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The Ignition Target for the National Ignition Facility

L. Jeffrey Atherton[1], Edward I. Moses [1], Keith Carlisle [1], Joseph Kilkenny [2]

[1] Lawrence Livermore National Laboratory, Livermore CA USA 94550

[2] General Atomics, San Diego CA USA 92123

atherton1@llnl.gov

Abstract

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/cm^3). 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. Targets for the National Ignition Campaign are both complex and precise, and are extraordinarily demanding in materials fabrication, machining, assembly, cryogenics and characterization. An overview of the campaign for ignition will be presented, along with technologies for target fabrication, assembly and metrology and advances in growth and x-ray 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.

1 Target Function and Requirements

In the cryogenic ignition target, shown schematically in Figure 1, the DT fuel is contained in a 2-mm diameter, 160-µm thick, smooth spherical beryllium shell. The 75-µm 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 an R_a of less than 0.5-µm over the range of spatial scales

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from 1-mm down to 50-µm, be free of voids larger than 1.5-um^3, and contain less than 0.1 % of the total volume in cracks at the inner surface. The capsule and its fuel layer sit at the center of a cylinder with gold/depleted uranium walls called a hohlraum. For several hours prior to shot time, this hohlraum provides the infrastructure to form the tailored thermal environment that precisely shapes the DT fuel layer and then, during an approximately 20-ns shaped laser pulse at shot time, 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 approximately 30, creating the extremely high density and temperature need for fusion ignition and burn of the DT [1].

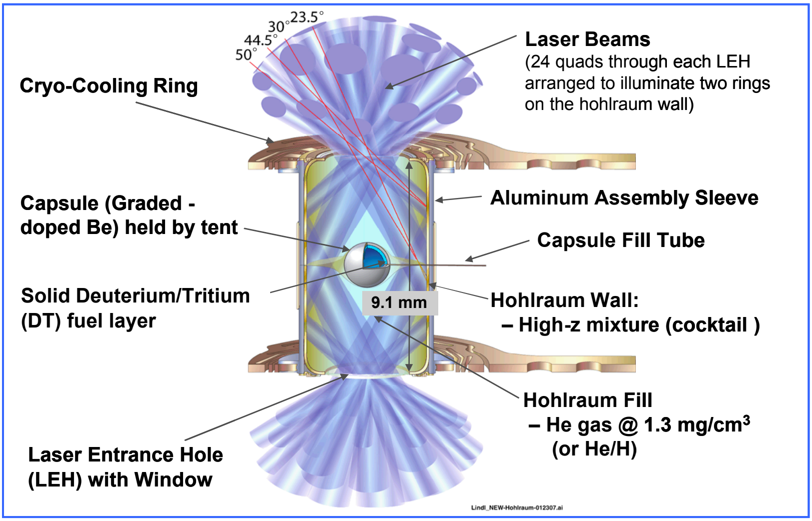

Figure 1. Schematic of the cryogenic ignition target showing the 48 "quads" of laser beams entering the hohlraum at each end. There are 4 laser beams to each quad.

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 +/- 0.5-mK. Just prior to layering, the DT fuel is transferred from a reservoir into the capsule through a fine 10-µm-diameter fill tube. To perform correctly at shot time, the target must meet a series of requirements including: dimensional precision of 5-µm at cryogenic temperatures; helium gas fill of 330-Torr; polyimide sealing windows over the laser entrance holes of 0.5-µm thickness; capsule held by polyimide films (called tents) less than 80-nm thick; and target motion and vibration of less than 7-µm at target chamber center.

2 Physics Components - Capsule Ablator, DT Ice 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 counterbored to form a 6-µm diameter hole – an aspect ratio of almost 30:1 - for attaching the 10-µm polyimide fill tube. The capsule is then dimensionally inspected and characterized before infusion of the ice layer.

Because commercially available metrology equipment is not ideally suited for certifying these meso-scale capsules, we have developed several unique characterization tools. These including a sphere mapper based on atomic force microscopy (AFM), a phase shifting diffraction interferometer (PSDI), an extremely sensitive transmission radiography system for monitoring the uniformity of these coatings, and quantitative analysis methods for analyzing radiographs to verify 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 record 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. LLNL has applied an x-ray phase contrast imaging technique to this metrology challenge that results in good contrast at the edges of even extremely low absorbing materials like hydrogen ice [6,7]. This allows us to quantitatively evaluate the quality of the DT ice surface in optically opaque materials like beryllium. Figure 3 shows an x-ray image of solid DT in a capsule with resolution of approximately 3-µm.

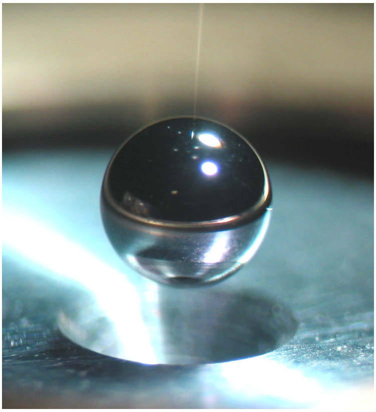

Figure 2. Polished 2 mm diameter beryllium ablator capsule suspended from a 10-µm diameter fill tube.

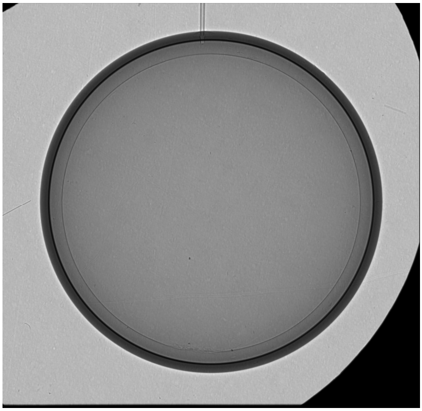

Figure 3. X-ray phase contrast image of a deuterium-tritium ice layer in a 2-mm diameter beryllium capsule.

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

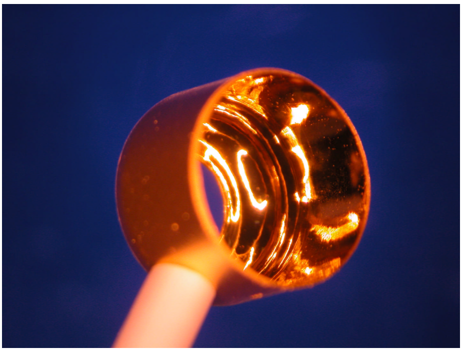

Figure 4. 'Cocktail' hohlraum made of uranium and gold multilayers.

3 Thermal-Mechanical Package (TMP)

Our target design utilizes a thermal-mechanical package (TMP) that performs the positioning and thermal engineering functions of the target, shown in Figure 5. The TMP shell is an aluminium cylinder that has the silicon heat sinks, wire heaters, and temperature sensors attached.

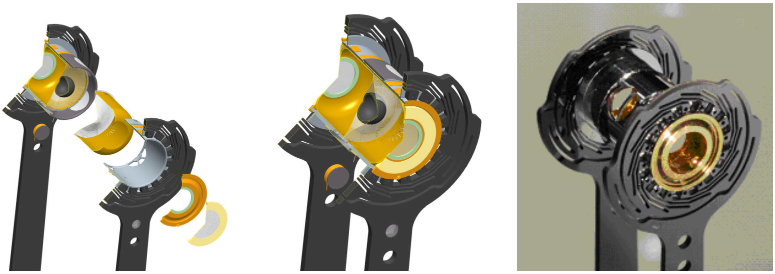

Figure 5. Solid models and photograph of assembled TMP target package.

In a sub-assembly operation, the hohlraum halves are inserted into the TMP shells. During final assembly the two TMP halves are mated around the capsule, with a central band aligning and attaching the halves. An error budget guides the component and process design specifications. Critical dimensions are the position of the capsule in the hohlraum, the hohlraum dimensions, and alignment of the starburst-shaped ice x-ray imaging apertures in the hohlraums. TMP and hohlraum components are held to tolerances of 1- to 3-µm to facilitate the assembly and precise alignment of the structure. The rotational alignment of the two hohlraum halves must be controlled to 2 milli-radian or 5-µm at a 2.5-mm radius. All of the assembled critical dimensions will be inspected with optical metrology techniques on the assembly station.

4 Agile Manufacturing and Production

During the course of the ignition campaign, a number of the target specifications will be refined as we begin to generate data and analyze the results. One of the principle challenges for target manufacturing is to establish the ability to manufacture and assemble target packages whose designs will vary in response to this evolving understanding.

Our strategy to address this challenge involves ‘binning’ components and sub-assemblies with a range of sizes, doping levels, etc. in order to minimize the time from final definition of the target to the shot. We have worked with each element of the ignition campaign to develop specific ranges for each component and sub-assembly, and built a production model for the target fabrication operation. This model guides us in defining the quantities and lead-times of the binned components and the size of the production factory.

With the combination of robust processes for producing and characterizing the physics components, the engineering design and assembly processes for positioning and thermal control, and the binning approach to enable a rapid and agile response to evolving experimental results, we are well positioned to produce targets that will meet all of the requirements of the ignition campaign.

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