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Target Performance at the Low Energy Neutron Source

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Abstract

The Indiana University Low Energy Neutron Source (LENS) production target was recently upgraded to handle the high power 13 MeV proton pulsed beam. The target, a 2 inch diameter beryllium disk, is 1.2 millimeters thick allowing the 13 MeV protons to pass completely through the target and stop in the cooling water eliminating the buildup of protons inside the beryllium. This change along with upgrading the cooling water system has produced the most reliable target to date for LENS operations. Details about the failure modes will be presented.

Keywords: Neutron Target; Beryllium target

1. Introduction

The LENS facility neutron production target's original requirements included many lofty goals based on the design of the proton accelerator. The proton accelerator was envisaged to supply 50 milliamps of protons at 13 MeV with a 5% duty cycle. This combined to specify an initial goal for an average proton beam power of 39 kilowatts.

This high proton beam power forced many design constraints on the Beryllium neutron production target. First, the target was made large in area to accept the uniformly spread proton beam. Secondly the target was turned 45 degrees relative to the beam to further distribute the heat load. The target cooling system evolved after several design studies in recognition of the challenges associated with this power goal. This cooling system had hypervapotron cooling channels machined into the back of the Beryllium surface. These channels force turbulent flow, which wash away any steam bubbles that form from the high heat load and typically lead to a factor of 2 or 3 increase in the critical heat flux over that for a flat-plate geometry. A high pressure water system was included to maintain the hypervapotron action and minimize the steam bubbles on the back of the target.

The neutron production considerations imposed additional requirements on the target [1]. High efficient use of every neutron produced forces geometry and material constraints. The close coupling between the target and the cold methane moderator can greatly change the number of neutrons emerging from the

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moderator and therefore the flux of useful neutrons for the experimenter. The neutron reflector surrounding the target and moderator enhances this neutron flux. The rest of the neutron shielding surrounding the target, moderator and reflector affect the background neutrons. In addition the requirement of low gamma and beta radiation both during operations and residual time, produced constraints on the choice of materials.

At the end of the design and development phases, when budget and engineering realities set in, several of these design criteria were dropped. Specifically the 39 kilowatt maximum beam was reduced to 6 kW (with a retained goal of upgrading to 1kW3). In addition the hypervapotron design was dropped as this was very costly given the machining costs of Beryllium and is not needed at the lower power levels. Many other design details remained.

Thus the first production target was made with the following features (See Figures 1, 2, 3):

1. A large area (105 mm x 160 mm x 4 mm) flat beryllium plate. The thickness was chosen to stop the 13 MeV protons, hold a high pressure differential but still be thin enough to have adequate heat transfer to the water.
2. The targetwas held at a 45 degree angle to the proton beam. This was to spread out the beam power and put the target close to the cold methane moderator.
3. Aluminum target housing. Aluminum was chosen for the target housing material because of its transparency to neutrons and its low activation in a neutron field.
4. Aluminum metal seals on both sides of beryllium. O-rings were considered to be a source of failure in this high radiation area.
5. Aluminum bolts (studs) to compress seal. Aluminum hardware was again chosen for its low neutron activation and high transparency. Many large bolts were needed to achieve the compression force needed for the aluminum seals.
6. The whole target assemble is mounted inside the water reflector.

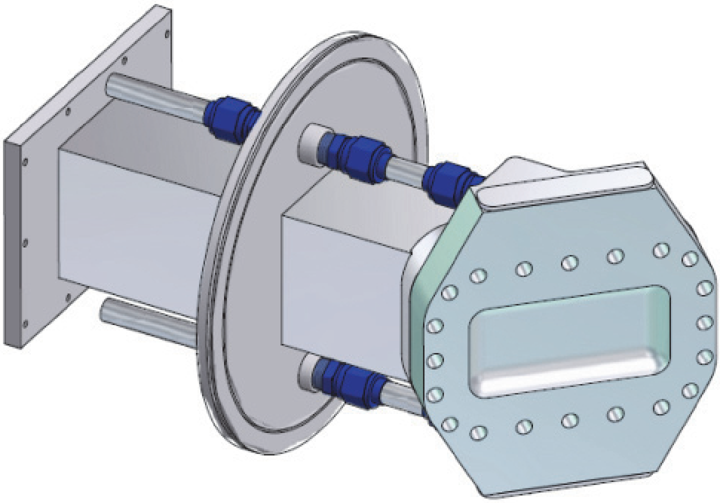

Fig. 1 Target Vacuum Chamber for the initial LENS target. The cavity in the middle increases the water between the target and the moderator, which provides premoderation and increases the neutronic coupling.

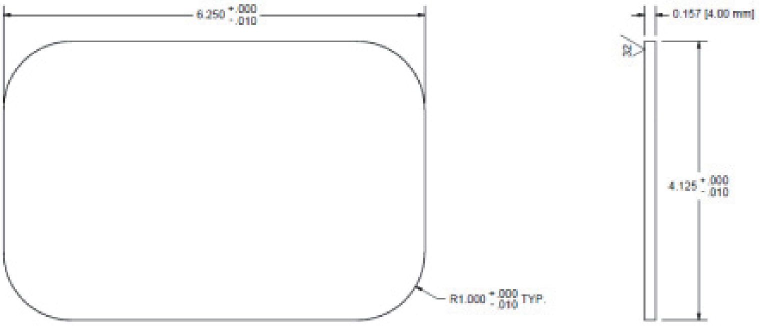

Fig. 2. Beryllium Target Blank for the target design used for initial operation of LENS. The large area was forced by a desire to minimize the power density at the envisage eventual 39kW power goal. This area, in turn forced a thickness of more than 3mm to sustain the pressure differential.

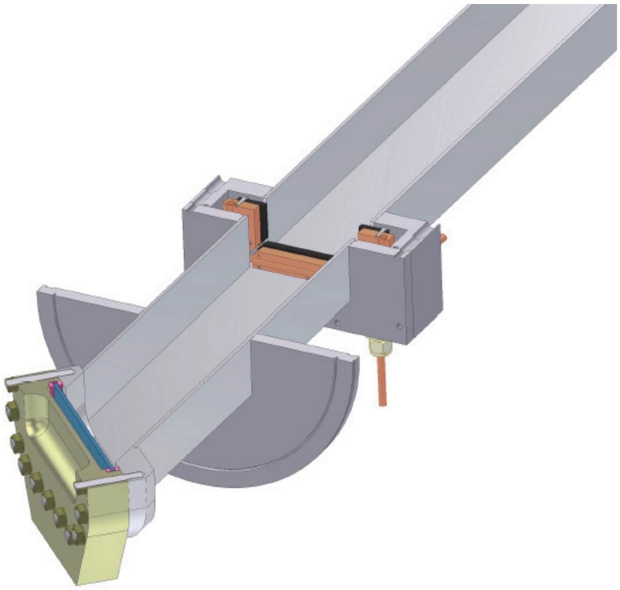

Fig. 3. Cut away view of beam pipe and target assembly. Upstream from the target you can see a set of graphite slits used to constrain the proton beam and provide diagnostic information regarding its position.

2. Target Failures

The target system described above was used in the commissioning phases and the first production running of the LENS facility. This target failed a number of times during this early operation phase. During each failure new experience was gathered and used to guide further evolution of the target design. This section describes these failures and the learning experience. Recovery from any target failure takes many days: waiting for radiation decay, unstacking shielding, removing the highly radioactive (typically 5 Rem/hr on contact) beryllium target, cleaning the vacuum system, reassembling the system and waiting for vacuum recovery.

The first target failure mode is displayed in Figure 4. The beryllium target cracked letting the cooling water enter the vacuum chamber (note cracks outlined on beam side picture in Figure 4). Notice that on the beam side, the proton beam image (in dark color) shows a rectangular shape (enlarged by the 45 degree angle) as delivered in the beam optics. Notice the buildup of gunk on the water side of the beryllium target. This gunk is actually thick enough to flake off.

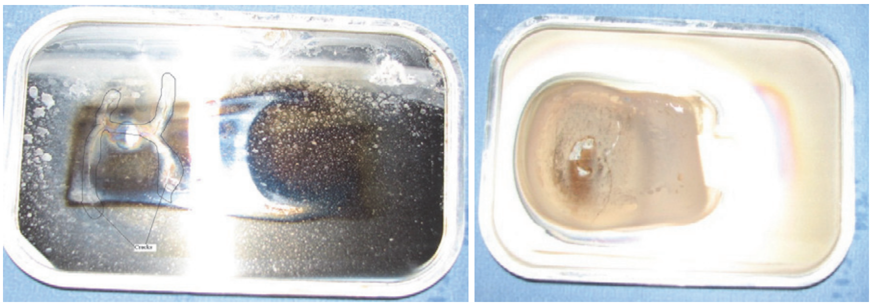

Fig. 4. First Target Failure Beam on right, water side on left.

The problem for this target failure was determined to be the “gunk” buildup on coolant side of target lead to loss of cooling power. The solution was to change the cooling system to all aluminum water system minimizing galvanic reactions with Al and copper, putting sodium nitrate water additive and adding a sacrificial element in cooling loop. As seen below these simple changes succeeded in limiting this buildup for modest levels of radiolysis in the cooling water, however these techniques were inadequate in a later design in which the target was made thin enough to allow proton-induced radiolysis in the cooling water.

The aluminum seals were the cause of the second target failure mode associated with this design. The turning on and off of the proton beam causes the beryllium target blank to expand and contract. This movement at the aluminum seal location eventually wore a vacuum leak at this location. This seal was changed to have elastomer O-rings on both the vacuum and water sides of the beryllium blank. The redesigned seals are shown in Figure 5.

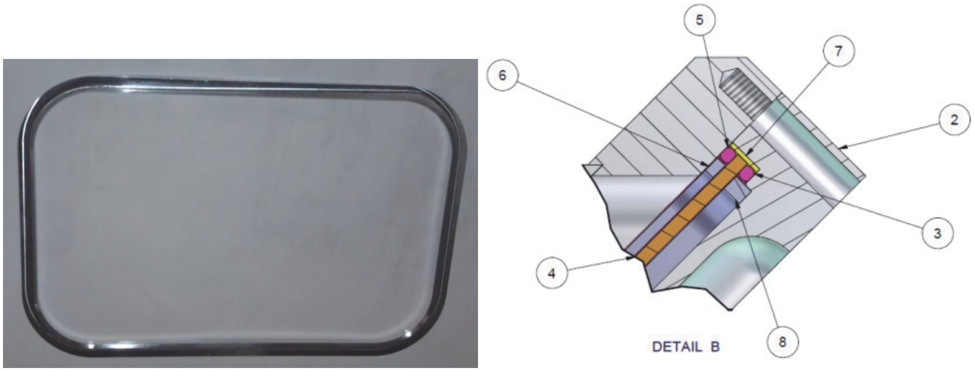

Fig. 5. O-ring redesign of target seals. In detail B (the blowup of the target corner) items 3 and 5 are the new O-rings. Item 4 is the target blank.

The third failure mode associated with this initially-deployed target design was hydrogen impregnation of the target itself. At 13 MeV proton energy, 4 kW of beam power and a week of continuous operation (roughly 670 kW-hr of beam) a vacuum excursion was observed which shutdown the accelerator (closing a fast-acting valve installed to protect the accelerator in the event of a coolant breach of the target). Upon examining the target system (See Figure 6), we found that the target was not breached, i.e. there was no water in the vacuum. Instead the target had blistered into the vacuum. After much discussion, the cause of this blister was determined to be the protons stopping in the beryllium and not migrating out until the concentration reached the point where internal pressure exceeded the strength of the material (as reduced by supersaturated hydrogen). When enough protons were put into the target blank, it blistered and the hydrogen being released caused the vacuum excursion.

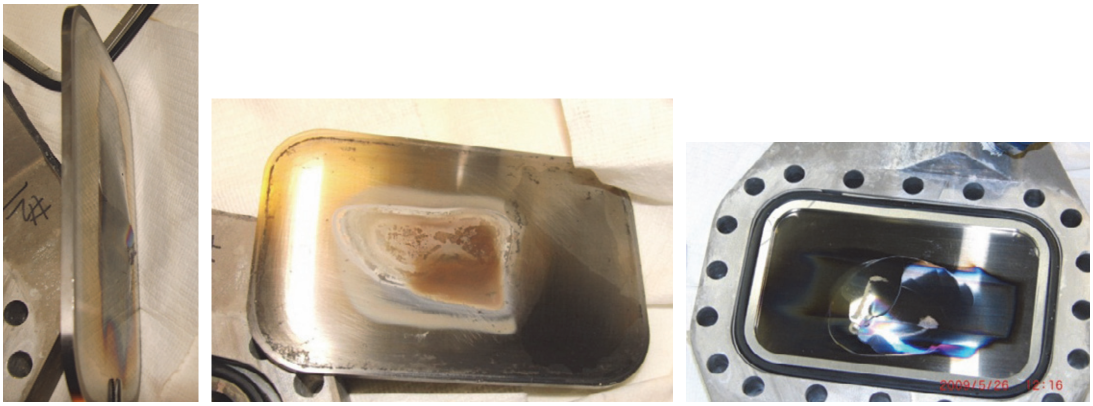

Fig. 6. Hydrogen impregnation failure at 13 MeV

Figure 7 shows a similar target failure. This failure occurred after making the beam smaller. This smaller beam size was thought to make the target hotter which would allow the hydrogen to migrate out faster. The target failure is very similar to the previous except for the smaller blister.

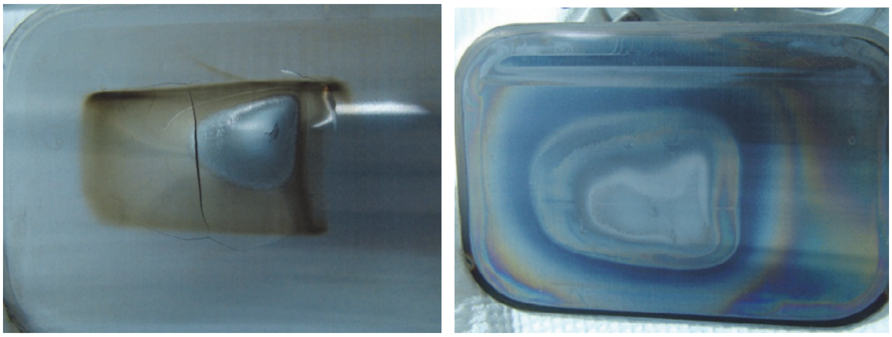

Fig. 7. Hydrogen impregnation failure at 13 MeV with a smaller beam spot size

The diffusion of hydrogen within the Be at 200 C (5x10-14 cm2/s [2]) is simply not sufficient to allow it to migrate the roughly 1mm to the vacuum interface as rapidly as it builds up in the Bragg peak for a 4kW beam. The average concentration of hydrogen inside the beryllium at the observed point of failure is on the order of 1%, which is far above the negligible solubility of hydrogen in this metal.

Figure 8 shows a target failure from hydrogen impregnation at 7 MeV proton energy. At 7 MeV the protons range out in 0.5 mm of beryllium as opposed to 1.2 mm at 13 MeV. This failure occurred when the accelerator was with only 2 cavities because of klystron problems. Here the vacuum excursion occurred after a few days of operation. Because the vacuum excursion was small, beam operation was continued after several excursions. Eventually the target broke. Upon opening of the target system, it was discovered that each new blister had been burnt through with the proton beam. This blister of beryllium had been deposited on the vacuum walls of the target chamber. Cleanup after these events took significantly longer.

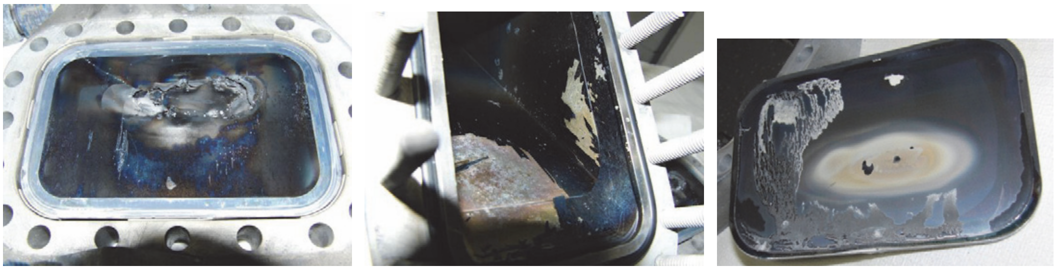

Fig. 8 Multiple Target Failures at 7 MeV

Figure 9 shows a target failure at 7 MeV after only one vacuum excursion. The blister measures 0.5 mm.

Fig. 9. Target failure at 7 MeV

3. New Target Design

After these target failures a new target system was designed. The major new constraint of this design was to avoid having the proton beam stop in the beryllium in order to prevent this blistering problem. The thickness of the target was carefully chosen so that the 13 MeV protons go through the beryllium and stop in the cooling water. As seen in Figure 10 a 1.2 mm thick beryllium target degrades the energy from 13 MeV to 2 MeV with this last 2 MeV energy deposited in the cooling water behind the target. This last 2 MeV of proton energy stopping in the water, but since their energy is below the threshold for the (p,n)^{9}Be reaction, this does not result in any significant decrease in the primary neutron flux.

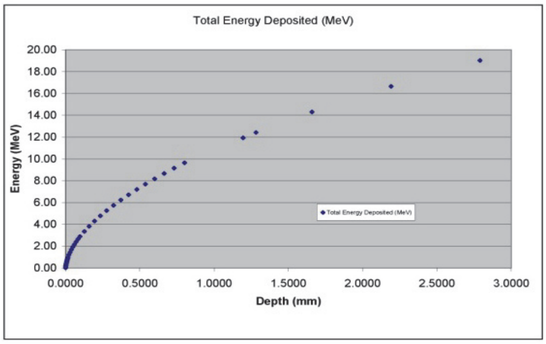

Fig. 10. Energy deposited versus material depth for protons on beryllium.

This design constraint forces other changes to the target system. The target can no longer be at 45 degrees to the proton beam, increasing the distance from the target to the cold moderator. Initially it was feared that this would cause additional loss in cold neutron flux, but subsequent spectral measurements suggest that the increased water between the target and the moderator resulted in a more efficient premoderator which acted counter to the reduction expected from decreased geometric coupling.

Secondly the thinner target forced a smaller target area since the thinner target will still have to support the differential pressure of the water cooling system against the vacuum.

The smaller target area forced beam optics changes to make smaller proton beam size and also change to the beam collimation system. The new beam size is shown in Figure 11.

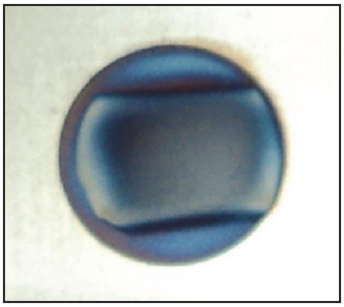

Fig. 11. Proton beam image with the new target and collimators.

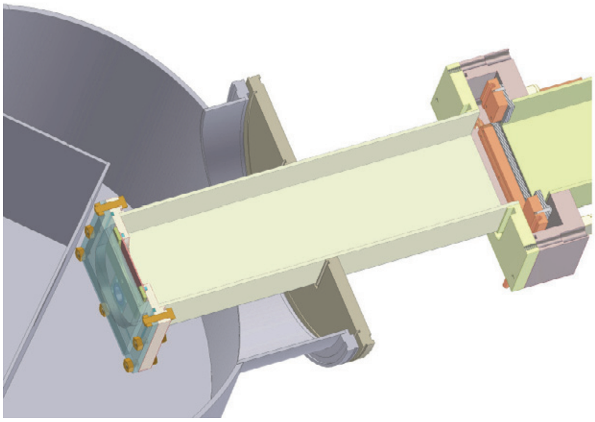

Fig. 12. Cut away view of the new target assembly.

The new target assembly is shown in an exploded view in Figure 13. As shown the beryllium is a 63.5 mm diameter x 1.2 mm thick flat disk, oriented perpendicular to the proton beam. The target has an O-ring seal (50 mm ID) on the vacuum side of Beryllium and an aluminum cover plate held with 6 small screws (SS) holding cover plate to compress seal. The water cooling is across the back of the target plate. The whole system can be simply disassembled for changing the target quickly. The whole system is made of aluminum except for the smaller screws and was hard anodized to minimize water corrosion.

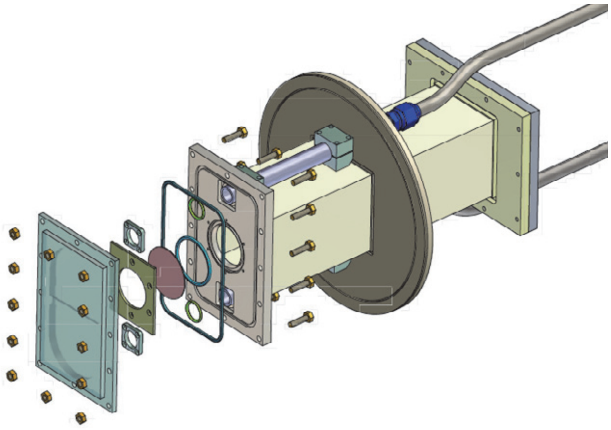

Fig. 13. Exploded view of the new target system.

4. New Water System

The first operating experience with the new Target ended with a vacuum break after about 200 beam hours. This failure seen in Figure 14, was caused by junk buildup on the back of the target and little buildup elsewhere. This failure forced another upgrade to the target water system, since the proton beam hitting the water is roughly 2 orders of magnitude more intense than the neutron beam leaving the target, and therefore the problem with water radiolysis is much more pronounced with this new design.

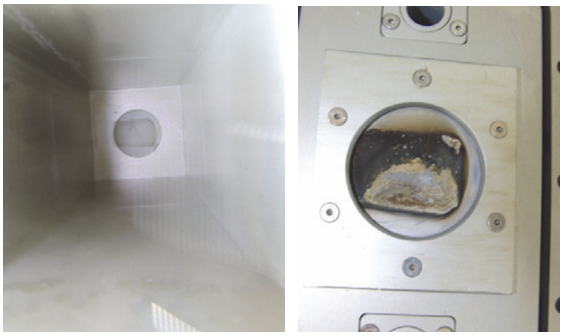

Fig. 14. New Target failure; beam side on left and water side on right.

The target water system which consisted of a charcoal filter, a 20 micron filter followed by a 5 micron filter was augmented with a de-Ionizing filter (Pentek model BBF1-20MB). This additional unit raised the resistivity a factor of 10 to > 1 Mohm-cm and dropped the total dissolved solids (TDS) to < 0.5 milligrams/liter. The water system flows 5 gallons per minute behind the target with a target pressure of 5 PSI. Current practice has this de-ionizing filter being changed every 4 months as the resistivity starts to go below 1 Mohm-cm.

5. New Target Latest Failure – O-Rings

After the water system changes this new target design lasted 600 Beam Hours @ 3 kW before we again experienced vacuum excursions in the proton delivery system. The assembly is shown in Figure 15. Notice that the water side of the target is quite clean and the beam side shows a beam image which fills most of the area of the beryllium. The difficulty on this occasion was a failure of the O-ring around the beryllium target was hard from radiation damage, the target itself was intact and relatively clean. All the O-rings were replaced with Viton. Since that change the current target has run for 760 beam hours at 3 kilowatts, and no problems have yet been encountered with its operation.

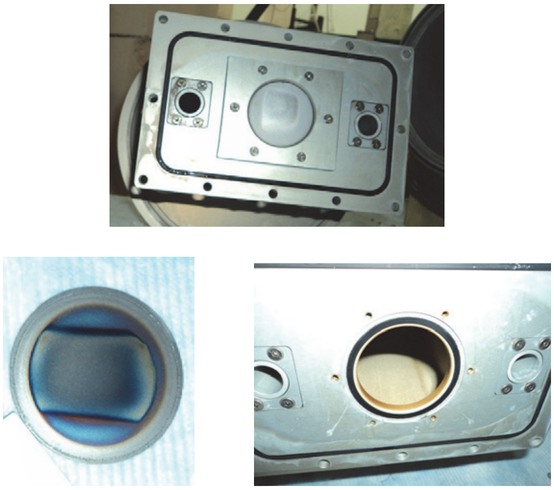

Fig. 15. Latest target failure, an O-ring failure attributed to radiation damage: Top is water side, left bottom is beam side of the beryllium and right is target housing.

6. Summary

The LENS target system has been redesigned based on failures modes. This new target has a thickness of 1.2 mm chosen so 13 MeV protons stop in the cooling water not in the target. The target area is now 50 mm diameter to hold the pressure differential of the cooling water to the vacuum. The proton beam is focused and collimated to this size to fit inside this 50 mm. The cooling water system now includes De-Ionizing filters which have eliminated the junk buildup on the backside of the beryllium target. The water system is monitored for resistivity and total dissolved solids to replacing filters. The current LENS target design has now outlasted all others by a factor of 2 in beam hours.

References

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