Status of High Power Target R&D for Neutrino Factory and Neutrino Superbeam

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4 MW Proton Drivers - Realistic?

- An order of magnitude higher of operating drivers
- Are sub-systems capable in providing/dealing with such power?
- While the target may represent a tiny portion of the overall infrastructure, its role in the functionality of the system is paramount
- Since no one-size-fits-all works, the target choice must satisfy accelerator parameters that are set by physics
- Unfortunately, it is a two-way negotiation !!!!
Parameter Space
A happy medium between physics goals and engineering reality

Protons per pulse required for 4 MW

\[ \bar{P}_{\text{adc}}(w) = E[eV] \times N \times e \times f_{\text{rep}} \text{ [Hz]} \]

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>10 Hz</th>
<th>25 Hz</th>
<th>50 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GeV</td>
<td>$250 \times 10^{12}$</td>
<td>$100 \times 10^{12}$</td>
<td>$50 \times 10^{12}$</td>
</tr>
<tr>
<td>20 GeV</td>
<td>$125 \times 10^{12}$</td>
<td>$50 \times 10^{12}$</td>
<td>$25 \times 10^{12}$</td>
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</tbody>
</table>

Efficiency of muon collection at exit neutron factory of front end

Acceptance after cooling vs. proton bunch length

Maximum energy penalty (GeV per proton)

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Neutrino factory

8.0 GeV < Energy < 20.0 GeV
Rep Rate ~ 50(25) Hz
Intensity $50 \times 10^{12}$ ppp, at 10(20) GeV
Bunch Length < 3 ns, for longitudinal acceptance

Proton Driver MAY NOT be dedicated to Neutrino Factory and must have the potential of serving other experiments \(\rightarrow\) compromise
The functionality of any scheme is most definitely controlled by our target choice.

Whether we generate and sell isotopes or diamonds we are into a new branch of targetry named MRT.

Money

Recovering

Target
How Can We Get There?

- Liquid or Solid?
- Stationary or Moving?
- Something in between (i.e. packed particle beds)?

**Common denominator**: always going through window or a “solid” target !!!!
Pulse Structure

Pulse length effect on a Cu target radial stress generated at target center

Bunch length effect on target response

Bunch period in BASELINE pulse structure (12 bunches in 4.2 microsecs)
Why is Pulse Structure Important?

<table>
<thead>
<tr>
<th>Target</th>
<th>25 GeV</th>
<th>16 GeV</th>
<th>8 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Deposition (Joules/gram)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>376.6</td>
<td>351.4</td>
<td>234</td>
</tr>
</tbody>
</table>

Gaussian and equivalent uniform beam distribution for same number of particles

Operating Temperature

Too HIGH for most solids
What R&D is a MUST in addressing the desired or optimized parameter space?
Solid Target Considerations

• Low, mid- or high Z? (we have been looking into all of them)
• Stationary or moving?
• Primary concerns:
  • Absorption of beam-induced shock
  • premature failure due to fatigue (RAL thermal shock studies and their central role)
  • radiation damage from long exposure
Putting a real face to radiation damage!!
Proton and neutron exposure of fused silica (LHC 0-degree Calorimeter)
Fused silica damage visualization
Solid Target Option

• Anticipated cocktail far exceeds what current facilities can provide
  • while past experience (material behavior from reactor operation; experimental studies) can provide guidance, extrapolation to conditions associated with multi-MW class accelerators is risky
  • inch ever closer to the desired conditions by dealing with issues individually

• Embark on a comprehensive R&D in hope to:
  • deal with the implications of high power
  • identify promising candidates ==> target schemes
  • identify limits
<table>
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<tr>
<th><strong>1 MW ?</strong></th>
<th><strong>4 MW ?</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer is <strong>YES</strong> for several materials</td>
<td><strong>Answer dependant on 2 key parameters:</strong></td>
</tr>
<tr>
<td><strong>Irradiation damage is of primary concern</strong></td>
<td>1 – rep rate</td>
</tr>
<tr>
<td><strong>Material irradiation R&amp;D pushing ever closer to anticipated atomic displacements while considering new alloys is needed</strong></td>
<td>2 - beam size compliant with the physics sought</td>
</tr>
</tbody>
</table>

A1: for rep-rate > 50 Hz + spot > 2mm RMS → 4 MW possible (see note below)

A2: for rep-rate < 50 Hz + spot < 2mm RMS → Not feasible (ONLY moving targets)

**NOTE:** While thermo-mechanical shock may be manageable, removing heat from target at 4 MW might prove to be the challenge.

**CAN only be validated with experiments**
Overview of R&D Realized to-date on Solid Targets

- Target Shock Studies (BNL-E951)
- Radiation damage Studies (BNL)
- Target Lifetime Studies (RAL)
Target Shock Studies

Holding Fixture

Graphite

Fiberoptic strain gauges

24 GeV proton beam

Measured strains

Beam arrival

Predicted Strain

microstrain

microseconds

microstrain

microseconds
Beam-induced shock on thin targets

- Experiment
- Prediction

24 GeV protons

fibreoptic strain gauges
Solid Target Shock Studies – Assessment Overview

- Delineated between Graphite and Carbon composites
- Some super-alloys (titanium, inconel) exhibit favorable
- Materials “appear” more shock resilient than conventional estimates
- Simulation-based predictions based proved that computational tools can help push the envelope to higher power
- BUT, computational tools need scrutiny at even more severe conditions

Tracking code prediction on energy deposition (GEANT, MARS) were confirmed

Shock, however, is one part of the story !!!
Target Radiation Damage R&D

Irradiation at BLIP
(200 MeV or 117 MeV protons at the end of Linac)
Irradiation Damage Analysis

Thermal Expansion/Heat Capacity Measuring System

Remotely operated mechanical testing system
Target Irradiation Damage R&D in a Nutshell

• PHASE I: Super-Invar & Inconel-718

• PHASE II:
  • 3D-weaved Carbon-Carbon
  • Toyota “Gum Metal”
  • Graphite (IG-43)
  • AlBeMet
  • Beryllium
  • Ti Alloy (6Al-4V)
  • Vascomax
  • Nickel-Plated Aluminum

• PHASE II-a: 2D-weaved CC composite

PHASE III:

• 3-D and 2-D weaved Carbon-Carbon Composites
• Toyota “Gum Metal” (90% cold-worked)
• Graphite (IG-43 and isotropic IG-430)
• Ti Alloy (6Al-4V)
• Copper (annealed)
• Glidcop_15AL – Cu alloyed with .15% Al
• Bonded graphite to Titanium and Copper
• Tungsten and Tantalum
• Re-irradiation of super-Invar
• AlBemet and Vascomax
• Nickel-Plated Aluminum of the NuMI horn
• Fused Silica (LHC) and special ceramics
Superbeam Target Concept

[Diagram showing the components of a superbeam target, including BEAM, CC TARGET, COOLING WATER COLLECTION, CARBON-CARBON BLOCK, HE helium in, and Baffle Cooling Loops.]

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Radiation Damage in Carbon-Carbon Composites

The GOOD News
Radiation Damage in Carbon-Carbon Composites and Graphite

The BAD News

2-D carbon

3-D carbon

[fluence \(\sim 10^{21} \text{ p/cm}^2\)]
A low-Z material such as AlBemet (need low-Z but with good strength to not impede the flight of pions produced in the target) that has exhibited (thus far) excellent resistance to corrosion while maintaining strength and ductility under irradiation could be the magnetic horn material.
Radiation Damage - mid-Z Target Options
“annealing” of super-Invar

Following 1st irradiation

Following annealing and 2nd irradiation

ONGOING 3rd irradiation phase: neutron exposure
Radiation Damage of Super Alloy “Gum” metal

Enhancement of properties are attributed to the “dislocation-free” plastic deformation mechanism.

As observed in other studies (AlMg-alloy), 0.2 dpa was enough to remove cold-work microstructure.
Radiation Damage Studies – Super-alloys with encouraging results
Radiation Damage Studies – High-Z Materials

Tantalum

![Graph showing linear expansion vs. temperature for 0 dpa and 0.25 dpa with different CTE values.](image)

![Image of tantalum material.](image)
Tungsten

CTE (100 - 650 C) = 4.46 e-06/K

* CTE from literature = 4.4 - 4.6 e-06/K
Neutron Irradiation Studies using the BNL Accelerator Complex and its potential benefits
Whether Hg Jet or Solid, it is the functionality/survivability of the overall target infrastructure that is important.
Relevance to Hg Jet: Jet nozzle survivability
We need to venture outside the safety envelope to identify the limits

Simulations around MERIT for example can allow the study of beam structure/jet velocity/jet destruction etc.
Hg Explosion Simulations
Hg explosions and Target Infrastructure
SUMMARY

• Keep inching closer to the baseline conditions of a multi-MW class accelerator by solving pieces of the puzzle individually and with proof-of-principle experiments
  – We do not have or can have all the conditions in a single setting because these accelerators have not materialized as of yet

• Focus on irradiation damage and thermal shock/fatigue of key components that could be the limiting factors in the lifetime of the overall experiments

• Appreciate the value of multi-physics based simulations for the engineering side of things (where actual limitations lie) and use them to push the envelope