The E-951 15-T Pulsed Solenoid Magnet R&D Facility for a Neutrino Factory / Muon Collider Source

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C-AD Safety Review

BNL, Sept. 6, 2002

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: ≈ 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, ⇒ Adiabatic reduction of pion transverse momentum, ⇒ Focusing.

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.
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 × 10^7 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 × 10^{10}</td>
<td>10^{12}</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Hg containment</td>
<td>18</td>
<td>10^9</td>
<td>10^{11}</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Hollow conductor</td>
<td>18</td>
<td>10^9</td>
<td>10^{11}</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 coil</td>
<td>65</td>
<td>5 × 10^6</td>
<td>10^8</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

Some components must be replaceable.

Kirk T. McDonald  Sept. 6, 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.

We are now beginning the “Mid Term” phase, but with a more affordable 15-T magnet.
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 $\mu$s 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 $\mu$s.
Studies of Proton Beam + Mercury Jet

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

Model: $v_{\text{dispersal}} = \frac{\Delta r}{\Delta t} = \frac{r \alpha \Delta T}{r/v_{\text{sound}}} = \frac{\alpha U}{C} v_{\text{sound}} \approx 50$ 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.
Tests of a Mercury Jet in a 20-T Magnetic Field (CERN/Grenoble High Magnetic Field Laboratory)

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, \( v \approx 12 \text{ m/s} \), \( B = 0, 10, 20 \text{ T} \).

⇒ Damping of surface tension waves (Rayleigh instability).

Will the beam-induced dispersal be damped also?
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.
Target System Support Facility

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 suggest little problem if nozzle within field (CERN, Grenoble, 2002).

• Superinvar samples irradiated in BLIP facility to study effect of radiation damage on the very low thermal expansion coef.
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.]
What Magnetic Field Strength is Appropriate?

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

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{magnet_performance.png}
\caption{Meson yield (0.05<p<0.8 GeV/c) per proton}
\end{figure}

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 15-T pulsed magnet for about twice the cost of a 5-T pulsed magnet.

• ⇒ We propose to construct a 15-T pulsed magnet, that can be staged as a 5-T and 10-T magnet.
### A 15-T Pulsed Magnet with 5- and 10-T Phased Options

#### Phase  No. of PS  Coolant  Temp.  Field

<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>N₂</td>
<td>84 K</td>
<td>5 T</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>N₂</td>
<td>74 K</td>
<td>10 T</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>H₂</td>
<td>30 K</td>
<td>15 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, Mulholland].
  - 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 LH₂ dewar in a concrete enclosure that extends the present A3 beam stop.
Presentations

• P. Titus (MIT): Pulsed Solenoid Magnet Engineering.
• G. Mulholland (ACT): Cryogenic Systems.
• I. Marneris (BNL): Electrical Systems.
• J. Scaduto (BNL): ODH Considerations.