Limits for Radiation Damage to and Thermal Loads on Magnet Conductors

(Preliminary Survey: Radiation Damage Only)

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(February 8 2011)

Overview

The magnets at a Muon Collider and Neutrino Factory will be subject to high levels of radiation damage, and high thermal loads due to secondary particles, unless appropriately shielding.

To design appropriate shielding it is helpful to have quantitative criteria as to maximum sustainable fluxes of secondary particles in magnet conductors, and as to the associated thermal load.

We survey such criteria first for superconducting magnets, and then for room-temperature copper magnets.

A recent review is by H. Weber, Int. J. Mod. Phys. *20* (2011),
http://puhep1.princeton.edu/~mcdonald/examples/magnets/weber_ijmpe_20_11.pdf

Most radiation damage data is from exposures to "reactor" neutrons.

Models of radiation damage to materials associate this with "displacement" of the electronic (not nuclear) structure of atoms, with a defect being induced by ≈ 25 eV of deposited energy. Classic reference: G.H. Kinchin and R.S. Pease, Rep. Prog. Phys. *18*, 1 (1955),
http://puhep1.princeton.edu/~mcdonald/examples/magnets/kinchin_rpp_18_1_55.pdf

Hence, it appears to me most straightforward to relate damage limits to (peak) energy deposition in materials. [Use of DPA = displacements per atom seems ambiguous due to lack of a clear definition of this unit.]

Radiation Damage to Superconductor

The ITER project quotes the lifetime radiation dose to the superconducting magnets as 10^{22} n/m^2 for reactor neutrons with E > 0.1 MeV. This is also 10^7 Gray = 10^4 J/g accumulated energy deposition.

For a lifetime of 10 "years" of 10^7 s each, the peak rate of energy deposition would be 10^4 J/g / 10^8 s = 10^{-4} W/g = 0.1 mW/g.

The ITER Design Requirements document, http://puhep1.princeton.edu/~mcdonald/examples/magnets/iter_fdr_DRG1.pdf reports this as 1 mW/cm^3 of peak energy deposition (which seems to imply $\rho_{magnet} \approx 10$ g/cm^3).

Table 1.17-1 Maximum Nuclear Load Limits to the Magnet

Parameters	Unit	H	DT	TBA
Local nuclear heat in the conductor	kW/m^3	0	1	
Local nuclear heat in the case and structures	kW/m^3	0	2	
Peak radiation dose to coil insulator	Gray	0	10×10^6	
Total neutron flux to coil insulator	N/m^2	0	10^{22}	
Total nuclear heat in the magnets	kW	See Table 1.15-5		

Damage to Nb-based superconductors appears to become significant at doses of 2-3 × 10^{22} n/m^2 :

A. Nishimura *et al.*, Fusion Eng. & Design **84**, 1425 (2009)

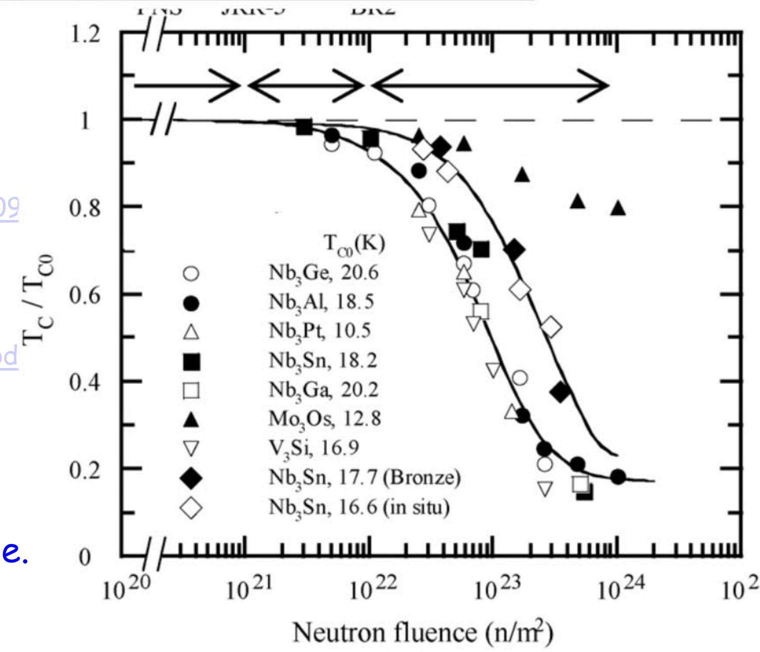
http://puhep1.princeton.edu/~mcdonald/examples/magnets/nishimura_fed_84_1425_09

Reviews of these considerations for ITER:

J.H. Schultz, IEEE Symp. Fusion Eng. 423 (2003)

http://puhep1.princeton.edu/~mcdonald/examples/magnets/schultz_ieeesfe_423_03.pd

http://puhep1.princeton.edu/~mcdonald/examples/magnets/schultz_cern_032205.pdf



Reduction of critical current of various Nb-based Conductors as a function of reactor neutron fluence. From Nishimura *et al.*

Radiation Damage to Organic Insulators

R&D on reactor neutron damage to organic insulators for conductors is carried out at the Atominstitut, U Vienna, http://www.ati.ac.at/ Recent review:

R. Prokopec *et al.*, Fusion Eng. & Design **85**, 227 (2010)

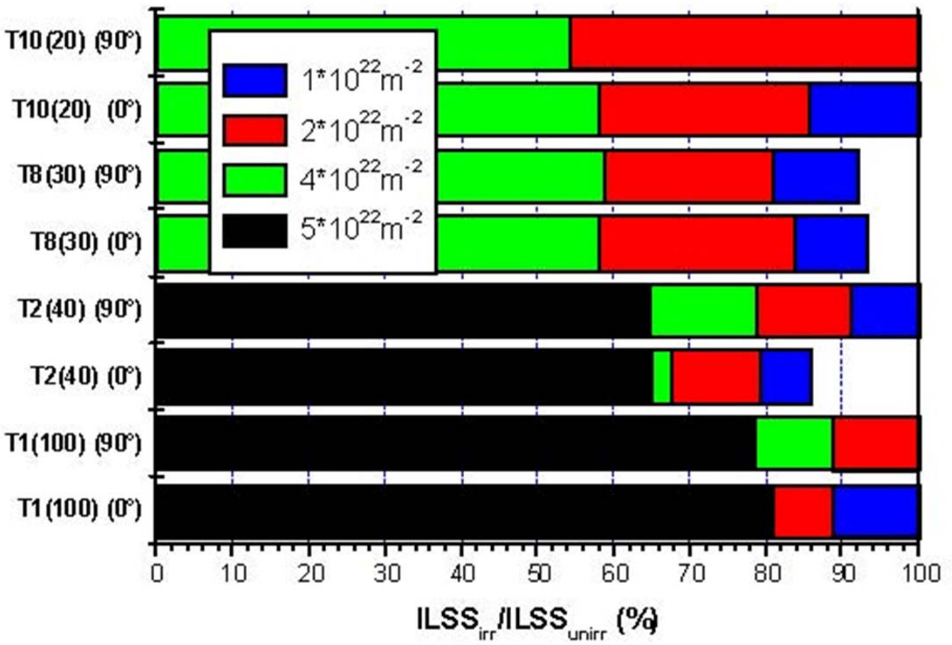
http://puhep1.princeton.edu/~mcdonald/examples/magnets/prokopec_fed_85_227_10.pdf

The usual claim seems to be that “ordinary” expoy-based insulators have a useful lifetime of 10^{22} *n*/m^2 for reactor neutrons with E > 0.1 MeV. This is, I believe, the underlying criterion for the ITER limit that we have recently adopted in the Target System Baseline,

http://puhep1.princeton.edu/~mcdonald/mumu/target/target_baseline_v3.pdf

Efforts towards a more rad hard epoxy insulation seem focused on cyanate ester (CE) resins, which are somewhat expensive (and toxic) . My impression is that use of this insulation brings about a factor of 2 improvement in useful lifetime, but see the cautionary summary of the 2nd link above.

Failure mode is loss of shear strength.
Plot show ratio of shear strentgth (ILSS)
To nominal for several CE resin variants at
reactor neutron fluences of 1-5 × 10^{22} *n*/m^2.
From Prokopec *et al.*



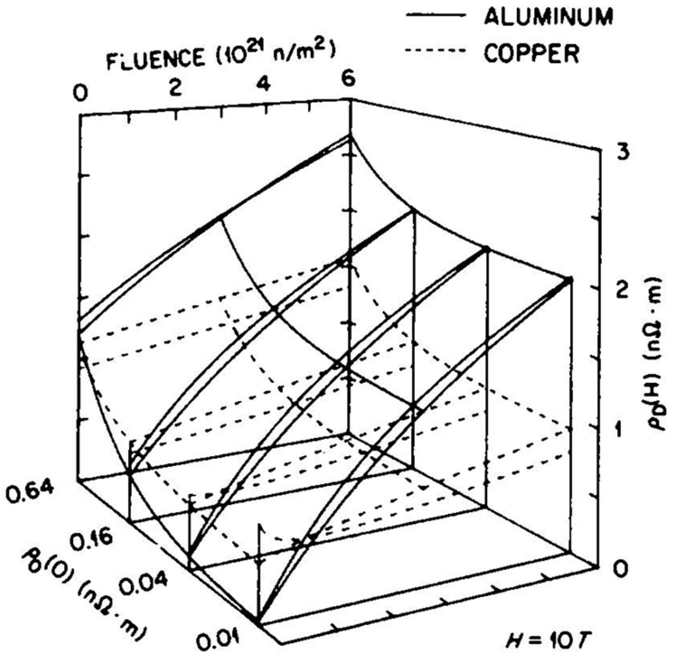
Radiation Damage to the Stabilizer

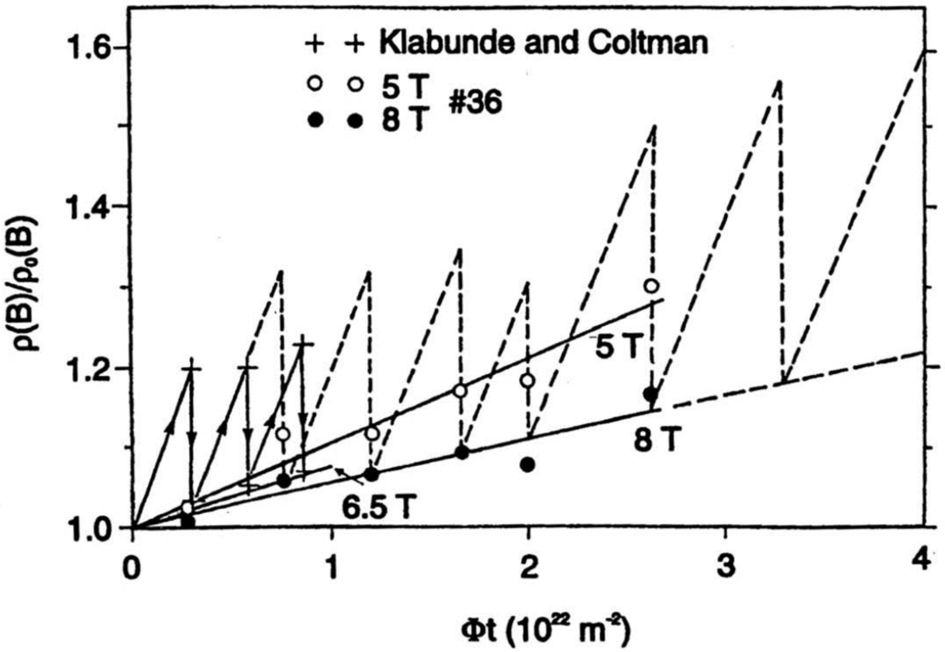
Superconductors for use in high thermal load environments are fabricated as cable in conduit, with a significant amount of copper or aluminum stabilizer (to carry the current temporarily after a quench).

The resistivity of Al is about 4 times that of Cu at 4K, ⇒ favorable to use copper.

Radiation damage equivalent to 10^{21} n/m^2 doubles the resistivity of Al and increases that of Cu by 10%.

http://puhep1.princeton.edu/~mcdonald/examples/magnets/klabunde_jnm_85-86_385_79.pdf





Annealing by cycling to room temperature gives essentially complete recovery of the low-temperature resistivity of Al, but only about 80% recovery for copper.

Cycling copper-stabilized magnets to room temperature once a year would result in about 20% increase in the resistivity of copper stabilizer in the “hot spot” over 10 years; Al-stabilized magnets would have to be cycled to room temperature several times a year (and have much higher resistivity).

http://puhep1.princeton.edu/~mcdonald/examples/magnets/guinan_jnm_133_357_85.pdf

Hence, Cu stabilizer is to be preferred.

Radiation Damage to Inorganic Insulators

MgO and $MgAl_2O_4$ “mineral insulation” is often regarded as the best inorganic insulator for magnets. It seems to be considered that this material remains viable mechanically up to doses of 10^{26} *n*/m^2 for reactor neutrons with E > 0.1 MeV., i.e., about 10,000 times that of the best organic insulators.

F.W. Clinard Jr *et al.*, J. Nucl. Mat. **108-109**, 655 (1982),
http://puhep1.princeton.edu/~mcdonald/examples/magnets/clinard_jnm_108-109_655_82.pdf

Question: Is the copper or SS jacket of a cable-in-conduit conductor with MgO insulation also viable at this dose?

The main damage effect seems to be swelling of the MgO, which is not necessarily a problem for the powder insulation used in magnet conductors.

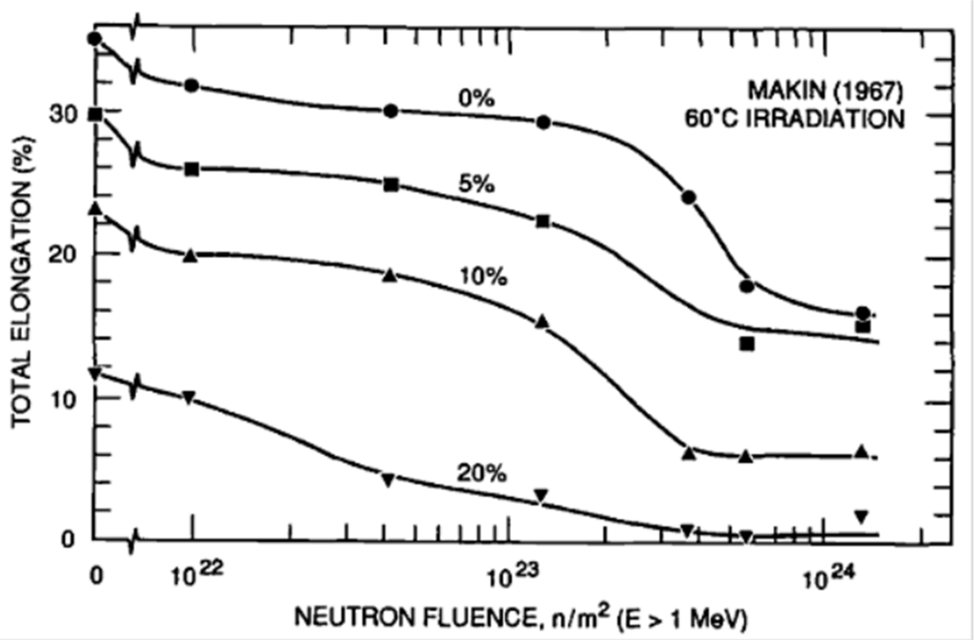
PPPL archive of C. Neumeyer: http://www.pppl.gov/~neumeyer/ITER_IVC/References/

KEK may consider MgO-insulated magnets good only to 10^{11} Gray ~ 10^{26} *n*/m^2.
http://www-ps.kek.jp/kekpsbcg/conf/nbi/02/radresmag_kusano.pdf

Zeller advocates use of MgO-insulated superconductors, but it is not clear to me that this would permit significantly higher doses due to limitations of the conductor itself.

Radiation Damage to Copper at Room Temperature

Embrittlement of copper due to radiation becomes significant at reactor neutrino doses > 10^{23} n/m^2.



Not clear if this is a problem for resistive copper magnets.

N. Mokhov quotes limit of 10^{10} Gy = 100 mW/g for 10 "years" of 10^7 s each.

http://www-ap.fnal.gov/users/mokhov/papers/2006/Conf-06-244.pdf