

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  $\pi^\pm \rightarrow \mu^\pm \nu_\mu (\bar{\nu}_\mu)$ . (Pions from  $pA \rightarrow \pi^\pm X$ .)
    - Factory neutrinos from  $\mu^\pm \rightarrow e^\pm \bar{\nu}_\mu \nu_e (\nu_\mu \bar{\nu}_e)$ . (Muons from  $\pi^\pm \rightarrow \mu^\pm \nu_\mu (\bar{\nu}_\mu)$ .)
    - $\beta$ -beam neutrinos from  ${}^6\text{He} \rightarrow {}^6\text{Li} e^- \bar{\nu}_e$ ,  ${}^{18}\text{Ne} \rightarrow {}^{18}\text{F} e^+ \nu_e$  (not discussed here).
  - **Detectors:** Cheapest large detectors are calorimeters with no magnetic field.
    - ⇒ Cheapest to study  $\nu_\mu \rightarrow \nu_e$  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.  
⇒  $0.8-2.5 \times 10^{15}$  pps;  $0.8-2.5 \times 10^{22}$  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:**  
≈  $0.1 \text{ cm}^2$  for Neutrino Factory, ≈  $0.2 \text{ cm}^2$  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  $10^{22}/\text{cm}^2$ .

⇒ 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.)

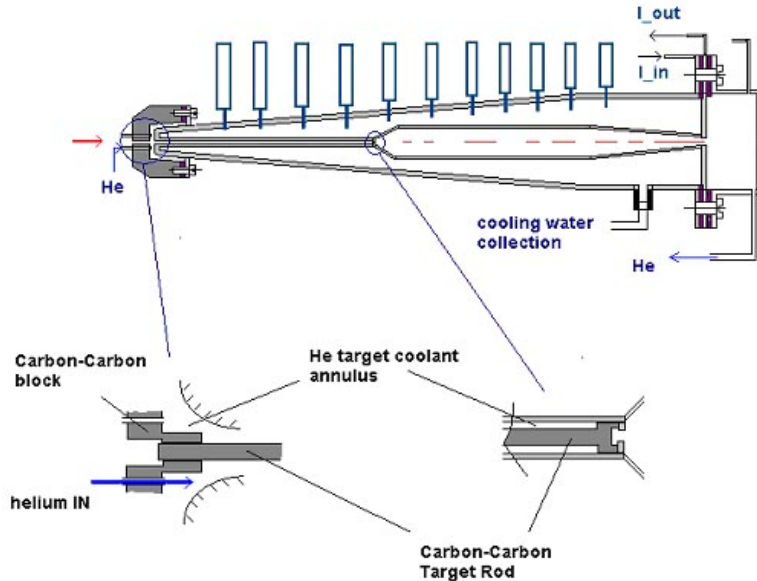
The proton beam should be tilted with respect to the axis of the capture system at a Neutrino Factory, so that the beam dump does not absorb the captured  $\pi$ 's and  $\mu$ 's.

## Target and Capture Topologies: Toroidal Horn

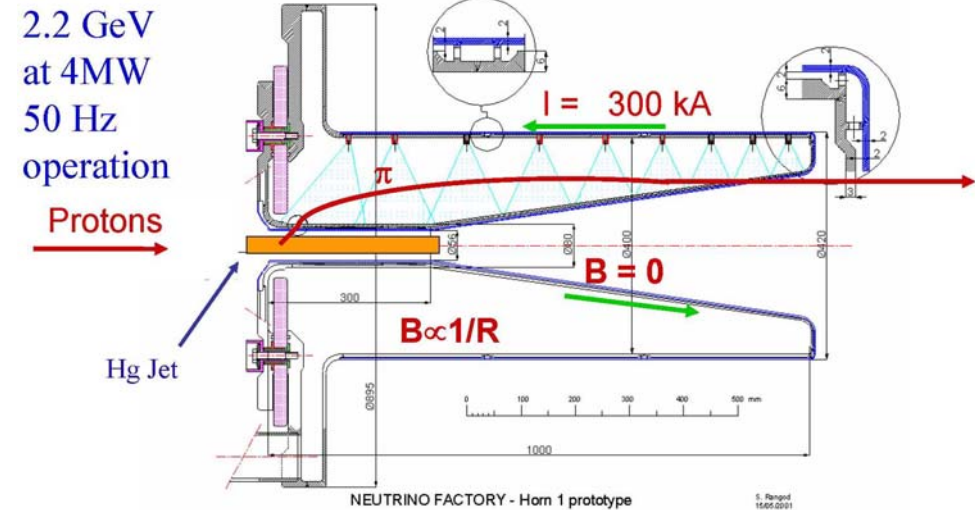
The traditional topology for efficient capture of secondary pions is a toroidal “horn” (Van der Meer, 1961).

- 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  $\pi$ 's and  $\mu$ 's,  $\Rightarrow$  Shorter data runs (with magnetic detector).
- Solenoid coils can be some distance from proton beam.

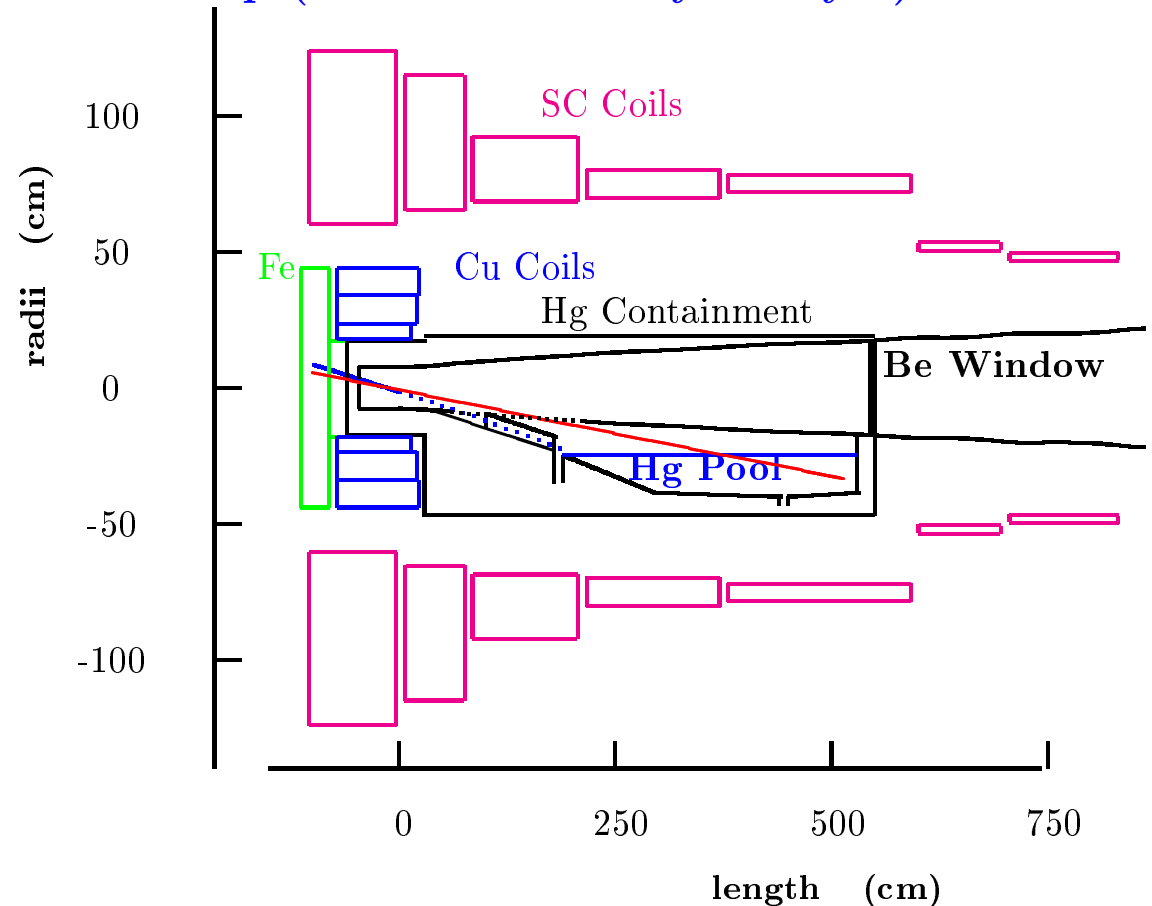
$\Rightarrow \gtrsim 4$  year life against radiation damage at 4 MW.

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

$\Rightarrow$  Beam dump out of the way of secondary  $\pi$ 's and  $\mu$ '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  $P_\phi$ ,  $\Rightarrow P_\perp = 0$  on exiting the solenoid.

$\Rightarrow$  Point-to-parallel focusing for

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

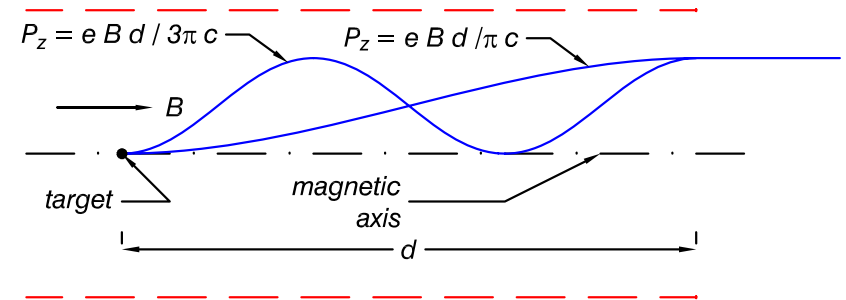
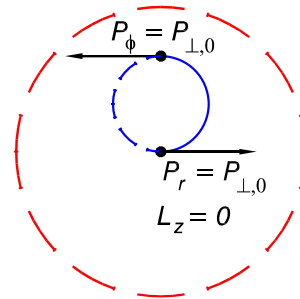
$\Rightarrow$  Narrowband (less background) neutrino beams of energies

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

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

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

(Marciano, hep-ph/0108181)



(KTM, physics/0312022)

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

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

$\Rightarrow$  Magnetized liquid argon TPC.

(astro-ph/0105442).

# Thermal Issues for Liquid Targets (Neutrino Factory)

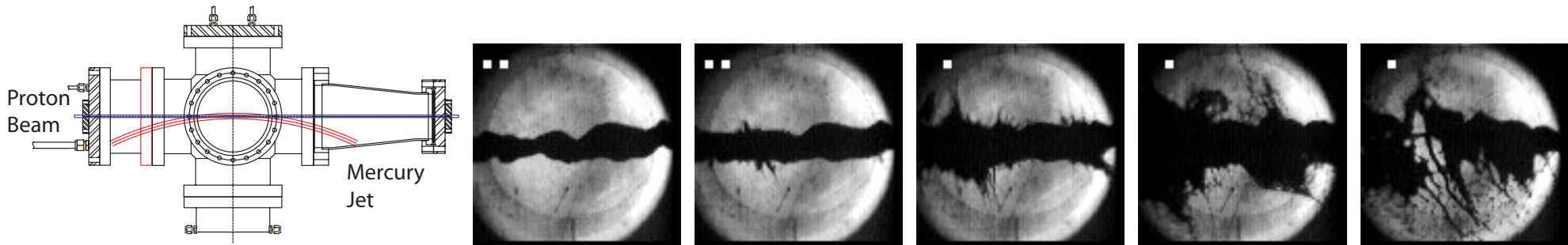
Liquid target/dump using mercury, or a Pb-Bi alloy.

$\approx 400 \text{ J/gm}$  to vaporize Hg (from room temp),

$\Rightarrow$  Need flow of  $> 10^4 \text{ g/s} \approx 1 \text{ l/s}$  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  $t = 0, 0.75, 2, 7, 18 \text{ ms}$  (BNL E-951, 2001).

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

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



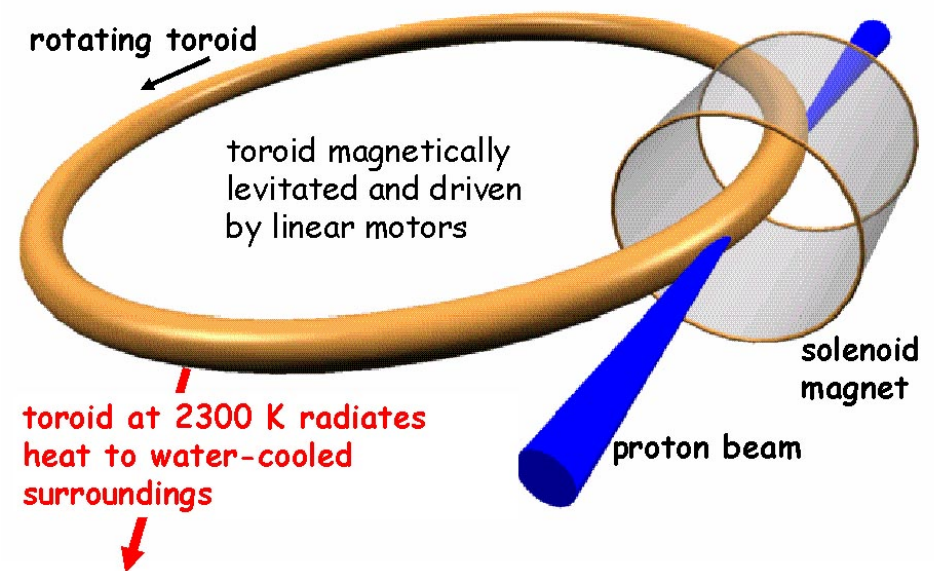
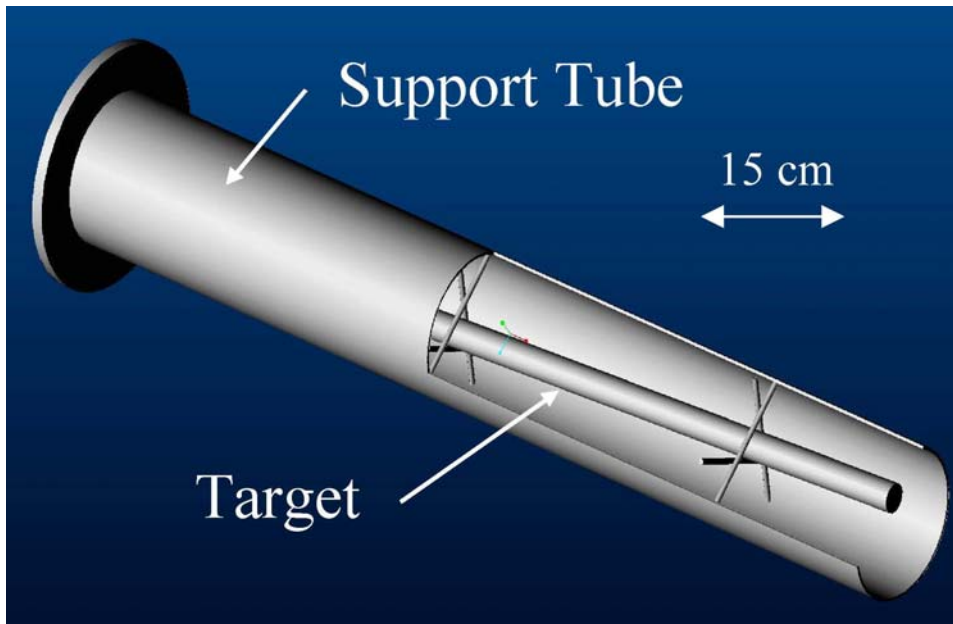
## Thermal Issues for Solid Targets (Superbeams), I

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.  $\Rightarrow$  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  $v_{\text{sound}}$ , 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  $\Delta T$  is given by

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

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

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

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

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

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

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

⇒ Best candidates for solid targets have high strength (Vasomax, Inconel, TiAl6V4) and/or low thermal expansion (Superinvar, Toyota “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<sup>2</sup>.

Ans: If we ignore “showers” in the material, we still have  $dE/dx$  ionization loss, of about 1.5 MeV/g/cm<sup>2</sup>.

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

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

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 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

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

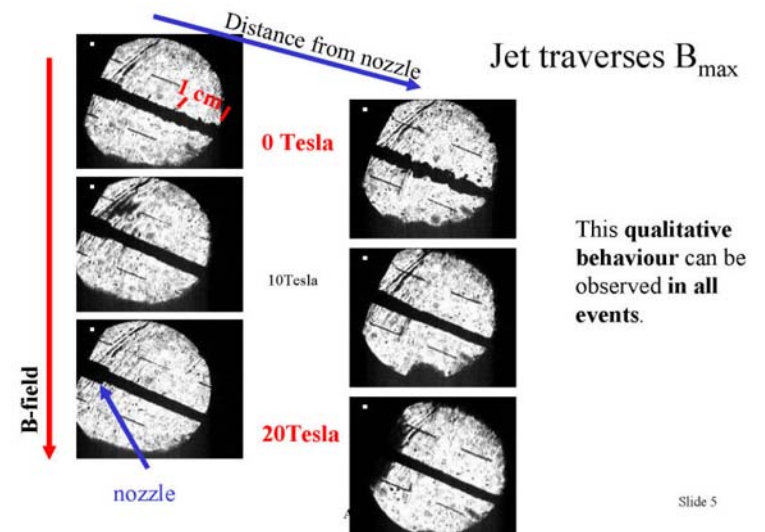
50-Hz rep rate requires  $v = 20$  m/s for new target each pulse, so no problem for baseline design with  $r = 0.5$  cm. The associated eddy-current heating is negligible.

[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).



Slide 5



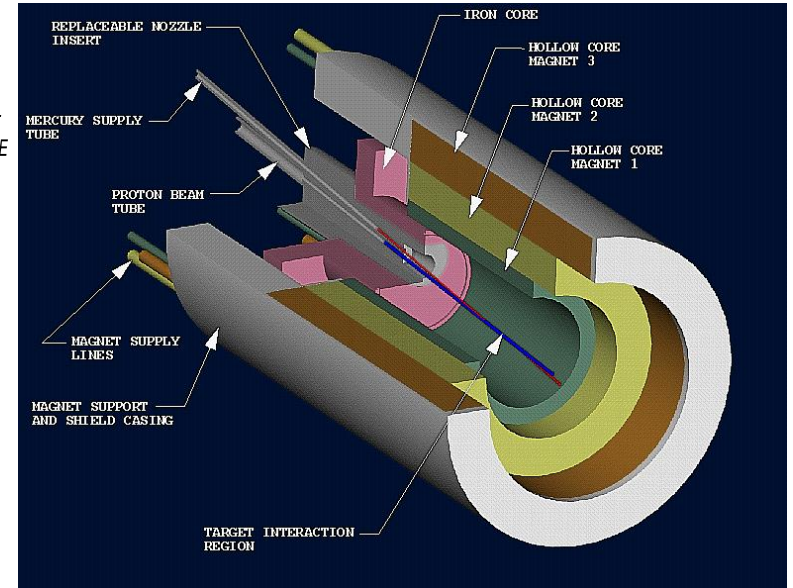
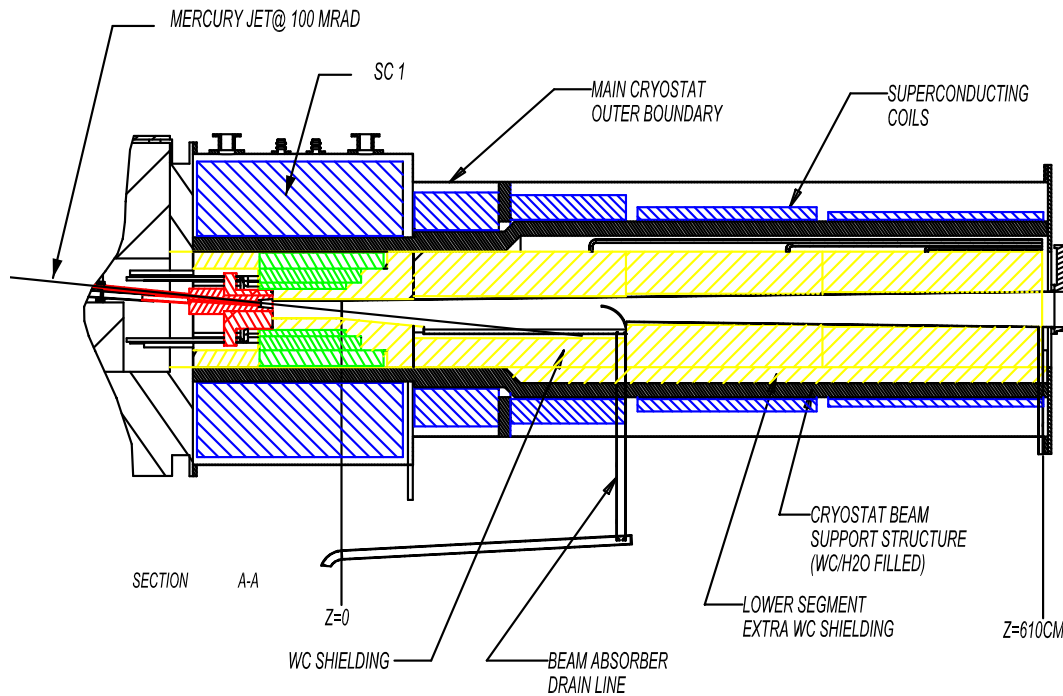
## DRAFT Recommendations

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 ( $\approx 20 \text{ T}$ ) with adiabatic transition to solenoidal decay channel ( $\approx 1 \text{ T}$ ).
- Continuous, free mercury jet target ( $r = 0.5 \text{ cm}$ ,  $v = 20 \text{ m/s}$ ) 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 base-line 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 ( $\nu_\mu$  and  $\bar{\nu}_\mu$  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).

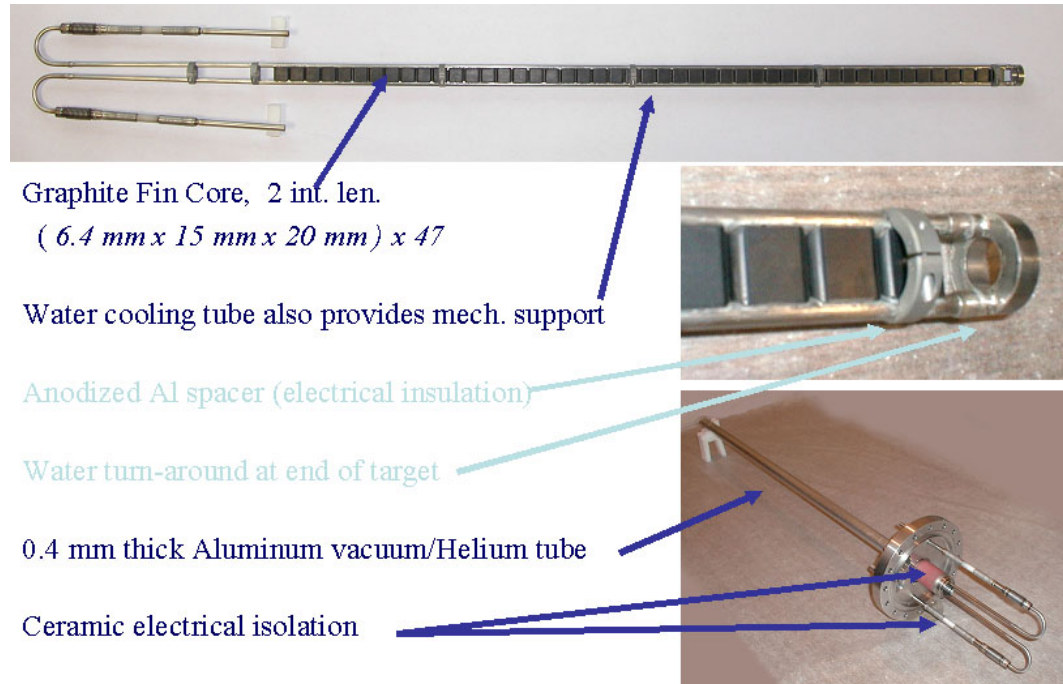
Target repaired during 1-month downtime.

Target has now operated up to ~ 300 kW.

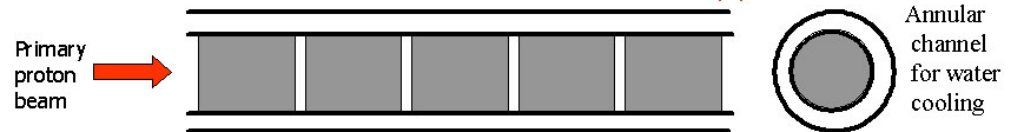
R&D in progress towards a 2-MW target.

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

Mitigated slightly by the 10- $\mu$ s pulse length of the NuMI proton beam.



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):

Ø58 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.