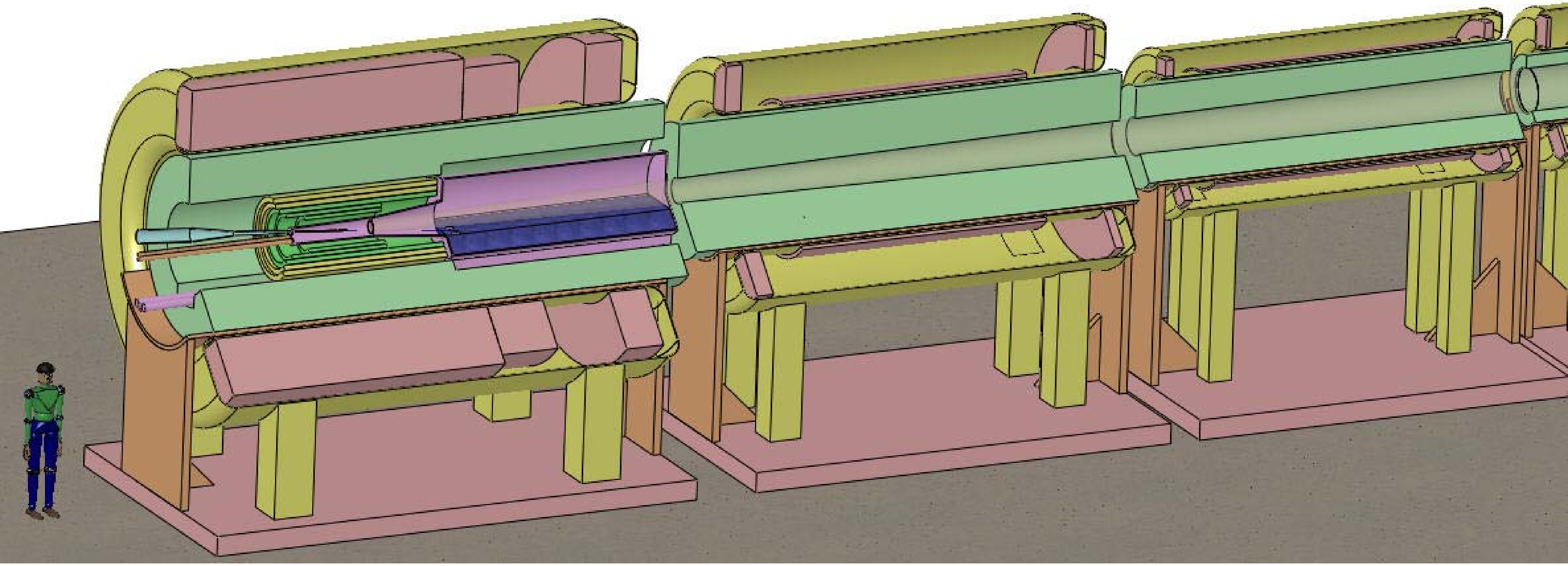
The High-Power-Target System of a Muon Collider or Neutrino Factory

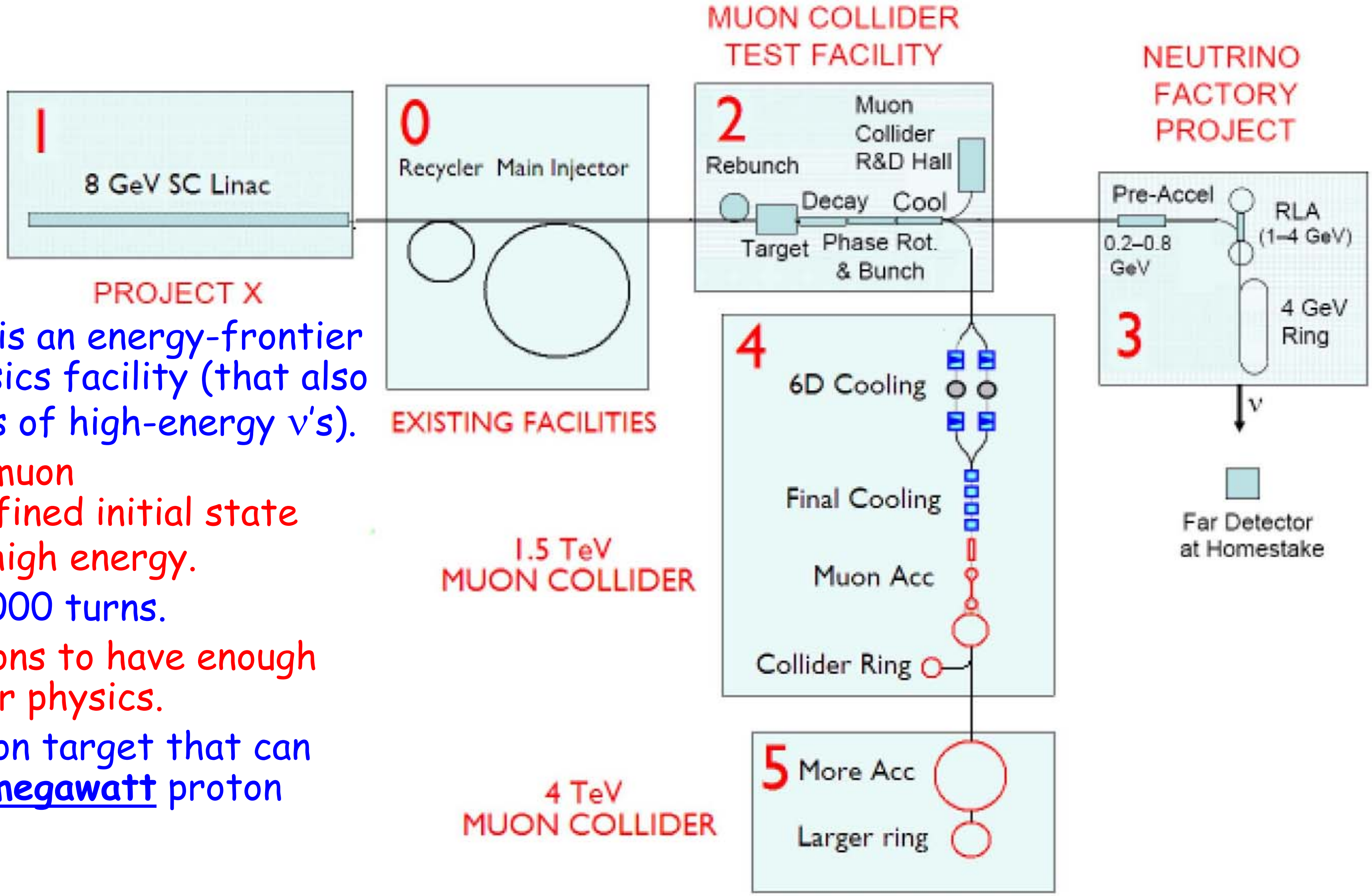


K. McDonald
Princeton U.

(March 5, 2012)

Muon Accelerator Program Winter Meeting
SLAC

The Target is the Interface 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
$\Rightarrow$ Better defined initial state than e^+e^- at high energy.

A muon lives $\approx$ 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 $\approx 10^{14}$ μ/s from $\approx 10^{15}$ p/s ($\approx$ 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.

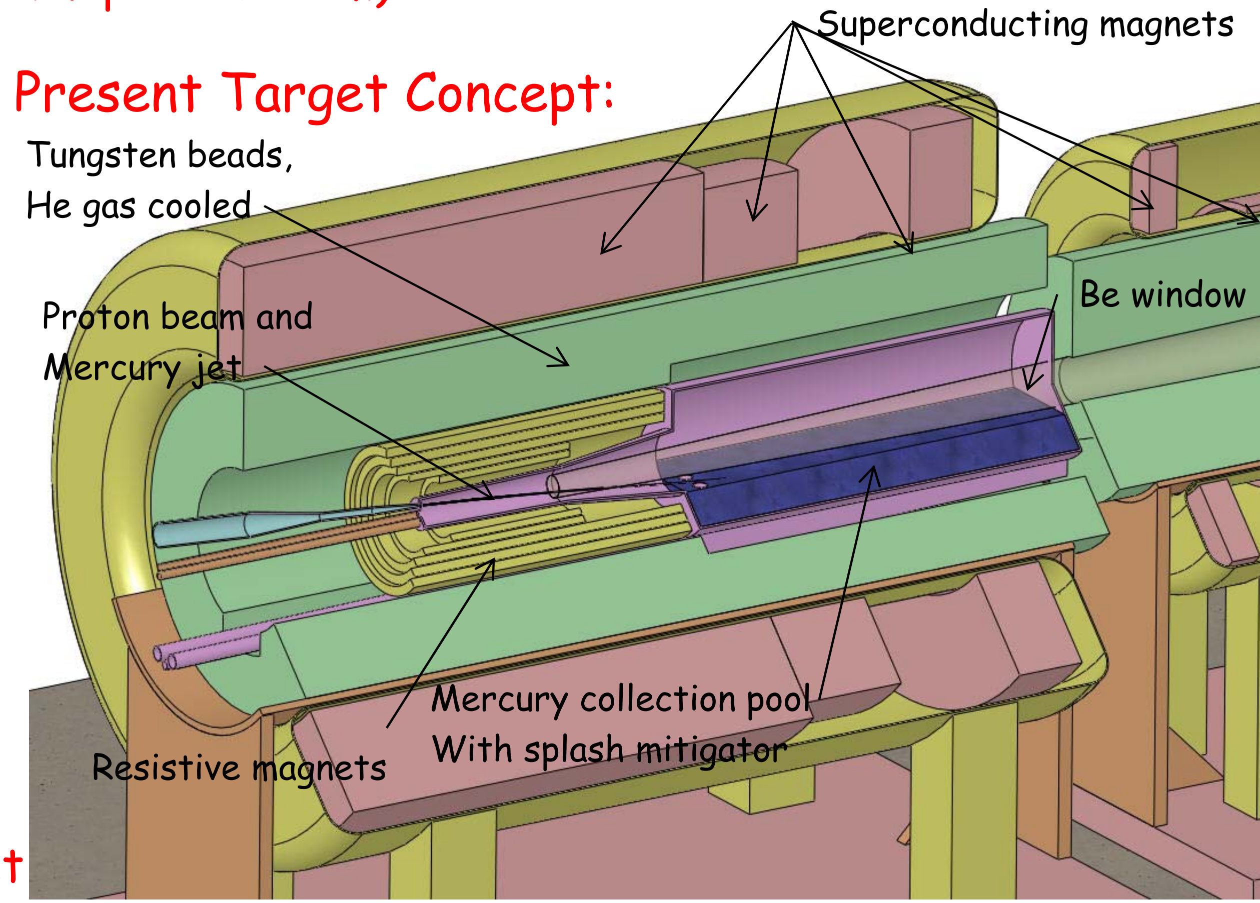
⇒ $\geq$ 10-year life against radiation damage at 4 MW.

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:



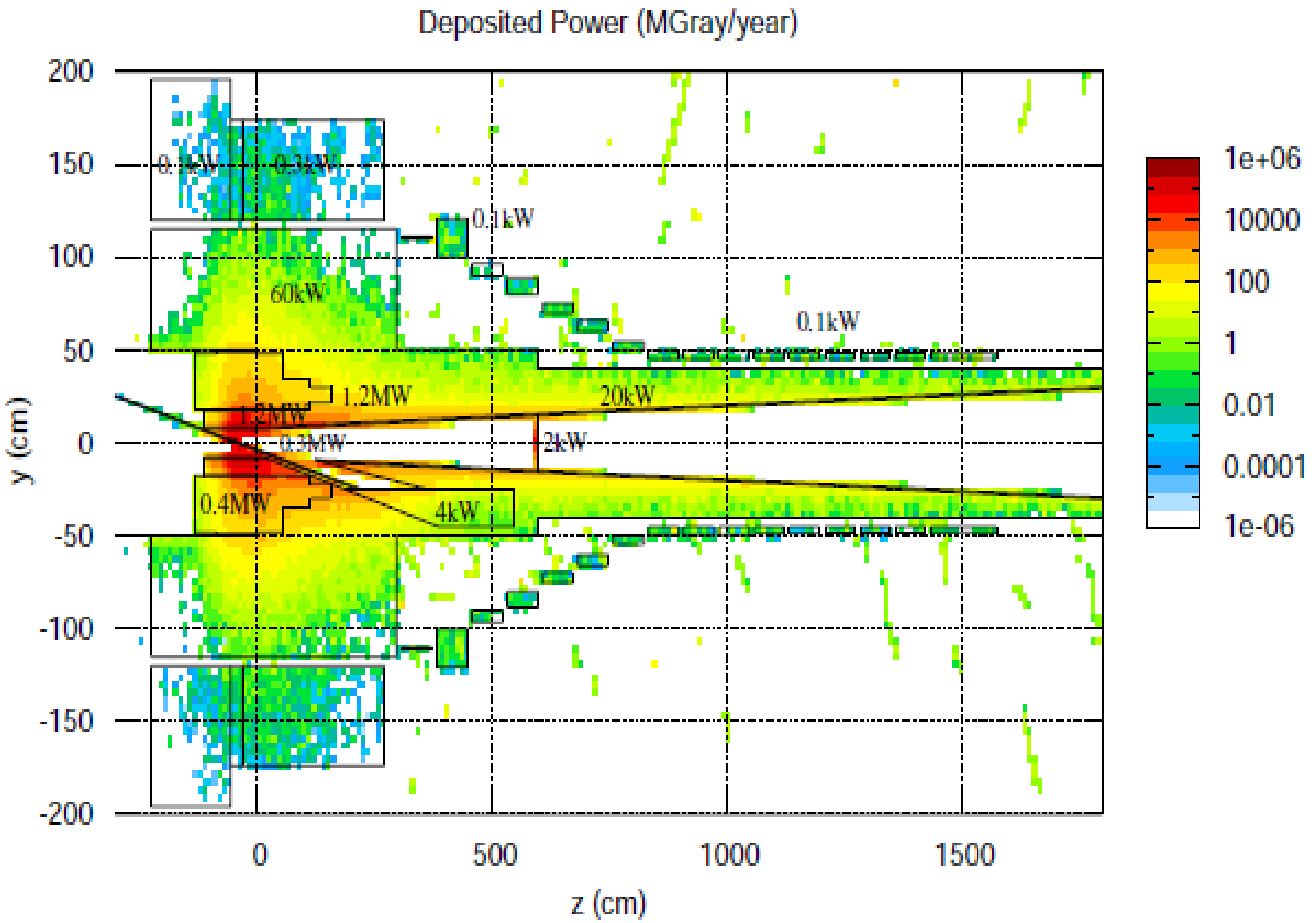
Shielding of the superconducting magnets from radiation is a major issue.

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.

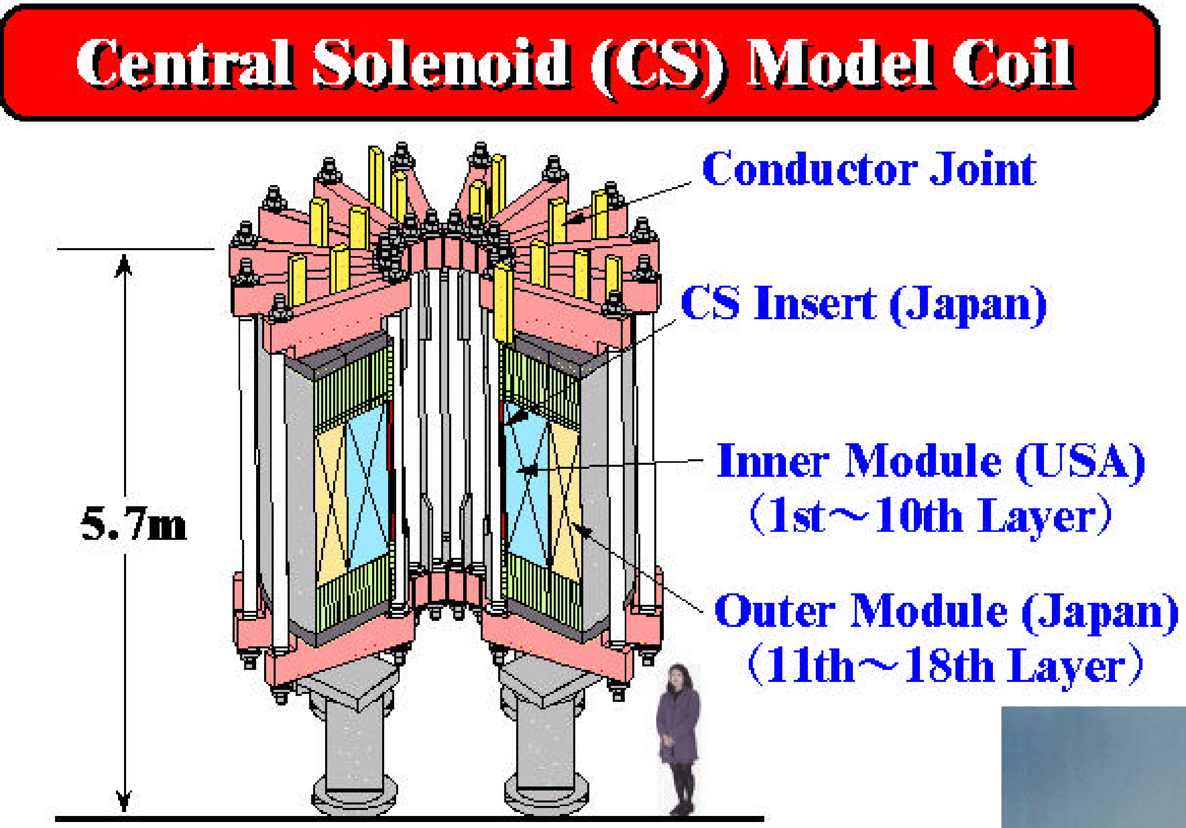
Some 800 kW flows out of the target system into the downstream beam-transport elements.

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

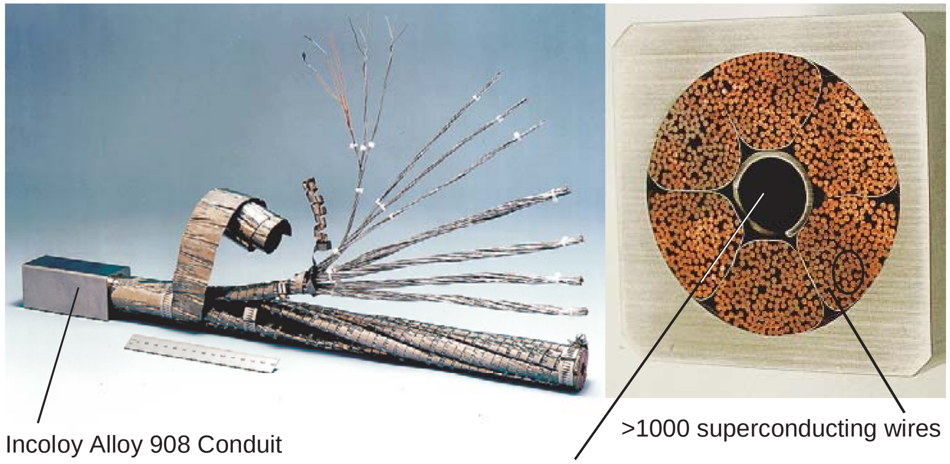
The high heat load of the target magnet requires Nb_3Sn cable-in-conduit technology, more familiar in the fusion energy community than in high energy physics.



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.

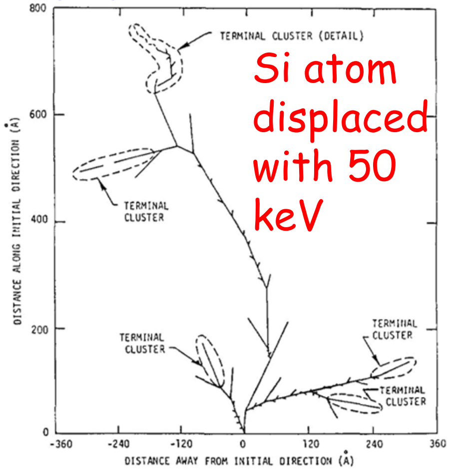
To design appropriate shielding it is helpful to have quantitative criteria as to maximum sustainable fluxes of secondary particles in magnet conductors,
and as to the associated thermal load.

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
Also, RESMM'12: https://indico.fnal.gov/conferenceDisplay.py?confId=4982

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



Si atom displaced with 50 keV

"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 $\rho_{\mathrm{magnet}} \approx 10$ 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)

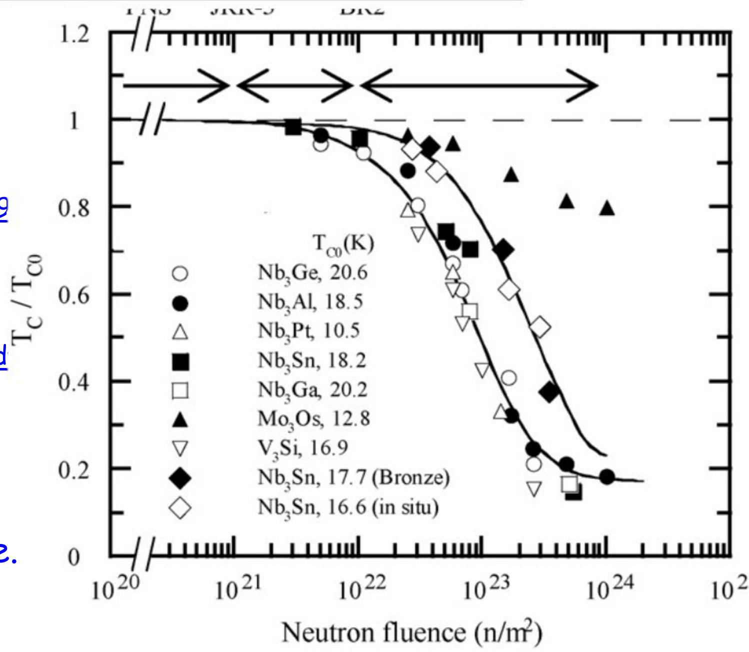
http://puhep1.princeton.edu/~mcdonald/examples/magnets/nishimura_fed_84_1425_09

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

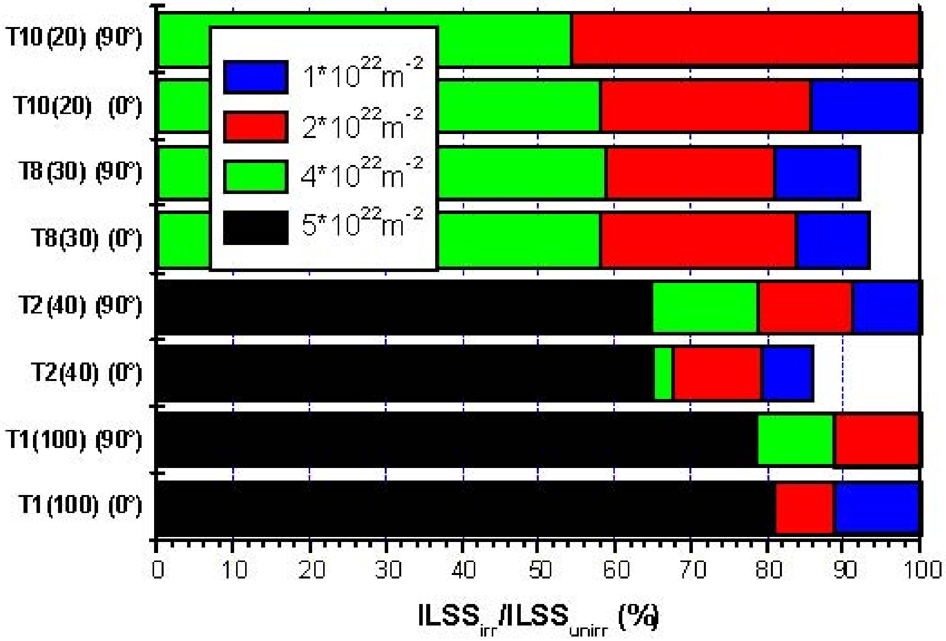
R&D on reactor neutron damage to organic insulators for conductors is carried out at the Atominstitut, U Vienna, http://www.ati.ac.at/ Recent review:

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

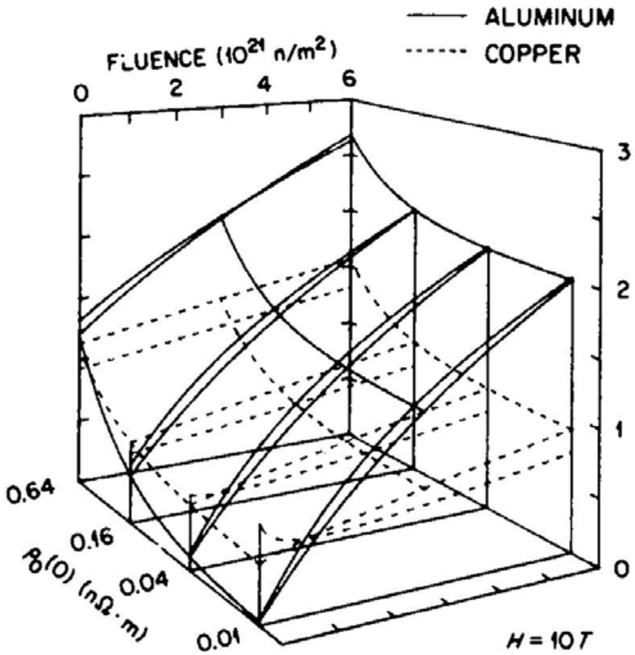
Superconductors for use in high thermal load environments are fabricated as cable in conduit, with a significant amount of copper or aluminum stabilizer (to carry the current temporarily after a quench).

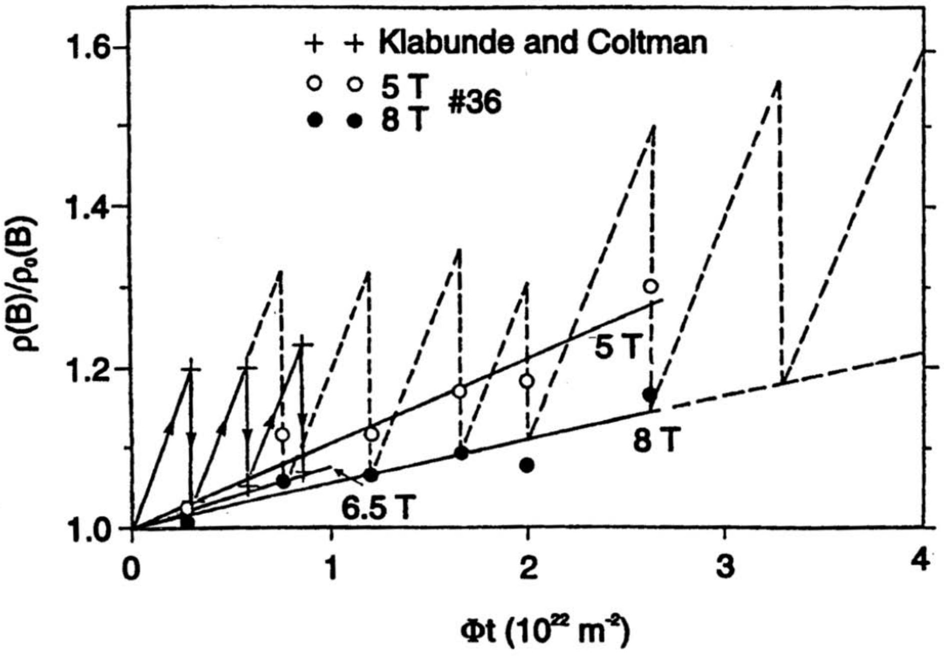
The resistivity of Al is 1/3 that of Cu at 4K (if no radiation damage), ⇒ Could be favorable to use Al.

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

Radiation damage equivalent to 10^{21} n/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.

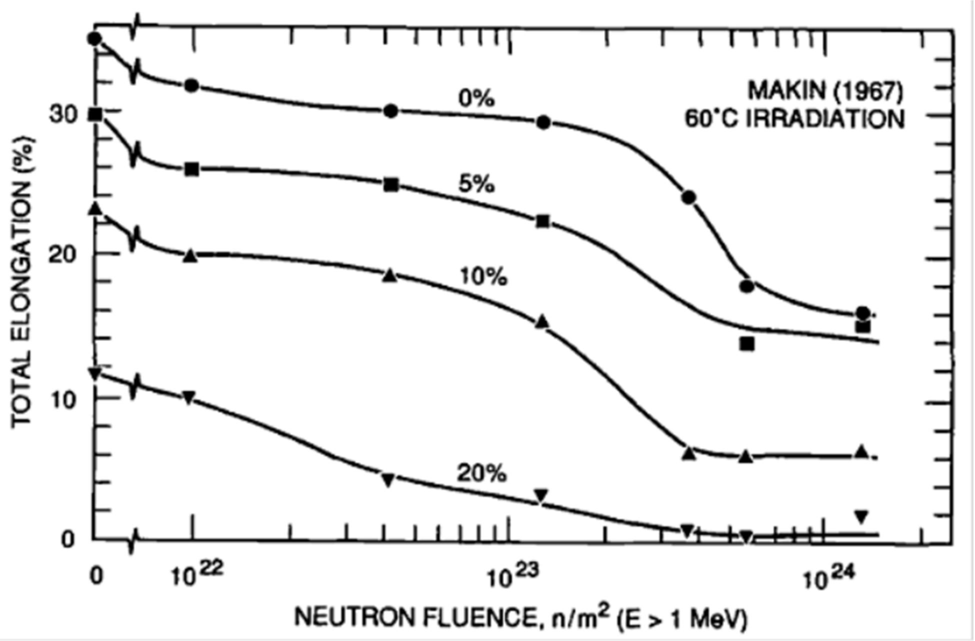
PPPL archive of C. Neumeyer: http://www.pppl.gov/~neumeyer/ITER_IVC/References/

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

A. 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.

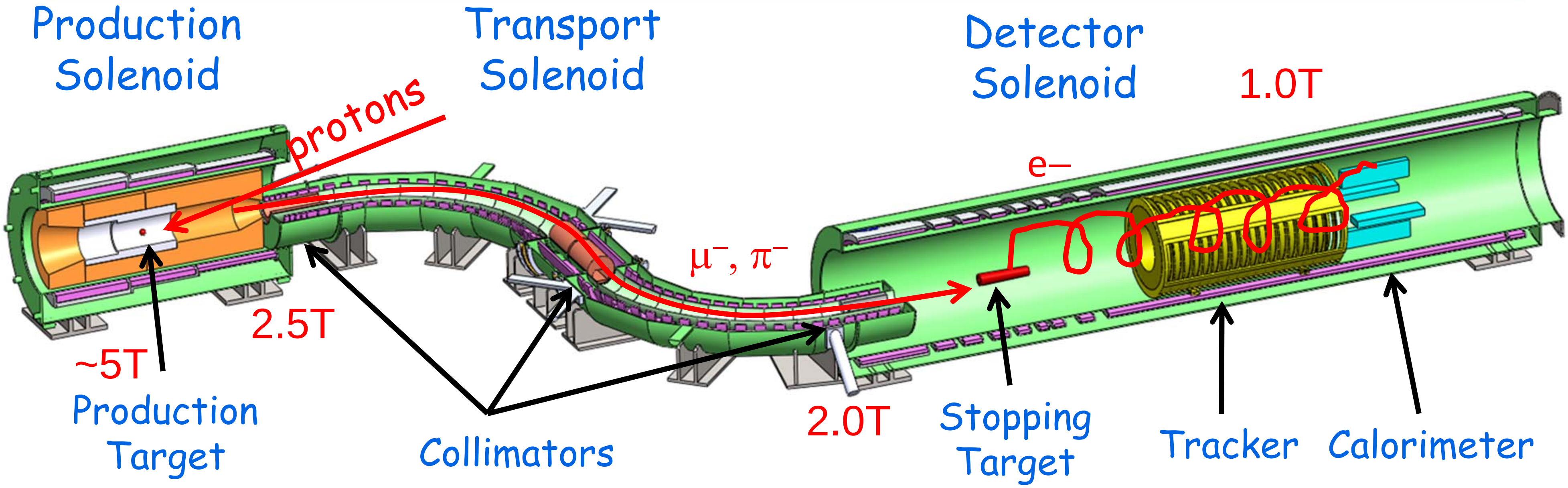
N. Mokhov quotes limit of 10^{10} Gy = 100 mW/g for 10 "years" of 10^7 s each.

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.

COMET, Mu2e Target Solenoid Magnets



10-50 kW proton beam

Collection of backward pions in a 5-T magnetic bottle.

Limit field to 5 T so can use NbTi (and don't have to use cable in conduit).

Use existing ATLAS conductor with Al stabilizer.

If operate this at ITER limit, must aneal at room temp 3 or more times a year.

Or, use more shielding (COMET) to be at < 1/10 ITER limit.

Project X Targetry for a Neutral Kaon Beam and for Mu2e Upgrade

1 MW proton beam @ 3 GeV

Search for $K^0_{long} \to \pi^0 \nu\nu$

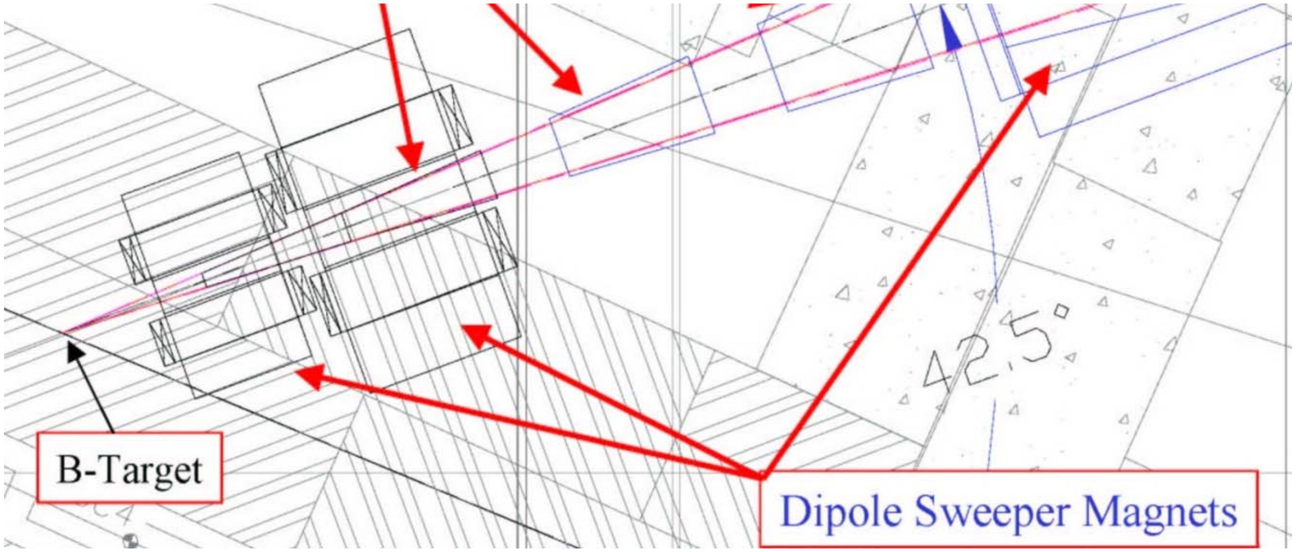
K^0_{long} secondaries at 15-45°

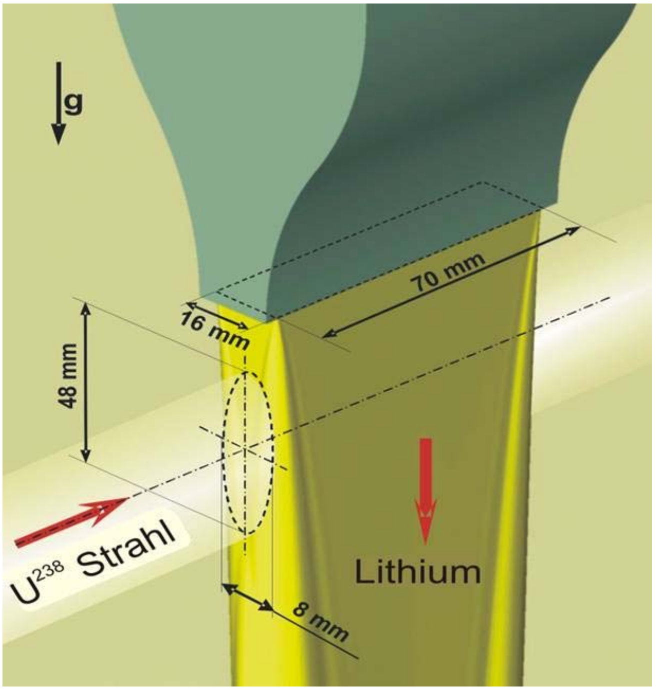
Small solid angle

High-Z target favored

Ga, Hg or PbBi "waterfall" could be optimal

$\Rightarrow$ MARS simulations…





Mu2e could upgrade to a 1-MW beam.

Could use radiation-cooled carbon target as considered in Neutrino Factory Study 1.

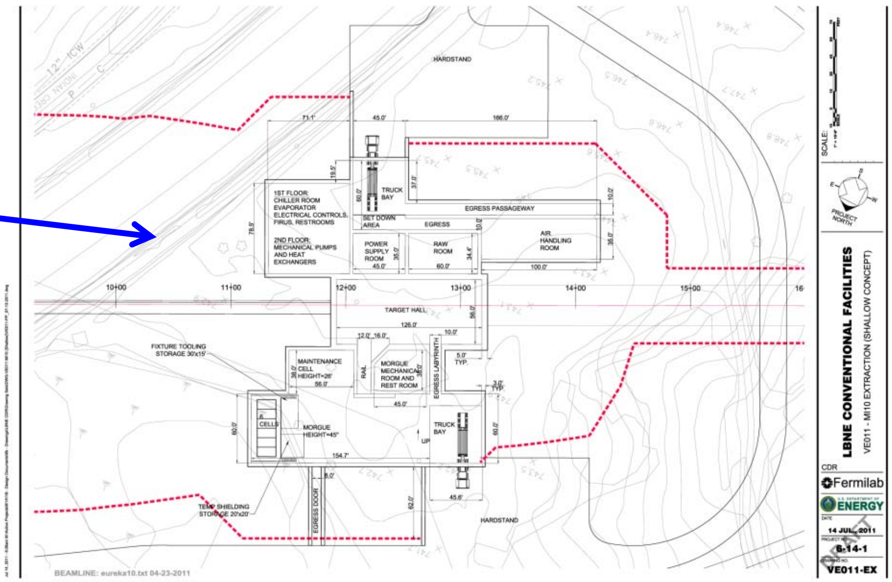
V. Lebedev advocates use of a rotating cylinder of carbon to increase lifetime against radiation damage.

However, a high-Z target is still favored, which could also be a liquid metal "waterfall"

Target Hall

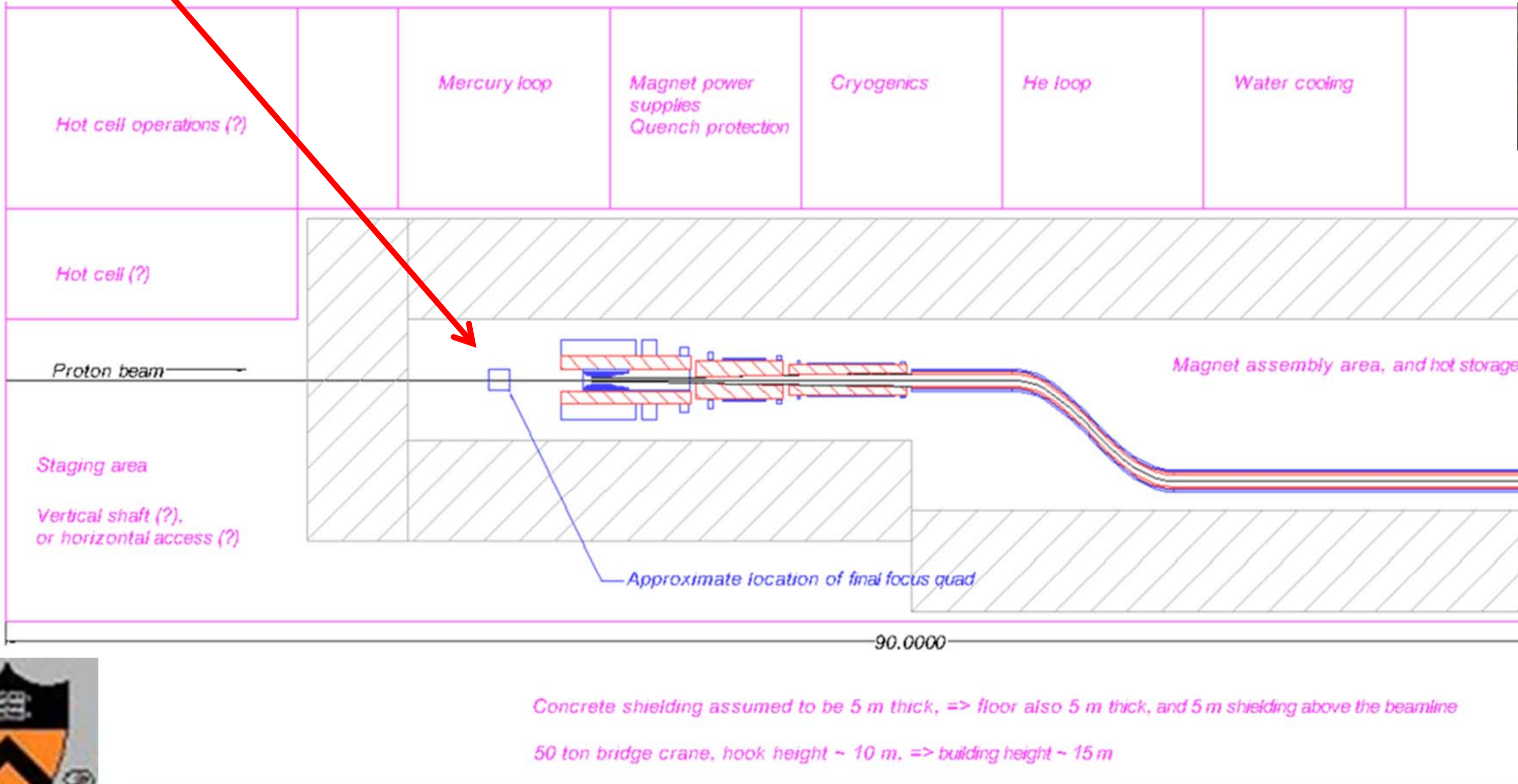
Cost driver will be civil construction and shielding.

LBNE 2-MW target station ~ $300m



NuMI target hall

Crude sketch to start IDS-NF costing



Concrete shielding assumed to be 5 m thick, => floor also 5 m thick, and 5 m shielding above the beamline

50 ton bridge crane, hook height ~ 10 m, => building height ~ 15 m

Do We Need 20 T?

It has been 14 years since Nikolai Mokhov studied the effect of varying the capture solenoid field.

New BNL postdoc Hisham Sayed has started to review this.

Ultimately can vary:

1. Peak field (nominally 20 T)
2. Aperture at target (nominally 7.5 cm)
3. Field in front end (nominally 1.5 T)
4. Aperture of front end (nominally 30 cm)
5. Length of “taper” from peak field to front-end field (nominally 15 m)

First study only varied parameters at the target:

$Bz_{(at\ target)}$ [T]	R_{target} [cm]	$Bz_{(End\ of\ taper)}$ [T]	$R_{end\ of\ taper}$ [cm]	N_{μ} [10^4]
20	7.5	1.5	30	2.9
15	10	1.5	30	2.766

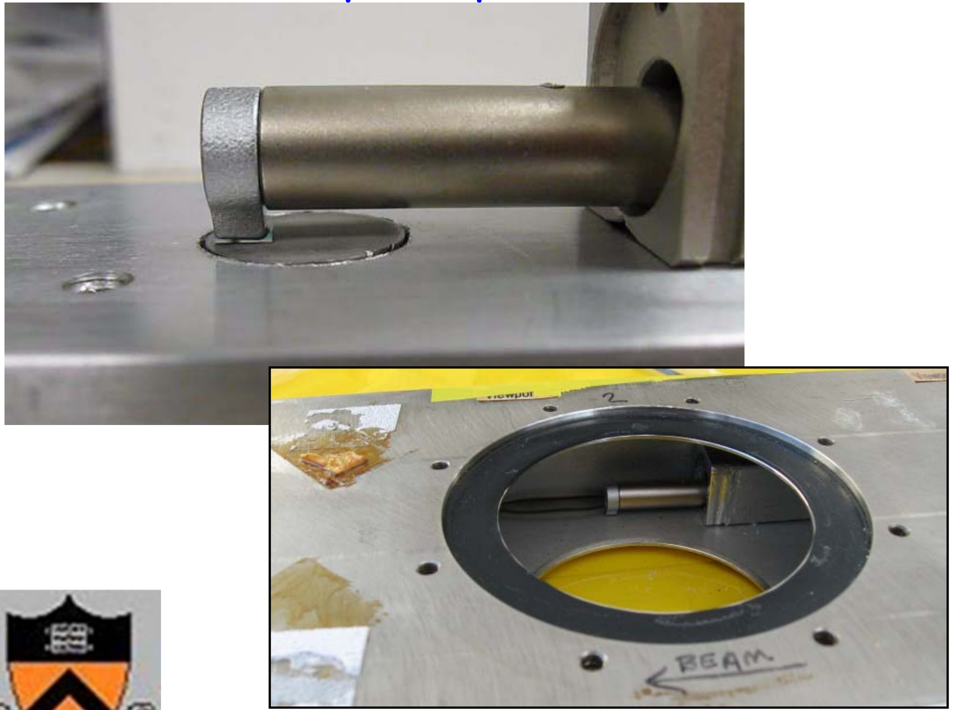
Only 5% loss!

⇒ We may be able to operate at 15 T peak field, and dispense with the resistive copper magnets!

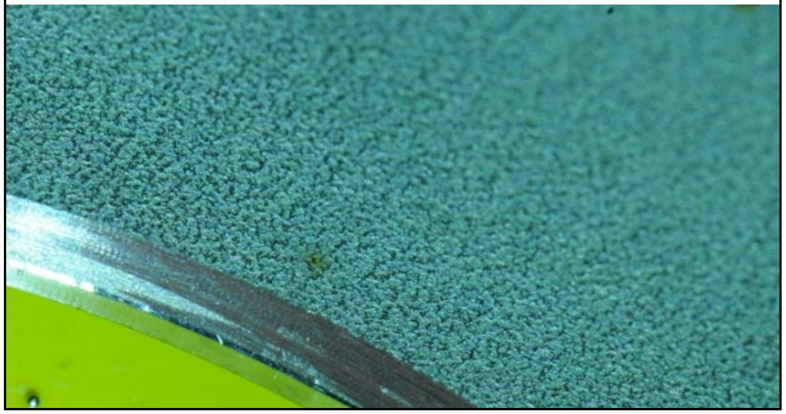
Hardware Activities 1

MERIT Primary Containment Vessel Surface Inspection, Van Graves (ORNL)

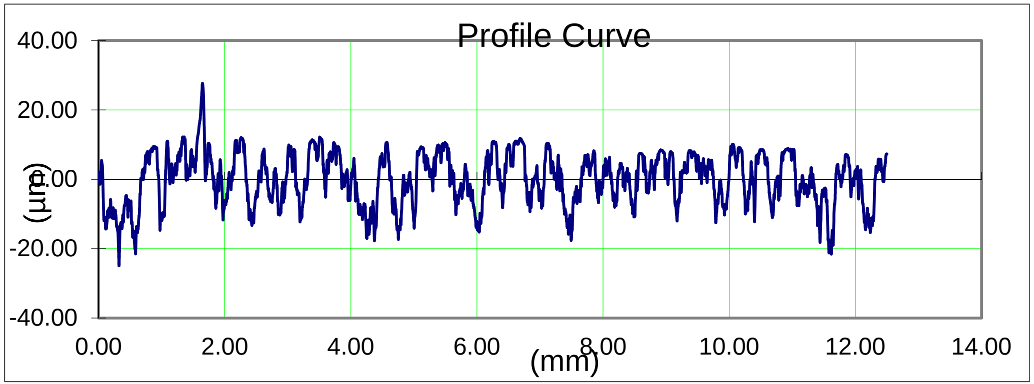
Use Zeiss Handysurf profilometer.



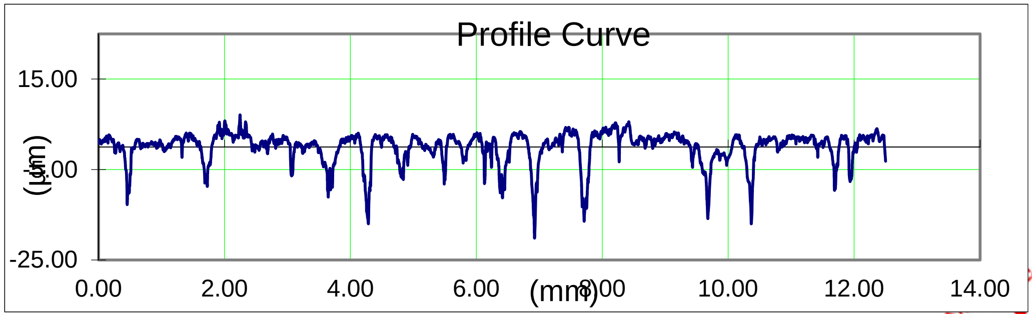
Surface from vendor is mottled.



Interior:



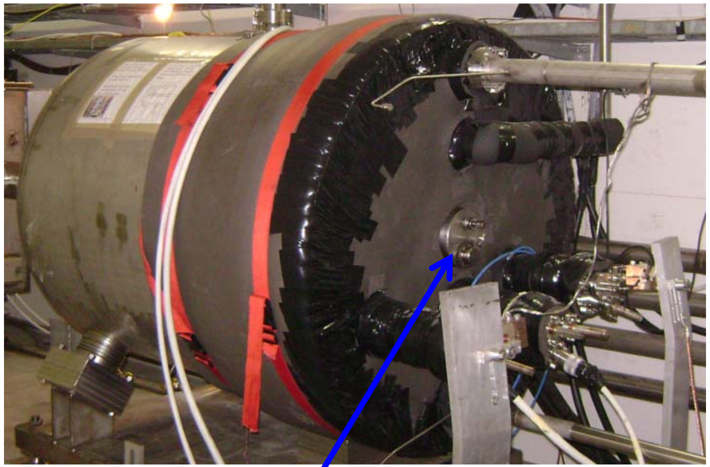
Exterior:



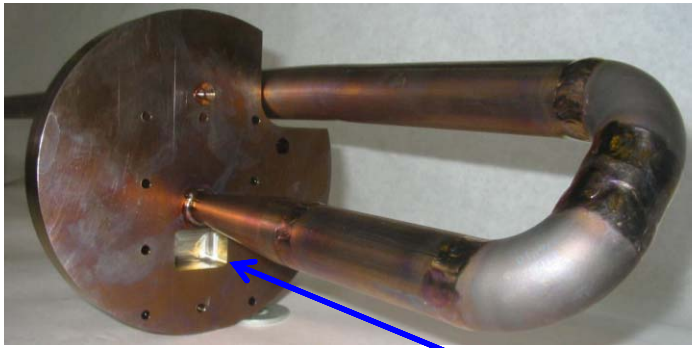
No evidence of pitting @ 20 μm

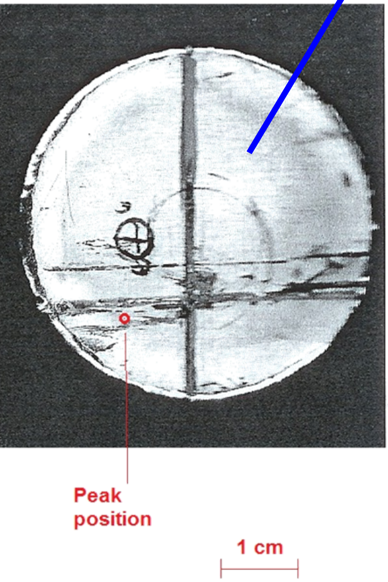
Hardware Activities 2

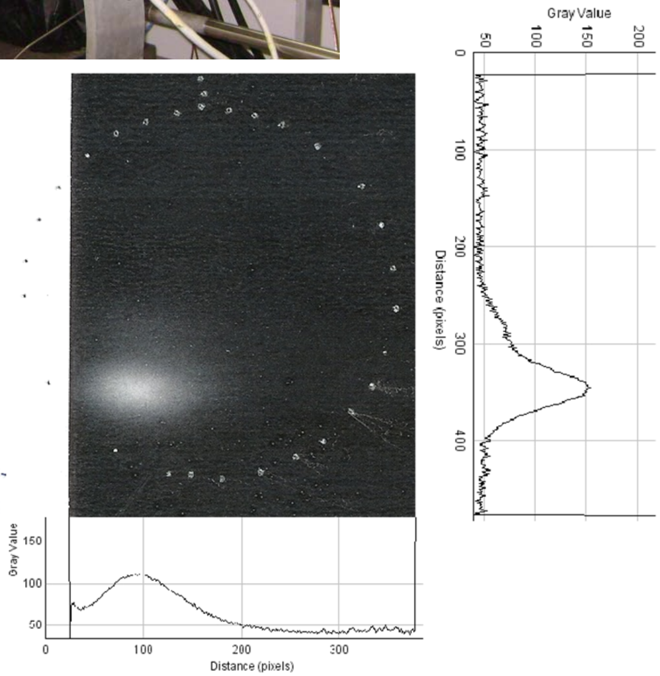
Autoradiography of MERIT beam windows,
Peter Thieberger (BNL)

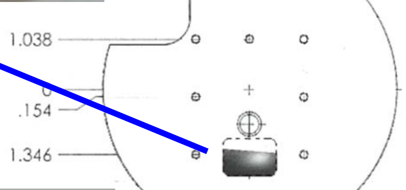


Autoradiograph of window on the
Ti “pieplate “close to nozzle

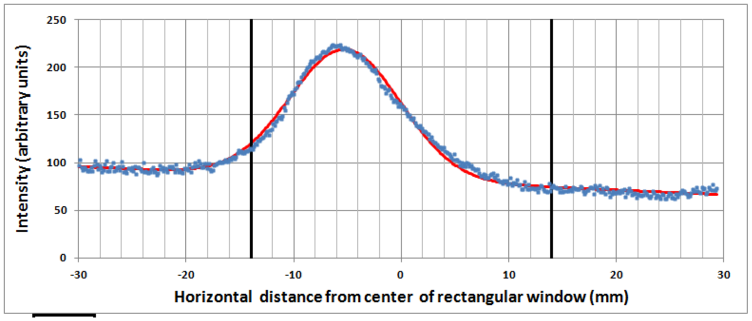




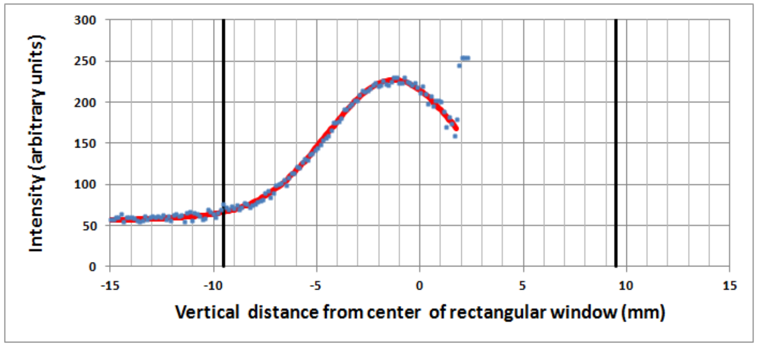




Horizontal, σ = 5 mm



Vertical: σ = 3 mm



σ_H = 4 mm, σ_V = 2.3 mm

Targetry Presentations

Yan Zhan (Stony Brook) *Nozzle and Jet Studies* (towards improving the jet quality)

Roman Samulyak (Stony Brook) *MHD Simulations* (including beam-jet interactions)

Xiaoping Ding (UCLA) *Particle-Production Simulations* (including comparison of Ga with Hg)

Nicholas Souchlas (PBL) *Energy-Deposition Studies* (to determine whether the superconducting magnets are sufficiently well shielded from the 4-MW beam power)

Bob Weggel (MORE) *Magnet and Shielding* Configurations (now including gaps for services and supports)