A MW Class Target System for Muon Beam Production

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Harold G. Kirk
Brookhaven National Laboratory
High-power Targetry Challenges

High-average power and high-peak power issues

- **Thermal management**
  - Target melting
  - Target vaporization

- **Radiation**
  - Radiation protection
  - Radioactivity inventory
  - Remote handling

- **Thermal shock**
  - Beam-induced pressure waves

- **Material properties**
PRODUCTION OF INTENSE MUON BEAMS

Muon beams produced as tertiary beams: $p \rightarrow \pi \rightarrow \mu$

Meson Production - 16 GeV $p + W$

$dN/d(KE) / (1/GeV/interacting$ $proton)$

Pion Kinetic Energy, GeV

Tracks E=20 MeV

Feasibility Study: 24 GeV $p$ on Hg-jet, MARS2(2001)

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The Capture Solenoid

A Neutrino Factory and/or Muon Collider Facility requires challenging magnet design in several areas:

- Target Capture SC Solenoid (15T with large aperture)
- Stored Energy ~ 3 GJ
- 10MW, 5T resistive coil in high radiation environment

Possible application for High Temperature Superconducting magnet technology
Choice of Target Materials

We consider proton beam powers of 1-, 2- and 4-MW

Solid and liquid targets considered:

- High-Z, eg. W, Hg, PbBi
- Mid-Z, eg. Ga, Cu, Ni
- Low-Z, eg. Be, C
Choice of Target Materials II

- High Z (e.g. Hg)
- Mid Z (e.g. Ga)
- Low Z (e.g. Carbon)

A 25% advantage of using high-Z Hg compared to low-Z Carbon
Low-z Carbon is attractive due to it’s simplicity and robustness

Proton Beam: KE = 6.75 GeV
Normalization: For Hg $\Sigma(\mu^+ + \mu^-)/\text{proton} \approx 30\%$

X. Ding, UCLA
Captured Muon Spectra

For $p + Hg$
Total Captured Muons per incoming protons

$\mu^+/p = 14.6\%$
$\mu^-/p = 14.8\%$

For 6.75GeV protons
$1MW \Rightarrow 10^{15}$ protons

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A Graphite Target Core

15 T superconducting coil outsert, Stored energy ~ 3 GJ, ~ 100 tons

Stainless-steel target vessel (double-walled with intramural He-gas flow for cooling) with graphite target and beam dump, and downstream Be window.

He-gas cooled W-bead shielding (~ 100 tons)

Proton beam tube
Last Final-Focus quad
Upstream proton beam window
5 T copper-coil insert. Water-cooled, MgO insulated

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Optimization of Carbon Target Dimensions

X. Ding, UCLA

**Target Radius**
6cm < R < 12cm

**Target/Solenoid Axis Angle**
50 mrad < θ < 80 mrad

- Gaussian beam radius constrained to \( \frac{1}{4} \) target radius
- \(~15\%\) advantage for tilted target

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Graphite targets of various radii (0.8 to 40cm). Proton beam has an rms radius of 2mm at the center of the target and $\beta^* = 80 \text{ cm}$. N. Souchlas, PBL

Largest power deposition for R=8mm case is 4 cm into target, but at ~60cm in targets with large radii...

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Total power absorbed in the target

The steady-state power increases with magnetic field.

For R=8mm, total power is 150kW for 4MW proton beam.
Peak Energy Deposition

N. Souchlas, PBL

80cm graphite target with various radii

Simulations for a 1.8g/cm³ graphite target

Peak energy deposition occurs 3 to 4 cm into the target.

Peak energy deposition is \textbf{3600J/g} for a 4-MW, 6.75 GeV proton beam
# Energy Deposition on Carbon Target

<table>
<thead>
<tr>
<th>Beam Power</th>
<th>Rep Rate</th>
<th>Peak ED</th>
<th>Steady State ED</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW</td>
<td>Hz</td>
<td>J/g</td>
<td>kWatts</td>
</tr>
<tr>
<td>1</td>
<td>60</td>
<td>15</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>60</td>
<td>38</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>30</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>120</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>240</td>
<td>150</td>
</tr>
</tbody>
</table>

**Figure of Merit:** T2K Graphite Target Peak ED Design Limit is **200 J/g**
The T2K Target Design

Titanium target body

Graphite (purified) (ToyoTanso IG-430)

Graphite to titanium diffusion bond

Graphite (purified) (ToyoTanso IG-43)

Remote connector + bellows + isolator ($\text{Al}_2\text{O}_3$)

Stainless pipe + flange

Ti-6Al-4V tube and windows (0.5 mm thick)

Titanium pipe + flange

Isolators

Aluminium support plate

IG43 Graphite
L – 90cm
R=13mm
The CERN CNGS Target

13 graphite rods, each 10cm long,
\( \Phi = 5\text{mm} \) and/or 4mm
2.7 interaction lengths
Target magazine holds 1 target plus
4 spares

Graphite Core
Carbon-Carbon Support
AGS E951: Graphite & Carbon-Carbon Targets

Key Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>ATJ</th>
<th>CC X/U</th>
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</thead>
<tbody>
<tr>
<td>Y, GPa</td>
<td>10</td>
<td>54/5.3</td>
</tr>
<tr>
<td>$\alpha_T \cdot 10^{-6}/^\circ K$</td>
<td>2.5</td>
<td>~0</td>
</tr>
<tr>
<td>Tensile Strength, MPa</td>
<td>15</td>
<td>182/44</td>
</tr>
</tbody>
</table>
24 GeV, 3 x 10^{12} protons/pulse
Consider High-Z Targets

Advantages:
- 30% enhanced $\pi/\mu$ production
- If liquid then free jet mitigates shock damage

Disadvantages:
- Enhanced energy deposition $\rightarrow$ liquid targets
- Enhanced radionuclide inventory
The MERIT Experiment

The MERIT Experiment at the CERN PS

- Proof-of-principle demonstration of a liquid Hg jet target in high-field solenoid
- Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid with a 115 KJ/pulse beam!

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Key MERIT Results

Jet Disruption Length

Filament Ejection Velocity
Study with 4 Tp + 4 Tp at 14 GeV, 10 T

Single-turn extraction

⇒ 0 delay, 8 Tp

4-Tp probe extracted on subsequent turn

⇒ 3.2 μs delay

4-Tp probe extracted after 2nd full turn

⇒ 5.8 μs Delay

Threshold of disruption is > 4 Tp at 14 GeV, 10 T.

⇒ Target supports a 14-GeV, 4-Tp beam at 172 kHz rep rate without disruption.
CERN ISOLDE Hg Target Tests

A. Fabich, J. Lettry, CERN

Proton beam 5.5 TP per Bunch.

Bunch Separation [ns]

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Pump-Probe Test

Production Efficiency: Normalized Probe / Normalized Pump

No loss of pion production for bunch delays of 40 and 350 \( \mu s \),
A 5% loss (2.5-\( \sigma \) effect) of pion production for bunches delayed by 700 \( \mu s \).
Key MERIT Results

- Jet surface instabilities reduced by high-magnetic fields
- Hg jet disruption mitigated by magnetic field
  - 20 m/s operations allows for up to 70Hz operations
- 115kJ pulse containment demonstrated
  - 8 MW capability demonstrated
- Hg ejection velocities reduced by magnetic field
- Pion production remains stable up to 350μs after previous beam impact
- 170kHz operations possible for sub-disruption threshold beam intensities
SUMMARY

- A solenoid capture system could be a source for intense muon beams
- A solid graphite based target looks promising for 1-MW and 2-MW drive beam applications and may be possible at 4-MW for high-rep rates (50-60 Hz)
- Liquid high-Z targets are more efficient in the production of π/μ beams and are suitable for low rep-rate, 4-MW class drive beams
Maximize Pion/Muon Production

- Soft-pion Production
- High-Z materials
- High-Magnetic Field

Meson Production - 16 GeV $p + W$

$\pi^-$

$\pi^+$

Palmer, PAC97

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The NF Study 2 Target System

Proton Beam
Nozzle Tube
Water Drain
Mercury Plug
Resistive Magnets
Mercury Pool/Beam Dump
Beam Window
Water-Cooled Tungsten-Carbide Shield

Neutrino Factory Study 2 Target Concept

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