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Mu2e Production Solenoid

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Role of Production Solenoid

The Mu2e magnet system consists of three large superconducting solenoids. Production Solenoid (PS) is the first magnet in the chain, which collects and focuses pions and muons generated in interactions of an 8-GeV proton beam with a tilted high-Z target and directs them towards Transport Solenoid (TS).

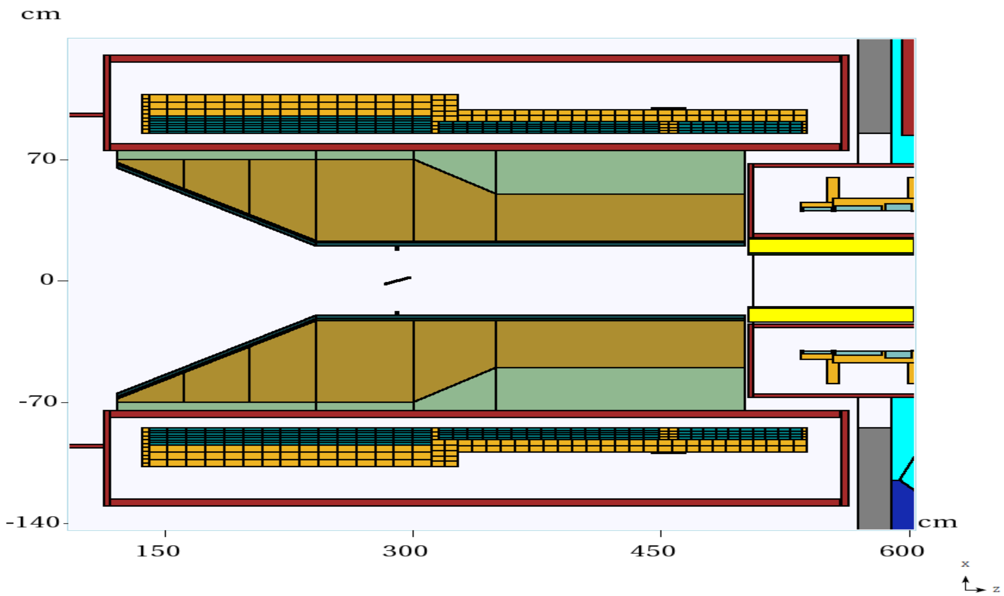
PS performs the following functions in the mu2e:

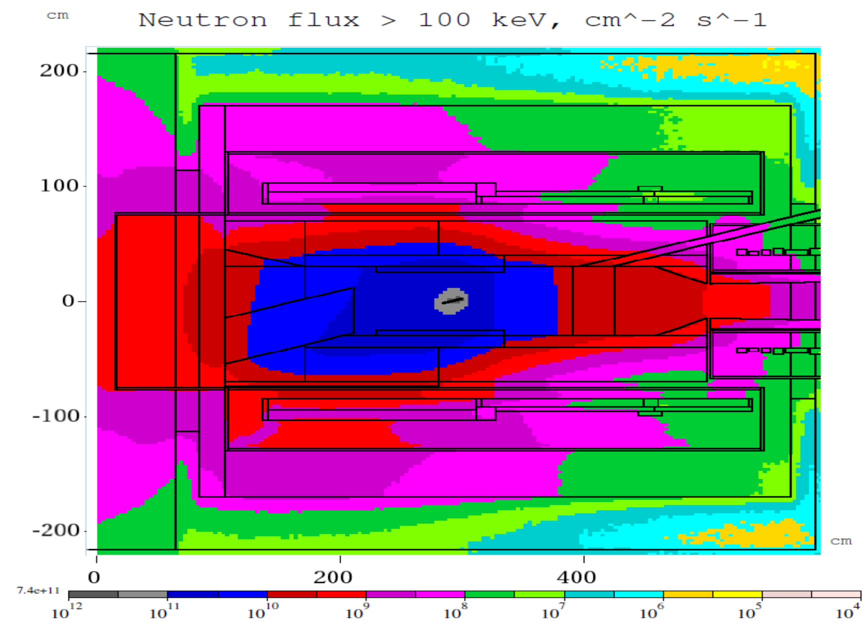
- Maximizes muon yield by efficiently focusing secondary pions and subsequent secondary muons towards the Transport Solenoid (TS) system, in the momentum range to be stopped in the stopping target;
- Provides a clear bore for beam line elements such as the primary production target and secondary particle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

General requirements

- Magnetic:
  - Nominal peak field on the axis 4.6 T;
  - Maximum peak field on axis 5.0 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 4.7 K;
  - Total heat flow to LHe ≤ 100 W;
  - Cryostat ID 1.5 m;
  - Conduction cooling.
- Radiation:
  - Absorbed dose ≤ 7 MGy total;
  - Minimum RRR of Al stabilizer in the operating cycle ≥ 100.

Unique feature: radiation environment

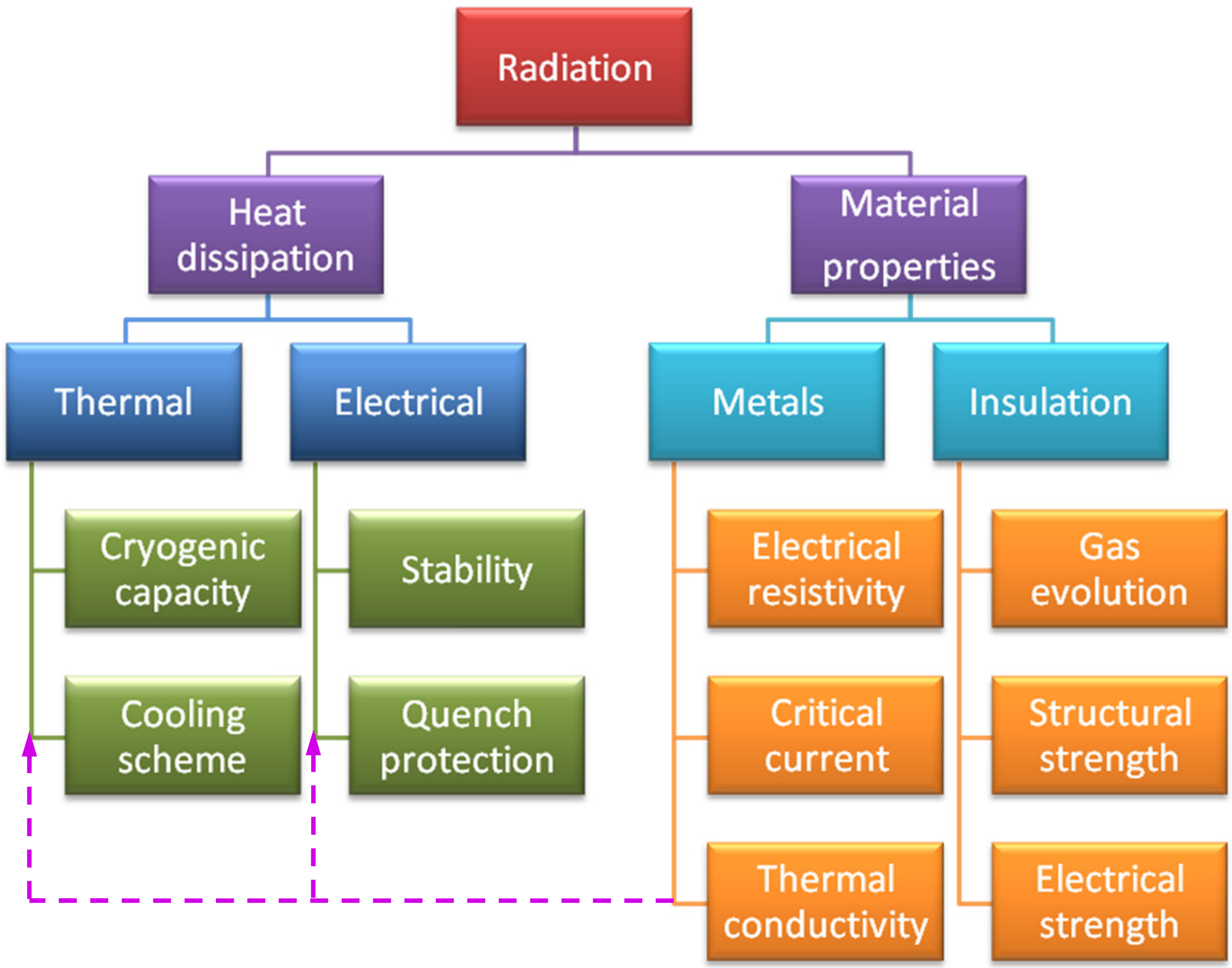




Parameter	Unit	Value
Peak absorbed dose	kGy/yr	240
Peak power density	μW/g	13
Total CM dynamic heat load	W	28
Peak DPA	1/yr	$2.5\cdot10^{-5}$

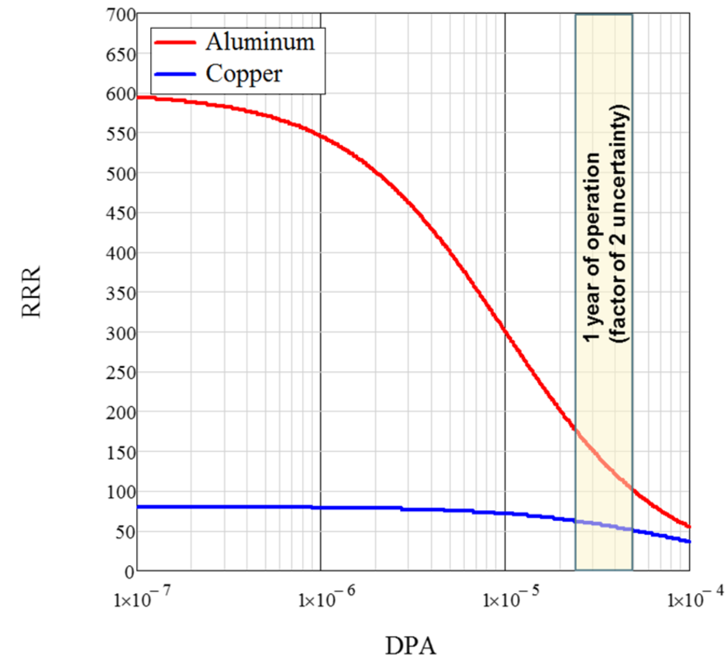
- It is expected that RRR will degrade after one year of operation as follows:
  - Al RRR 500 → 100;
  - Cu RRR 100 → 50;
- Once the critical degradation is detected, the magnet will be thermo-cycled to recover the resistivity.

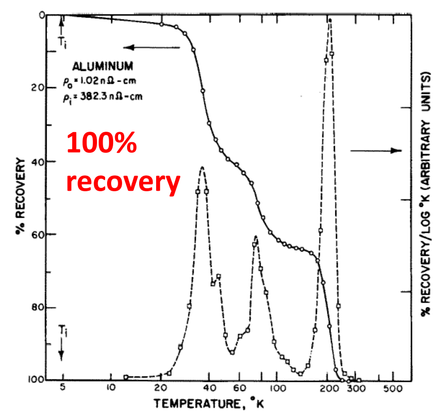
Impact of radiation on the magnet performance

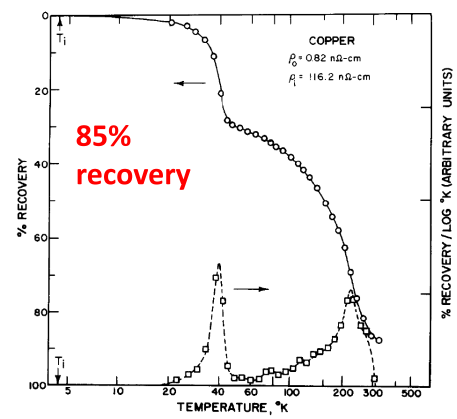


Radiation effects

- Thermal:
  - Heat deposition in the coil reduces the thermal margin.
  - The heat should be extracted from the coil to the cryogenic system.
- Electrical:
  - Degradation of the stabilizer properties (RRR).
- Structural/electrical:
  - Degradation of the organic insulating materials (epoxy).
  - Limit for conventional epoxies - 10 MGy.







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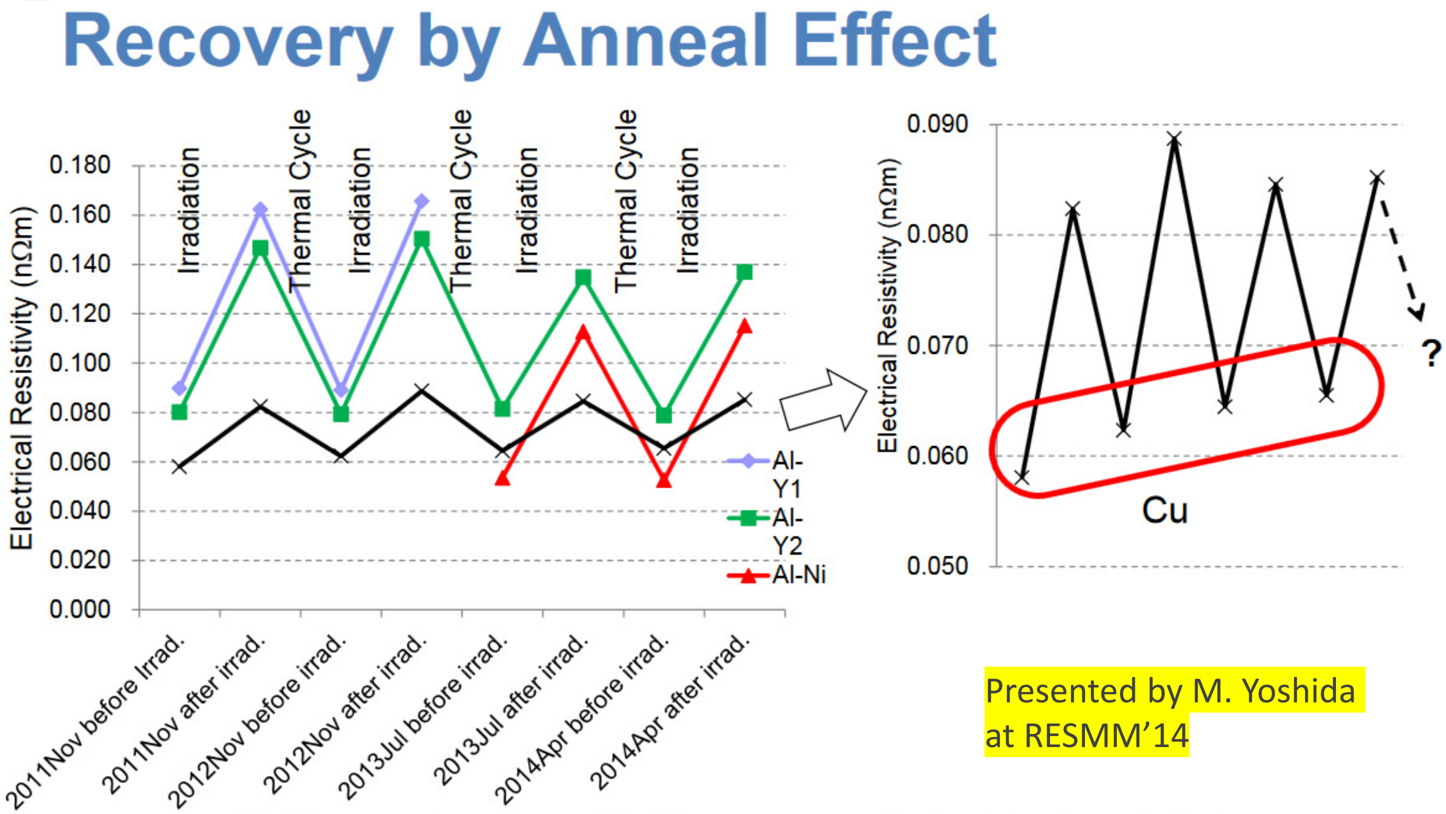
Irradiation experiments at Kyoto University



Presented by M. Yoshida at RESMM'14

- All Al samples show "full" recovery of electrical resistivity after thermal cycle to RT.
- Nevertheless, Cu sample shows "partial" recovery of 82%~95%.

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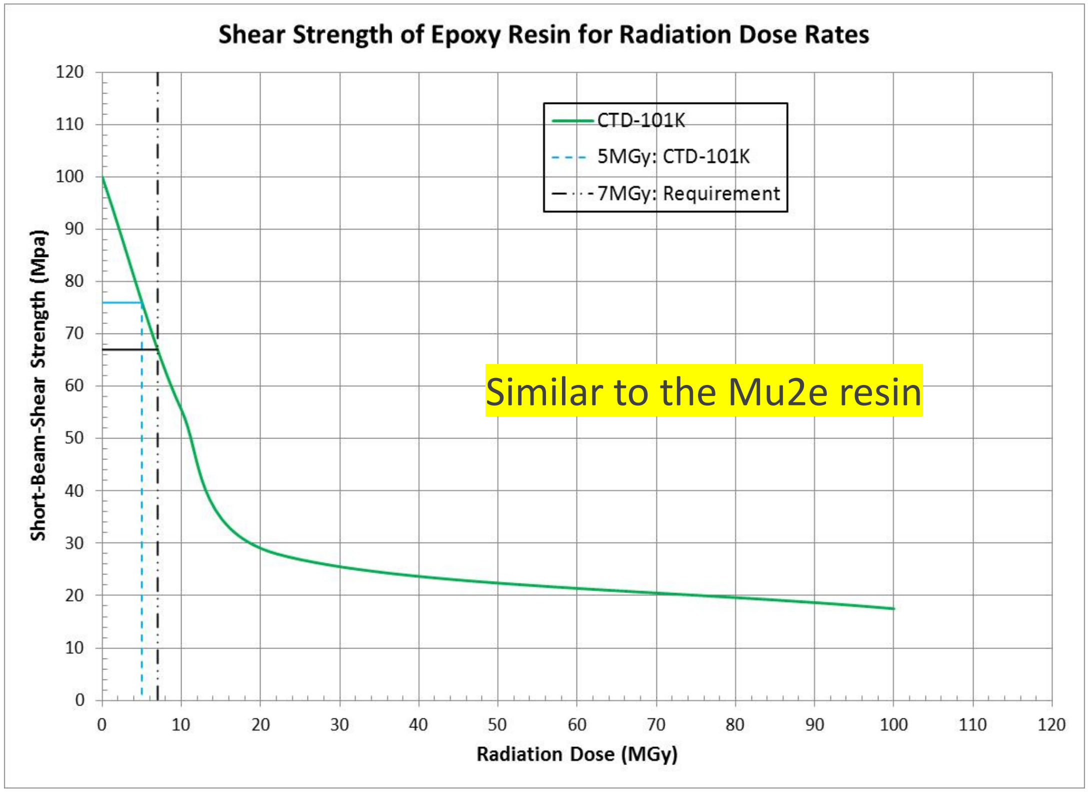
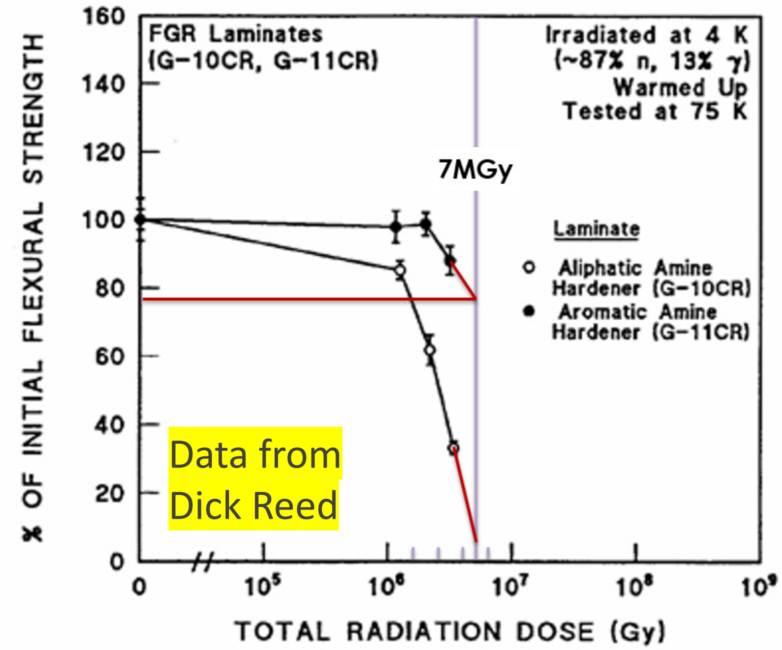
Radiation damage to insulating materials





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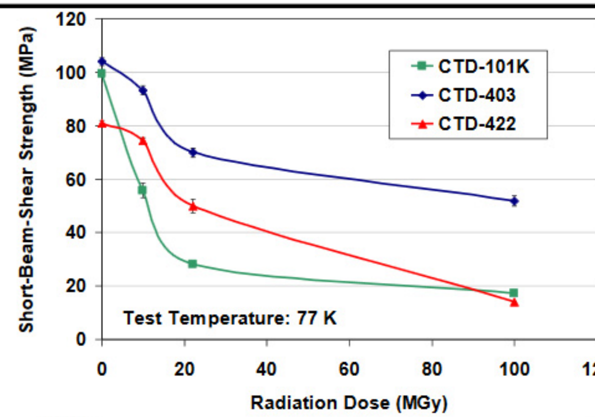
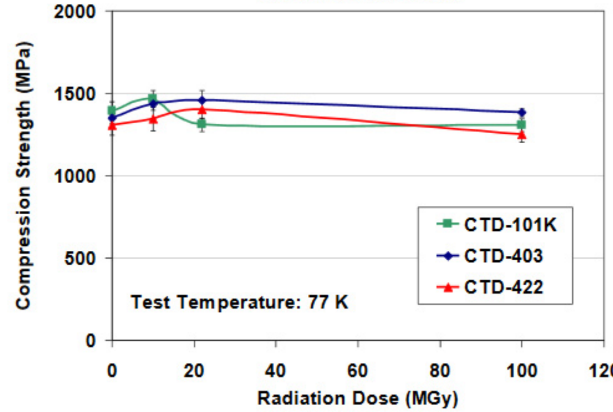
Advanced resin systems

Insulation Irradiations

- **Fiber-reinforced VPI systems**
  - CTD-101K (epoxy)
  - CTD-403 (cyanate ester)
  - CTD-422 (CE/epoxy blend)
- **Insulation performance**
  - Shear strength most affected by irradiation
  - Compression strength largely un-affected by irradiation
- **Ongoing irradiations**
  - Ceramic/polymer hybrids
  - CTD-403
  - 20, 50, & 100 MGy doses
  - Expect to complete by 8/07

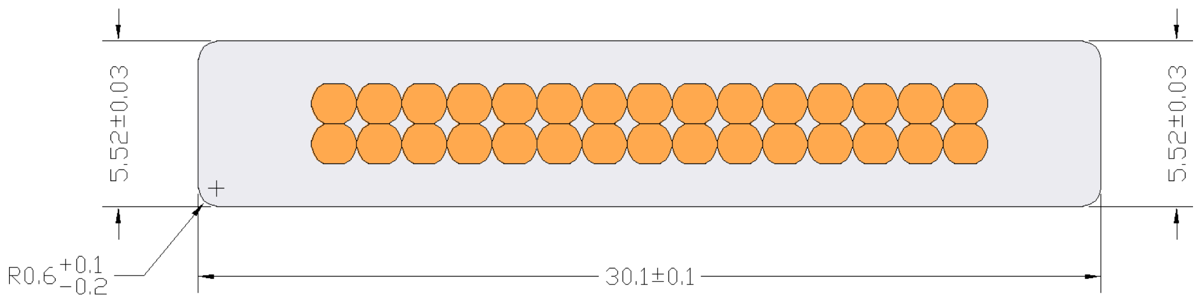




18 *Radiation-Resistant Insulation for High-Field Magnets*

Overview of the Mu2e-I Production Solenoid Design

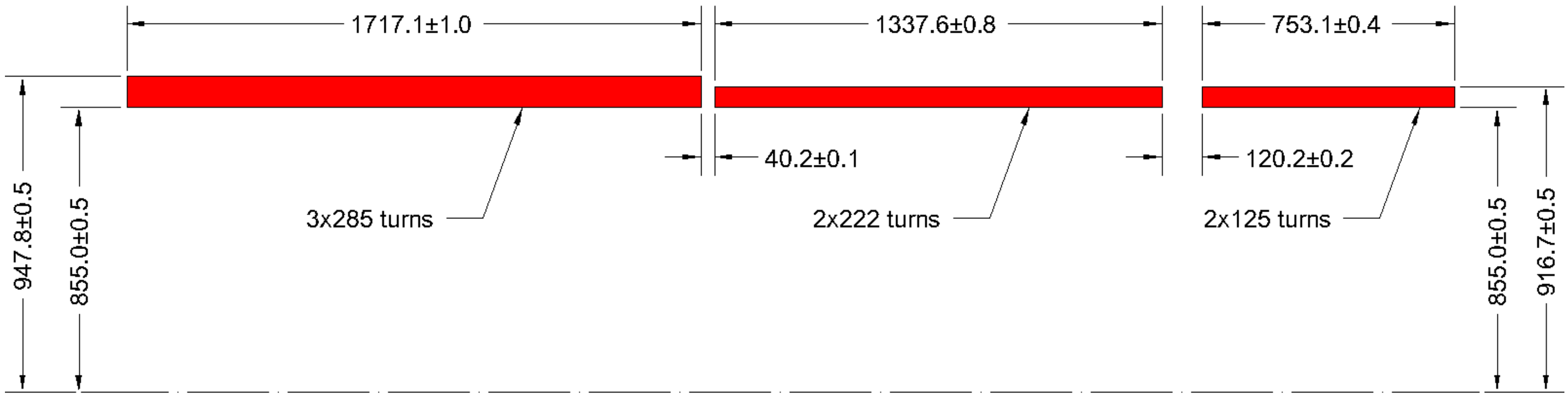
Cable

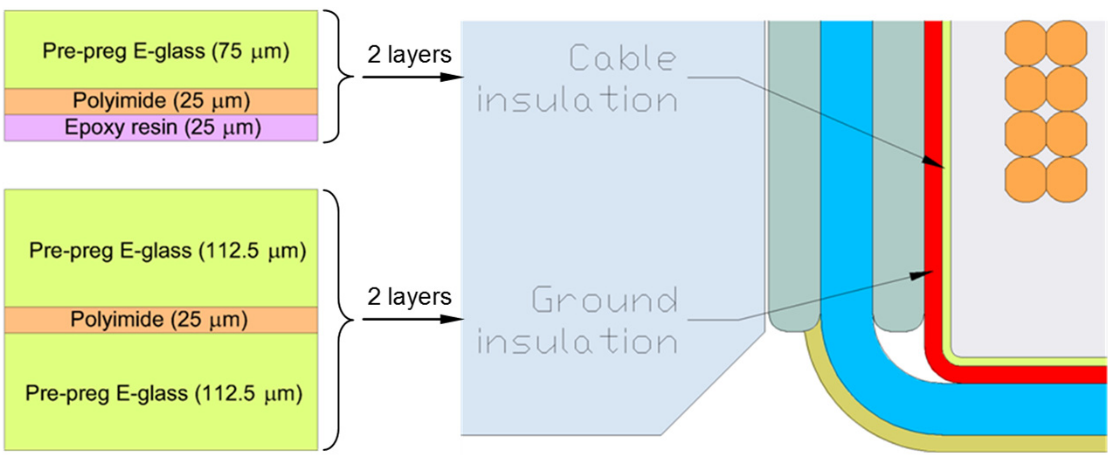


Parameter	Unit	Value	Tolerance
Cable critical current at 5.0T, 4.22K	kA	≥66.2	
Cable critical current at 5.0T, 6.60K	kA	≥9.2	
NbTi filament diameter	μm	<40	
Strand diameter at 293K	mm	1.466	±0.005
Number of strands	-	30	
Strand Cu/non-Cu ratio	-	0.90	±0.05
RRR of Cu matrix	-	≥100	
RRR of Al stabilizer	-	≥500	
0.2% yield strength of Al stabilizer at 4.2K/293K	MPa	≥80/60	
Shear strength of Al-Cu bond at 293K	MPa	≥40	
Overall cable width at 293K	mm	30.1	±0.1
Overall cable minor edge thickness at 293K	mm	5.52	±0.03
Total delivered cable length	km	≥14.4	

All the cable unit lengths have been fabricated and delivered to FNAL. Meet all the requirements.

Coils and insulation





- Coil envelope: exact number of turns and dimensions are important;
- Insulation:
  - Must contain 2 layers of polyimide in the cable and ground insulation per the design requirement.
  - Must not contain any voids (i.e. be impregnated with epoxy).
  - The final insulation design is under the discussion with the magnet vendor.

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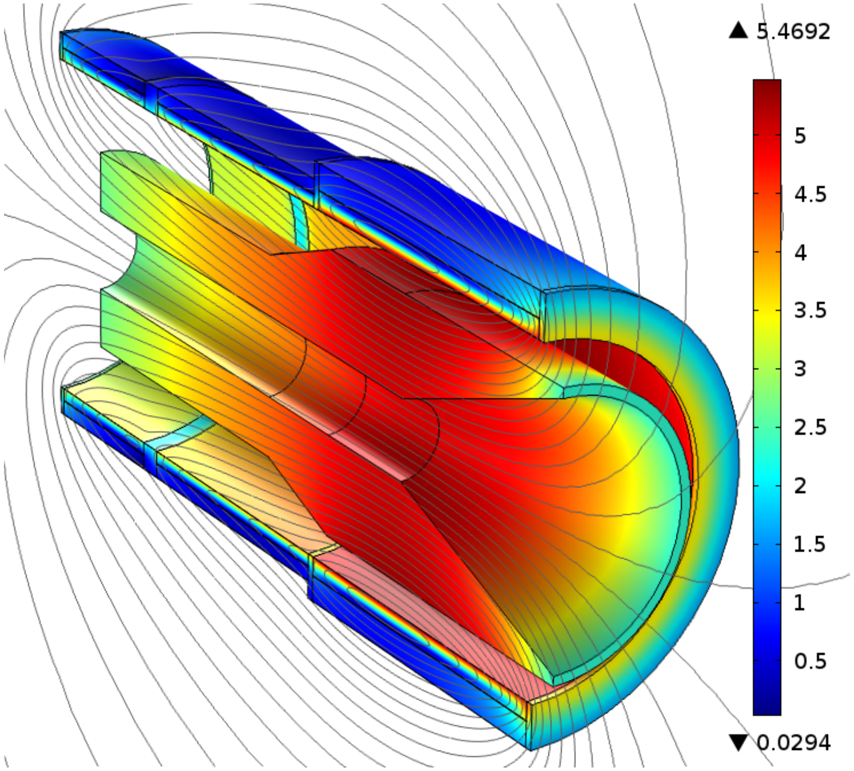
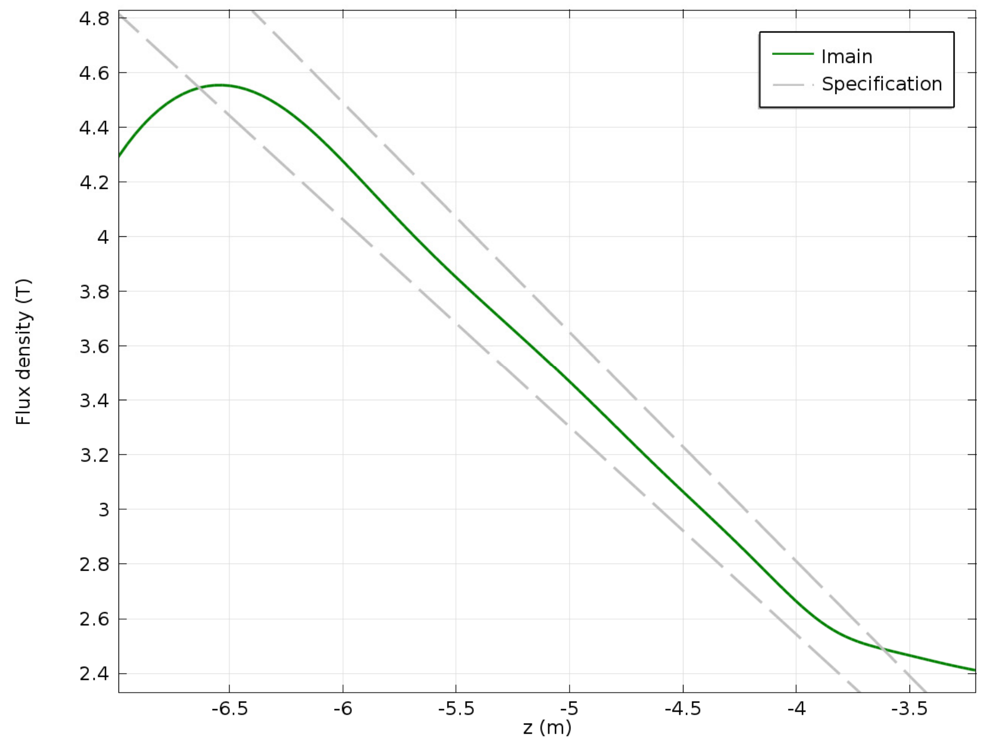
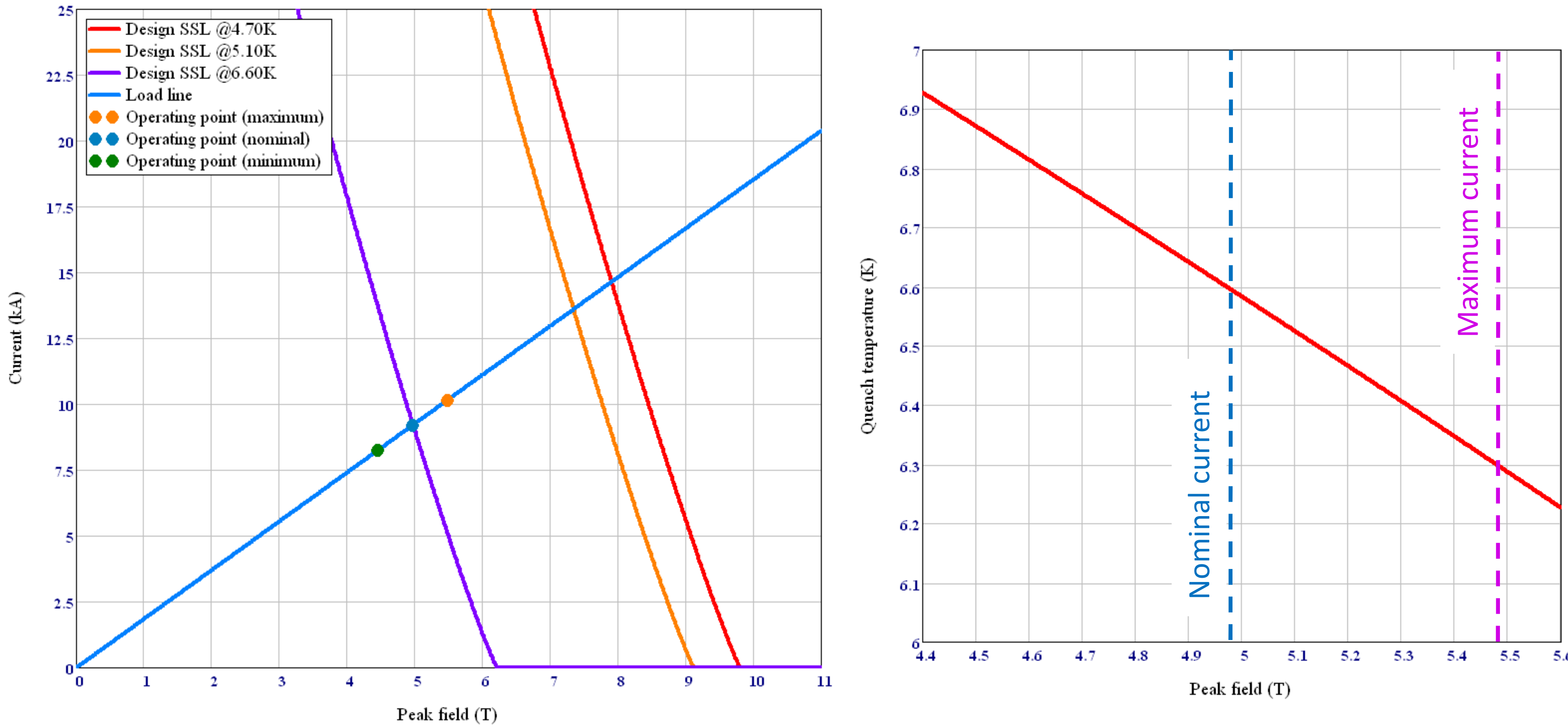
Magnetic field





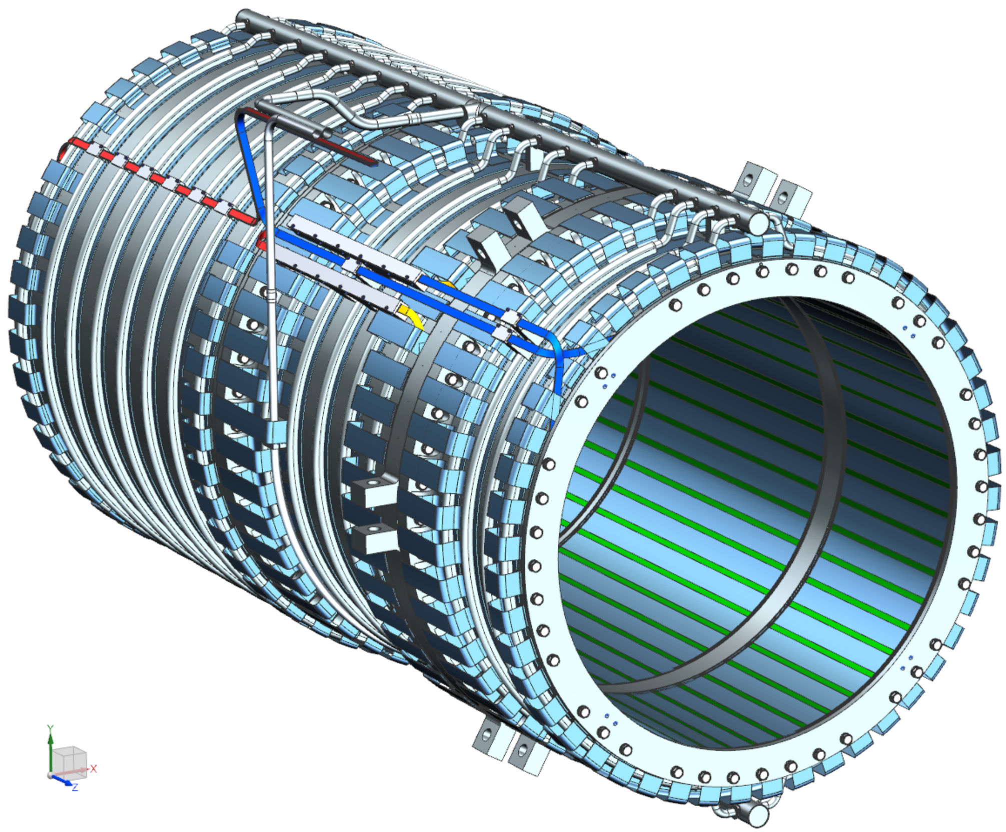
- The magnetic field profile is within the specification;
- Radiation shield (shown) made of high-resistivity bronze (magnetic permeability of ≤1.04) has a minor impact on the field quality.

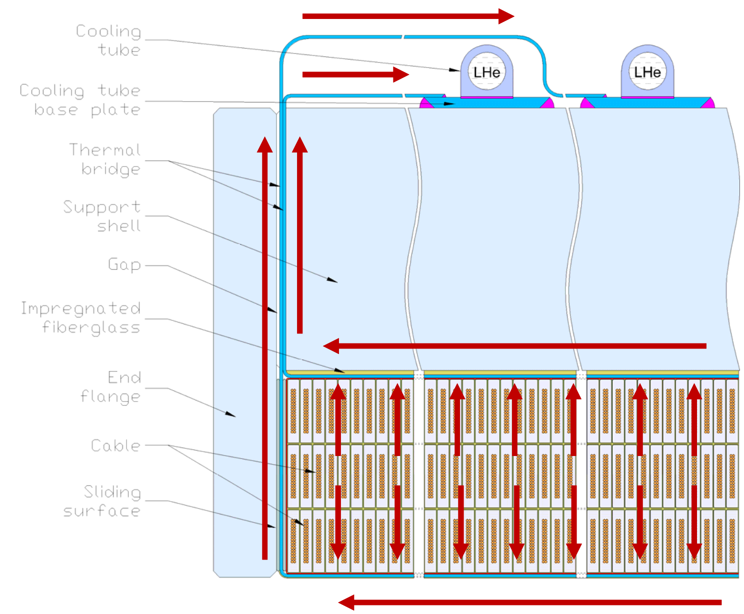
Operating margins



- The 1.50 K thermal margin must be maintained during the nominal operation per the magnet requirements;
- It defines the maximum allowed coil temperature of 5.10 K (at the nominal current).

"Conventional" technology with advanced features

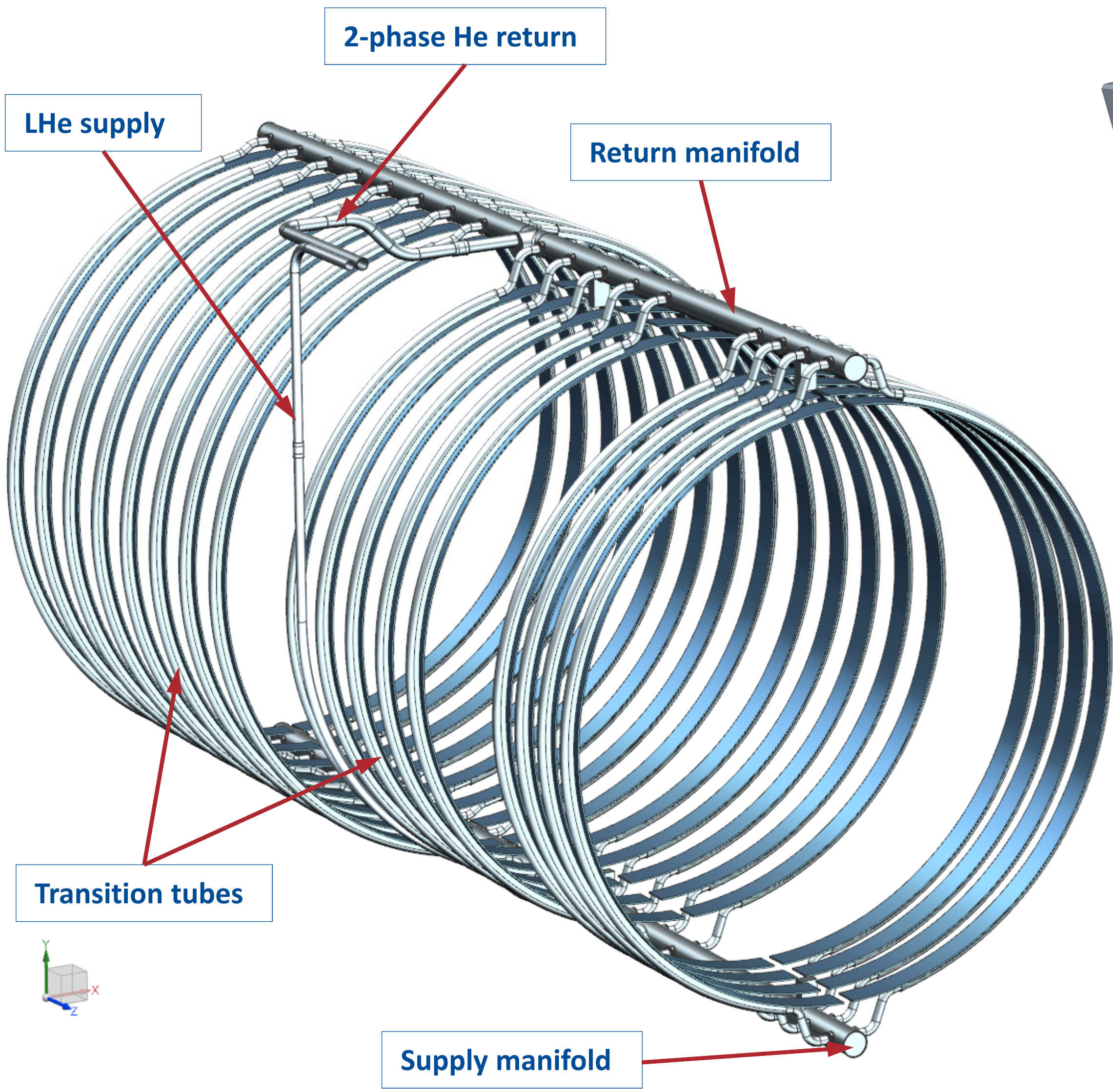


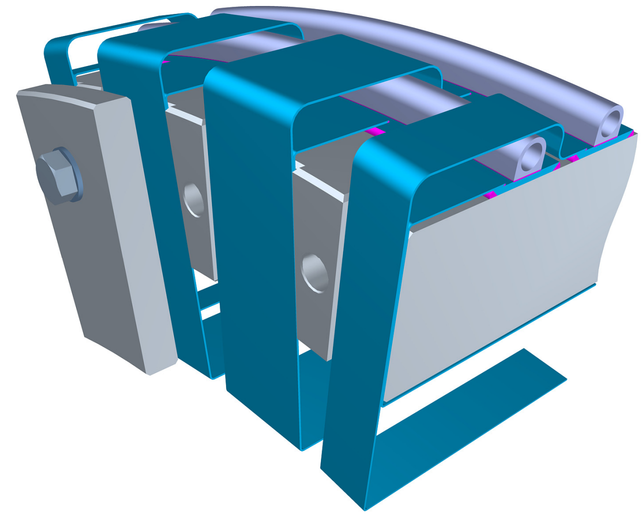


- The radiation heat escapes from the coil in the radial direction.
- Because of that, the number of layers (i.e. the number of thermal barriers in the radial direction) should be minimized.
- Cable with a large aspect ratio that has to be wound in the "hard" way... which is literally hard to wind.

This design has already been pushed to the limit of what can be achieved using conventional technology. The Mu2e-II would require other technical solutions.

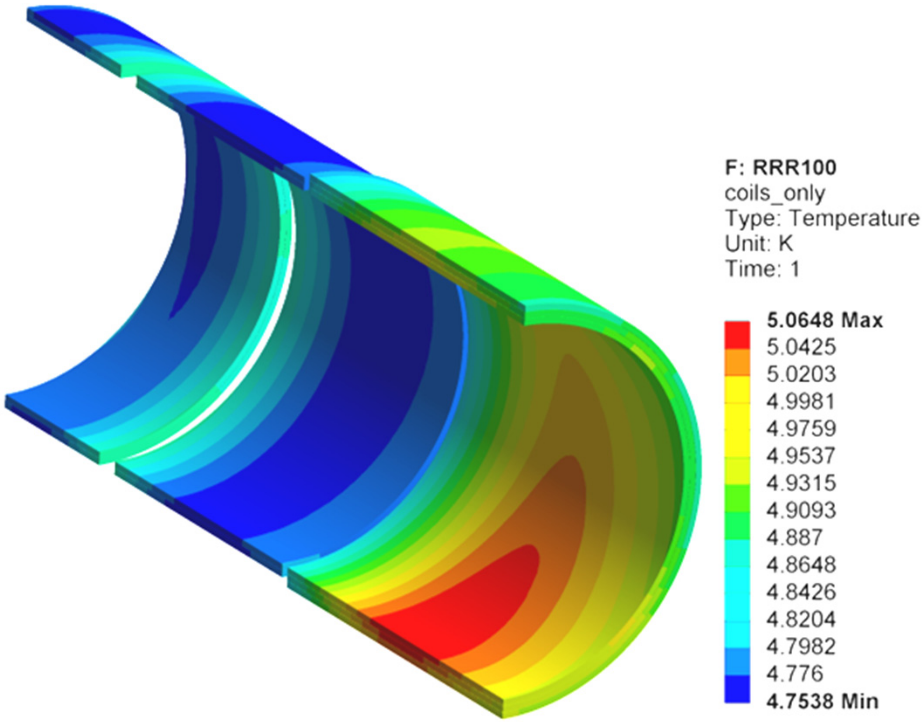
Thermosiphon system

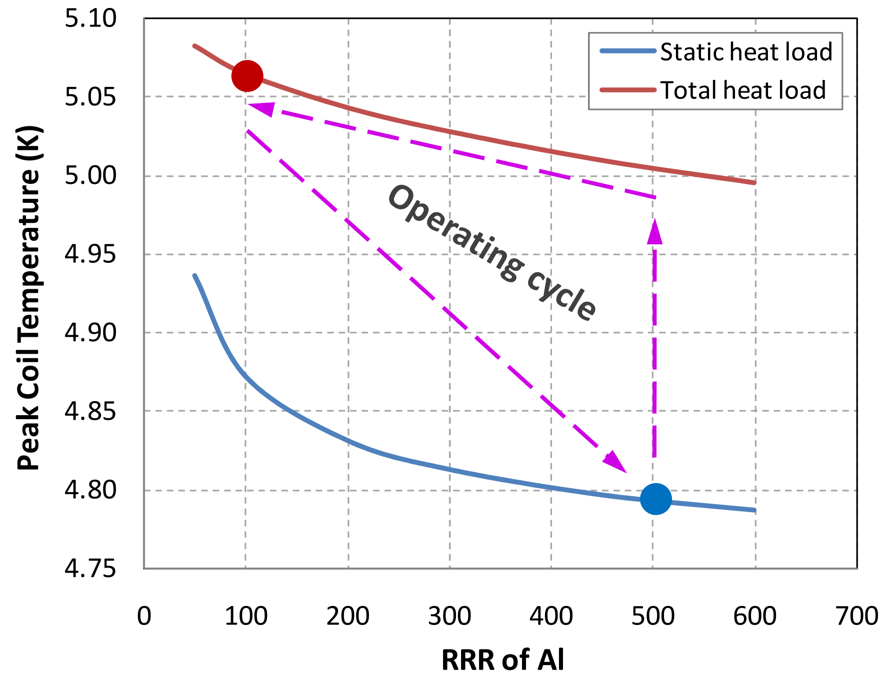




- Thermal bridges (TB) are the main elements of the heat extraction:
  - TB connection to the cooling system is an important design detail;
- The cooling tubes are EB-welded to the plates of 5N Al;
- TBs are TIG welded to the 5N plates;
- This design minimizes the ΔT between TB and LHe.

Thermal analysis at T_0=4.7 K: static+dynamic heat load





- The peak ΔT in the coil due to the static heat load is 100 mK;
- When the beam is turned on, the peak temperature goes up by 200 mK;
- As the magnet gets irradiated and the RRR of Al drops to its minimally allowed value of 100, the temperature goes up by another 50 mK;
- After that, the magnet is thermo-cycled to the room temperature to recover the RRR.

Transition to Mu2e-II

Possible scenarios

- By the time of the Mu2e-II experiment, the Production Solenoid of the Mu2e-I may already consume a substantial fraction of its absorbed dose budget (i.e. 7 MGy) and become activated.
- Even though only one coil will see the peak radiation level, it may be difficult or impossible to perform the following tasks:
  - Remove or replace the HRS;
  - Transport the magnet to the vendor;
  - Disassemble the vacuum vessel and replace the coils.
- Two most realistic scenarios:
  - Use the PS/HRS "as is" at the Mu2e-II radiation load - until it fails;
  - Rebuild the PS/HRS entirely (or substantially):
    - Depending on the activation level, it may be possible to recycle the vacuum vessel, the thermo-shield and the cold mass supports, but the cold mass will have to be replaced.
    - Since the new cable and coils will have to be fabricated, it makes sense to design them for the increased radiation load.

Is it possible to use Mu2e-I PS and HRS for Mu2e-II?

- If the thermal conductivities are constant, the temperature raise in the coil is proportional to the power density of the heat source times the insulation thickness.
- For the Mu2e-I, the ΔT in the coil is 0.25 K. If the power density goes up by a factor of 10, the ΔT becomes 2.5 K.
- The cable critical temperature is 6.6 K at the nominal operating current. The magnet quench temperature will be 6.6 K – 2.5 K = 4.1 K.
- The magnet operating temperature shall be 4.1 K – 1.5 K = 2.6 K - pretty close to the lambda point (2.17 K) – may be difficult to stabilize at that temperature.
- Also, the thermal conductivity of the insulation goes down by about a factor of 2 in the 5.1 K - 2.6 K range. Requires further reduction of the cooling temperature. The magnetic field may also have to be reduced to gain an additional thermal margin.
- Using of the superfluid helium cooling at <1.9 K seems to be the only viable option. The cryo system will need a substantial change. The thermosiphon system will not function as designed. The insulation lifetime will be drastically reduced.

A possible solution: Cable-In-Conduit Conductor (CICC)

ITER Central Solenoid cable

SSC GEM detector cable

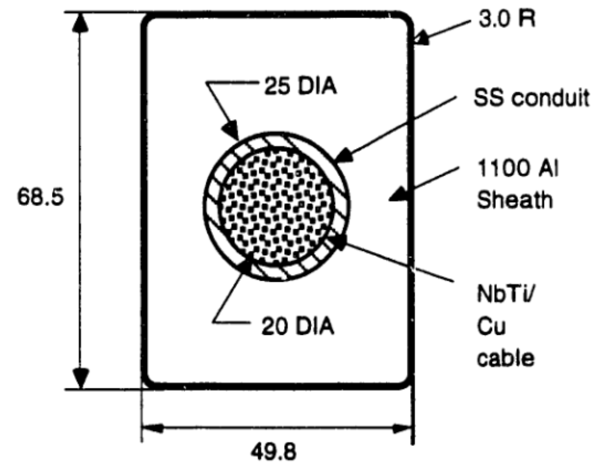
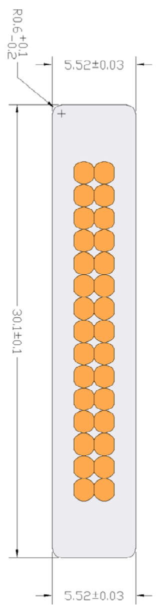


Figure 1. Cross section of the GEM Conductor. Dimensions are in mm.

- Advantages:
  - Direct cooling of superconductor by liquid helium.
  - Cable and magnet technology is relatively well developed by the fusion community.
- Disadvantages:
  - Using of high-density materials (Cu for the stabilizer and SS for the conduit). Would triple the heat dissipations comparing with the Al-stabilized conductors.
  - May have to use (expensive) Nb3Sn instead of NbTi to cope with the higher thermal load.
  - Electrical conductivity of Cu permanently degrades under irradiation, while the electrical conductivity of Al completely recovers during a thermo-cycle.

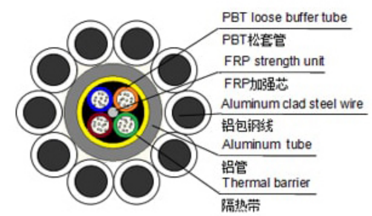
Proposed technical solution: combine 3 cable technologies

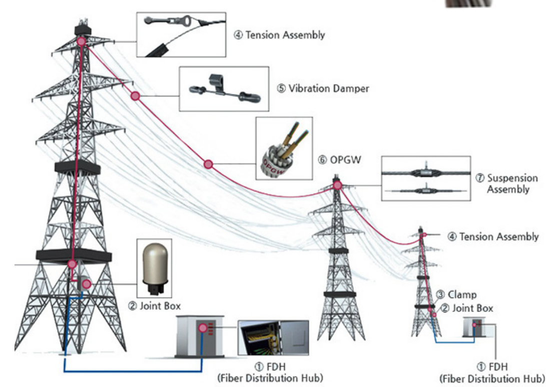
Al-stabilized cable

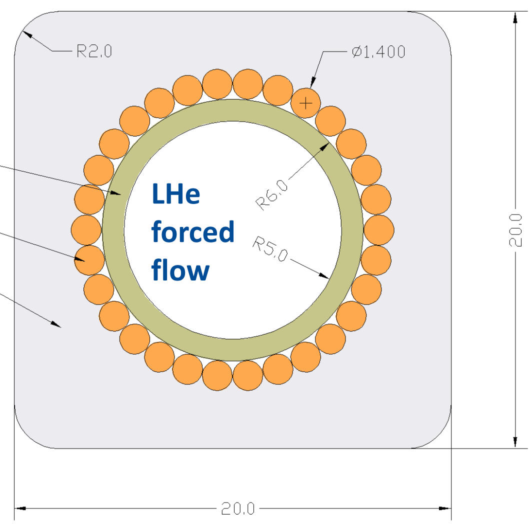


CICC

OPGW







- Advantages:
  - Nearly direct cooling of superconductor by LHe.
  - Low-density materials.
  - No permanent degradation under irradiation.

- Disadvantages:
  - No one ever made such a cable (but the vendor was optimistic and willing to try).

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Proposed R&D steps

- Numerical simulations and industry studies to determine the optimum cable design and parameters (12 months).
- Procurement of the “proof of principle” internally-cooled Al-stabilized cable with a length of 200-300 m (18-24 months).
- Performing the electrical, mechanical and thermal tests on the cable samples (6 months).
- Building and testing a sub-scale solenoid model (12-18 months):
  - Use the radiation-resistant epoxy (e.g. cyanate ester resin or ITER type blend);
  - Instrument the model with heaters and thermal gauges to simulate the radiation environment of the Mu2e-II (and potentially Mu2e-III) experiment;
  - Testing the model would yield the data on the critical heat flux and stability of the forced flow cooling in this new type of the cable.
- The project deliverable will be a tested internally-cooled solenoid model suitable for the radiation environment of the future muon experiments.

Other benefits

- The new internally-cooled cable and magnet technology can also be used in magnets for muon sources and fragment separators for secondary beam facilities that require large-aperture focusing and steering magnets working in high-radiation environments.
- It may be a good substitute for CICC in some fusion experiments.
- The same technology can potentially be used in superconducting detector magnets for the energy frontier experiments (FCC-hh):
  - Improved cooling increases the thermal margin that can be used to reduce the amount of superconductor (and cost).
  - No need to wind the cable in the hard-way to minimize the number of layers since each layer is cooled internally – simplifies fabrication.
  - Low helium inventory in the system minimizes the helium losses during a quench.