Considerations on
Target (and Beam Dump), Capture and Decay
for a
4-MW Neutrino Factory
and a
4-MW Neutrino Superbeam

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`http://puhep1.princeton.edu/mumu/target/`

The Context

- **Physics:** Nature presents us with the opportunity to explore the richness of the mixing of massive neutrinos: Mass hierarchy, $\sin^2\theta_{13}$, CP violation.
- **Neutrino Beams:**
  - Superbeam neutrinos from $\pi^\pm \to \mu^\pm \nu_\mu(\overline{\nu}_\mu)$. (Pions from $pA \to \pi^\pm X$.)
  - Factory neutrinos from $\mu^\pm \to e^\pm \overline{\nu}_\mu \nu_e(\nu_\mu \overline{\nu}_e)$. (Muons from $\pi^\pm \to \mu^\pm \nu_\mu(\overline{\nu}_\mu)$.)
  - β-beam neutrinos from $^6\text{He} \to {}^6\text{Li}e^-\overline{\nu}_e$, $^{18}\text{Ne} \to {}^{18}\text{F}e^+\nu_e$ (not discussed here).
- **Detectors:** Cheapest large detectors are calorimeters with no magnetic field.

⇒ Cheapest to study $\nu_\mu \to \nu_e$ oscillations with a sign-selected source.

⇒ Long time to study both neutrino and antineutrino oscillations.

Alternatives to permit simultaneous studies of neutrinos and antineutrinos:

- Magnetized iron calorimeter with Neutrino Factory ($\mu^\pm$ only).
- Magnetized liquid argon detector with Superbeam and/or Neutrino Factory.

(Only magnetized LAr detector can distinguish $e^\pm$.)

(Neutrino Factory needs magnetized detector even if sign-selected beam.)

4-MW Proton Beam

- 10-30 GeV appropriate for both Superbeam and Neutrino Factory.

  ⇒ 0.8-2.5 $\times 10^{15}$ $p$ps; 0.8-2.5 $\times 10^{22}$ protons per year of 10^7 s.

- Rep rate 15-50 Hz at Neutrino Factory, as low as 2 Hz for Superbeam.

  ⇒ Protons per pulse from 1.6 $\times 10^{13}$ to 1.25 $\times 10^{15}$.

  ⇒ Energy per pulse from 80 kJ to 2 MJ.

- Small beam size preferred:

  ≈ 0.1 cm^2 for Neutrino Factory, ≈ 0.2 cm^2 for Superbeam.

⇒ Severe materials issues for target AND beam dump.

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

Radiation Damage

The lifetime dose against radiation damage (embrittlement, cracking, ...) by protons for most solids is about 10^{22}/cm^2.

⇒ Target lifetime of about 5-14 days at a Neutrino Factory (and 9-28 days at a Superbeam).

⇒ Mitigate by frequent target changes, moving target, liquid target, ...

Remember the Beam Dump

Target of 2 interaction lengths ⇒ 1/7 of beam is passed on to the beam dump.

Long distance from target to dump at a Superbeam,
⇒ Beam is much less focused at the dump than at the target,
⇒ Radiation damage to the dump not a critical issue (Superbeam).

Short distance from target to dump at a Neutrino Factory,
⇒ Beam still tightly focused at the dump,
⇒ Frequent changes of the beam dump, or a moving dump, or a liquid dump.

A liquid beam dump is the most plausible option for a Neutrino Factory, independent of the choice of target. (This is so even for a 1-MW Neutrino Factory.)

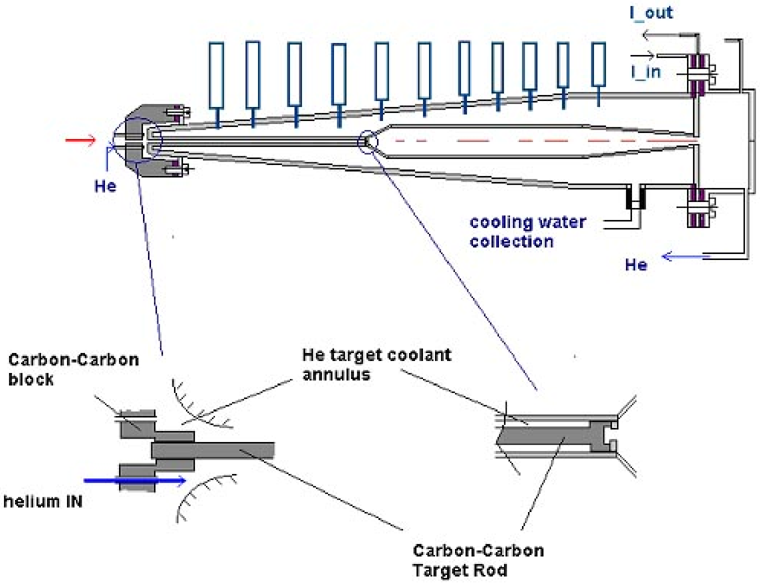
The proton beam should be tilted with respect to the axis of the capture system at a Neutrino Factory, so that the beam dump does not absorb the captured π's and μ's.

Target and Capture Topologies: Toroidal Horn

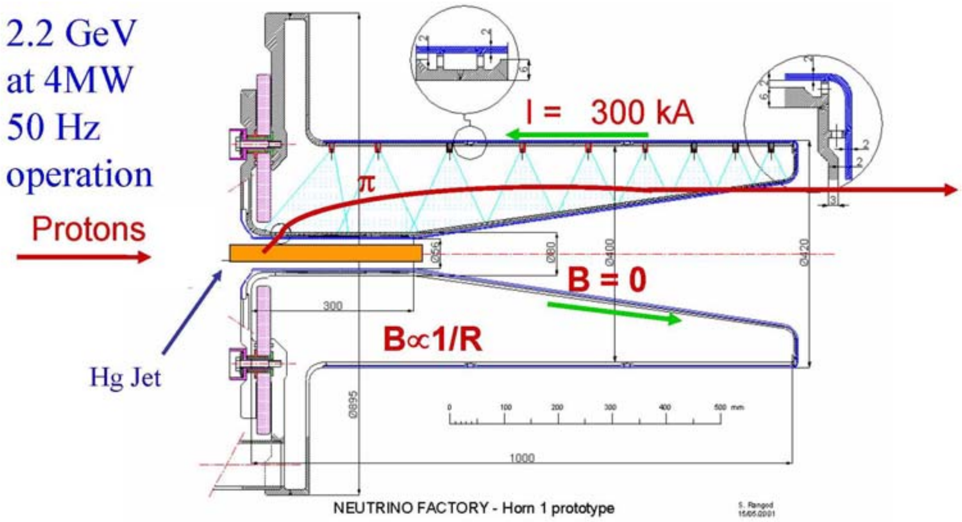
The traditional topology for efficient capture of secondary pions is a toroidal "horn" (Van der Meer, 1961).

- Collects only one sign, ⇒ Long data runs, but nonmagnetic detector (Superbeam).
- Inner conductor of toroid very close to proton beam.
  ⇒ Limited life due to radiation damage at 4 MW.
  ⇒ Beam, and beam dump, along magnetic axis.
  ⇒ More compatible with Superbeam than with Neutrino Factory.

Carbon composite target with He gas cooling (BNL study):



Mercury jet target (CERN SPL study):



If desire secondary pions with $E_\pi \lesssim 5$ GeV (Neutrino Factory), a high-Z target is favored, but for $E_\pi \gtrsim 10$ GeV (some Superbeams), low Z is preferred.

Target and Capture Topologies: Solenoid

Palmer (1994) proposed a solenoidal capture system for a Neutrino Factory.

- Collects both signs of π's and μ's, ⇒ Shorter data runs (with magnetic detector).
- Solenoid coils can be some distance from proton beam.

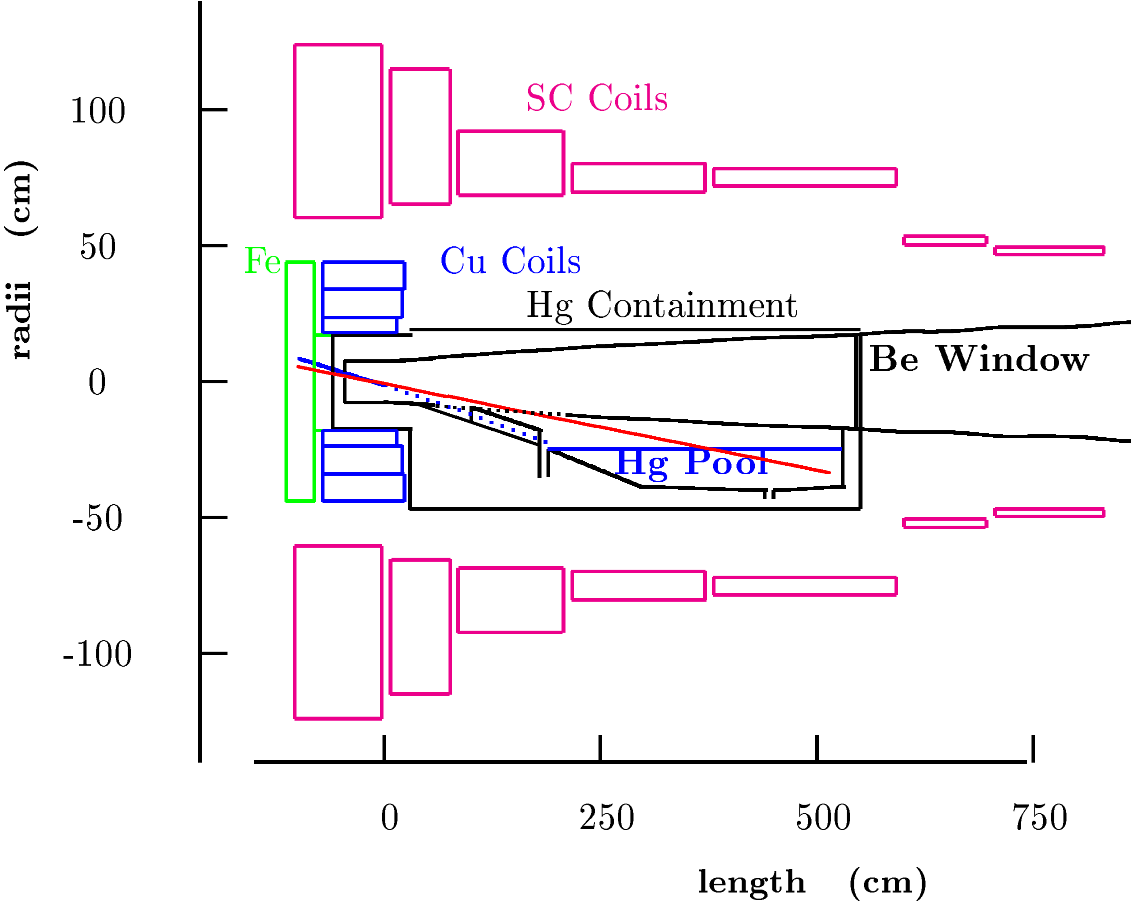
⇒ $\gtrsim$ 4 year life against radiation damage at 4 MW.

⇒ Proton beam readily tilted with respect to magnetic axis.

⇒ Beam dump out of the way of secondary π's and μ's.

Mercury jet target and proton beam tilt downwards with respect to the horizontal magnetic axis of the capture system.

The mercury collects in a pool that serves as the beam dump (Neutrino Factory Study 2):



Solenoid Capture System for a Superbeam

- **Pions produced on axis inside the (uniform) solenoid have zero canonical angular momentum, $L_z = r(P_\phi + eA_\phi/c) = 0$, $\Rightarrow P_\phi = 0$ 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, $\Rightarrow P_\perp = 0$ on exiting the solenoid.**

$\Rightarrow$ Point-to-parallel focusing for

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

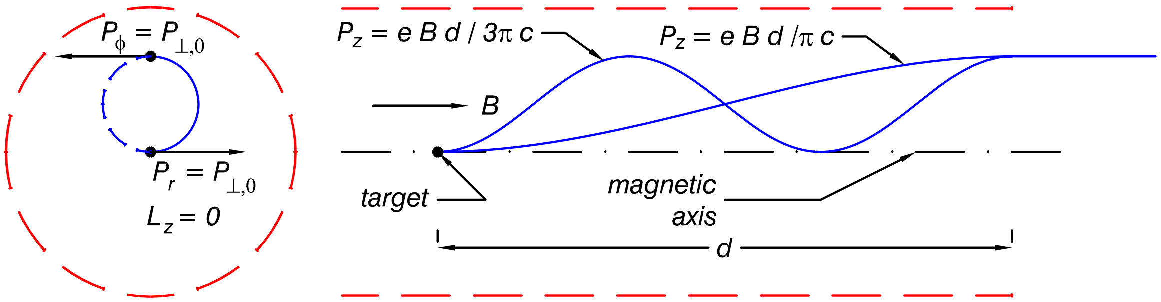
$\Rightarrow$ Narrowband (less background) neutrino beams of energies

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

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

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

(Marciano, hep-ph/0108181)



(KTM, physics/0312022)

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

$\Rightarrow$ Detector must identify sign of μ and e.

$\Rightarrow$ Magnetized liquid argon TPC.

(astro-ph/0105442).

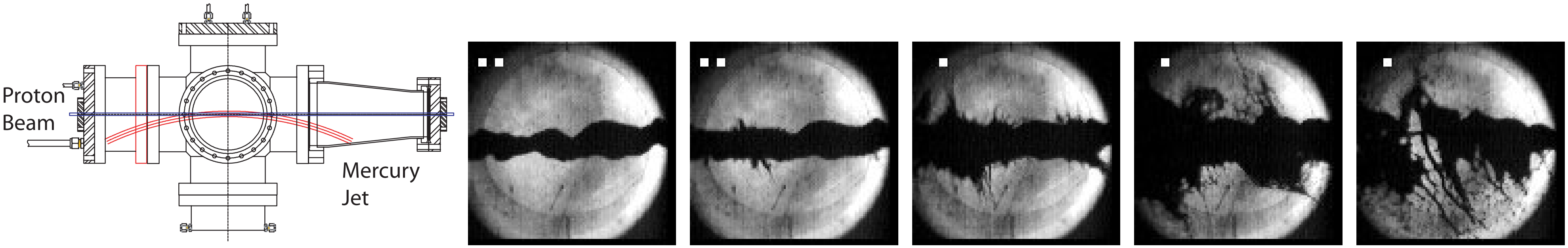
Thermal Issues for Liquid Targets (Neutrino Factory)

Liquid target/dump using mercury, or a Pb-Bi alloy.

≈ 400 **J/gm to vaporize Hg (from room temp),**
$\Rightarrow$ **Need flow of** $> 10^4$ **g/s** ≈ 1 **l/s in target/dump to avoid boiling in a 4-MW beam.**

Neutrino Factory Study 2 design has 1.5 l/s flow of Hg, so no critical thermal issues.

Energy deposited in the mercury target (and dump) will cause dispersal, but at benign velocities (10-50 m/s).



1-cm-diameter Hg jet in 2e12 protons at $t = 0$**, 0.75, 2, 7, 18 ms (BNL E-951, 2001).**

Model (Sievers): $$v_{\rm dispersal} = \frac{\Delta r}{\Delta t} = \frac{r\alpha\Delta T}{r/v_{\rm sound}} = \frac{\alpha U}{C} v_{\rm sound} \approx 12.5 \text{ m/s for } U \approx 25 \text{ J/g}.$$

Data: $v_{\rm dispersal} \approx$ **10 m/s for** $U \approx$ **25 J/g.**

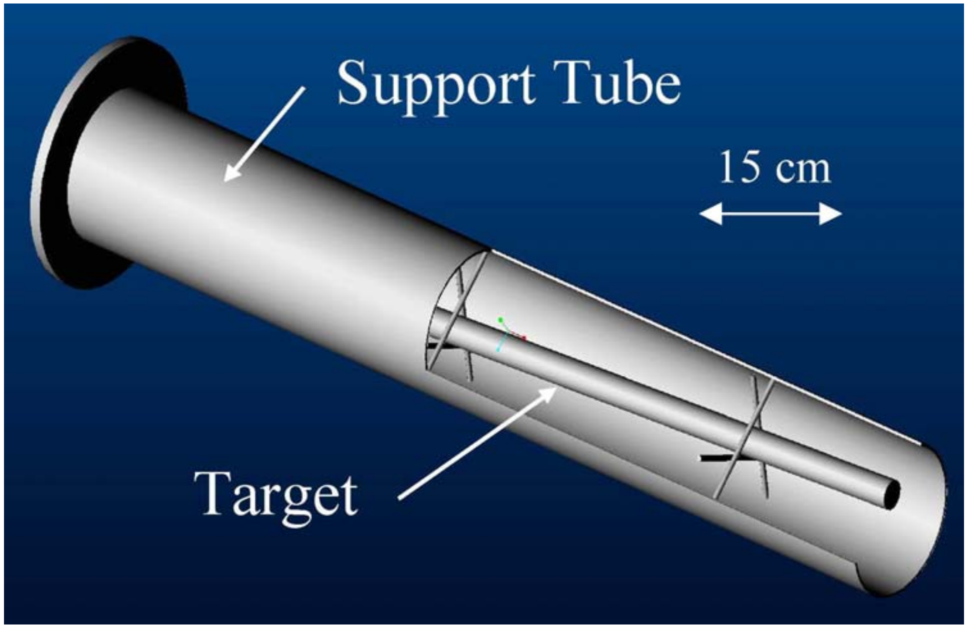
Thermal Issues for Solid Targets (Superbeams), I

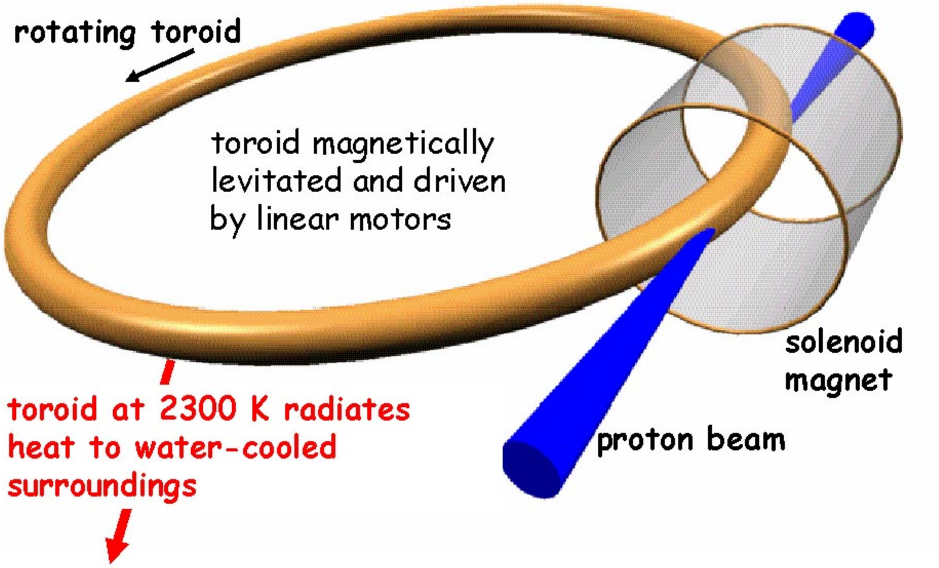
The quest for efficient capture of secondary pions precludes traditional schemes to cool a solid target by a liquid. (Absorption by plumbing; cavitation of liquid.)

A solid, radiation-cooled stationary target in a 4-MW beam will equilibrate at about 2500 C. ⇒ Carbon is only candidate for this type of target.

(Carbon target must be in He atmosphere to suppress sublimation.)

A moving band target (tantalum) could be considered (if capture system is toroidal).





Thermal Issues for Solid Targets (Superbeams), II

When beam pulse length t is less than target radius r divided by speed of sound $v_{\rm sound}$, beam-induced pressure waves (thermal shock) are a major issue.

Simple model: if U = beam energy deposition in, say, Joules/g, then the instantaneous temperature rise ΔT is given by

$$\Delta T = \frac{U}{C}, \qquad \text{where } C = \text{heat capacity in Joules/g/K.}$$

The temperature rise leads to a strain $\Delta r/r$ given by

$$\frac{\Delta r}{r} = \boldsymbol{\alpha}\Delta T = \frac{\boldsymbol{\alpha} U}{C}, \qquad \text{where } \boldsymbol{\alpha} = \text{thermal expansion coefficient.}$$

The strain leads to a stress P (= force/area) given by

$$P = E\frac{\Delta r}{r} = \frac{E\boldsymbol{\alpha} U}{C}, \qquad \text{where } E = \text{modulus of elasticity.}$$

In many metals, the tensile strength obeys $P \approx 0.002E$, $\boldsymbol{\alpha} \approx 10^{-5}$, and $C \approx 0.3$ J/g/K, in which case

$$U_{\rm max} \approx \frac{PC}{E\boldsymbol{\alpha}} \approx \frac{0.002 \cdot 0.3}{10^{-5}} \approx \textbf{ 60 J/g}.$$

⇒ Best candidates for solid targets have high strength (Vasomax, Inconel, TiAl6V4) and/or low thermal expansion (Superinvar, Toyata "gum metal", carbon-carbon composite).

How Much Beam Power Can a Solid Target Stand?

How many protons are required to deposit 60 J/g in a material?

What is the maximum beam power this material can withstand without cracking, for a 10-GeV beam at 10 Hz with area 0.1 cm^2.

Ans: If we ignore "showers" in the material, we still have dE/dx ionization loss, of about 1.5 MeV/g/cm^2.

Now, 1.5 MeV $= 2.46 \times 10^{-13}$ **J, so 60 J/ g requires a proton beam intensity of** $60/(2.4 \times 10^{-13}) = 2.4 \times 10^{14}$**/cm^2.**

So, $P_{\max} \approx 10\ \mathbf{Hz} \cdot 10^{10}\ \mathbf{eV} \cdot 1.6 \times 10^{-19}\ \mathbf{J/eV} \cdot 2.4 \times 10^{14}/\mathbf{cm}^2 \cdot 0.1\ \mathbf{cm}^2 \approx 4 \times 10^5\ \mathbf{J/s} = \mathbf{0.4\ MW}$**.**

If solid targets crack under singles pulses of 60 J/g, then safe up to only 0.4 MW beam power!

Empirical evidence is that some materials survive 500-1000 J/g,
⇒ May survive 4 MW if rep rate $\gtrsim$ 10 Hz.

Ni target in FNAL $p$bar source:
"damaged but not failed" for peak energy deposition of 1500 J/g.

Magnetic Issues for Moving Targets

Conducting materials that move through nonuniform magnetic field experience eddy-current effects, $\Rightarrow$ Forces on entering or leaving a solenoid (but not at its center).

$\Rightarrow$ Free jet of radius r cannot pass through a horizontal solenoid of diameter D unless

$$v > \frac{3\pi\sigma r^2 B_0^2}{32\rho D} \approx 6\left[\frac{r}{1\ \mathrm{cm}}\right]^2\ \mathbf{m/s}, \qquad \textbf{for Hg or Pb-Bi jet, } D = \mathbf{20\ cm}, B_0 = \mathbf{20\ T}.$$

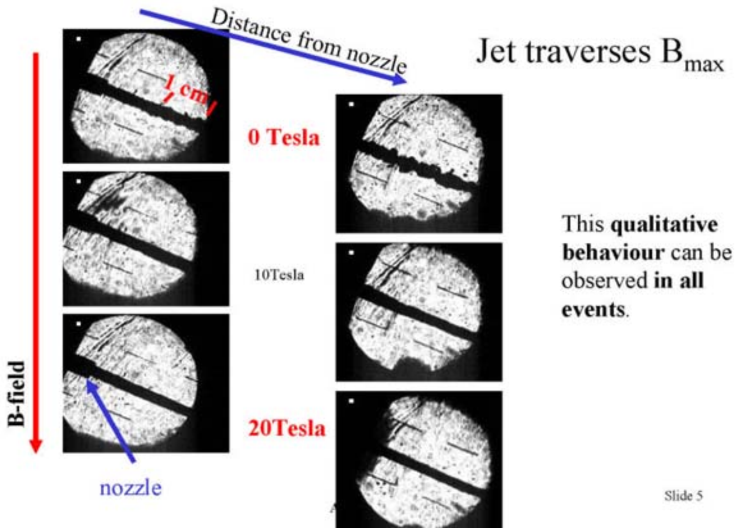
50-Hz rep rate requires v = 20 m/s for new target each pulse, so no problem for baseline design with r = 0.5 cm. The associated eddy-current heating is negligible.

[Small droplets pass even more easily, and can fall vertically with no retardation.]

A liquid jet experiences a quadrupole shape distortion if tilted with respect to the solenoid axis. This is mitigated by the upstream iron plug that makes the field more uniform.

Magnetic damping of surface-tension waves (Rayleigh instability) observed in CERN-Grenoble tests (2002).

The beam-induced dispersal will be partially damped also (Samulyak).



This **qualitative behaviour** can be observed **in all events**.

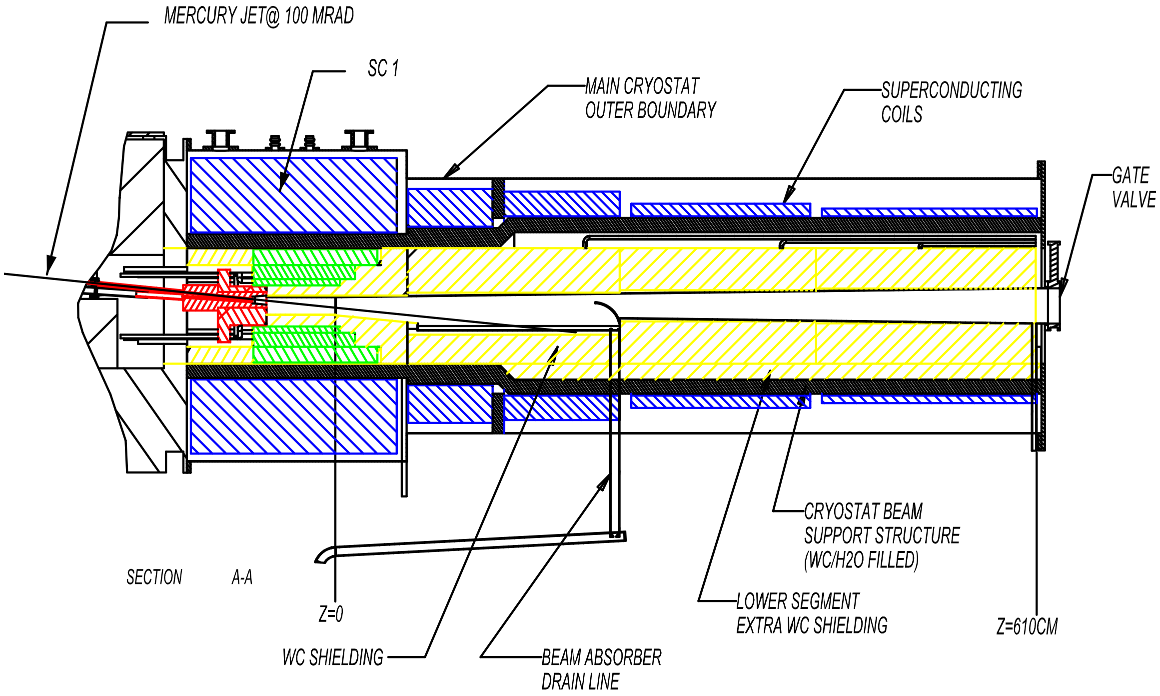
DRAFT Recommendations

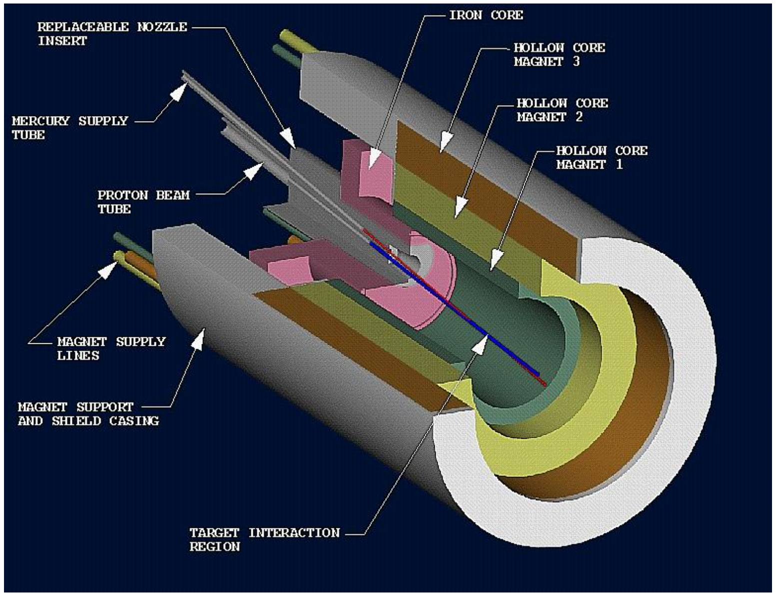
This presentation ends with a preliminary set of recommendations on a baseline, alternatives, and relevant R&D for target, dump, capture and decay at a 4-MW Neutrino Factory and a 4-MW Neutrino Superbeam.

These draft recommendations are the personal opinion of KTM.

Neutrino Factory: Baseline

The baseline is essentially that of the Neutrino Factory Study 2,
http://www.cap.bnl.gov/mumu/studyii/





- Solenoidal capture magnet (≈ 20 T) with adiabatic transition to solenoidal decay channel (≈ 1 T).
- Continuous, free mercury jet target ($r = 0.5$ cm, $v = 20$ m/s) tilted at 100 mrad to magnetic axis.
- Beam dump = pool of mercury fed by the target jet.

Neutrino Factory: Alternatives

No alternatives have been proposed to the mercury pool beam dump.

No alternatives have been proposed to the solenoidal decay channel.

Conceivable to use mercury pool + solid target, but not recommended.

Toroidal capture system not recommended as provides only one sign of muons, has awkward matching into a solenoidal decay channel, and is not well matched to use of a mercury pool dump.

Neutrino Factory: R&D

- Complete the proof-of-principle demonstration of mercury jet + proton beam + 15-T solenoid (CERN MERIT experiment in the TT2A line).
- Continue simulations of thermal magnetohydrodynamical properties of the baseline system.

Neutrino Superbeam: Baseline

[This recommendation is particularly personal, and reflects KTM's belief that a 4-MW Neutrino Superbeam is some ways off, and should provide better capability than simply scaling up present plans for 0.4-MW beams.]

- **Capture and decay in a uniform solenoid magnet tuned to provide a "comb" of narrowband neutrino beams (ν_μ and $\overline{\nu}_\mu$ simultaneously) at successive oscillation maxima.**
- **Conventional water-cooled copper dump at end of decay channel.**
- **Carbon-carbon composite target in a He atmosphere, primarily radiation cooled.**
- **This option linked to use of a detector that can distinguish $e^\pm$, *i.e.*, a magnetized liquid argon detector.**

Neutrino Superbeam: Alternative

- **Capture in a toroidal horn, followed by decay in zero magnetic field.**
- **Conventional water-cooled copper dump at end of decay channel.**
- **Carbon-carbon composite target in a He atmosphere, primarily radiation cooled.**
- **This option compatible with use of a nonmagnetic detector such as water Čerenkov.**

Neutrino Superbeam: NuMI Target R&D

NuMI target failed due to leak in cooling channels (April 2005).

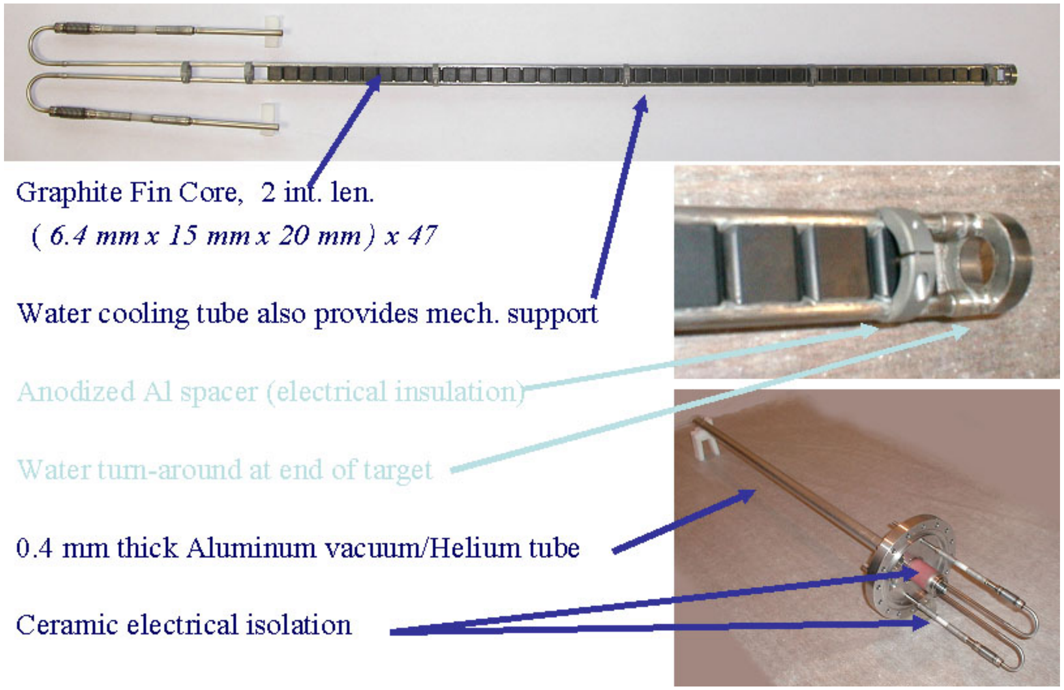
Target repaired during 1-month downtime.

Target has now operated up to ∼ 300 **kW.**

R&D in progress towards a 2-MW target.

Substantial risk of failure of water jacket due to beam-induced cavitation pitting of the Al (or SS) wall.

Mitigated slightly by the 10-μs pulse length of the NuMI proton beam.



Graphite Fin Core, 2 int. len.
(*6.4 mm x 15 mm x 20 mm) x 47*

Water cooling tube also provides mech. support

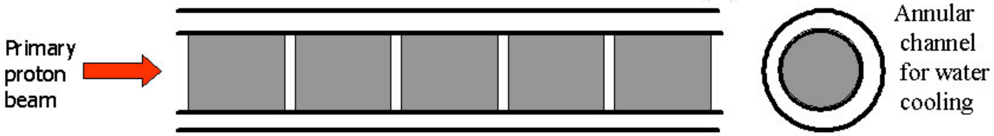
Anodized Al spacer (electrical insulation)

Water turn-around at end of target

0.4 mm thick Aluminum vacuum/Helium tube

Ceramic electrical isolation

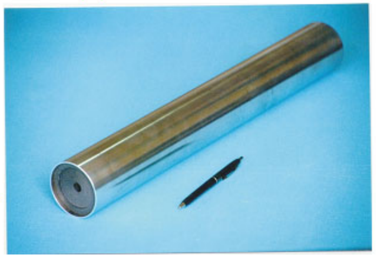
Encapsulation of graphite cylinders (segments) with a prestress of about 10 MPa into stainless steel or aluminum thin-walled pipe:



- Provides an integrity of the target core and keeps it even in the case of thermo-mechanical or radiation damages of some segments
- Prevents a direct contact of the cooling water with the heated surface of graphite
- Provides a good thermal contact between graphite and metal pipe

Prototype of the baffle collimator (2002):

∅58 mm graphite cylinders are encapsulated into 1.5 mm thick *aluminum pipe* ⇨



Neutrino Superbeam: Target Alternatives

A low-Z target is preferred for a Neutrino Superbeam. High-Z alternatives include:

- **Free mercury jet target.**
- **Rotating band target, if toroidal capture system.**
- **Fluidized pebble-bed target.**

Neutrino Superbeam: R&D

- **GEANT simulation of solenoidal capture option.**
- **Hardware development of a 50-Hz toroidal horn for a high-radiation environment.**
- **Continued irradiation studies of candidate target materials.**
- **Technical evaluation of scheme for weekly replacement of carbon target. (A positive evaluation could lead to a hardware R&D program.)**
- **Technical evaluation of the rotating band scheme.**
- **Technical evaluation of the fluidized pebble-bed scheme.**