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Disclaimer

Lead (Pb) Hohlraum: Target for Fusion Energy

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A series of laser experiments was performed comparing gold (Au) and lead (Pb) hohlraum soft x-ray drive for imploding inertial confinement fusion (ICF) capsules. All target shots demonstrated that the Pb hohlraum temperature is as high as the ICF baseline Au hohlraum. The measured backscattered laser energy and hohlraum soft x-ray radiation drive shows no discernible difference between lead (Pb) and gold hohlraums, in agreement with simulations. Capsule implosion performance was also assessed using the measured capsule x-ray peak emission time, image size and neutron yield and shows that the performance of implosions in Pb hohlraums perform as well as or better than those in Au. These results demonstrate that lead is a viable hohlraum target material and an attractive alternative to Au for inertial fusion energy and other high energy density studies of soft x-ray radiation drive.

Recent progress towards demonstrating inertial confinement fusion (ICF) ignition at the National Ignition Facility [1] has sparked wide interest in Laser Inertial Fusion Energy (LIFE) [2] for carbon-free large-scale power generation. A LIFE-based fleet of power plants promises clean energy generation with no greenhouse gas emissions and a virtually limitless, widely available thermonuclear fuel source. A schematic of the power cycle envisioned for a LIFE power plant is shown in Figure 1. With a shot rate of ~16 Hz a LIFE power planet will require over five hundred million targets per year. For the LIFE concept to be economically viable, target costs must be minimized. Current ICF targets on the NIF utilize a gold or depleted uranium cylindrical radiation cavity (hohlraum) with a plastic capsule at the center that contains the deuterium and tritium fuel. The hohlraum efficiently absorbs the incident laser light, converting to soft x rays that bathe the capsule and drive the thermonuclear implosion. Current LIFE designs [3] focus on lead (Pb) as the primary hohlraum material due to its low cost. The price of lead is approximately one dollar per pound; a similar amount of gold would cost over 20,000 times that amount. Thus, the continued use of gold as a target material is prohibitively expensive in the context of inertial fusion energy (IFE). A summary of the projected target material costs is shown as an inset in Figure 1. With that concern in mind a series of experiments has begun to explore new target materials. The first experiment directly compared gold and lead hohlraums in efficiently ablating deuterium-filled plastic capsules with soft x rays, demonstrating superior hohlraum radiation performance and robust capsule implosions.

In this paper we demonstrate that lead hohlraum performance is indistinguishable from gold, yet costing only a small fraction. For an ongoing research effort, hohlraum fabrication costs are presently substantial, but for an IFE power plant an economy of scale using Pb is expected to reduce fabrication costs to the order of 30 cents per target [4].

The target geometry is shown in Figure 2 (a). The target is a cylindrical vacuum hohlraum 2.3 mm in length and 1.6 mm in diameter with a pair of 0.8 mm diameter laser entrance holes. The hohlraum is heated with 14 kJ of 3ω (351 nm wavelength) laser energy delivered by 38 beams, which heat the hohlraum wall, which in turn radiates x-rays that ablate the capsule and compress the fuel. In a LIFE reactor the hohlraum will provide the soft x-ray radiation drive and additionally protect the fuel capsule from debris and radiation during transit of the target chamber. A diagnostic window with a diameter of 0.4 mm is located 0.2 mm below the hohlraum equator and is used to image x-ray self-emission from the imploding capsules. The capsules have a diameter of 0.46 mm and are suspended by a Formvar® web for placement at the center of the hohlraum. Twenty atmospheres of deuterium gas are used to fill the capsule and 0.025 atm of argon is added to enhance 3-5 keV x-ray core imaging.

Figure 2 (b) shows an example of an x-ray image of the symmetrically compressed capsule core. Symmetric compression is critical for robust ICF performance and is typically described as a decomposition of Legendre polynomials P_n. Low order even modes [5,6] result from intrinsic asymmetries in the soft x-ray drive. For the 30% contour shown in Figure 2 (b), $P_0 = 61 \pm 3$ μm, which is about a factor-of-4 compression from the initial capsule radius of 240 μm. Experiments on the National Ignition Facility (NIF) [8] and an eventual LIFE power planet will require ~30-fold compression. Here, we observe excellent symmetry and compression with $P_2 = 2 \pm 1$ μm, and $P_4 = 2 \pm 1$ μm, meeting requirements for ICF implosions [9].

These implosions have been carried out using two temporally shaped laser pulses, as shown in Figure 3 (a). The initial 1 ns of the pulse or "foot" is varied between pulse shapes to span the effective 1st shock pressure delivered to the capsule for several ignition ablator candidates, including CH, Be and high-density carbon. The low foot pulse shape results in a pressure of ~3.6 Mb and the 2x foot pulse in a pressure of ~7.5 Mb during the foot of the laser pulse. These pressures are very close to one and two times the pressure at the center of the earth, 3.6 Mb [11]. The length of the pulse is then adjusted based on simulations to optimize the shock timing in the capsule shell. Multiple shocks are used to efficiently compress the capsule and fuel. Fast, strong shocks are more stable, but they increase the entropy of the target and make it harder to compress. The goal with shock timing is to find the correct balance.

The laser energy delivered to the hohlraum is converted to x-rays and characterized through the laser entrance hole using a calibrated array of x-ray diodes (DANTE) [12]. The measured radiation drive is compared for each material in Figure 3 (b). The gold and lead hohlraums have similar peak radiation temperatures within the uncertainty (±5 eV) of the diagnostic for both laser pulse shapes with a maximum temperature of 225 eV, which is very close to the peak temperature requirement of ~250 eV [3] planned for a LIFE power plant. This small variation in radiation temperature is consistent with previous measurements comparing Au and cocktail ($U_{0.52}Nb_{0.08}Au_{0.2}Dy_{0.2}$) hohlraums where an increase of 2.5 eV in radiation temperature, smaller than the experimental uncertainty of the measurement, is expected for a peak temperature of 225 eV [13].

The performance of the deuterium-filled CH capsules shows similar total neutron yields with each hohlraum material, a direct indication that both Au and Pb produce comparable radiation drive. The time of peak neutron emission, or "bang time", is measured and the neutron yield time history is shown in Figure 3 (c). The Au and Pb hohlraums have very similar bang times for both pulse shapes, providing strong evidence that the capsule implosion velocities are similar and that the hohlraums produce a similar capsule drive. The total neutron yield is compared to simulations in Figure 4 (a). Two-dimensional (2D) "YOC" contours of 100%, 50% and 30% are shown in Figure 4 (a), where the 2D YOC is defined as the ratio of the measured neutron yield to the predicted clean yield from 2D integrated (hohlraum + capsule) simulations in the absence of hydrodynamic instability and atomic mixing of capsule materials. The Pb and gold hohlraum performance for both the 2x foot and low-foot pulse shapes was similar: 2D YOCs of ~100% and ~60% are found for the 2x foot and low foot pulse shapes, respectively. The simulated yields for the two pulse shapes dominate the variation in 2D YOC. The simulations predict relatively larger yield for the low foot pulse, which might be due to increased fuel convergence and uncertainties in the equation of state for CH_2 that could affect shock timing. A 2D YOC of ~40% is required for a successful ignition demonstration [14], and we have met this threshold owing largely to the comparatively low fuel convergence.

The ion temperature and bang time are reported in Figure 4 (b). The measured ion temperatures range from 2.5 to 3.5 keV (30 – 40 million Kelvin) with the Pb targets having a slightly higher ion temperature for both pulse shapes. Ion temperatures approaching 50 million Kelvin are required for central hot spot ignition. At an ion temperature of 50 million Kelvin in the target core the energy loses due to radiation are balanced by energy gain due to fusion based on calculations. The neutron bang times are measured with the bang time differences dominated by the change in pulse shapes. The difference between Au and Pb is within the uncertainty of the measurement.

In conclusion, we have shown that lead (Pb) is a viable hohlraum material and performs as well as (or better than) gold. The measured hohlraum and capsule performance were characterized using a suite of diagnostics and show similar performance for lead and gold targets. For LIFE and cost-conscious future applications lead is an ideal target material.

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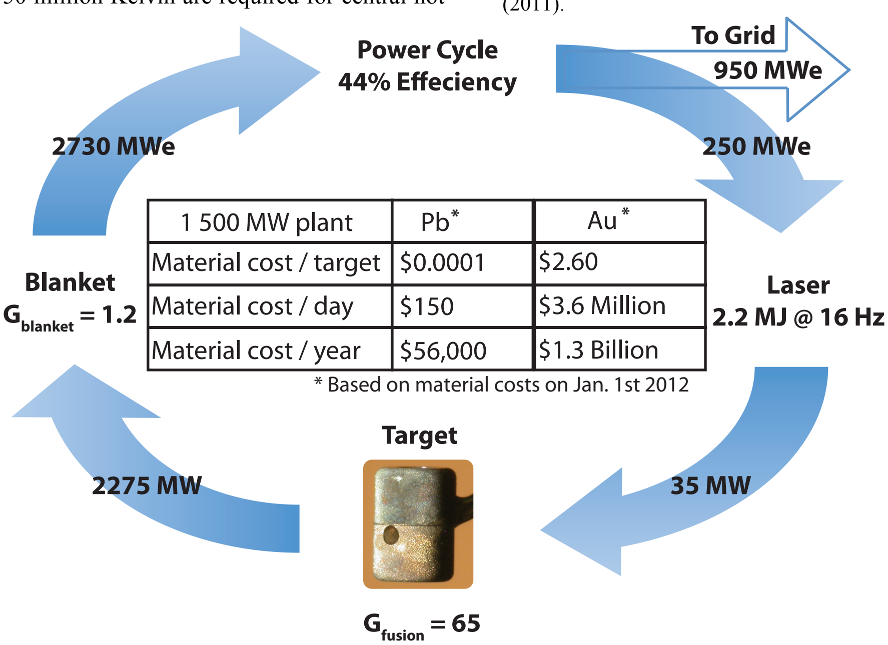

1 500 MW plant	Pb*	Au*
Material cost / target	$0.0001	$2.60
Material cost / day	$150	$3.6 Million
Material cost / year	$56,000	$1.3 Billion

Fig. 1: The power cycle of a LIFE power plant. Inset is a cost comparison between Au and Pb hohlraums assuming 16 target shots per second.

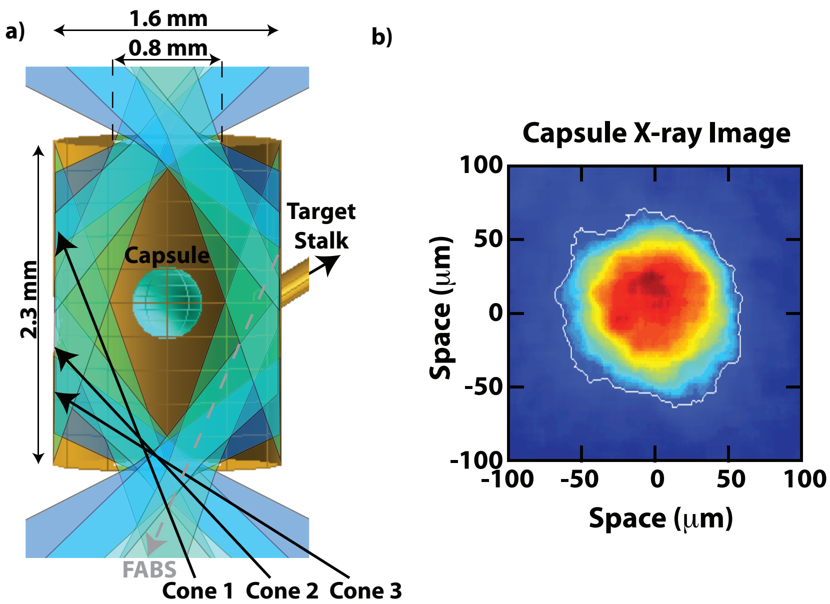

Fig. 2: (a) The hohlraum target geometry is shown. 38 laser beams enter the hohlraum through 2 laser entrance holes with diameters of 0.8 mm. b) An x-ray self-emission image [7] of the compressed capsule.

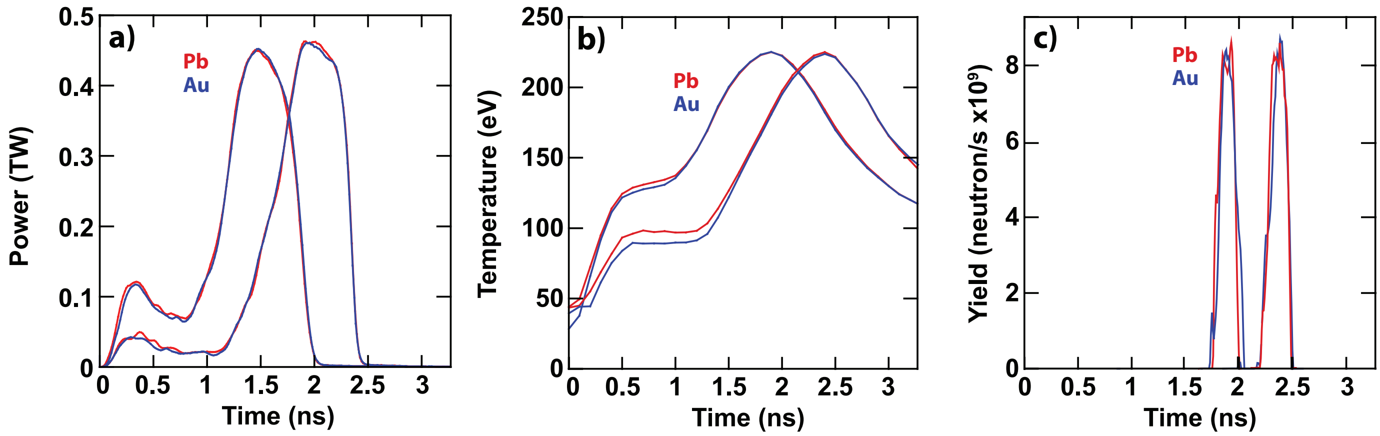

Fig. 3: (a) Total laser powers are shown for both pulse shapes for each target material. (b) The radiation temperature is measured with DANTE. (c) The neutron time history measured with the Neutron Temporal Diagnostic [10] is compared for each hohlraum material and each pulse shape.

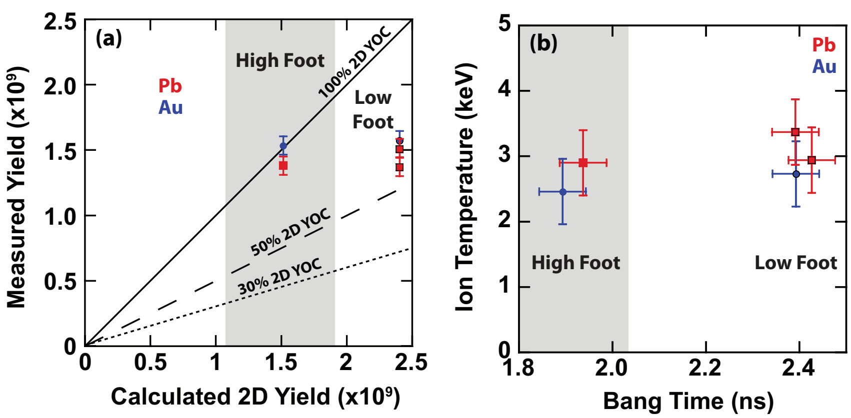

Fig. 4: (a) The measured neutron yield is plotted against the calculated 2D clean yield for lead (red squares) and gold (blue circles). The 2x foot pulse (no outline) and low foot pulse (black outline) show comparable yields. (b) The ion temperature is shown for a range of measured neutron bang times.

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MATERIALS AND METHODS

The experiment in this work was performed at the Omega Laser facility at the Laboratory for Laser Energetics. A total of 38 laser beams enter the hohlraum through the laser entrance holes. The laser beams are distributed on each side of the hohlraum and grouped into three beam cones defined by the angle the lasers enter the hohlraum relative to the symmetry axis. There are a total of 9 cone 1 beams entering the hohlraum at an angle of 21.4^o, 9 cone 2 beams with an angle of 42.0^o and 20 cone 3 beams with an angle of 58.9^o. Two lower beams (one cone 1 and one cone 2) that would pass through the diagnostic window have been disabled for this experiment, breaking the up-down laser symmetry. Each laser beam delivers an average of 370 J of 351 nm laser light to the target, resulting in a total energy of ~14 kJ on target. The laser beams are smoothed using distributed phase plates and spectral smoothing by dispersion in 1D.

The radiation temperature was inferred from the measured total x-ray hohlraum emission. An absolutely calibrated broadband x-ray spectrometer (DANTE) measures the x-ray flux emitted from the LEH in the energy range of $0 < E_{X\text{-ray}} < 20$ keV. The x-ray power in the direction of Dante in units of GW/sr is determined by $dP/d\Omega = A_{LEH} \cos\theta\, \sigma T_{RAD}^4/\pi$, where θ is the view angle of Dante towards the hohlraum axis. To determine T_{RAD}, we assume a constant source area, A_{LEH} =0.5 mm^2; x-ray pinhole camera images of the LEH show no significant LEH closure. The hohlraums reach peak radiation temperatures of 225 eV.

X-ray images of the capsule core are recorded using the OMEGA Kirkpatrick-Baez Microscope [1]. The KB microscope uses pairs of grazing-incidence mirrors arranged to reflect and focus x-rays forming an image. The KB microscope at OMGEA is sensitive from 1- 7 keV and has a solid angle of ~ 3×10^{-7} sr. The x-ray images are captured on film, which is then digitized. The images are smoothed using a rolling ball smoothing method and then a 30% contour is fit to the central hot spot emission. The contour is then analyzed using a decomposition of Legendre polynomials up to 4th order.

The neutron yield and ion temperature are measured using a neutron time-of-flight (nToF) diagnostic [2]. This detector consists of a scintillator optically coupled to a photomultiplier tube at a fixed stand-off distance from the target. The intensity of the observed signal is used to measure the total neutron yield. The primary DD reaction produces monoenergetic neutrons at an energy of 2.45 MeV. The ion temperature is measured from the broadening of the neutron pulse arriving at the detector due to center-of-mass motion of the reacting ions.

The neutron time history is measured using the Neutron Temporal Diagnostic (NTD) [3]. The NTD is based on a thin, fast rise time plastic scintillator. As neutrons pass through the scintillator some have elastic collisions with hydrogen nuclei. These elastic collisions generate recoil photons, which transfer their energy to luminescent states in the scintillator. This luminescence is then measured using a fast optical streak camera.

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