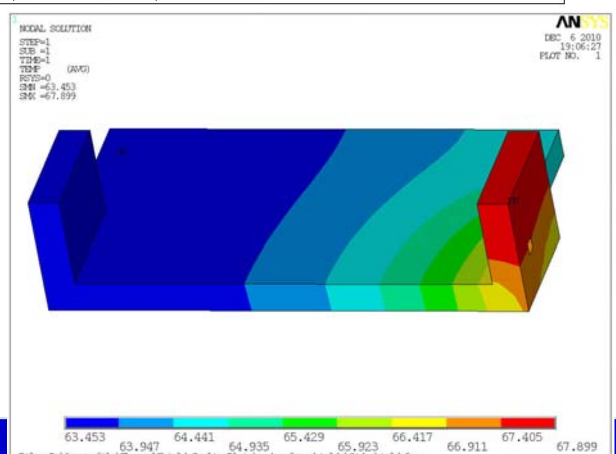
ΔT=14.767 K

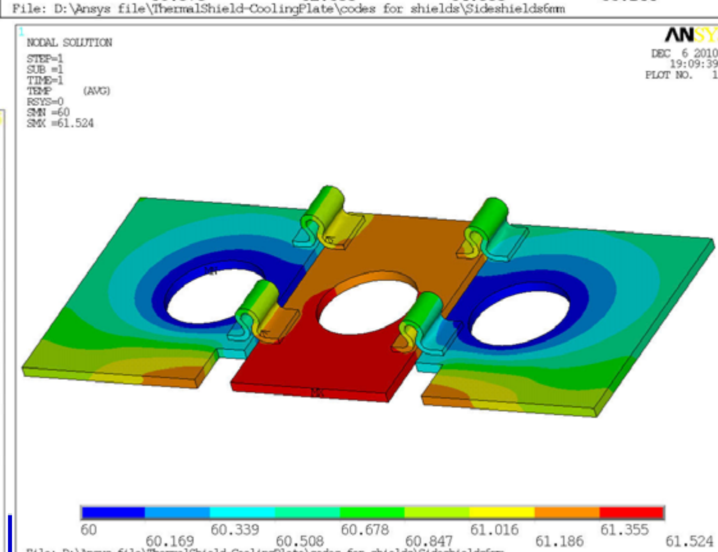
CASE VI: The thickness of side shields is 6mm w/2 coolers running



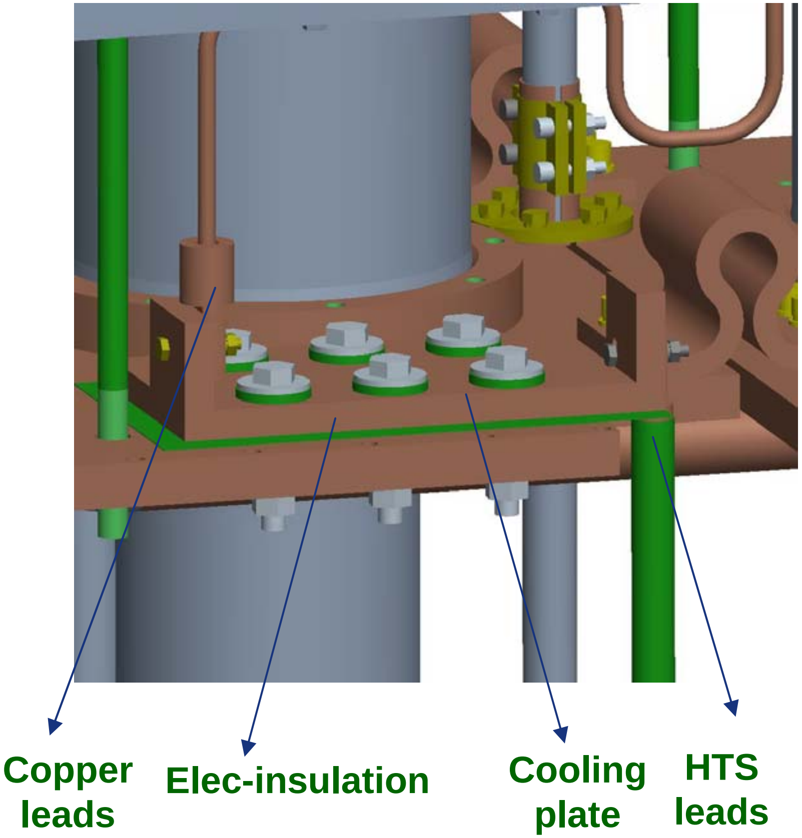


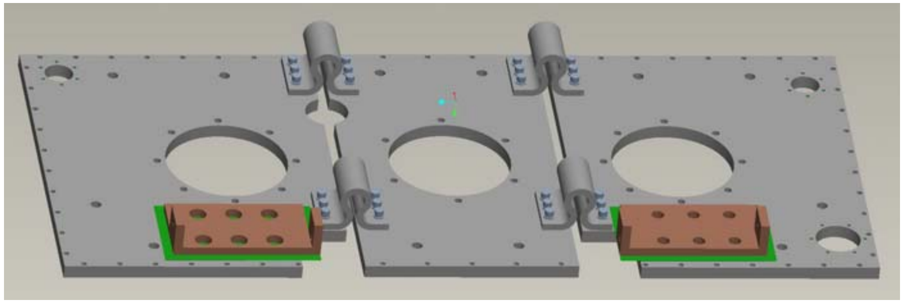
ΔT=15.57 K

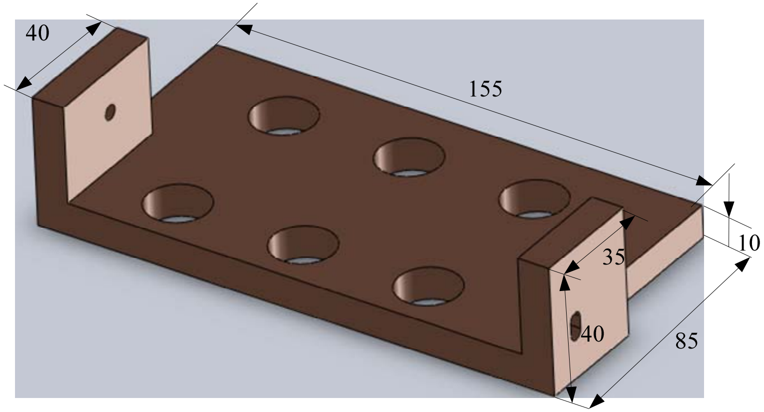




Current leads' cooling

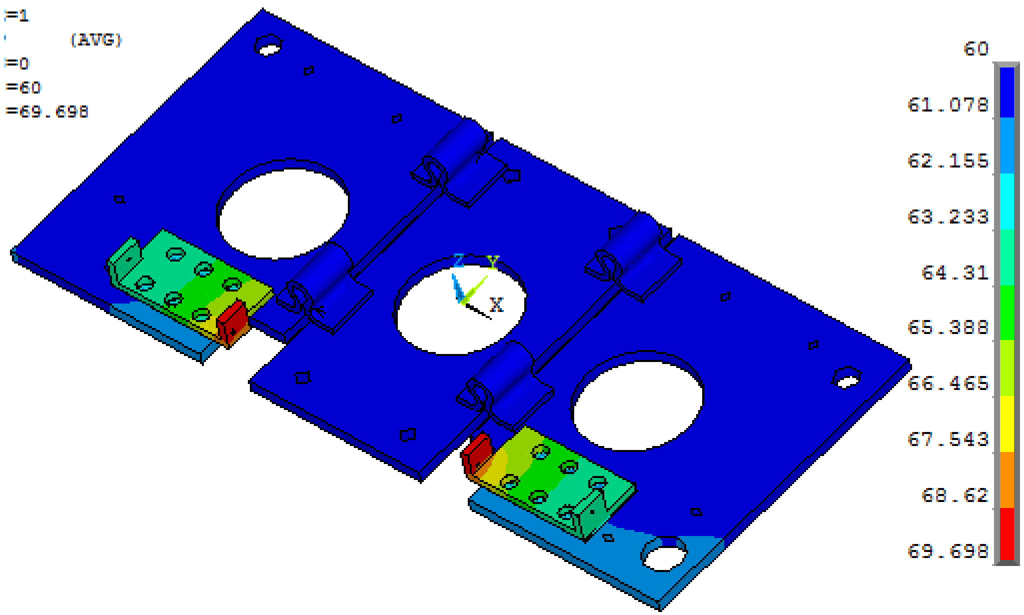


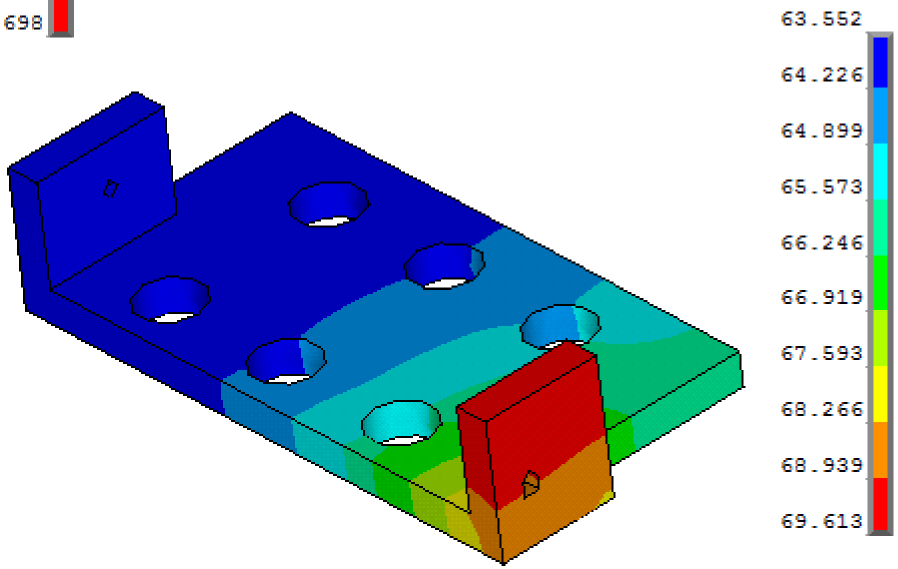




FEA model

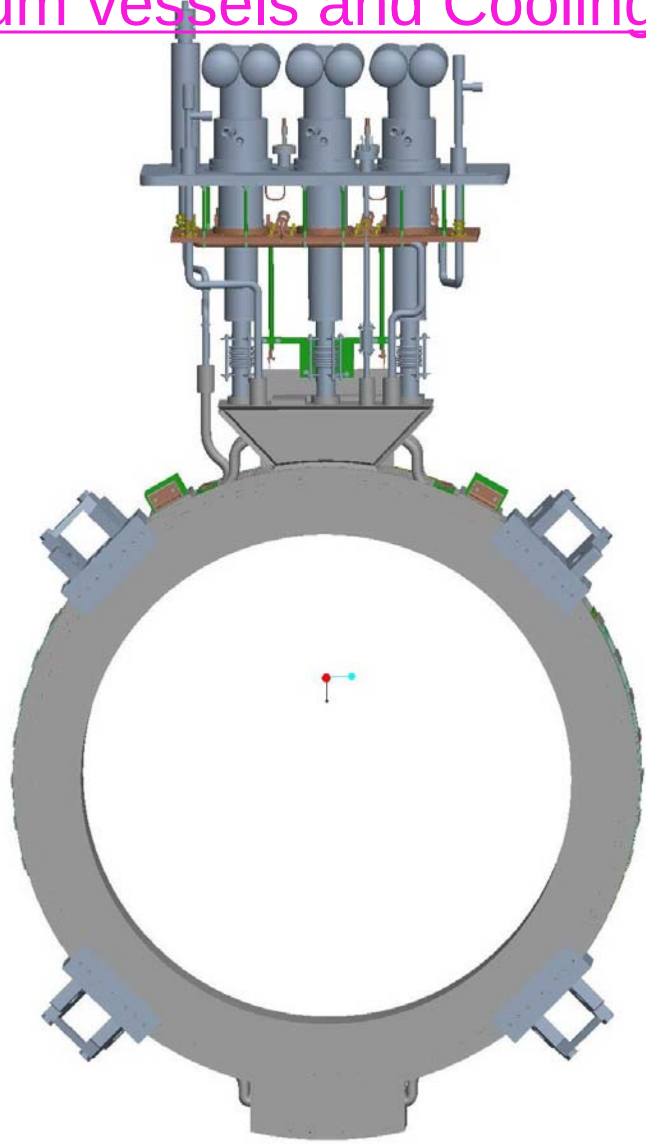
Simulation results:





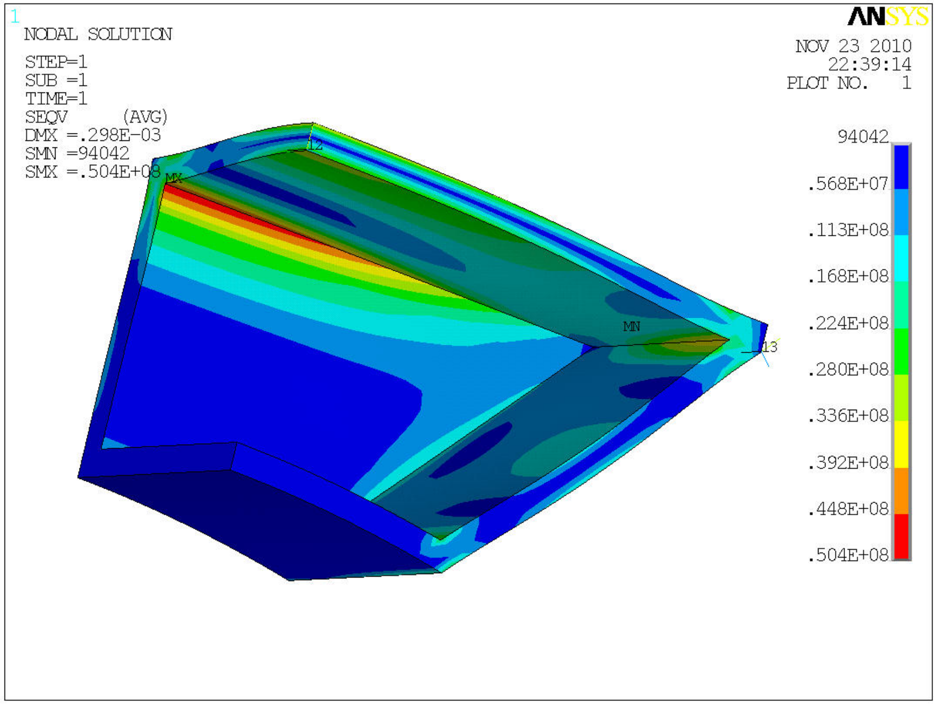
Thickness of all shields=4mm
Tmax=69.613 at Cu lead side,
T=63.552 at HTS lead side

Helium vessels and Cooling piping



Main parameters of top LHe vessel

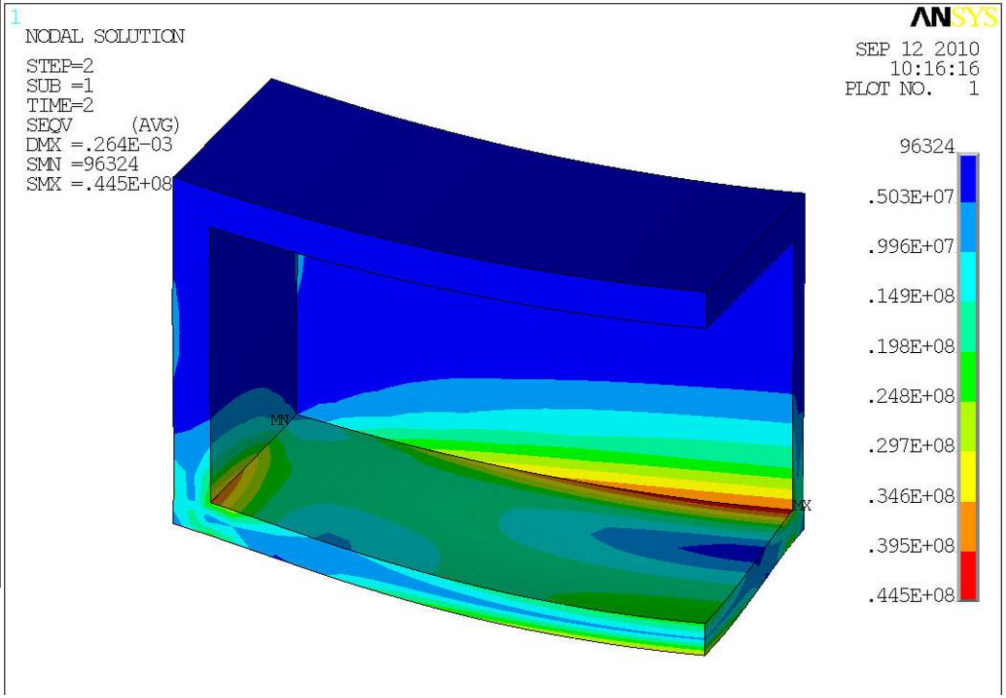
Inner diameter of lower plate (mm)	1860
Height of side plate (mm)	180
Length of long side plate (mm)	638
Length of short side plate (mm)	290
Thickness of lower plate (mm)	15.88
Thickness of long side plate (mm)	15.88
Thickness of short side plate (mm)	15.88
Thickness of upper plate (mm)	15.88
Volume (Liter)	19.2
Design internal pressure (bara)	4
Peak stress (MPa)	50.4
Allowable stress (MPa)	66



Von Mises Stress for top LHe container

Main parameters of bottom LHe vessel

Inner diameter of lower plate (mm)	1860
Height of side plate (mm)	146
Length of long side plate (mm)	460
Length of short side plate (mm)	290
Thickness of upper plate (mm)	15.88
Thickness of lower plate (mm)	15.88
Thickness of long side plate (mm)	15.88
Thickness of short side plate (mm)	15.88
Volume (Liter)	12.6
Design internal pressure (bara)	4
Peak stress (MPa)	44.5
Allowable stress (MPa)	66



Von Mises Stress for bottom LHe container

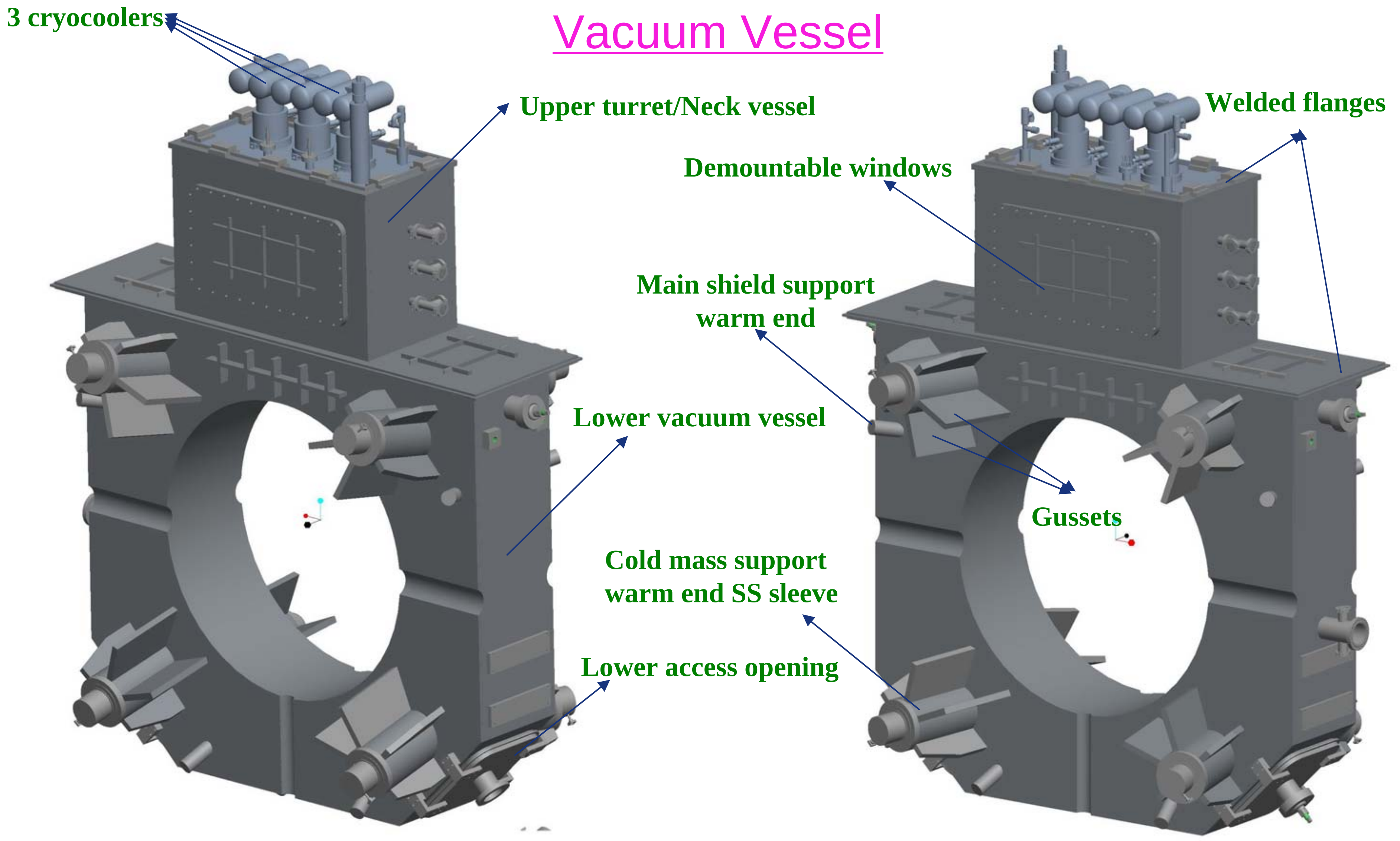
$$t_s = \frac{PD_o}{2([\sigma]^t E_j + PY)}$$

$$t_{sd} = t_s + C$$

Verification calculation results of cooling pipes

Material	6061-T6Al	Copper		SS304		
Allowable stress [σ] (MPa)	72	45		137		
Welding joint coefficient E_j	0.8	0.8		0.9		
Coefficient Y	0.4	0.4		0.4		
Design internal pressure (bara)	21	21		21		
Outer Diameter D_o (mm)	30	8	10	18	22	24
Calculated thickness t_s (mm)	0.539	0.228	0.285	0.152	0.186	0.211
Additional thickness C (mm)	0.35	0.03	0.03	0.6	0.6	0.6
Allowable Min. thickness t_{sd} (mm)	0.889	0.258	0.315	0.752	0.786	0.811
Pipe size (mm)	Φ30×4	Φ8×1	Φ10×1	Φ18×1	Φ22×1	Φ24×1

Vacuum Vessel



Main design dimensions of the inner cylindrical shell

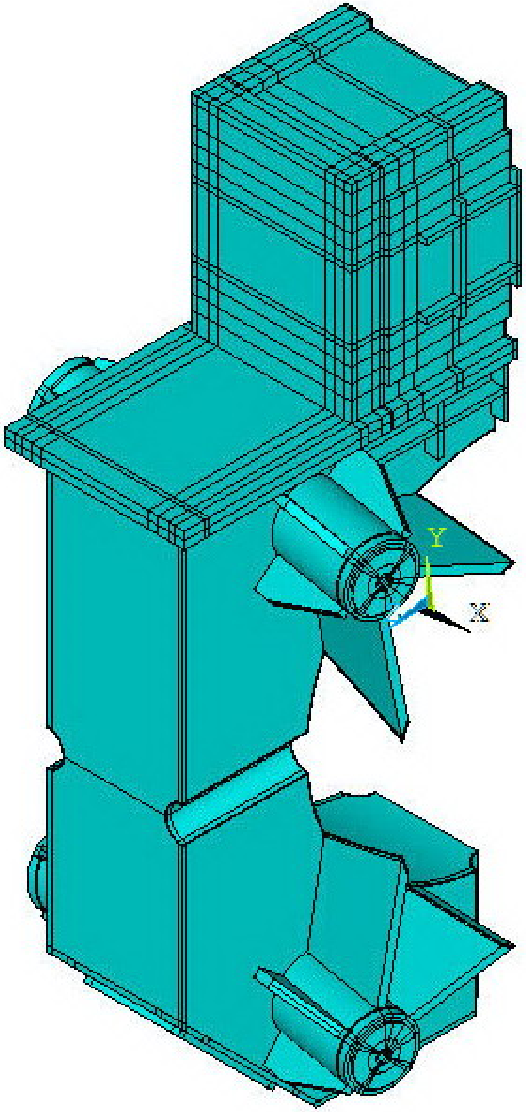
Design dimension (mm)	ID	OD	Thickness	Length
Inner Vessel	1388.80	1396.80	4	501

Verification calculation of vacuum vessel under external pressure

Under External Pressure	Inner Vessel (Vacuum Break)
Material	S.S-304
Shell Thickness (mm)	4
Max. allowable P (MPa)	0.26
Actual Working P (MPa)	0.1
Hook stress=AWP*OD/4/thk (MPa)	8.73
Longitudinal Stress =AWP*OD/2/thk (MPa)	17.46

Verification Calculation of vacuum vessel under internal pressure

Under Internal Pressure	Inner Vessel (Leak check)
Design Pressure (MPa)	0.1
Stress Limit (MPa)	120.6
Joint Efficiency	0.7
Thickness Required=DPres*IR/(SLtd*JE-0.6) (mm)	0.828
Actual design thickness (mm)	4
Hook Stress=Dpres*2*IR/4/ADThk (MPa)	8.68
Longitudinal Stress=Dpres*2*IR/2/ADThk (MPa)	17.36



FE Model

FE Model:

Two gussets around each cold mass support sleeve are constrained by welding onto the RF cavities vacuum vessel. Considering symmetry of the vacuum vessel, 1/2 model is developed for FEA.

Assumption:

The force on the rectangular neck top plate of the vacuum vessel is 250kg (gravity of the coolers and other force). And assuming this force is loaded uniformly on the top plate.

Boundary conditions and loads:

UX, UY and UZ of gussets surface welded to the RF cavities vacuum vessel are set as zero.

Gravity of vacuum vessel about 2 tons.

Outer pressure of 1bar.

The force on the top plate of neck 250 kg.

The forces on the sleeve cover caps transferred from cold mass support bands, different at different stages.

Main structure parameters:

Design dimensions of main vacuum vessel

Design dimension (mm)	ID	OD	Thickness	Length
Inner shell	1388.8	1396.8	4	501
	length	Height	Thickness	Length
End plates	2320	2155	16	----
side walls	----	1655/707	16	501
Large Flange/Flange Weld	2508/2538		16	689/719

Design dimensions of neck vessel (mm)

Distance between the inner vessel axis center and neck top plate	1817
neck length	1150
neck width excluding thickness of windows	599
neck height excluding flanges	764
Thickness of neck end plates	25
Thickness of neck end plates	30
Thickness of neck top plate	25
Thickness of neck window plate	30
Top flange length/width/thickness	1176/617/25
烟囱顶板尺寸长度/宽度/厚度	1092/533/30

Forces on SS sleeve cover caps at different stages

	Sleeve 1	Sleeve 2	Sleeve 3	Sleeve 4
Stage 1 (1g+1bar) (kN)	0	0	0	0
Stage 2 (1g+1bar+300K) (kN)	90.4	90.4	50.0	50.0
Stage 4a-normal operation case (1g+1bar+4K+magnetic force 253kN) (kN)	180	125.5	150	85.1
Stage 4b-the worst operation case (1g+1bar+4K+magnetic force 416kN) (kN)	211.2	107.9	171.5	62.8

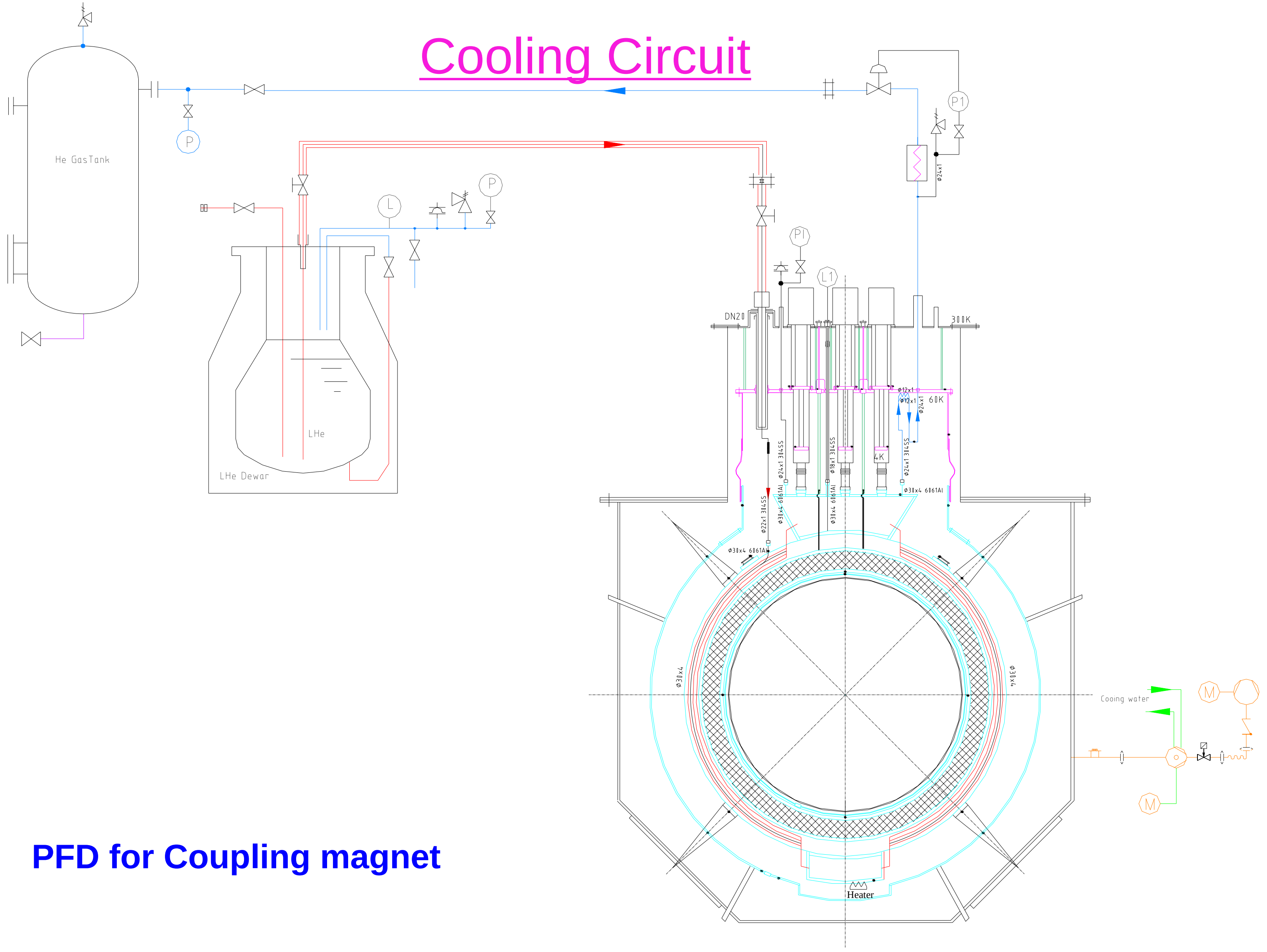
Note: *1g stands for the gravity of the vessel; 1bar stands for the outer pressure; 300K stands for the cold mass is at 300K; 4K stands for the cold mass is at 4.2 K; magnetic force stands for the magnetic force form other coils in the channel at the worst case.

Simulation results

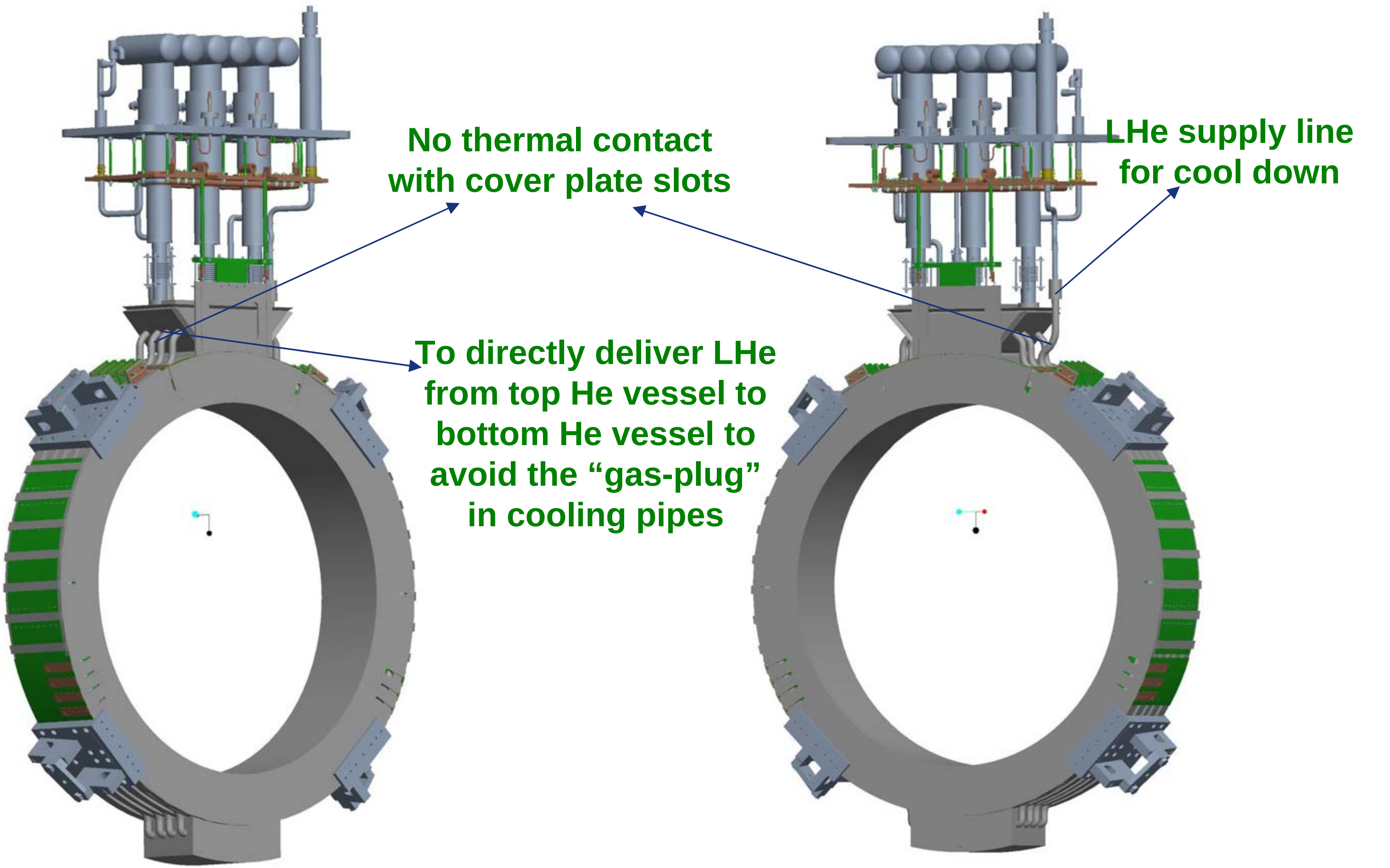
To be added

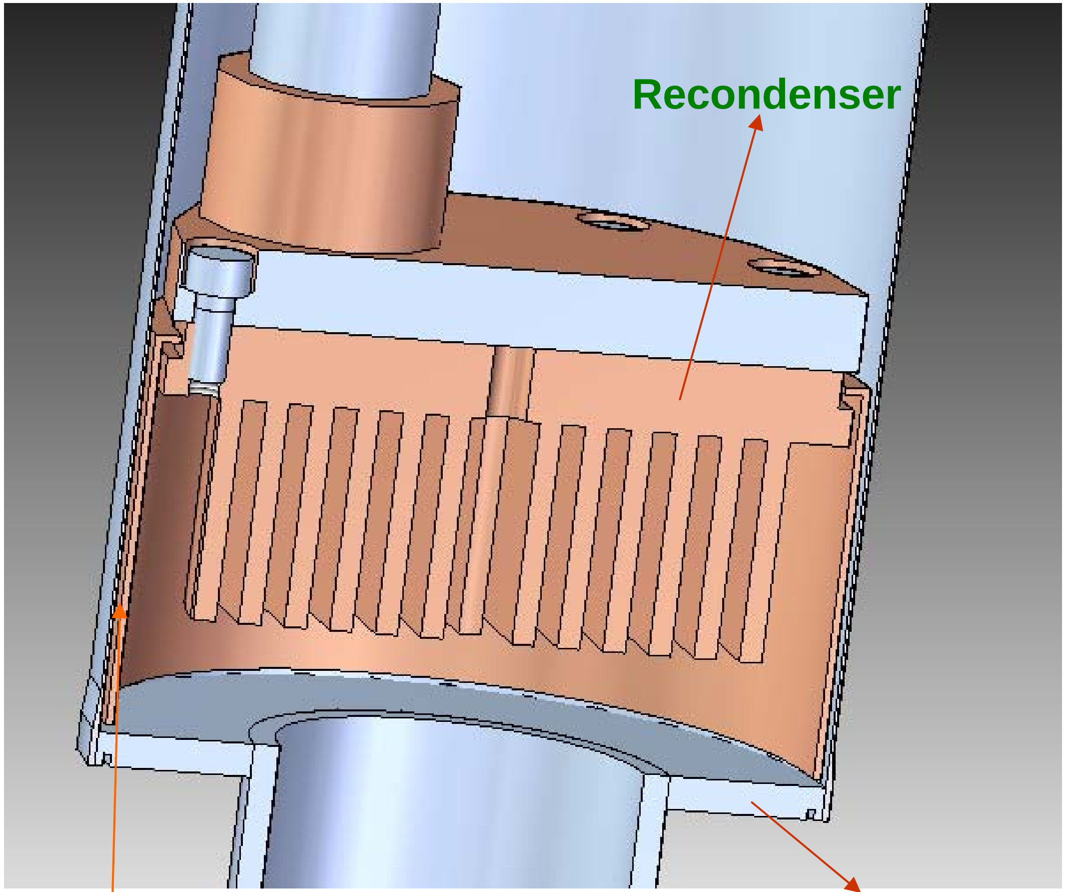
Deformation of vacuum vessel under gravity and vacuum

Cooling Circuit



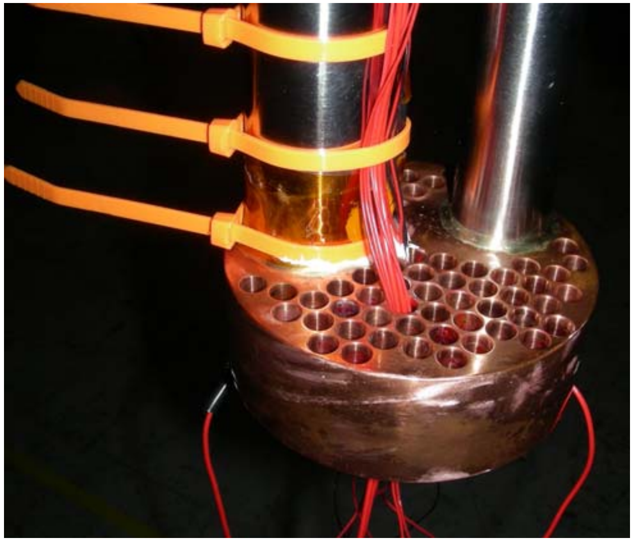
PFD for Coupling magnet


No thermal contact
with cover plate slots
LHe supply line
for cool down
To directly deliver LHe
from top He vessel to
bottom He vessel to
avoid the “gas-plug”
in cooling pipes



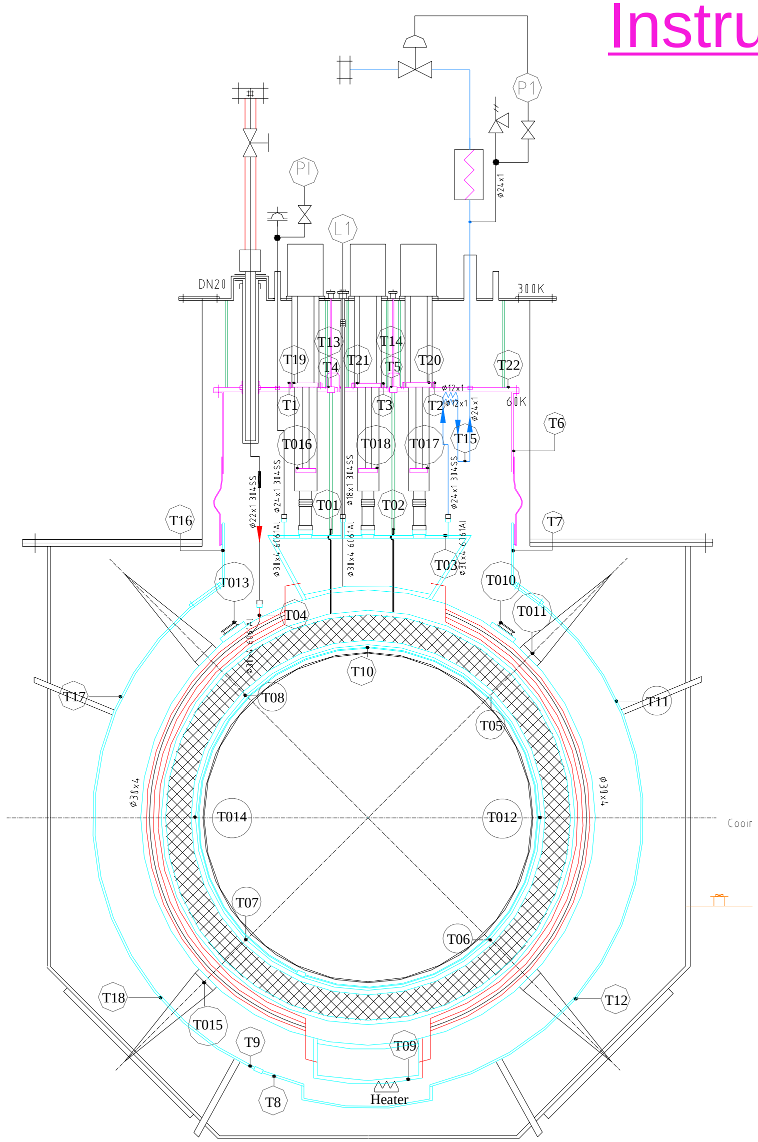
3D model for cryocooler 2-stage cold head re-condenser

- The configuration of the re-condenser has been modified in order to enhance the heat exchange, and the heat transfer area is increased from 42000 mm^2 to 56477 mm^2 (1.35 times).

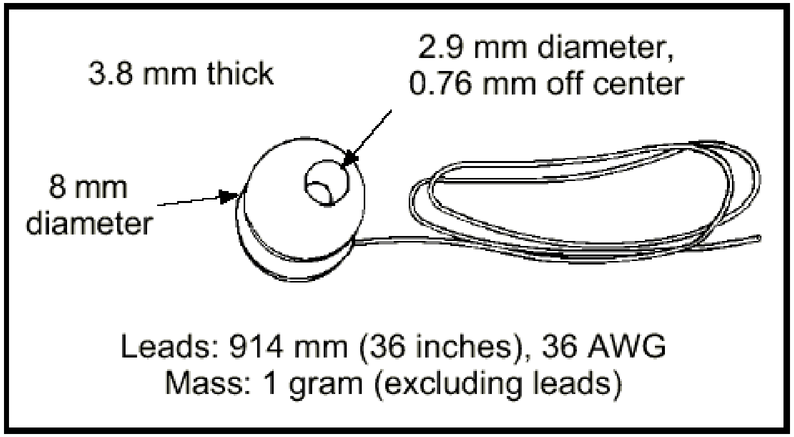


Previous re-condenser

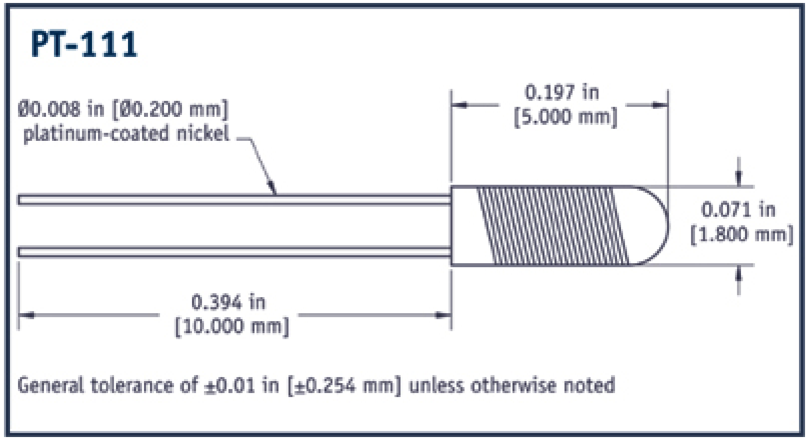
Instrumentation



- Level meter: 2, one for top He vessel, one for cooling tubing nested in cover plate, 10 pins feedthrough x 1
- Pressure transducer: 1
- Pressure gauge: 1
- Heater: 1 on the bottom He vessel
- Voltage taps: 13 pairs, 10 pins feedthrough x 3
- Current leads, 1 pair, 1 pin feedthrough x 2



CX-1010



Temperature sensors:

- For measurement at the range of 3.5K-300K, the Lakeshore CERNOX RTD temperature sensors (CX-1010 model) with the CU (4-wire) package are chosen. There are 18 in total including 3 for redundancy at key points, and 3 feedthroughs with 32 pins each are to be applied.
- For measurement at the range of 40K-300K, the Platinum resistor temperature sensors (PT111 model) are chosen. There are 22 in total including 3 redundancy at key points, and 3 feedthroughs with 32 pins each are to be applied.
- The locations of the temperature sensors are mainly determined based on the simulation results for the temperatures of coil cold mass and the thermal shields.
- The mounting of the sensors and thermal anchor of the leads to the sensors will strictly follow the instruction provided by the vendor.

Conclusions

The updated engineering design is proposed involving:

- ✓ Available space for one more cryocooler to keep more margin for magnet cooling
- ✓ Demountable vacuum chamber and local windows on vacuum chamber & thermal shields for easier assembly and maintenance
- ✓ Cooling piping system was simplified for lower heat loads and easier fabrication & assembly
- ✓ Detailed 3D mechanical design was done, and related calculations and simulations were performed to verify the mechanical structure design

WISH MICE CC and MICE SUCCESSFUL!

Thank You !