Mu2e Production Solenoid Design

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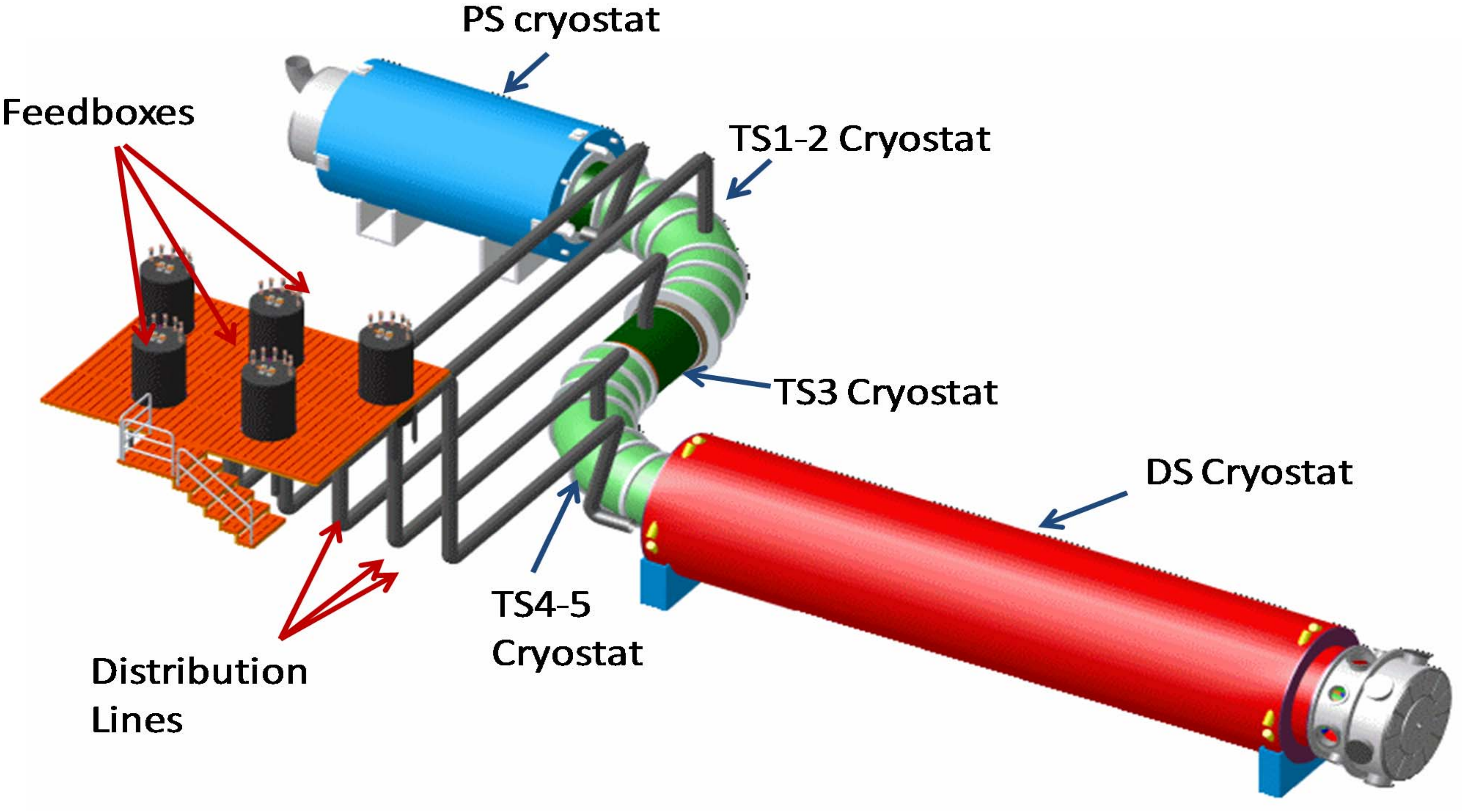
Workshop on Radiation Effects in Superconducting Magnet Materials (RESMM'12)

Mu2e magnet layout



Introduction

Production Solenoid (PS) performs the following functions in the mu2e:

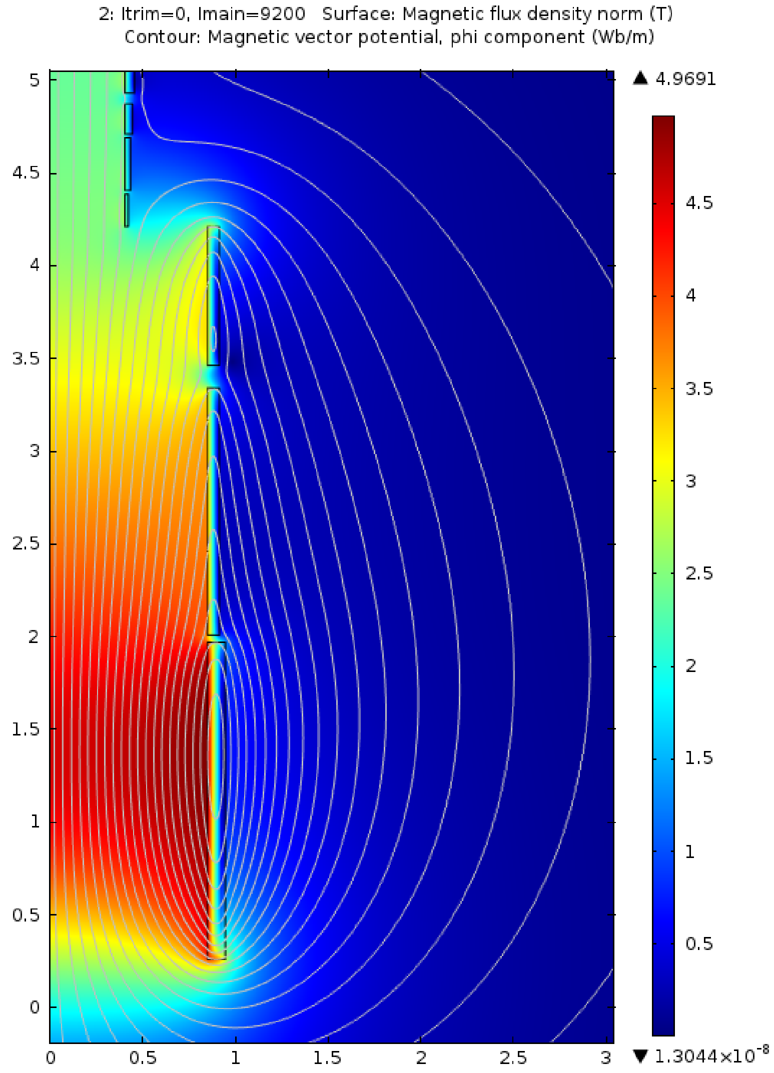
- Maximizes muon yield by efficiently focusing secondary pions and subsequent secondary muons towards the Transport Solenoid (TS) system, in the momentum range to be stopped in the stopping target.
  - PS meets this function by supplying a prescribed magnet field profile within a prescribed aperture.
- Provides a clear bore for beam line elements such as the primary production target and secondary particle radiation shield.
- Allows the primary proton beam to be steered into primary target; allows outgoing proton beam to exit without striking

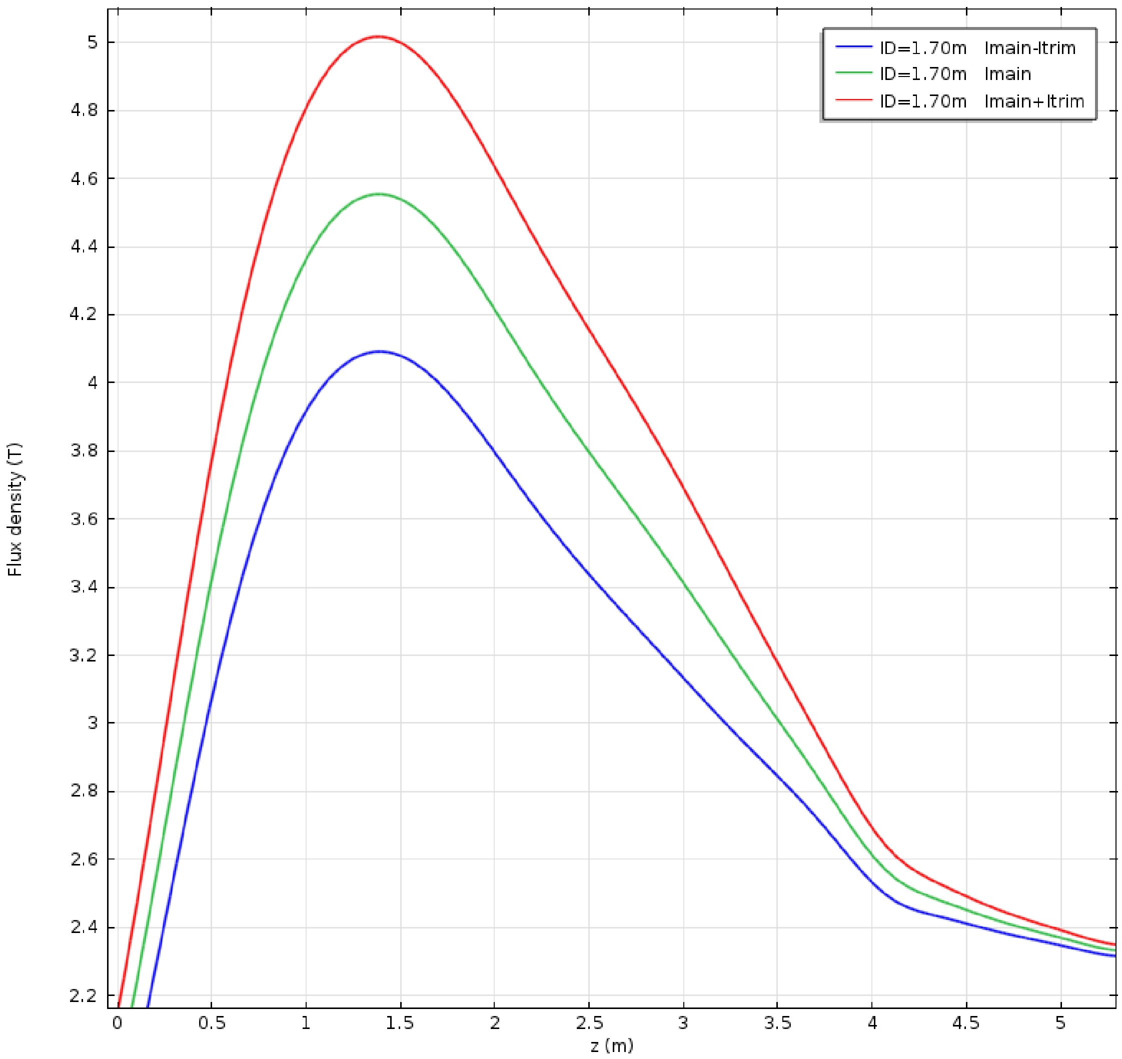
Requirements

- Magnetic:
  - Peak field on the axis 5 T ;
  - Axial gradient -1 T/m ;
  - Gradient uniformity ±5 %.
- Electrical:
  - Operating margins: ≥ 30 % in I_c, ≥ 1.5 K in T_c ;
  - Operating current 9÷10 kA;
  - Peak quench temperature ≤ 130 K;
  - Voltage across terminals ≤ 600 V.
- Structural:
  - Withstand forces at all conditions while part of the system or stand-alone;
  - Cryostated magnet weight ≤ 60 tons;
  - Compliance with applicable structural codes.
- Cryogenic:
  - Cooling agent: LHe at 4.6 K;
  - Total heat flow to LHe ≤ 100 W;
  - Cryostat ID 1.5 m;
  - Conduction cooling.
- Radiation:
  - Absorbed dose ≤ 6 MGy total;
  - Minimum RRR of stabilizer in the operating cycle ≥ 100.

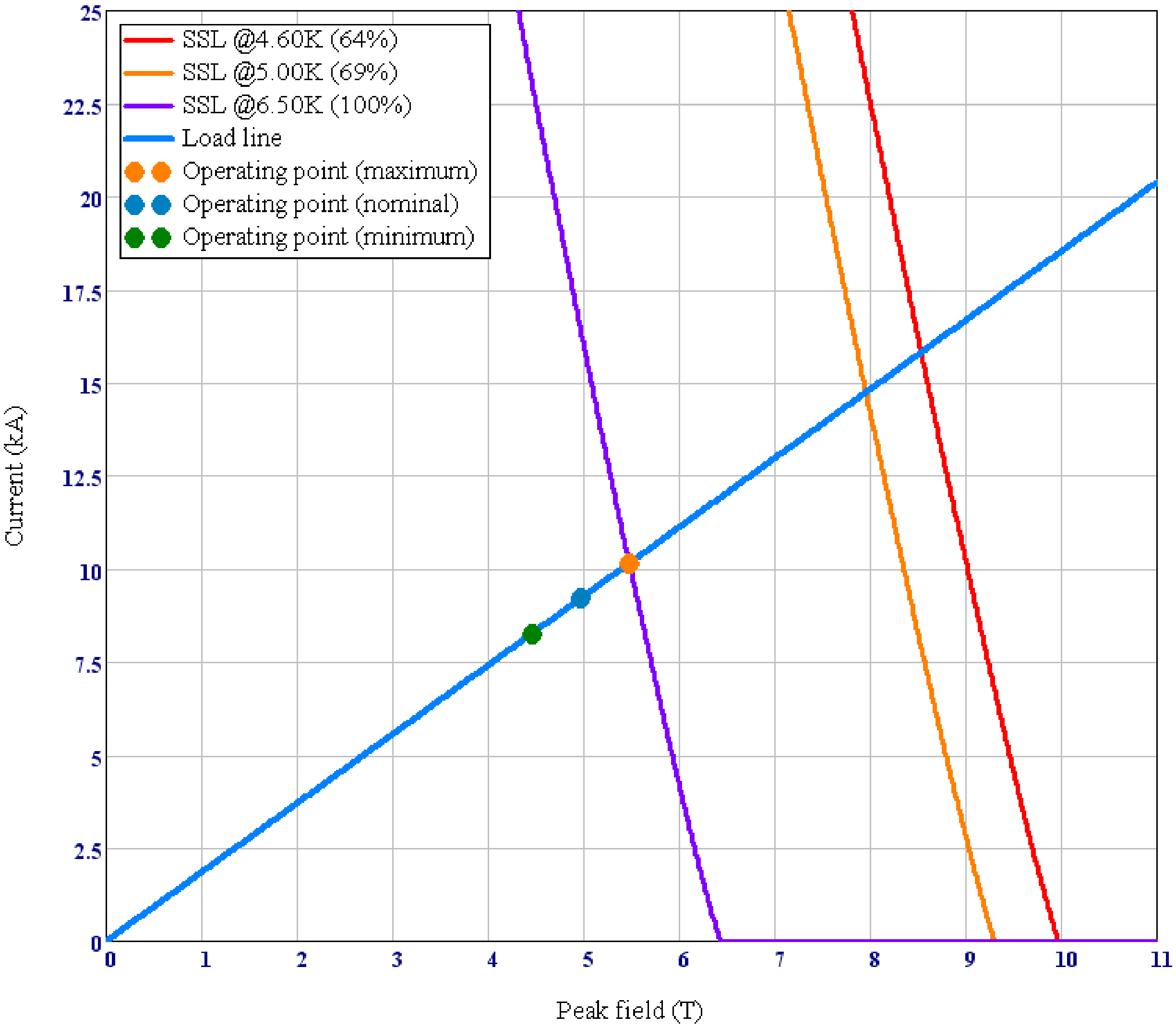
Magnetic design

Magnetic field

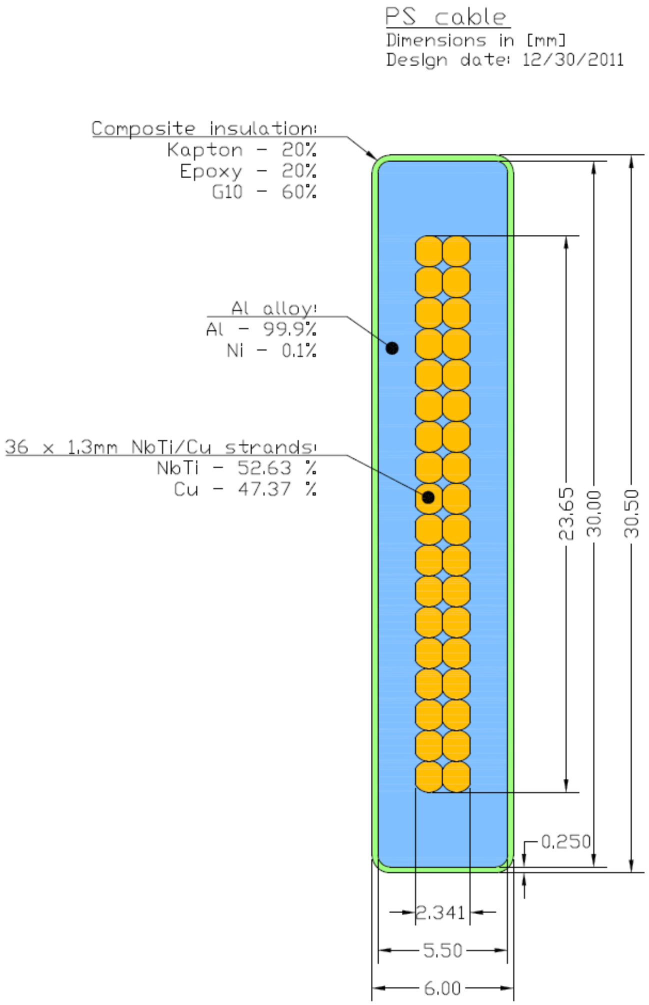




Load line


SSL @4.60K (64%)
SSL @5.00K (69%)
SSL @6.50K (100%)
Load line
Operating point (maximum)
Operating point (nominal)
Operating point (minimum)
Current (kA)
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Peak field (T)
0
1
2
3
4
5
6
7
8
9
10
11

Cable parameters



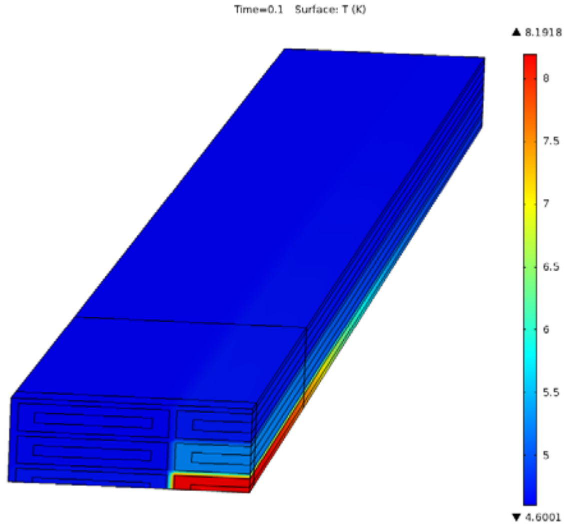
Parameter	Unit	Value
Rutherford cable		
Strand diameter	mm	1.300
Number of strands	-	36
Cable width	mm	23.65
Cable thickness	mm	2.34
Critical current density at 5T, 4.2K	A/mm^2	>3000
Strand Cu/non-Cu ratio	-	0.9
Initial RRR of Cu matrix	-	>100
Filament diameter	µm	<30
Al-stabilized cable		
Bare cable width	mm	30.00
Bare cable thickness	mm	5.50
Overall stabilizer/superconductor ratio in the bare cable	-	5.56
Initial RRR of Al stabilizer	-	>1000
Cable insulation		
Type: pre-preg Kapton + E-glass		
Pre-preg Kapton thickness	mm	0.1
E-glass thickness	mm	0.15

Magnet parameters

Parameter	Unit	3-layer design
Liquid helium temperature (T_{LHe})	K	4.6
Operating current (I_{op})	kA	9.20±0.95
Peak axial field at I_{op}	T	4.56±0.46
Peak coil field at I_{op}	T	4.97±0.51
Quench current at T_{LHe}	kA	15.81
Current sharing temperature at I_{op}	K	7.04-6.50
Minumum temperature margin	K	1.50
Maximum allowable temperature (T_{maxall})	K	5.54-5.00
Fraction of SSL at T_{LHe}		0.523-0.642
Fraction of SSL at T_{maxall}		0.628-0.689
Stored energy	MJ	55.15-79.74
Self-inductance	H	1.58
Peak coil voltage	V	600
Fast dump resistance	mΩ	59.11
Initial time constant of fast discharge	s	26.7
MIITs during current decay	MA^{2}s	910-1376
Cable length	km	8.67
Cold mass inner diameter	m	1.70
Cryostat inner diameter	m	1.50
Cold mass length	m	4.02
Cryostat length	m	4.50
Cold-mass weight	tonnes	~10
Cryostat weight	tonnes	10.7
Axial force on the cold mass (TS=on)	MN	1.28-1.36

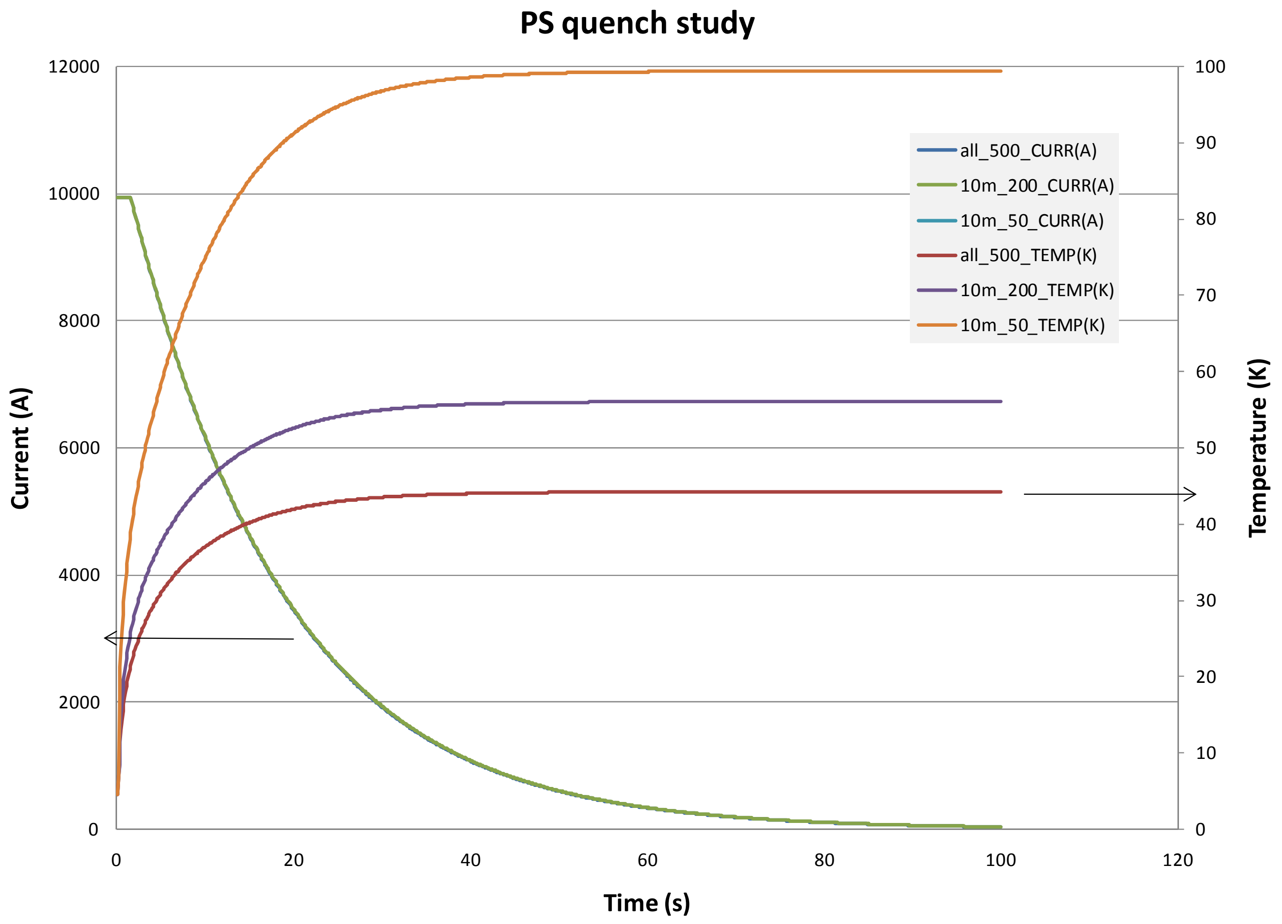
Magnet stability

- Ability of the magnet to recover from a short-term transition from superconducting to normal state.
- Characterized by the minimum quench energy (MQE) – the minimum energy deposited in the coil causing the irreversible transition to normal state (quench)
- In the absence of a strict stability criteria, we chose the MQE to be comparable with other large solenoids that were built and tested:
  - CMS MQE = 620 mJ
  - ATLAS CS MQE = ~400 mJ



Case: 3-layers	MQE, mJ	
	Al-stab	Cu-stab
Cable stack, RRR_{Al}=1000, RRR_{Cu}=100, T_0=4.6K		
Maximum performance, I_{3L}=10.15 kA, B_{peak}=5.48 T	157	34
Nominal performance, I_{3L}=9.20 kA, B_{peak}=4.97 T	263	56
Minimum performance, I_{3L}=8.25 kA, B_{peak}=4.46 T	411	92

Quench protection



- Adiabatic analysis by QLASA;
  - No quench-back from the structure;
- The peak coil temperature reaches ~45 K for non-degraded RRR;
- In case of a factor of 10 RRR degradation in a short cable segment (worst case):
  - $RRR_{Al} = 50$;
  - $RRR_{Cu} = 10$
  - Peak coil temperature < 100 K;
- Meets the design requirement on the peak coil temperature.

Structural design

Stress criteria

Measured strength of Al-stabilized ATLAS cable.

From A. Yamamoto, et al., “Design and Development of the ATLAS Central Solenoid Magnet,” *IEEE Trans. Appl. Supercond.*, Vol. 9, No. 2, June 1999, pp.852-855.

Material/Property	Temp., K	Al stabilizer	Overall cable
Yield strength, MPa	300	81	128
Ultimate strength, MPa		86	184
Maximum allowable stress, MPA		**43**	**85**
Yield strength, MPa	4.2	110	147
Ultimate strength, MPa		294	-
Maximum allowable stress, MPA		**73**	**98**

Maximum allowable stress of Al 5083-O at cryogenic temperatures (<77K). From 2010 ASME BPVC.

Thickness, mm	Maximum allowable stress, MPa
1.30 - 38.10	**107.6**
38.13 - 76.20	**101.3**
76.23 - 127.00	**95.8**

- The maximum allowable stress in the superconducting coils that are supported by the external support structures is the lesser of:
  - 2/3 of the minimum specified Yield Strength;
  - 1/2 of the minimum specified Ultimate Strength.
- The measured cable strength data were taken from ATLAS CS cable.
  - The actual PS cable is expected to be stronger because of the lower fraction of Al stabilizer.
- The maximum allowable stress in the support shells was chosen according to 2010 ASME Boiler and Pressure Vessel Code.

RRR vs. cable strength

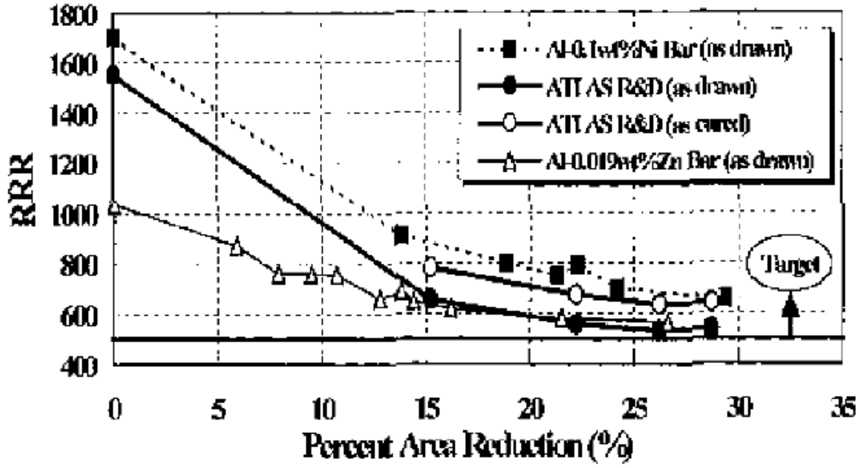


Fig.2. RRR as a function of area reduction

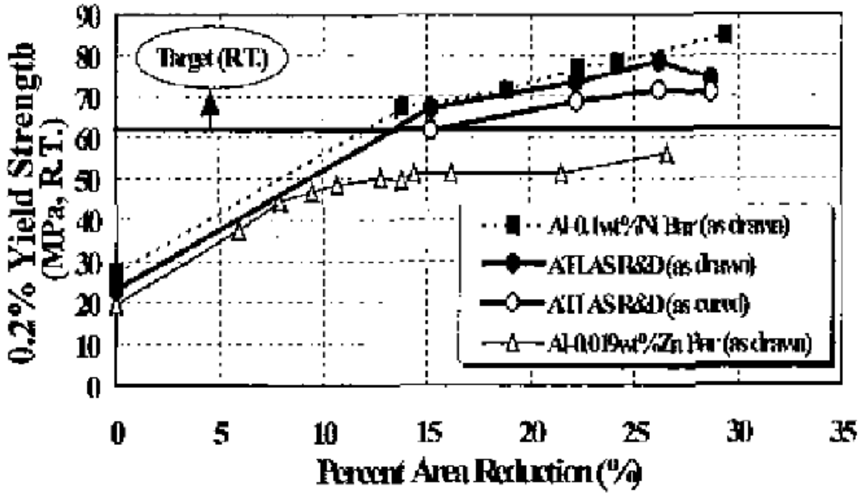


Fig.3. 0.2% yield strength as a function of area reduction

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 10, NO. 1, MARCH 2000

Development of High-Strength and High-RRR Aluminum-Stabilized Superconductor for the ATLAS Thin Solenoid

K. Wada, S. Meguro, H. Sakamoto, T. Shimada, Y. Nagasu, I. Inoue, K. Tsunoda and S. Endo
The Furukawa Electric Co., Ltd. , Nikko, Japan

A. Yamamoto, Y. Makida, K. Tanaka, Y. Doi and T. Kondo
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

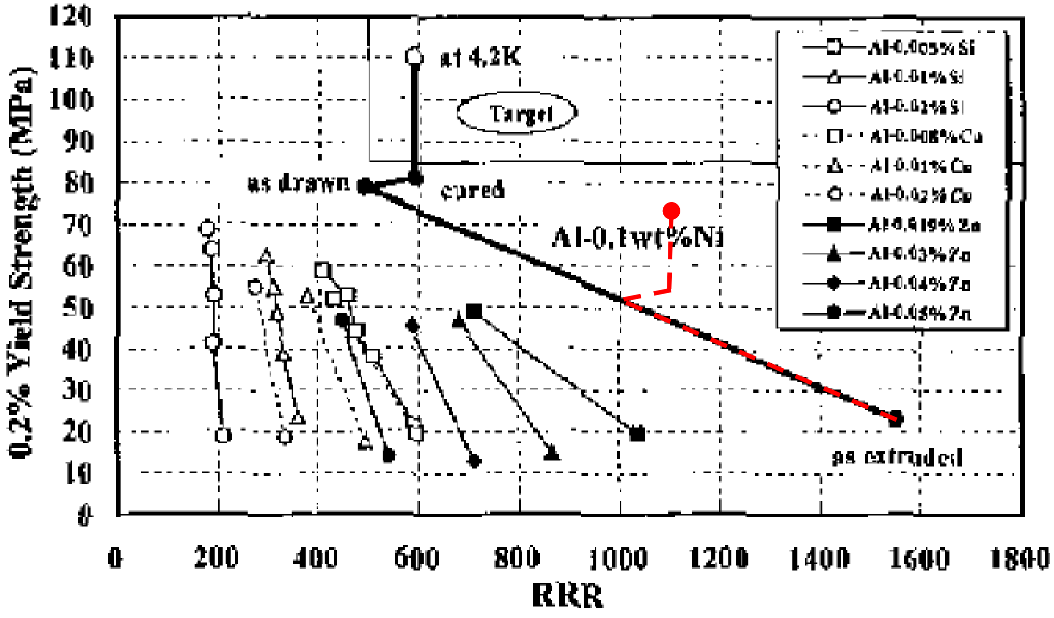
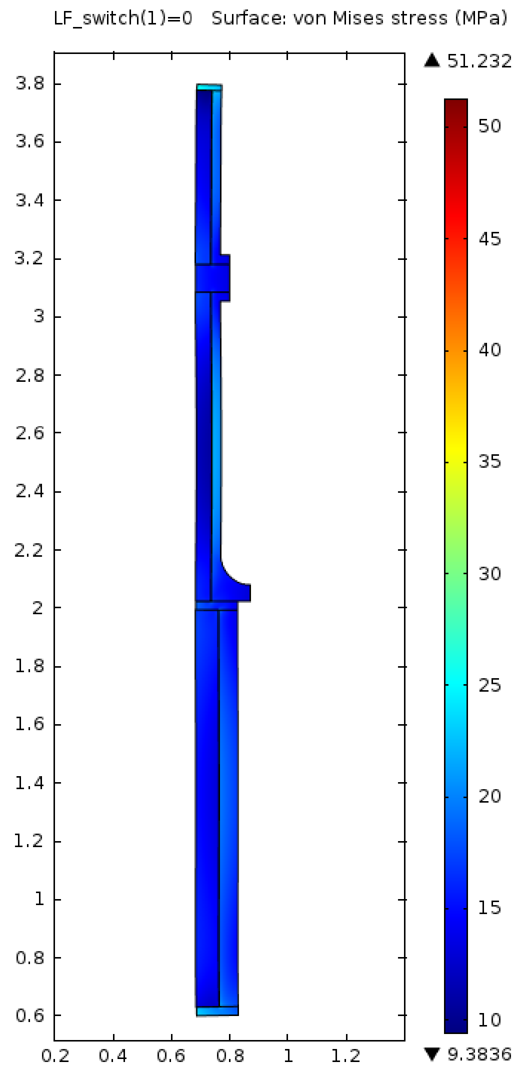
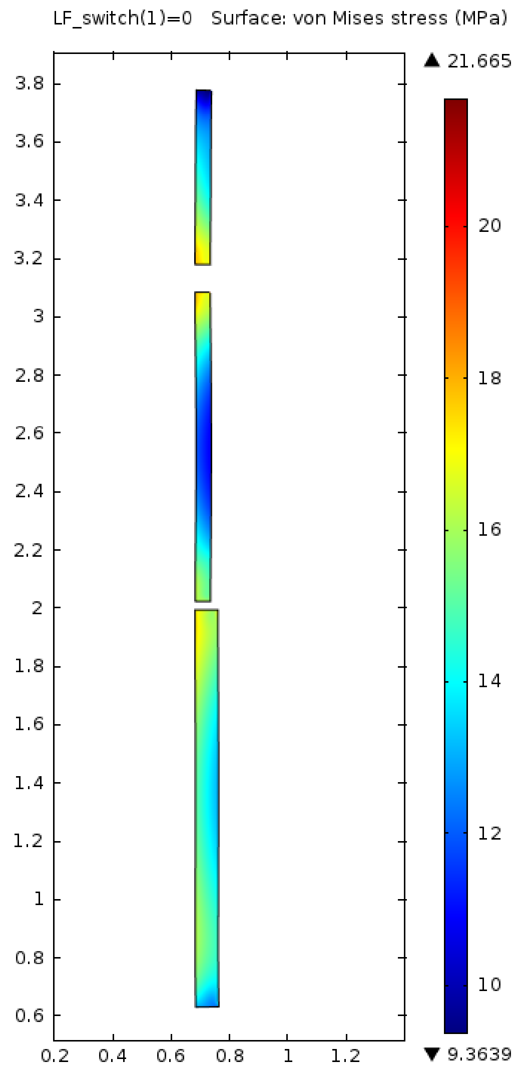


Fig.7 Relationship between RRR and yield strength

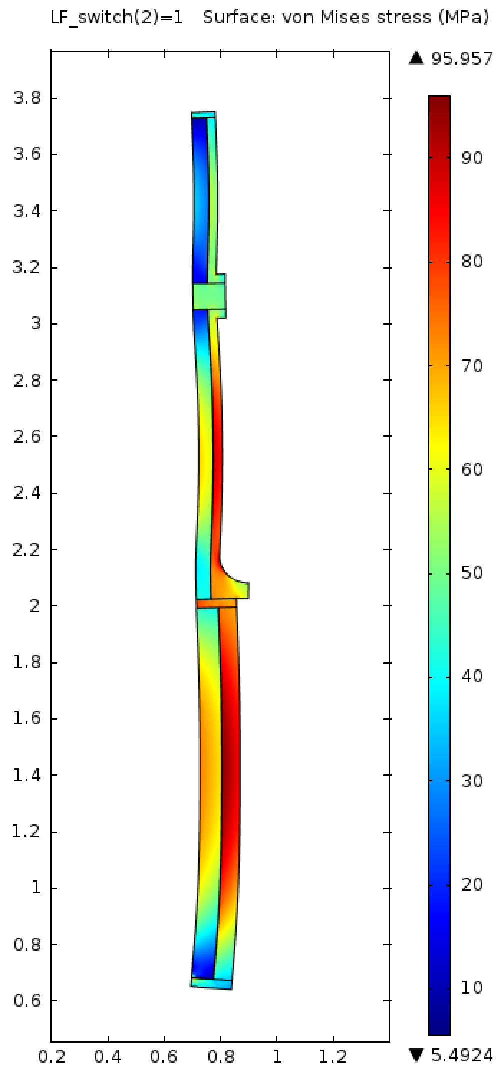
300 K -> 4 K, I = 0

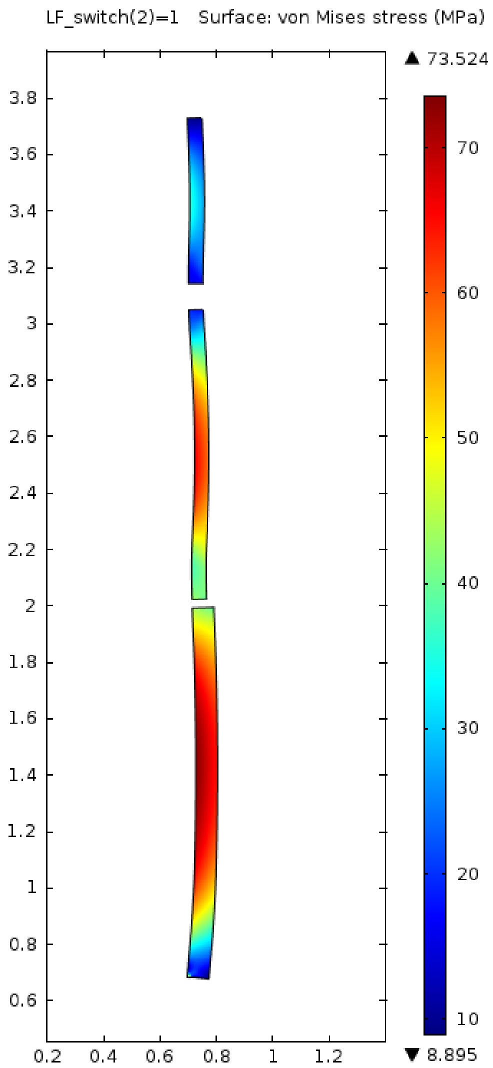




- Peak stress in the support structure: 51 MPa;
- Peak stress in the coil: 21 MPa

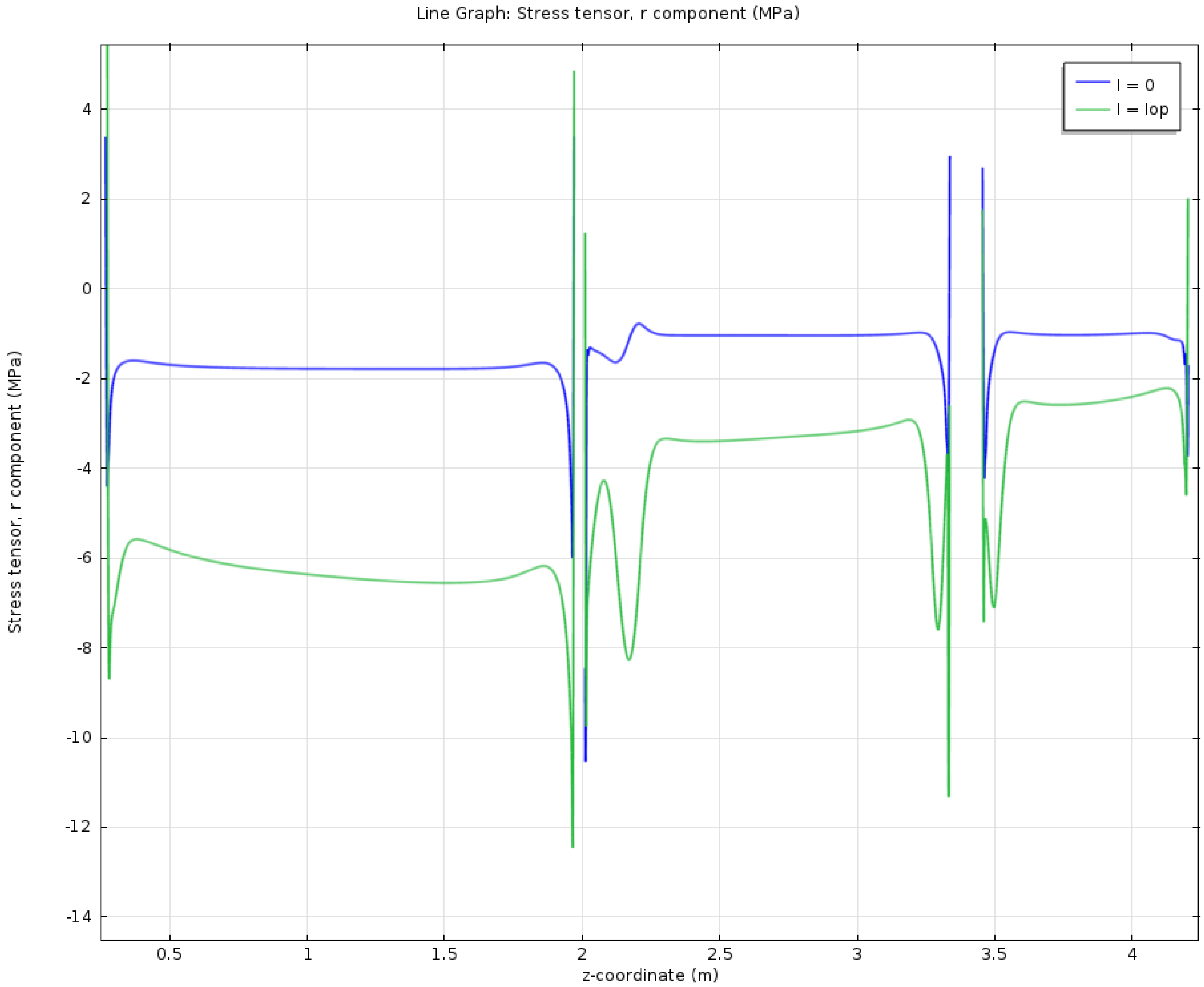
300 K -> 4 K, I -> I_{op}





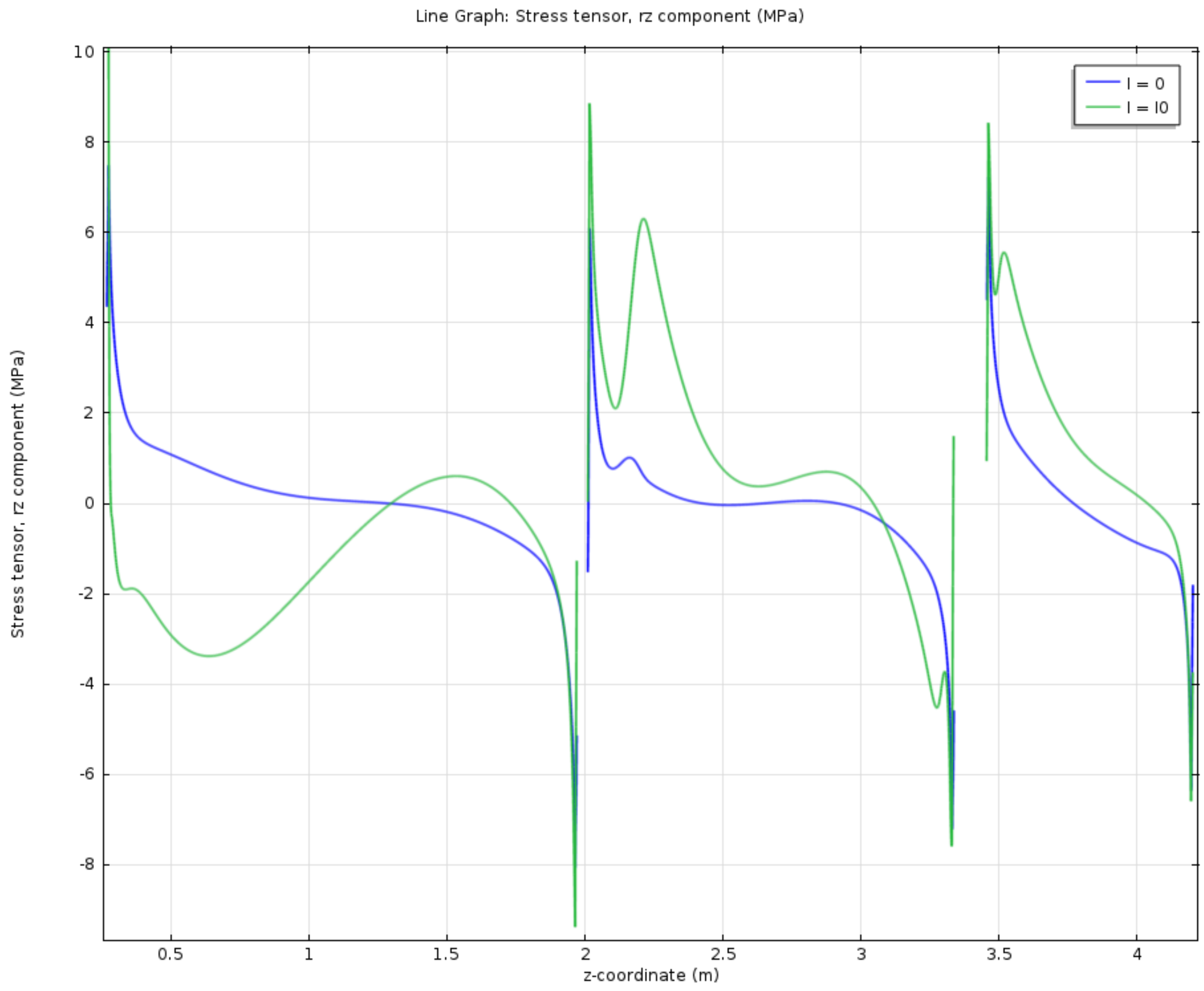
- Peak stress in the support structure: 96 MPa;
- Peak stress in the coil: 73 MPa

Coil-shell normal stress

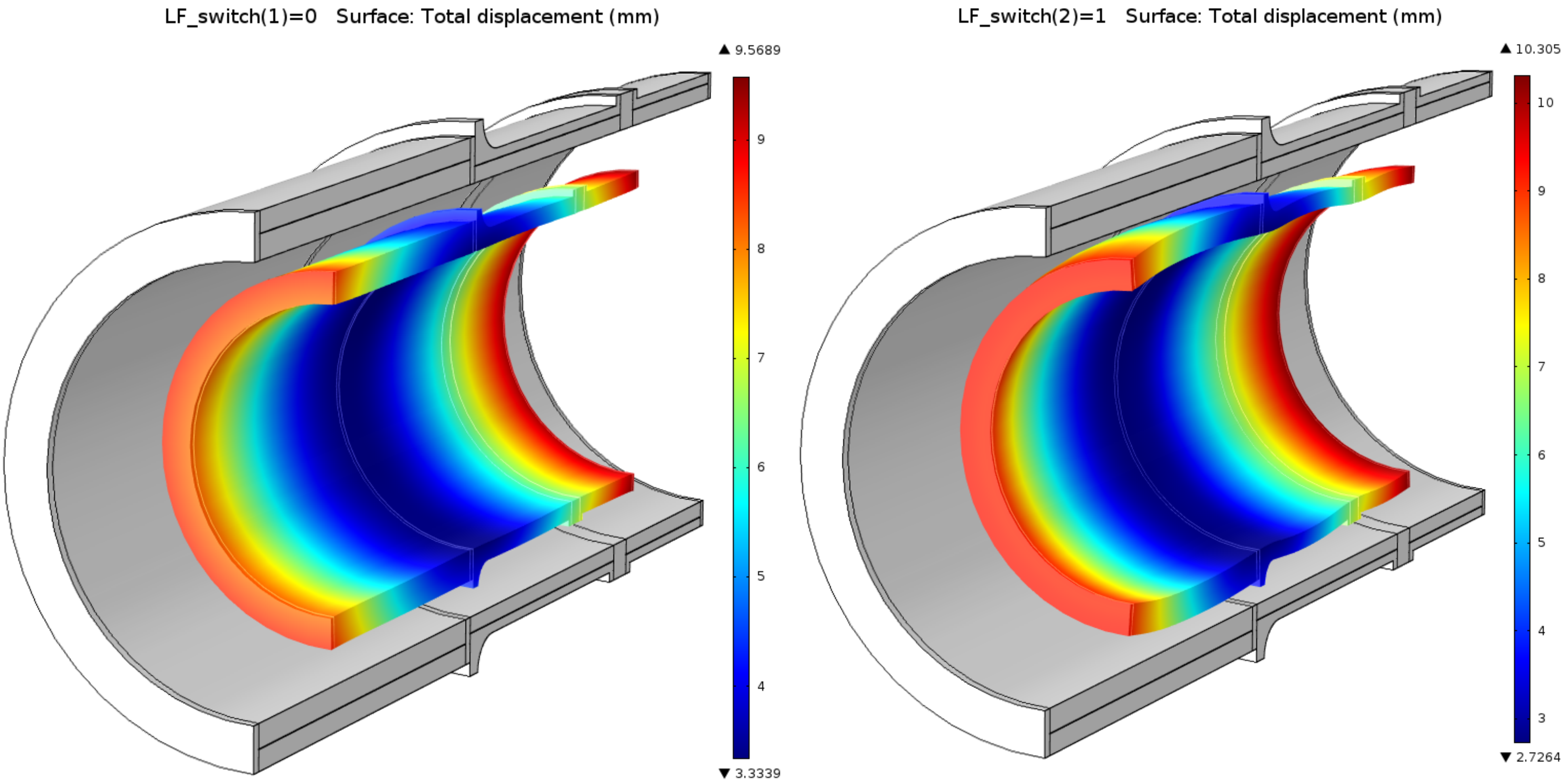


Coil-shell shear stress

Line Graph: Stress tensor, rz component (MPa)

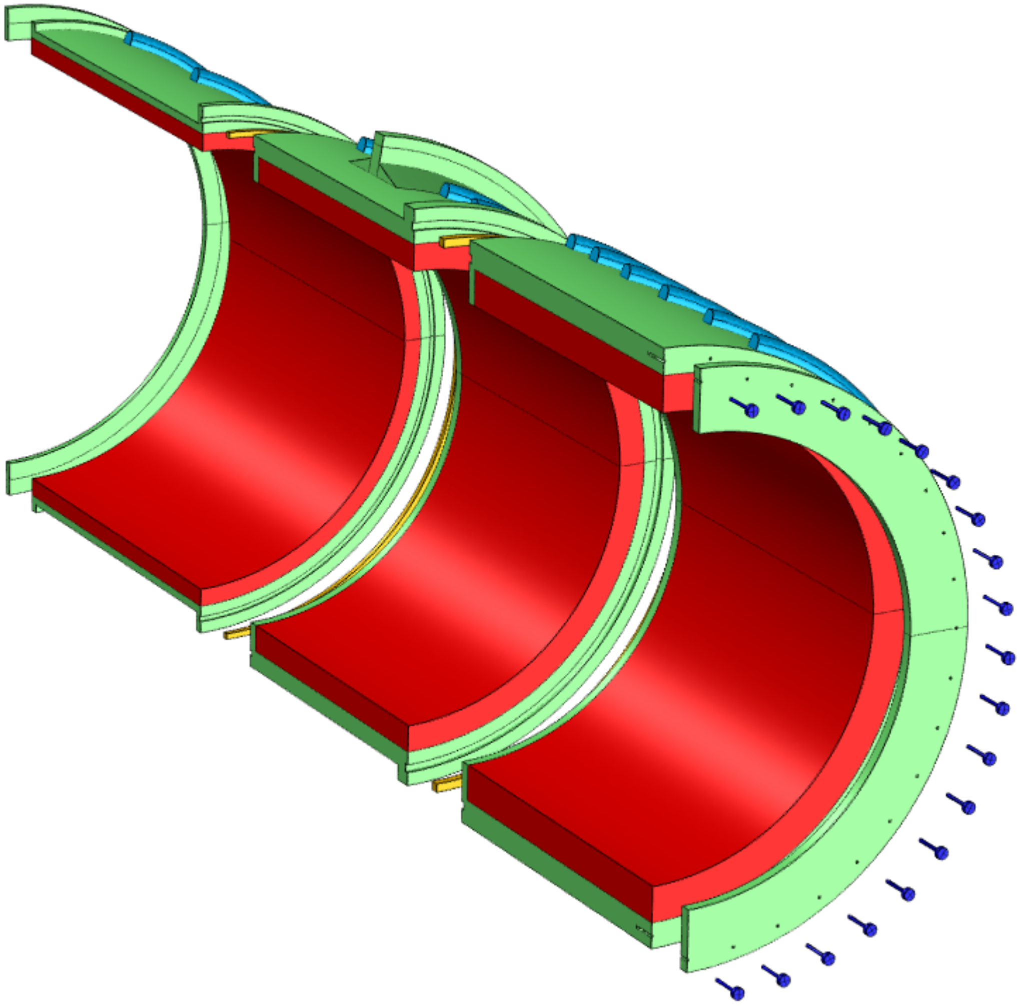


Displacements



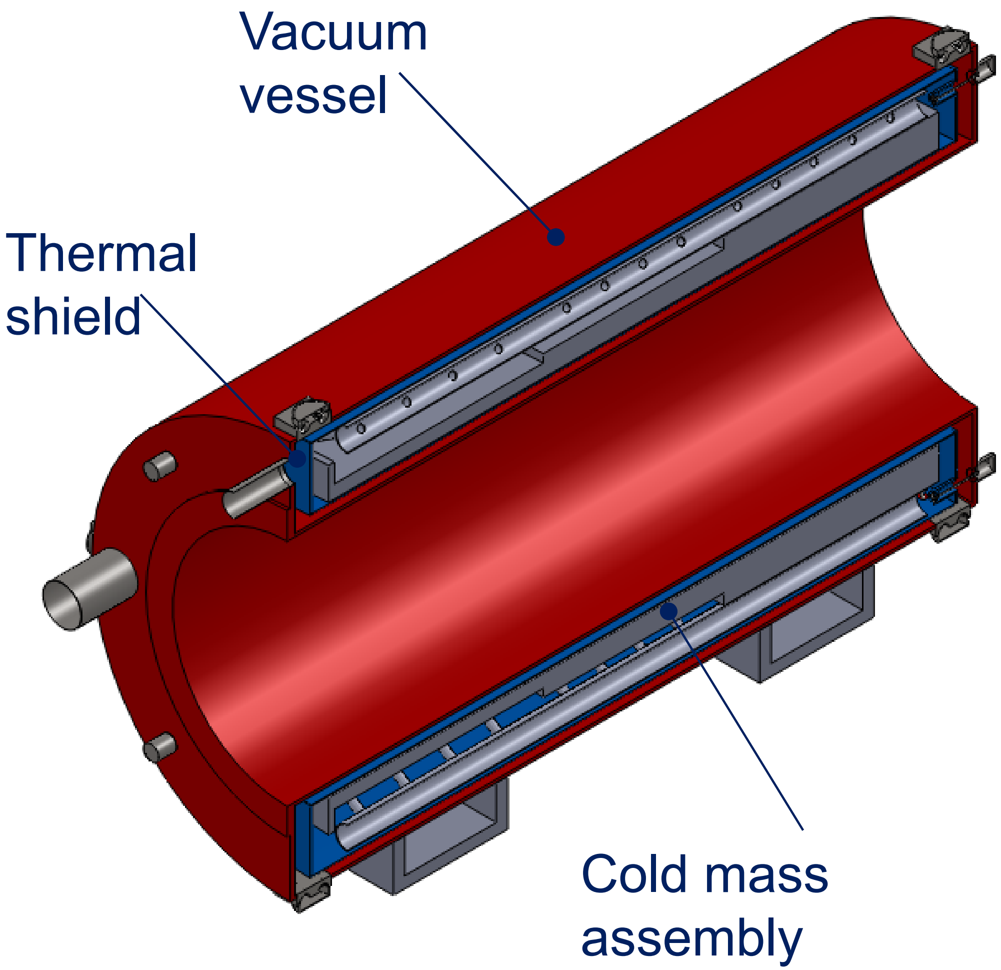
- ~10 mm at the end flanges;
- ~3 mm at the middle support.

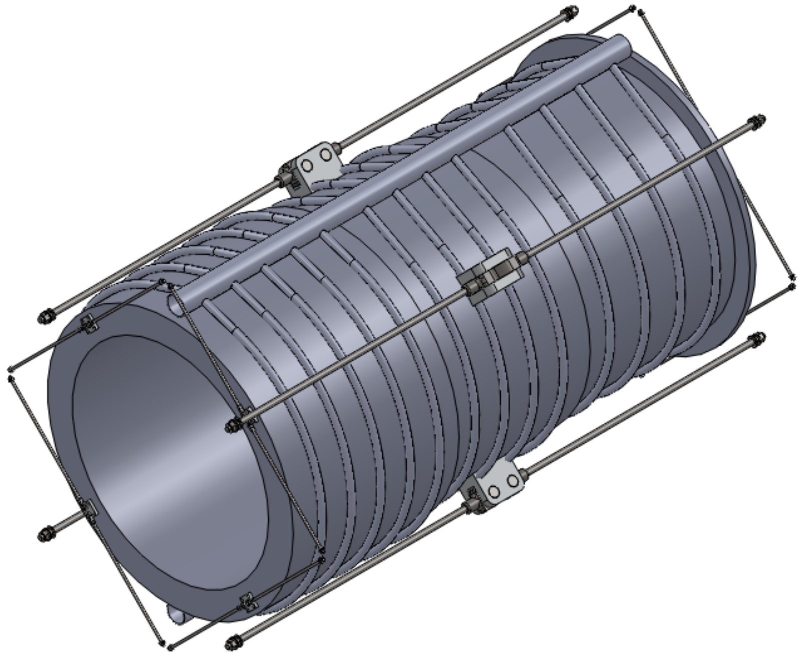
Cold mass



- The coils are assembled inside the support shells made of Al 5083-O;
- Each coil section is individually vacuum-impregnated with epoxy resin;
- The three coil sections are bolted together during assembly to form a single cold mass;
  - The azimuthal keys lock the sections together.
- Cold mass dimensions:
  - ID = 1.70 m;
  - OD = 2.12 m (ex. cryo/supp.);
  - Length = 4.0 m.

Cryostat

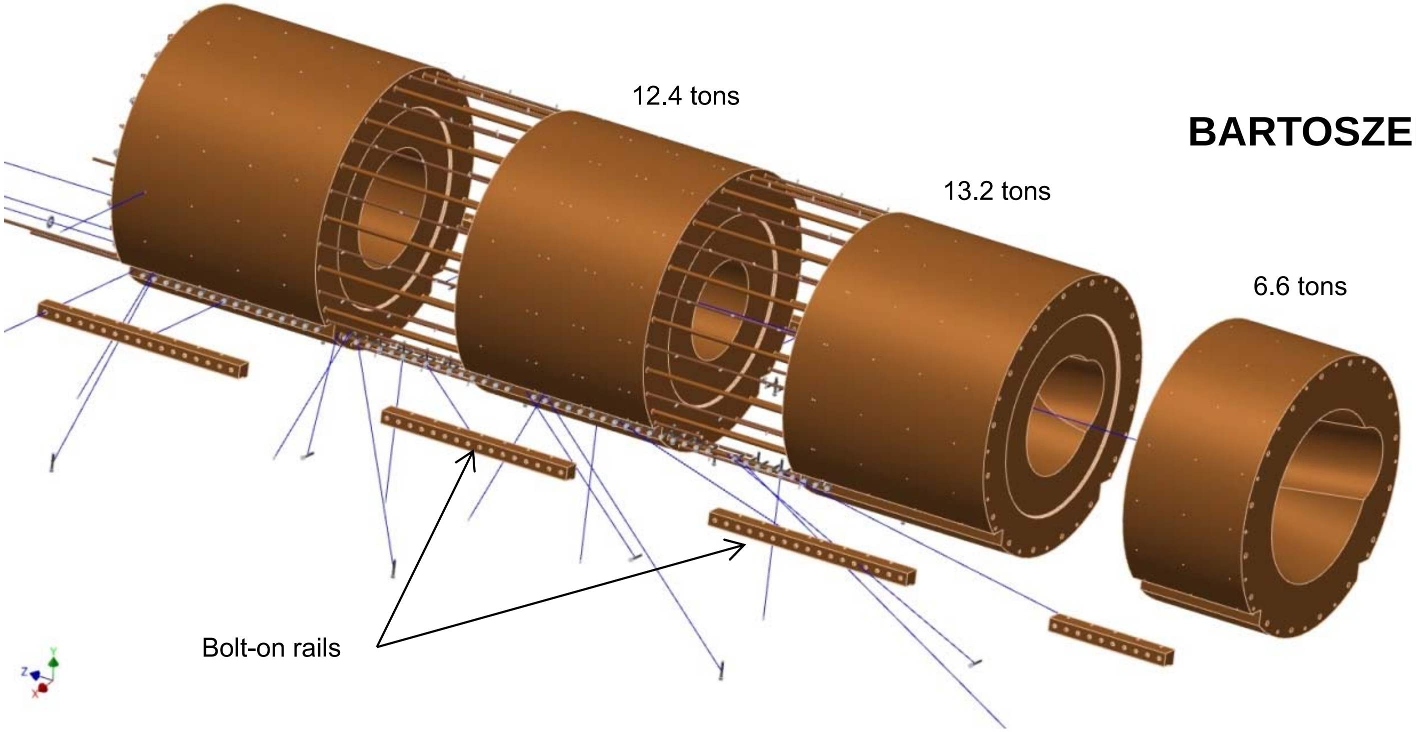




- The cold mass is internally supported by the suspension system;
- The loads are transferred to the experiment’s floor through the cryostat walls, support posts and iron yoke;
- The cryostat is designed to support the additional weight of the radiation shield (~50 tons).

Radiation/thermal analysis

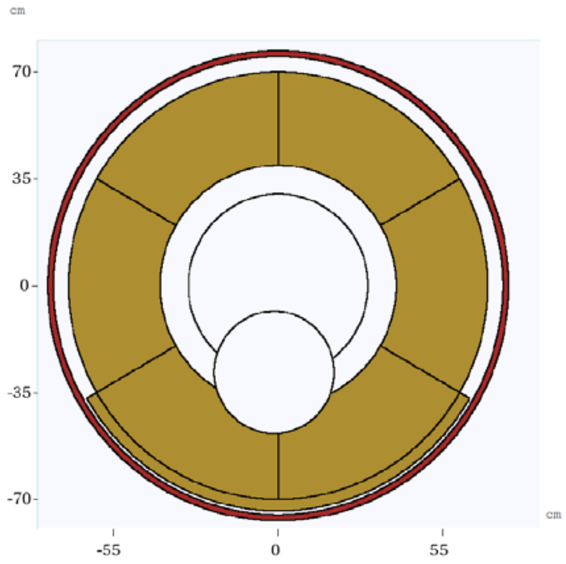
Heat and radiation shield

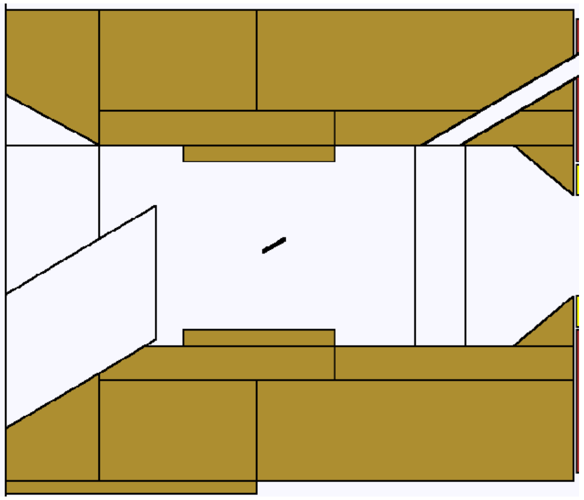


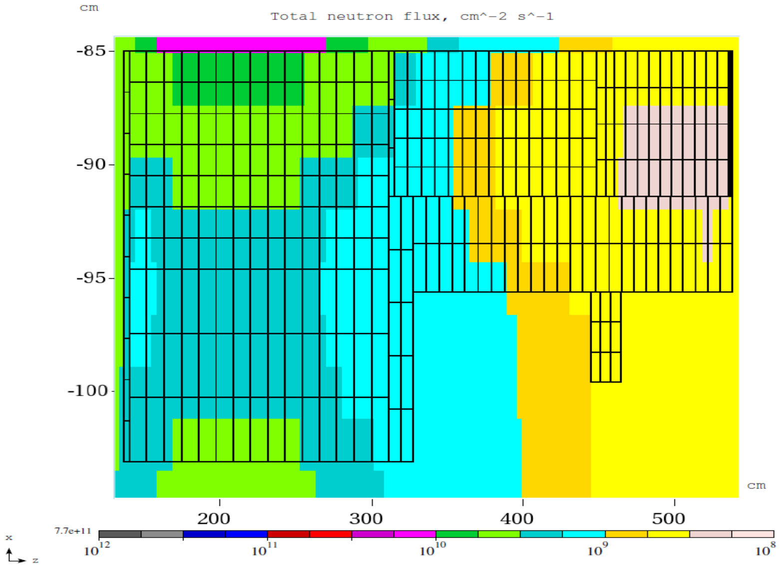
BARTOSZEK ENGINEERING

- Installed within the warm magnet bore;
- Made from low-conductivity bronze;
- Protects the superconducting coils from radiation coming from the primary proton target.

MARS radiation analysis





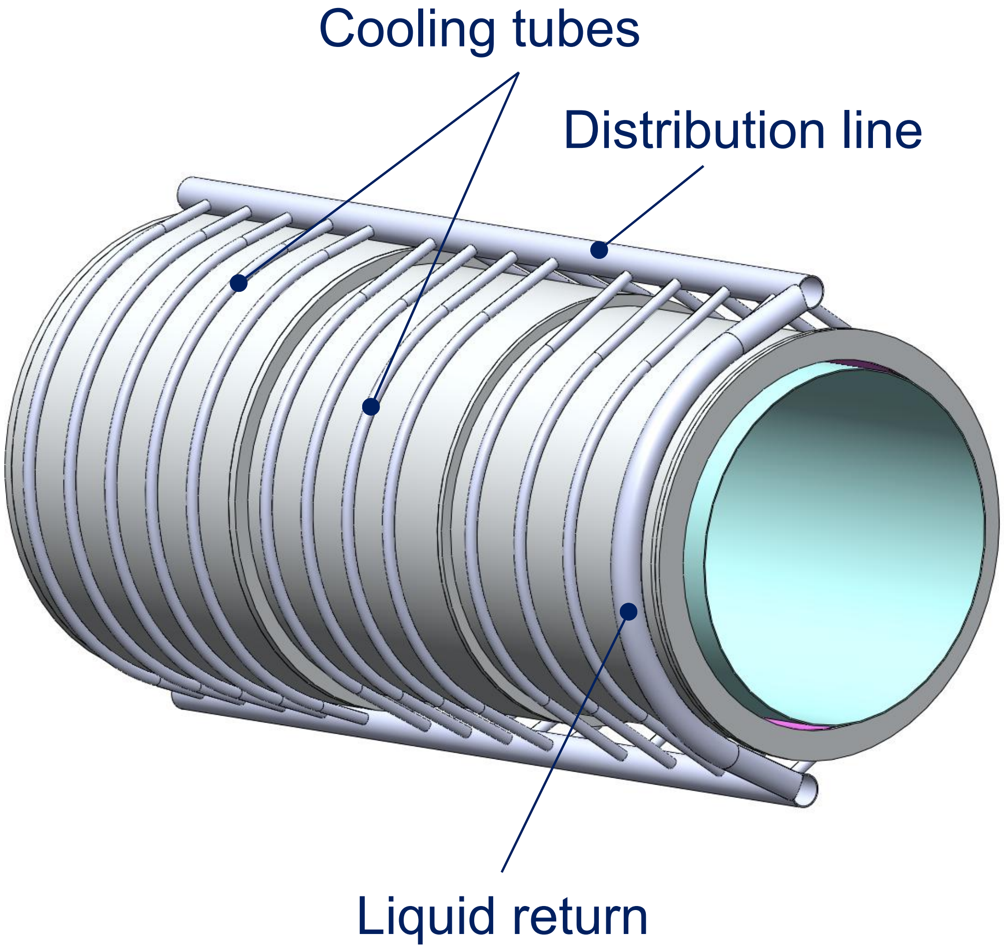


Parameter	Unit	Value
Peak absorbed dose	kGy/yr	330
Peak power density	μW/g	18
Total CM dynamic heat load	W	21
Peak DPA	1/yr	$3.2\cdot10^{-5}$

See presentation of Vitaly Pronskikh

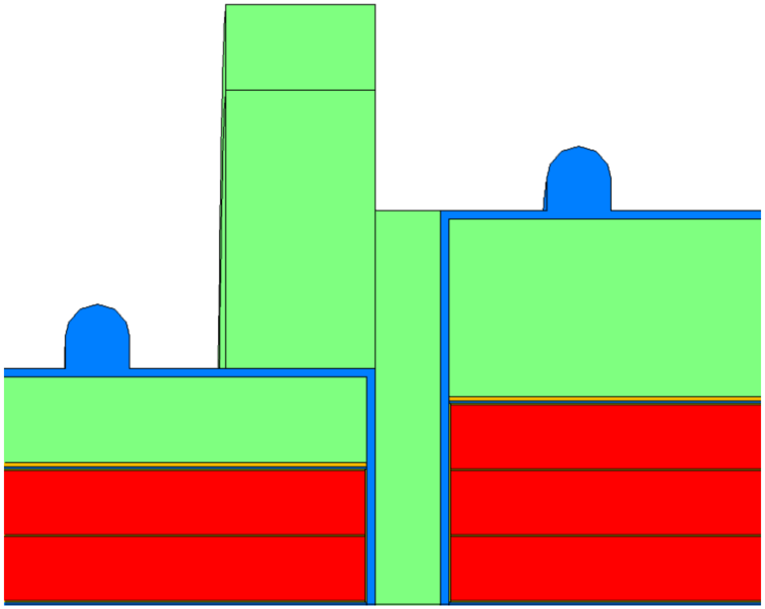
- 3D MARS model included all the details of the PS magnet and the radiation shield;
- The coil properties were approximated as a mixture of the relevant materials.

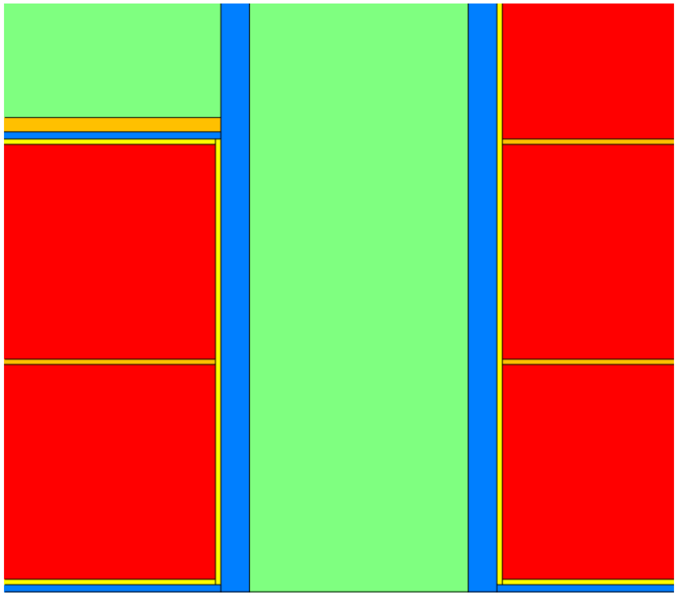
Cooling system



- The cold mass is conduction cooled via thermal siphon scheme;
- The support shells are equipped with azimuthal cooling tubes that create the parallel flow paths;
- The tubes are connected to the upper and lower distribution lines;
- A return column not thermally connected to the cold mass supplies cold

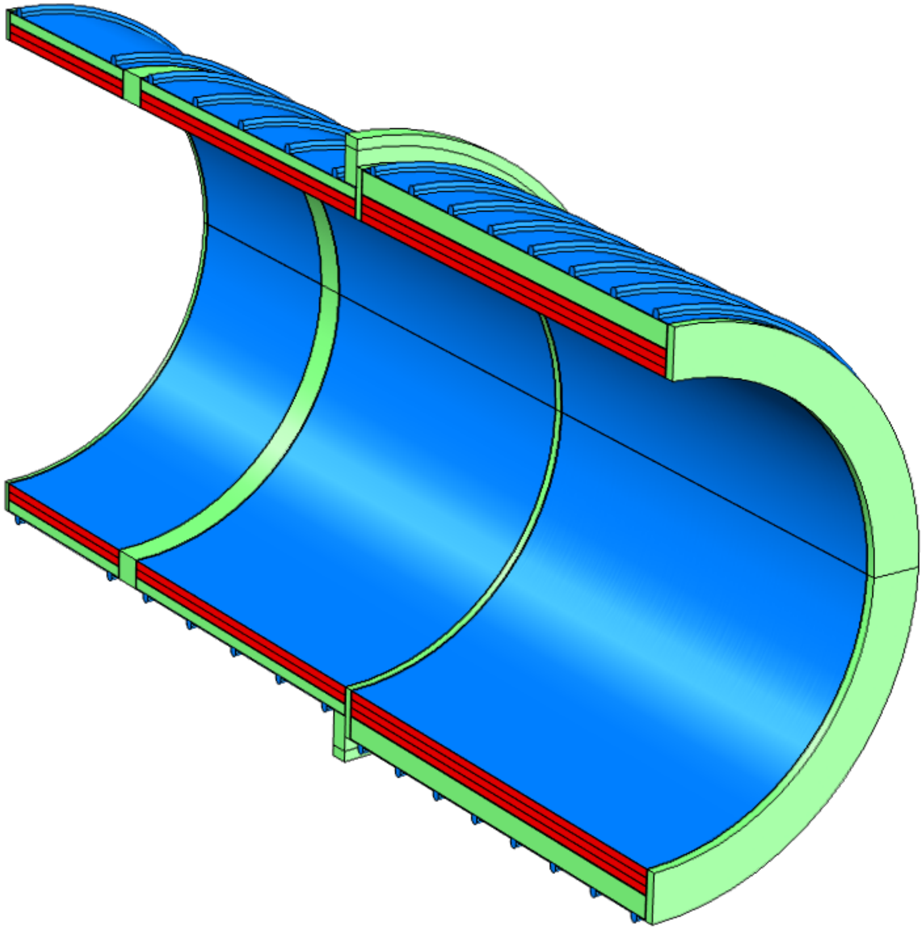
Coil-flange interface

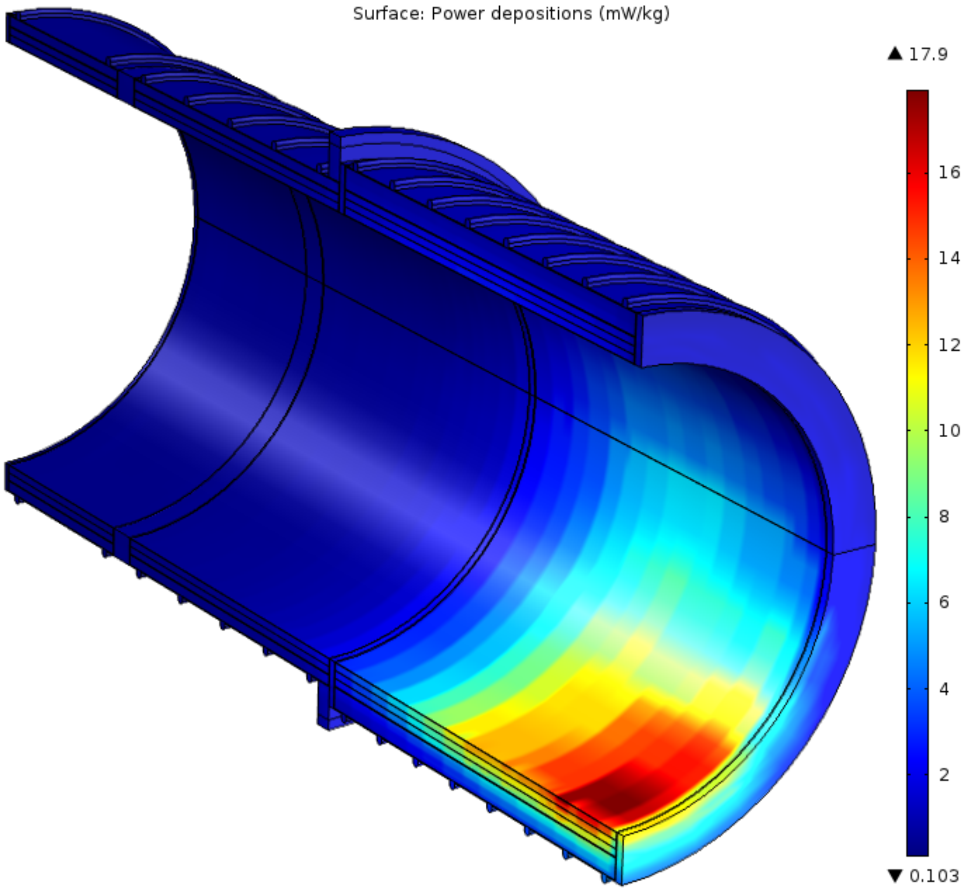




- Coil envelope is surrounded with the ground insulation:
  - 2x250 μm of composite insulation (2x25 μm of Kapton, fiberglass balance);
- Thermal bridges at the inner and outer surfaces;
- Metal to metal connection between thermal bridges and plates;
- Thermal plates are stress-relieved at the corners of the support shells;
- Layers of mica between the thermal plates, flanges and shells.

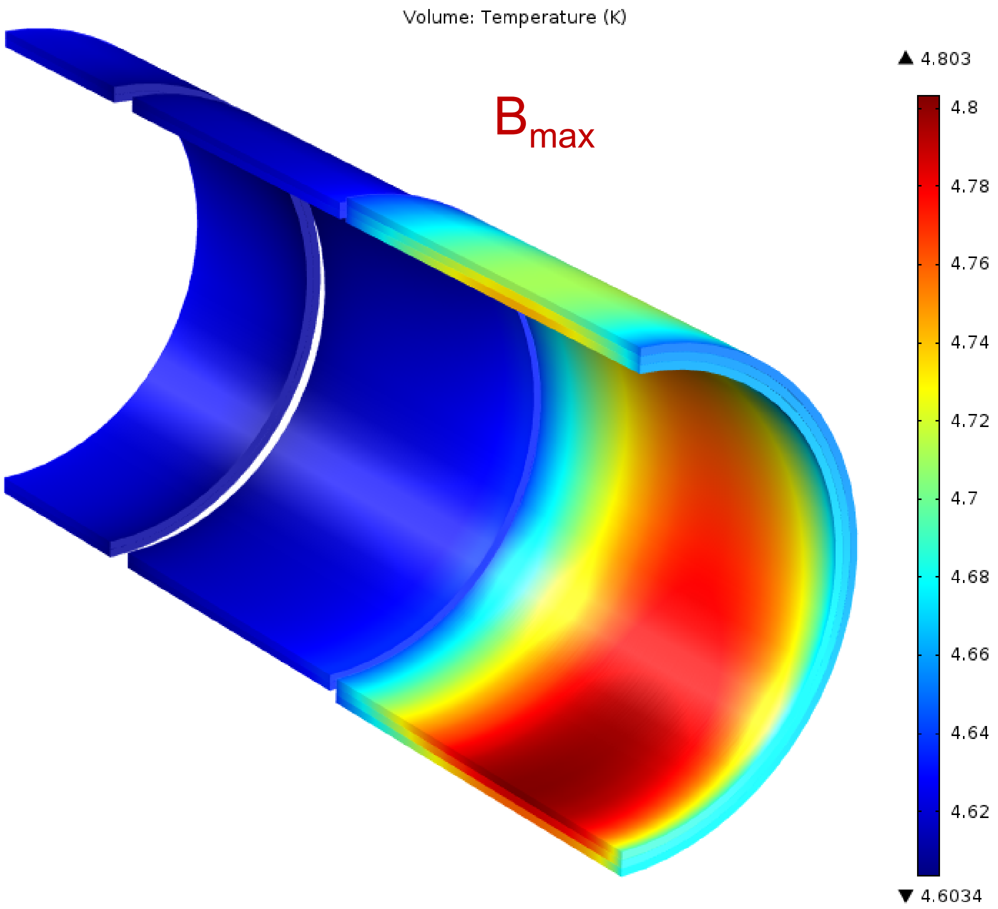
Thermal model

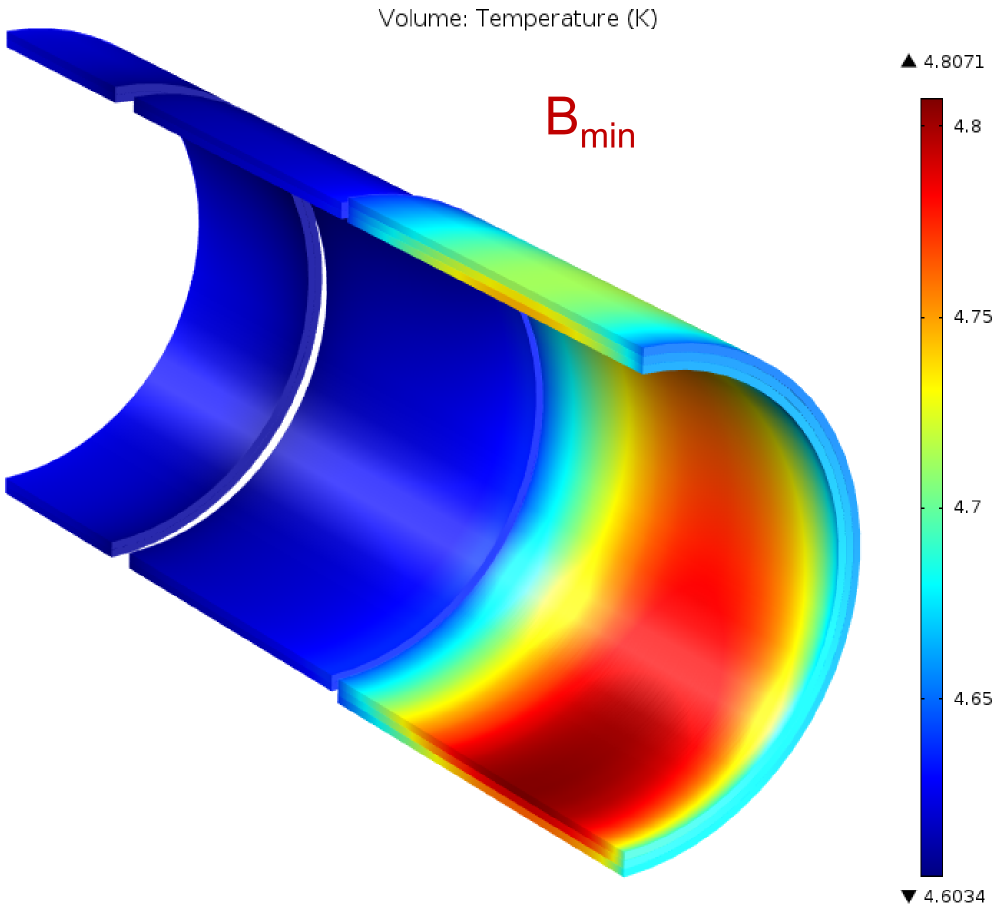




- Peak power density is 17.9 mW/kg;
- Total power deposition in the cold mass 21.0 W.

T_0=4.6 K, static+dynamic heat load

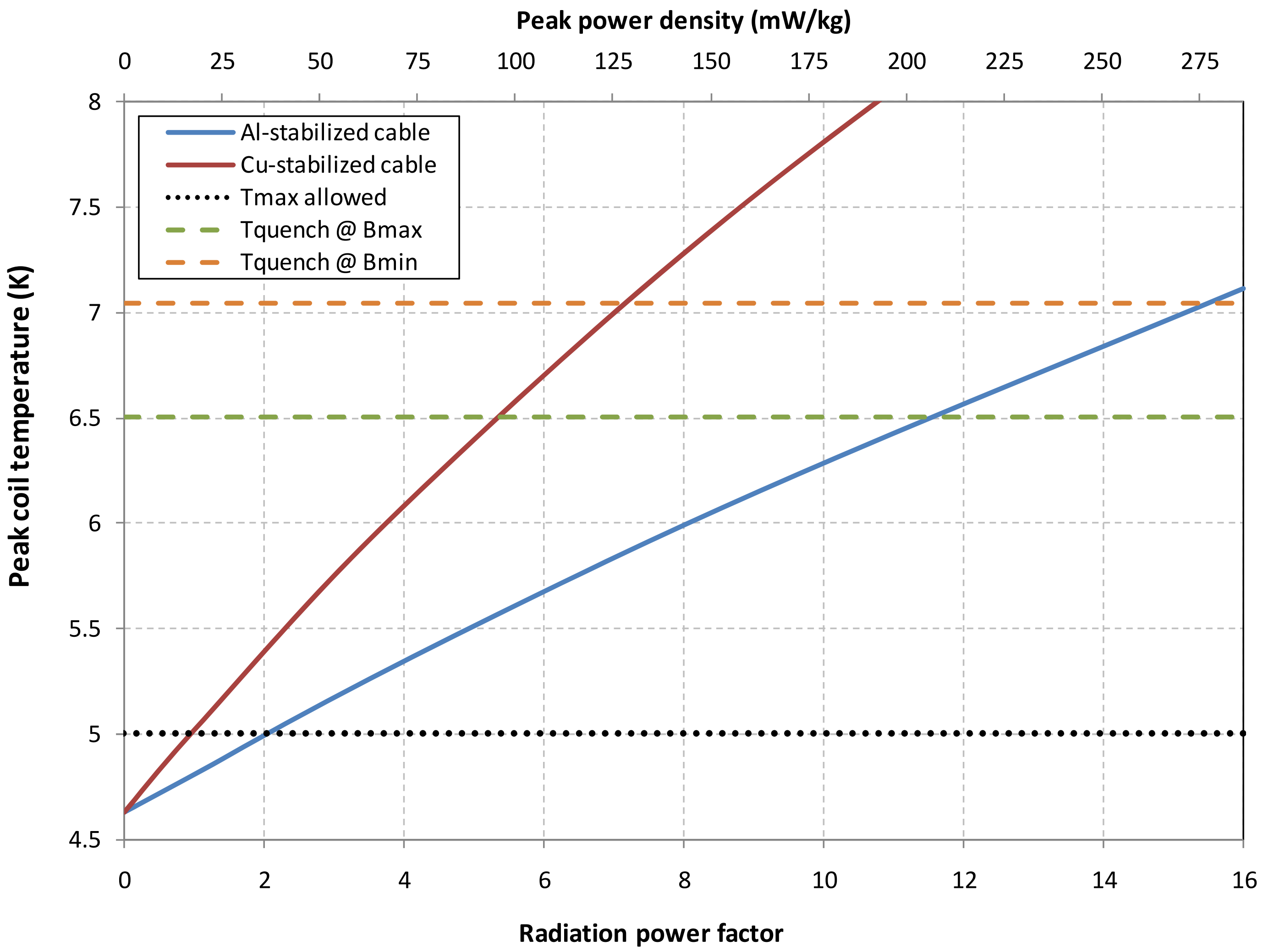




- Peak coil temperature at the max performance is 4.803 K;
- Azimuthally non-uniform distribution.

- Peak coil temperature at the min performance is 4.807 K;
- Azimuthally non-uniform distribution.

Thermal parameter space



- The thermal models are identical: same geometry, boundary conditions and heat sources;
- The only difference is the material of cable stabilizer and thermal bridges/plates (Al or Cu, RRR=100);
- The difference in thermal performance is due to the change of densities and thermal conductivities.

Summary

- The PS magnet design meets the requirements;
- It offers a flexibility in adjusting the peak axial field and gradient;
- Conservative margins are built in;
- Al stabilizer offers an advantage over Cu for the selected magnet technology and radiation environment.