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National Ignition Facility target design and fabrication

R.C. COOK,[1] B.J. KOZIOZIEMSKI,[1] A. NIKROO,[2] H.L. WILKENS,[2] S. BHANDARKAR,[1] A.C. FORSMAN,[2] S.W. HAAN,[1] M.L. HOPPE,[2] H. HUANG,[2] E. MAPOLES,[1] J.D. MOODY,[1] J.D. SATER,[1] R.M. SEUGLING,[1] R.B. STEPHENS,[2] M. TAKAGI,[1] AND H.W. XU[2]

[1]Lawrence Livermore National Laboratory, Livermore, California
[2]General Atomics, San Diego, California

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Abstract

The current capsule target design for the first ignition experiments at the NIF Facility beginning in 2009 will be a copper-doped beryllium capsule, roughly 2 mm in diameter with 160-μm walls. The capsule will have a 75-μm layer of solid deuterium-tritium on the inside surface, and the capsule will be powered by X-rays generated from a gold/uranium cocktail hohlraum. The design specifications are extremely rigorous, particularly with respect to interfaces, which must be very smooth to inhibit Rayleigh-Taylor instability growth. This paper outlines the current design, and focuses on the challenges and advances in capsule fabrication and characterization; hohlraum fabrication, and deuterium-tritium layering and characterization.

Keywords: National Ignition Facility; NIF target design; NIF target fabrication

1. INTRODUCTION

This paper is a summary of the status of the National Ignition Facility (NIF) and the target design and fabrication capabilities as of October 2007. We will first give a brief update on the status and plans for the NIF. Following this, we will outline the current target design, highlighting some of the fabrication challenges that will be detailed in the remaining three sections on the capsule and hohlraum fabrication, and deuterium-tritium (DT) fuel layer formation.

2. THE NATIONAL IGNITION FACILITY

The National Ignition Facility (Moses & Wuest, 2005; Moses *et al.*, 2006, 2007; Haynan *et al.*, 2007; Landen *et al.*, 2007) is a laser fusion facility being constructed at the Lawrence Livermore National Laboratory in Livermore, California. When completed in mid-2009, it will have 192 neodymium glass laser beams and is designed to deliver 1.8 MJ at 500 TW at 351 nm in order to achieve energy gain (ignition) in a DT nuclear fusion target. The facility has a 10-m diameter target chamber and room for 100 diagnostics. Matter temperatures in excess of 10^8 K, and radiation temperatures in excess of 3.5×10^6 K are expected, along with matter densities in excess of 10^3 g/cm^3. The first 96 beams will be completed in mid-2008, and will allow for preliminary experiments on symmetry, shock timing, and ablation rate. With 192 beams, a set of experiments will be performed to optimize various aspects of the ignition configuration before the ignition campaign begins in mid- 2010. The NIF master strategy is to open the NIF to the outside scientific community to pursue the frontiers of high energy density laboratory science.

Address correspondence and reprint requests to: Robert Cook, Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94550. E-mail: bobcook@llnl.gov

3. IGNITION TARGET DESIGN

The design of ignition targets for the NIF is an ongoing task. Lindl and co-workers (Lindl, 1998; Lindl *et al.*, 2004) have detailed the basic physics required for ignition, and Haan and co-workers (Haan *et al.*, 2005, 2006, 2007*a*, 2007*b*; Kilkenny *et al.*, 2005; Nobile *et al.*, 2006) have documented specific target designs. These designs are for indirect-drive ignition, in which the laser energy is focused onto the inside walls of a hohlraum, and converted to X-rays which drive the target capsule. Direct-drive designs for ignition have also been developed (McCrory *et al.*, 2007), but are not covered in this paper.

The basic indirect-drive target consists of a 2-mm diameter Cu-doped Be capsule with 160-μm walls, with 75 μm of DT fuel layered on the inside, the capsule being suspended in an Au/U cocktail hohlraum with thin polymer membranes. The

Table 1. *Cu-doping concentration and layer thickness for the Be capsule in the current NIF design target. Layers are listed from the inside wall. The layer thickness is given in μm, the Cu concentration [Cu] is given in atom %*

Layer	Thickness	[Cu]
1	5	0.0
2	5	0.5
3	35	1.0
4	10	0.5
5	105	0.0

Cu-doping, which is present to prevent preheating of the DT fuel layer and limit the growth of hydrodynamic instabilities, is not uniform, but rather in layers. The doping concentration and layer thickness are shown in Table 1. The purpose of the varying dopant concentration is to minimize the density discontinuity at the shell/DT interface, which contributes to Rayleigh-Taylor instability growth. Be absorbs X-rays from the drive much better than the relatively transparent DT, and the Cu-doped layers are even better absorbers. The hot Be expands, and will be at a lower density than the cold compressed solid DT. Reducing the Cu-doping on the inside layers near the fuel layer allows them to stay cooler, and thus at a higher density, reducing the density mismatch at the ablator-fuel interface.

Another feature of the target design that is new is the use of a "cocktail" hohlraum. The basic purpose of the hohlraum is to convert laser light into X-rays. Important in this conversion is the loss of energy to the hohlraum material, historically pure Au. It has now been shown that if the hohlraum wall is composed of a mixture of materials, a higher net wall opacity can be achieved, resulting in less energy loss and a higher net conversion (Schein *et al.*, 2007). The current design calls for a cocktail that is 75% U and 25% Au. A 100% U hohlraum is also being considered. In either case, the inside of the hohlraum is coated with 0.1 to 0.5 μm of Au.

The design calls for the DT fuel layer to be at 18.3 K, about 1.5 K below its triple point temperature (Souers, 1986). The solid DT temperature is chosen to reduce the DT vapor pressure in the capsule center to 0.3 mg/cm^3 from the 0.6 mg/cm^3 at the triple point. Calculations show that such a reduction in gas density increases the capsule yield in otherwise identical targets (Strobel *et al.*, 2004). The reasons for this are complex, but fundamentally a lower internal vapor density decreases the work of compression and thus increases the convergence for a given laser energy.

4. CAPSULE FABRICATION

The fabrication of graded, Cu-doped Be capsules has been well documented (Xu *et al.*, 2007; McElfresh *et al.*, 2006) and the details will not be repeated here. The capsules are produced by sputtering Be and as needed co-sputtering Cu onto CH mandrels (McQuillan *et al.*, 1997; Nikroo *et al.*, 2004) in a bounce pan. Variation of the power to the Cu-sputter-gun allows one to precisely control the radial Cu concentration in the deposited material, and meeting the specification outlined in the previous section has not been a problem. The coating rate is from 0.25 to 0.40 μm/h depending on power conditions used, thus 3–4 weeks are necessary in order to produce a capsule with a 160-μm wall. Typically, 10 to 20 capsules are coated together.

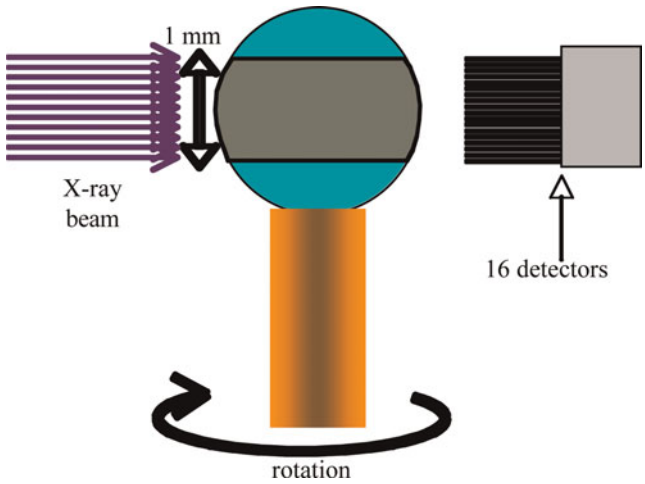

Fig. 1. (Color online) Shown is a cartoon of the precision radiograph apparatus.

The accurate characterization of coated shells for dopant layer geometry and concentration has required considerable development, the details of which have been published (Huang *et al.*, 2007*a*, 2007*b*). The measurement is made by a careful analysis of a contact radiographic image of the shell. There is also a requirement that there be azimuthal X-ray optical depth uniformity of at least one part in 10^4 at mode 25. This requirement stems from the need to suppress Rayleigh-Taylor instability growth during the implosion. Surface roughness is of course one manifestation of this requirement, and on the outside of the capsule, it can easily be measured. But the specification is also impacted by "roughness" at doping layer interfaces or azimuthal variations in either the Cu concentration (quite unlikely) or the material density. There has been concern about this last factor since the deposited material is known to contain small voids (Xu *et al.*, 2007; Nikroo *et al.*, 2007), which can lead to azimuthal variations. The measurement is made by continuous radiographic analysis of the shell while it is rotated in front of an X-ray source, the transmission through the shell being measured by 16 detectors, data taken at each 0.1°. A cartoon of the apparatus is shown in Figure 1. X-rays pass through the two shell walls, the transmission, T, is given by $T = T_0 e^{-\mu x}$, where μx is the optical depth. The shell rotates at about 1 revolution per minute (rpm), and the data is interleaved to eliminate long term drift. The system counts every photon, and thus by counting long enough the noise, which is proportional to $1\sqrt{\text{counts}}$,

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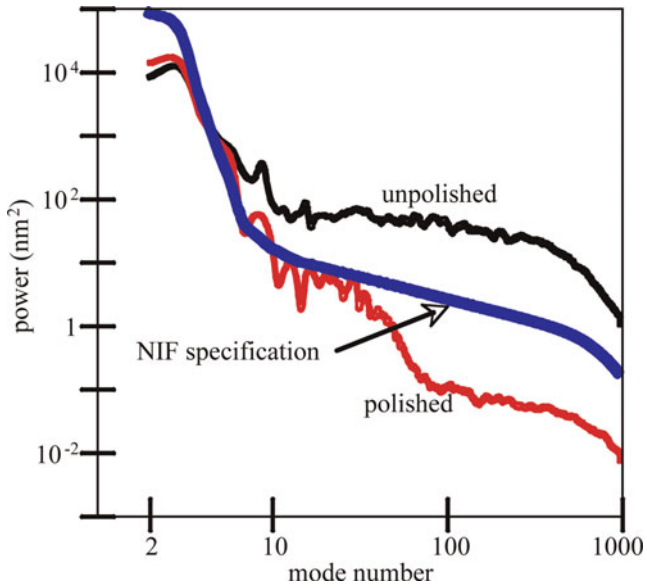

Fig. 2. (Color online) Shown is an example of the effect of polishing on the outer surface power spectra.

can be sufficiently reduced so that the measurement can give the required one part in 10^4 accuracy (Eddinger *et al.*, 2007). Current measurements show that our Cu-doped Be capsules meet the specification, though a recent tightening of the internal capsule-fuel interface roughness specification requires re-evaluation of the data.

As noted above, the outside surface roughness can be easily measured. Polishing is necessary to achieve the required high mode outer surface finish (Hoppe & Castillo, 2006). Figure 2 shows the effect polishing can have on the outer surface finish, dramatically lowering the high mode roughness while leaving unchanged the low mode shell geometry, which is fixed primarily by the mandrel. Historically, measurement of the outer surface finish has been done with an atomic force microscope based sphere-mapper (McEachern *et al.*, 1995; Stephens *et al.*, 2004). More recently, a phase sensitive diffractive interferometer (PSDI) has been adapted to provide complete mapping of the exterior capsule surface (Montesanti *et al.*, 2006). The PSDI provides detailed information for 500-μm circular patches with lateral and height resolutions of 700 and 2 nm, respectively. This is particularly useful for detecting and quantifying isolated defects on the capsule surface, which may be partially or totally missed by traditional sphere-mapper technology. Perhaps more important is that this technique can be used to analyze patches on the inside surface of a shell. Although such analysis is destructive for the shell being analyzed, confidence can be gained that the inside surfaces of similar shells from the same batch are acceptable (Xu *et al.*, 2007).

The CH mandrel upon which the Be is deposited must be removed after the full thickness coating is deposited. Laser drilling a hole through the wall and "burning out" the mandrel in air at an elevated temperature (Cook *et al.*, 2006; Bhandarkar *et al.*, 2007; Youngblood *et al.*, 2007) accomplishes this. The specification on the hole, which is necessary for DT fuel filling as well, are severe, with a diameter of 5-μm maximum through most of the 160-μm wall. This is accomplished with an Nd-YAG laser, wavelength equal to 532 nm, 4-ns laser pulses using a double pulse technique (Forsman *et al.*, 2005). A radiographic image of a typical laser drilled hole through a 167.1-μm Be capsule wall is shown in Figure 3. The darkening in the bottom third of the image is due to the Cu-doping in the shell wall. A counterbore at the outside surface is also drilled to accommodate fill tube attachment.

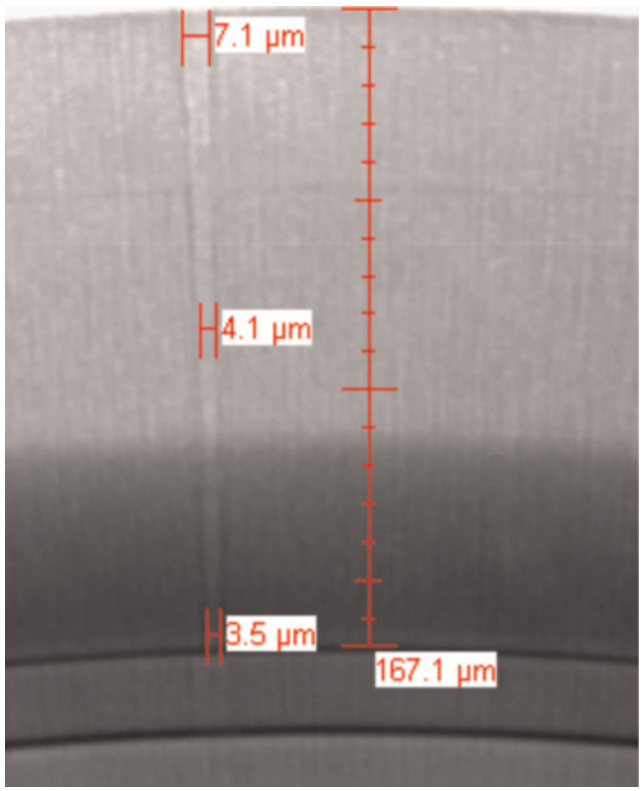

Fig. 3. (Color online) A radiograph of a typical laser drilled hole through a 167.1 μm Be capsule wall is shown. The darkening in the bottom third of the image is due to the Cu-doping in the shell wall.

The shells are filled with DT through a fill tube attached at the laser drilled hole. Precise polyimide fill tubes are fabricated with a custom micro-heater, which pulls commercial polyimide tubes with an outer diameter of 150 μm to tubes with an outer diameter of 10–12 μm and an inner diameter of 5–6 μm (Takagi *et al.*, 2007). The tips of the fabricated fill tubes are laser cut in order to produce a flat surface. Glass tubes, which can be obtained commercially with the right dimensions, can be hand cut to the proper length. To achieve a gastight attachment, the hole entrance is enlarged to 12–15 μm in diameter to a depth of ~20 μm. The fill tube is inserted into the hole and securely bonded in place with not more than 2 picoliters of ultraviolet curable epoxy. A scanning electron microscopy (SEM) image of a fill tube bonded onto a Be capsule is shown in Figure 4.

In summary, graded Cu-doped Be capsule fabrication and fill tube attachment is in good shape; all design specifications have been met. Current effort focuses on optimizing all of

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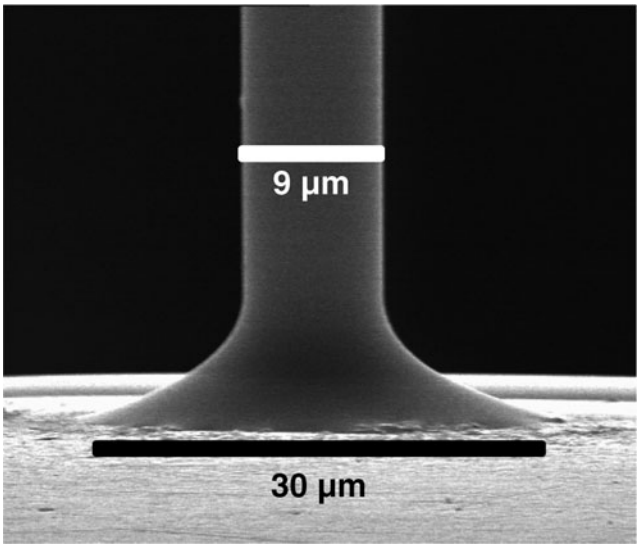

Fig. 4. Shown is an SEM image of a fill tube bonded into a Be capsule.

the steps and improving techniques for the precise assembly of both the fill tube to the capsule and the fill tube/capsule assembly into the hohlraum. In closing this section, it should be noted that graded, Ge-doped CH designs exist and that capsules meeting these specifications have been successfully fabricated (Chen *et al.*, 2006, 2007; Theobald *et al.*, 2007). We also note that good progress is being made on a high-density carbon capsule *via* diamond chemical vapor deposition techniques (Biener *et al.*, 2006).

5. HOHLRAUM FABRICATION

It has been a significant challenge to fabricate Au/U cocktail hohlraums (Wilkens *et al.*, 2007). Pure Au hohlraums have been fabricated for many years by electroplating Au onto an appropriately shaped Cu mandrel, which is then leached out with HNO_3 to leave the chemically inert Au hohlraum. Details such as diagnostic windows could easily be machined before the leaching.

It is relatively easy to co-sputter Au and U in the proper design cocktail proportions, and if ambient oxygen exposure is carefully controlled, the problems begin with the leach step, for coatings on either Al (NaOH leach) or Cu (HNO_3 leach) mandrels. Uranium is very susceptible to oxidation, which is bad for two reasons. First, the effectiveness of the cocktail in reducing wall energy losses is markedly reduced by the presence of O in the wall. Second and perhaps more immediately important, the oxidation leads to loss of the hohlraum physical integrity. The solution to the problem was to protect the U from oxidation by developing a dense, multilayer Au/U coating, and then developing techniques to limit the time the cocktail surfaces are exposed to the leaching bath.

To limit the time in the leach bath a hybrid mandrel was developed. A basic mandrel was machined from solid Al stock and then overcoated with a thin layer of Cu. This was then overcoated with 0.2 to 0.5 μm of Au before 185–30 nm U and 8 nm of Au layers were applied in a specially designed high vacuum sputter chamber, building up a 7-μm thick wall of cocktail. Finally, a 30-μm capping layer of Au was applied. The Al mandrel is then exposed by machining out the laser entrance hole and cutting to make two half hohlraums. As shown in Figure 5, the first leach is done in NaOH to remove the solid Al mandrel. The thin layer of Cu is not affected by NaOH, and protects the cocktail layers. After the Al is completely removed, the part is exposed to a very short leach in HNO_3 to remove the Cu, the leach being completed in about 3 min. During this leach, the part is watched carefully under a microscope so that it spends no longer in the leach bath than necessary. Preliminary work on pure U hohlraums has shown that the combination of the short final leach and the promotion of a dense structure have resulted in more than 50% of the finished parts remaining in pristine condition for up to 4 weeks, the shelf life required for assembly. In some cases, damage still initiates through the back-machined edges, diagnostic patterns (see next section), and work is ongoing to improve this situation.

6. DT FUEL LAYERS

The current inertial confinement fusion design for the ignition target involves having a capsule with an inside layer of solid DT, 75-μm thick, at 18.3 K. The solid must

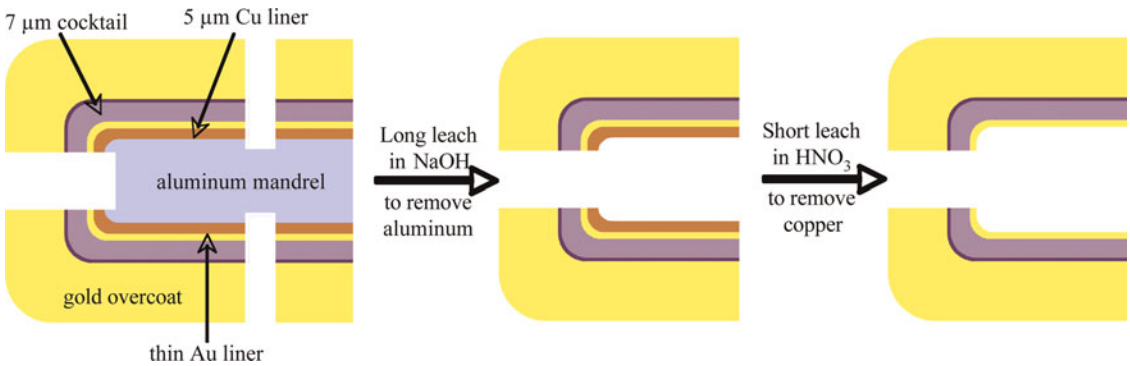

Fig. 5. (Color online) Shown is the leaching process for cocktail hohlraums. The dimensions in the figure are not to scale.

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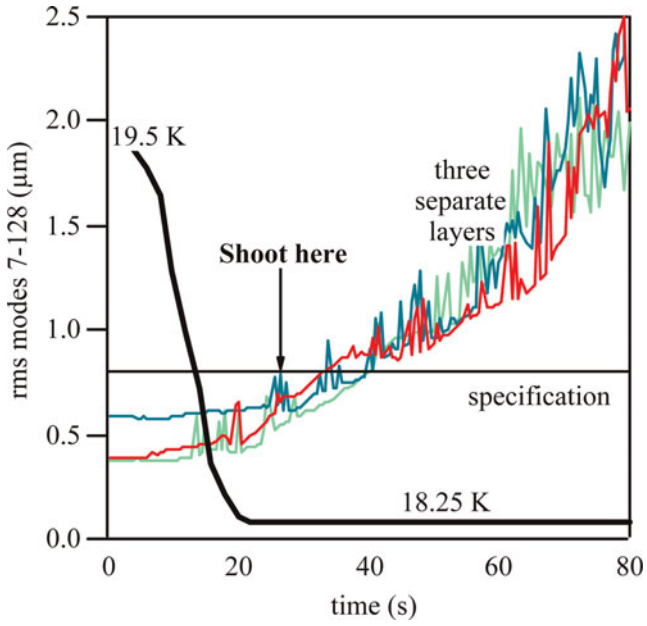

Fig. 6. (Color online) Plotted are the rms data for three separate experimental runs. In each case a good DT layer was made near the triple point (19.8 K) and then the shell was quenched in about 20 s to 18.25 K. The rms of the layer was monitored as a function of time.

have a smooth surface and uniform thickness, with a total root-mean-square (rms) deviation of less than 1.25 μm (all modes). Fortunately, a natural process known as beta layering (Hoffer & Forman, 1988; Sater *et al.*, 1999), makes it possible to make such a smooth surface in an inherently non-contact environment. The basic process is as follows. Imagine a shell of DT below its triple point in a spherically symmetric isothermal environment containing enough DT to form a 75-μm solid layer. The nuclear decay of the tritium produces ^{3}He, a beta particle, and an antineutrino. The beta-particle quickly loses its mean energy of 5 keV to the solid as heat, uniformly distributed in the solid DT (Souers, 1986). Since the entire capsule is kept in a spherical isothermal environment, there is an increase in solid DT temperature as one moves away from the ablator wall toward the center of the shell. Thus the temperature on the inside surface of the solid DT is highest where the solid DT is thickest. Because of this higher temperature, the rate of sublimation is highest where the fuel layer is thickest, resulting in a redistribution of the DT from the thickest parts of the layer to the thinnest. This natural process has become known as beta layering, and has a time constant for redistribution of about 30 min for a 50–50 DT mixture, with an additional dependence on ablator thermal conductivity and ^{3}He concentration (Martin *et al.*, 1988; Bernat *et al.*, 1991; Geidt *et al.*, 2006).

The beta-layering process works qualitatively very well, however the specification for the surface quality of the DT solid-vapor interface is very stringent. At a few tenths of a Kelvin below the triple point temperature of 19.8 K, it has been demonstrated that sufficiently smooth layers can be formed (Moody *et al.*, 2006; Kozioziemski *et al.*, 2007). However, as the temperature is dropped to the design temperature of 18.3 K the layer roughens and surface defects develop, generally to a level in excess of the specification. Up until recently, these experiments have involved a slow decrease in temperature over 24 h. However, we are now exploring a "rapid quench" technique recently documented (Martin *et al.*, 2006, 2007) that shows promise.

The idea is to first form a quality layer near the triple point, characterize it, and then rapidly quench to 1.5 K below the triple point. The current NIF cryogenic target fielding system will support rapid cooling and calculations show that a cool down of 1.5 K in a NIF hohlraum is feasible in a few seconds. Our experiments show that the layer begins to roughen as soon as the temperature is dropped, but the NIF laser shot can

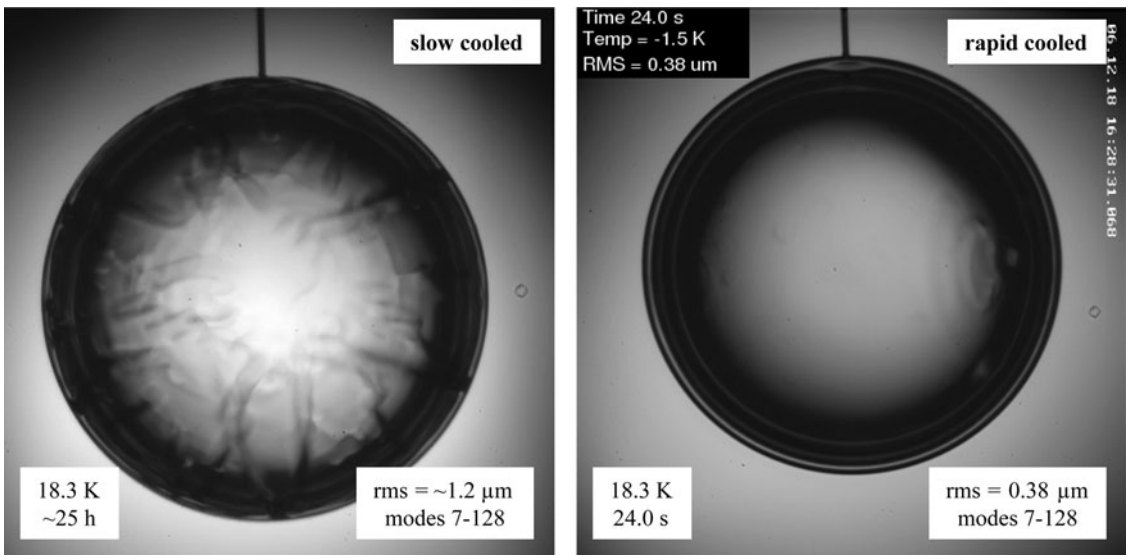

Fig. 7. Shown are optical backlit photos of DT layers in plastic shells after slow (**left**) and rapid (**right**) temperature quenches to 18.3 K.

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occur before the roughness exceeds the specification. Several example runs of the time dependent roughening after a rapid cool down are shown in Figure 6. Plotted is the rms roughness in μm over modes 7 to 128 as a function of time in seconds. The time dependent quench profile is shown, about 20 s are needed in this case for the quench. What we see is that if the laser is fired within 15 s after the quench is complete, the roughness of the layer is still within specification (0.83-μm rms for modes 7–128). Figure 7 shows optical backlit images of slow and rapid cooled DT layers in 2-mm CH shells. The difference is striking. Work is on-going to optimize this technique, for instance, by exploring different cooling rates and understanding time dependent surface roughness mechanisms, but it shows promise for enabling DT fuel layers that meet all the ignition specifications at 18.3 K.

We will conclude this section with a few words about DT fuel layer characterization. The use of opaque Be shells became particularly attractive with the development of X-ray phase contrast characterization (Montgomery *et al.*, 2004; Kozioziemski *et al.*, 2007). Previous to this optical shadowgraph (Koch *et al.*, 2000) was used, and this restricted layering research to transparent shells, typically CH shells (Chen *et al.*, 2006), or polyimide shells (Letts *et al.*, 2006). In addition to being able to characterize the fuel layer through optically opaque shells, the X-ray images are generally more representative of the surface roughness. The X-ray phase contrast technique requires a small (less than 5-μm diameter) yet powerful X-ray spot source along with a high-resolution X-ray sensitive detector. Both the source and detector requirements have been met with current technology (Kozioziemski *et al.*, 2007), and this technique has proven extremely useful in characterizing the rms roughness in single views. We have studied the accuracy of the X-ray imaging technique when compared to a known standard. The X-ray imaging is currently limited because of the long (∼2 min) exposure time required for a high signal-to-noise image, which limits its usefulness in characterizing the dynamics of rapid quench fuel layers.

For a shell in a normal hohlraums, there is only one full view of the fuel layer—through the laser entrance holes. Though useful, this is by far an incomplete picture of the fuel layer surface. To remedy this situation, we have designed what we call "starburst" hohlraums, which have two sets of aligned slots cut into the hohlraum wall mid-plane in order to provide an axial view of the capsule. Figure 8 shows at the top an artist rendition of the center part of the hohlraum showing one of each set of starbursts, at the bottom is a photo of a machined starburst pattern. Because the two sets are aligned, one can use either X-ray phase contrast or optical techniques (with a transparent capsule) to get characterization data on the fuel layer up to about mode 10. This coupled with characterization thorough the laser entrance holes will give the required information about the low mode symmetry of the fuel layer. We will rely on the single laser entrance holes view to provide a representative characterization of the higher mode roughness.

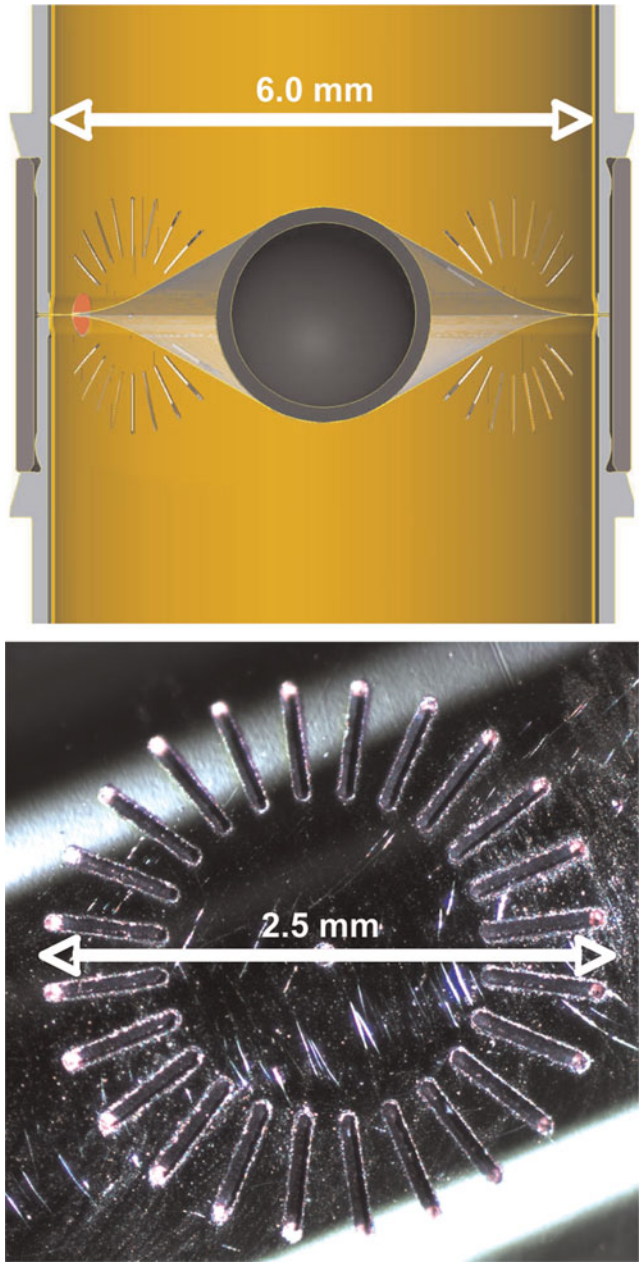

Fig. 8. (Color online) At the top is an artist depiction of the center of a hohlraum showing two of the four starbursts that allow one to view the capsule axially. At the bottom is a photo of a machined starburst.

7. FINAL COMMENTS

The targets for the first experiments at the NIF are nearly ready, there appears at this time no technological barrier to their production. Most of the very tight target specifications that have been set by the designers have been met, and to verify this in many cases new characterization methods have been developed. The details of the design are still evolving, and discussions between the fabricators and the designers are ongoing to meet new technical challenges. We have every confidence that quality targets will be ready for a successful ignition campaign in 2010.

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