Mitigation of helium-induced tungsten morphology change using the tamped target design*

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HAPL Chamber Problem

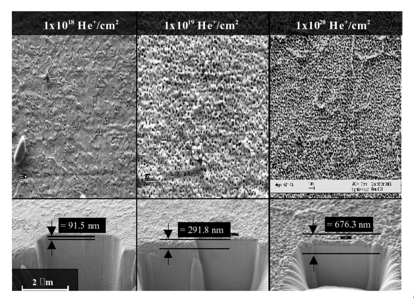
The reference HAPL chamber design consists of a 10.5 m radius chamber with an ambient temperature of 600 °C and a nominal background gas pressure of 0.5 mtorr. 365 MJ deuterium-tritium targets are imploded in the chamber at a rate of 5 Hz. Until recently, it was thought that the first wall and breeding blanket lifetime was limited by neutron damage. Recent experiments with low-energy helium ion bombardment performed by the University of Wisconsin – Madison Inertial Electrostatic Confinement (IEC) experimental group indicate significant erosion of the plasma-facing surface due to alpha particle implantation. The limiting factors of the armor and/or first wall lifetime now appear to be:

1. Neutron damage due to atomic displacements in the crystal structure (DPA lifetime).
2. Thermal stress due to rapid cyclical temperature rise.
3. Morphology change and armor erosion due to low-energy alpha implantation.
4. Armor erosion due to high-energy alpha accumulation in subsurface grain boundaries.

MCNP neutronics simulations show that the DPA lifetime of the first wall and blanket structures is approximately 3¼ full-power years (FPY). The chamber radius was specified to be 10.5 m, based on thermal analysis that limits the temperature rise on any given target shot to 2400 °C with tungsten armor.

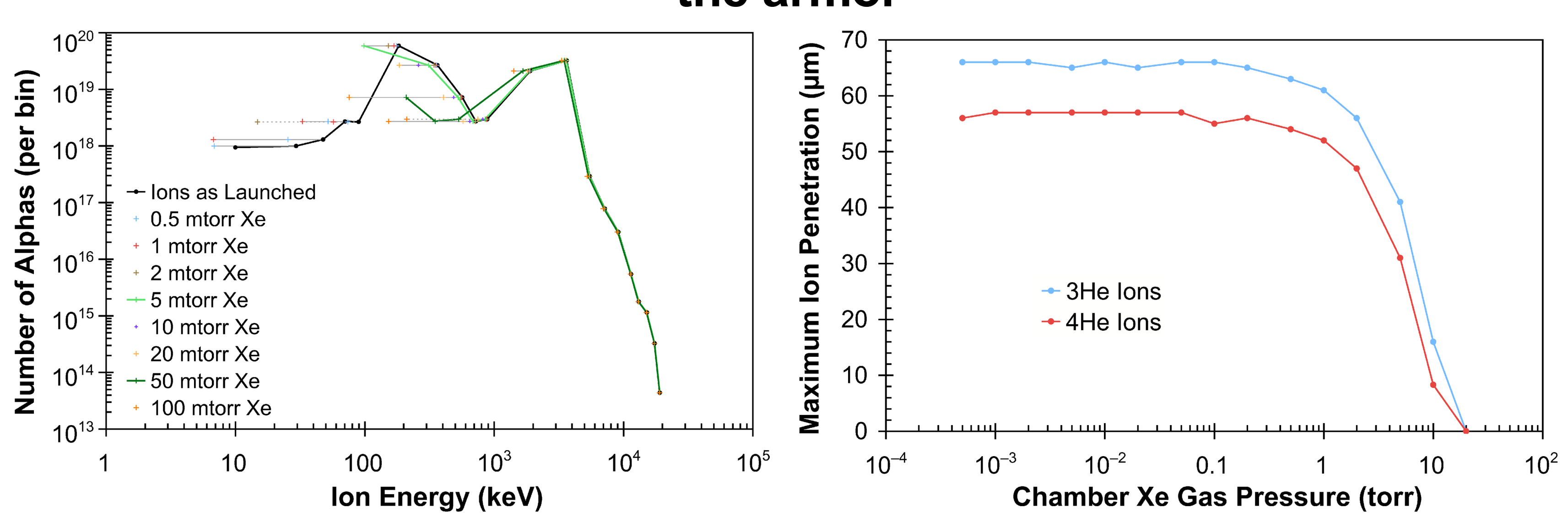
IEC experiments show that low-energy alpha implantation erodes the tungsten armor at rate of 1.1 μm per 10^{19} ions/cm². The current HAPL chamber design is based on a 250 μm layer of tungsten over a ferritic steel substrate. Based on the erosion rate from the IEC experiments and the alpha ion spectrum produced by simulations performed at Lawrence Livermore National Laboratory (LLNL), the tungsten armor will erode at a rate of 126 μm/FPY. Thus, the tungsten armor will be completely eroded in just under 2 FPY, neglecting the damage done by the high-energy (above 600 keV) alpha particles.

IEC Helium Ion Implantation Experimental Results

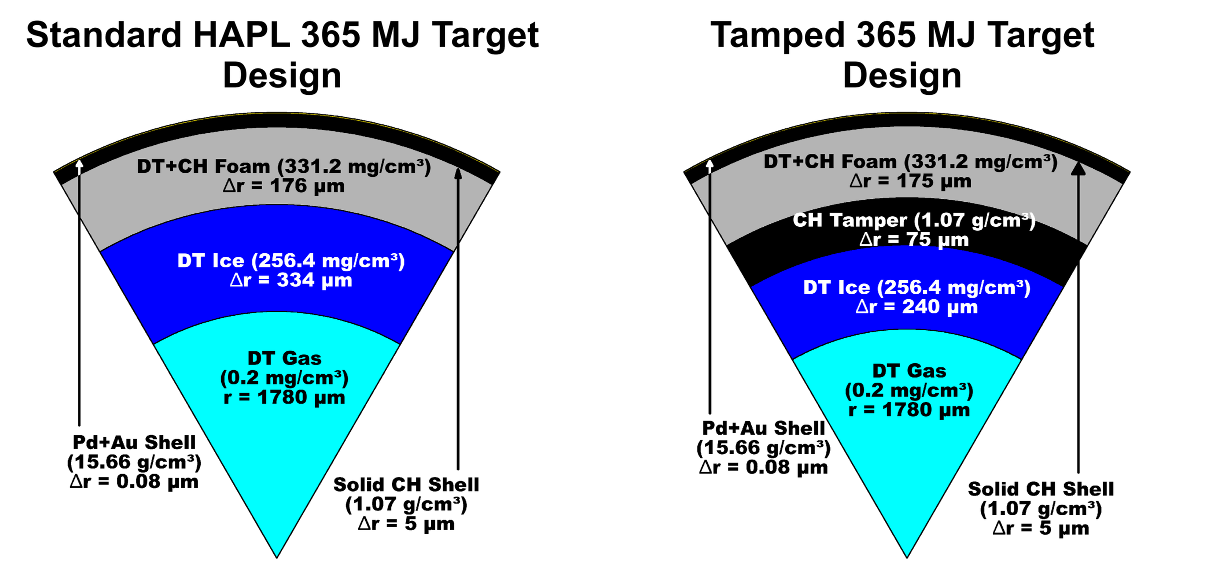


To prevent the low-energy alpha implantation from becoming the lifetime limiting damage mechanism, steps must be taken to prevent the low-energy alphas from reaching the armor. One can stop the ions by introducing a buffer gas. First we explored the possibility of stopping all alpha particles from reaching the armor by simply increasing the pressure of a xenon buffer gas. Our simulations indicated it would take an excessive amount of gas — on the order of 20 torr — to stop all alphas from impacting the armor. The amount of buffer gas required was determined to be unacceptable due to frictional target heating during injection into the chamber.

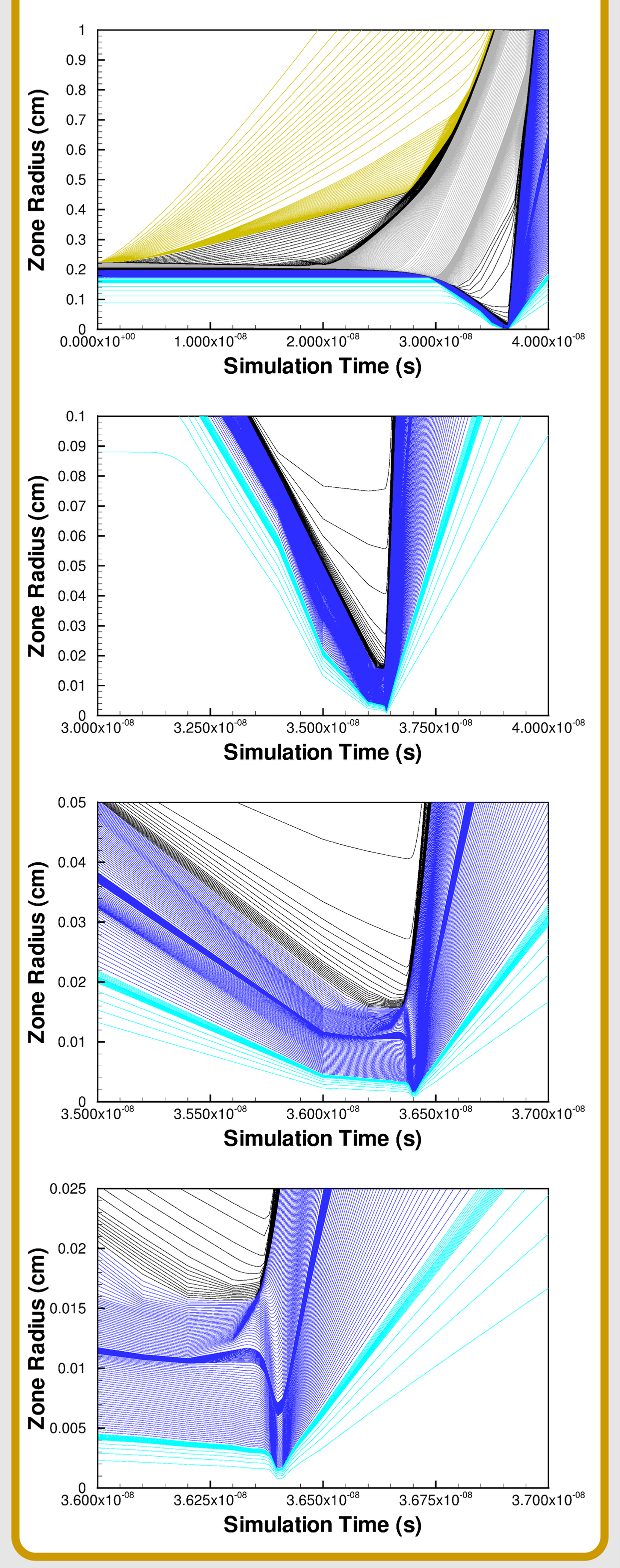
Xenon buffer gas causes alphas to lose energy before impacting the armor



Tamped Target Solution



1-D BUCKY Simulations show good target compression and burn



To prevent the alphas from reaching the tungsten armor, 0.35 g/cm² of areal density must lie between the burning DT plasma and the tungsten armor. This can be achieved via a high-pressure buffer gas (see previous panel) or the introduction of a tamper into the target design. The tamper is a material that lies in the compressed core of the target and reaches the appropriate ρR value of (0.35 g/cm²) during the fusion burn process.

For the purposes of this analysis, a 75 μm plastic tamper was added to the HAPL target between the DT ice and ice-wicked plastic foam layers. 1-D BUCKY simulations were performed that achieved a 364 MJ fusion yield using the same driver energy (2.4 MJ) and power profile as the original HAPL target design.

Plotted below are the x-ray and alpha spectra from both the HAPL target (produced by LLNL) and the BUCKY simulation of the tamped target design. Note that the energy from the high-energy alphas has been converted to x-rays by virtue of being stopped in the tamper region (0.5% of the fusion alphas escape the tamper).

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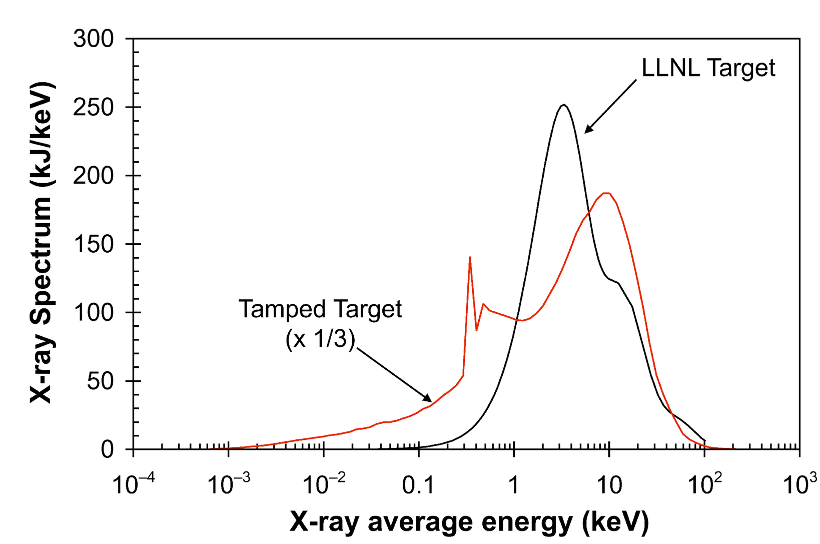
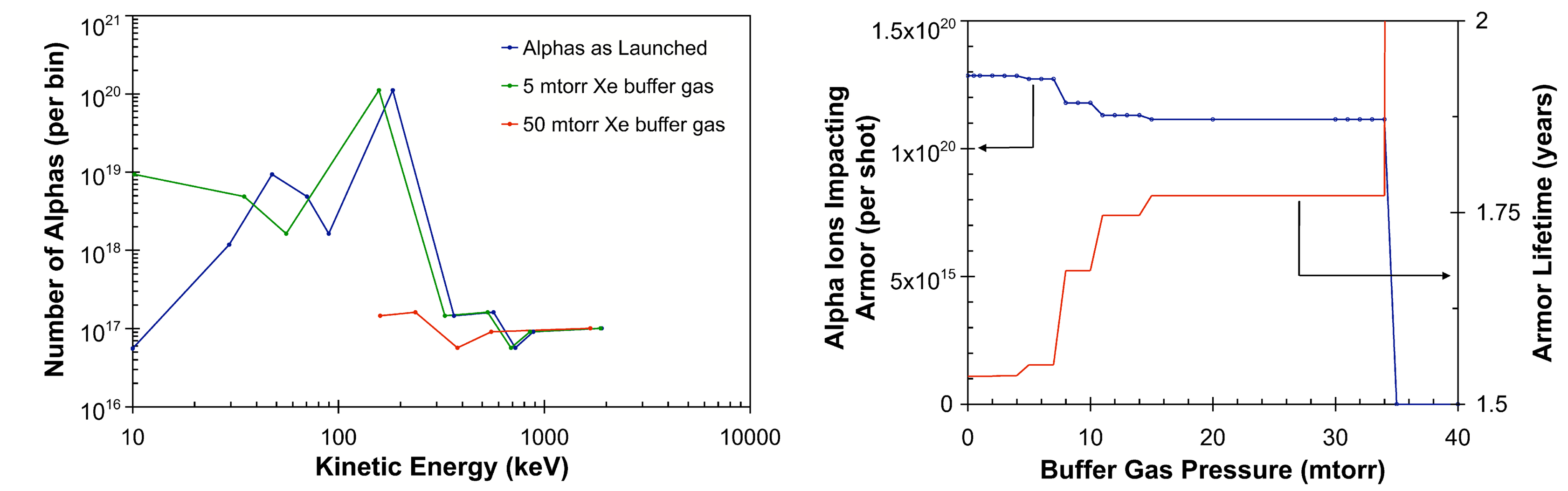
Comparison of x-ray and alpha spectra from the LLNL and Tamped Targets shows significant improvement in the threat spectra



Chamber Buffer Gas is Essential

Xenon buffer gas stops the low-energy alphas, causing a significant increase in armor lifetime at a pressure of 35 mtorr

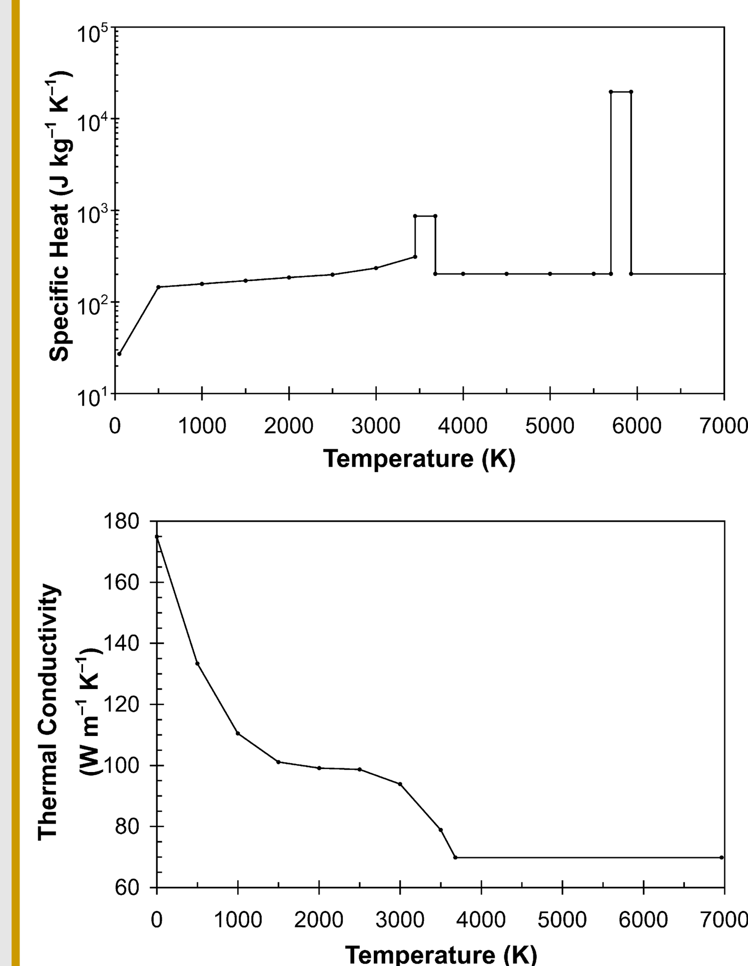


By itself, the tamped target design reduces the armor lifetime (from 2 FPY to 1½ FPY) by the production of more low-energy alpha particles. The tamped target design is only viable if used in conjunction with a low-pressure xenon buffer gas. Adding 35 mtorr of xenon buffer gas at 600 °C to the chamber is sufficient to stop nearly all alphas (see above), increasing the tungsten armor lifetime to 357 FPY (neglecting high-energy alpha and neutron damage).

As shown below, the tamped target design in conjunction with 35 mtorr of xenon buffer gas also satisfies the thermal stress limiting criterion of a surface temperature maximum of no greater than 2400 °C.

Additional 2-D simulations need to be performed to ensure that the target has enough hydrodynamic stability to ignite and burn without drastic modifications to the laser power profile or total driver energy delivered to the target.

1-D BUCKY Simulations show good target compression and burn



Tungsten Armor Surface Temperature — 10.5 m radius Chamber