Solid Target Studies

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The Fundamental Problem with Solid Targets

What do we need materials to possess to get us to multi-MW Power Levels?

- low elasticity modulus (limit \( \text{Stress} = E \alpha \Delta T / (1 - 2\nu) \))
- low thermal expansion
- high heat capacity
- good diffusivity to move heat away from hot spots
- high strength
- resilience to shock/fracture strength
- resilience to irradiation damage

That’s All!

Parameters Affecting Shock Level in Solid Target
- Heat capacity (controlling temperature spike)
- Speed of sound in the material
- Pulse length
- Coeff. of thermal expansion
- Young’s modulus

\[ \sigma \sim E \alpha \Delta T / (1 - 2\nu) \cdot RF \]

\[ RF = \frac{T_{\text{sound}}}{T_{\text{pulse}}} \quad (\text{if } T_{\text{sound}} < T_{\text{pulse}}) \]

\[ RF = 1.0 \quad (\text{if } T_{\text{sound}} > T_{\text{pulse}}) \]

\[ T_{\text{sound}} = \frac{d}{V_s} \]

\[ V_s = \text{sound velocity in material} \]

NOTE: If pulse is too short NO reduction in peak stress can be realized since heated zone does not have time to relax during deposition

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How do these parameters control limits?

Change in hydrostatic pressure $\Delta P$ is related to the energy density change $\Delta E_m$ through the Gruneisen equation of state

$$\Delta P = \Gamma \rho \Delta E_m$$

$\Gamma$ is the Gruneisen parameter related to material thermo-elastic properties such as:
- Young’s Modulus $E$
- Poisson’s ratio $\nu$
- density $\rho$
- thermal expansion $\alpha$
- constant volume specific heat $c_v$.

$$\Gamma = \left[ \frac{E}{(1-2\nu)} \right] \frac{\alpha}{(\rho \ c_v)}$$
Can Solid Targets Support a MW-class Machine and How?

Several “smart” materials or new composites may be able to meet some of the desired requirements:

- new graphite grades
- customized carbon-carbon composites
- Super-alloys (gum metal, albemet, super-invar, etc.)

While calculations based on non-irradiated material properties may show that it is possible to achieve 2 or even 4 MW, irradiation effects may completely change the outlook of a material candidate.

ONLY way is to test the material to conditions similar to those expected during its life time as target.
Are there things we can do? YES!

<table>
<thead>
<tr>
<th>Target</th>
<th>25 GeV</th>
<th>16 GeV</th>
<th>8 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>376.6</td>
<td>351.4</td>
<td>234</td>
</tr>
</tbody>
</table>

Energy Deposition (Joules/gram)

Gaussian and equivalent uniform beam distribution for same number of particles
Relevant Activity Status

- Beam on targets (E951)
- Material irradiation
- New activities
  - irradiation studies/beam on targets
  - Laser-based shock studies
- Simulations and benchmarking
  - LS-DYNA (highly non-linear simulations which reflect on the 4-MW conditions)
## Irradiation Matrix (2004-05 Run)

<table>
<thead>
<tr>
<th>Ni-plated Al</th>
<th>Carbon-Carbon</th>
<th>Carbon-Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IG43 (graphite)</td>
<td>AlBeMet</td>
</tr>
<tr>
<td></td>
<td>Gum Metal</td>
<td>Beryllium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ti-6Al-4V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vascomax</td>
</tr>
</tbody>
</table>

### Cooling Water Channels

- **200 MeV (~ 70 μA)**
- **BNL LINAC Proton Beam**

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*Proton Beam Footprint (1σ)*
“annealing” behavior of Super Invar

Graphite (IG-43) response to irradiation

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GUM Metal

90% cold-worked may be of interest (if it holds these properties after irradiation)
<table>
<thead>
<tr>
<th><strong>1 MW ?</strong></th>
<th><strong>4 MW ?</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Answer is YES for several materials</strong>&lt;br&gt;Irradiation damage is of concern&lt;br&gt;Material irradiation studies are still needed</td>
<td><strong>Answer dependant on 2 key parameters:</strong>&lt;br&gt;1 – rep rate&lt;br&gt;2 - beam size compliant with the physics sought</td>
</tr>
<tr>
<td>A1: for rep-rate &gt; 50 Hz + spot &gt; 2mm RMS ➔ 4 MW possible (see note below)</td>
<td><strong>A2: for rep-rate &lt; 50 Hz + spot &lt; 2mm RMS ➔ Not feasible (ONLY moving targets)</strong></td>
</tr>
</tbody>
</table>

**NOTE:** While thermo-mechanical shock may be manageable, removing heat from target at 4 MW might prove to be the challenge.<br>CAN only be validated with experiments
It is not ONLY the thermo-mechanical shock due to pulse intensities that prevents targets from operating at high power BUT also the ability to remove heat from target

Even at 1 MW it is tough to keep a high-Z target operating within reasonable temperatures

2 MW is most likely the limit for low-Z stationary target (Carbon composite, graphite) operating at low rep rate and 2mm beam spot

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Rotating Solid Targets

1 MW? ….yes
4 MW? ….maybe

Issues
Beam size
Irradiation damage
Operational challenges

MARS & ANSYS predictions for pion yields, energy depositions and induced stress. Proton bunch charge resulting in $3.2 \times 10^{13}$ captured protons.

<table>
<thead>
<tr>
<th>band material</th>
<th>proton energy [GeV]</th>
<th>inconel 718</th>
<th>Ti-alloy</th>
<th>nickel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>24</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>captured $\pi^+$ yield/proton</td>
<td>0.102</td>
<td>0.303</td>
<td>0.080</td>
<td>0.249</td>
</tr>
<tr>
<td>captured $\pi^-$ yield/proton</td>
<td>0.105</td>
<td>0.273</td>
<td>0.083</td>
<td>0.224</td>
</tr>
<tr>
<td>$ppp^{3.2} [10^{13}]$</td>
<td>15.5</td>
<td>5.56</td>
<td>19.6</td>
<td>6.78</td>
</tr>
<tr>
<td>$E_{\text{pulse}} [kJ]$</td>
<td>149</td>
<td>214</td>
<td>188</td>
<td>260</td>
</tr>
<tr>
<td>$U_{\text{max}}^3 [J/g]$</td>
<td>32.0</td>
<td>31.7</td>
<td>25.6</td>
<td>21.3</td>
</tr>
<tr>
<td>$\Delta T_{\text{max}}^{3.2} [^\circ C]$</td>
<td>74</td>
<td>73</td>
<td>49</td>
<td>40</td>
</tr>
<tr>
<td>stress, $VM_{\text{max}}^{3.2} [MPa]$</td>
<td>330</td>
<td>360</td>
<td>72</td>
<td>68</td>
</tr>
<tr>
<td>% of fatigue strength</td>
<td>53-69%</td>
<td>58-75%</td>
<td>10-14%</td>
<td>10-13%</td>
</tr>
</tbody>
</table>

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WHAT’S NEXT?

Phase III Target Irradiation
Target Heat Removal Experiments
Series of Post-Irradiation Tests/Analyses
Off beam Shock Tests
Last (but not least) Beam-Target Simulations
PHASE III Target Irradiation

Materials exhibiting interesting properties
(Carbon-Carbon, super Invar, AlBeMet,
Tantalum, Copper Alloy, Gum Metal)
are going back in

GOAL: assess the relation between damage and self-healing through annealing

Push for damage up to 1 dpa.
Off-beam Target Shock Studies

Use of High-Power Laser (BNL) – to be completed by Summer ‘06

Generation of stress waves/shock by transient surface heating

Nd:YAG (400 mJ/pulse) → target

focused beam

strain gauges

ASSESS target degradation through micro-fracturing using ultrasound

Ultrasonic transducers
Solid Target Concepts – Neutrino Beam

insulator

Target

Forced helium

Horn

\[ p_1 - p_2 = \frac{1}{2} \frac{\lambda}{\rho u} \]

\[ \lambda \]

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SUMMARY

- **High power targets**, regardless of the physics they will support, are inherently coupled with material R&D (shock and irradiation damage).
- Information to-date is available from low power accelerators and mostly from reactor (neutron irradiation) experience. **Extrapolation is not allowed!**
- **Advancements in material technology** (alloys, smart materials, composites) provide hope BUT must be accompanied by R&D for irradiation damage.
- **Liquid targets (Hg jets)** may be the answer to neutrino factory initiative BUT the necessary experiments of the integrated system must be performed. Too many unknowns to be left unexplored.
- **Solid target shock experiments** with pulse intensities anticipated in the multi-MW proton driver are necessary.
- **Simulations of target/beam interaction** (solids and liquid jets) that are benchmarked on the various experiments are a MUST. Predicting the mechanics of shock and of magneto-hydrodynamics (while benchmarking simulations to experiments) will allow us to push the envelope to the conditions of the multi-MW drivers.