Recent experience with NuMI graphite targets and dumps
(plus some NOVA & LBNE target information)

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Graphite Fin Core
6.4 mm wide
(1.1 mm RMS beam spot)

95 cm long, 1.8 g/cm³, segmented

Helium containment

Water cooling tube

IHEP Protvino design

Target fits 60 cm deep in the 200 kA focusing horn without touching.
NuMI Target operation summary

7 targets over 7 years of operation
(coincidentally, average matches CDR/TDR plan of 1 target per year)

Total of $\pi/2 \times 10^{21}$ POT at 120 GeV

Integrated beam power = 0.97 MW-year

5 targets replaced due to failure of water-cooling line

1 target replaced due to gradual deterioration of graphite (changing neutrino spectrum)

(1 target temporarily out of action due to frozen motion drive)

Target 7 is still in good shape.
# NuMI Target operation summary

<table>
<thead>
<tr>
<th>target</th>
<th>Date of 1st POT</th>
<th>Date of last POT</th>
<th>(last - 1st) in weeks</th>
<th>Integrated POT</th>
<th>max beam power</th>
<th>max POT/spill</th>
<th>reason taken out of service</th>
<th>Modification from previous target</th>
</tr>
</thead>
<tbody>
<tr>
<td>design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>400 kw</td>
<td>4.0E+13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT01</td>
<td>5/1/2005</td>
<td>8/13/2006</td>
<td>67</td>
<td>1.6E+20</td>
<td>270 kw</td>
<td>3.0E+13</td>
<td>drive stuck in high energy position, experiment wanted low energy position</td>
<td>(run at higher helium pressure after leak)</td>
</tr>
<tr>
<td>NT02</td>
<td>9/11/2006</td>
<td>6/12/2009</td>
<td>144</td>
<td>6.1E+20</td>
<td>340 kw</td>
<td>4.0E+13</td>
<td>graphite deteriorating, 10%-15% fewer nu/POT at peak</td>
<td>restraining collar put on water pipe bellows and upstream water tubing</td>
</tr>
<tr>
<td>NT03</td>
<td>9/11/2009</td>
<td>7/12/2010</td>
<td>44</td>
<td>3.1E+20</td>
<td>375 kw</td>
<td>4.4E+13</td>
<td>break at ceramic tube-holder (probably water leak -&gt; explosion)</td>
<td>no water pipe bellows, helium pressure lowered</td>
</tr>
<tr>
<td>NT04</td>
<td>8/22/2010</td>
<td>9/17/2010</td>
<td>4</td>
<td>2.0E+19</td>
<td>375 kw</td>
<td>4.3E+13</td>
<td>water leak; explosion (blew off upstream beryllium window, no water leak during autopsy*)</td>
<td>(* water leak only during beam hammering!)</td>
</tr>
<tr>
<td>NT05</td>
<td>10/29/2010</td>
<td>2/24/2011</td>
<td>17</td>
<td>1.3E+20</td>
<td>337 kw</td>
<td>4.0E+13</td>
<td>water leak; eventual external water leak (water turnaround fell off at downstream laser weld)</td>
<td>higher helium pressure to help keep water out of target tube</td>
</tr>
<tr>
<td>NT06</td>
<td>4/7/2011</td>
<td>5/16/2011</td>
<td>6</td>
<td>2.0E+19</td>
<td>305 kw</td>
<td>3.5E+13</td>
<td>water leak; eventual external water leak, leak was upstream, not at downstream turnaround</td>
<td>different downstream water turnaround; tig weld instead of laser weld downstream</td>
</tr>
<tr>
<td>NY01'</td>
<td>6/11/2011</td>
<td>7/8/2011</td>
<td>4</td>
<td>2.1E+19</td>
<td>228 kw</td>
<td>2.6E+13</td>
<td>water leak; eventual high level of water in target; spray at downstream laser weld seen at autopsy</td>
<td>(repaired motion mechanism; recycled target, so could not modify target core)</td>
</tr>
<tr>
<td>NT02'</td>
<td>7/29/2011</td>
<td>9/15/2011</td>
<td>7</td>
<td>4.5E+19</td>
<td>330 kw</td>
<td>3.8E+13</td>
<td>removed when NT07 was ready, still available as spare but with deteriorated graphite</td>
<td>(recycled target, so could not modify)</td>
</tr>
<tr>
<td>NT07</td>
<td>9/24/2011</td>
<td>4/29/2012</td>
<td>31</td>
<td>2.6E+20</td>
<td>345 kw</td>
<td>4.0E+13</td>
<td>Still running, no leaks</td>
<td>downstream and upstream laser welds replaced by tig; water pipe ceramic moved outside tube</td>
</tr>
</tbody>
</table>
NT-02

10% - 15% $\nu$ decrease over 6.1e20 POT

radiation damage? (~1 DPA)

or oxidation, or ...?

plan to autopsy next year

NT-03

No indication of degradation over 1.8e20 POT


NT-07

No indication of degradation over 2.6e20 POT

Why does later graphite appear more robust?
What joints can fail, to produce water leaks in helium volume?

- Weld sleeve
- Ceramic transitions
- Water turn-around

This joint gets worst pounding by showering beam.
What does water leak do?

Water leak inside helium volume leads to unacceptable conditions in couple ways:

1) Beam ionization dissociates water to H and O; gas then explodes, causing misalignments or bursting windows

2) Water partly fills helium volume; extra material would cause experimental systematic errors by changing beam spectrum, so target must be discarded

If outer tube is breached, water may run out, and target may continue operation as long as reasonable helium over-pressure can be maintained.

Each target was rather unique in how it limped through water and helium leaks.
Outline of 2011 target problems

NT-01, NT-02, NT-03 had all lasted reasonable amount of time

NT-04, NT-05, NT-06 - - rapid series of failures, all due to bad water line joints from vendor

NT-04  infant mortality.  *NT-04 would not leak during autopsy, only with beam pounding on it*

NT-05  To get back on air, installed NT-05 with no hardware changes,
       but with high helium pressure to try to keep water from entering the helium volume.
       NT-05 water line failed almost immediately, *but the helium strategy did keep NT-05 working long enough to pretty much get NT-06 ready*

NT-06  Autopsy of NT-05 showed water leak at welds at target tip,
       so FNAL redid target tip welds on NT-06 with high Q.A.
       NT-06 failed quickly as well, but autopsy showed it was *upstream, not the tip welds*

Refurbished and ran NT-01 and NT-02 until NT-07 was ready

NT-07  first target built after NT-04 failure,
       all water-pipe joints inside redone by FNAL with high Q.A.  Ran well.  Finally, no problems!

Down total of 1/3 of the time over 13 months:

spares not ready, 5 change-outs, 4 autopsies, 2 modifications based on autopsies, 2 refurbishments

*shortest downtime for target replacement: 9 days*
Some damage of outer tube

Cut off end of tube
– see water-pipe welds had failed completely

Not corrosion or pipe failure; just break of laser welds

1st direct view of graphite after running!

Visible graphite looks perfect after 1.25e20 POT
(NT02 took 6e20 POT)

No corrosion of aluminum
Solder joint to graphite fine
Steel cooling pipes look fine
Downstream spacer ring walked several inches upstream
NT-06 tip reworked, but water-line failed elsewhere

Autopsy, showing water flowing down from upstream end of target
Re-did NT-07 welds with high Q.A.

Original welds from target vendor showed tungsten inclusions. Replaced these even though they passed pressure test.

Re-did all welds internal to the hydrogen volume.

Rework welding development and microstructure analysis was conducted by contracted material science engineering experts.

CT Scan to Qualify Downstream Turnaround Ring Weld Integrity (Difficult Geometry for Conventional X-ray Inspection)
NOVA target

Graphite fins
Helium atmosphere
Beryllium windows
Water cooled aluminum pressing plates
Water cooled outer can

Will NOT fit inside horn
(Fins end 20 cm upstream of horn)
Target ready to install, except want to add one more monitor to carrier

1st one built by R.A.L. in U.K.
R.A.L. and F.N.A.L now building one more each.
NoVA target not nearly as problematic because:

**M.E. target is further upstream, does not have to fit in horn**

Comparison to scale:

- Water cooling moved 8 times as far away
  - but only 1.2 x more proton per pulse
  - *so water-line stress is very modest!*

- Does not need to be electrically insulated
  - *no ceramic break in water line*
Target Vertical Position Thermometer

Beryllium pins on upstream window of target to watch beam position

*note baffle drawn behind target, although it is actually in front*

- Beryllium pins, 1 mm diam.
- Beam profile, 1 sigma, 2 sigma 
  \( r = 1.3 \text{ mm, } 2.6 \text{ mm} \)
- Heat Sink
- Baffle hole, 13 mm diameter
- NOVA Target, 7.4 mm wide
- Thermocouples
- Support (but minimize thermal contact)
LBNE Target

Developed from the NuMI Low-Energy Target

- Same overall geometry
- Conservative approach to design
- Flexible tune for neutrino energy

Key change 1: Cooling lines made from continuous titanium tubing

- Previous was stainless with welded junctions
- Eliminates water joints
- Stronger and more resistant to heating, water pressure
- Less heat produced / pions absorbed

Key change 2: outer containment tube beryllium instead of aluminum

- Beryllium stronger, take higher temperature
- Eliminates Al-Be brazing joint to the downstream beam window (beryllium)
- Reduces horn heating / pion absorption

Partially prototyped already for NuMI

Reference material: POCO ZXF5Q graphite

Option remains for beryllium as target material if it can be validated

Prototype

Input from RAL
NUMI Absorber ("dump")

Core: 8 Aluminum blocks
Each block: 51” x 51” x 12”
with redundant water cooling lines

Surrounded by layers of steel and concrete

Thermocouples mounted in middle of core, at shower maximum, for monitoring.

Air from this region is dehumidified to extract tritiated water, then travels through 1100 ft of passageway before exhaust, so short-lived isotopes have time to decay.
NuMI Absorber operation and upgrade for 700 kW beam operation

- 7 years of operation (1 MW-year of proton beam power) with zero absorber problems.

- Was designed for ½ hour of accident condition: full 400 kW beam power, without target.
- For use beyond design (700 kW) have hooked its thermocouples to beam permit, to stop beam if target disappears.
Absorber core temperature as target diagnostic

May 4, 2010 hydrogen explosion damages ceramic holding the target tube, throwing target out of alignment.

Absorber core temperature relative to beam power (and baffle temperature) clearly indicates problem

For comparison:

- Muon monitors
- Hadron monitor