Carbon and Mercury Targets for Neutrino Beams and a Muon Collider Source

(BNL E951)

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

- Maximal production of soft pions → muons in a megawatt proton beam.
- Capture pions in a 20-T solenoid, followed by a 1.25-T decay channel.
- A carbon target is feasible for 1.5-MW proton beam power.
- For $E_p \gtrsim 16$ GeV, factor of 2 advantage with high-Z target.
- Static high-Z target would melt, ⇒ Moving target.
- A free mercury jet target is feasible for beam power of 4 MW (and more).
The Neutrino Horn Issue

• A precursor to a Neutrino Factory is a Neutrino Superbeam based on decay of pions from a multimegawatt proton target station.

• 4 MW proton beams are achieved in both the BNL and FNAL (and CERN) scenarios via high rep rates: $\approx 10^6$/day.

• Classic neutrino horns based on high currents in conductors that intercept much of the secondary pions will have lifetimes of only a few days in this environment.

• Consider instead a solenoid horn with conductors at larger radii than the pions of interest – similar to the Neutrino Factory capture solenoid.

• Adiabatic reduction of the solenoid field along the axis, $\Rightarrow$ Adiabatic reduction of pion transverse momentum, $\Rightarrow$ Focusing.

A carbon-carbon composite with near-zero thermal expansion is largely immune to beam-induced pressure waves.

Sublimation of carbon is negligible in a helium atmosphere.

Radiation damage is limiting factor: \( \approx 12 \) weeks at 1 MW.

A rotating band target is another option:
Pion/Muon Yield

For $E_p \gtrsim 10$ GeV, more yield with high-$Z$ target.

Mercury target radius should be $\approx 5$ mm, with target axis tilted by $\approx 100$ mrad to the magnetic axis.

Can capture $\approx 0.3$ pion per proton with $50 < P_{\pi} < 400$ MeV/c.
Target System Layout

Mercury jet target inside a magnetic bottle: 20-T around target, dropping to 1.25 T in the pion decay channel.

Mercury jet tilted by 100 mrad, proton beam by 67 mrad.
Lifetime of Components in the High Radiation Environment

<table>
<thead>
<tr>
<th>Component</th>
<th>Radius (cm)</th>
<th>Dose/yr (Grays/2 × 10⁷ s)</th>
<th>Max allowed Dose (Grays)</th>
<th>1 MW Life (years)</th>
<th>4 MW life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner shielding</td>
<td>7.5</td>
<td>5 × 10¹⁰</td>
<td>10¹²</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Hg containment</td>
<td>18</td>
<td>10⁹</td>
<td>10¹¹</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Hollow conductor</td>
<td>18</td>
<td>10⁹</td>
<td>10¹¹</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superconducting</td>
<td>65</td>
<td>5 × 10⁶</td>
<td>10⁸</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>coil</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Some components must be replaceable.

Kirk T. McDonald  May 9, 2002
Viability of Targetry and Capture For a Single Pulse

- Beam energy deposition may disperse the jet.

- Eddy currents may distort the jet as it traverses the magnet.
**Overall Goal:** Test key components of the front-end of a neutrino factory in realistic single-pulse beam conditions.

**Near Term** (1-2 years): Explore viability of a liquid metal jet target in intense, short proton pulses and (separately) in strong magnetic fields.

**Mid Term** (3-4 years): Add 20-T magnet to beam tests; Test 70-MHz rf cavity (+ 1.25-T magnet) 3 m from target; Characterize pion yield.
The Neutrino Factory and Muon Collider Collaboration

The E951 Collaboration


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Solid Target Tests (5e12 ppp, 24 GeV, 100 ns)

Carbon, aluminum, Ti90Al6V4, Inconel 708, Havar, instrumented with fiberoptic strain sensors.

Incoming optical fiber
Gauge length
Fabry-Perot cavity length

Measured Strain (500 KHz) in the 10-mil Aluminum Window
Beam Intensity = 2.5 TP

Predicted Strain in the 10-mil Aluminum Window
Beam Intensity = 2.5 TP with 1mm RMS sigma
Passive Mercury Target Tests

Exposures of 25 µs at
\( t = 0, 0.5, 1.6, 3.4 \) msec,
\( \Rightarrow v_{\text{splash}} \approx 20 - 40 \) m/s:

Two pulses of \( \approx 250 \) ns give larger dispersal velocity only if separated by less than 3 µs.
Studies of Proton Beam + Mercury Jet

1-cm-diameter Hg jet in 2e12 protons at $t = 0, 0.75, 2, 7, 18$ ms.

Model: $v_{\text{dispersal}} = \frac{\Delta r}{\Delta t} = \frac{r \alpha \Delta T}{r/v_{\text{sound}}} = \frac{\alpha U}{C} v_{\text{sound}} \approx 50 \text{ m/s}$

for $U \approx 100$ J/g.

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

$v_{\text{dispersal}}$ appears to scale with proton intensity.

The dispersal is not destructive.
Eddy currents may distort the jet as it traverses the magnet.

Analytic model suggests little effect if jet nozzle inside field.

4 mm diam. jet, $v = 4.6 \text{ m/s}$, $B = 0 \text{ T}$; $v = 4.0 \text{ m/s}$, $B = 13 \text{ T}$:

$\Rightarrow$ Damping of surface tension waves (Rayleigh instability).
20-T Capture Magnet System

Inner, hollow-conductor copper coils generate 6 T @ 12 MW:

Bitter-coil option less costly, but marginally feasible.

Outer, superconducting coils generate 14 T @ 600 MJ:

Cable-in-conduit construction similar to ITER central solenoid.

Both coils shielded by tungsten-carbide/water.
Extensive shielding; remote handling capability.
Summary of Targetry Activities Through FY01

- Liquid metal targets in vessels show beam-induced cavitation damage to entrance window (ISOLDE, 1995, LANL, 2001).

- Beam tests of large passive mercury target for SNS (BNL 1998, LANL 2000) suggest velocity of sound may be reduced temporarily by beam-induced microcavitation).

- MARS simulations of beam-target interactions ⇒ advantage of high-Z target, of high-field capture solenoid, of tilted beam and target, and disadvantages of high radiation dose (Mokhov).

- Analytic simulations of beam-induced pressure waves in target (Sievers), and of MHD effects of mercury jet entering magnet (KTM, Palmer, Weggel) indicate “feasibility”, but need for R&D.

- Numerical simulations (Hassanein, Samulyak) tend to confirm these analytic estimates.
• Beam tests of high-strength solid targets show good agreement between strain-sensor data and ANSYS simulation, and suggest that they can survive single-pulse stresses up to Study-2 design intensity, $= 16 \, \text{TP} / 8 \, \text{mm}^2$ (BNL, March ’01).

• Calculation and experiment indicate that a carbon target could survive against sublimation in a He atmosphere in a 4 MW beam (Thieberger, ORNL).

• Beam tests of active and passive mercury targets indicate dispersal velocities of manageable size, proportional to proton pulse energy (BNL, April ’01; ISOLDE, Aug. ’01).

• Tests of mercury jets entering a high-field solenoid not yet definitive (CERN, Grenoble, 2001).
Issues for Further Targetry R&D

• Continue numerical simulations of MHD + beam-induced effects [Samulyak].

• Continue tests of mercury jet entering magnet [CERN, Grenoble].

• For solid targets, study radiation damage – and issues of heat removal from solid metal targets (bands, chains, etc.).

• Confirm manageable mercury-jet dispersal in beams up to full Study-2 intensity – for which single-pulse vaporization may also occur. Test Pb-Bi alloy jet.

• Study issues when combine intense proton beam with mercury jet inside a high-field magnet.
  1. MHD effects in prototype target configuration.
  3. Beam-induced damage to jet nozzle – in the magnetic field.
Further Beam Studies without High-Field Magnet

- Studies of production of mercury jets up to 20 m/s. Jet quality is the issue.
- Construction of new liquid metal jet targets with continuous flow: mercury and Wood’s metal.
- Upgrade AGS to 8/16 TP single pulses [Roser].
  1. Improve control of fast extraction with bipolar power supply for a key vertical sextupole.
  2. Improve control of chromaticity of bunches during transition with heftier power supply for main ring horizontal sextupoles.
- Test the continuous-flow targets in beam once at least 8 TP per pulse are available.
- [Radiation damage studies of solid targets at BNL booster.]
Further Beam Studies with a High-Field Magnet

• Study jet dispersal, and possible damage to nozzle, as a function of beam intensity, magnetic field strength, and nozzle position.

• Online diagnostics will primarily be optical (+ possible use of fiberoptic strain sensors).

CERN/Grenoble optical system that fits in 20-cm magnet bore:

• To be affordable, construct a 15-T pulsed solenoid magnet.
What Magnetic Field Strength is Appropriate?

- Our muon collider and neutrino factory designs have long called for a 20-T capture solenoid.

A 20-T magnet must be a hybrid: 6-T copper “insert” + 14-T superconducting “outsert”.

The small gain in performance from 14 to 20 T may not warrant the cost and complexity of the hybrid magnet.

A capture solenoid for a superbeam needs a larger bore to trap higher $P_\perp$ pions, for which 14 T is then sufficient.

⇒ Our physics goals are well satisfied by a 14-T capture solenoid.
Should the Pulsed R&D Magnet have Lower Field?

- Most magnetic-field effects on the mercury jet scale as the magnetic pressure $B^2/8\pi$ (for a fixed geometry).
- Thus, a study using a 5-T magnet would require a factor of 8 extrapolation to the desired performance at 14 T.
- Present cost estimates indicate that we can build a 14-T pulsed magnet for about twice the cost of a 5-T pulsed magnet.
- $\Rightarrow$ We propose to construct a 14.5-T pulsed magnet, that can be staged as a 5-T and 10-T magnet.
A 14.5-T Pulsed Magnet with 5- and 10-T Phased Options

14.5-T Pulsed Magnet (using all 3 coils)
5- or 10-T magnet using inner 2 coils

<table>
<thead>
<tr>
<th>Phase</th>
<th>No. of PS</th>
<th>Coolant</th>
<th>Temp.</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>N$_2$</td>
<td>84 K</td>
<td>5 T</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>N$_2$</td>
<td>74 K</td>
<td>10 T</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>H$_2$</td>
<td>30 K</td>
<td>14.5 T</td>
</tr>
</tbody>
</table>
Keeping Costs Low

- Simple solenoid geometry with rectangular coil cross section and smooth bore (of 20 cm diameter) [Weggel, Titus].
- Power supply built out of 4 existing 540 kVA supplies that can be fed by a single, existing substation [Marneris].
- Cryogenic system reduces coil resistance to give high field at relatively low current [Iarocci].
  - Circulating coolant is gaseous He to minimize activation, and to avoid need to purge coolant before pulsing magnet.
  - Heat exchanger recycled from the SSC.
  - Phase 1 & 2 cooling via N$_2$ boiloff; Phase 3 via H$_2$. 
• Locate the 4 x 540 kVA power supplies on the east side of the A3 cave, feed power in via the trench.

• If satisfactory to Safety Committee, locate the heat exchanger and LH$_2$ dewar in a concrete enclosure that extends the present A3 beam stop.
Other Works in Progress

- AGS sextupole power supply upgrades (Brown, Sandberg).
- $2 \rightarrow 1$ AGS bunch merging via rf manipulation (Brown, Brennan).
- 2nd round of liquid metal jets: $2.5 \rightarrow 20$ m/s; Hg and Pb/Bi alloy (Kirk, McDonald).
- Radiation damage studies of Invar at BLIP (Thieberger, Weggel).
- Graphite sublimation in a He atmosphere (Haines, Spampinato).
- FEA simulations (Samulyak).