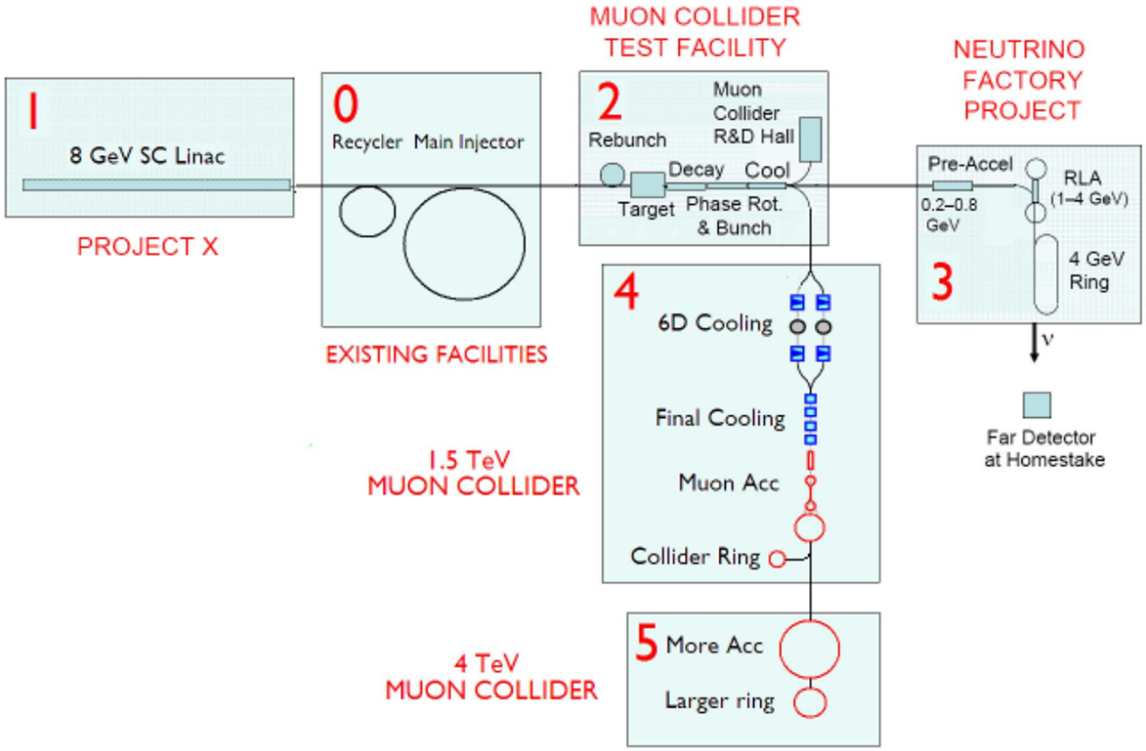
Target-System Challenges at a Muon Collider and Neutrino Factory



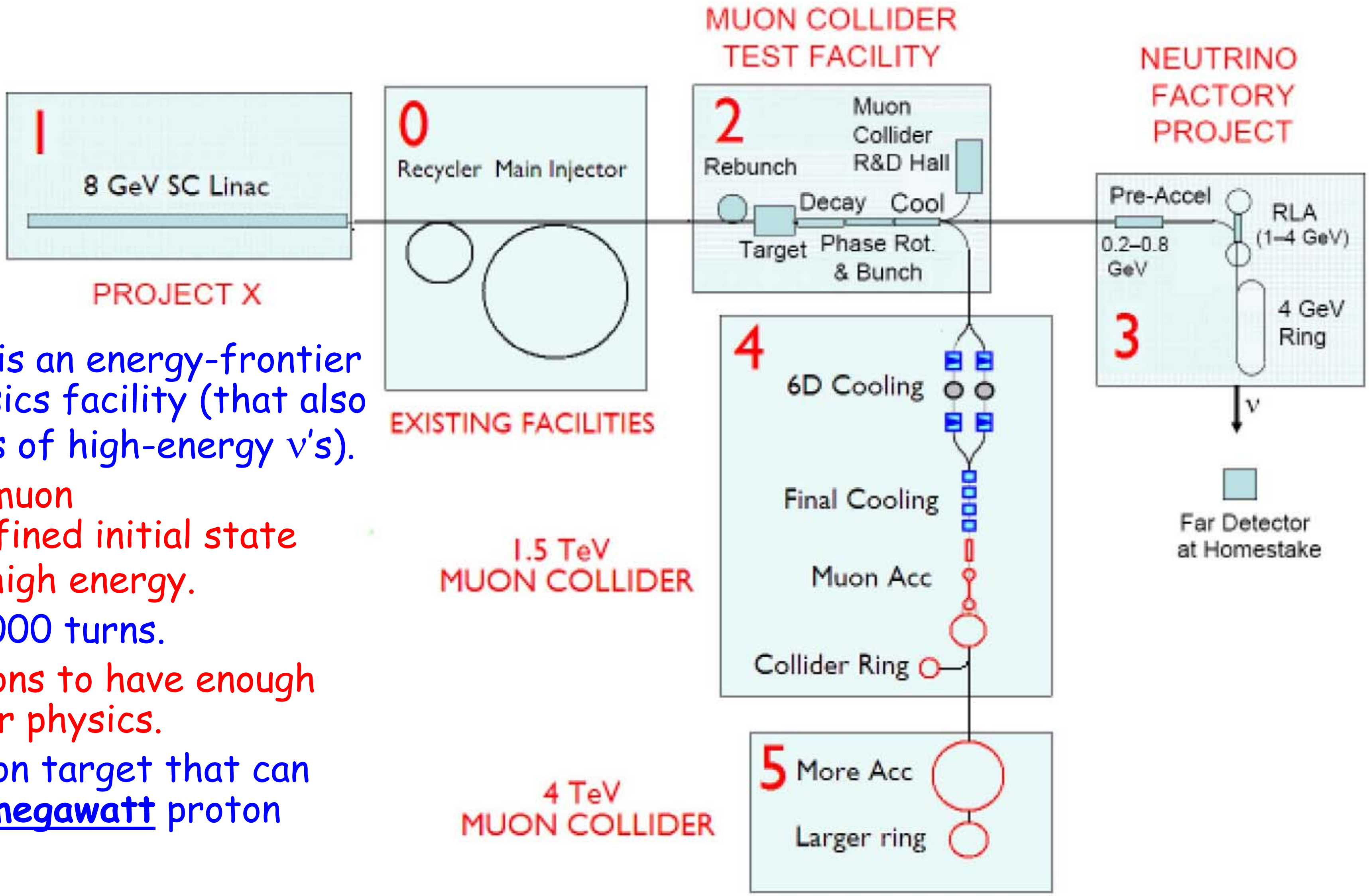
K. McDonald
Princeton U.

(Jan 13, 2012)

Proton Accelerators for Science and Innovation Workshop

Fermilab

Sketch of a Muon Collider (and a Neutrino Factory)



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.

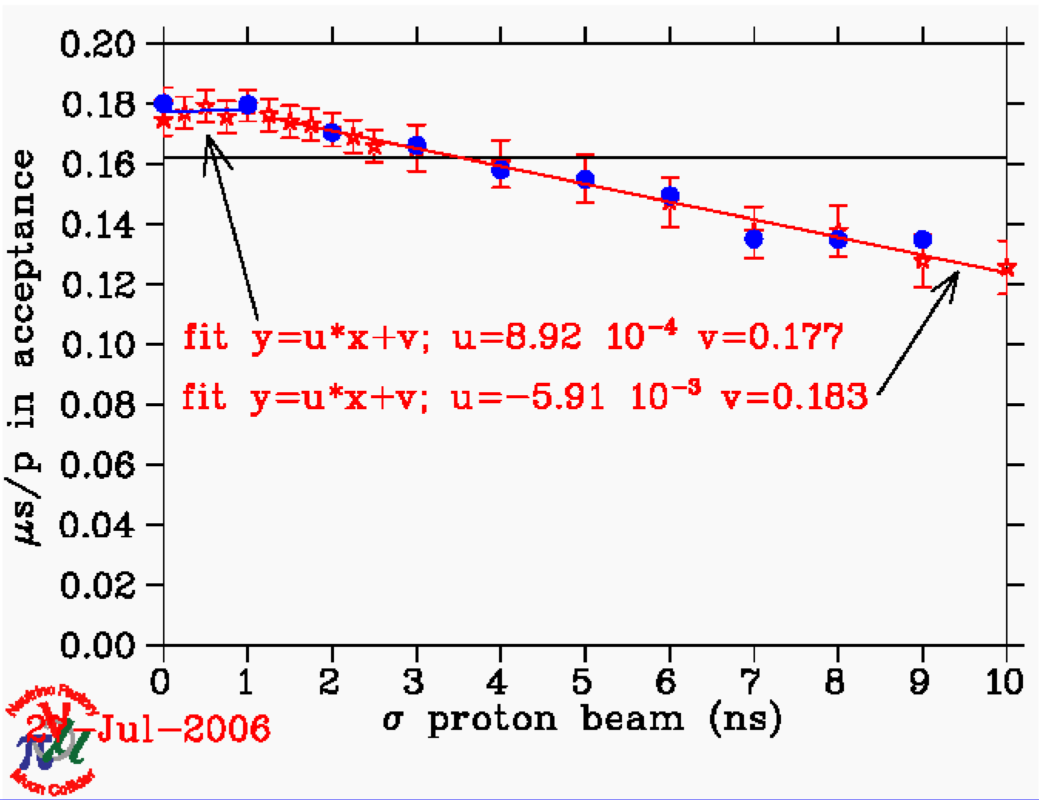
Need a production target that can survive **multmegawatt** proton beams.

Muon Collider Technical Challenges (1)

- **Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)**
  - low production rate
    - need target that can tolerate multi-MW beam
  - large energy spread and transverse phase space
    - need emittance cooling
    - high-acceptance acceleration system and decay ring
- **Muons have short lifetime (2.2 μs at rest)**
  - puts premium on rapid beam manipulations
    - high-gradient radio-frequency (RF) cavities (in magnetic field for cooling)
    - presently untested ionization cooling technique
    - fast acceleration system

Muon Collider Technical Challenges (2)

- **Proton beam parameters**
  - desired proton intensity for Neutrino Factory is 4 MW
    - *e.g.*, 3.1 × 10^{15} *p*/s at 8 GeV or 6.2 × 10^{13} *p*/pulse at 50 Hz
    - prefer only 15 Hz at a Muon Collider ⇒ 2 × 10^{14} *p*/pulse
  - desired rms bunch length is 1-3 ns to minimize intensity loss
    - not easily done at high intensity and moderate energy

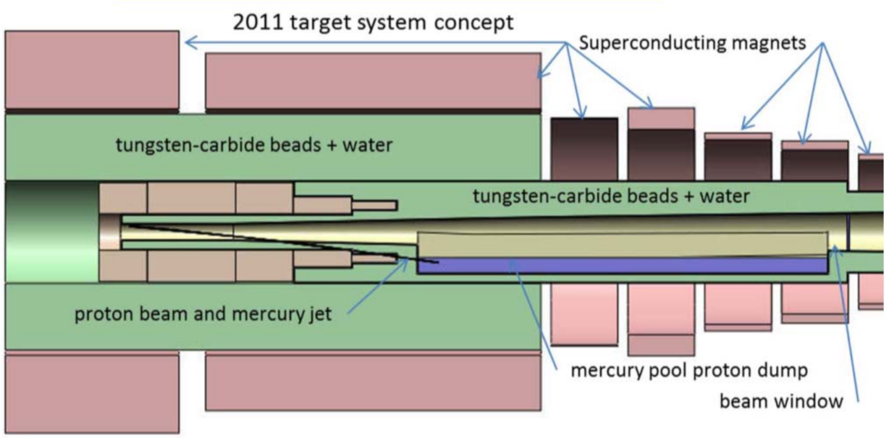


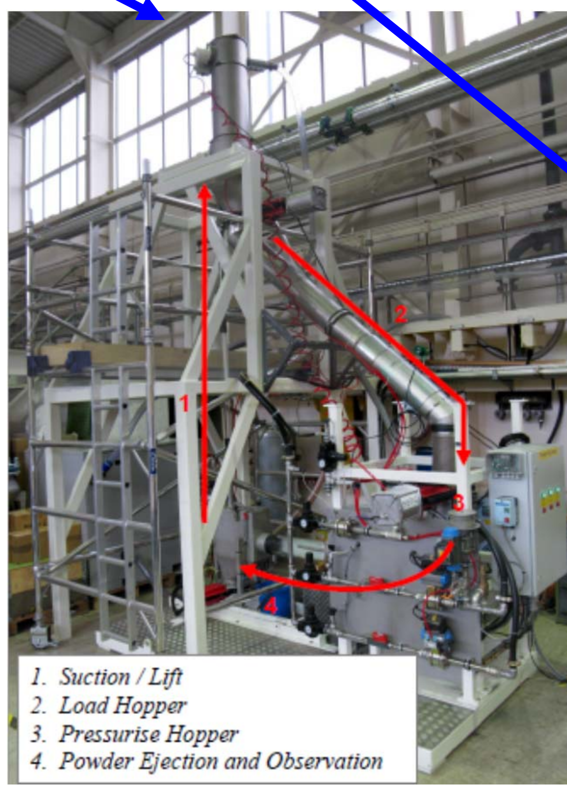
Difficult requirement at low beam energy (5-10 GeV)

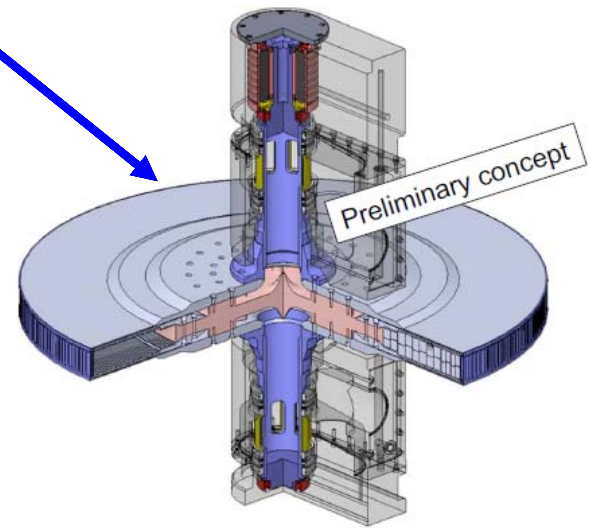
Muon Collider Technical Challenges (3)

- **Target**
  - — favored target concept based on Hg jet in 20-T solenoid
    - jet velocity of ~ 20 m/s establishes "new" target each beam pulse
      - magnet shielding is daunting, but appears manageable
  - — alternative approaches (powder or solid targets) also being pursued within EUROnu

Hg-jet target (MERIT)







Challenges ↔ Opportunities

↑

R&D

In the USA, an R&D consortium has existed since 1997 [first called the Muon Collider (and Neutrino Factory) Collaboration)] and now called the Muon Accelerator Program.
http://map.fnal.gov/

The Neutrino Factory is pursued in a worldwide context via the International Design Study for a Neutrino Factory.
https://www.ids-nf.org/wiki/FrontPage

Example: Challenges in the Target System

- 5-50 GeV beam energy appropriate for Superbeams, Neutrino Factories and Muon Colliders.
  0.8-2.5 $\times$ 10^{15} $p$ps; 0.8-2.5 $\times$ 10^{22} protons per year of 10^7 s.

- MW energy dissipation requires liquid coolant somewhere in system!

  $\Rightarrow$ No such thing as "solid-target-only" at this power level.

- Rep rate 15-50 Hz at Neutrino Factory/Muon Collider, as low as $\approx$ 2 Hz for Superbeam.
  $\Rightarrow$ Protons per pulse from 1.6 $\times$ 10^{13} to 1.25 $\times$ 10^{15}.
  $\Rightarrow$ Energy per pulse from 80 kJ to 2 MJ.

- Small beam size preferred:
  $\approx$ 0.1 cm^2 for Neutrino Factory/Muon Collider.

- Pulse width: < 2 ns desired for Neutrino Factory/Muon Collider.

$\Rightarrow$ Severe materials issues for target AND beam dump.

- Radiation Damage.
- Melting.
- Cracking (due to single-pulse "thermal shock").

Target and Capture Topology: Solenoid

Desire $\approx 10^{14}$ μ/s from $\approx 10^{15}$ p/s ($\approx$ 4 MW proton beam).

Highest rate μ^+ beam to date: PSI μE4 with $\approx 10^9$ μ/s from $\approx 10^{16}$ p/s at 600 MeV.

⇒ Some R&D needed!

R. Palmer (*BNL*, 1994) proposed a solenoidal capture system.

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

Collects both signs of π's and μ's,

⇒ Shorter data runs (with magnetic detector).

Solenoid coils can be some distance from proton beam.

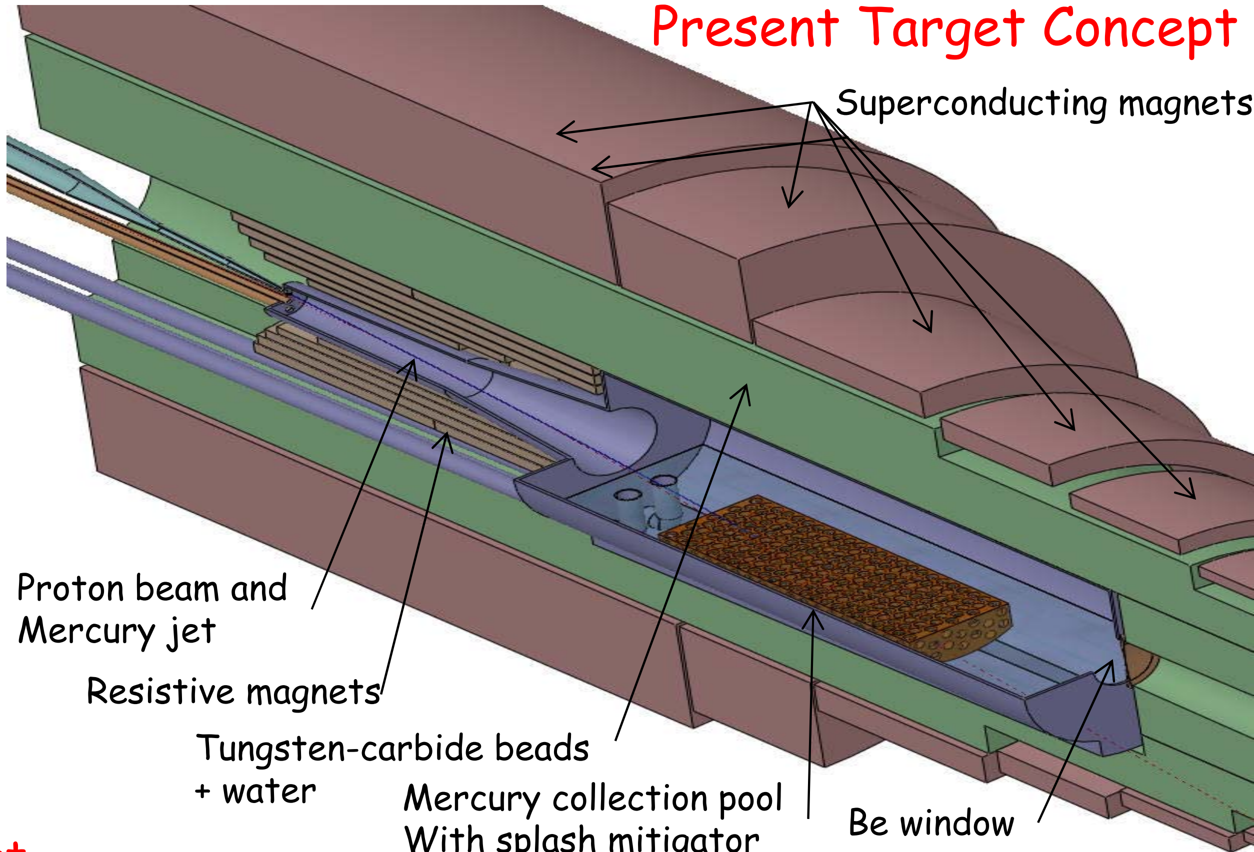
⇒ $\geq$ 4-year life against radiation damage at 4 MW.

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!

Use of "magnetic bottles" around production targets proposed by Djilkibaev and Lobashev,
http://puhep1.princeton.edu/~mcdonald/examples/detectors/djilkibaev_aipcp_372_53_95.pdf

Why 20 T?

The baseline scenario has pions produced (almost) on axis of a 20-T solenoid, followed by an "adiabatic" field taped down to 1.5 T = field strength of front-end π/μ beam transport.

We desire to capture all pions with $p_\perp \leq 200$ MeV/c.

If used a 1.5-T solenoid around the target, would need aperture of radius 80 cm to capture these pions.

But, if use a 20-T solenoid these pions fit within an aperture of 7.5 cm.

The adiabatic taper down to 1.5 T has the adiabatic invariant $\Phi_0 = \pi R_0^2 B_0 = \pi c^2 p_{0\perp}^2 / e^2 B_0$, which implies that at the end of the taper the pions fit in an aperture of only 30 cm.

That is, the use of an initial strong solenoid provides a kind of "transverse cooling".

In principle, this "cooling" would be even stronger if we could use a field higher than 20 T.

Solenoid Capture System for a Superbeam

- Pions produced on axis inside the (uniform) solenoid have zero canonical angular momentum, $L_z = r(P_\varphi + eA_\varphi / c) = 0, \Rightarrow P_\varphi = 0$ on exiting the solenoid.
- If the pion has made exactly 1/2 turn on its helix when it reaches the end of the solenoid, then its initial P_r has been rotated into a pure P_φ, $\Rightarrow P_r = 0$ on exiting the solenoid.

$\Rightarrow$ Point-to-parallel focusing for

$$P_\pi = eBd / (2n+1)\,\pi c.$$

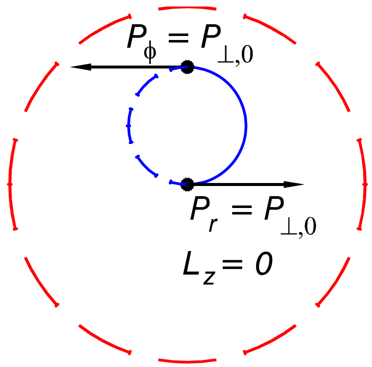
$\Rightarrow$ Narrowband (less background) neutrino beams of energies

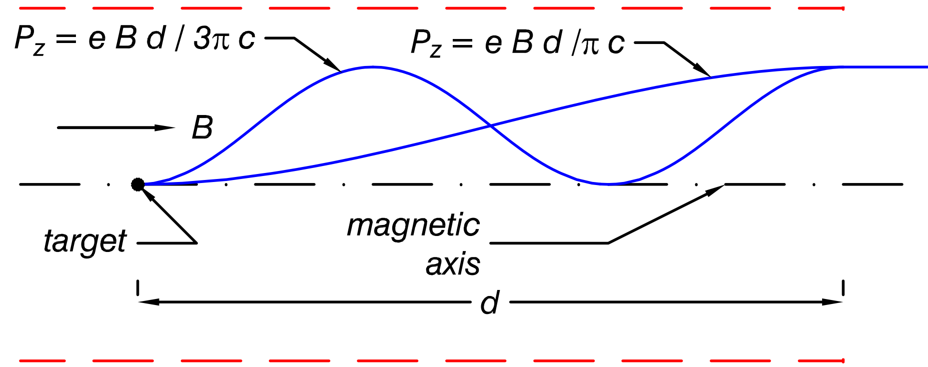
$$E_\nu \approx \frac{P_\pi}{2} = \frac{eBd}{(2n+1)2\pi c}.$$

$\Rightarrow$ Can study several neutrino oscillation peaks at once,

$$\frac{1.27 M_{23}^2[\mathrm{eV}^2]\, L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]} = \frac{(2n+1)\pi}{2}.$$

(Marciano, hep-ph/0108181)





(KTM, physics/0312022)

Study both ν and $\bar{\nu}$ at the same time.

$\Rightarrow$ Detector must tell ν from $\bar{\nu}$.

$\Rightarrow$ MINOS, TASD magnetized iron detectors

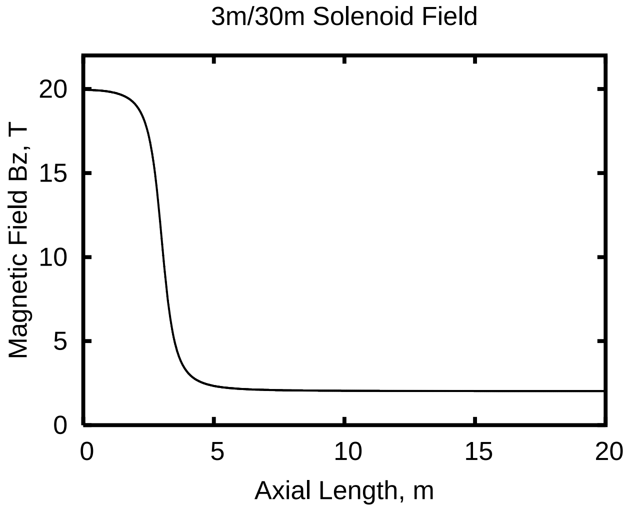
$\Rightarrow$ Liquid argon TPC that can identify slow protons:

$\nu\, n \to p\, e^- X$ vs. $\bar{\nu}\, p \to n\, e^+ X$

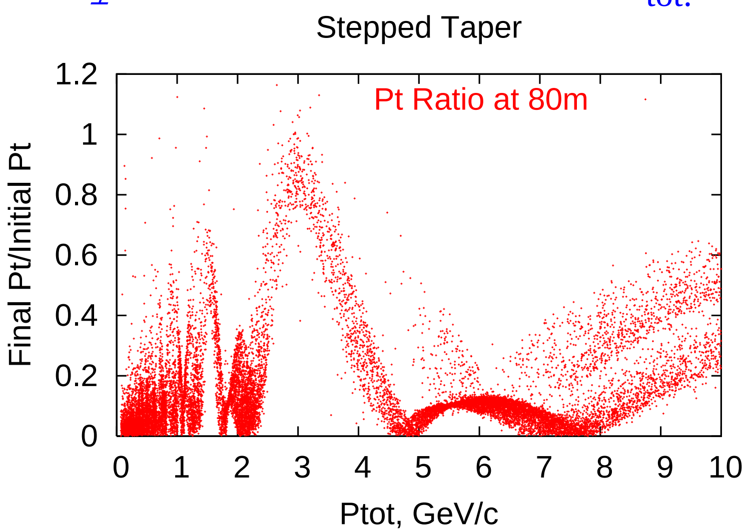
Simulation of Solenoid Horn

(H. Kirk and R. Palmer, *BNL*, NuFACT06)

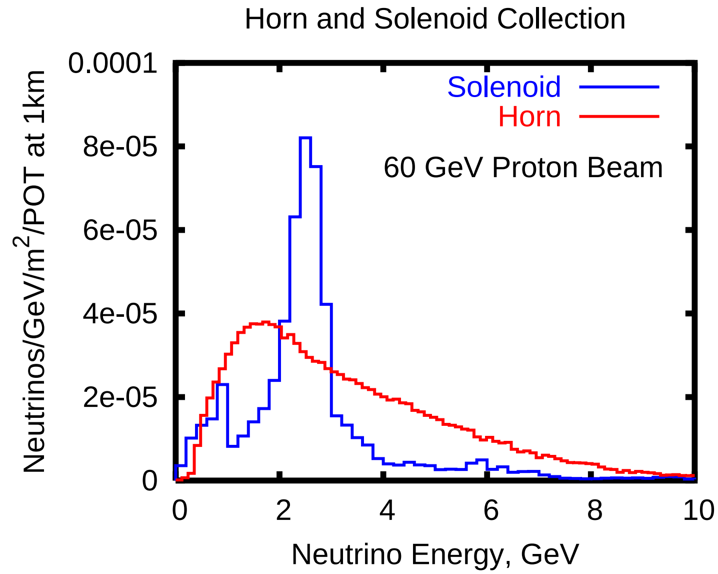
B *vs.* z for 3 + 30 m solenoid:



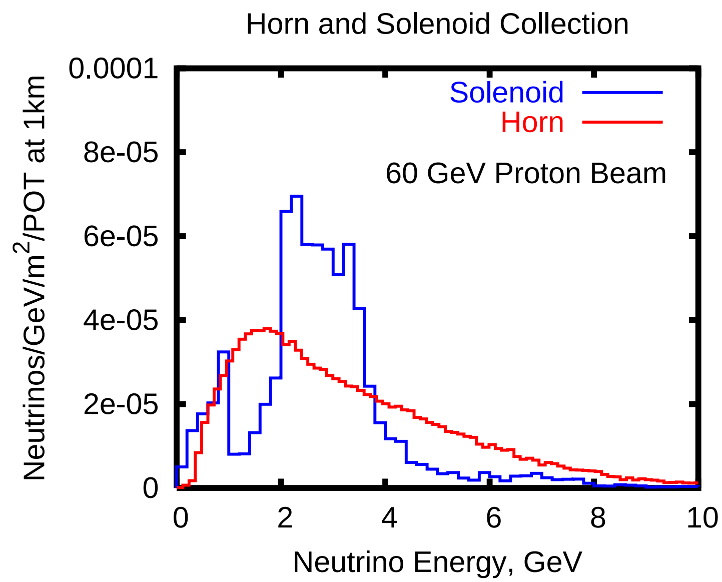
$\Rightarrow P_\perp$ minimized at selected P_{tot}:



3-m solenoid gives 2 narrow peaks in ν spectrum:



3+30-m solenoid broadens the higher energy peak:

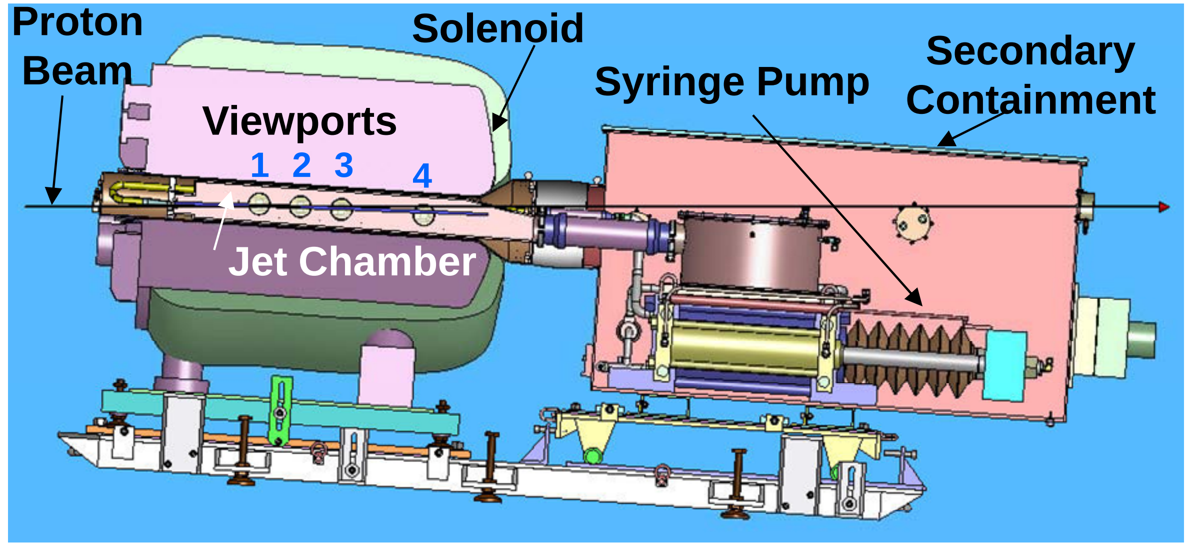


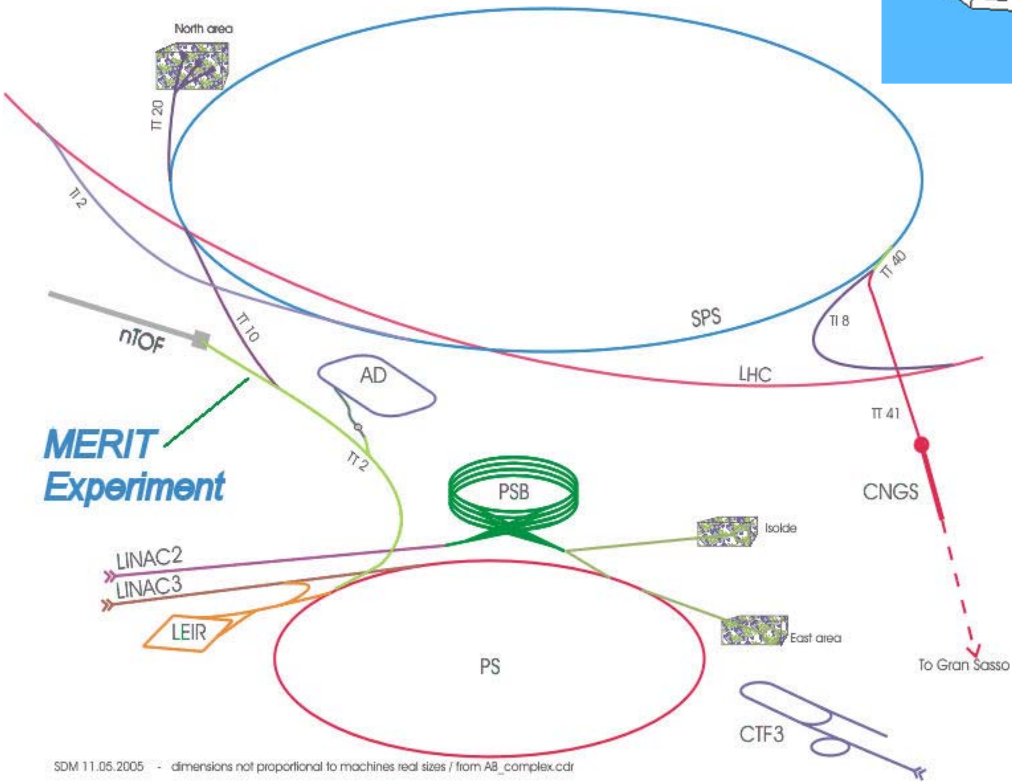
Results very encouraging, but comparison with toroid horn needs confirmation.

CERN MERIT Experiment (Nov 2007)

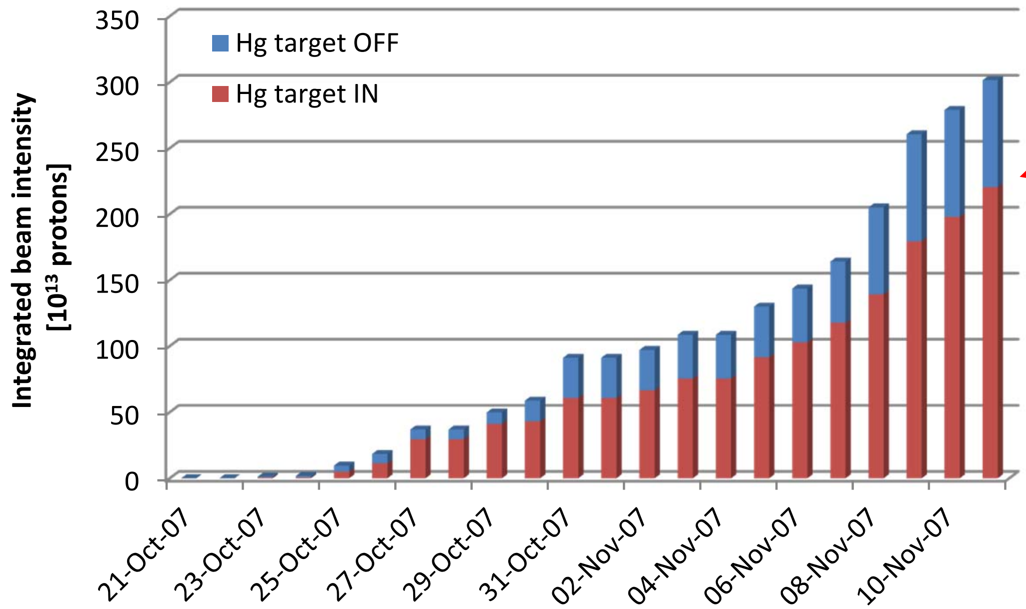
Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4-MW beam.

Performed in the TT2A/TT2 tunnels at CERN.



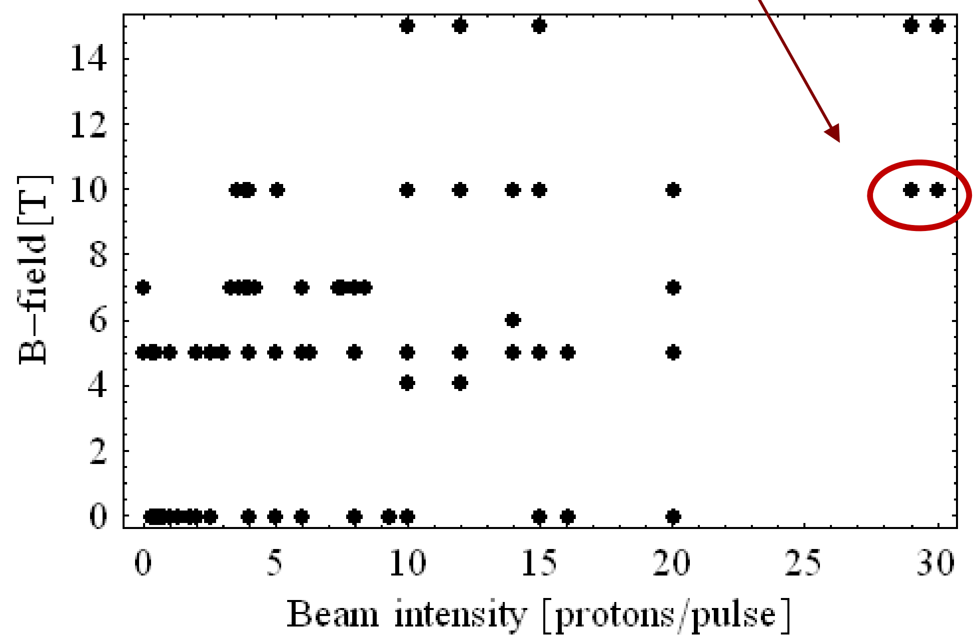


MERIT Beam Pulse Summary



MERIT was not to exceed 3×10^{15} protons on Hg to limit activation.

30 T*p* shot @ 24 GeV/c
- **115 kJ** of beam power
- a PS machine record !

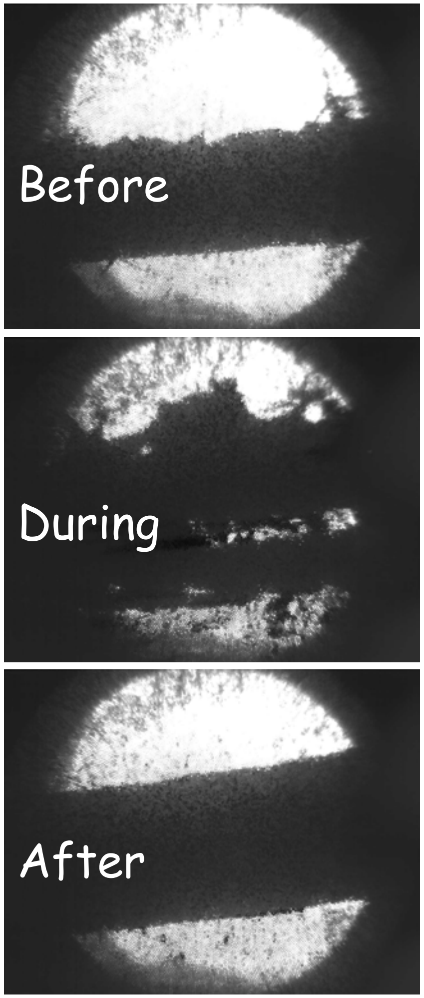


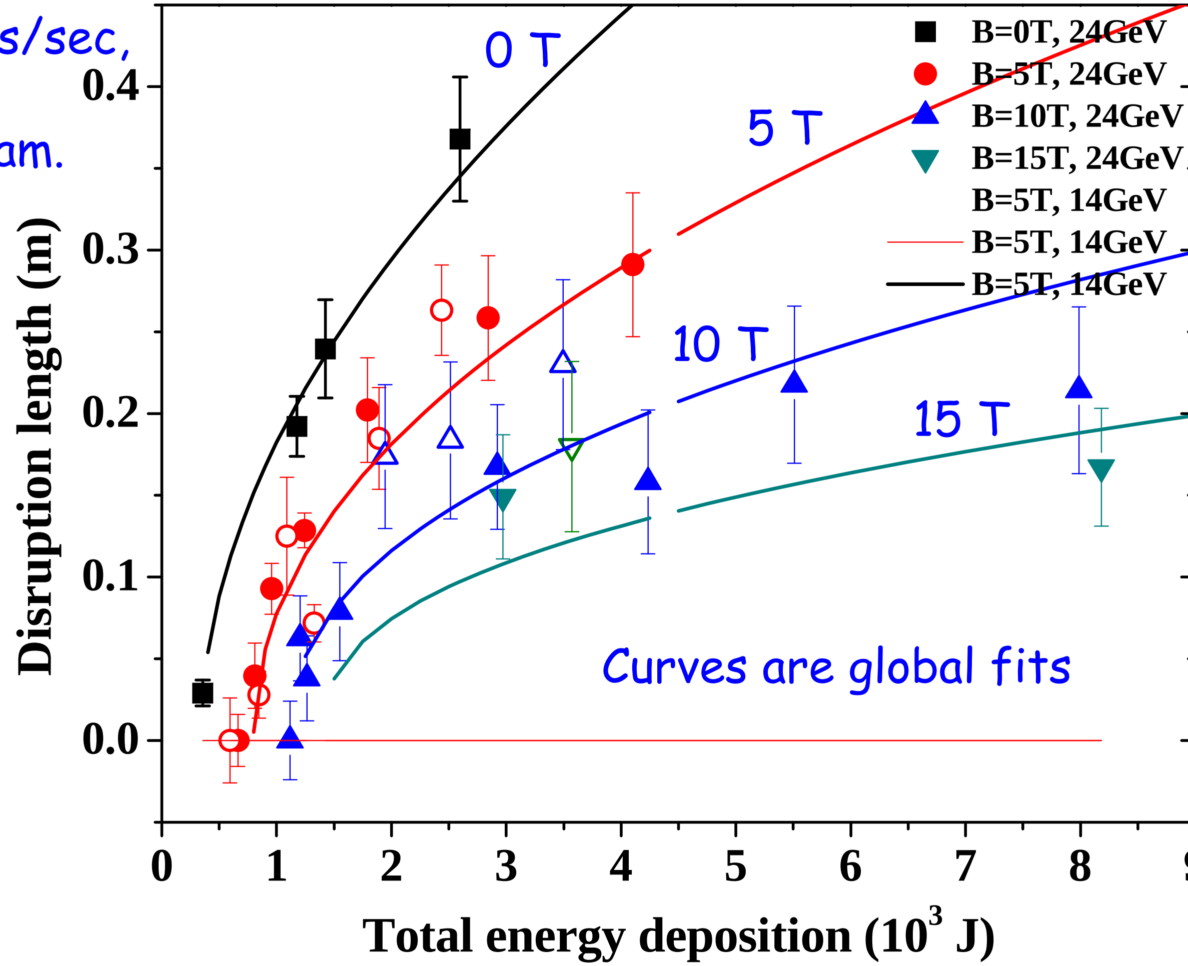
1 T*p* = 10^{12} protons

Disruption Length Analysis (H. Park, PhD Thesis)

Observe jet at viewport 3 at 500 frames/sec,
measure total length of disruption
of the mercury jet by the proton beam.

Images for 10 T*p*, 24 GeV, 10 T:



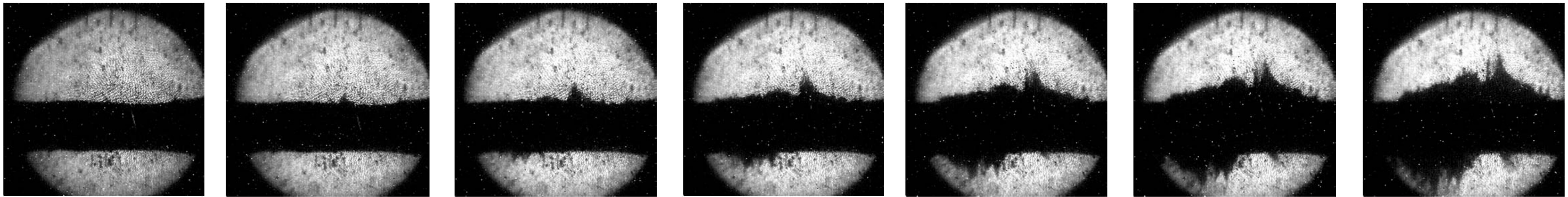


Disruption length never longer than region of overlap of jet with proton beam.

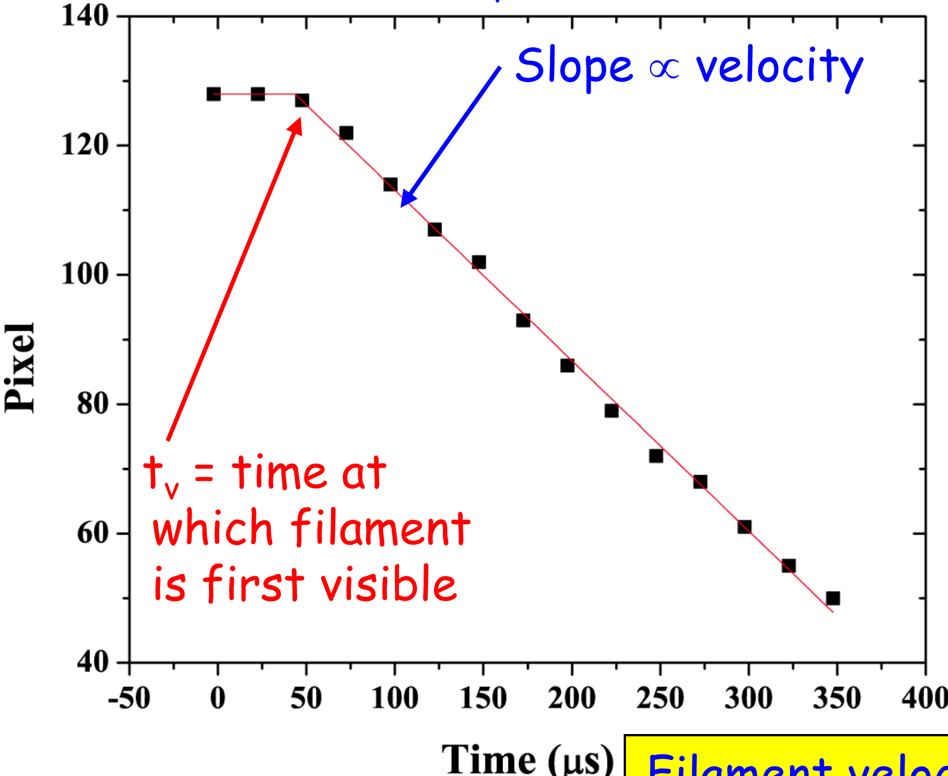
No disruption for pulses of < 2 T*p* in 0 T (< 4 T*p* in 10 T).

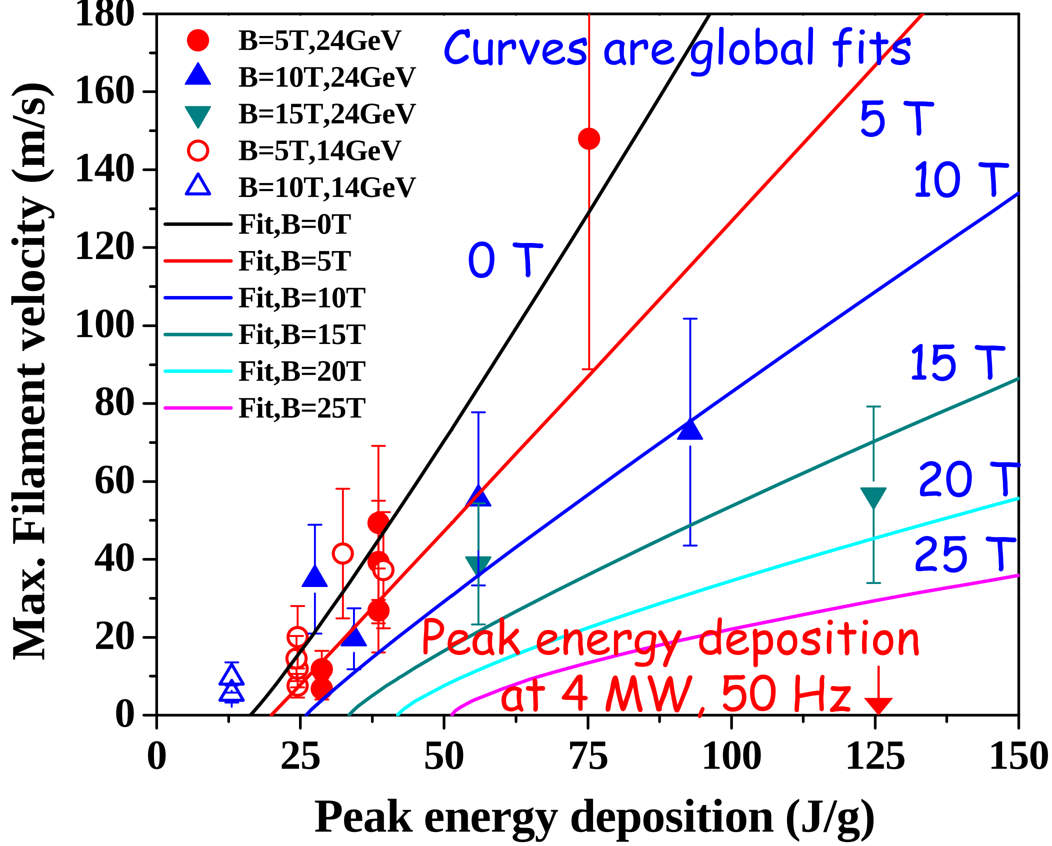
Disruption length shorter at higher magnetic field.

Filament Velocity Analysis (H. Park)



Measure position of tip of filament in each frame, and fit for t_v and v.





Filament velocity suppressed by high magnetic field.

Filament start time >> transit time of sound across the jet.

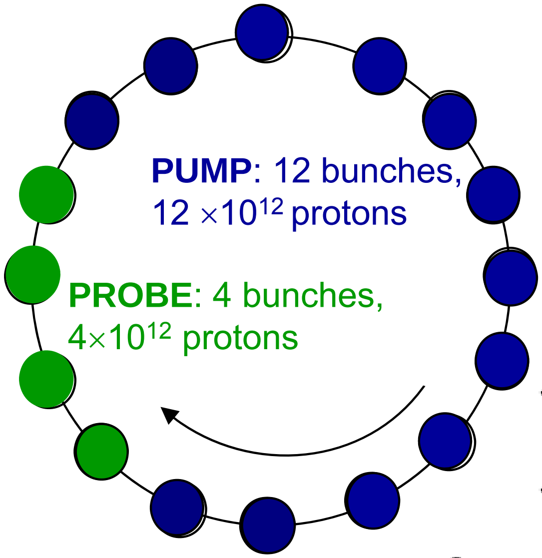
⇒ New transient state of matter???

Pump-Probe Studies

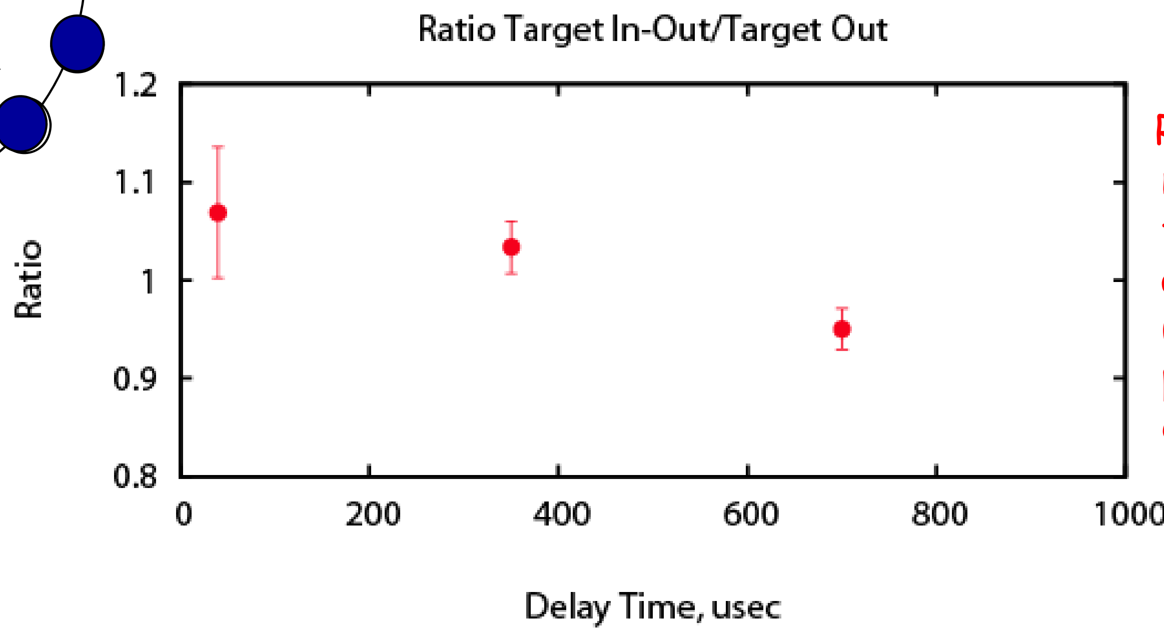
? Is pion production reduced during later bunches due to disruption of the mercury jet by the earlier bunches?

At 14 GeV, the CERN PS could extract several bunches during one turn (pump), and then the remaining bunches at a later time (probe).

Pion production was monitored for both target-in and target-out events by a set of diamond diode detectors.



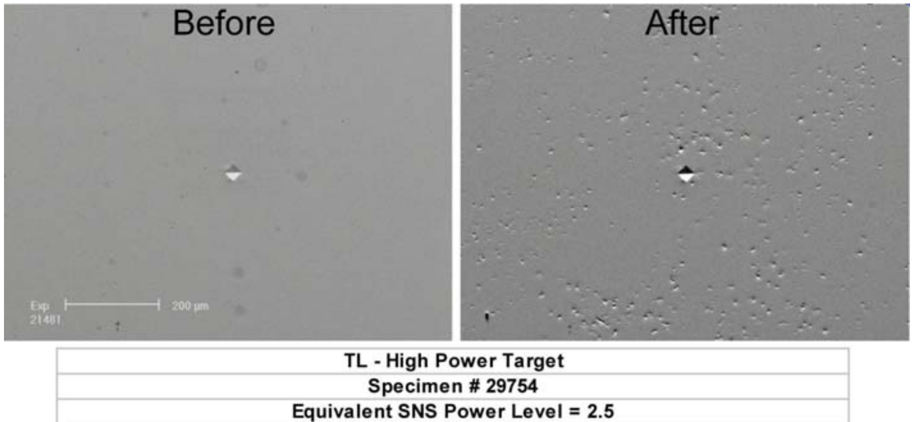
$$\text{Ratio} = \frac{\dfrac{\text{Probe}_{\text{target in}} - \text{Probe}_{\text{target out}}}{\text{Pump}_{\text{target in}} - \text{Pump}_{\text{target out}}}}{\dfrac{\text{Probe}_{\text{target out}}}{\text{Pump}_{\text{target out}}}}$$



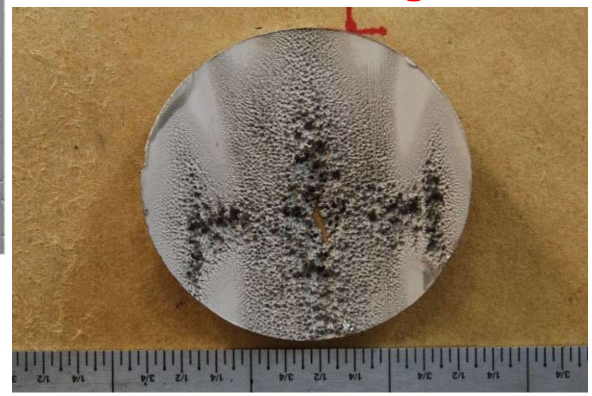
Results consistent with no loss of pion production for bunch delays of 40 and 350 μs, and a 5% loss (2.5-σ effect) of pion production for bunches delayed by 700 μs.

Damage by Mercury Droplets?

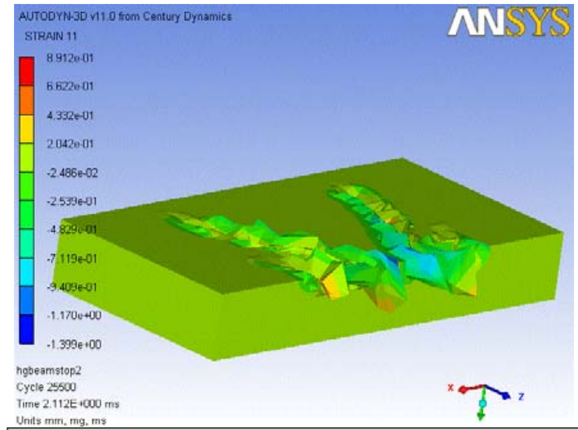
Cavitation pitting of (untreated) SS wall
surrounding Hg target after 100 pulses (SNS):



Numerical model by T. Davenne (RAL) suggests that droplets can cause damage.

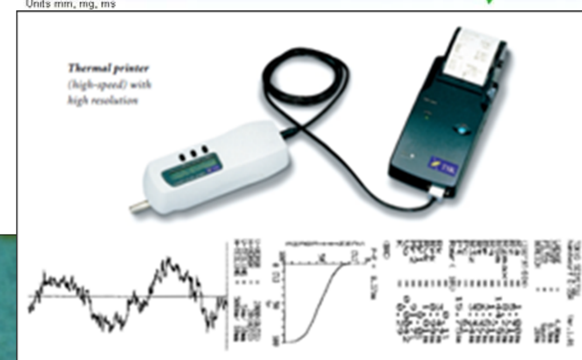


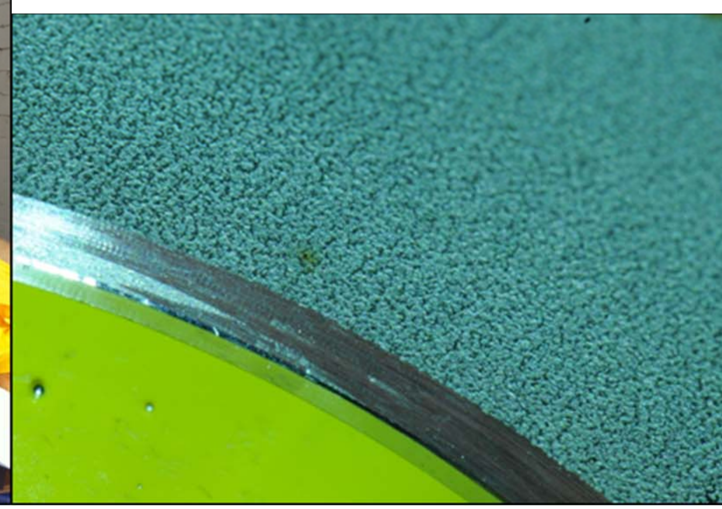
SNS Target-1
Post mortem



Avoid this issue with free jet. But, is damage caused by mercury droplets from jet dispersion by the beam?

Preliminary survey of MERIT primary containment vessel shows no damage.





Further studies to be made with Zeiss surface profiler.

MERIT Experiment Summary

The MERIT experiment established proof-of-principle of a free mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

- The magnetic field stabilizes the liquid metal jet and reduces disruption by the beam.
- The length of disruption is less than the length of the beam-target interaction, $\Rightarrow$ Feasible to have a new target every beam pulse with a modest velocity jet.
- Velocity of droplets ejected by the beam is low enough to avoid materials damage.
- The threshold for disruption is a few $\times 10^{12}$ protons, permitting disruption-free operation at high power if can use a high-rep-rate beam.
- Even with disruption, the target remains fully useful for secondary particle production for $\approx 300\ \mu$s, permitting use of short bunch trains at high power.
- No apparent damage to stainless-steel wall only 1 cm from interaction region.

Integrated Design Study of the Target System

Prior efforts on the target system for a Muon Collider/Neutrino Factory have emphasized proof-of-principle demonstration of a free mercury jet target inside a solenoid magnet.

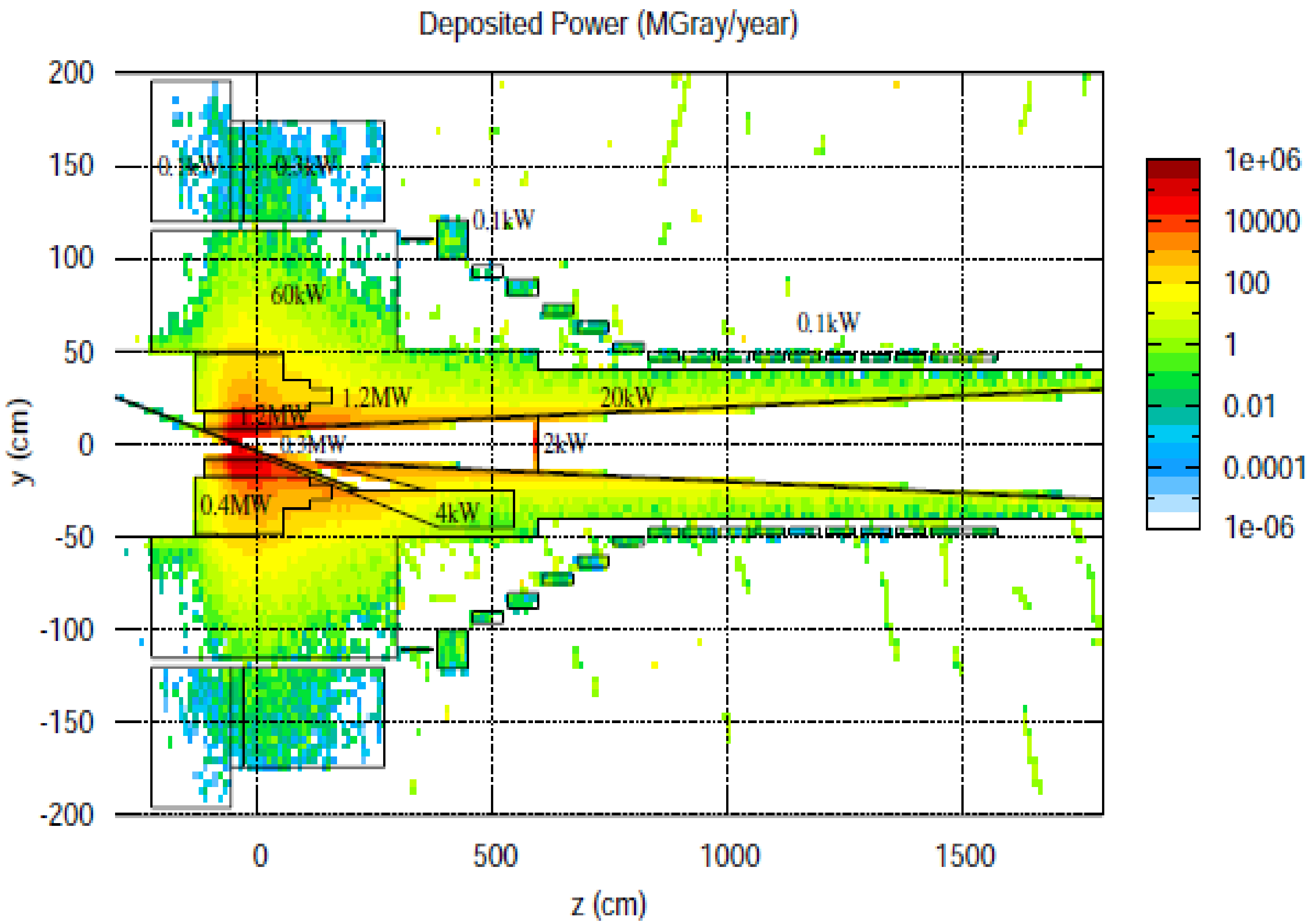
Future effort should emphasize integration of target, beam dump and **internal shield** into the capture magnet system.

The target system has complex subsystems whose design requires a large variety of technical expertise.

- Nozzle configuration (fluid engineering at high Reynolds number)
- Solid-target alternatives (mechanical and thermal engineering)
- Mercury collection pool/beam dump (fluid, mechanical and thermal engineering)
- Internal shield of the superconducting magnets (fluid, mechanical and thermal engineering)
- Magnet design (SC-1:Nb_3Sn outsert, copper insert with option for high-T_C insert; cryogenic, fluid, mechanical engineering)
- Mercury flow loop (fluid engineering)
- Remote handling for maintenance (mechanical engineering)
- Target hall and infrastructure (mechanical engineering)

- Interface with proton accelerator: final focus magnet system (mechanical engineering)
- Interface with the "front-end" of the muon cooling channel (cryogenic, mechanical engineering)

High Levels of Energy Deposition in the Target System



Power deposition in the superconducting magnets and the tungsten-carbide + water 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.

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 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.]

Workshop on Radiation Effects in Superconducting Magnet Materials (RESMM'12), Fermilab, Feb 13-15, 2012

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).

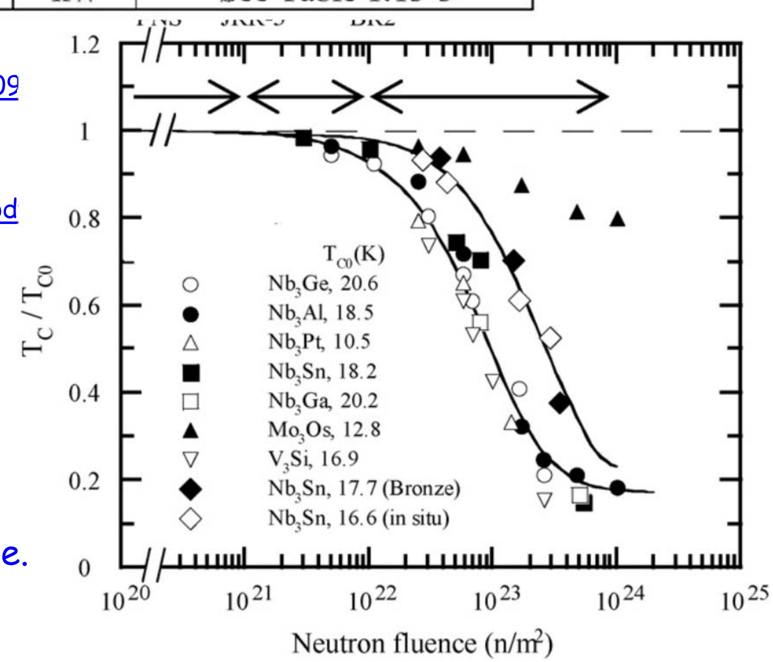
Table 1.17-1   Maximum Nuclear Load Limits to the Magnet

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	10x10^6	
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-bas
become significant

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.*

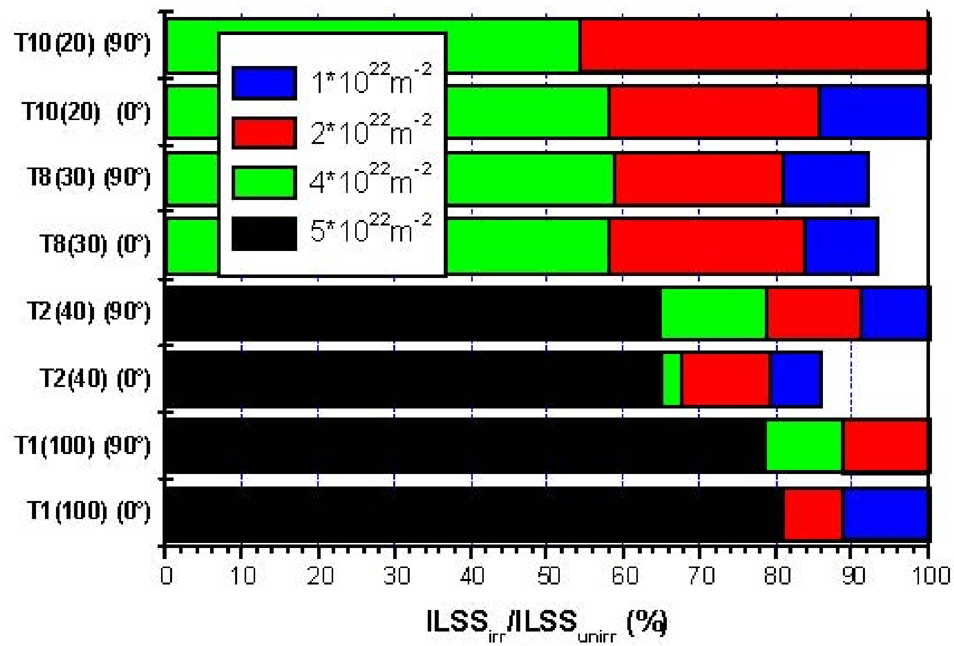
Radiation Damage to Organic Insulators

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.*



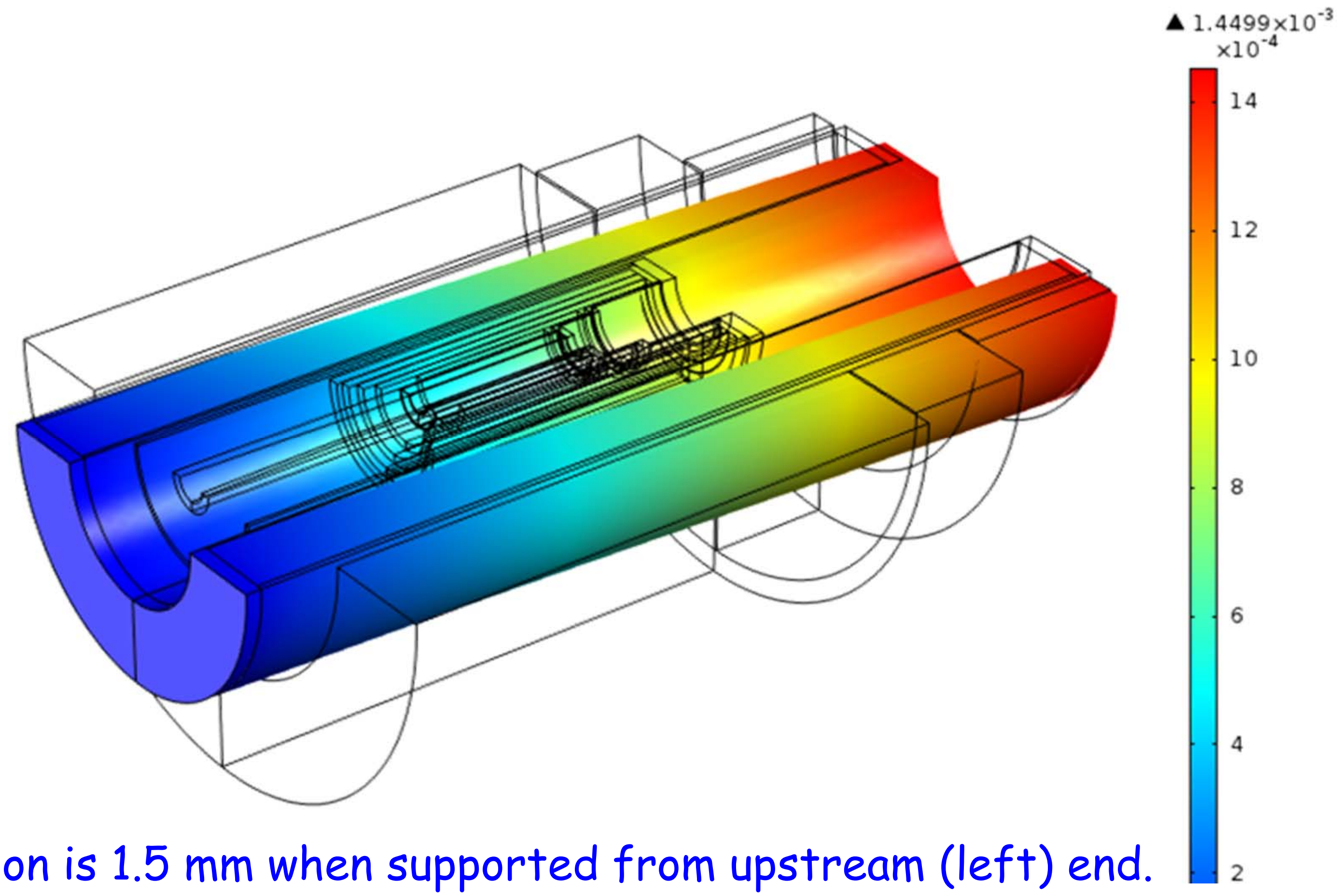
Massive Shielding Needed to Protect Superconducting Solenoids

Radiation shielding of He-gas-cooled tungsten beads.

Shielding must extend to ~ 1.2 m radius close to target ⇒ Very large stored energy in the target magnet system (~ 3 GJ).

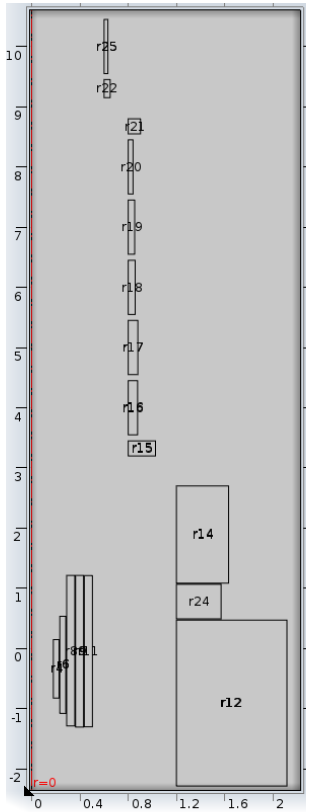
Shielding weighs ~ 100 tons. Can this be supported from one end only?

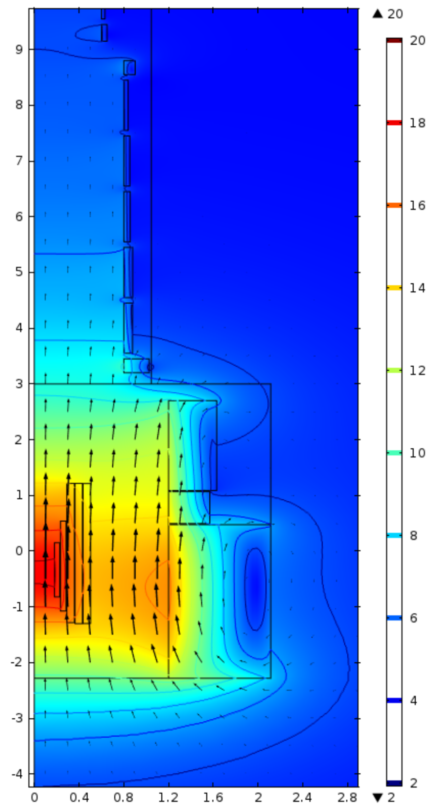
Shielding may need to extend for 50-100 m into the "front-end" system.

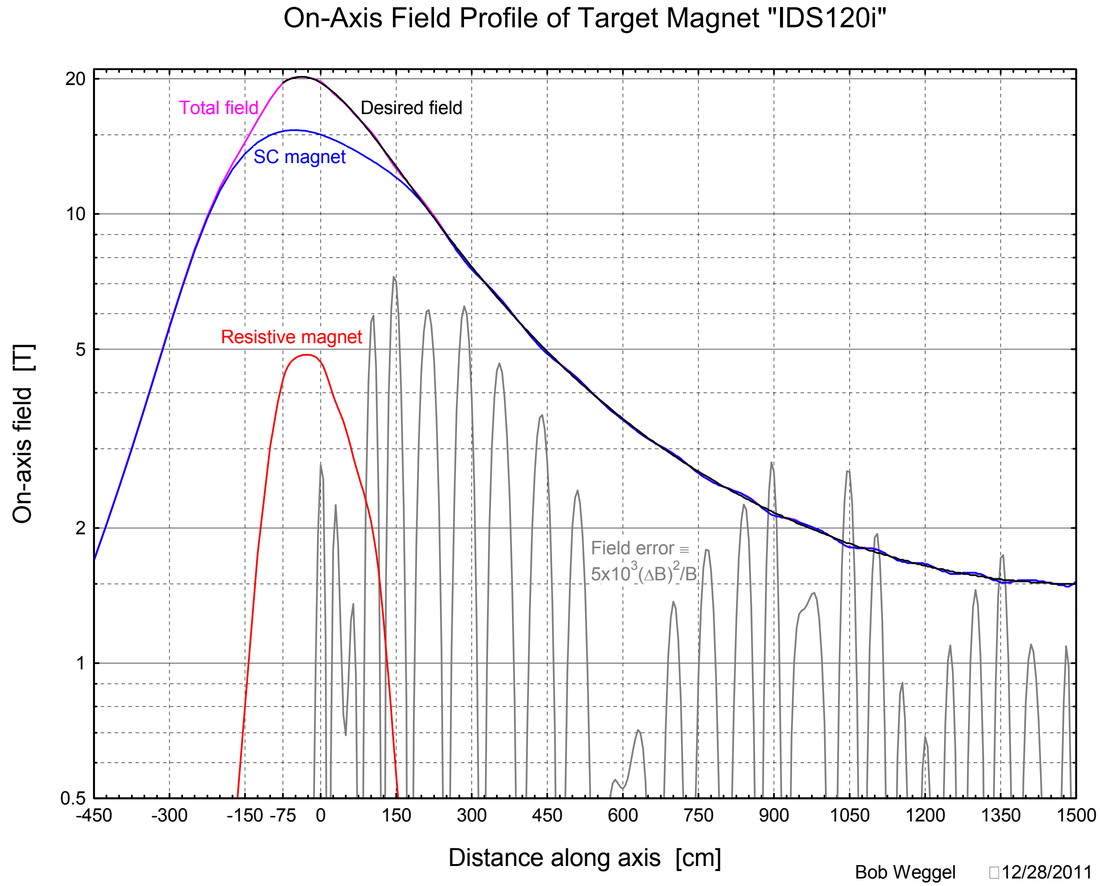


Deflection is 1.5 mm when supported from upstream (left) end.

Massive Shielding Implies Large Diameter Magnets





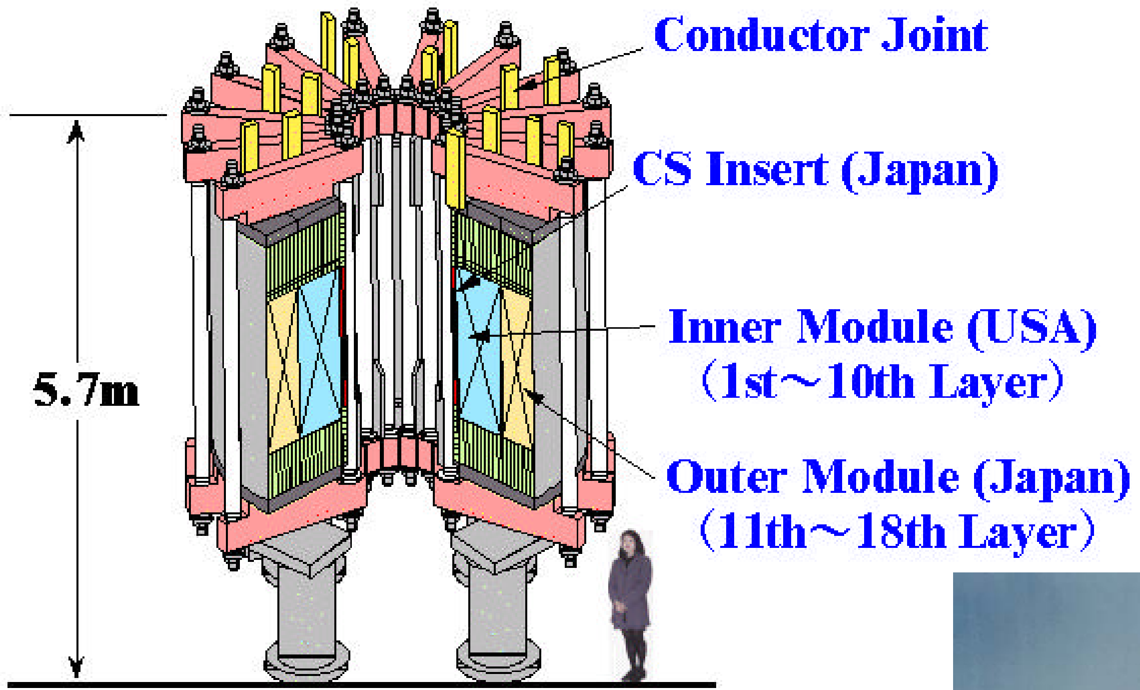


Large diameter, high field, ⇒ High stored energy (~ 3 GJ), large intermagnet forces.
Need space between some coils for cooling services for the shielding.
Magnet quench protection is a key challenge.

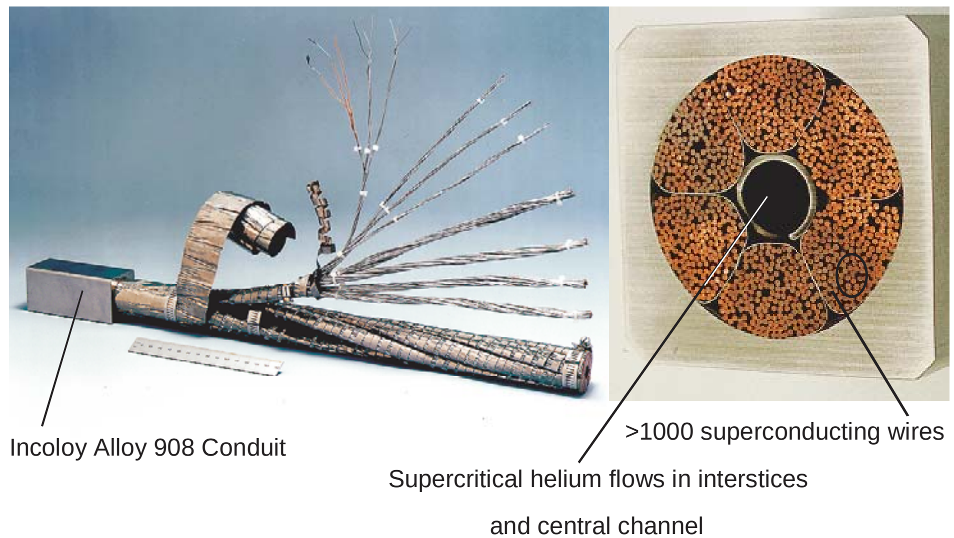
Large Cable-in-Conduit Superconducting Magnets

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

Central Solenoid (CS) Model Coil

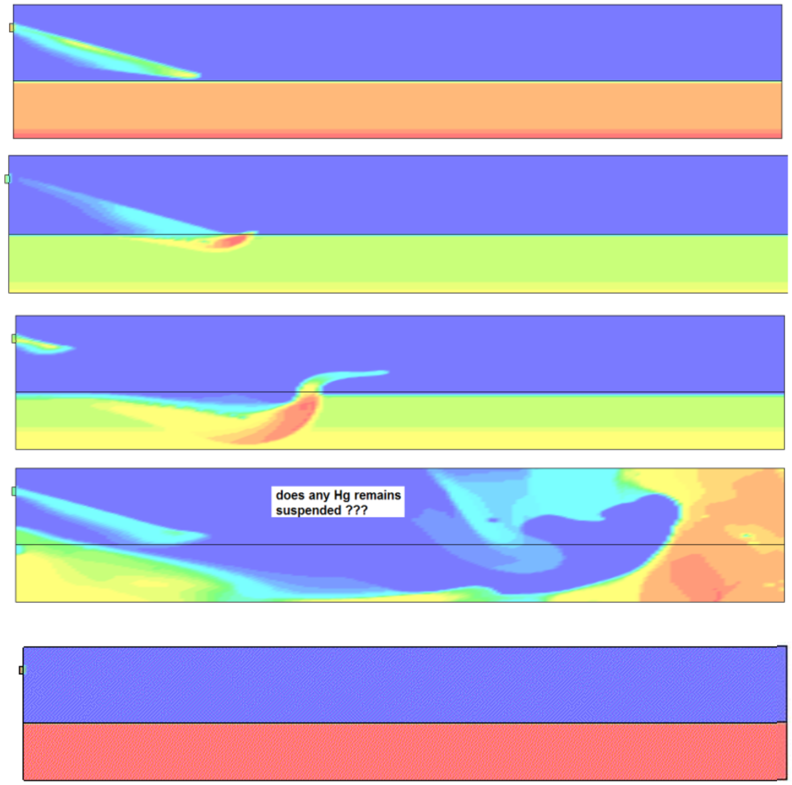


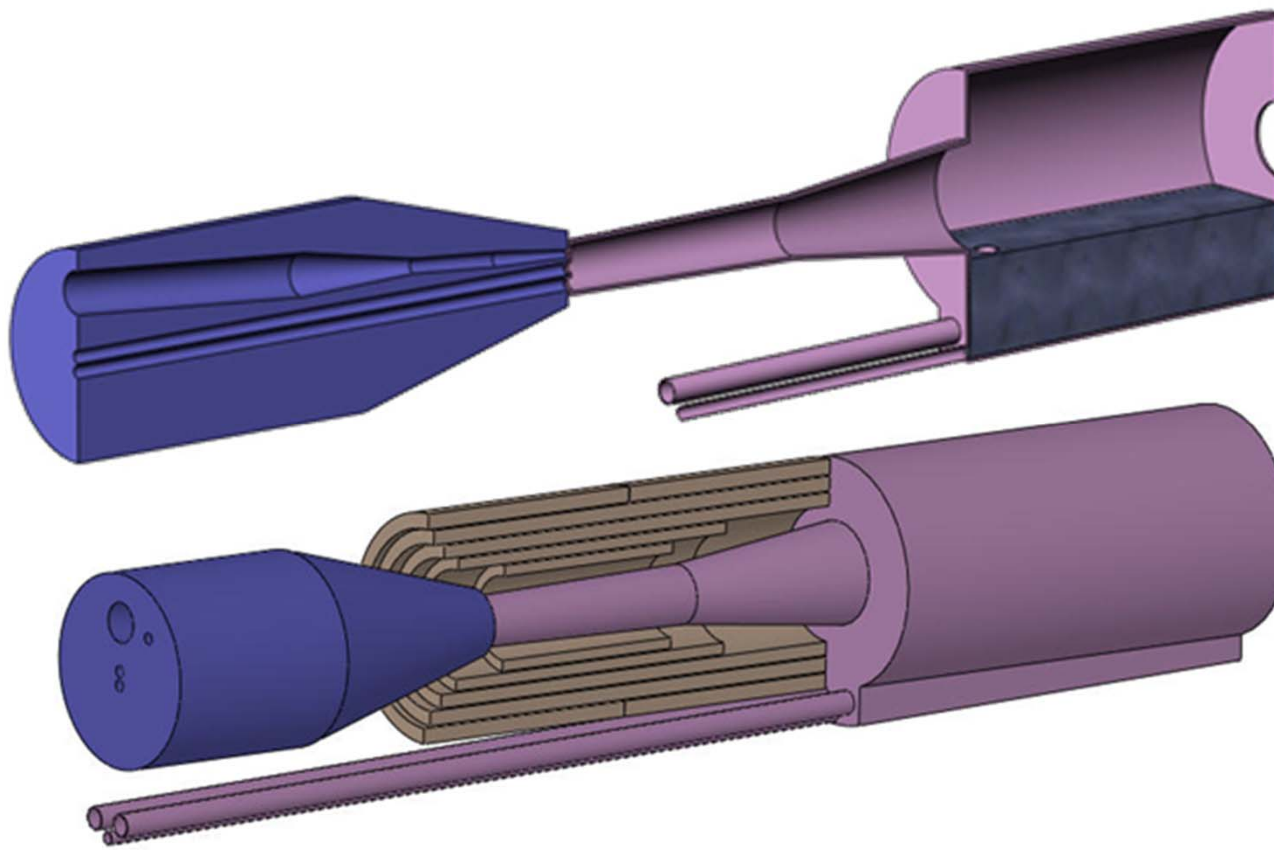
A high-temperature superconducting insert of 6+ T is appealing – but its inner radius would also have to be large to permit shielding against radiation damage.



Mercury Target and Return Flow Loop is Inside the Shielding

Mercury collection pool acts as the proton beam dump ⇒ Need splash mitigation.
System would be simpler if had no 6-T copper magnet close to target.





Radiation Tolerant Alloys

The reactor community has been developing radiation tolerant Fe alloys with nanostructure that mitigates effects of He gas production by radiation.
If available in sufficient quantity, it would be advantageous to use such an alloy for the Hg containment vessel – which will be subject to intense radiation.

Irradiation-tolerant Nanostructured Ferritic Alloys: Transforming Helium from a Liability to an Asset

G.R. Odette and D.T. Hoelzer

Journal of Metals vol. 62, no. 10, p. 84 (2010)

These alloys are "nanoporous". Are they still sufficiently strong when radiation hard?

Likewise, it would be advantageous to build the resistive copper magnet from a radiation tolerant copper alloy. However, R&D on radiation-tolerant copper alloy is underfunded.

Challenges $\leftrightarrow$ Opportunities

↑

R&D

Particle production & energy deposition simulation, including optimization for beam delivered to the front end.
Magnetohydrodynamic simulations (including perturbations by beam energy)
Liquid metal alternatives: Ga, Hg, Pb-Bi
Splash mitigation in the liquid metal collection pool (among other flow loop issues)
Magnet design, quench protection, radiation resistant insulators, HTC option
Shielding materials (including nanoporous alloys), mechanical design
System design/integration including remote handling capabilities
Final focus beam design (with multiple beams for Muon Collider)