High Power Proton Beam Targets: Technological Evolution, Current Challenges, and the Future

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High Power Proton Beam Targets: The Ultimate (De)accelerator

• Design Considerations
  – Maximize intense secondary yield production
  – Remove heat
  – Handle pressure pulse
    • High cycle fatigue
    • Cavitation
  – Radiation damage
  – Robotic access / disposal

• Unfortunate reality
  – Impossible to have realistic test stand
    • New high power targets pushing frontier are experiments
    • Complicated fabrication – long lead time
Targets Can Limit Facility Performance

- At SNS, targets have had a stronger limit on operational beam power than the accelerator the last 3.5 years.

- J-PARC neutron source beam power is presently limited by target.
SNS Target History: Unplanned Leakage is the Norm

• Unplanned outages have a large impact on the SNS user program

<table>
<thead>
<tr>
<th>Target</th>
<th>Date Installed</th>
<th>Date Failed</th>
<th>Calendar days between beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>4/26/06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>8/17/09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>7/29/10</td>
<td>4/3/11</td>
<td>17</td>
</tr>
<tr>
<td>T4</td>
<td>4/19/11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>1/25/12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>8/2/12</td>
<td>9/22/12</td>
<td>14</td>
</tr>
<tr>
<td>T7</td>
<td>10/3/12</td>
<td>10/11/12</td>
<td>45</td>
</tr>
<tr>
<td>T8</td>
<td>11/16/12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T9</td>
<td>10/14/13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T10</td>
<td>7/23/14</td>
<td>9/12/14</td>
<td>37</td>
</tr>
<tr>
<td>T11</td>
<td>9/22/14</td>
<td>10/27/14</td>
<td>23</td>
</tr>
<tr>
<td>T12</td>
<td>11/18/14</td>
<td>9/25/2015</td>
<td>14</td>
</tr>
<tr>
<td>T13</td>
<td>10/8/15</td>
<td>3/22/2016</td>
<td>7</td>
</tr>
<tr>
<td>T14</td>
<td>3/28/2016</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• 7 of 14 installed targets were replaced because they leaked

• “Fast” replacement mitigates science impact
Irradiated Targets are Nuclear Technology

- SNS exposed target dose rate ~ 35,000 Rads/hr (350 Sv/hr)
- Robotic manipulation is a must
- Disposal is complicated
  - Approved disposal container
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First Generation: Stationary Solid Targets

- Neutron production:
  - Ta clad tungsten targets
  - Water cooled
- Works well up to few hundred KW
ISIS Target Station 1
(Courtesy D. Jenkins)

• Purpose: neutron production, operated over 30 years
  – ~ 150 kW, 800 MeV, 50 Hz
  – Short pulse (< 1 μs)
  – Monolithic target/moderator assembly – horizontal insertion

• 5 year life, monolithic moderator/target
LANL Lujan Center
(Courtesy C. Kelsey)

• Purpose: neutron production, operated over 30 years
  – 100 kW, 800 MeV, 20 Hz
  – Short pulse (250 ns)
  – Split target for multiple moderator optimization
  – Monolithic target/moderator assembly
    • Vertical insertion into target crypt
PSI: SINQ Target
(Courtesy B. Blau)

• Purpose: Neutron scattering
  – ~ 1MW on target
  – 0.59 GeV, CW @ 1.6 mA

• Solid target
  – Cannelloni target:
    • Pb in Zircalloy tubes
    • Pb blanket
    • Water cooled
  – Some tubes contain irradiation samples

• Operations never stopped prematurely for target failure
KOMAC High Power Target
(Courtesy Yong-Sub Cho)

- Purpose: Isotope production, multi-purpose
  - 30 kW, 100 MeV, 30 Hz
  - Long pulse, 0.5 ms
  - Solid (RbCl and Zn, SS clad) water cooled
  - RI production commissioning ongoing
  - Maintenance with high activation a challenge
Second Generation: Liquid Metal Targets

- Advantage: combine secondary (neutron) production material and coolant
  - Hg is high Z and liquid

- Disadvantage: cavitation damage
ORNL: Spallation Neutron Source

• Purpose: neutron production
  – 1.4 MW, 940 MeV, 60 Hz
  – Short pulse (700 ns)
  – Hg target
  – Horizontal rail system / hot-cell

• Lessons
  – Weld failures and cavitation erosion pitting
  – Directed flow adjacent to vessel inhibits cavitation damage
Cavitation Induced Pitting

- Vessel wall facing the Hg has pitting damage in nose area

Cavitation damage to target inner wall
Directed Hg Flow Mitigates Pitting

- Both cases: 1MW x 600 hours
- Dramatic effect!

Nominal target, poor flow at nose wall

Direct flow along wall at target nose

Extracted inner wall cores:
J-PARC: Material Life Science Facility
(Courtesy H. Katsuhiro)

• Purpose: neutron production
  – 1 MW, 3 GeV, 25Hz
  – Short pulse (2 x 150 ns)
  – Hg target
  – Horizontal rail system / hot-cell

• Lessons
  – He gas injection mitigates pressure pulse intensity
  – Weld failures

No gas injection
With gas injection
J-PARC gas injection demonstration

TS-09

1.0 L/s, Swirl A, 40 sccm
1.0 L/s, Swirl C, 40 sccm
1.3 L/s, Swirl C, 40 sccm
1.3 L/s, Swirl C, 800 sccm
Third Generation Neutron Source Targets: Rotating Target

- Future neutron sources are adopting rotating targets
  - Advantages
    - Spread heat load of larger volume
    - Residual activation decay heat issue is also mitigated
  - Disadvantage
    - Moving parts, rotating seals
    - Replacement complicated
Second Target Station / SNS

• Purpose: Neutron scattering
  – 467 kW
  – 1.3 GeV, 10Hz

• Rotating target
  – W target, Ta clad
  – Water cooled
  – Vertical access
European Spallation Source
*(Courtesy E. Pitcher)*

• Purpose: Neutron scattering – world’s first long pulse
  – 5 MW!
  – 2 GeV: 357 kJ x 14 Hz @ 2.9 ms

• Rotating target
  – W: 6700 bricks, 3.5 tonnes
  – He cooled: 3 kg/s
  – Vertical access
P-C interactions produce pions, which are focused, decay to produce neutrinos. *Long, narrow target: pions can escape out sides, reducing pion re-interactions.*

50 Graphite fins: 24 mm long & 7.4mm wide

*Proton beam spot sigma = 1.3 mm*

Cooled by water cooled Al pressing plates

<table>
<thead>
<tr>
<th></th>
<th>Design</th>
<th>So far</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>120 GeV</td>
<td>120 GeV</td>
</tr>
<tr>
<td>POT / 10 micro-second spill</td>
<td>4.9e13</td>
<td>4.4e13</td>
</tr>
<tr>
<td>Repetition time</td>
<td>1.33 sec</td>
<td>1.33 sec</td>
</tr>
<tr>
<td>Beam power</td>
<td>700 kW</td>
<td>580 kW</td>
</tr>
</tbody>
</table>

No operational issues so far, have not replaced target yet.
CERN CNGS engineering challenges  
*(courtesy M. Calviani)*

- CNGS target unit conceived as a static sealed system with 0.5 bar of Helium
  - 130 cm long graphite target (~3\(\lambda\))
  - Radiative-cooled target, \(~1200\ °C\)
  - Run at 500 kW
China- ADS: Gravity fed granular target (courtesy Lei Yang, IMP)

• Combines solid / liquid target attributes

Prototype test setup
# High Power Proton Targets Take a Beating

<table>
<thead>
<tr>
<th>Neutron Sources</th>
<th>Power on Target (MW)</th>
<th>Peak Power – Time Average (MW/m$^3$)</th>
<th>Peak Power – Instantaneous (MW/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISIS TS1</td>
<td>0.14</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Lujan</td>
<td>0.1</td>
<td>250</td>
<td>50,000</td>
</tr>
<tr>
<td>PSI</td>
<td>0.94</td>
<td>820</td>
<td>NA</td>
</tr>
<tr>
<td>SNS</td>
<td>1.4</td>
<td>552</td>
<td>10,000</td>
</tr>
<tr>
<td>J-PARC</td>
<td>1.0</td>
<td>430</td>
<td></td>
</tr>
<tr>
<td>ESS</td>
<td>5</td>
<td>90</td>
<td>80,000</td>
</tr>
<tr>
<td>SNS-STS</td>
<td>0.47</td>
<td>18</td>
<td>20,000</td>
</tr>
</tbody>
</table>

| Isotope production | | |
|-------------------| | |
| KOMAC             | 0.03                | 350                                  |                                      |

| Neutrino Production | | |
|---------------------| | |
| FNAL NOVA           | 0.75                 | 470                                  | $10^5$                               |
| CERN CNGS           | 0.4                  |                                      | $10^6$                               |
Radiation Damage In Accelerator Target Environments

Broad aims are threefold:

- to generate new and useful materials data for application within the accelerator and fission/fusion communities
- to recruit and develop new scientific and engineering experts who can cross the boundaries between these communities
- to initiate and coordinate a continuing synergy between research in these communities, benefitting both proton accelerator applications in science and industry and carbon-free energy technologies
RaDIATE Current Activities
(Courtesy P. Hurh)

- HE proton irradiations & Post-Irradiation Examinations (PIE)
  - Many materials of interest from Be to Ir!
- LE ion irradiations & PIE
  - Utilize advanced techniques to correlate damage to HE proton regime
- PIE of spent targets/windows
- Thermal Shock studies
Outlook

• 1st generation: Stationary Solid Targets
  – Works well for 100 kW class applications
  – Higher power demonstrated for neutrino applications

• 2nd generation: Liquid Hg targets
  – Targets accepting ~MW beam for short pulse beams
  – Upgrades for robust operation under development

• Moving forward
  – Rotating targets look good
  – Granular-flow target