HIGH POWER PROTON BEAM TARGETS: TECHNOLOGICAL EVOLUTION, CURRENT CHALLENGES, AND THE FUTURE *

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Abstract

This talk reviews the history of proton beam target development and the current challenges associated with the operation of high power beam targets. Beyond providing high power proton beams, accelerator facilities must also engineer robust targets to accept the load and satisfy mission needs. Recently some high power facilities are limited by target operations, rather than accelerator capabilities. The outlook for targets for future high power facilities is also considered.

INTRODUCTION

High power proton accelerators typically are designed to impact a fixed target to produce an intense secondary beam (neutrons, neutrinos, muons, etc.) Generally, the power density on the target is high, to facilitate production of an intense secondary beam, which presents technical challenges. Target design needs to be as robust as the accelerator components for high overall facility availability. Recent experience at some high power facilities indicates that target concerns can limit the beam power [1]. Target design and experience at high power facilities are described here, with an emphasis on challenges faced. Also, some cases where target concerns has forced reduced power operation are discussed.

DESIGN CONSIDERATIONS

High power target design must take into account the following considerations:

- Maximizing intense secondary particle yield production
- Heat removal
- Pressure pulses (for non-CW applications)
  - High cycle fatigue
  - Cavitation in liquid targets
- Radiation damage
- Robotic access for maintenace
- Waste disposal

Some of these considerations push the design in opposite directions. For example creating an intense secondary beam drives the design to a high power density proton footprint on the upstream end, and as low a cooling fluid volume fraction as possible. These are the opposite trends as desired to handle heat removal during operation and for residual activation heat removal. For pulsed systems, there can be millions of pulses per day. Beyond this, high power accelerators experience 10's of trips per day lasting over one minute [2], which leads to thermal cycling of the target systems. These effects drive the design towards the high cycle fatigue regime.

An unfortunate reality is that for ground-breaking applications, it is impossible to fully simulate operational target conditions before the facility is built. While it is often possible to prototype components for beam acceleration on test stands, creating a MW proton beam test facility for the target prototyping is not practical. Hence the beam targets at facilities that are pushing existing intensity frontiers are effectively experiments themselves. Another present design limitation is the lack of knowledge of radiation damage effects on target material structural parameters. The RaDIATE [3] collaboration is addressing this issue.

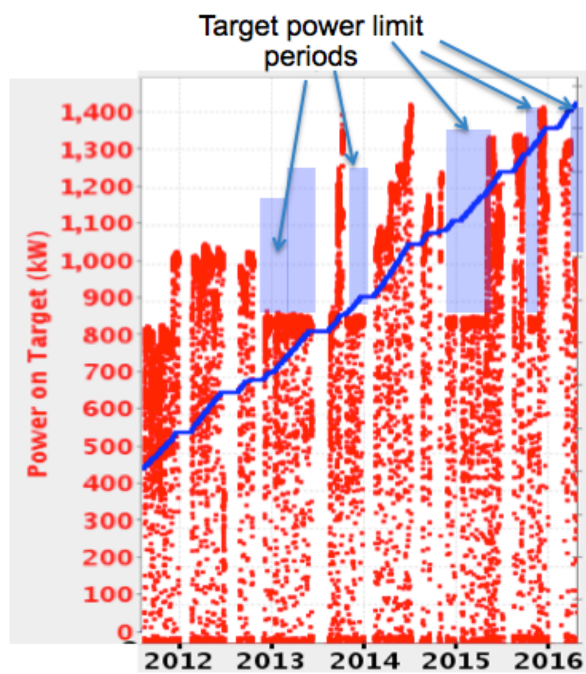

Figure 1: SNS Operational beam power, with periods limited by target concerns indicated in blue.

OPERATIONAL IMPACT

As an example of a high power proton facility operationally impacted by target issues, consider the Spallation Neutron Source [4]. Figure 1 shows the operational beam power since 2012. The overlaid blue bars are periods when the operational power was restricted due to concerns on target survivability. The top of the blue bar represents an approximation of the beam power the accelerator could have provided. There have been five periods since 2012 in which the beam power was limited by the target, not the accelerator. While 1.4 MW operations have been achieved, with reliable targets a smoother approach to sustained 1.4 MW would have been possible.

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Seven of the 14 installed targets at SNS have unexpectedly failed while in service. Target replacement is an involved procedure with robotic access, due to the quite high radiation levels of exposed targets (~ 350Sv/hr). Figure 2 shows a target inside the SNS service bay with robotic arms visible, and the outside of the service bay with manipulator equipment. At SNS target replacements have required several weeks to complete. Recently, a new target was installed with a complete turn-around (target leak to operation resumption) of only 7 days. Minimizing the target replacement time is an important area of emphasis, to minimize the operational impact of unanticipated failures.

Figure 2: A target assembly inside the SNS hot-cell (top) and a view of the hot-cell outside (bottom) with manipulator equipment.

The SNS target failure causes are primarily weld failures and more recently cavitation erosion (discussed later). Actions have been initiated to address these concerns, but there is a substantial lag time in actual implementation. Design change with quality assurance checks takes 6-12 months, fabrication of a new target takes about 12 months, and if successful, a target can last ~ one year.

HIGH POWER TARGETS

Solid, Stationary

The initial generation of spallation neutron sources use stationary solid targets. This is the most straightforward approach, and works quite well for the beam power levels up to ~ 1 MW for the case of SINQ [5]. Figure 3 shows a schematic of the ISIS target station 1 target [6]. Both ISIS and the Lujan center at LANL [7] incorporate stationary water-cooled tungsten targets. The tungsten is coated with tantalum (edge cooled with water) to prevent tungsten erosion from direct contact with the water coolant. Tungsten is a high Z material, which is good for neutron production and also can be operated at elevated temperatures. The plates are thicker downstream to provide roughly equal heat deposition. Both the LANL and ISIS targets have proved to be quite reliable.

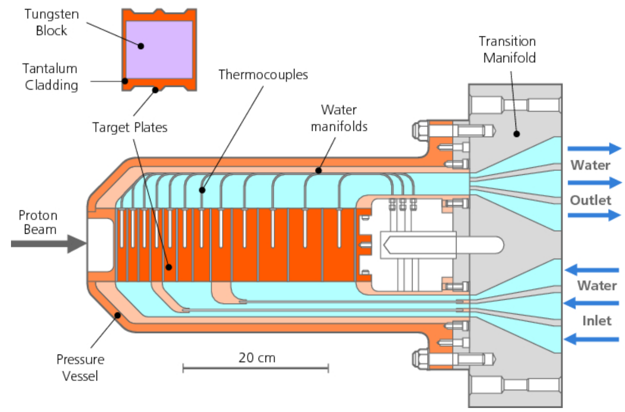

Figure 3: ISIS stationary solid target schematic.

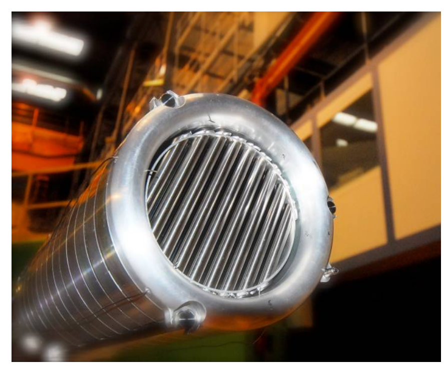

Figure 4: The SINQ Cannelloni target.

The ISIS and Lujan targets are contained in a monolithic assembly that also includes the neutron moderators. This allows for a compact design, but requires removal of the entire assembly to rework moderators for example, which is a complex task. For the Lujan case access is vertical and for the ISIS case access is horizontal.

The SINQ spallation neutron source at PSI [5] is another solid stationary target type. This target uses lead as the target neutron production material, is water-cooled and contained in Zircaloy tubes - and is referred to as a “cannelloni” target (see Fig. 4). Some tubes also contain irradiation samples. This is a CW source, with close to 1MW power on the target.

Stationary solid high power targets have proved quite reliable. The ISIS targets typically last 5 years, and are replaced when the last temperature thermocouple fails, even though the target may still be structurally sound. The PSI target has never caused an operations interruption due to premature failure. The Lujan target does not limit beam power (the accelerator is the limiting constraint). The straightforward approach of a water-cooled stationary

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solid target is demonstrated to work well up to ~ 200 kW for pulsed sources and ~ 1 MW for CW application.

Liquid Targets

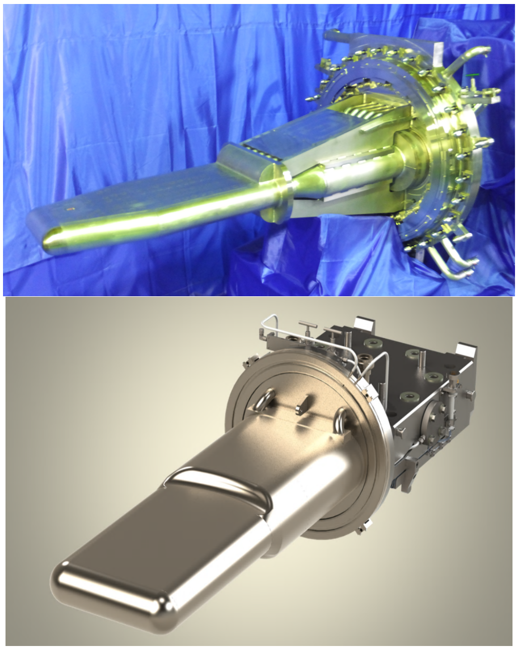

Figure 5: J-PARC (top) and SNS (bottom) targets.

The SNS and J-PARC neutron facilities are the first pulsed MW class spallation neutron sources and adopted a "second generation" liquid metal (Hg) target, to handle the pulsed MW level power levels. The mercury targets have the advantage of combining the high Z spallation material with the coolant function. The Hg circulates through a steel vessel, and has a heat exchanger remote from the interaction region. Figure 5 shows the SNS [8] and J-PARC [9] targets. These targets also contain an outer water-cooled shroud (visible in the photographs) encapsulating the separate steel vessel containing the mercury. This outer vessel's purpose is to contain any mercury that may leak from a failed inner vessel.

A consequence of the high instantaneous energy deposition for short pulse (< 1 μs) neutron sources is the generation of cavitation induced damage. The rapid heating of the Hg can create intense pressure waves, which generate local bubbles (Hg vapour) on the vessel wall. Those bubbles subsequently collapse, generating jets of Hg that impinge on the vessel wall and induce pitting damage. Figure 6 shows representative pitting erosion damage from a sample cored from the Hg facing wall of an SNS target containment vessel. Cavitation damage mitigation efforts include providing well-directed Hg flow directly adjacent to the vessel wall, and injection of gas bubbles in the Hg. An example of the directed flow cavitation mitigation is shown in Fig. 7. The left figure is from the inner wall of a nominal SNS target – which has regions of eddy and turbulent flow adjacent to the wall. A design modification was introduced to add a "jet" of direct Hg flow adjacent to this wall area (right figure), and erosion is greatly reduced. Both samples in Fig. 7 were operated for ~ 600 hours at 1 MW. Measurements at J-PARC indicate that the injection of gas bubbles entrained in the flowing Hg reduce the magnitude of the induced pressure pulse (and resultant vessel strain) by factors of 3-4. This not only alleviates direct vessel stress, but should also mitigate cavitation driven from the pressure pulse.

Figure 6: Representative cavitation induced damage on the inside wall of an SNS target vessel.

Mercury target operational experience has not been as favourable as with solid stationary targets. As discussed above, SNS has experienced 7 unanticipated target failures. J-PARC has also experienced 2 unanticipated target failures (weld issues) and operated at reduced power due to target concerns. There are well-identified paths forward to mitigate weld failure and cavitation failure issues. J-PARC plans to operate its target at 1 MW and SNS design is for 1.4 MW, with plans to upgrade to 2 MW.

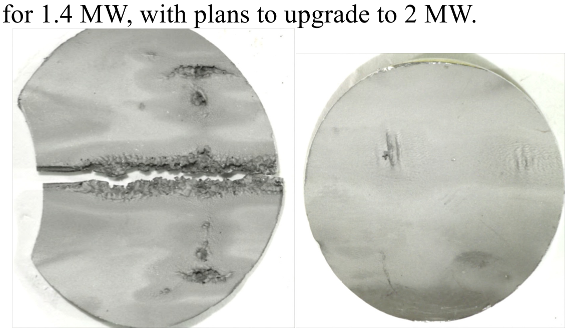

Figure 7: SNS target samples for nominal target (left) and jet flow (right).

Rotating Targets

Another approach to handling high power is to incorporate a rotating disk [10]. This approach has the advantage of retaining a high local power density (secondary particle production intensity), and spreading out the heat load to a larger volume over time. The ESS [11] is a 5 MW neutron source under construction in Sweden, will be the first long pulse spallation neutron source and incorporates a rotating target design, as shown in Fig. 8. The target is 10 cm tall with a 2.6 m diameter, and contains 6700 tungsten blocks. It incorporates He gas cooling, obviating the need to clad the tungsten. Challenges include assuring high quality fabrication of the blocks, holding the bricks in place while allowing for thermal expansion during the

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pulses, measuring the tungsten temperature during operation assuring stable configuration throughout the expected 5 year target lifetime, and high gas flow rates

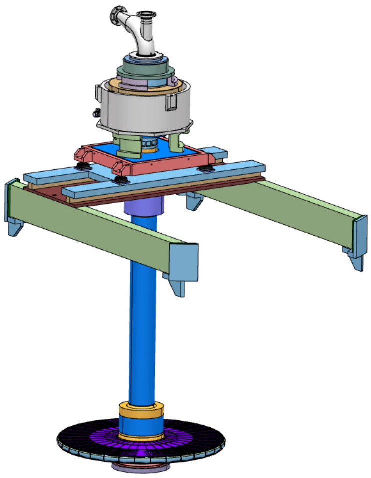

Figure 8: The ESS rotating target concept.

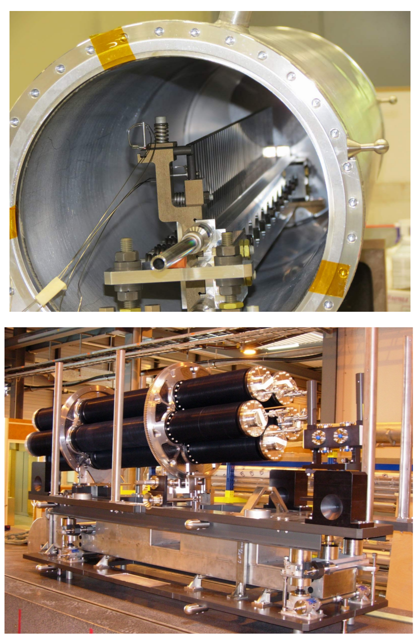

Figure 9: NOVA (top) and CGSN (bottom) neutrino targets.

Neutrino Targets

High power proton beams on fixed targets are used at high energy physics facilities for the generation of intense neutrino beams for long baseline oscillation experiments. This application has its own issues and constrains. These targets tend to be long and narrow, so that the generated pions (which subsequently decay to neutrinos) can escape and be captured by an encompassing electromagnetic focusing "horn" region of the target assembly. The targets are typically long (~1.5 m) and narrow (~ 1 cm diameter) graphite rods. The impinging proton beams are typically much higher energy than the neutron sources (100-400 GeV), much more focused (~ mm RMS transverse size), and have much higher instantaneous heat loads than the neutron source targets. A challenge of these designs is the long narrow target assembly fitting within the nearby focusing horn.

The NOVA neutrino target in use at FNAL [12] will accommodate a 700 kW, 120 GeV beam. Water cooled Al plates pressing against the rod cool it. Earlier lower power level targets for the NuMI program did limit the operational beam power, but the present higher power FNAL NOVA targets have performed well. Future plans for the LBNF/DUNE target station are 1.2 MW beam power on target with an upgrade to 2.4 MW. The CERN Neutrino Grand Sasso (CNGS) neutrino source operated at 500 kW with up to a 440 GeV proton beam. The CGSN target [13] is radiatively cooled. Figure 9 shows the NoVA and CNGS target assemblies.

Other Applications

The KOMAC [14] facility in S. Korea is a general purpose proton accelerator, including radio-isotope production. This application typically uses beams of ~ 100 MeV, and water cooled solid targets of different material, depending on the desired isotope product. Concerns include long-term maintenance given the high activation levels, and cooling loop contamination from target leakage.

A novel target concept is being pursued by the Accelerator Driven Subcritical-system effort at the IMP in China (C-ADS) [15]. This application will require a very high CW proton beam power (10's of MW) spallation target surrounded by a sub-critical fissile assembly. A gravity fed dense granular material (e.g. sand hour-glass) approach is being considered. The granular material serves as both the spallation material and the heat removal media (a secondary heat exchanger is employed after the material has fallen below the interaction region). On-going prototype tests are being pursued.

SUMMARY

Table 1 gives a summary of high-level proton beam and target parameters for some high power neutron and neutrino facilities. A key characteristic is the high local power deposition – driven by the desire to produce intense secondary beams. The pulsed beam sources have even higher instantaneous power deposition rates.

Solid stationary targets are a proven robust approach. The second generation liquid targets have experienced failures, but efforts are underway to mitigate this. Finally, the next generation of high power beam proton applications are adopting a rotating target approach to distribute the high power deposition.

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Table 1: Target Parameter Summary

	Target Type	Avg. Power (MW)	Beam Energy (GeV)	Beam Time Structure	Power deposition (MW/m3)	Power deposition, instant. (GW/m3)
Neutron Sources: Solid Target						
Lujan (LANL)	Ta clad W	0.1	0.8	20 Hz x 250 ns	250	50,000
ISIS TS1	Ta clad W	0.144	0.8	40 Hz, < 1 μs	400	
PSI	Pb in Zr tubes	0.94	0.59	CW	820	NA
KOMAC (isotope prod.)	Solid / water cooled	0.03	0.1	30 Hz x 0.5 ms	350	
Neutron Sources: Liquid Target						
J-PARC	Hg in SS vessel	1	3	25 Hz x 1 μs	430	
SNS - FTS	Hg in SS vessel	1.4	0.94	60 Hz x 700 ns	552	10,000
Neutrino Sources						
CERN CNGS	Graphite	0.5	1.4-440	7 ns pulses		> 10^6 (?)
FNAL NO-vA	Graphite	0.750	120	0.75 Hz x 10 μs	470	$7x10^4$ (?)
Future Neutron Sources						
ESS	Rotating W, He cooled	5	2	14 Hz x 2.9 ms	90	80,000
SNS - STS	Rotating W, water cooled	0.47	1.3	10 Hz x 700 ns	18	20,000

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