Beam-Related Design Limits for Superconducting Magnets

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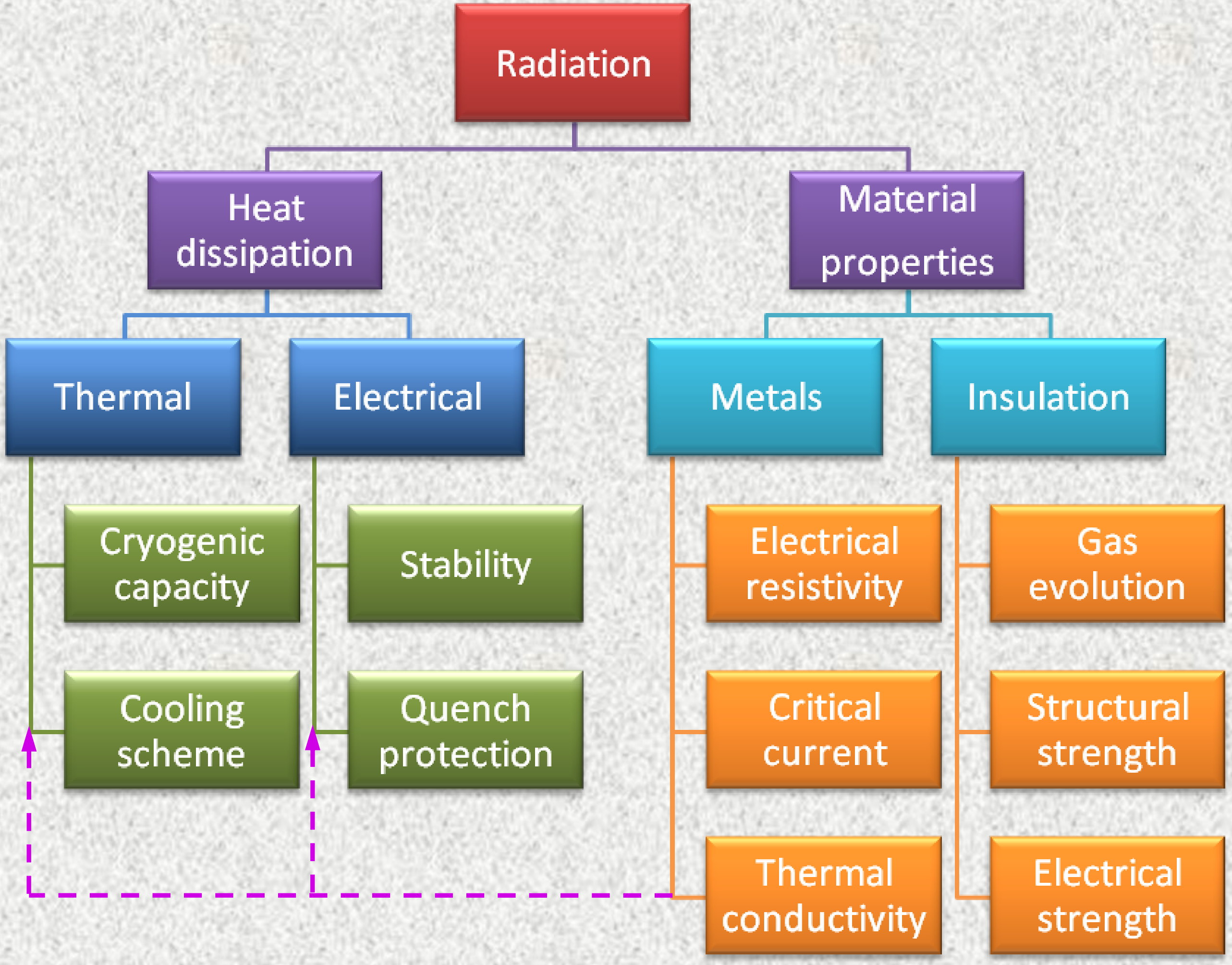
Outline

- Beam-Related Design Constraints and Limits
- Colliders
- Fixed Target Experiments
- Summary

Superconducting Magnets Under Irradiation



Beam-Related Design Constraints and Limits*

- **Operational stability: peak power density** in the innermost cable < 40 mW/cm^3 and < 13 mW/cm^3 in Nb_3Sn and NbTi, respectively, that can be removed while keeping the coil below the magnet quench temperature (with a safety margin of 3 in the LHC)
- **Lifetime: peak dose** on the innermost coil layer over operational lifetime < 25-35 MGy in organic materials and a fraction of DPA in coil inorganic materials
- **Cryoplant capacity and operational cost: dynamic heat loads** < 10-15 W/m in cold mass
- **Hands-on maintenance: residual dose** rate on the component outer surfaces < 0.1 mSv/hr

*) Numbers here are current for collider superconducting magnets

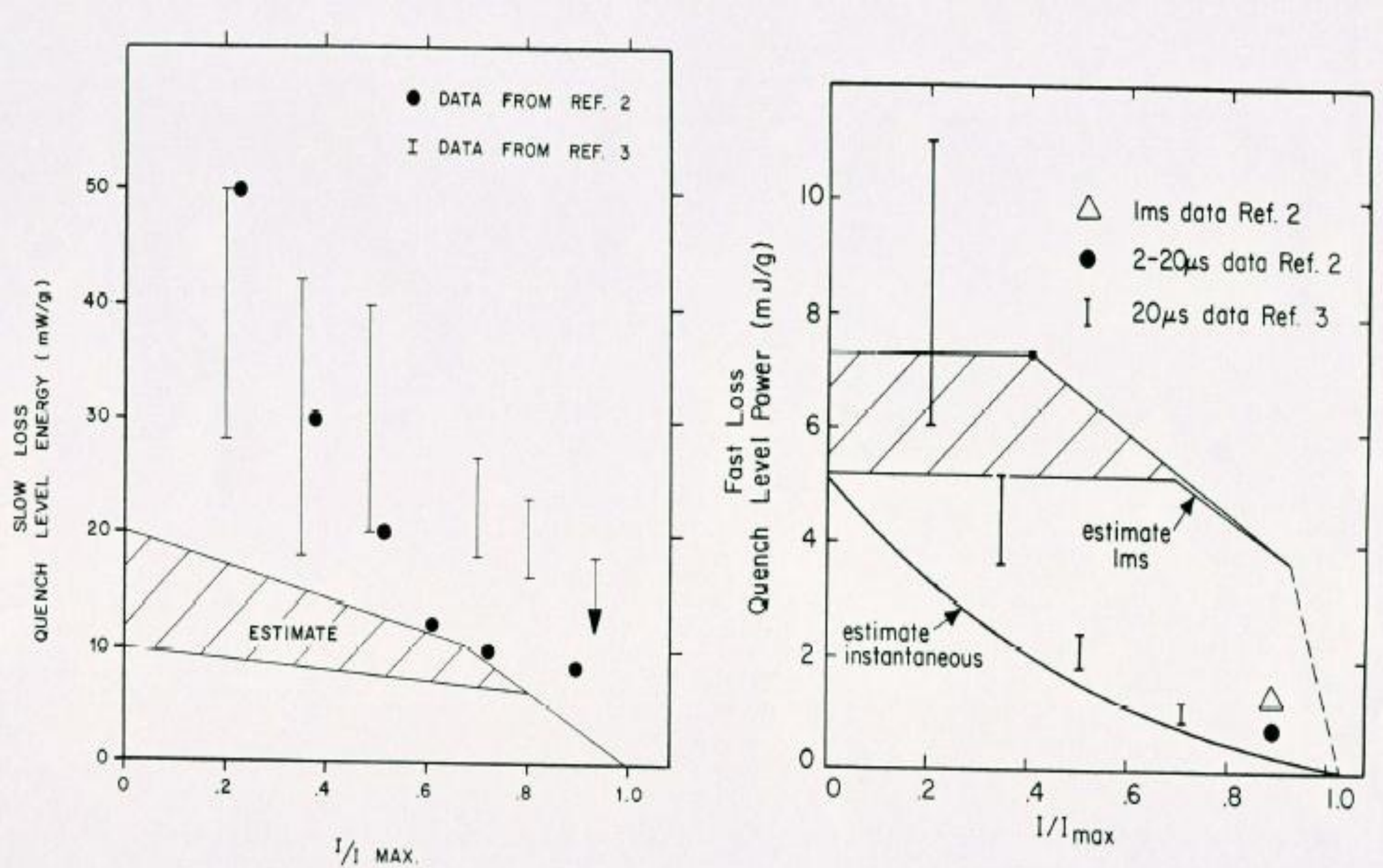
Collider Magnet Protecting Components

- **IP Collision Debris:**
  - 0.95 kW LHC, 4.76 kW HL-LHC and 43.2 kW FCC on each side of IP
  - Inner triplet (IT): front absorber (TAS, L~20m), large-aperture quads with tungsten inner absorbers, absorbers in interconnect regions
  - Neutral beam dump (TAN, L~147m) and Single-Diffraction collimators in dispersion suppression regions (TCL, L~149 and 190m)

L is a distance from IP1/IP5 in LHC and HL-LHC

- **Beam Loss:**
  - Energy stored in each beam: ~0.3 GJ LHC and >8 GJ FCC
  - Betatron and momentum multi-stage collimation systems (L=1/4 C)
  - Beam abort system (L=1/8 and 3/8 Circumference)
  - Tungsten tertiary collimators (TCT, L~150m) and TAS (L~20m)
  - FCC-hh: intercepting synchrotron photons at elevated temperature

Slow and Fast Quench Levels in Tevatron NbTi Dipoles



Quench Limits

Tevatron NbTi Dipoles

Based on measurements and analyses by H. Edwards et al (1977-1978), the following design limits (4.4 T, I/I_c=0.9, 4.6 K) have been chosen (*with reliable operation for 25 years*):

- Slow loss (DC) 8 mW/g
- Fast loss (1 ms) 1 mJ/g
- Fast loss (20 μs) 0.5 mJ/g

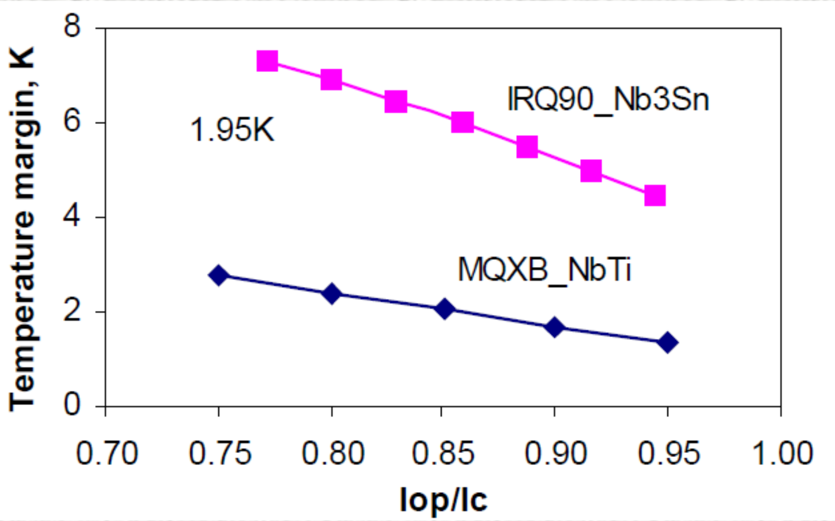
LHC IR Quads

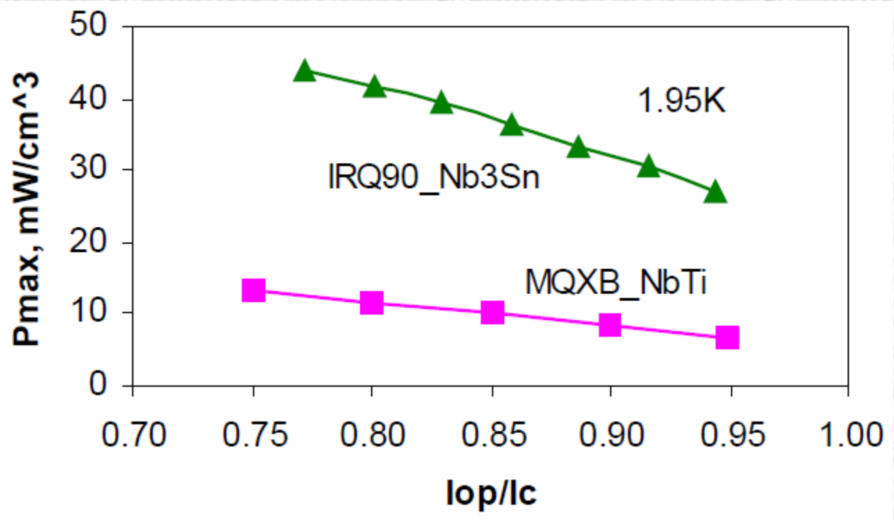
Based on thorough studies by A. Zlobin et al within LARP, the following design limits have been chosen (*with no beam-induced quench observed at LHC so far*):

LHC NbTi: 1.6 mW/g (13 mJ/cm^3) DC. Used in design: 0.5 mW/g

HL-LHC Nb_3Sn: ~5 mW/g (40 mW/cm^3) DC. Used in design: 1.7 mW/g

Temperature Margin and Quench Limits in LHC Quads



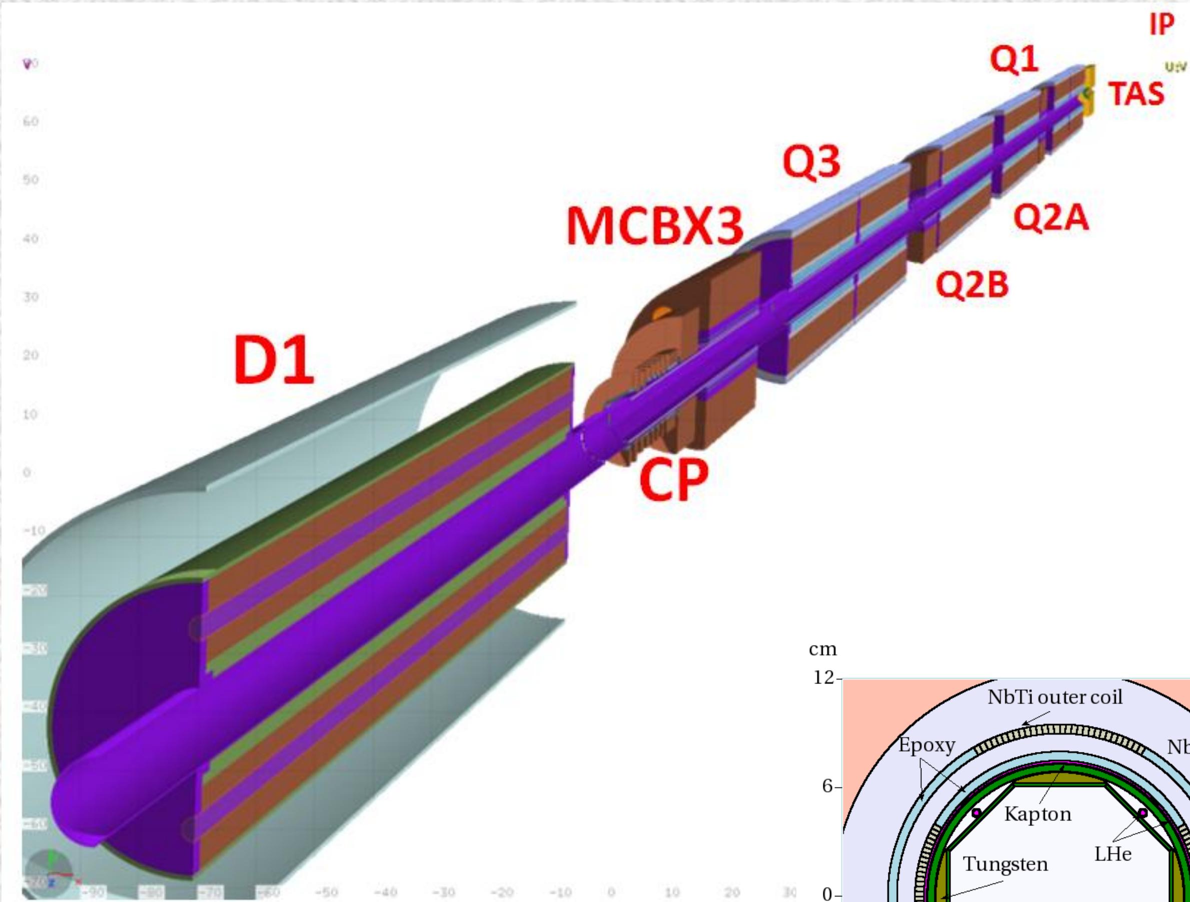


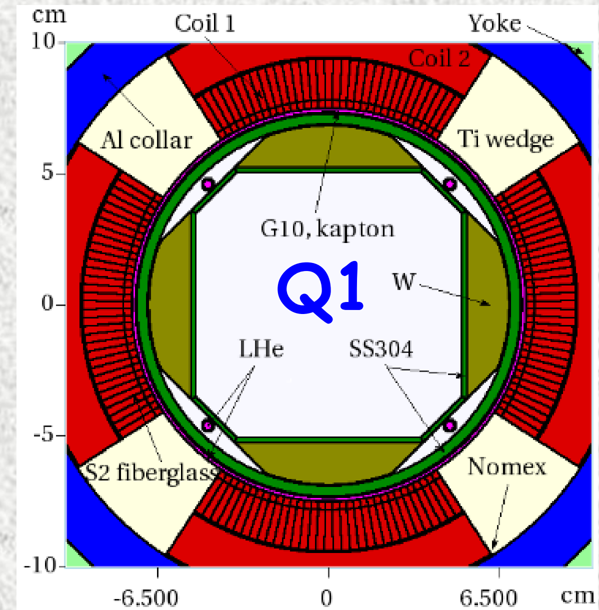
A. Zlobin et al.

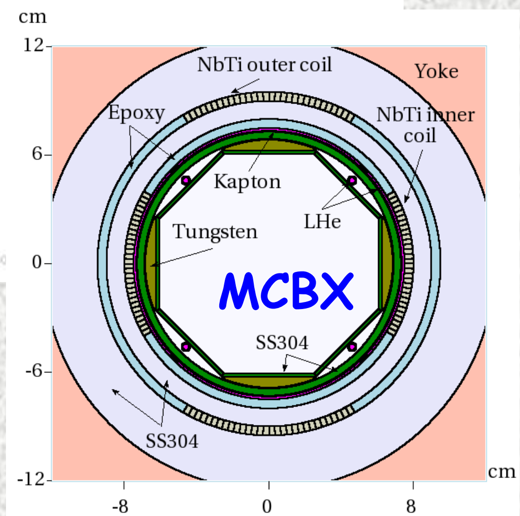
Where are we with respect to the operational and lifetime limits in the current grand-projects based on the superconducting technology?

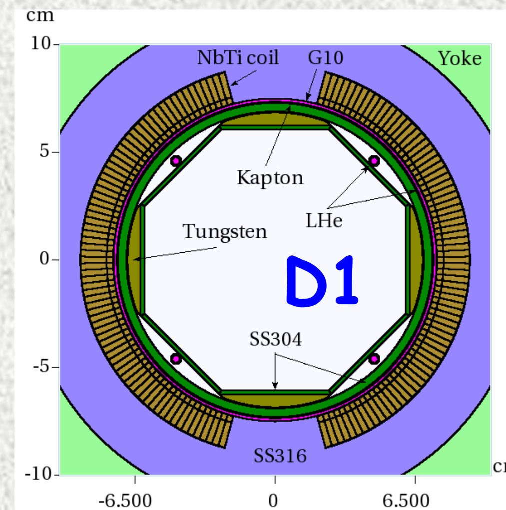
Consider two examples: High Luminosity LHC upgrade and Mu2e/COMET

FLUKA-MARS15 for HL-LHC Triplet



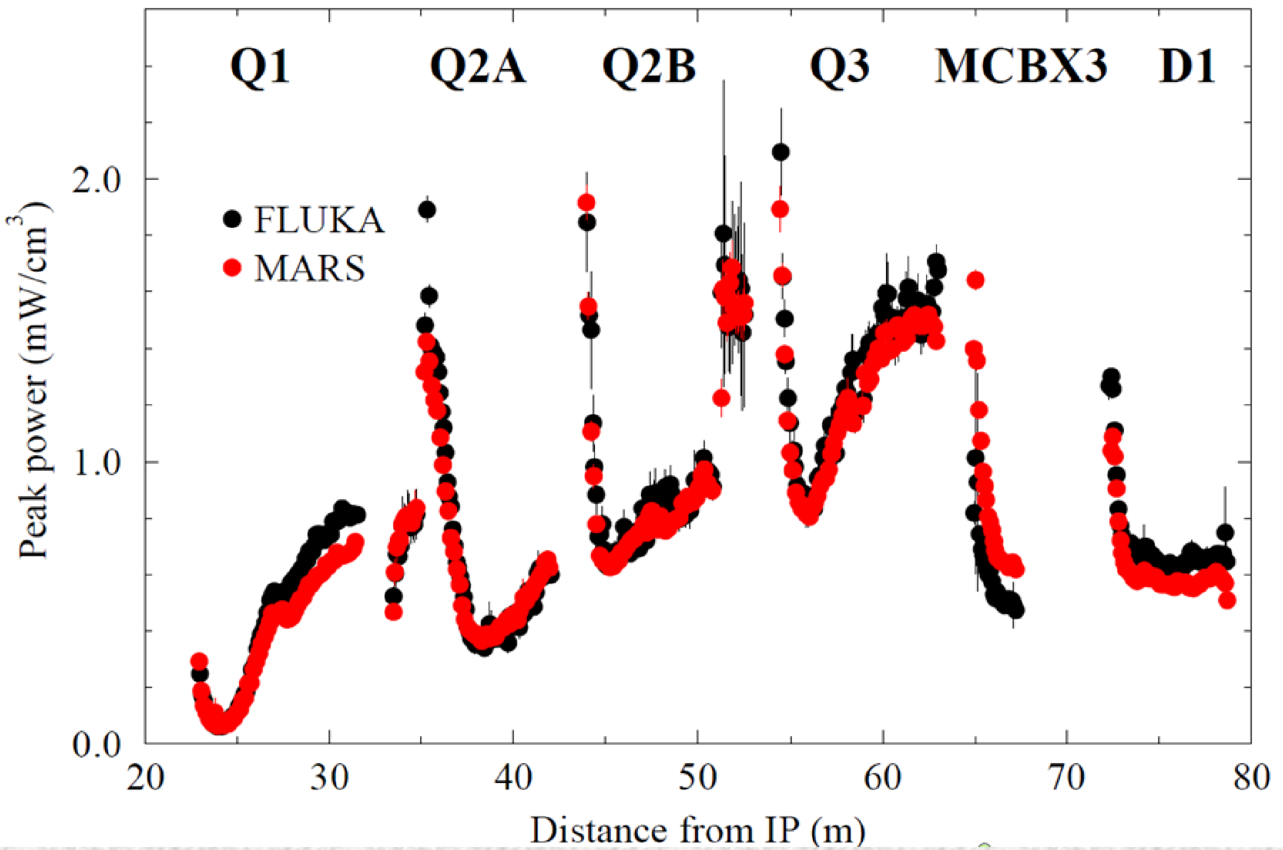






150-mm coil ID magnets with optimized tungsten inserts

Operational Stability: Power Density P_{max}



P_{max} ~ 2 mW/cm^3 in Nb_3Sn quads, 20 times below the limit at I_{op}/I_c = 0.8

P_{max} ~ 1.5 mW/cm^3 in NbTi D1, ~10 times below the limit at I_{op}/I_c = 0.8

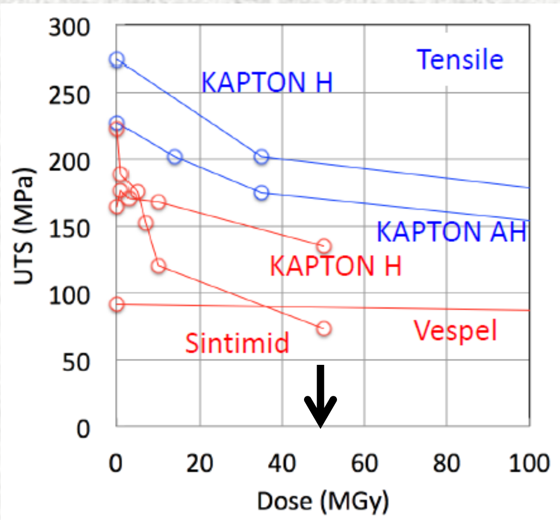
Operational: Dynamic Heat Loads

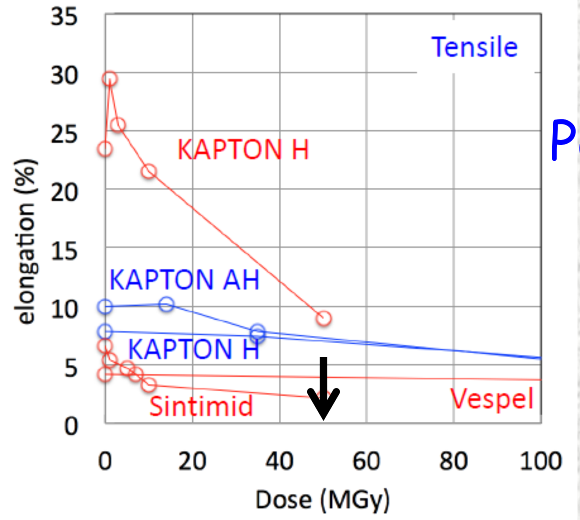
TABLE I. Integral power dissipation (W) in components of inner triplet calculated with FLUKA and MARS codes. FLUKA results are given for both 10 and 50 cm shielding gaps in the fixed-length ICs.

	FLUKA				MARS	
	10 cm gap in ICs		50 cm gap in ICs		50 cm gap in ICs	
Component	Magnet cold mass	Beam screen	Magnet cold mass	Beam screen	Magnet cold mass	Beam screen
Q1A + Q1B	100	170	100	170	95	170
Q2A + orbit corrector	95	60	100	65	100	65
Q2B + orbit corrector	115	80	120	80	115	80
Q3A + Q3B	140	80	140	80	135	75
Corrector package	55	55	60	55	60	65
D1	90	60	90	60	90	55
Interconnects	20	140	20	105	15	85
Total	615	645	630	615	615	600

Average dynamic heat load on the cold mass of 14 W/m is within a design range of 10-15 W/m used for the LHC and assumed for the HL-LHC

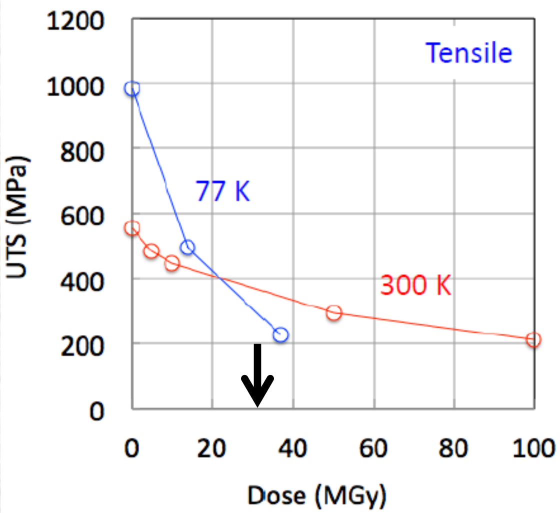
Material Limits: Polyimide and G11



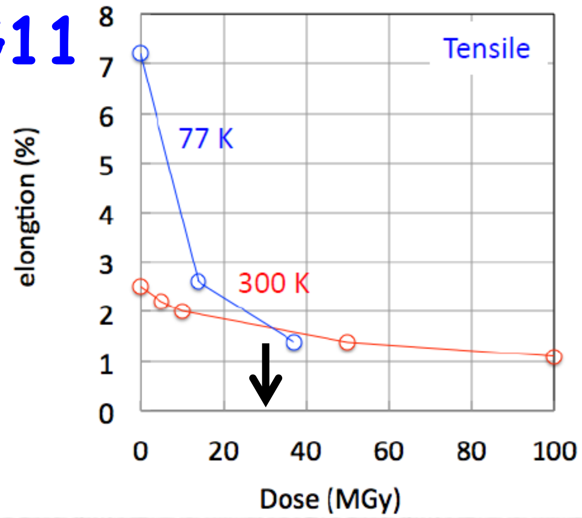


Polyimide becomes brittle

M. Tavlet et al.



G11



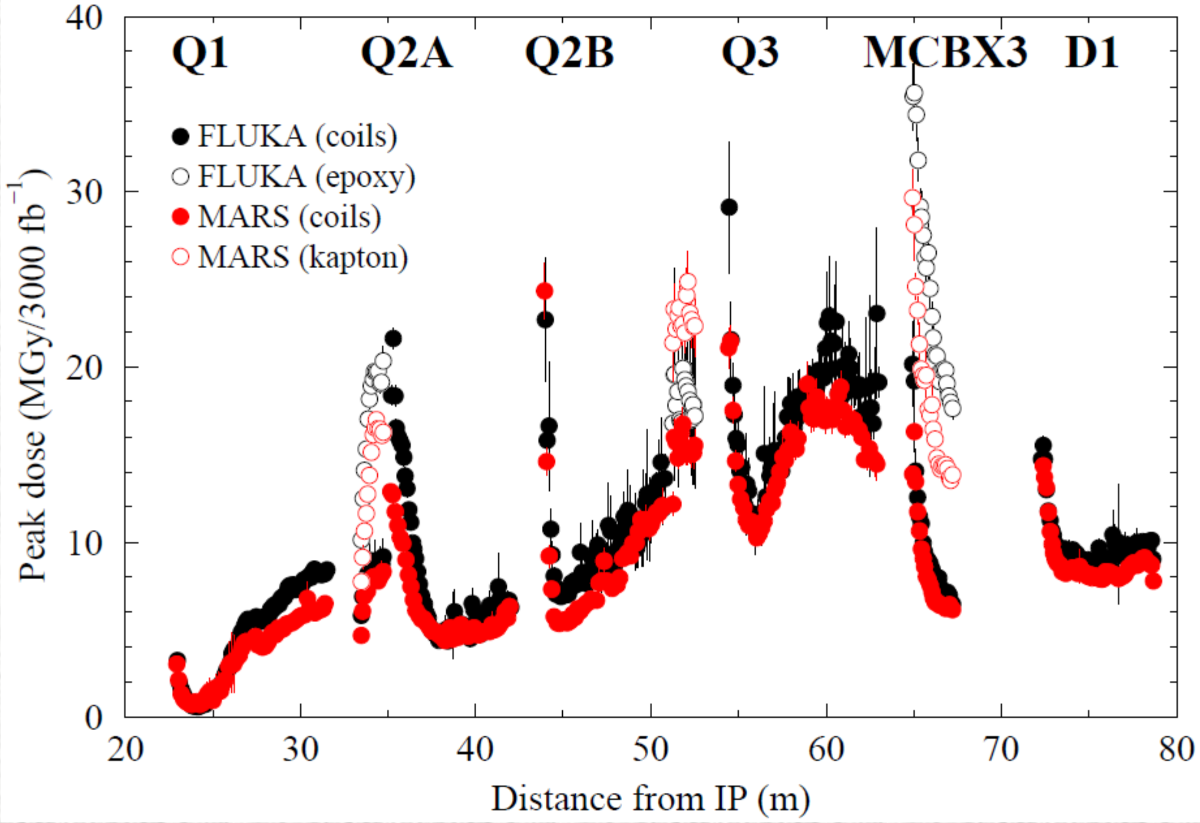
G11: loss of strength and elongation

Courtesy L. Bottura

Magnet Organic Materials Limits

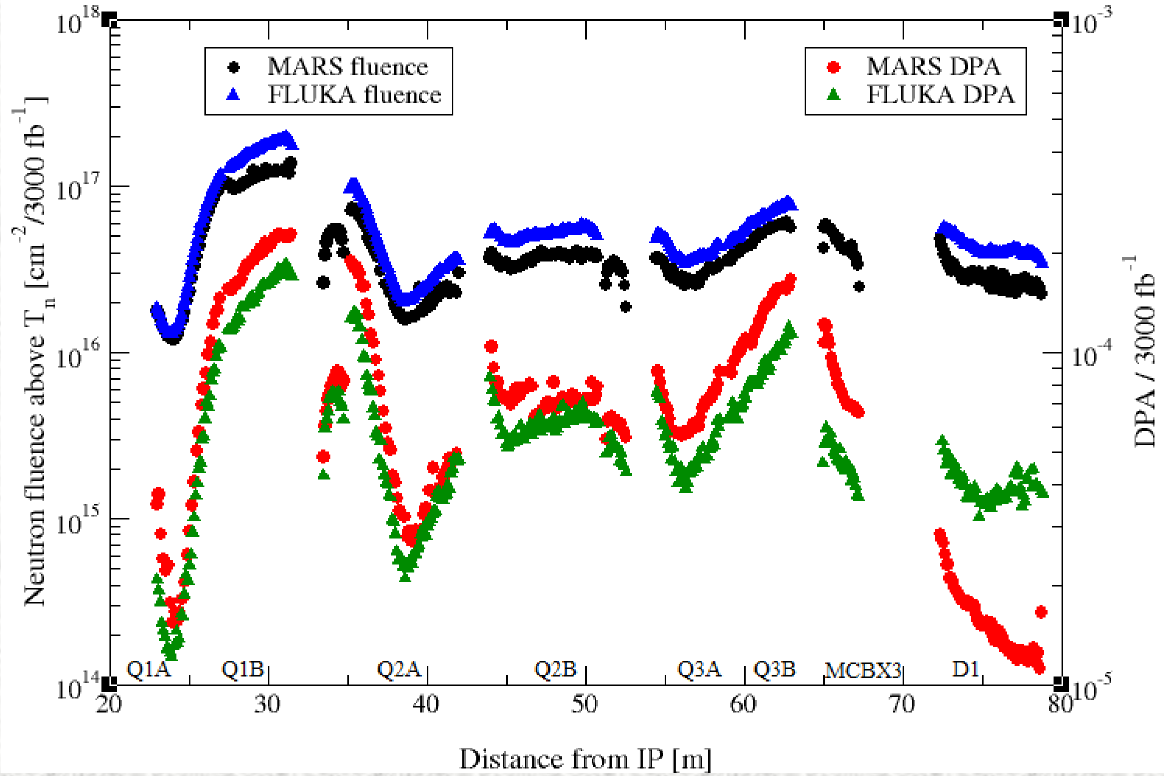
- Bonding strength (shear) of epoxies is strongly degraded (80 %) above 20 MGy
- Fracture strength of insulating materials degrades by about 50 % in the range of 20 MGy (G11) to 50 MGy (epoxies, kapton)
- Insulations (polyimide) become brittle above 50 MGy

Lifetime Peak Dose: HL-LHC



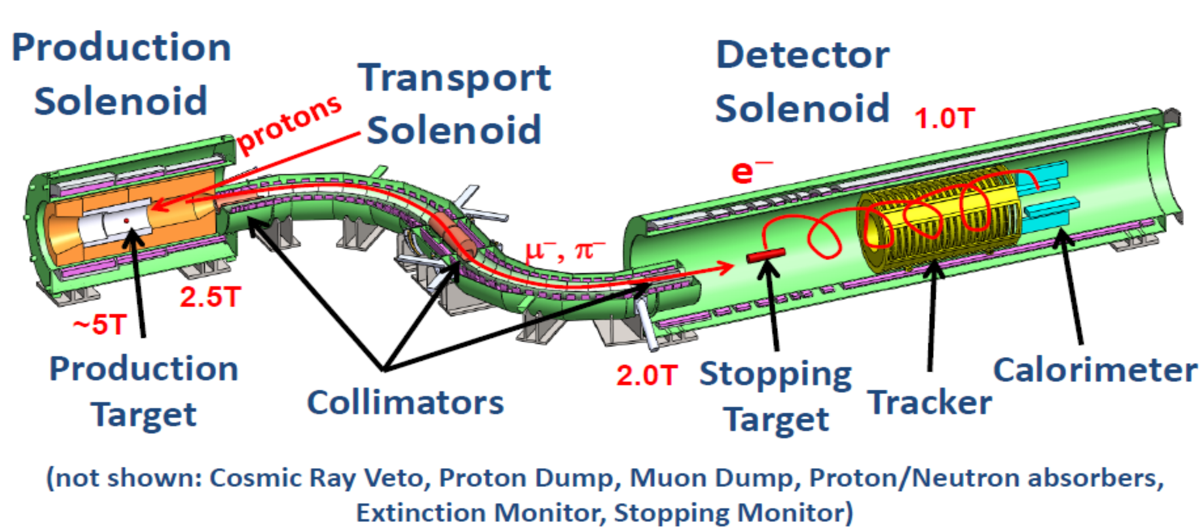
The maximum peak dose in the coils is about 25 MGy for quadrupoles and ~15 MGy for the D1 dipole. The peak dose in the IT magnet insulation reaches 30-36 MGy in the MCBX3 corrector, 28-30 MGy in the quadrupoles and ~22 MGy in the D1 dipole. This is at the common limits for kapton (25-35 MGy) and CTD-101K epoxy (25 MGy) or slightly above them.

Lifetime DPA and Neutron Fluence



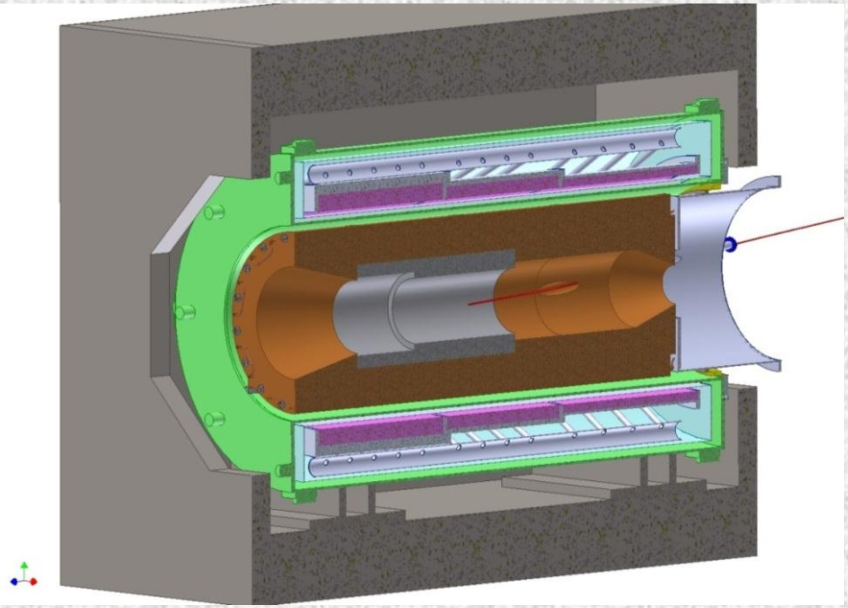
The peak in Q1B inner coil is ~2×10^{-4} DPA per 3000 fb^{-1} integrated luminosity. In other IT components it is about (1.0±0.5)×10^{-4}. These numbers are acceptable for SC and copper stabilizer provided periodic annealing during the collider shutdowns. In the quad coils, the peak neutron fluence is ~2×10^{17} cm^{-2} which is lower than the 3×10^{18} cm^{-2} limit used for the Nb_3Sn. In corrector and D1 dipole NbTi coils, the peak fluence is ~5×10^{16} cm^{-2}, lower than the 10^{18} cm^{-2} limit.

Mu2e Production Solenoid

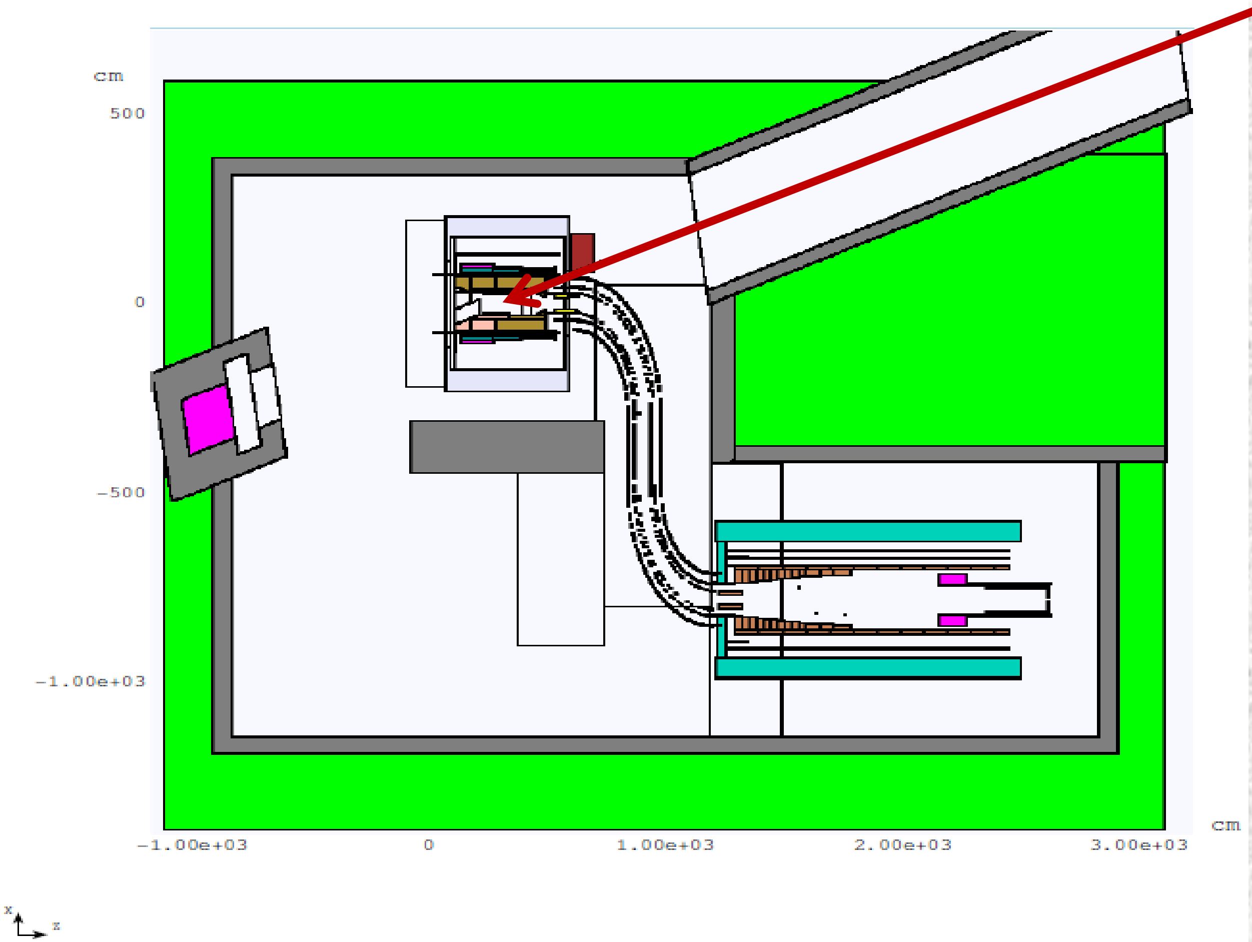


Mu2e: Measurement of conversion of μ^- to e^- in the field of a nucleus without emission of neutrinos.

One of the main parts of Mu2e is its SC production solenoid (PS), in which negative pions are generated in interactions of the primary proton beam with high-Z target. Pions then decay into muons which are delivered by transport solenoid to the detectors. Off-axis 8-GeV proton beam of 6×10^{12} p/s on target. Min operational lifetime 3.6×10^{20} pot.



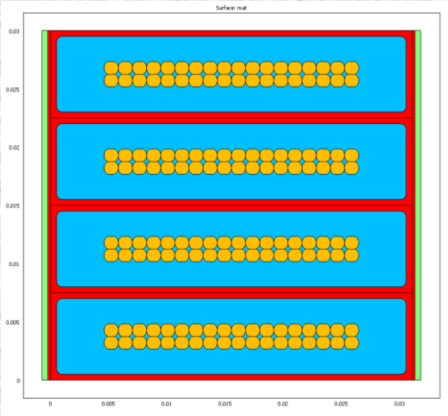
RRR Degradation: DPA limit for SC coils ~5×10^{-5} /yr



8-GeV p, 8 kW

Mu2e and COMET

SC coil



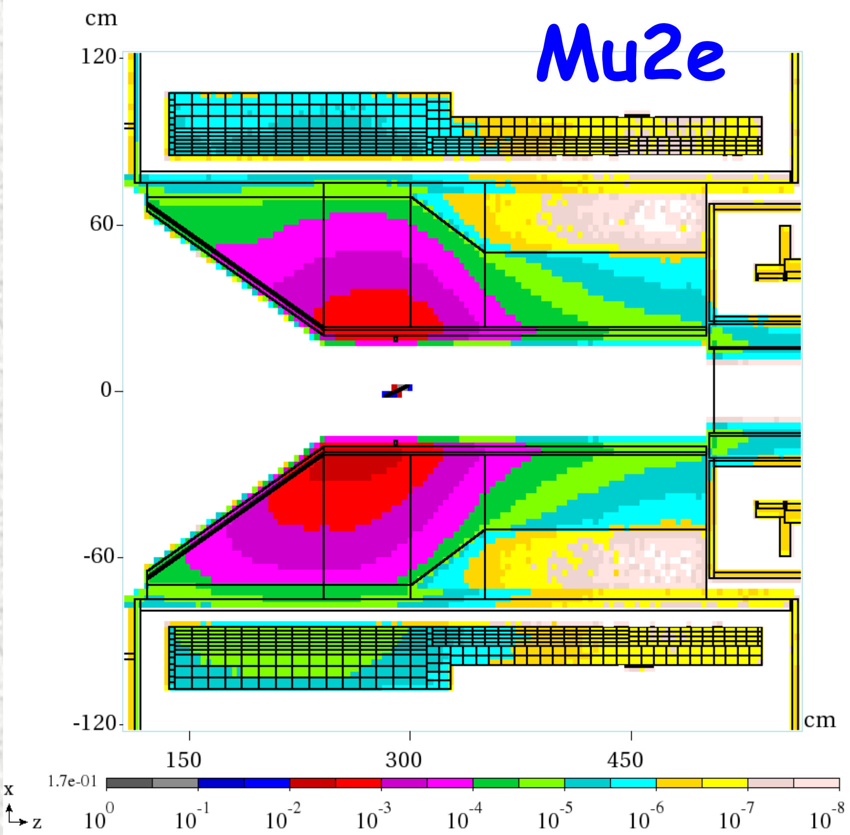
Bottleneck: degradation of Residual Resistivity Ratio (RRR) of **stabilizer** (ratio of electric resistivity of a conductor at room temperature to that at the liquid He one).

Mu2E SC Production Solenoid Design Constraints

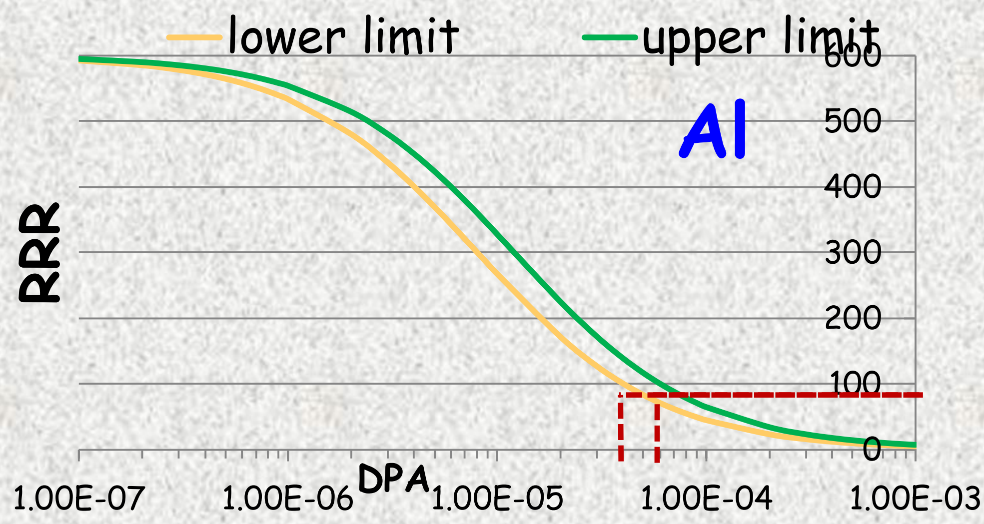
Based on detailed energy deposition and DPA MARS simulations, thorough thermal analysis and analysis of the KEK/KURRI data, the following limits have been derived:

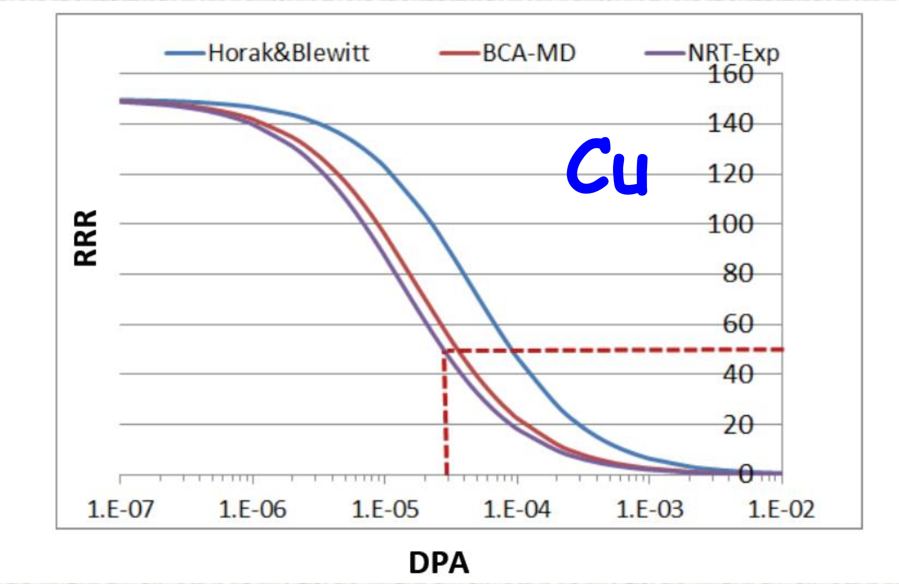
- **Peak power density** in the innermost NbTi superconductor: below 30 μW/g
- **Dynamic heat load**: below 100 W in cold mass
- **Peak dose** on the innermost SC coil layer over system lifetime: below 7 MGy for epoxy to bond insulation (10% degradation in its shear modulus)
- **Peak** DPA in Aluminum stabilizer: below $(4\text{-}6)\times10^{-5}$ DPA per year (RRR reduction from 600 to 100) followed by a warm-up to anneal the Al stabilizer

DPA/yr Map and RRR *vs* DPA in Al and Cu Stabilizers

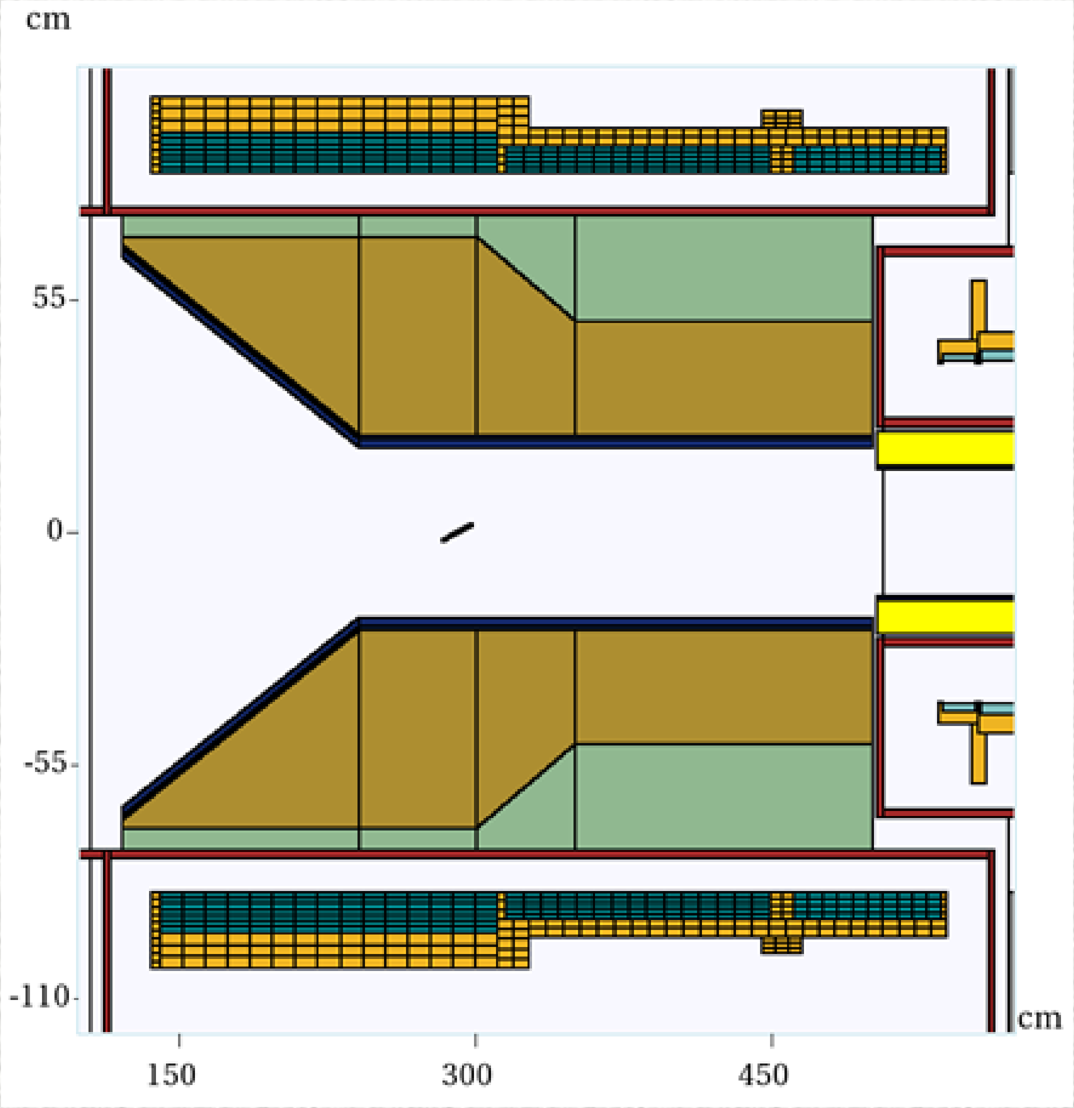


MARS15 calculated DPA/yr map in Mu2e PS for 8-kW beam





Production Solenoid HRS



Sophisticated Heat and Radiation Shield (HRS) has been designed on the basis of optimization MARS15 simulations and thermal analysis.

HRS safely protects SC coils against radiation with all the critical operational and lifetime quantities being within the derived limits.

Summary

- Beam-related constraints are considered which drive the design of superconducting magnets and respective protection systems for the current collider and fixed-target experiment projects.
- Appropriate magnet design and protective systems optimized in simulations using established independent Monte-Carlo codes assure – as proven in the LHC case – operational stability and design lifetime of the large superconducting systems.
- To further increase safety margins in the designs - especially in various upgrade scenarios - more work is needed on radiation damage models, more efficient protective systems and advanced radiation-resistant materials.