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**FABRICATION OF PRESSURIZED 2 MM BERYLLIUM TARGETS FOR ICF EXPERIMENTS**

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*We have successfully fabricated 2 mm beryllium targets pressurized with a gas mixture of ~20 atm deuterium and ~0.1 atm argon. These targets have been used for indirect drive Inertial Confinement Fusion (ICF) experiments on the Z-pinch machine at Sandia National Laboratories leading to record neutron yields of  $\sim 3.5 \times 10^{11}$  [J.E. Bailey, et al., "Be Capsule Implosions Driven by Dynamic Hohlräum X-rays," Bull. Am. Phys. Soc. **51**, 107 (2006)]. This paper will discuss the process of fabricating such targets from intact shells (Be sputter coated CH mandrels). These processes include laser drilling a  $\sim 6 \mu\text{m}$  diameter fill hole in a shell, removing the CH mandrel by pyrolysis, pressurizing the target with a deuterium/argon gas mixture and sealing the fill hole using UV glue while under pressure. The targets were characterized for gas pressure and deuterium gas permeation half-life by utilizing techniques including mass spectrometry, x-ray fluorescence spectroscopy and controlled shell bursting.*

**I. INTRODUCTION**

Be targets are needed for ICF experiments on the National Ignition Facility (NIF) as well as Sandia's Z-pinch machine. The current NIF specifications call out for a  $\sim 2$  mm diameter Be capsule with Cu-doped layers in the  $\sim 160 \mu\text{m}$  thick wall.<sup>1</sup> The Be coating is produced by magnetron sputter coating onto a spherical plastic mandrel.<sup>2</sup> Beryllium is one of the preferred ablator materials for ICF experiments<sup>3</sup> due to its hydrodynamic stability and mechanical strength. Unlike plastic or glass, full density Be is impermeable to gas therefore requiring a fill-hole to allow for pyrolysis of the CH mandrel as well as for a  $\text{D}_2/\text{Ar}$  pressure fill. Although NIF specifications call out for the CH mandrel to be removed, initial Be target fabrication for the Sandia Z-pinch implosions left the CH mandrel intact due to gas leakage issues through the walls of early trial sputter coated Be shells. The combination of the CH

and Be layers gave a  $\text{D}_2$  gas permeation half-life of  $>7$  days, which was sufficient time for the experiments to be completed.

This paper discusses the ICF target fabrication process from an intact shell (post-sputter-coating). A laser drilling process was developed for drilling high aspect ratio holes up to  $\sim 25:1$ ; pyrolysis using a furnace was used for CH mandrel removal; a pressure sealing chamber was engineered to allow for gas fill of a target; and mass spectrometry, x-ray fluorescence and a shell bursting chamber were used to confirm and characterize gas retention. It should be noted that the following processes discussed in this paper are experimental and continue to be developed.

**II. LASER DRILLING AND HOLE CHARACTERIZATION**

According to NIF specifications, a fill-hole with mass deficit less than or equal to that of a  $6.25 \mu\text{m}$  through-hole must be laser drilled through a Be shell wall to allow for a gas fill.<sup>4</sup> Fill-hole diameter and glue mass must be minimized so as not to interfere with symmetric compression during ICF target implosion. Hole aspect ratios range from  $\sim 1:1$  to  $\sim 25:1$  (depending on the final target application) through Be wall thicknesses ranging from  $\sim 10$ – $175 \mu\text{m}$ .

Laser drilling a fill-hole is accomplished using a diode-pumped, Nd:YAG laser with 10 kHz repetition rate and 4 ns pulse-width, frequency-doubled to 532 nm with an average power of 1.5 W (150  $\mu\text{J}/\text{pulse}$ ). The laser is configured to perform double-pulse machining.<sup>5</sup> In the double pulse format, a primary pulse trailed by a secondary pulse of nominal energy greatly enhances hole characteristics and machining speed. The primary pulse ablates material creating plasma and other ejecta in front of the target and the secondary pulse, delayed by nanoseconds (in our case 20 ns was found experimentally to be optimal), interacts with partially cooled

ejecta. This now reheated ejecta then causes efficient ablation and effectively clears the hole.

Shells are placed on a horizontal mount attached to micron resolution, motorized XYZ linear stages, which are located inside of the laser drilling vacuum chamber. The chamber is pumped down to  $<200$  mTorr during laser drilling. Using several optical and focusing diagnostics along with the linear stages, the shells can be accurately traversed to the focal point of the focusing lens and subsequently shot. The focal spot is a diffraction-limited  $5\ \mu\text{m}$  spot produced by a 25 mm focal length plano-convex lens. To achieve minimum hole size, the focal spot needs to be  $\pm 20\ \mu\text{m}$  from the middle of the shell wall.

Due to the varying thicknesses and material dopants in the Be coatings,<sup>2</sup> drilling time and energy must be altered to ensure a through-hole is created, as well as to avoid back-wall damage and larger hole diameters. Optimal drilling times and energy settings for the different types of shells were found through repeated experiments in various flats and shells. For most holes, a soft start procedure is used to help minimize the entrance hole diameter. The soft start procedure consists of firing a burst of laser pulses at a reduced power before drilling with a longer burst of pulses at higher power. The typical parameters for drilling full thickness NIF shells ( $\sim 160\ \mu\text{m}$ ) are: soft start at average power of 50 mW ( $5\ \mu\text{J}/\text{pulse pair}$ ) with exposure time of 10 ms, main drilling burst at average power of 400 mW ( $40\ \mu\text{J}/\text{pulse pair}$ ) with exposure time of 250 ms.

Hole characterization is done using the X-Radia MicroXCT, which is an x-ray transmission microscope that uses 20–90 keV x-rays to produce high-resolution 2D as well as 3D tomographic images. A 2D X-Radia image of a laser-drilled shell is shown in Fig. 1.

### III. PYROLYSIS

The CH mandrel must be removed from a sputtered Be shell in order to conform to the NIF specifications for x-ray opacity profile. Furthermore, the coefficient of thermal expansion is much less for Be than for plastic and some of the targets must be fielded at  $\sim 18\ \text{K}$ , which would likely cause the CH to delaminate from the inside walls of the Be shells.<sup>6</sup> The method used for removing the CH mandrel is pyrolysis, which is the decomposition of a compound caused by heat. In this case, the burn up of CH in air produces  $\text{CO}_2$  and  $\text{H}_2\text{O}$ . From

experiments using a thermogravimetric analyzer, CH was found to have a pyrolytic temperature of  $\sim 400^\circ\text{C}$ .

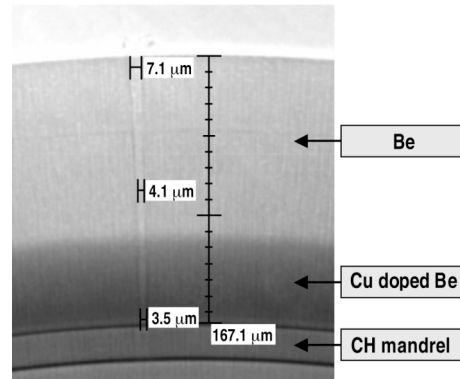


Figure 1. X-Radia image of a Be shell ( $\sim 2240\ \mu\text{m}$  o.d.,  $\sim 170\ \mu\text{m}$  Be wall thickness,  $\sim 20\ \mu\text{m}$  GDP mandrel thickness) with a laser drilled hole. This shell was exposed to two bursts of laser pulses. The first was a soft start that lasted 10 ms with an average power of 50 mW ( $5\ \mu\text{J}/\text{pulse pair}$ ). The second burst lasted 250 ms with an average power of 450 mW ( $45\ \mu\text{J}/\text{pulse pair}$ ). The mass deficit of the cleared ejecta is approximately that of a  $5.4\ \mu\text{m}$  through-hole.

Once the Be shells are laser drilled, they are placed in a furnace and baked in air at atmospheric pressure for  $\sim 60$  h. The baking process is as follows: furnace temperature is increased from room temperature to  $325^\circ\text{C}$  at  $10^\circ\text{C}/\text{min}$ ; temperature increased from  $325^\circ\text{C}$ – $425^\circ\text{C}$  at  $1^\circ\text{C}/\text{min}$  and held for 60 h; furnace temperature decreased to  $50^\circ\text{C}$  at  $5^\circ\text{C}/\text{min}$  until removal. Once pyrolysis is complete, contact radiography or X-Radia are used to verify mandrel removal. X-Radia images of a Be coated CH mandrel pre- and post-pyrolysis are shown in Fig. 2.

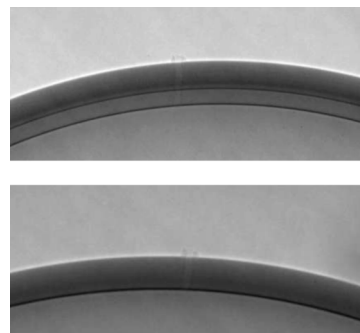


Figure 2. (Top) X-Radia image of a 2 mm Be shell with  $\sim 25\ \mu\text{m}$  Be coating on a  $\sim 14\ \mu\text{m}$  CH mandrel, post laser drilling. (Bottom) the same shell with CH mandrel removed through pyrolysis for  $\sim 60$  h at  $\sim 425^\circ\text{C}$ .

**IV. GAS PRESSURE FILL**

For ICF experiments on NIF, the shells need to be pressurized and sealed with ~20 atm of a 99.6% D<sub>2</sub> and 0.4% Ar gas mixture calculated by vapor phase mole fractions. Ar is added to the gas mixture because, during implosion, time- and space-resolved spectra from Ar tracer atoms can be used as a diagnostic to examine implosion core conditions.<sup>7</sup>

A 5-way valve was modified and engineered into a pressure-sealing chamber, shown in Fig. 3, which was pressure tested for up to a ~35 atm pressure fill – the chamber volume is <1 in<sup>3</sup>. A Be shell with the laser-drilled hole facing up is placed onto a gel sheet attached to a base-plate located in the bottom of the sealing chamber. The base-plate can be traversed in the X, Y and Z directions to several micron resolution using modified metering valves as manipulators. Four viewports are located 90° apart, two for microscope cameras and two for lighting the chamber interior. UV glue is applied to the correctly positioned shell using a ~120 μm metal tube attached to a modified valve in the top of the chamber. Figure 4 shows a schematic of the sealing process.

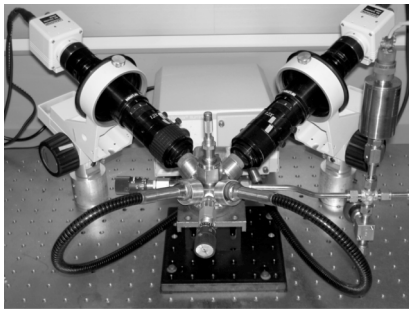


Figure 3. Photo of pressure-sealing chamber.

Before applying UV glue, the chamber must be evacuated to maintain purity of the fill gas, then filled to the specified pressure of the D<sub>2</sub>/Ar gas mixture and allowed to soak for ~5 min to ensure that the shell is full of gas. Once UV glue is applied to the fill-hole, UVA light is introduced through the viewports which polymerizes the glue, hence, sealing the shell. Hundreds of shells have been sealed using the system with a very high success rate. An image of a sealed shell is shown in Fig. 5.

**V. GAS RETENTION TESTING**

The sealed shells then need to be tested for gas retention and D<sub>2</sub> gas permeation half-life — the NIF

requirement for D<sub>2</sub> half-life is >7 days. This can be done nondestructively using mass spectrometry and x-ray fluorescence, as well as destructively using a shell-bursting chamber.

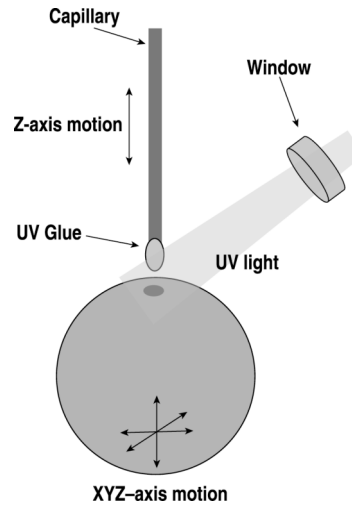


Figure 4. Schematic of UV glue sealing process. The Be shell can be traversed in the X, Y and Z directions to position the laser-drilled hole underneath the capillary. The capillary then lowers to deposit a drop of UV glue on the hole. UV light is then introduced through a viewport to polymerize the glue.

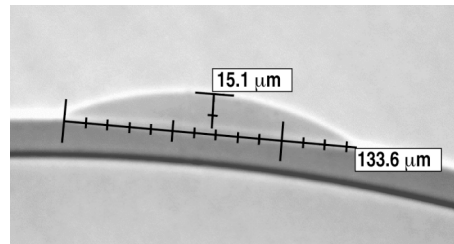


Figure 5. X-Radia image of a UV glue seal.

A mass spectrometer residual gas analyzer is used to measure the ion current of D<sub>2</sub> gas permeating through the shell wall of an ICF target.<sup>8</sup> Permeation half-life can be calculated knowing the fill pressure and volume of the target along with comparing its resultant ion current with that of a calibrated leak flow, as shown in Fig. 6. The calibrated leak flow is pressurized with helium and has a vacuum leak rate of 1.7x10<sup>-7</sup> atm-cc/s. This technique is valuable because a permeation half-life of days or weeks can typically be calculated in <20 min. Some targets outgas so slowly that the resulting mass spectrometer ion current plot approaches the noise level making it very hard to calculate permeation half-life or even decipher whether the target is retaining gas at all. Therefore, another non-destructive technique used to

confirm gas retention is x-ray fluorescence (XRF) spectroscopy.

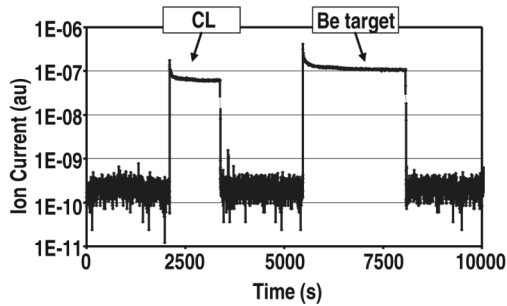


Figure 6. Ion current measured on the mass spectrometer system. The left portion of the plot shows the ion current of the calibrated leak (CL) flow and the right portion shows the ion current through a Be target ( $\sim 2200 \mu\text{m}$  o.d.,  $\sim 58 \mu\text{m}$  Be wall thickness,  $\sim 33 \mu\text{m}$  GDP mandrel thickness) pressurized with  $\sim 310$  psi of  $\text{D}_2$ . Comparing the two leak rates at steady state gives a half-life of  $\sim 7$  days for the Be target.

XRF makes it possible to qualitatively and quantitatively determine the elemental composition of an ICF target in minutes.<sup>9</sup> The x-ray source is used to irradiate the sample causing secondary x-ray fluorescence from which the elemental concentration can then be calculated. The XRF system in use in our laboratory can measure elements with  $Z \geq 11$  (Na), therefore the corresponding Ar ( $Z = 18$ ) signal from a gas filled ICF target can be used as a diagnostic to determine gas retention, as shown in Fig. 7. Ar counts for unfilled Be shells were compared to shells filled with a known amount of Ar. Unfilled Be shells typically show  $\sim 10$  Ar counts/s due to residual Ar trapped in the grain structure from the sputter coating process. For each psi of Ar contained in a shell the counts increase by  $\sim 30$  Ar counts/s, so fill pressure can be estimated using this method.

Finally, some ICF targets are destructively tested in a shell-bursting chamber to compare and confirm permeation half-life results with that of the mass spectrometer. A target is placed in the bursting chamber which is then pumped down to  $\sim 10^{-3}$  Torr. A nail is dropped on the target to burst it and the subsequent pressure change in the chamber can then be compared with that of a bursted reference shell — usually a poly( $\alpha$ -methylstyrene) shell filled to 1 atm. Initial fill pressure and permeation half-life of the Be target can then be calculated. Measurements from both the destructive testing technique and the mass spectrometer system typically agree to within 15%.<sup>8</sup>

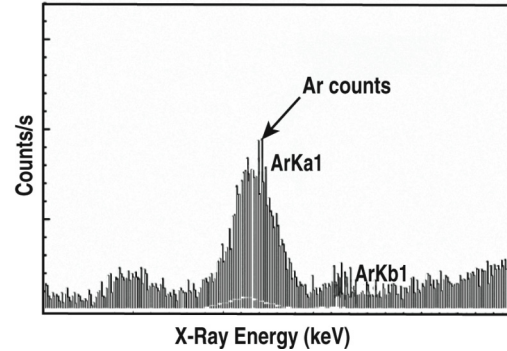


Figure 7. XRF graph showing Ar signal in a Be target. The magnitude of the Ar in counts/s can be used to estimate the Ar fill pressure inside of a shell.

## VI. SUMMARY

We have successfully fabricated and characterized 2 mm Be targets pressurized with a gas mixture of  $\sim 20$  atm  $\text{D}_2$  and  $\sim 0.1$  atm Ar. These targets have been used for room temperature experiments at Sandia's Z-pinch facility and are being developed for future NIF experiments. We have developed a target fabrication process which includes laser drilling of a fill hole, mandrel pyrolysis, pressure sealing the target and testing for gas retention.

## ACKNOWLEDGMENT

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