Target and Absorbers for a Muon Collider/Neutrino Factory

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Muon Accelerator Program Advisory Committee Review
Fermilab (July 11-13, 2012)
Mission

Target:
• Maximum production of $\mu^\pm$ of energies $\sim$ 100-400 MeV from a 4-MW proton beam (E $\sim$ 8 GeV).
• Both signs needed simultaneously at a Muon Collider.

Absorbers:
• Absorb the 4-MW beam power inside the target system.
• Absorb muon energy as a step in the process of ionization cooling.

Overview

Target:
• Free liquid-metal-jet target inside a high-field superconducting solenoid magnet
• Backup (not actively considered): solid target in toroidal horn; 2 needed for Muon Collider.

Absorbers:
• Absorb primary proton beam in liquid-metal pool.
• Absorb secondary particles in He-gas-cooled tungsten beads - inside solenoid magnets.
• Low-Z solid/liquid muon absorbers under study in MICE (D. Kaplan)
• High-pressure H$_2$-gas absorbers under study by Muons Inc (H. Kirk, K. Yonehara poster).
The Target System of a Muon-Collider or Neutrino Factory

In the IDS-NF costing scenario, the Target System includes the production target and the magnetized pion-decay channel. This system is about 50 m long. A very preliminary cost estimate now exists (slide 5).
R.B. Palmer (BNL, 1994) proposed a 20-T solenoidal capture system.

Low-energy π's collected from side of long, thin cylindrical target.

Solenoid coils can be some distance from proton beam.

⇒ ≥ 10-year life against radiation damage at 4 MW.

Liquid mercury jet target replaced every pulse.

Proton beam readily tilted with respect to magnetic axis.

⇒ Beam dump (mercury pool) out of the way of secondary π's and μ's.

5-T copper magnet insert; 10-T Nb₃Sn coil + 5-T NbTi outsert.

Desirable to eliminate the copper magnet (or replace by a 20-T HTS insert).

Shielding of the superconducting magnets from radiation is a major issue. Magnet stored energy ~ 3 GJ!
From A. Kurup’s IDS-NF Costing Talk

Target System Cost Breakdown

- Target Module (= Mercury Module): 39%
- Magnets: 25%
- Magnet Shielding: 11%
- Remote Handling and Hot Cells: 11%
- Buildings, tunnels and Infrastructure: 11%
- Other: 3%

[See Backup Slides for supporting details.]

Neutrino Factory Cost Breakdown

- Proton Driver: 26%
- Target, Capture and Decay: 7%
- Muon Front-End: 11%
- Muon Acceleration: 22%
- Decay Ring: 33%

[See Backup Slides for supporting details.]
Targetry Activities

2. Simulation of turbulent flow inside, and out of, the nozzle (F. Ladiende, Y. Zhan).
3. Simulation of particle production vs. beam & target parameters (X. Ding).
4. Simulation of the effect of the magnetic configuration on particle production (H. Sayed).
5. Simulation of secondary-energy deposition in the target system (N. Souchlas).
6. Design of the magnets and shielding for the target system (R.J. Weggel).
7. Design of the mercury-handling system (V.B. Graves).
8. Coordination of the above, and interface with other MC/NF Systems (J.S. Berg, H.G. Kirk, K.T. McDonald).

The above activities are projected to continue well beyond FY15.

Past activities included a proof-of-principle demonstration of a free mercury jet in a 15-T magnetic field in an intense proton beam (CERN MERIT experiment).
The MERIT experiment established proof-of-principle of a free mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

• The magnetic field stabilizes the liquid metal jet and reduces disruption by the beam.

• The length of disruption is less than the length of the beam-target interaction, \(\Rightarrow\) Feasible to have a new target every beam pulse with a modest velocity jet.

• Velocity of droplets ejected by the beam is low enough to avoid materials damage.

• The threshold for disruption is a few \(\times 10^{12}\) protons, permitting disruption-free operation at high power if can use a high-rep-rate beam.

• Even with disruption, the target remains fully useful for secondary particle production for \(\approx 300\ \mu\text{s}\), permitting use of short bunch trains at high power.

• No apparent damage to stainless-steel wall only 1 cm from interaction region.

[See Backup Slides for additional details.]
Simulation of Beam-Jet Interaction in a Magnetic Field  
(R. Samulyak, T. Guo, SUNY Stony Brook)

FronTier simulation of high-speed-jet cavitation and breakup:

Smoothed-Particle-Hydrodynamics simulation of MERIT beam-jet interaction:

Simulation of mercury thimble experiments (2001) using the Lagrangian particle code:
Simulation of Turbulent Flow in the Nozzle  
(F. Ladiende, Y. Zhan, SUNY Stony Brook)

Issue in MERIT: Free jet took on elliptical cross section, major axis vertical.

FLUENT simulations indicate that if no perturbations inside the pipe, the flow out of the nozzle would be nearly axisymmetric.

The last weld of the titanium nozzle had an asymmetric weld bead. Simulation underway.
Simulation of Particle Production vs. Beam & Target Parameters (X. Ding)

Vary: beam energy, beam radius, beam angle, target radius, target angle, target material (MARS15 simulations)

Particle production best in only one quadrant, centered on p11 (baseline for single beam)

Previous Incident Beam at z=75 cm for optimization

Mercury

Gallium

Hg ~ 1.15 Ga

Production peaks at ~ 8 GeV

Normalized Distribution

Mesons/Protons/GeV

8 GeV, 100000 Protons in the Incident Beam

Proton Kinetic Energy, GeV

Number of Runs

Mean Production Per Incoming Proton

0

20

40

60

80

100

0

0.2

0.4

0.6

0.8

1

2

4

6

8

10

Proton Beam

Hg Jet

Solenoid Axis

θ_{\text{BEAM}}

θ_{\text{CROSS}}

z=0 \text{ cm}

z=37.5 \text{ cm}

z=75 \text{ cm}

Consider option of multiple beams converging on the target from various azimuthal directions.
The magnetic field of the target system varies from $B_i$ at the target to $B_f$ at the front end, over distance $z_{end}$.

Vary $B_i$, $B_f$ and $z_{end}$.

Results: Better production if $B_i$, $B_f$ and $z_{end}$ are larger.

Present baseline:
$B_i = 20$ T, $B_f = 1.5$ T, $z_{end} = 1500$ cm.

Could reduce $B_i$ from 20 to 15 T if compensate with larger $B_f$ and $z_{end}$.

[Reduce cost, and simplify the mercury target module.]
Secondary-Energy Deposition in the Target System
(N. Souchlas + J. Back)

Practical lifetime of superconducting coils (insulation) against radiation damage is ~ 10 MGray = 10^4 J/g. For a lifetime of 10 “years” of 10^7 s each, the peak rate of energy deposition would be 10^4 J/g / 10^8 s = 10^{-4} W/g = 0.1 mW/g (= 1 MGray/year of 10^7 s).

Use MARS15 (Souchlas) [and Fluka (Back)] to simulate energy deposition.

⇒ With shielding, most energy deposition in the SC magnets is due to 1-100 MeV neutrons.
⇒ Dense shield most effective. We now consider He-gas-cooled W beads.
⇒ Present baseline is R_{outer,shield} = R_{inner,magnet} = 120 cm.

~ 500 kW of power (mostly scattered protons) leaves target system and enters the front end.

Peak energy deposition ≤ 0.1 mW/g
Evolution of coil design to permit gaps for services to the internal He-gas-cooled W-bead shielding:  

Cable-in-conduit conductor, as in ITER Central Solenoid

3 GJ stored magnetic energy  
(6 GJ in ITER Central Solenoid; 3 GJ in LHC octant)

Shield mass ~ 200 tons,  
⇒ Sag when cantilevered.

Shield module inside first SC magnet
Design of the Mercury-Handling System
(V.B. Graves)

- Superconducting magnet
- Outer shielding module
- Inner shielding module
- Mercury target module

Magnet/shielding/mercury modules weigh ~ 200 tons

Double containment
Mercury vessel

Mercury/He-gas services at upstream end of mercury module

Splash mitigator in mercury collection pool

Magnet/shielding/mercury modules weigh ~ 200 tons
Targetry Effort in FY12-15

Targetry activities in FY13-15 will continue the engineering design studies listed on slide 6.

Beyond FY15: Similar level of effort, with addition of hardware studies of mercury-pool splash issues.

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<th>FY13</th>
<th>FY14</th>
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M&S (FY12 k$)

| BNL Travel | 25 | 25 | 25 | 25 |
| Princeton Travel | 8.5 | 8.5 | 8.5 | 8.5 |
| Total M&S | 33.5 | 33.5 | 33.5 | 33.5 |
Backup
<table>
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<th>Total Cost</th>
<th>Comments</th>
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<td>Target Module</td>
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<td>Magnets</td>
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<td>Remote Handling and Hot Cells</td>
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<td>Buildings, tunnels and Infrastructure</td>
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<tr>
<td>Total</td>
<td>USD</td>
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Target Module Costs Scaled from SNS (ORNL)

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</table>

SNS/JNS Mercury target

Mercury-loop utilities

Neutrino Factory Study 2 concept

Heat exchanger 600 kW
Mercury pump (PM pump) 41 m³/h
Surge tank
Shield block
Target Magnet IDS120j: three solenoids per cryostat; large axial gaps at z = 4, 10, 15 & 20 m [drawing courtesy Van Graves]. Target Magnet IDS120k is very similar, but the outboard solenoids in all cryostats except the first are of optimized (larger) inner radius, to improve field profile. U = 3.34 GJ.
Selected Parameters of Target Magnet IDS120k

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Current density $\mu\Omega$ m⁻¹</td>
<td>5.00</td>
</tr>
<tr>
<td>Coil length (mm)</td>
<td>100.2</td>
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<tr>
<td>Gap between coils (mm)</td>
<td>0.00</td>
</tr>
<tr>
<td>Upstream end (mm)</td>
<td>-87.6</td>
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<tr>
<td>Downstream end (mm)</td>
<td>12.6</td>
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<tr>
<td>Inner radius (cm)</td>
<td>18.34</td>
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<tr>
<td>Radial depth of conductor (cm)</td>
<td>7.80</td>
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<tr>
<td>Outer radius (cm)</td>
<td>23.10</td>
</tr>
<tr>
<td>Volume, inc. SSi shell (m³)</td>
<td>39.93</td>
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<tr>
<td>Maximum on-axis field (T)</td>
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<tr>
<td>SC $\gamma$, MPa &amp; fr.</td>
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</tr>
<tr>
<td>Cu $\gamma$, MPa &amp; fr.</td>
<td>8.95</td>
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<tr>
<td>SSt $\gamma$, MPa &amp; fr.</td>
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<tr>
<td>SSt cm &amp; SC M$\gamma$</td>
<td>30M</td>
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<tr>
<td>Coils tons (m²)</td>
<td>6.50</td>
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<td>MS@9400kg</td>
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<td>Magnet MW or MA-m</td>
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Coil dimensions are in rows 3 through 11. Anticipated for the complete magnet, but not tabulated above, are an additional seven sets of three solenoids each that repeat solenoids SC #10, SC #11 and SC #12 at multiples of 5 m, to a distance $z = 50$ m. The cost estimates in the columns with first-row entries “KA” and “0.1” include solenoids to $z = 20$ m.

The cost of each solenoid is based on its mass of superconductor (if any), copper, stainless steel and insulation. The assumed unit cost of fabricated Nb$_3$Sn (SC #1-#3) is 30 M$\$/m³; that of NbTi (SC #4 and up) is $X$ M$\$/m³. The assumed cost of copper, stainless steel and insulation is $X/kg. Costs of cryostats, shielding vessels, shielding and other components have yet to be estimated.

The estimated cost of the resistive magnet is 6.50 metric tonnes x $X/kg = SY$ M. The cost of SC#1 is the sum of two components: superconducting and non-superconducting. The non-superconducting cost is 159.0 tonnes x $X/kg = Y$ M$. The cost attributed to the superconductor is 26.51 m³ x 0.093 x Y M$\$/m³ = Z M$, for a total of $X$. $M$.

The non-superconducting unit cost of $X/kg compares to the $Y/kg reported for resistive magnets at the National High Magnetic Field Laboratory (NHMFL) at Tallahassee, Florida. The superconducting unit cost of Z M$\$/m³ approximately doubles the non-superconducting unit cost a superconducting magnet. The average unit cost for all the superconducting magnets is X M$/224.4$ tonnes = $Y/kg. This compares with the$Z/kg reported for superconducting and hybrid magnets at the NHMFL.

Weggel's cost estimate agrees to within 2% with the Green-Strauss algorithm (A. Bross).
A major cost driver will be civil construction and shielding.

LBNE 2-MW target station ~ $175m

Crude sketch to start IDS-NF costing.
Neutrino Factory Study 2 Concepts
LBNE Target Hall Concept
LBNE 20 – TARGET COMPLEX
Site Plan

“Beam Left” Support Rooms

“Beam Right” Support Rooms

Target Hall

Re-Route Main Injector Road

LBNE CD-1 Director's Review - 26-30 March 2012
LBNE 20 – Target Complex
Target Hall, Support Rooms, Service Rooms

Target Hall

LBNE CD-1 Director's Review - 26-30 March 2012
“Beam Left” Service and Support Rooms

Power Supply Room, RAW Room, Air Handling Room, Truck Bay, 2 Story Mechanical Wing

LBNE CD-1 Director’s Review - 26-30 March 2012
“Beam Right” Service and Support Rooms

- Target Hall w/ 50 Ton Crane
- Maintenance Cell w/ 15 Ton Crane
- Crane Remote Control Room
- 6 Cell Morgue, Staging Area, Truck Bay w/ 50 Ton Crane
The NF Target System Hall is equivalent in many ways to the LBNE Decay Pipe.
We may need concrete shielding ~ 5.5 m thick around the entire target system.
We must have an activated-air-handling system for the Target System Hall.
CERN MERIT Experiment

Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4-MW beam.

Performed in the TT2A/TT2 tunnels at CERN, Nov. 2007.
Disruption Length Analysis (H. Park, PhD Thesis)

Observe jet at viewport 3 at 500 frames/sec, measure total length of disruption of the mercury jet by the proton beam.

Images for 10 Tp, 24 GeV, 10 T:

- Before
- During
- After

Disruption length never longer than region of overlap of jet with proton beam.

No disruption for pulses of < 2 Tp in 0 T (< 4 Tp in 10 T).

Disruption length shorter at higher magnetic field.
Filament Velocity Analysis (H. Park)

Measure position of tip of filament in each frame, and fit for $t_v$ and $v$.

$t_v = \text{time at which filament is first visible}$

Slope $\propto$ velocity

Filament velocity suppressed by high magnetic field.

Filament start time $\gg$ transit time of sound across the jet.

$\Rightarrow$ New transient state of matter???
Pump-Probe Studies

Is pion production reduced during later bunches due to disruption of the mercury jet by the earlier bunches?

At 14 GeV, the CERN PS could extract several bunches during one turn (pump), and then the remaining bunches at a later time (probe).

Pion production was monitored for both target-in and target-out events by a set of diamond diode detectors.

**PUMP**: 12 bunches, $12 \times 10^{12}$ protons

**PROBE**: 4 bunches, $4 \times 10^{12}$ protons

Single-turn extraction $\Rightarrow$ 0 delay, 8 $T_p$

4-$T_p$ probe extracted on next turn $\Rightarrow$ 3.2 $\mu$s delay

4-$T_p$ probe extracted after 2nd full turn $\Rightarrow$ 5.8 $\mu$s Delay

Results consistent with no loss of pion production for bunch delays of 40 and 350 $\mu$s, and a 5% loss (2.5-$\sigma$ effect) of pion production for bunches delayed by 700 $\mu$s.