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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ISS Plenary Meeting, KEK

Jan 24, 2006

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

(Presented by M. Zisman)

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.

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

  $\Rightarrow$ 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.**

  $\Rightarrow$ **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.**

  $\Rightarrow$ **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,** $\approx$ **0.2 cm**^{2} **for Superbeam.**

$\Rightarrow$ **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 $10^{22}/\text{cm}^2$.

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

$\Rightarrow$ Mitigate by frequent target changes, moving target, liquid target, ...

Remember the Beam Dump

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

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

Short distance from target to dump at a Neutrino Factory,
$\Rightarrow$ Beam still tightly focused at the dump,
$\Rightarrow$ 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.
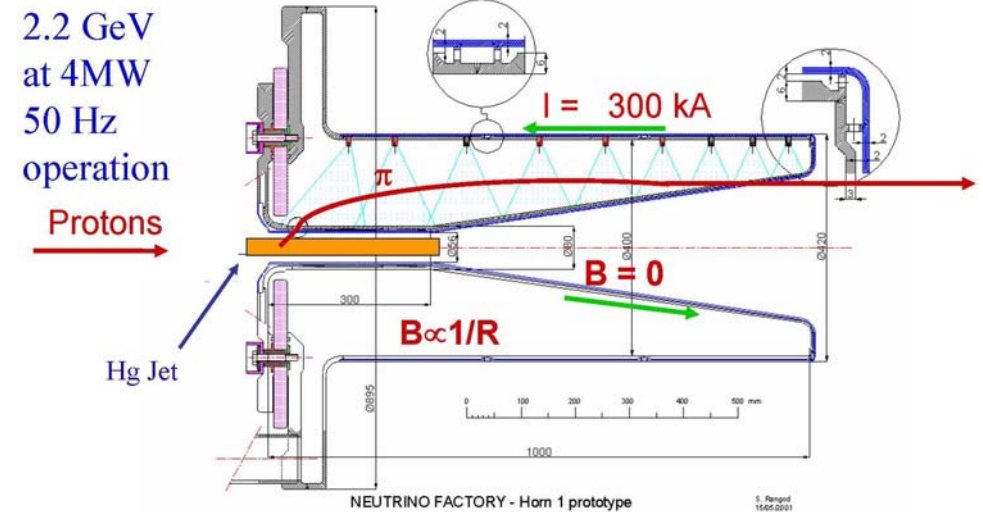
Target and Capture Topologies: Toroidal Horn

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

- Collects only one sign, $\Rightarrow$ Long data runs, but nonmagnetic detector (Superbeam).

- Inner conductor of toroid very close to proton beam.
  - $\Rightarrow$ Limited life due to radiation damage at 4 MW.
  - $\Rightarrow$ Beam, and beam dump, along magnetic axis.
  - $\Rightarrow$ More compatible with Superbeam than with Neutrino Factory.

Carbon composite target with He gas cooling (BNL study):
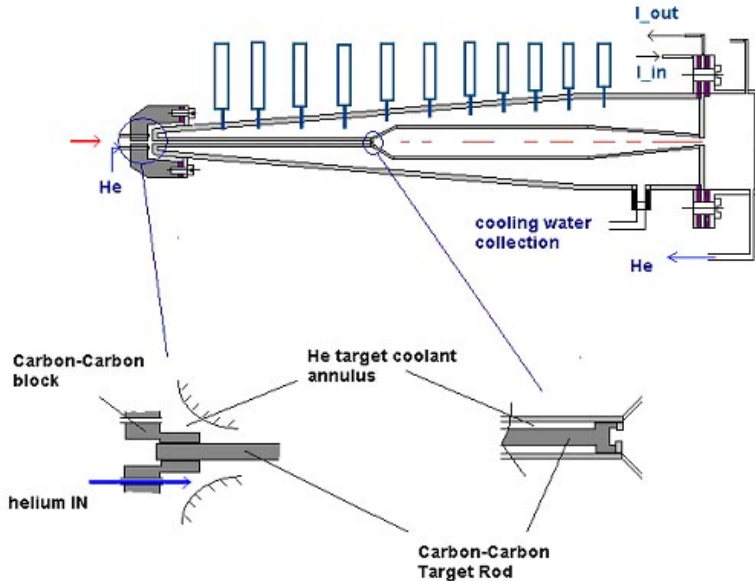
Mercury jet target (CERN SPL study):

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, $\Rightarrow$ Shorter data runs (with magnetic detector).**

- **Solenoid coils can be some distance from proton beam.**

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

$\Rightarrow$ **Proton beam readily tilted with respect to magnetic axis.**

$\Rightarrow$ **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):
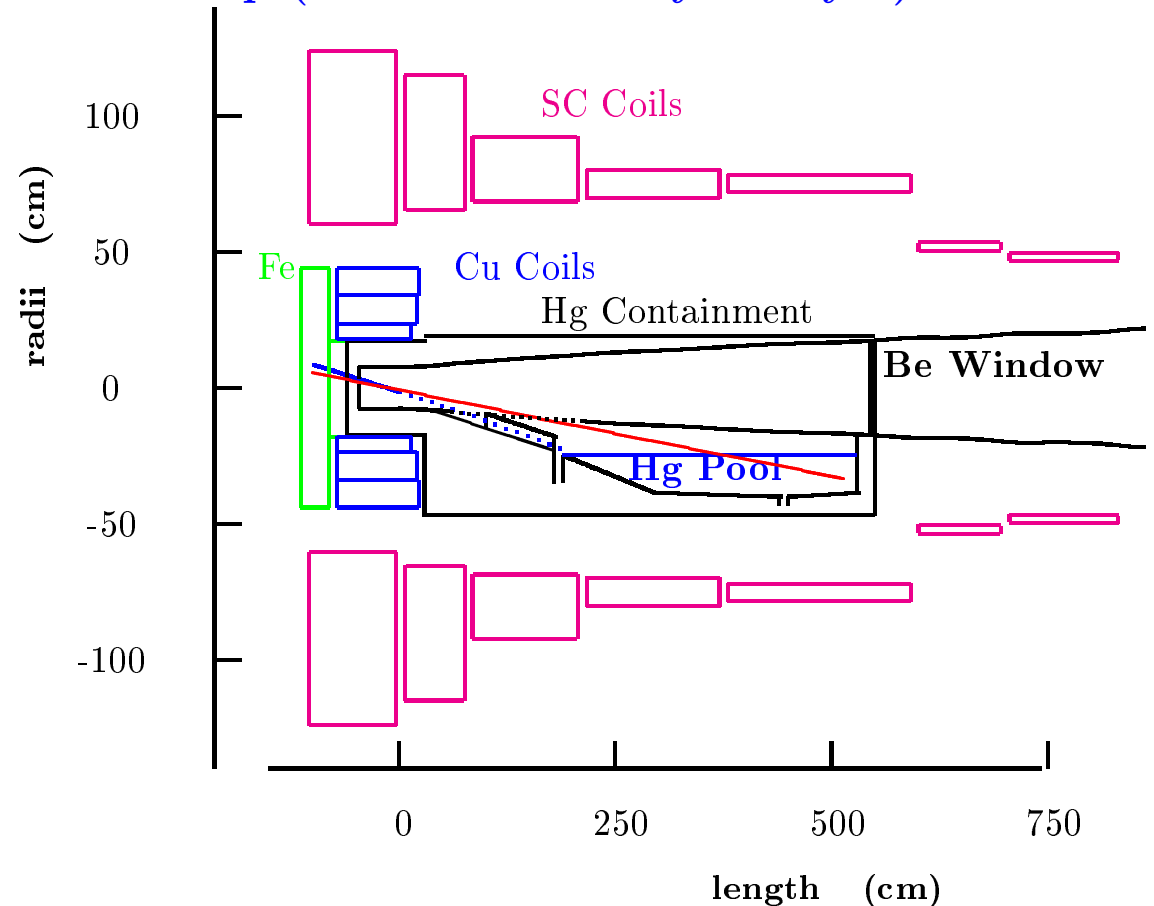
Solenoid Capture System for a Superbeam

- **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.**

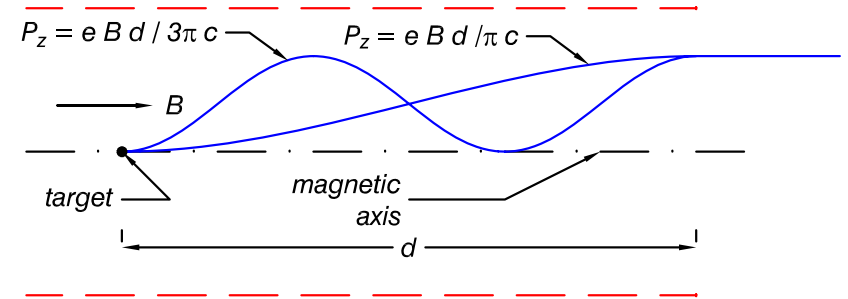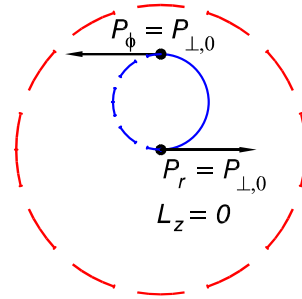$\Rightarrow$ **Point-to-parallel focusing for**

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

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

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

(KTM, physics/0312022)

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

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

(Marciano, hep-ph/0108181)

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)

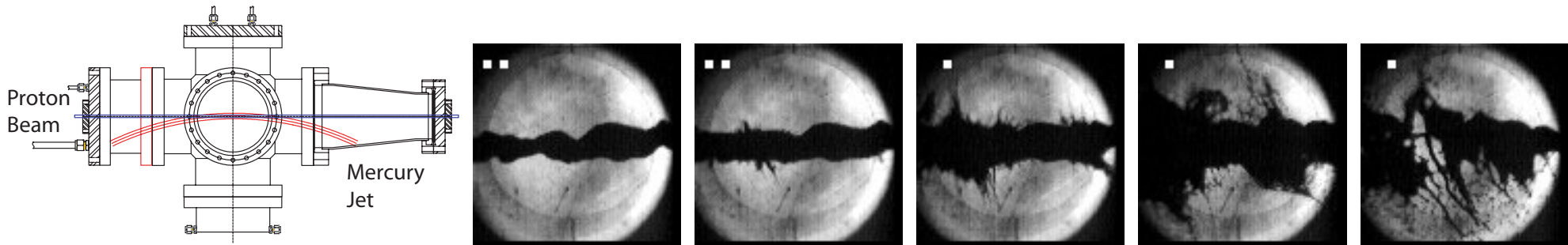Liquid target/dump using mercury, or a Pb-Bi alloy.

≈ 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): $\quad v_{\text{dispersal}} = \dfrac{\Delta r}{\Delta t} = \dfrac{r\alpha\Delta T}{r/v_{\text{sound}}} = \dfrac{\alpha U}{C}v_{\text{sound}} \approx$ **12.5 m/s** for $U \approx$ **25 J/g**.

Data: $v_{\text{dispersal}} \approx$ **10 m/s** for $U \approx$ **25 J/g**.
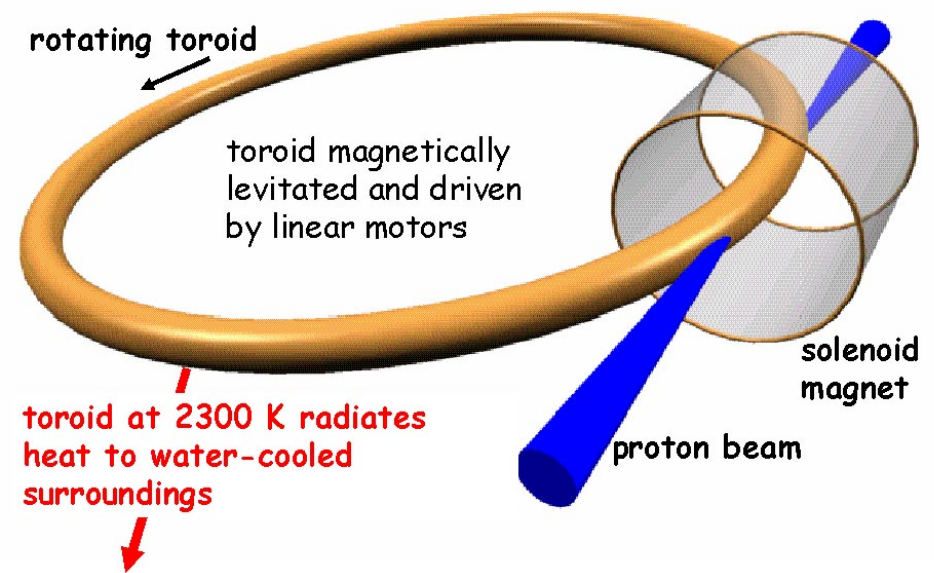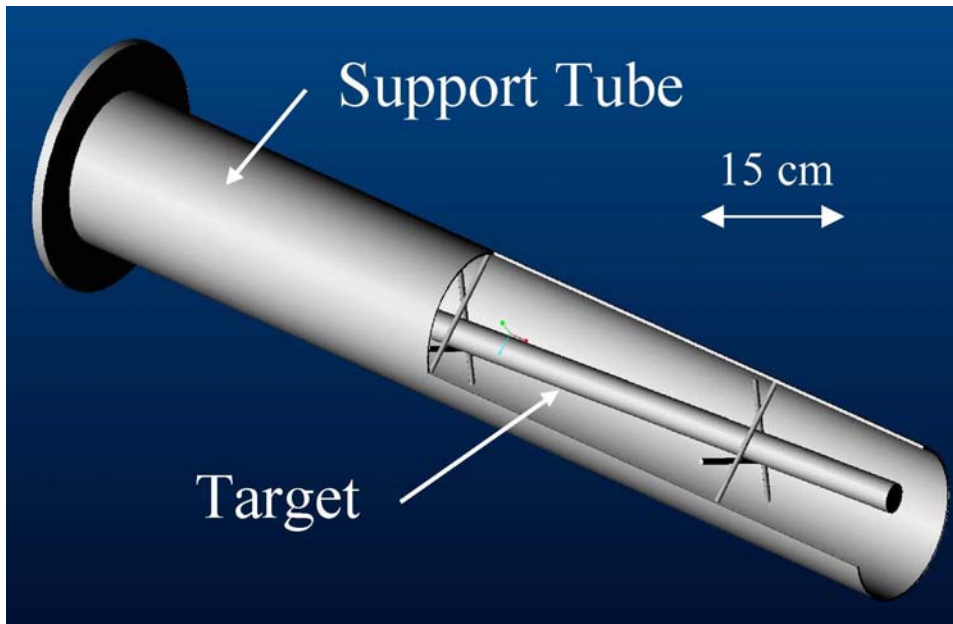
Thermal Issues for Solid Targets (Superbeams), I

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_{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

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

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

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

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

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

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

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

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

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).
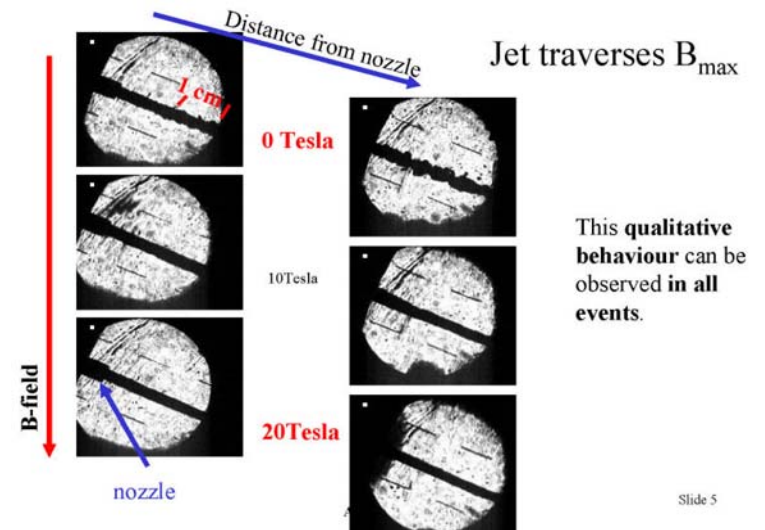
DRAFT Recommendations

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/
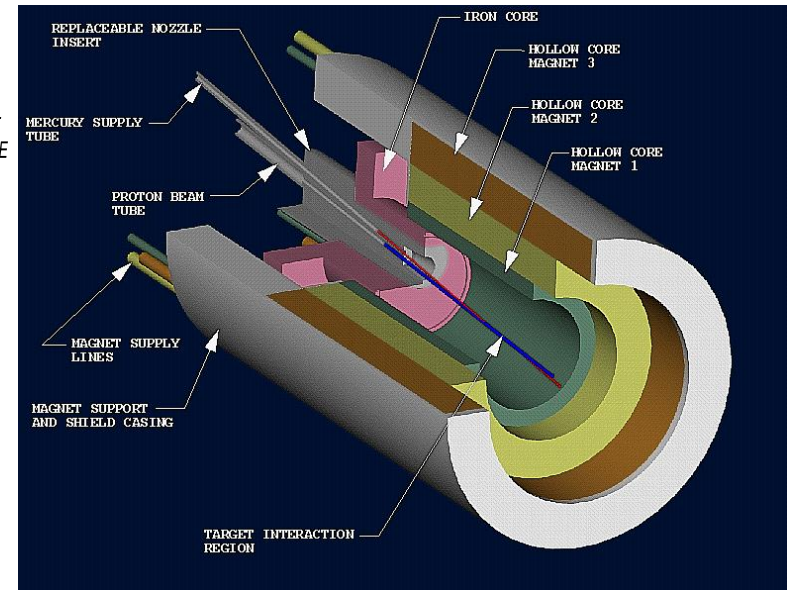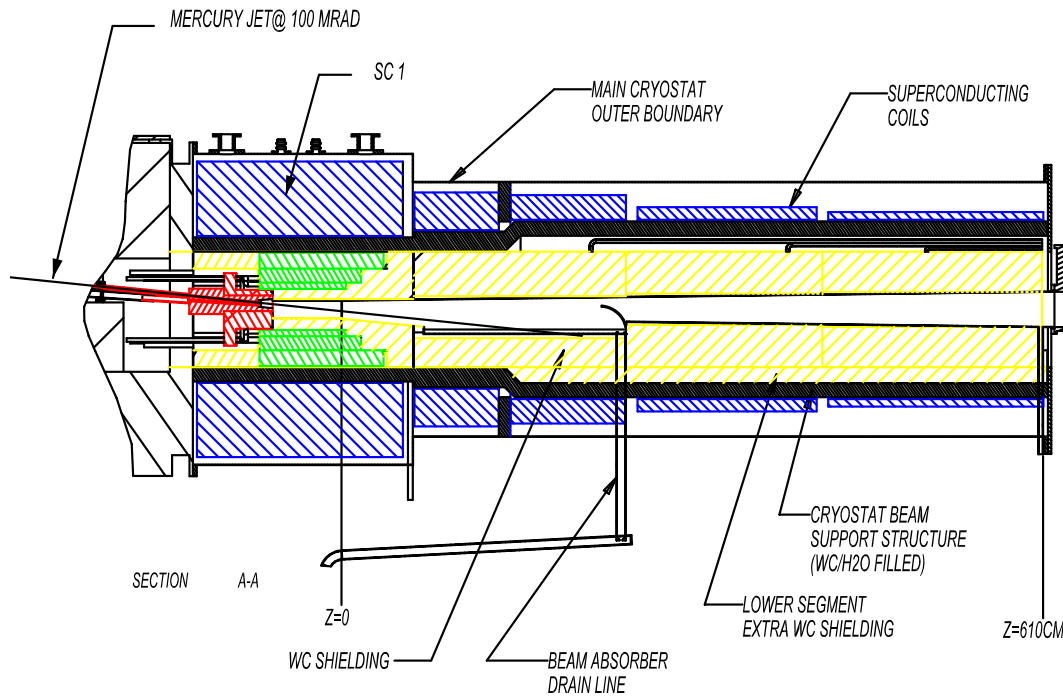
- **Solenoidal capture magnet ($\approx$ 20 T) with adiabatic transition to solenoidal decay channel ($\approx$ 1 T).**

- **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 a water Čerenkov.

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.