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Targets for the National Ignition Campaign

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Targets for the National Ignition Campaign

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The National Ignition Facility (NIF) is a 192 beam Nd-glass laser facility presently under construction at Lawrence Livermore National Laboratory (LLNL) for performing inertial confinement fusion (ICF) and experiments studying high energy density (HED) science. When completed in 2009, NIF will be able to produce 1.8 MJ, 500 TW of ultraviolet light for target experiments that will create conditions of extreme temperatures ($>10^8$ K), pressures (10 GBar) and matter densities (>100 g/cm³). A detailed program called the National Ignition Campaign (NIC) has been developed to enable ignition experiments in 2010, with the goal of producing fusion ignition and burn of a deuterium-tritium (DT) fuel mixture in millimeter-scale target capsules. The first of the target experiments leading up to these ignition shots will begin in 2008. The targets for the NIC are both complex and precise, and are extraordinarily demanding in materials fabrication, machining, assembly, cryogenics and characterization.

The DT fuel is contained in a 2-millimeter diameter graded copper/beryllium or CH shell. The 75 μ m thick cryogenic ice DT fuel layer is formed to sub-micron uniformity at a temperature of approximately 18 Kelvin. The capsule and its fuel layer sit at the center of a gold/depleted uranium "cocktail" hohlraum. Researchers at LLNL have teamed with colleagues at General Atomics to lead the development of the technologies, engineering design and manufacturing infrastructure necessary to produce these demanding targets. We are also collaborating with colleagues at the Laboratory for Laser Energetics (LLE) at the University of Rochester in DT layering, and at Fraunhofer in Germany in nano-crystalline diamond as an alternate ablator to Beryllium and CH.

The Beryllium capsules and cocktail hohlraums are made by physical vapor deposition onto sacrificial mandrels. These coatings must have high density (low porosity), uniform microstructure, low oxygen content and low permeability. The ablator capsule has a 5 μ m diameter hole laser drilled to permit removal of the mandrel and introduction of the DT fuel. A 10 μ m diameter fill tube is bonded to the capsule to enable filling with the DT gas. These components must then be assembled to tolerances of approximately 5-10 microns, with comprehensive characterization and metrology. The DT ice is formed through controlled seeding, aided by beta decay of the tritium to help smooth the layer, and differential heating of the hohlraum to counteract the effects of natural convection.

We present an overview of the technologies for target fabrication, assembly and metrology and advances in growth and imaging of DT ice layers. The sum of these efforts represents a quantum leap in target precision, characterization, manufacturing rate and flexibility over current state-of-the-art.

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Target Overview

In the cryogenic ignition target, shown schematically in Figure 1, the DT fuel is contained in a 2 mm diameter, 160 μ m thick, smooth spherical graded copper/beryllium shell. The 75 μ m thick DT fuel layer is carefully crystallized from a DT seed using precise thermal protocols. This ice layer must be uniform in thickness, meet a power spectral density (PSD) curve with roughness less than 0.8 μ m over the range of spatial scales from 1 mm

down to 50 μm , free of voids larger than 1.5 μm^3 , and contain less than 0.2 % of the total volume in cracks at the inner surface at $\sim 1.5\text{K}$ below the DT triple point of 19.8K. To be able to form DT ice layers of sufficient uniformity, the target must control temperature axisymmetrically and with a tailored axial gradient to within $\pm 0.5\text{ mK}$.

The capsule and its fuel layer sit at the center of a cylinder with uranium or gold/uranium hohlraum. Prior to the shot the hohlraum provides the infrastructure to form the tailored thermal environment that precisely shapes the DT fuel layer and establishes the proper absolute temperature. Then, during a $\sim 20\text{ ns}$ shaped laser pulse at shot time the hohlraum converts the high intensity laser light to x-rays that uniformly heat the capsule. The intense x-rays ablate the capsule material, accelerating it outward and, by reaction, the DT fuel is driven inward. This action compresses the fuel by a factor of ~ 30 , creating the extremely high density and temperature need for fusion ignition and burn of the DT [1].

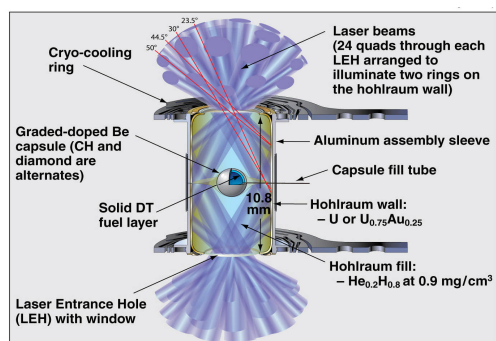


Figure 1. Schematic of the cryogenic ignition target showing the 48 “quads” of laser beams entering the hohlraum from above and below. There are 4 individual laser beams within each quad.

Target Components – Capsule and Hohlraum

The ablator capsule shown in Figure 2 is formed by physical vapor deposition of beryllium doped with copper on a decomposable mandrel [2-4]. The capsule is then polished to precise dimensions with a roughness better than 200 nm rms, laser-drilled and counter bored to form a 6 μm diameter hole (an aspect ratio of over 25:1) for attaching the 10 μm polyimide fill tube. The capsule is then dimensionally inspected and characterized before infusion of the ice layer.

Since commercially available metrology equipment is not ideally suited for certifying these meso-scale capsules, several unique characterization tools have been developed. These include a sphere mapper based on atomic force microscopy (AFM), a phase sensitive diffractive interferometer (PSDI), a very sensitive x-ray transmission radiography system for monitoring the uniformity of these coatings, and quantitative analysis methods for analyzing radiographs which allow verification of the distribution and opacity of dopant layers. For example, the AFM system measures roundness of shells by mounting the capsule on an air bearing rotary table and probing the surface with an AFM to measure circular traces with nanometer resolution. The PSDI is able to measure the capsule radius and inspect for surface defects down to the 10 nm size. This five-axis metrology system [5] maps an entire hemisphere with a lateral resolution of 1 μm .

During the fielding process for an ignition experiment the capsule will be filled with a 75 μm thick DT ice fuel layer, which must be monitored for uniformity. LLNL has applied an x-ray phase contrast imaging technique which shows good contrast at the edges of even extremely low absorbing materials like

hydrogen ice [6,7]. This method provides for quantitative evaluation of the quality of DT ice surface in optically opaque materials like Be. Figure 3 shows an x-ray projection of solid DT in a Be capsule with a resolution of approximately $3\text{ }\mu\text{m}$. Optical techniques are similarly employed in transparent capsules to characterize the DT, and allow evaluation of both traditional “slow-cool” and “rapid-quench” methods for lowering the temperature from near the DT triple point of 19.8K to the point design temperature of 18.3K.

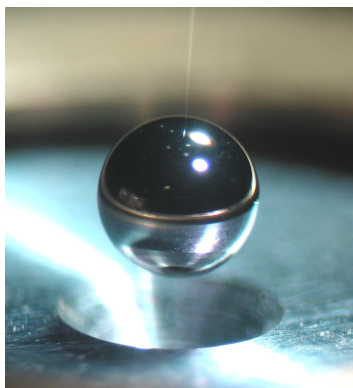


Figure 2. Polished 2 mm diameter beryllium ablator capsule suspended from a $10\text{ }\mu\text{m}$ diameter fill tube.

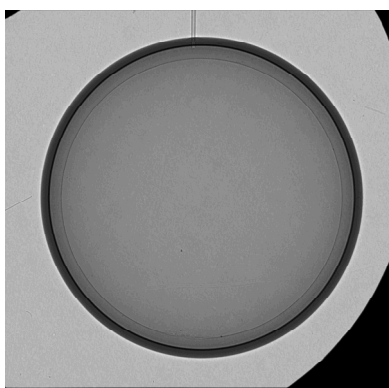


Figure 3. X-ray phase contrast image of a deuterium-tritium ice layer in a 2 mm diameter beryllium capsule.

The hohlraum, shown in Figure 4, is fabricated by depositing either uranium or alternating layers of gold and uranium on a mandrel made from copper that is leached out at a later step [8]. This layer must have less than 5% atomic oxygen to achieve the required x-ray opacity for driving the capsule implosion.

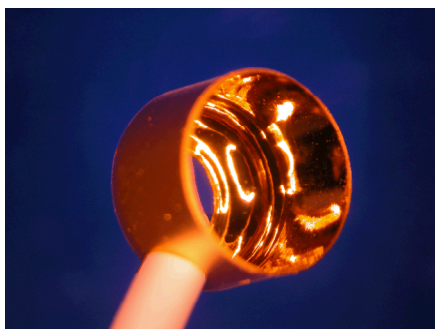


Figure 4. ‘Cocktail’ hohlraum made of uranium and gold multilayers.

Target Assembly - Thermal-Mechanical Package (TMP)

The ignition target design utilizes a thermal-mechanical package (TMP), which performs the positioning and thermal management functions of the target; see Figure 5. The TMP shell is an aluminum cylinder that has silicon heat sinks, wire heaters, and temperature sensors attached.

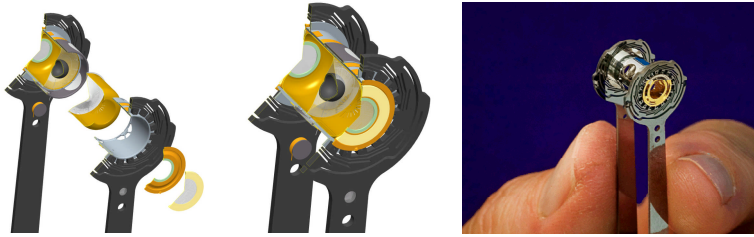


Figure 5. Solid models and photograph of assembled TMP target package.

In a sub-assembly operation, the hohlraum halves are inserted into the TMP shell. During final assembly the two TMP halves are mated around the capsule, with a central band that aligns and attaches the halves. An error budget guides the component and process design specifications. Critical aspects of the assembly are the position of the capsule in the hohlraum, the hohlraum dimensions, and alignment of the starburst apertures in the hohlraum walls which allow for x-ray imaging of the DT ice layer. TMP and hohlraum components are held to tolerances of 1-3 μm in order to facilitate the assembly and precise alignment of the structure. The rotational alignment of the two hohlraum halves must be controlled to within 2 milliradians, which is equivalent to 5 μm at a 2.5 mm radius. All of the assembled critical dimensions are inspected with optical metrology techniques on the assembly station. This approach will help enable the combined precision, agility and production rate needed to meet the NIC target objectives.

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