UCRL-CONF-216959

Using Laser Entrance Hole Shields to Increase Coupling Efficiency in Indirect Drive Ignition Targets for the National Ignition Facility (NIF)

D. A. Callahan, P. A. Amendt, E. L. Dewald, S. W. Haan, D. E. Hinkel, N. Izumi, O. S. Jones, O. L. Landen, J. D. Lindl, S. M. Pollaine, L. J. Suter, M. Tabak, R. E. Turner

November 9, 2005

American Physical Society Division of Plasma Physics
Denver, CO, United States
October 24, 2005 through October 28, 2005

Using Laser Entrance Hole Shields to Increase Coupling Efficiency in Indirect Drive Ignition Targets for the National Ignition Facility (NIF)

D. A. Callahan, P. A. Amendt, E. L. Dewald, S. W. Haan, D. E. Hinkel, N. lzurni, 0. S. Jones, 0. L. Landen, J. D. Lindl, S. M. Pollaine, L. J. Suter, M. Tabak, R. E. Turner
Lawrence Livermore National Laboratory

Abstract:

Coupling efficiency, the ratio of the capsule absorbed energy to the driver energy, is a key parameter in ignition targets. The hohlraum originally proposed for NIF coupled ~11% of the absorbed laser energy to the capsule as x-rays. We describe here a second generation of hohlraum target which has higher coupling efficiency, ~ 16%. Because the ignition capsule's ability to withstand 3D effects increases rapidly with absorbed energy, the additional energy can significantly increase the likelihood of ignition. The new target includes laser entrance hole (LEH) shields as a principal method for increasing coupling efficiency while controlling symmetry in indirect-drive ICF. The LEH shields are high Z disks placed inside the hohlraum to block the capsule's view of the cold LEHs. The LEH shields can reduce the amount of laser energy required to drive a target to a given temperature via two mechanisms: 1) keeping the temperature high near the capsule pole by putting a barrier between the capsule and the pole, 2) because the capsule pole does not have a view of the cold LEHs, good symmetry requires a shorter hohlraum with less wall area. Current integrated simulations of this class of target couple 140 kJ of x-rays to a capsule out of 865 kJ of absorbed laser energy and produce ~ 10 MJ of yield. In the current designs, which are not completely optimized, the addition of the LEH shields saves ~ 95 kJ of energy (about 10%) over hohlraums without LEH shields.

Introduction:

In indirect-drive inertial confinement fusion (1CF), the laser energy is converted into x-rays in a high-z hohlraum and those x-rays are then used to drive the capsule. This means that the coupling efficiency--the fraction of the total energy that ends up in the capsule--is an important parameter because it determines how much laser energy is needed to drive a given capsule. The first step in the process is for the laser photon to be converted into x-rays. This happens with a conversion efficiency; in a hohlraum, the conversion efficiency is quite high (~ 85%). Next, we consider where the x-rays can go. In a laser hohlraum, there are three places the x-rays can go--they can heat up the hohlraum walls, they can escape out the laser entrance hole (LEH), or they can drive the capsule. Typically, ~ 60% of the energy is used heating the hohlraum walls, ~ 30% of the energy escapes out the LEH, and ~ 10% of the energy ends up in the capsule. Although these numbers are rough estimates, they point out the importance of the coupling efficiency; if we can improve coupling efficiency, then a smaller laser can drive the same capsule. For a fixed-size laser, higher coupling efficiency means that the laser can drive a larger capsule; since larger capsules tend to be more robust, high coupling efficiency can translate to improved target robustness.

Over the past several years, the NIF ignition targets have been evolving to improve coupling efficiency. The effect of these changes is seen in Table 1. The first change shown in Table 1 is the change from a plastic (CH) ablator to a beryllium ablator. Since beryllium absorbs more energy due to its lower opacity, this results in an increase in the coupling efficiency. The second change was to move from a gold hohlraum to one made up of a mixture of materials (a "cocktail"). It has been shown that by mixing appropriately chosen materials, we can fill in the "gaps" in the opacity of a single material and the end result is a material with higher opacity than either of the components. Since the opacity of the hohlraum wall material is one of the factors in determining how much energy is used to heat the hohlraum walls, this is an important consideration--higher opacity results in lower wall loss. The combined effect of these two improvements--beryllium capsule and cocktail hohlraum--improves the coupling efficiency from 9.7% to 13%.

The final improvement is the addition of laser entrance hole (LEH) shields. The LEH shields are high-Z disks that are placed in the hohlraum between the capsule and the laser entrance hole. The LEH shields serve to block the capsule's view of the LEH, which is cold compared to the hot hohlraum walls. As we will discuss in the next section, the addition of the LEH shields allows us--in fact, requires us--to shorten the hohlraum. The shorter hohlraum has less wall area to heat and so it reduces the wall loss. This leads to another increase in the coupling efficiency. In the current generation of designs, the target with a beryllium capsule, cocktail hohlraum, and LEH shields has a coupling efficiency of 15%. Put another way, the total increase in coupling efficiency has reduced the size of the laser needed to drive a capsule that absorbs 140 kJ of x-rays by 33% -from 1.45 MJ down to 950 kJ.

Symmetry with LEH shields:

In general, we characterize asymmetry by decomposing into Legendre modes. We are generally concerned with modes P_2 and P_4 (see figure 1). Odd numbered modes are small because the target has left/right symmetry. Higher order modes tend to be smoothed by radiation transport smoothing [1] so they are generally less of a concern.

In standard NIF targets, we achieve symmetry by the placement of the two cones of beams (two cones per side) and by the relative strength of the two cones of beams (see figure 2). The capsule "sees" the hot laser spots and the cold laser entrance hole (LEH); we need to arrange the hotspot locations and relative strengths to balance these. The first step is to balance P_2, which is a measure of the relative strength of the drive at the capsule equator versus the strength of the drive at the capsule pole. Because the capsule sees the cold LEH, the NIF laser was designed to have 2/3 of the beams (and, hence, 2/3 of the energy) in the outer cone (the cone closest to the LEH) and 1/3 of the energy in the inner cone (the cone closest to the capsule equator); this choice of relative strengths balances out the P_2 symmetry.

The next step is to balance out P_4, which is a measure of the relative strength of the drive near 45 degrees vs the relative strength at the pole and equator. As is shown in figure 1, P_4 has two zeros in each quadrant of the capsule. We can balance the P_4 asymmetry by moving the laser hotspots relative to these zeros.

We have one additional method for tuning symmetry at our disposal. Since the two cones of beams can have different pulse shapes, we can change the fraction of the energy that is in each cone as a function of time. This allows us to control time-dependent swings in the P_2 symmetry. For example, when we want to increase the hohlraum temperature to launch a shock, we can increase the power in the inner cone before we increase the power in the outer cone. We might want to do this because the inner cone beams have a longer path length to the wall and so it takes longer for the inner cone beams to heat the material in the laser path.

When we add an LEH shield to the target, we change the symmetry. We still use these same basic techniques to "tune" the symmetry, however. If we take a standard NIF hohlraum and add LEH shields, then the capsule will see a drive that is too hot on the pole. This is because the capsule's view of the cold LEH is now blocked since the capsule “sees” the shield instead. To compensate for this, we move the outer cone of beams closer to the capsule equator so that they contribute more to the capsule equator and less to the capsule pole. As we move the outer cone beams, we can reduce the length of the hohlraum; this results in less hohlraum wall area to heat up and reduces the wall loss.

We can tune the P_4 symmetry by moving the laser hotspots relative to the zeros of P_4, just as we did for the standard hohlraum. Figure 3 shows the results of a viewfactor calculation showing this effect. In the viewfactor calculation, we model the laser spots as sources on the hohlraum wall. We then move the outer cone of beams relative to the center of the hohlraum and change the fraction of the energy in the two rings to balance out P_2. We scan over a variety of outer cone locations and monitor the P_4 asymmetry at the location of the capsule. The result of doing this is shown in figure 3. We see that by moving the outer cone of beams we can change the sign of P_4 from negative to positive.

Design of a helium-gas-filled target with LEH shields:

One of the sources of time-dependent asymmetry in NIF targets is motion of the laser spots due to hydrodynamic expansion of the hohlraum wall. As the wall heats, it expands and moves inward toward the capsule. Since the laser beam pointing is not changing, this means that the location of the laser spots move in time. Motion of the laser spots results in time-dependent changes in the symmetry on the capsule. To reduce this wall motion, we generally fill the hohlraum with a low-density, low-Z material to hold back the hohlraum wall. The low-Z material is transparent to the x-rays so that it does not interfere with radiation transport to the capsule.

We are currently exploring two hohlraum fill materials--helium gas and low-density glass ($Si0_2$) foam. There is a significant database of information on gas-filled targets from experiments done on Nova and Omega. Low-density (1 mg/cc) glass foam may be an attractive fill material, however, because the foam may allow non-cryogenic pre-ignition experiments. Current gas-filled targets would need to be cryogenic even if the capsule is not cryogenic because the window that holds the gas in the hohlraum is not thick enough to contain the gas pressure at room temperature. Since many tuning experiments can be done without a cryogenic capsule, fielding of pre-ignition experiments. In addition, experiments using hohlraums filled with low-density glass foam carried out on Omega have shown very promising results.

The helium-gas-filled target with an LEH shield is shown in figure 4. The target uses a cocktail hohlraum that is made up of 75% uranium and 25% gold. The hohlraum is lined with a thin (0.2

micron) layer of gold; the purpose of this layer is to prevent the uranium from oxidizing. (Adding oxygen to the hohlraum material adds excess heat capacity and increases the wall loss so it is to be avoided.) The capsule is a graded-doped beryllium ablator capsule [2] that is shown in detail in figure 5. The hohlraum is filled with 1 mg/cc helium gas that is held in the hohlraum by a 0.5 micron polyimide window. The LEH shield, which is made of the same cocktail as the hohlraum wall, is placed one millimeter from the capsule. It is 0.53 min in radius--nearly half the capsule radius. The LEH side and the edge of the shield are coated with 8 microns of CH to further reduce hydrodynamic expansion of the shield. The edge of the laser entrance hole is also lined with low-Z material (beryllium in this case) to reduce motion of the edge of the LEH. The laser power and resulting radiation temperature are shown in figure 6. The hohlraum reaches a temperature that slightly exceeds the required 300 eV.

The location of the shield is a compromise between two effects. If the shield is located too far from the capsule, then the inner cone of beams can hit the shield. This results in problems with both symmetry and getting enough energy into the region around the capsule and so it is to be avoided. If the shield is too close to the capsule, then the capsule-side of the shield does not have a clear "view" of the hot laser spots on the wall because it is shadowed by the capsule itself. If the capsule-side of the shield does not heat up quickly, then it is not very effective because the capsule "sees" a cold surface rather than a hot one. Placing the shield at about two times the capsule radius seems to be a good compromise. Figure 7 shows the hohlraum materials at 11 nsec, which is just before the peak power for the inner cone of beams. Shown in green are the 23 degree beams (the shallowest angle of the inner cone). The beams do clear the shield material at this time.

Figure 8 shows the ablation pressure asymmetry, decomposed into P_2 and P_4 moments as a function of time. The P_2 has a fairly significant swing just after the second shock is launched (around 7 ns). Otherwise, it if fairly well behaved with symmetry swings on the order of 5%. There is some evidence of early time P_4 asymmetry from about 1 ns to about 6 ns; this is during the time that the first shock is traversing the shell. Figure 9a shows the shape of the imploded core near ignition time. The dense fuel shows some pole-high P_2, which results in a pancake shape. The lower density contours on the outside of the fuel show some diamond-shape, which is characteristic of a P_4. While the symmetry of this calculation was good enough to produce 10.6 MJ of yield (out of a nominal 1-d yield of 12 MJ), future work will be needed to further optimize the symmetry. In particular, the hohlraum will need to be further shortened because this calculation had too much energy in the inner cone of beams (43% of the energy while the optimal fraction for the NIF configuration is 33%).

We can compare the symmetry of the target with LEH shields to a similar design without LEH shield (1.3 mg/cc He gas filled, cocktail hohlraum, graded-doped beryllium ablator). Figure 9a and 9b shows that comparison. We see similar features in the two imploded cores--both are slightly pancaked (although the LEH shield case is more so) and both show evidence of a higher density jet near the axis. The calculation without the LEH shield used 960 kJ of absorbed laser energy while the calculation with LEH shields used 866 kJ of absorbed laser energy. Although neither target is optimized, we currently see a 95 kJ of absorbed laser energy saved when we include LEH shields. Future work will concentrate on optimizing both of these designs.

Design of a glass-foam-filled target with LEH shields:

In addition to the helium gas filled target, we have done a design for a target with LEH shields that uses low density (1 mg/cc) glass aerogel foam fill rather than gas fill. Figure 10 shows a diagram of the target; it is very much like the He gas filled target with the difference being that the hohlraum is mainly filled with $Si0_2$ foam except for a nearly spherical region surrounding the capsule. The region surrounding the capsule has very low density (0.01 mg/cc) helium filled region. This was included in the design because there was concern about having the foam come in contact with the capsule; the structure of the foam might imprint on the capsule and cause perturbations. Instead, a "clear region" was included around the capsule to avoid problems.

A version of this target produced 9.3 MJ of yield from 864 kJ of absorbed laser energy. This calculation used the same pulse shape as the gas-filled design and with only minor changes to the power balance. This is very convenient since it means that the work we do on the design for the helium filled target will also be of use on the foam filled target. This increases our design flexibility.

The ablation pressure asymmetry, decomposed into P_2 and P_4 components, is shown in figure 11a. Again, there are some short duration excursions of P_2 and again there is a negative P_4 asymmetry seen from 1 ns to about 6 ns. The shape of the imploded core is shown in figure 11b. The P_2 asymmetry issues are similar to those of the gas-filled design--the imploded core tends to a pancake shape even though there is too much energy in the inner cone of beams (again, 43% of the energy was in the inner cone compared to the optimal 33% for the NIF laser configuration). There is more high-mode structure in the foam filled case; future work will focus on optimizing this design and improving the symmetry.

Design of Experiments to Test LEH Shields:

We plan to begin testing targets with LEH shields on the Omega laser. These experiments will build on experiments done with vacuum hohlraums on Nova [3,4]. These Omega experiments will have many of the elements of the ignition design: a high Z LEH shield (gold, rather than cocktail), a shaped laser pulse in a multicone geometry, a high convergence DD implosion, and symmetry tuning via changes in the hohlraum length. In addition, these hohlraums will be filled with either helium gas or glass foam, depending on target fabrication constraints. The capsule radius will be 240 microns, the hohlraum radius will be 1.6 mm, and the hohlraum length will be varied between 2.2 and 2.5 mm. The LEH for these targets is larger than for the NIF design - 66% of the hohlraum radius as opposed to 54% for the NIF design. The larger LEH makes the effect of the shields larger since we are blocking a larger hole. A diagram of the hohlraum is shown in figure 12.

Calculations using LEH shields of radius 100 microns, and 200 microns predict an increase in capsule absorbed energy of 16% for the 100 micron shield and 19% for the 200 micron shield. These calculations show that a large shield is not needed to get most of the benefit. The 100 micron shield works almost as well as a 200 micron shield. One difference between the Omega experiments and the NIF design is that the Omega experiments do not use any additional tamping material around the shield. The size of the shield and the presence or absence of tamping material in the NIF design will be explored in the future.

The Omega experiments will also explore symmetry tuning via changing the hohlraum length. Just as in the NIF design, the addition of the LEH shield requires a shorter hohlraum for good symmetry. Figure 13 shows simulated argon emission images for the proposed experiments. Across the horizontal, we explore the effect of larger shields--from 0 to 100 to 200 micron radius. As we increase the size of the shield, the length of the hohlraum is reduced (and pointing of the outer cone of beams is adjusted accordingly) from 2.5 mm to 2.3 min to 2.2 mm. The simulated images are all quite round. We will also do a set of experiments with a 100 micron radius shield to explore symmetry tuning. These are shown in the vertical in figure 13. For a fixed shield size, the hohlraum length is changed from 2.4 to 2.3 to 2.2 mm and the simulated core changes from a drive that is pole high, to one that is symmetric to one that is equator high.

Conclusions:

Laser entrance hole (LEH) shields are the latest step in an evolution to improve the coupling efficiency of indirect-drive NIF targets. The improved coupling efficiency can be used in one of two ways: we can either reduce the laser energy required to drive a given capsule or we can use the same laser energy and drive a larger, more robust capsule. In the current designs, we have chosen the former choice and tried to reduce the amount of laser energy required to drive a given capsule.

We have designed two NIF targets with LEH shields. The first uses a helium gas fill to hold back the wall, while the second is filled with low density glass aerogel foam. Both targets use ~ 865 kJ of absorbed laser energy to drive a beryllium capsule that absorbs 140 kJ of x-rays and produce yields of ~ 10 MJ in 2-d integrated calculations (1-d yield is 12 MJ). 1n the current generation of designs, which are still not fully optimized, the addition of the laser entrance hole shields saves ~ 95 kJ of absorbed laser energy a savings of about 10%.

We have also designed a first set of experiments to be carried out on the Omega laser to test many of the concepts of LEH shields. These experiments will include many of the features of the NIF design and should show the increase in capsule absorbed energy in the presence of LEH shields. In addition, these experiments will demonstrate symmetry tuning by changing the hohlraum geometry, as is done in the NIF ignition design.

Acknowledgement:

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

References:

[1] Lindl, J. D. Phys. Of Plasmas, 2, 3933 (1995).

[2] Haan SW, Amendt PA, Dittrich TR, Hammel BA, Hatchett SP, Herrmann MC, Hurricane OA, Jones OS, Lindl JD, Marinak MM, Munro D, Pollaine SM, Salmonson JD, Strobel GL, Suter LJ. Nuclear Fusion, vol.44, S171 (2004)

[3] Amendt P, Glendinning SG, Hammel BA, Landen OL, Murphy TJ, Suter LJ, Hatchett S, Rosen MD, Lafitte S, Desenne D, Jadaud JP. Physics of Plasmas, vol.4, 1862 (1997)

[4] Amendt P, Murphy TJ, Hatchett SP. Physics of Plasmas, vol.3, 4166 (1996).

	Au with CH capsule	Au with Be Capsule	Cocktails- Be capsule	Cocktails, LEH shields Be capsule
Laser light (MJ)	1.45	1.2	1.06	0.95
Absorbed	1.30	1.08	0.96	0.865
Xrays	1.10	0.92	0.81	0.735
Wall loss	0.68	0.58	0.47	0.365
Hole loss	0.28	0.20	0.20	0.23
Capsule	0.14	0.14	0.14	0.14
Efficiency	9.7%	11.7%	13%	15%

Table 1: Energy distribution and coupling efficiency of targets with a plastic (CH) ablator and gold hohlraum, a beryllium ablator and gold hohlraum, a beryllium ablator and a cocktail hohlraum, and a beryllium ablator, and a cocktail hohlraum with LEH shields

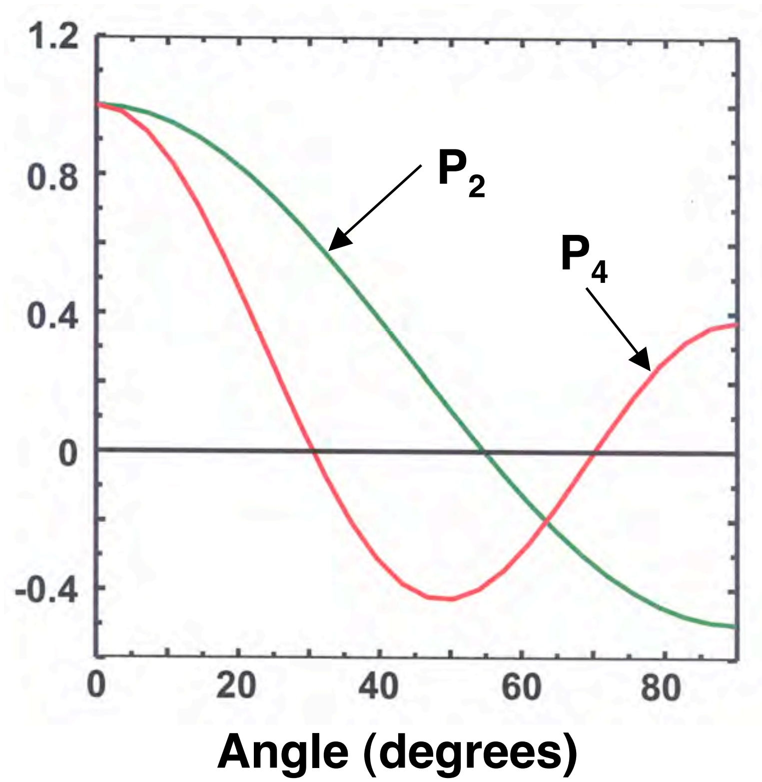


Figure 1: P_2 and P_4 Legendre modes are used to describe asymmetry in ICF targets. Odd numbered modes are small due to the left/right symmetry of the target

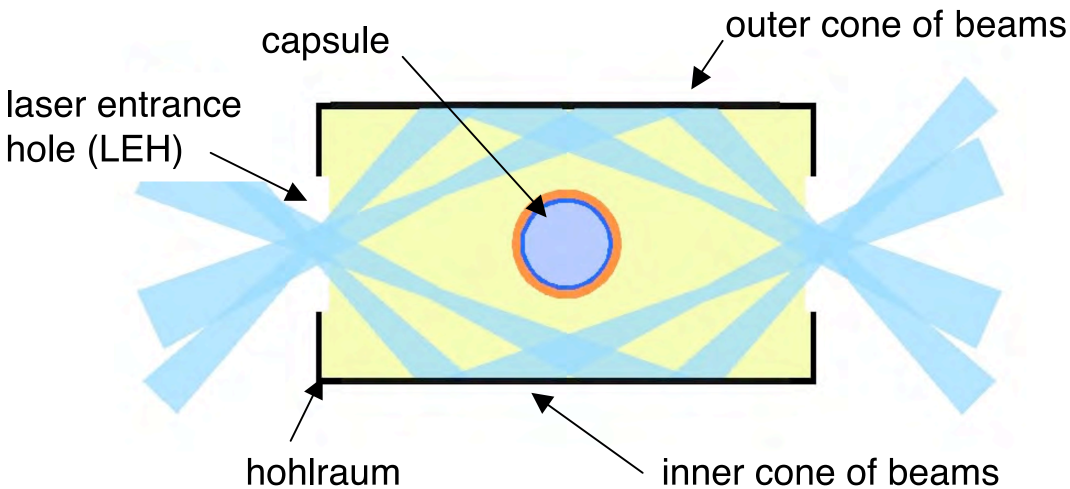
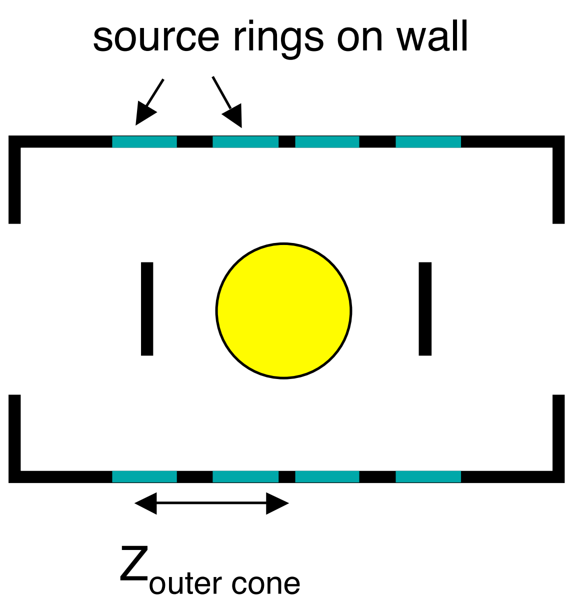


Figure 2: Diagram of a NIF target showing the capsule, hohlraum, laser entrance hole (LEH), inner and outer cones of beams



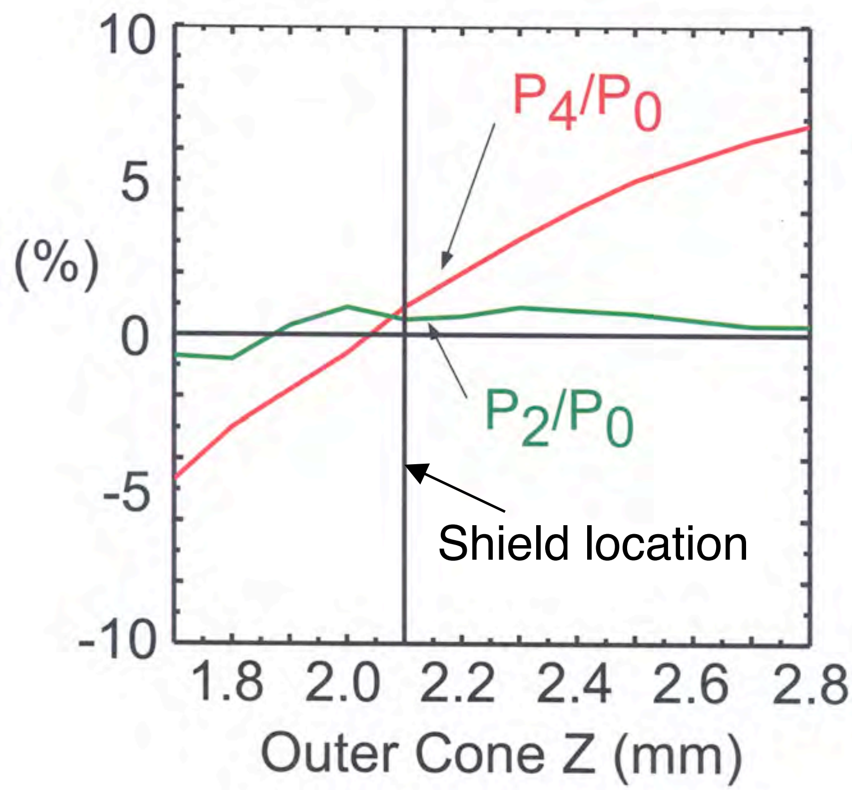


Figure 3: A viewfactor calculation show of an LEH shield target shows that we can tune P_2 by changing the fraction of the energy in the inner versus outer cone of beams and tune P_4 by moving the outer cone of beams relative to the center of the hohlraum

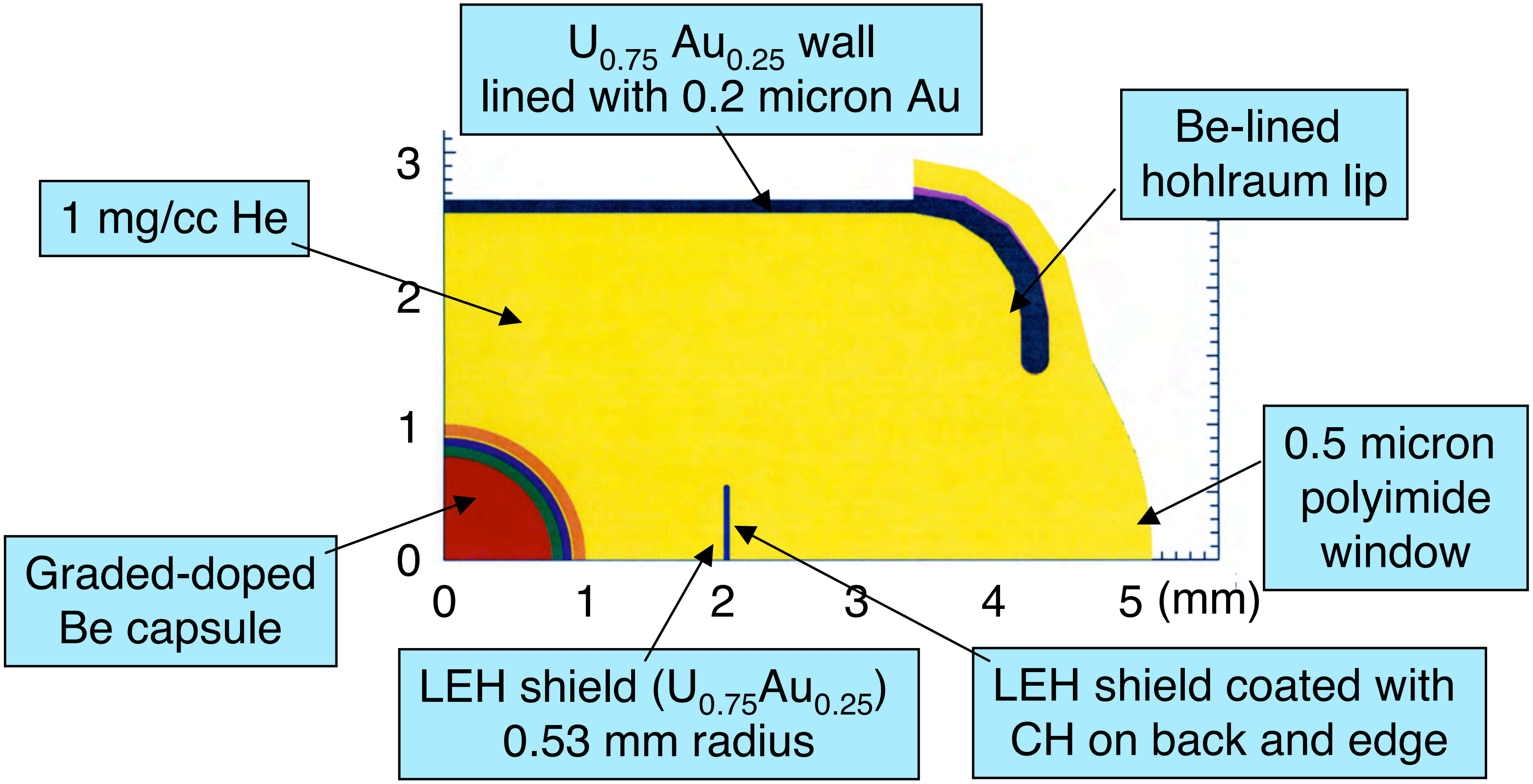


Figure 4: Diagram of 1/4 of the helium gas filled LEH shield target

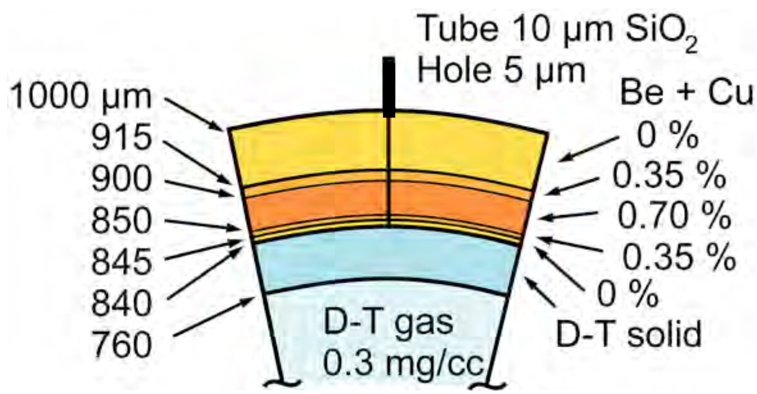


Figure 5: Diagram of the graded-doped, beryllium capsule. This capsule absorbs 140 kJ of x-rays and has a 1-d yield of 12 MJ

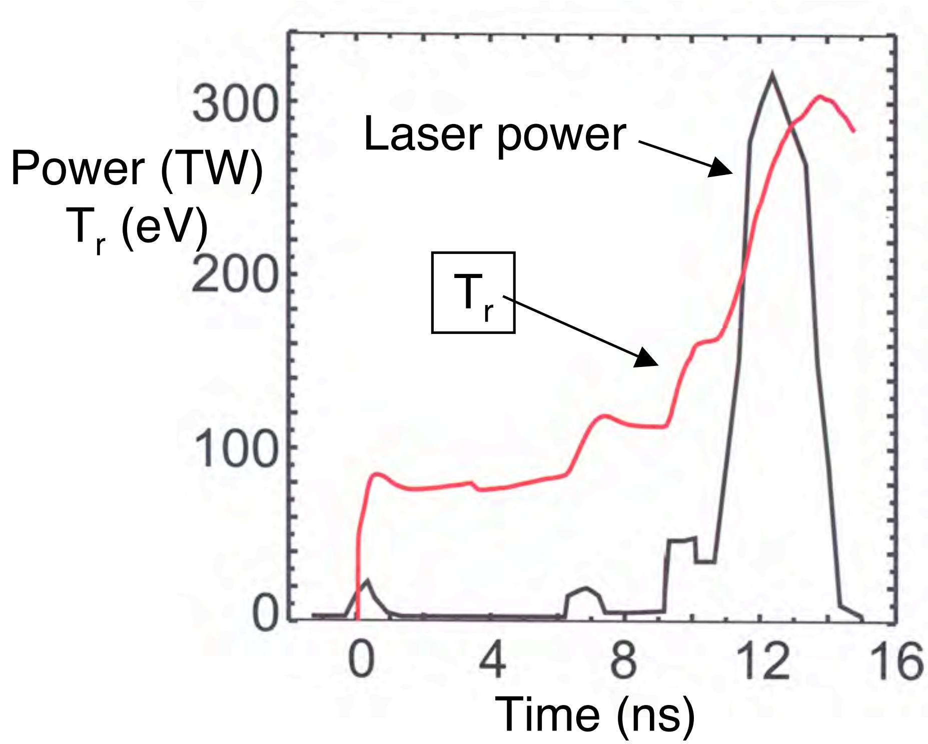


Figure 6: Laser power and resulting radiation temperature from the 2-d calculation of the helium filled LEH shield target.

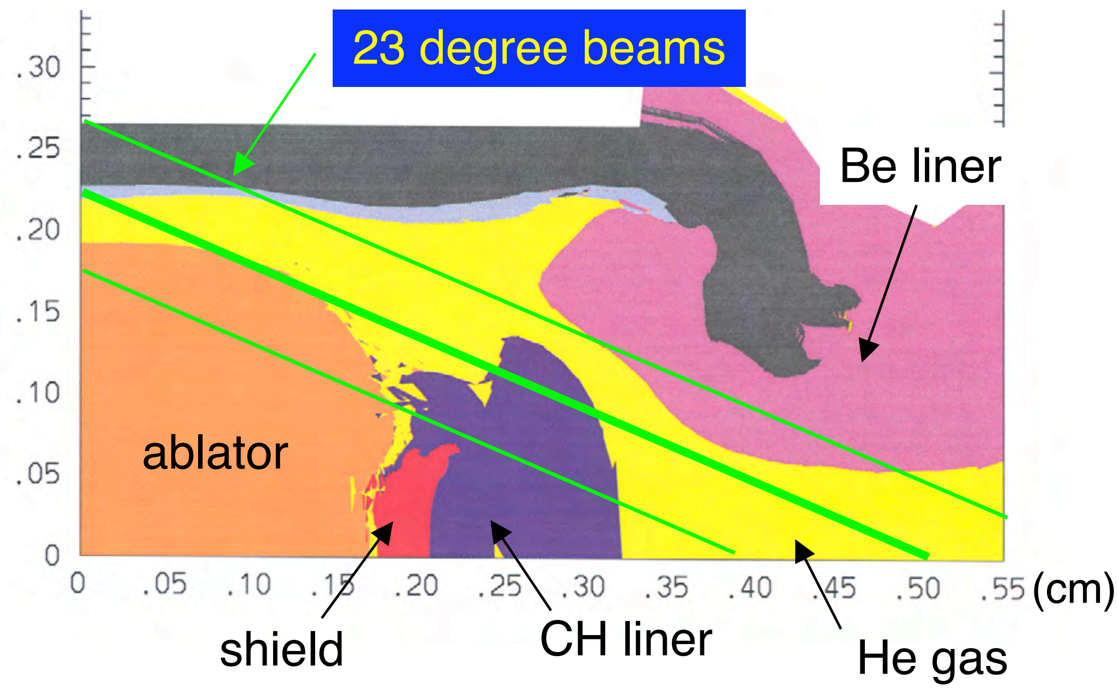


Figure 7: Hohlraum materials at 11 nsec, which is just before the peak power for the inner cone of beams. The shallow angle beams just clear the LEH shield.

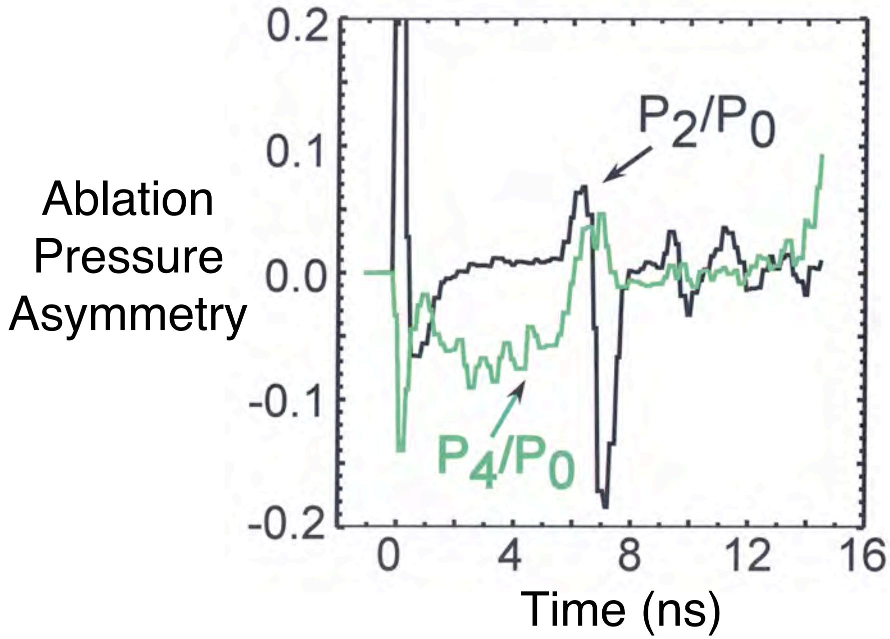


Figure 8: Ablation pressure asymmetry as a function of time for the helium gas filled LEH target

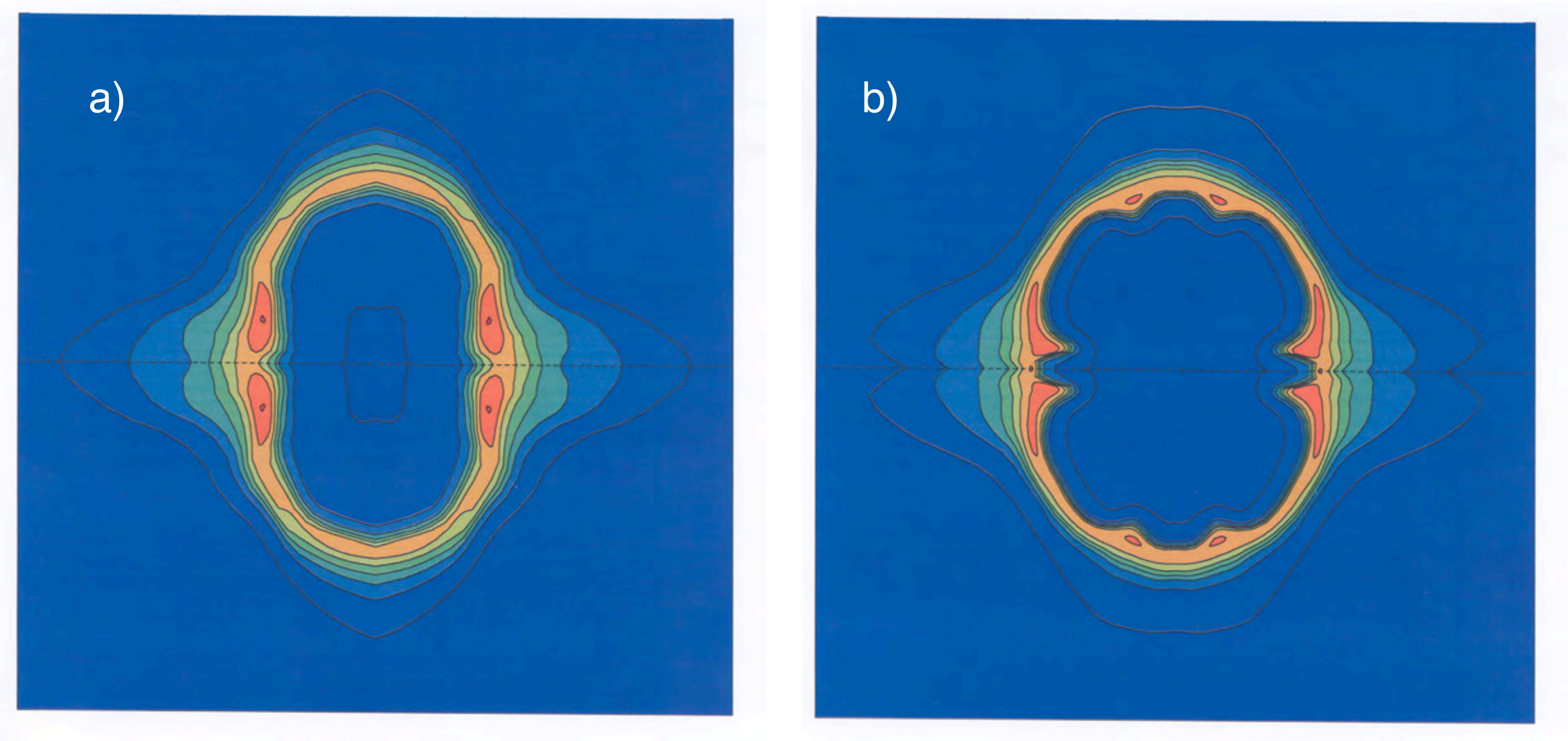


Figure 9: Shape of the imploded core near ignition time for the (a) helium gas filled LEH target, (b) helium gas filled target without LEH shield

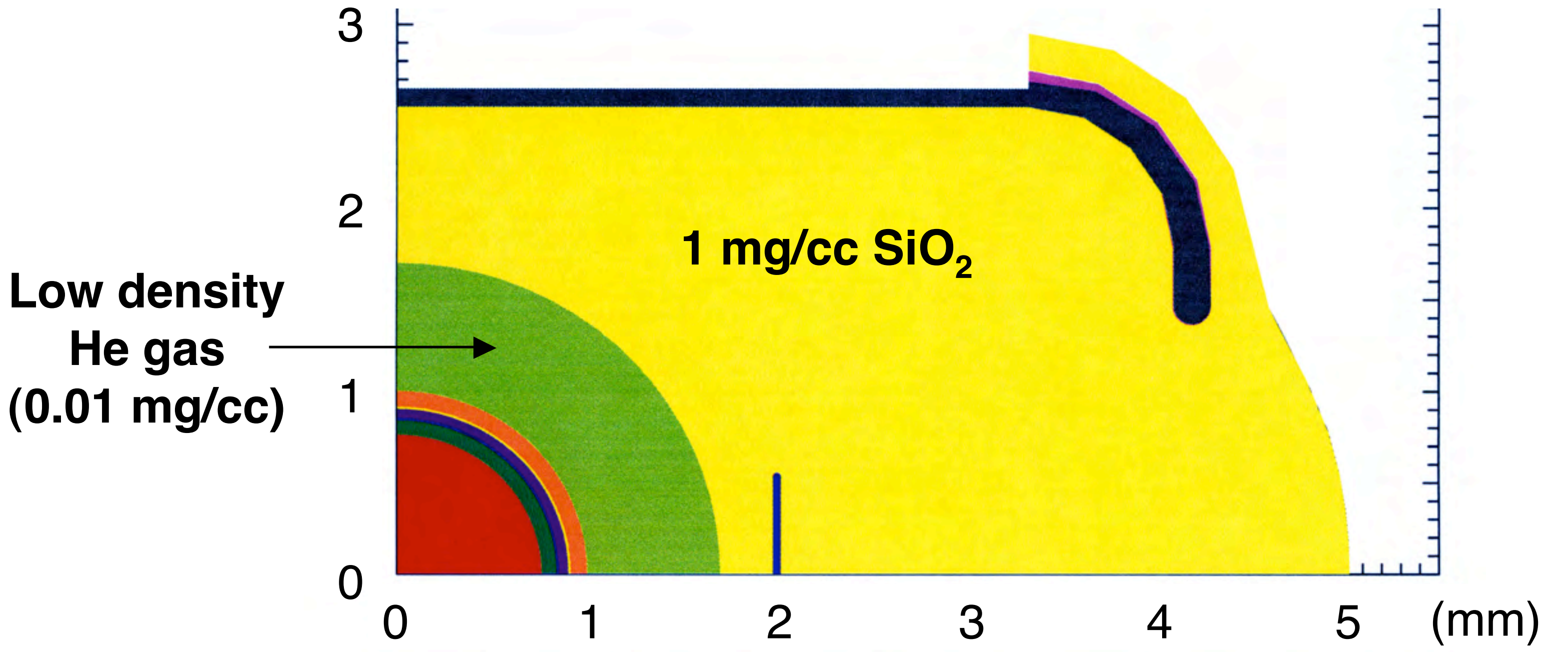


Figure 10: Diagram of 1/4 of the glass-foam filled LEH shield target showing differences between it and the helium gas filled LEH target (figure 4).

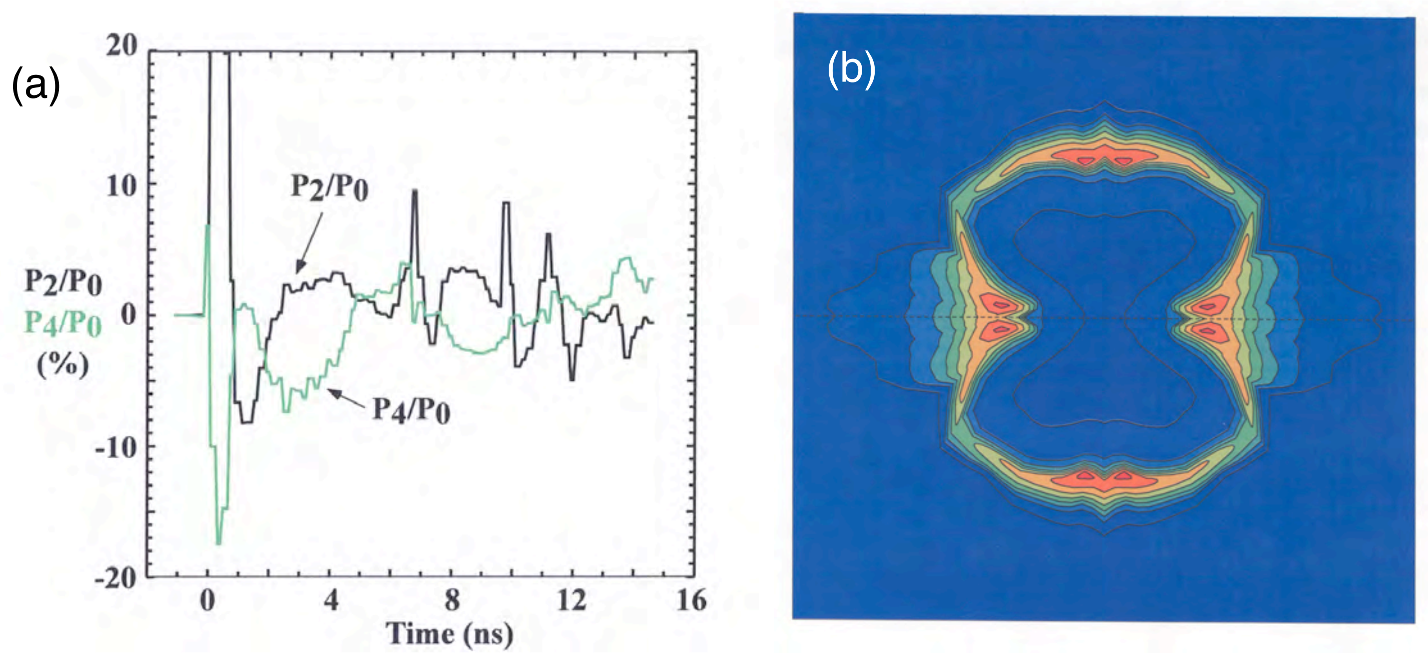


Figure 11: Ablation pressure asymmetry (a) and resulting core shape (b) for the foam filled LEH shield target

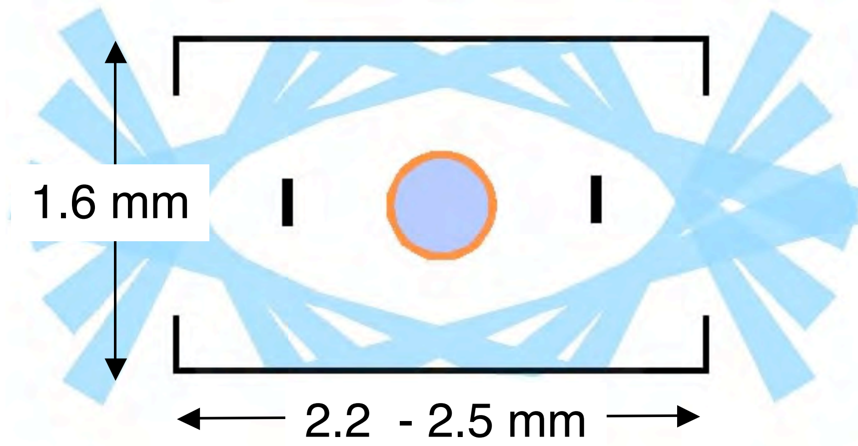


Figure 12: Diagram of the hohlraum for Omega experiments to test LEH shields.

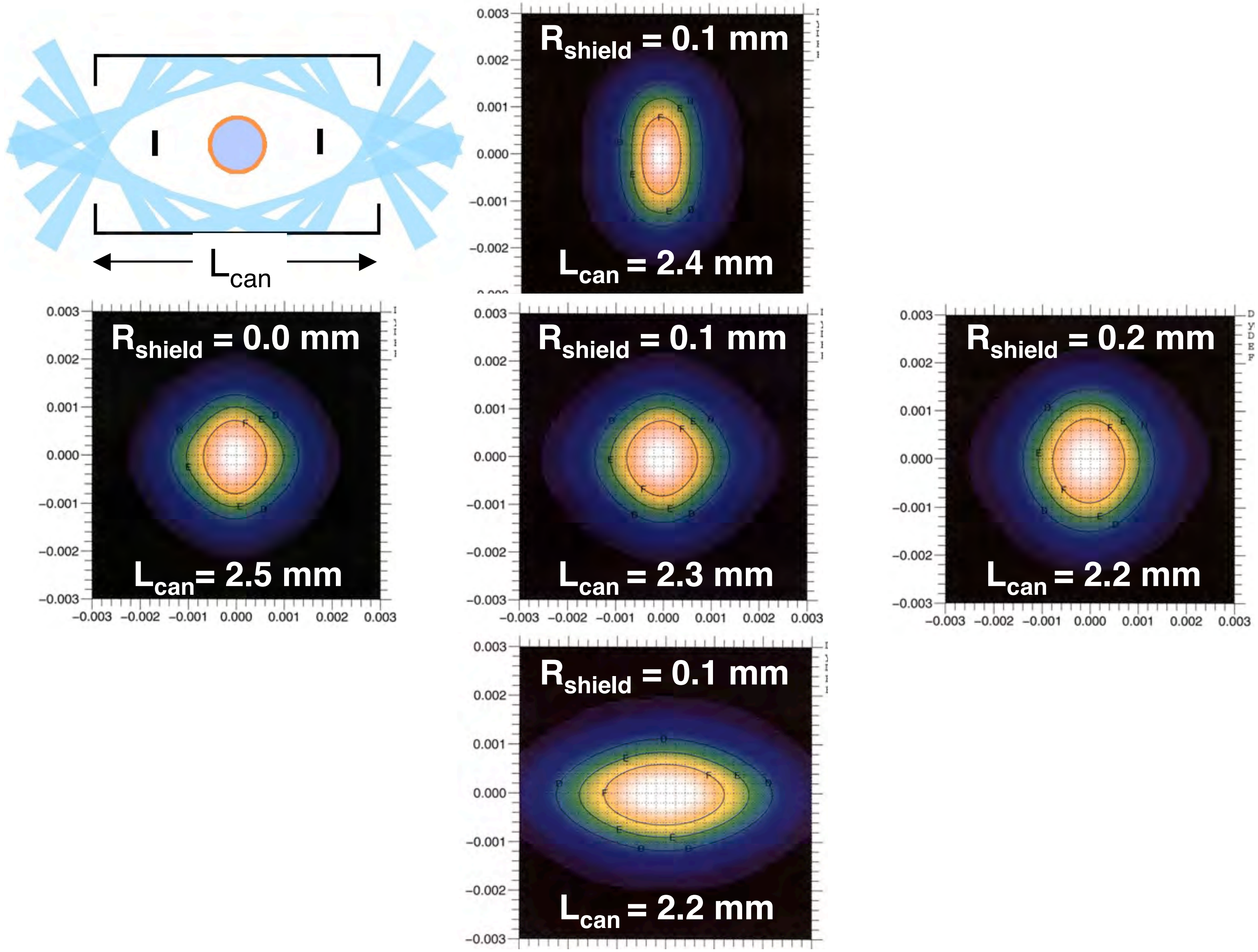


Figure 13: Simulated argon emission images of the proposed Omega experiments. Experiments will test shield sizes ranging from 0 to 200 micron radius and will test symmetry tuning by changing the hohlraum length and outer cone pointing.-=