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

K.T. McDonald
Princeton U.
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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 $\mu^\pm \rightarrow e^\pm \nu_\mu \nu_e (\nu_\mu \bar{\nu}_e)$. (Muons from $\pi^\pm \rightarrow \mu^\pm \nu_\mu (\bar{\nu}_\mu)$.)
  - $\beta$-beam neutrinos from $^6\text{He} \rightarrow ^6\text{Li} e^- \bar{\nu}_e, ^{18}\text{Ne} \rightarrow ^{18}\text{Fe}^+ \nu_e$ (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.
  \[ 0.8-2.5 \times 10^{15} \text{pps; } 0.8-2.5 \times 10^{22} \text{ protons per year of } 10^7 \text{ s.} \]

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

- Small beam size preferred:
  \[ \approx 0.1 \text{ cm}^2 \text{ for Neutrino Factory, } \approx 0.2 \text{ cm}^2 \text{ for Superbeam.} \]

\[ \Rightarrow \text{Severe materials issues for target AND beam dump.} \]

- 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 \(10^{22}/\text{cm}^2\).

\[ \Rightarrow \text{Target lifetime of about 5-14 days at a Neutrino Factory (and 9-28 days at a Superbeam).} \]

\[ \Rightarrow \text{Mitigate by frequent target changes, moving target, liquid target, ...} \]

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,
\[ \Rightarrow \text{Beam is much less focused at the dump than at the target}, \]
\[ \Rightarrow \text{Radiation damage to the dump not a critical issue (Superbeam).} \]

Short distance from target to dump at a Neutrino Factory,
\[ \Rightarrow \text{Beam still tightly focused at the dump}, \]
\[ \Rightarrow \text{Frequent changes of the beam dump, or a moving dump, or a liquid dump.} \]

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, ⇒ 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.
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.
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,

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

(Marciano, hep-ph/0108181)

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

\( \Rightarrow \) Detector must identify sign of \( \mu \) and \( e \).

\( \Rightarrow \) Magnetized liquid argon TPC.

Thermal Issues for Liquid Targets (Neutrino Factory)

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

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

\[ \Rightarrow \text{Need flow of } > 10^4 \text{ g/s } \approx 1 \text{ l/s in target/dump to avoid boiling in a 4-MW beam.} \]

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: \( v_{\text{dispersal}} \approx 10 \text{ m/s for } U \approx 25 \text{ J/g.} \)
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 $v_{\text{sound}}$, 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 $\frac{\Delta r}{r}$ 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 $P (= \text{force/area})$ 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 $C \approx 0.3$ J/g/K, in which case

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

$\Rightarrow$ 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$^2$.

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 = $2.46 \times 10^{-13} \text{ J}$, 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,
⇒ 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, ⇒ Forces on entering or leaving a solenoid (but not at its center).

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

$$v > \frac{3\pi \sigma r^2 B_0^2}{32 \rho D} \approx 6 \left( \frac{r}{1 \text{ cm}} \right)^2 \text{ m/s,}$$

for Hg or Pb-Bi jet, $D = 20 \text{ cm}, B_0 = 20 \text{ T}$.

50-Hz rep rate requires $v = 20 \text{ m/s}$ for new target each pulse, so no problem for baseline design with $r = 0.5 \text{ cm}$. 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.
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 ($\nu_{\mu}$ 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 $\sim 300$ 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.

Prototype of the baffle collimator (2002):
$\odot 58$ 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.