Radiation-Damage Considerations for the High-Power-Target System of a Muon Collider or Neutrino Factory

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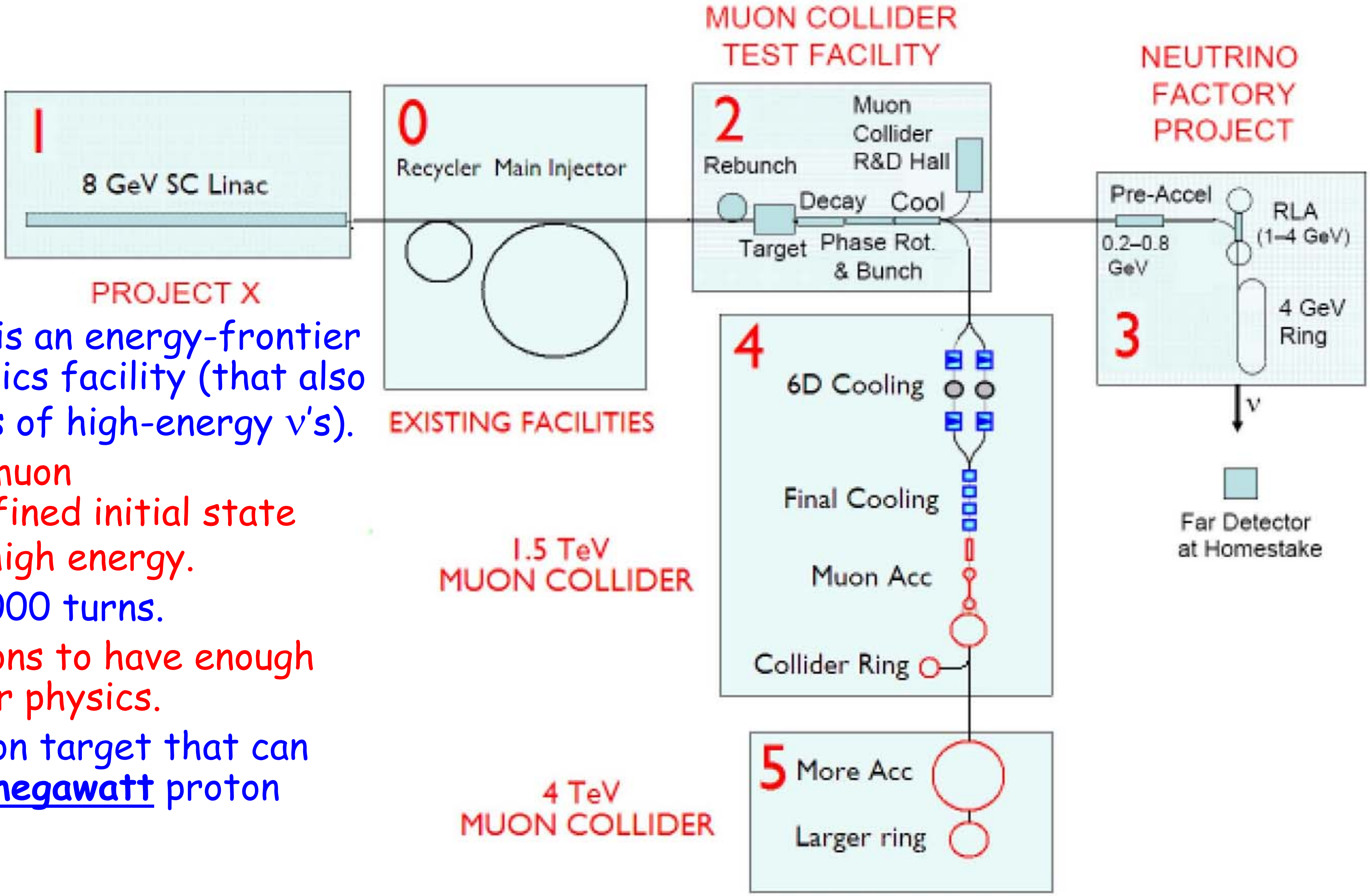
(Feb 13, 2012)

Workshop on Radiation Effects in Superconducting Magnet Materials
Fermilab

The Target is Pivotal between a Proton Driver and ν or μ Beams



A Muon Collider is an energy-frontier particle-physics facility (that also produces lots of high-energy ν's).

Higher mass of muon
⇒ Better defined initial state than e^+e^- at high energy.

A muon lives ≈ 1000 turns.

Need lots of muons to have enough luminosity for physics.

Need a production target that can survive **multmegawatt** proton beams.

Target and Capture Topology: Solenoid

Desire ≈ 10^{14} μ/s from ≈ 10^{15} p/s (≈ 4 MW proton beam)

R.B. Palmer (*BNL*, 1994) proposed a 20-T solenoidal capture system.

Low-energy π's collected from side of long, thin cylindrical target.

Solenoid coils can be some distance from proton beam.

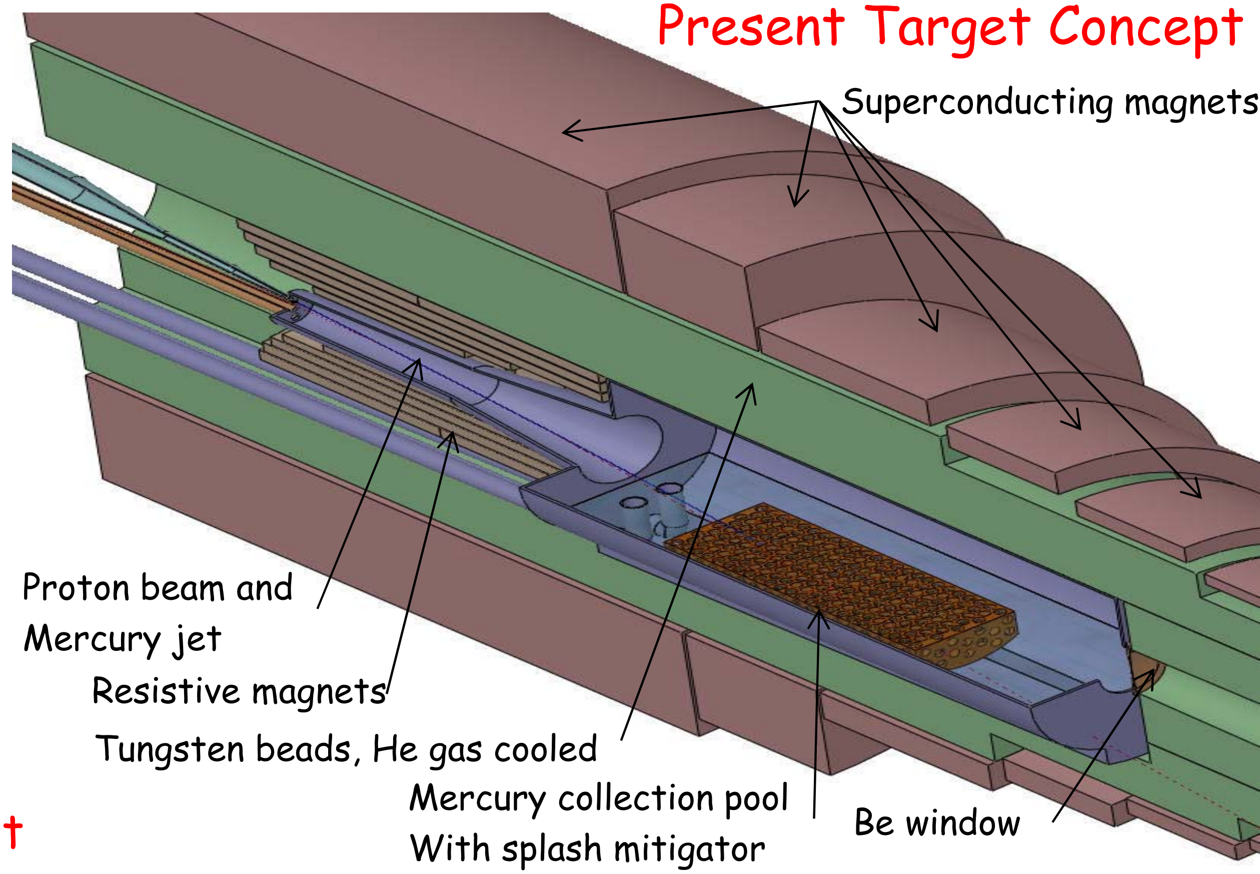
⇒ ≥ 10-year life against radiation damage at 4 MW.

Liquid mercury jet target replaced every pulse.

Proton beam readily tilted with respect to magnetic axis.

⇒ Beam dump (mercury pool) out of the way of secondary π's and μ's.

Present Target Concept



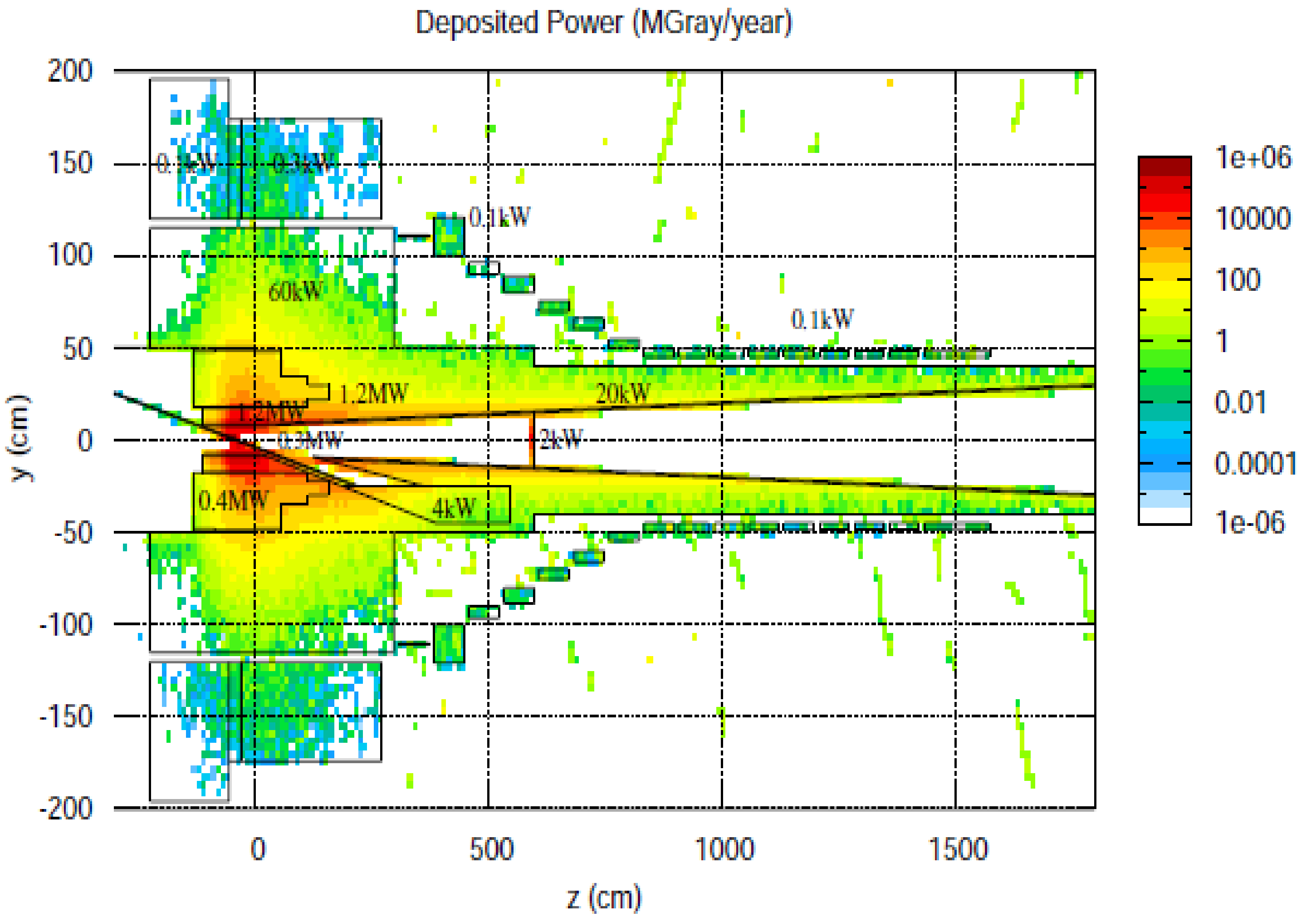
Shielding of the superconducting magnets from radiation is a major issue.

Magnet stored energy ~ 3 GJ!

5-T copper magnet insert; 15-T Nb_3Sn coil + 5-T NbTi outsert.

Desirable to replace the copper magnet by a 20-T HTC insert.

High Levels of Energy Deposition in the Target System



Power deposition in the superconducting magnets and the He-gas-cooled tungsten shield inside them, according to a FLUKA simulation.

Approximately 2.4 MW must be dissipated in the shield.

Some 800 kW flows out of the target system into the downstream beam-transport elements.

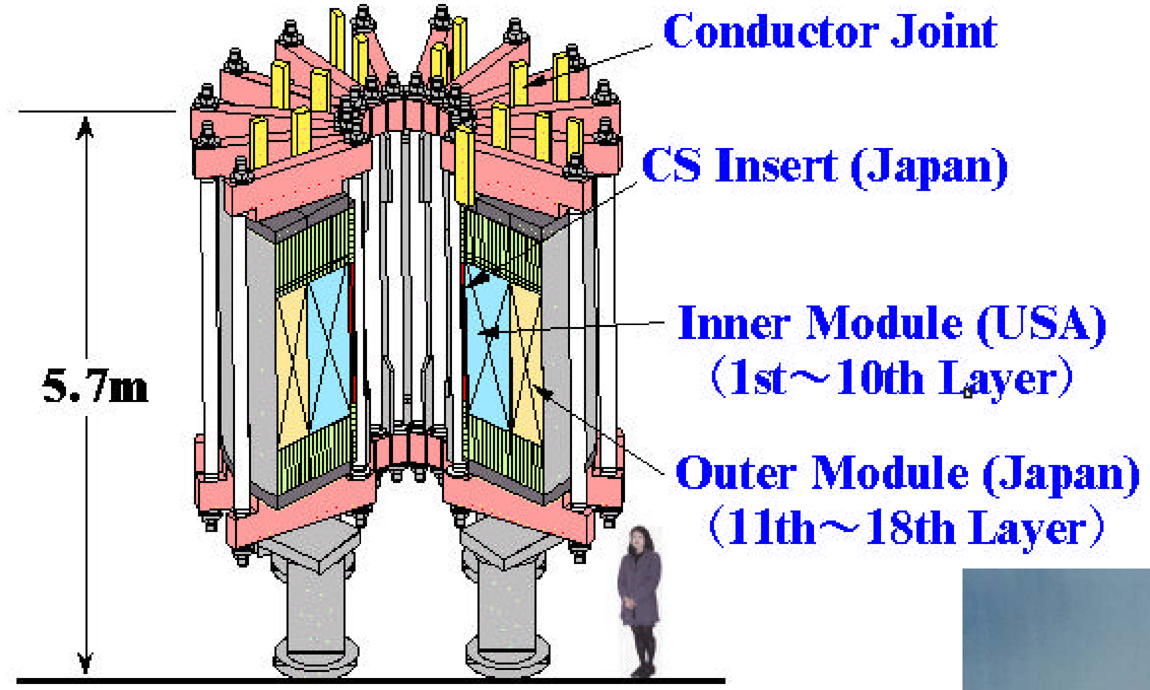
Total energy deposition in the target magnet string is ~ 1 kW @ 4k.

Peak energy deposition is about 0.03 mW/g.

Large Cable-in-Conduit Superconducting Magnets

The high heat load of the target magnet requires Nb_3Sn cable-in-conduit technology, more familiar in the fusion energy community than in high energy physics.

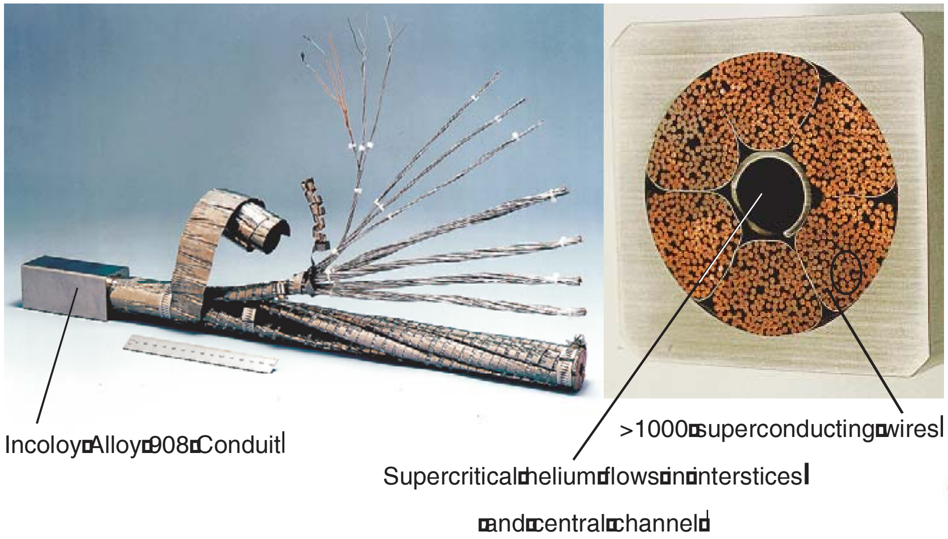
Central Solenoid (CS) Model Coil



The conductor is stabilized by copper, as the temperatures during conductor fabrication comes close to the melting point of aluminum.

The conductor jacket is stainless steel, due to the high magnetic stresses.

A high-temperature superconducting insert of 6+ T is appealing – but its inner radius would also have to be large to permit shielding against radiation damage.



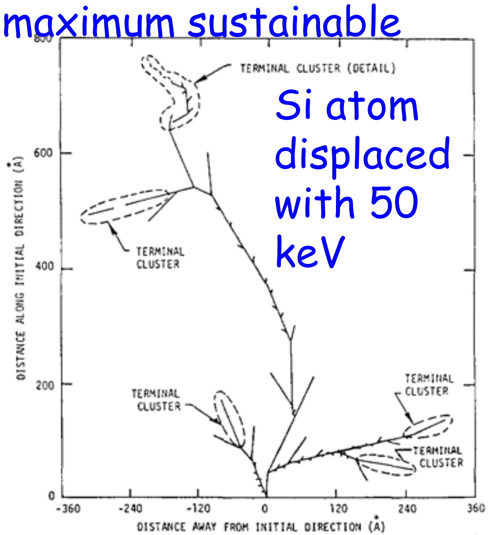
Overview of Radiation Issues for the Solenoid Magnets

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 shielded.

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



Si atom displaced with 50 keV

Most relevant radiation-damage data is from “reactor” neutrons (~ 1-10 MeV).

Models of radiation damage to materials associate this with “displacement” of the electronic (not nuclear) structure of atoms, with a “defect” being induced by ≈ 25-100 eV of deposited energy (although it takes only a few eV to displace an atom from a “lattice,” and defects can be produced by displacement of electrons from atoms without motion of the nucleus).
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

“For displacement effects, a useful parameter is the total amount of energy imparted in displacing collisions.” –V.A.J. van Lint, *The Physics of Radiation Damage in Particle Detectors*, NIM *A253*, 453 (1987),
http://puhep1.princeton.edu/~mcdonald/examples/magnets/vanlint_nim_a253_453_87.pdf

Hence, it appears to me most straightforward to relate damage limits to (peak) energy deposition in materials. [In our case, *use of DPA = displacements per atom is an unnecessary intermediate step, with no simple relation between DPA and damage*, http://www.hep.princeton.edu/~mcdonald/mumu/target/RESMM12/li.pdf]

Reactor-neutron radiation damage is closely equivalent to damage induced by high-energy cascades of the same local energy deposition (*but not to that from, say, an* ^{55}*Fe source*).

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 (= 1 MGray/year of 10^7 s).

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)

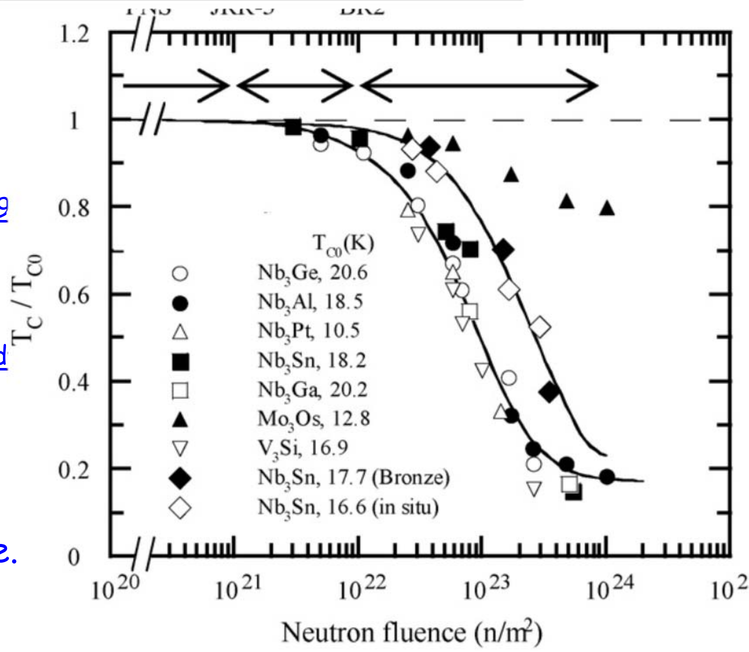
http://puhep1.princeton.edu/~mcdonald/examples/magnets/nishimura_fed_84_1425_09

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

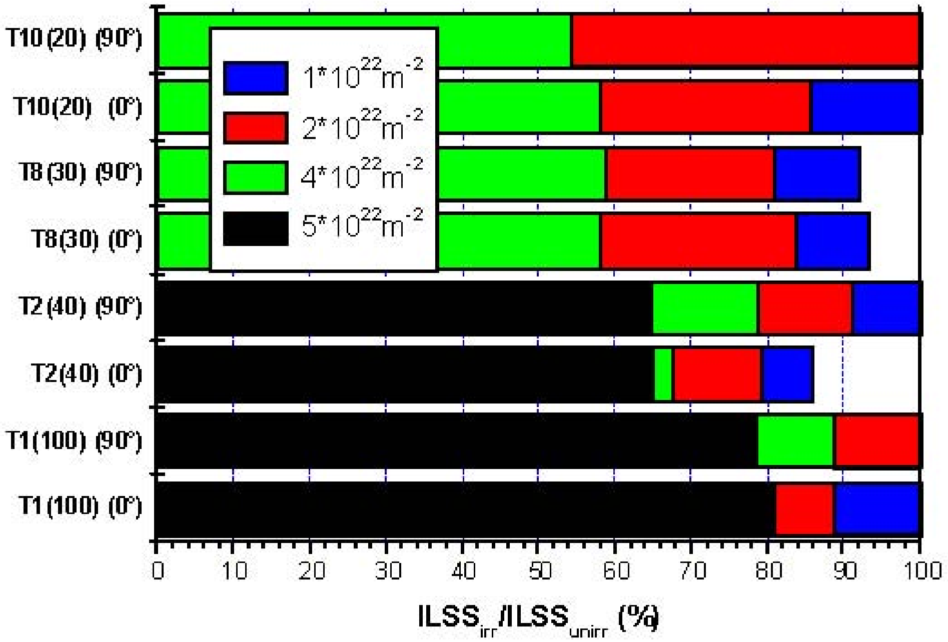
R&D on reactor neutron damage to organic insulators for conductors is carried out at the Atominstitut, U Vienna, http://www.ati.ac.at/ Recent review:

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

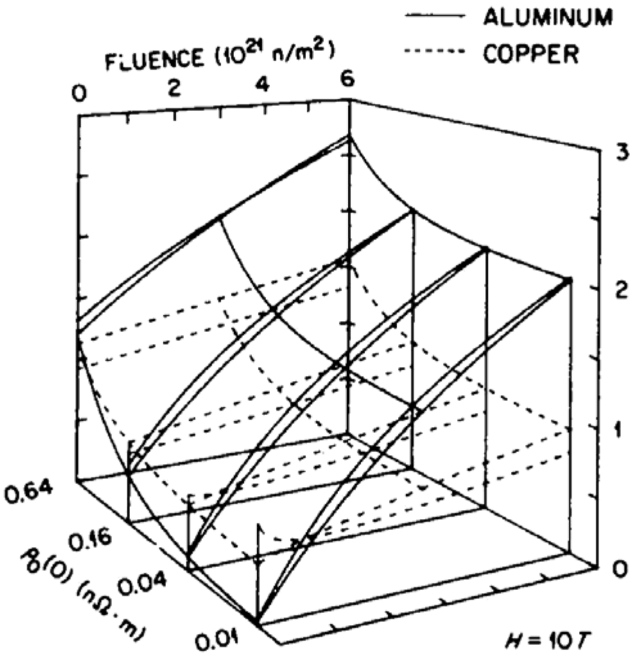
Superconductors for use in high thermal load environments are fabricated as cable in conduit, with a significant amount of copper or aluminum stabilizer (to carry the current temporarily after a quench).

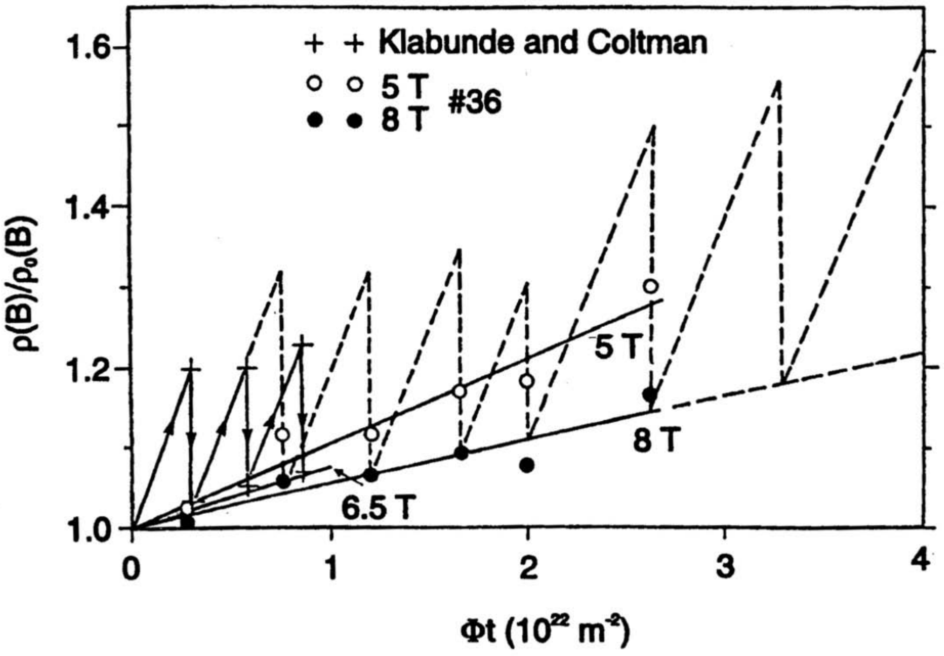
The resistivity of Al is 1/3 that of Cu at 4K (if no radiation damage), ⇒ Could be favorable to use Al.

[Al not compatible with Nb3Sn conductor fabrication ⇒ Must use Cu stabilize in high-field Nb magnets.]

Radiation damage equivalent to $10^{21}\ n/\mathrm{m}^2$ 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).

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

Hence, Cu stabilizer is preferred if want to operate near the ITER limit (and in high fields).

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.

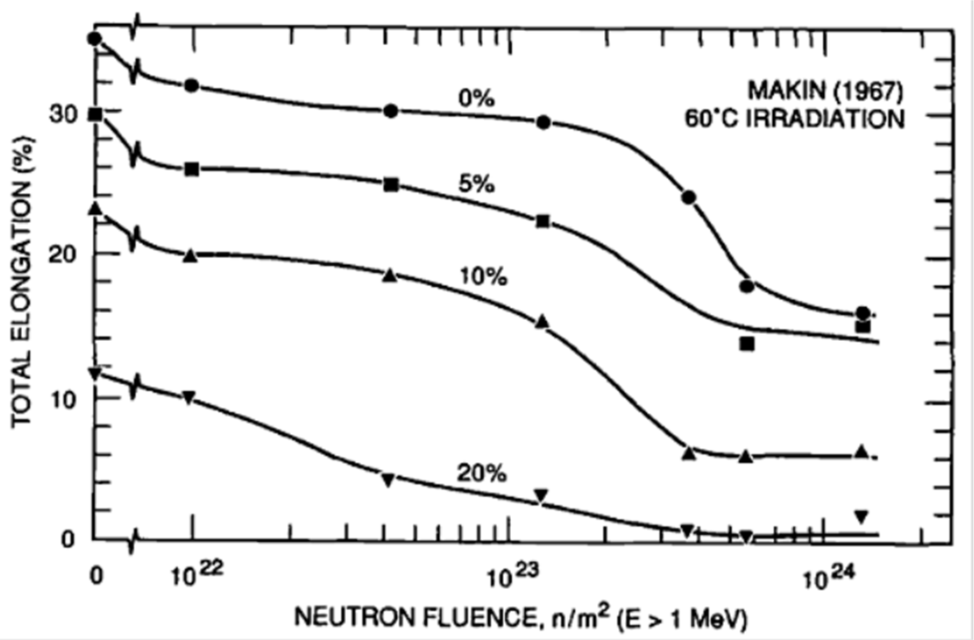
PPPL archive of C. Neumeyer: http://www.pppl.gov/~neumeyer/ITER_IVC/References/

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

Radiation Damage to Shielding Material, Beam Pipes, Target, …

Not discussed here, but shouldn't be ignored altogether.

Appendix

Aluminum in Superconducting Magnets

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January 28, 2012

For superconducting magnets a candidate material for some applications is aluminum, either ultrapure, as quench-stabilization matrix metal, and/or alloyed and cold-worked and heat treated for high strength, as reinforcement material. As reinforcement, aluminum is suitable only for magnets in which the stresses and strains are modest.

The strongest aluminum alloy commercially available, 7075-T6, has a strength at 4.2 K of 538-676 MPa[1] yield and 697-759 MPa ultimate. Nanostructure hierarchy can improve the ultimate strength to ~1.040 GPa[2]. A permissible-stress criterion of the lesser of ⅔ yield or ½ ultimate would permit loading nanostructure-hierarchy aluminum to 520 MPa. This is 37% shy of the 710 MPa allowable for 316LN stainless steel (the standard material used in the sheath of cable-in-conduit-conductors), for which the yield and ultimate strengths are[3] 1,065±15 MPa and 1,714±28 MPa. A further deficiency of aluminum that makes it completely unsuitable to strengthen magnets of wind-and-react Nb_3Sn is that aluminum permanently loses much of its strength upon exposure to the ~650°C reaction temperature for Nb_3Sn, a temperature so high as to risk melting the aluminum (m.p. = 660°C).

A limitation of aluminum for magnets of all types, not merely of the wind-and-react variety, is its low Young's modulus of 70 GPa, compared to 200 GPa for stainless steel. Whereas 316LN at its allowable stress limit of 710 MPa incurs a strain of only 0.710 GPa / 200 GPa = 0.355%, aluminum at its allowable limit incurs a strain of 0.52 / 70 = 0.74%—likely acceptable for NbTi, but for Nb_3Sn or high-temperature superconductors would require a winding geometry which guarantees that the strain in the superconductor is much less than that in the aluminum.

Aluminum is very good as a stabilizer. Its electrical conductivity can be much better than that of copper; that proposed for the COMET experiment has a residual resistivity ratio (RRR) of 500[4]; i.e., a residual electrical resistivity ρ_0 at 4 K of 300 nΩm / 500 = 0.6 nΩm. For copper co-processed with superconductor, it is difficult to achieve a RRR much better than ~100, for which $\rho_0 \approx 1.7$ nΩm, three times worse than aluminum. The superiority of aluminum over copper is even better in a magnetic field[5]. Aluminum also may be better than copper in a high-radiation environment. Irradiation of aluminum with 2.7x10^{20} n/m^2 increases its resistivity[6] by 0.064 nΩ m at 2.7x10^{20} n/m^2, a factor of 5.7/3.0, but cycling to room temperature restores 100% of the electrical conductivity. For copper the increase in resistivity is less—0.022 nΩ—but recovery is only 80-90% upon thermal cycling to room temperature.

[1] O N Senkov, et al., “Mechanical properties of commercial aluminum alloys at -253°C (–423°F),” NATO ARW, Kiev 7-13 Sept. 2003; Jeigh Shelley, Project Manager, Development of Super-high Strength Aluminum Alloys for Cryogenic Applications, AFRL Contract F04611-02-C-0014, Wright-Patterson Air Force Base.

[2] P V Liddicoa,t et al., “Nanostructural hierarchy increases the strength of aluminum alloy,” *Nature Communications*, MacMillan (2010).

[3] T Ogata, et al., “Results of VAMAS Activities on Pre-standardization of Mechanical Properties Evaluation at 4 K,”, Adv. in Cryo. Eng., **46A**, U. Balu Balachandran, et al., eds., pp. 431-434.

[4] M Yoshida, et al., “Superconducting Solenoid Magnets for the COMET Experiment,” IEEE Trans. Appl. Supercon., **21**, 1730 (2011).

[5] F R Fickett, “Magnetoresistivity of copper and aluminum at cryogenic temperatures,” BNL CONF-720908 (1972), http://lss.fnal.gov.conf/C720919/p539.pdf

[6] T Nakamototo, “Neutron Irradiation Measurements for Superconducting Magnet Materials at Low Temperature” (WASMSDO, CERN, Nov. 14, 2011), http://indico.cern.ch/contributionDisplay.py?contribId=31&sessionId=25&confId=113128