LA-UR-98-**2521**

Title:

Surface Roughness Statistics and Temperature Step
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CONF-980496--

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Submitted to:

Target Fabrication Specialists Meeting
Jackson, WY
4/20-24, 1998

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Form No. 836 R5
ST 2629 10/91

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Surface Roughness Statistics and Temperature Step Stress Effects for D-T Solid Layers Equilibrated Inside a 2 mm Beryllium Torus

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Abstract

Solid D-T layers are equilibrated inside a 2 mm diameter beryllium toroidal cell at temperatures ranging from 19.0 K to 19.6 K, using the beta-layering process. The experimental runs consist of multiple cycles of rapid- or slow-freezing of the initially liquid D-T charge, followed by a lengthy period of beta-layering equilibration, terminated by melting the layer. The temperature was changed in discrete steps at the end of some equilibration cycles in an attempt to simulate actual ICF target conditions. High-precision images of the D-T solid-vapor interface were analyzed to yield the surface roughness σ_{rms} as a sum of modal contributions. Results show an average σ_{rms} of $1.3 \pm 0.3 \mu\text{m}$ for layers equilibrated at 19.0 K and show an inverse dependence of σ_{rms} on equilibration temperature up to 19.525 K. Inducing sudden temperature perturbations lowered σ_{rms} to $1.0 \pm 0.05 \mu\text{m}$.

Introduction

Beta-layering¹ is a process in which an encapsulated solid layer of deuterium-tritium (D-T) is driven to high uniformity and smoothness by sublimation/condensation of the D-T solid from thicker to thinner layer regions. The mechanism that drives this process is the radioactive decay of tritium, which produces high-energy beta particles that are absorbed in the D-T solid. This absorption produces temperature gradients in the solid layer that correspond to its mass distribution, causing the redistribution of D-T solid into a uniform and smooth layer. Highly uniform and smooth D-T solid layers will be required for future ICF and National Ignition Facility (NIF) experiments in order to produce the implosion conditions² that are necessary for nuclear ignition.

Previous experiments³ performed in a re-entrant cylindrical copper layering cell showed that the equilibrated solid layers on the inner bore are highly uniform and smooth, with a minimum σ_{rms} of $\sim 1.7 \mu\text{m}$. (Here, σ_{rms} implies that the surface roughness is the root quadratic sum of the power of the cylindrical Legendre modes 2 to 256, inclusive, as analyzed from the image of the solid layer formed at the inner cylindrical waist. Likewise, for the present toroidal geometry, the surface roughness is analyzed from images focused at the narrow cylindrical waist of the torus.)

The accurate and precise optical measurement of σ_{rms} requires that the optical path be as free from distortion as possible. The measurements are made by back-lighting the solid layer through a 'rear' window and acquiring a layer image through a 'front' window. If either the solid layer or optical path are perturbed by abnormal features within the cell or anywhere along the optical path, then the surface roughness measurement will be distorted as well. In the re-entrant cylinder, both the solid layer surface and optical path could be distorted by certain cell features. For example, the layer edge of interest was 'wrapped' around the sharp front edge of the cylinder bore, possibly

distorting the layer and creating an abnormal surface roughness at the very edge that was being imaged. In addition, the cylinder cell windows were made of high thermal conductivity sapphire, a feature that allowed solid D-T to coat the windows and distort the image of the layer edge that we were observing³.

The solution to these problems was to design a copper cell with toroidal geometry and windows made of low-conductivity glass⁴. (A toroidal geometry differs from a re-entrant geometry in that the inner 'bore' is radiused along the cylindrical axis, instead of being abruptly stepped. By making that radius equal to the cylindrical radius at the waist, we simulate the conditions inside a sphere, i.e. two equal radii of curvature, except that in a toroidal waist, one radius of curvature is negative.) In the earliest version of this geometry⁴, the windows were coated with an ITO layer so that they could be heated. When it was later found that no heat was necessary to keep D-T solid from forming on the windows, the use of non-heated windows was employed. Values of σ_{rms} as low as $0.95 \mu\text{m}$ were reported for beta-layered surfaces⁴. The copper torus also contained an internal axial heater to apply additional heat flux through the solid D-T layer, resulting in values of σ_{rms} as low as $0.4 \mu\text{m}^a$.

In the present study we also address questions regarding the statistical nature of the beta-layering process, whether layers formed on beryllium are as smooth as those formed on copper, whether the D-T layer surface is changed by the introduction of sudden temperature perturbations, and the effect of slow freezing on the equilibrated D-T solid layer.

Experimental Apparatus and Procedures

^a Cell design by Jorge Sanchez of Lawrence Livermore National Laboratory, Livermore, Ca.

Figure 1 shows a sectioned profile of the 2 mm diameter beryllium torus. This torus is a machined insert to a cylindrical cell made of copper. The windows are a low-conductivity borosilicate glass that remain free of D-T solid, due to the small amount of window heating that occurs whenever D-T is present inside the cell. The D-T fill line is shown leading into the cell from below, via a drilled hole which makes a 45° turn before entering the beryllium insert space. D-T gas is forced into the cell under a driving pressure of several torr and condenses to a liquid at a cell temperature of ~20 K. Once the cell has been filled with the amount of liquid required to produce the desired solid layer thickness, the experiment is begun by freezing the D-T liquid at the desired equilibration temperature.

The experimental apparatus further consists of three primary systems: (1) the gas handling system which supplies D-T to the cell and supplies exchange gas or vacuum to other components of the cryostat, as necessary; (2) the cryostat or cooling system which includes the refrigerator and associated hardware; and (3) the computerized data acquisition, control, and analysis system.

The cryostat is cooled by a closed-cycle helium refrigerator^b. The cryostat consists of three nested 'cans' (cylindrical shape) mounted concentrically on the refrigerator stages, with the D-T cell (fig. 1) installed inside the innermost copper can, or 'cold can'. This configuration allows a relatively low-capacity refrigerator to cool the cold can to 10 K and creates the isothermal environment necessary for achieving solid layer uniformity⁵. The temperatures of the cell^c and the cold can^d are controlled independently. Consequently, the D-T in the cell can be completely melted while the D-T in the fill line remains frozen (at ~ 10 K). This allows us to keep a nearly constant charge of D-T inside the cell for multiple cyclic experiments, yielding a consistent solid layer thickness from experiment to experiment.

^b Model 22 Cryodyne was obtained from CTI Cryogenics, POB 9171, 266 Second Ave., Waltham, Ma. 02254-9171

^c Model LTC-20 was obtained from the Instrument and Systems Division of Conductus, 10623 Roselle St, San Diego, Ca. 92121, USA

^d Model DRC-93C was obtained from LakeShore Cryotronics, Inc., Westerville, Ohio, 43081

Images of the solid D-T layer are produced by CCD camera system^e that is interfaced to the acquisition/control computer. A long-range microscope^f is attached to the camera and focuses the solid layer images onto the camera CCD array of 1024 x 1024 pixels. This combination produces the equivalent of an f/4 optical system, with a single pixel resolution of 2.5 μm in the object plane. The cell is illuminated from behind by an electronic flash^g. Custom electronics provide a trigger pulse to the flash unit that is synchronized to the mechanical motion of the cryostat. This motion can be tens of microns and it is monitored by a 1V/g accelerometer^h mounted on the top of cryostat vacuum can. The synchronizing of the image acquisition to cryostat motion allows us to produce solid layer images that remain spatially fixed within the image frame. These experiments were begun by filling the cell with D-T liquid at a level that would produce a solid layer with a thickness near 80 μm . A fairly rapid freeze followed by a long equilibration period was the basis for most of the beta-layering experiments. For the majority of the beta-layering experiments, the equilibration temperature was set at 19.0 K. Equilibration times from 24 to 36 hours were generally adequate for the solid layer to reach surface roughness stasis.

Following the lengthy equilibration period, the cell was warmed to above the melting point for a long enough period that all solid D-T crystals melted. Then the process was repeated for up to twelve separate cycles. The set of cycles was initially set-up in a spreadsheet file used as a look-up table by an acquisition/control software programⁱ. Freeze rate, image acquisition rate, equilibration duration, and all temperature settings were written into the table prior to launching the program.

^e Model CE200A CCD camera was obtained from Photometrics, Ltd., 3440 E. Britannia Dr., Tucson, Az 85706

^f Model QM100 was obtained from Questar Corporation, POB 59, Route 202, New Hope, Pennsylvania 18938

^g The Ultra 1200 was obtained from Paul C. Buff, Inc., 2725 Bransford Ave., Nashville, Tn 37204

^h The TAA-31025-2000 accelerometer was obtained from NeuwGhent Technology, 3 Cross Road, LaGrangeville, NY 12540-5705

ⁱ Software written and developed by E. Mapoles

An on-line data analysis program^b allowed us to retrieve the solid layer image files over the local network, then analyze them in near real-time with a separate computer. This near real-time analysis gave us the opportunity to monitor experiments in progress, with the option of making changes if necessary. The on-line analysis also saved the considerable effort that is required to do the image analysis off-line.

Experimental Results

Beta-layering Equilibrations

The first two series of experiments were both multiple cycle beta-layering runs at 19 K. Figure 2 shows images of the typical D-T liquid fill in the beryllium torus (central image), along with the empty cell (left) and 80 μm solid layer (right). The solid layer shown in 2c coats the toroidal bore shown in 2a, and it is so uniform and smooth that very little difference can be seen between the two images.

Figure 3 shows the data for an 11-cycle experiment. The equilibration period had been set to 14 hours and was obviously too short to achieve complete solid layer equilibration for some cycles. Note that for each run, the measured σ_{rms} generally converges to a value of just over 1.0 μm . The σ_{rms} for later cycles is increasing slightly, possibly due to ^3He buildup in the D-T charge, which may increase roughness directly or may increase the equilibration time beyond that allotted for each cycle. The data show that the overall layer thickness is increasing during the later cycles. This is thought to be due to ^3He buildup in the D-T solid in the fill line, causing the solid to expand slowly and hence eventually force additional material into the cell.

^b Thanks to the efforts of D. Bernat of General Atomics in modifying the code developed by Mapoles

Figure 4 shows the results of the beta-layering experiments in which the end-point equilibration values of σ_{rms} were averaged. Figure 4a shows that the averaged σ_{rms} is a weak function of temperature, so that the equilibrations nearer the melting point are slightly rougher than those at 19.0 K. Figure 4b shows the same data set as a function of equilibration time. Here the RMS roughness data minimizes near $1.0 \mu\text{m}$ for equilibration times from 20 to 30 hours. In fact the solid surface roughness remains nearly flat after about 20 hours equilibration time. This is in contrast to our earlier experiments in the copper torus where we observed a minimum roughness at ~ 400 minutes, followed by a steady degradation which we argued was due to ^3He buildup⁴.

Slow-Freeze/Thaw Cycling

In order to determine the effect of D-T freezing rate on final σ_{rms} , we performed two sets of experiments in which the freezing process proceeded at either 0.005 K/min or 0.003 K/min, in a narrow temperature interval through the D-T triple point. Figure 5a shows the graph of the actual freeze profile, taken from measured temperature data, for the 0.003 K/min slow freeze experiments. The D-T triple point was measured to be 19.65 K, in contrast to the expected value of 19.79 K for a 50-50 D-T mixture. This is the result of a slightly deuterium-rich mixture, as well as contamination of the D-T sample with 1%–2% hydrogen³. This freeze profile was executed at the beginning of each of several freeze/thaw equilibration cycles. Two sets of slow-freezing experiments were performed, similar to the experiments shown in fig. 5, but where each beta-layering equilibration was followed by the application of sudden temperature perturbations. (This temperature ‘stepping’ feature will be discussed in detail in the next section.)

Figure 5b is a graph of the average σ_{rms} for five freeze/thaw cycles at 19.45 K, with a slow-freeze initial condition. The freeze rate for the data in fig. 5b was 0.003 K/min. The 19.45 K

equilibration shown in fig. 5b does appear to be fully equilibrated after only 6 hours, but with a σ_{rms} of $\sim 4.5 \mu\text{m}$ RMS. This equilibration at such a high value and at an early time is perhaps a result of layer softening within approx. 0.25 K of the triple-point temperature. Softening leads to a gravity induced sagging of the D-T layer, which is seen as unusually large amplitudes in the lowest l-modes. Due to the beta-layering phenomenon, all l-modes continually improve (reduce) with time, but the lower l-modes are slower in coming to equilibrium. At lower temperatures, much of the total equilibration period is spent waiting for the lowest modes to reach equilibrium and the whole process takes more time than at temperatures high enough to induce sagging.

Figure 6 shows the average initial equilibration σ_{rms} for many cycles of the slow-freeze experiments as a function of equilibration temperature. Each data point shown is an average of the final RMS roughness value for all cycles at the equilibration temperature indicated. This graph shows some dependence of σ_{rms} on temperature, but it is likely that the data above 19.4 K are rougher due to the solid layer softening discussed above. Notice that σ_{rms} for data taken at 19 K shown in fig. 6 is close to the σ_{rms} value for the 19 K normal-freeze experiments shown in fig. 4a, although somewhat higher. This residual σ_{rms} for both the normal and slow-freeze equilibrations was removed by subjecting the layer to sudden temperature perturbations.

Temperature Step Effects

Nuclear ignition of ICF targets requires that the D-T solid layers be uniform and smooth to about 1.0 to 2.0 μm RMS. Although the optimum temperature for forming smooth layers is near 19.0 K, the preferred initial temperature for ignition is nearer 18 K, because this yields the desired gas density in the center of the target. In addition, Omega and NIF target handling and storing procedures may subject the equilibrated targets to sudden temperature excursions.

Therefore, it was important to know the effect of temperature excursions on the equilibrated σ_{rms} . In order to examine this effect, we subjected the equilibrated solid layers to sudden temperature changes of 0.1 K to 1.5 K, to both increased and decreased temperatures, and observed the resultant change in σ_{rms} . The temperature changes were programmed as follow-on steps to each of the multiple-cycle beta-layering equilibration periods, for both the normal-freeze and slow-freeze runs. In some cases, the temperature was increased in 0.1 K steps from the equilibration temperature of 19.0 K up to about 19.45 K. In other cases, the temperature steps were larger and employed both increasing and decreasing steps.

Figures 7a and 7b show the average σ_{rms} for equilibration cycles with follow-on temperature stepping for both normal and slow-freeze equilibrations at 19.0 K. As in fig. 5b, these graphs are produced by averaging all same-temperature equilibration cycles. Figure 7a shows the data for the 8-cycle normal-freeze experiments in which 0.1 K incremental temperature stepping was performed at the end of each 19 K equilibration cycle. The equilibration cycle duration for each run was 8 hours, which was not quite long enough for the solid layer to completely equilibrate. The of each temperature step was 4 hours and the entire temperature profile is shown as the 'staircase function' line in fig. 7a. The σ_{rms} for these experiments reduced to an average value of $\sim 1.6 \mu m$ for the 19 K equilibrations as shown, which then smoothed to just over $1.2 \mu m$ following the temperature steps.

In addition to the incremental temperature stepping profile shown in fig. 7a, a second type of temperature perturbation was performed as shown in fig. 7b. In this case, the equilibrated layer was abruptly cooled from 19 K to 18 K for two hours, then increased to 19.35 K for four hours, and finally back to 18 K for two hours, which is shown by the dotted-line temperature profile. This temperature profile was executed following each of the slow-freeze equilibration cycles and was the most severe of the temperature perturbations that we performed. Figure 5b also shows the

effect of this type of temperature profile, but without a final step to 18 K. For the equilibrated D-T solid layers observed, it appeared that this temperature stepping process generally lead to smoother solid layers. As shown in fig. 7b, we typically observed a brief period of transient roughening immediately after each temperature step was executed.

The results of the temperature perturbation experiments for both normal and slow-freeze equilibrations are shown in figs. 8a and 8b. These graphs show both the pre-step σ_{rms} (square symbol) and the post-step σ_{rms} (round symbol), with arrows indicating the direction in change of roughness (down for decreases and up for increases). These graphs show that in nearly all cases, σ_{rms} is lowered by temperature stepping. Although the relevant physics is not currently understood, the residual σ_{rms} and the smoothing effect of sudden temperature perturbations raise questions about the contribution that the various l-modes make to both phenomena.

Modal Dependency of Residual Surface Roughness

In order to examine the contribution that the various l-modes made to the observed σ_{rms} , we examined a large number of FFT power spectra. In general, we found that most of the residual roughness for the solid D-T surfaces was the result of contributions made by l-modes 60 and below. As might be expected, the solid layer smoothing occurs within the same modes that are making the largest contributions to the residual roughness. For example, if a large mode 3 is making a significant contribution to overall surface roughness, then temperature steps will generally reduce mode 3 significantly more than modes that have contributed less to the total roughness.

Figure 9a shows σ_{rms} for one cycle of a slow-freeze experiment, with follow-on temperature steps.

Figure 9b shows the modal summation [$\Sigma(\text{modes } 1 \text{ to } n)$] for the 19 K equilibration and the follow-on temperature steps. This graph is an accumulative plot that shows the additive contribution made by each mode as the progression moves upward from mode 1. It clearly shows that the initial equilibration roughness results from modes 60 and under, with 90 % of the total roughness resulting from modes 30 and under. Figure 9b also shows that the largest smoothing contribution resulting from sudden temperature perturbations is due to the reduction of modes 10 and below.

Figure 10a displays σ_{rms} for one cycle of a slow-freeze experiment that was equilibrated at 19.45 K followed by temperature steps to 18 K and to 19.2 K. This figure shows the very rough σ_{rms} typical for D-T solid layers formed at temperatures where sagging presumably occurs. If this is true, then suddenly lowering the temperature should firm the layer and allow beta-layering to proceed normally. In fact, this appears to be what is happening as can be seen from the modal spectrum. It is clear from the graph of 10b that the σ_{rms} from the 19.45 K equilibration is the direct consequence of large amplitudes of the lower l-modes, i.e., modes 10 and below. This is precisely what one would expect from a soft D-T solid layer that is sagging due to gravity. The low mode roughness was observed in all solid layers equilibrated at 19.45 K or higher and tends to substantiate the postulate of layer softening and gravitationally induced sagging.

Conclusions

The results of the experiments performed in a smooth 2 mm-diameter beryllium toroidal insert have shown that σ_{rms} is statistical in nature and that its magnitude is $1.3 \pm 0.3 \mu\text{m RMS}$ for layers equilibrated at 19.0 K. This is only marginally greater than what was previously observed on a

smooth, toroidal copper surface. Occasionally, σ_{rms} fell below $1.0 \mu\text{m}$, with a lowest observed value of $0.81 \mu\text{m}$. However, these very low σ_{rms} values were not within the standard deviation computed for the overall data set and are observed infrequently. Smoother D-T surfaces were consistently produced by inducing temperature perturbations in the equilibrated solid layer, although the physical mechanism for such smoothing is not currently understood. Although target handling and storing procedures for the Omega and NIF programs may subject D-T filled and equilibrated targets to temperature perturbations, the experiments reported here have shown that modest temperature perturbations will probably not harm the D-T solid layer and could, in fact, actually reduce solid layer roughness.

We have observed that layer softening begins within 0.15 to 0.25 K of the triple-point temperature, resulting in large values of σ_{rms} dominated by large contributions from the lower l-modes. This layer softening probably prevents the beta-layering process from proceeding normally by producing gravity-induced layer sagging.

Our attempt to reduce the solid layer σ_{rms} by slow-freezing resulted in somewhat rougher layers than for normal-freeze experiments, producing an average value of $2.0 \pm 0.5 \mu\text{m}$ at 19.0 K. Some of this is due to the initial layering that occurs under conditions that promote sagging. In addition, the 0.003 K/min and 0.005 K/min slow-freeze rates may have been too fast and a known glitch in the temperature control process may have both contributed to the larger observed values of σ_{rms} for the present 'slow'-freeze experiments. We plan to correct these problems in further experiments in order to determine with greater confidence the effect of slow-freezing on the surface roughness of solid D-T layers.

The analysis of a large number of FFT power spectra for equilibrated solid layers showed that the residual σ_{rms} following the initial beta-layering equilibration period was produced by l-modes 60

and under, with 90% of the roughness due to modes 30 and under. When these equilibrated layers were subjected to temperature steps of various magnitudes, they were generally smoothed by reduction of these lower modes. The implication here is that smoothing techniques should be focused on the reduction of the lower l-modes and that high mode smoothing alone is likely to have little or no effect on the total surface roughness.

Acknowledgements

We thank Jorge Sanchez for many useful discussions concerning our studies. This work is supported by the U.S. Department of Energy under contract number W7405-ENG36.

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Figure Captions

1. Axial cross-section of 2 mm beryllium cell, showing the beryllium insert inside a copper bore. Liquid D-T enters the cell through the stainless fill tube shown at the bottom.
2. CCD camera image sequence for 2 mm beryllium torus showing the empty cell, the cell filled with the D-T liquid charge, and the equilibrated 80- μm -thick D-T solid layer resulting from freezing and beta-layering the charge.
3. D-T solid layer equilibration at 19 K, shown repeated for eleven cycles. The solid layer is melted, then refrozen at the end of each cycle. The process of solid layer thickness evolution is shown by the dotted line at the top of the graph.
4. Normal-freeze σ_{rms} data for D-T solid layers equilibrated inside 2 mm beryllium torus.
(a) Average σ_{rms} as a function of equilibration temperature. Each data point is an average of all the experiments performed at the selected equilibration temperatures. Layer thickness is averaged similarly and is shown at the top of the graph. (b) Average σ_{rms} as a function of equilibration time. Each data point is an average of all the experiments performed at the selected equilibration times.
5. Temperature and σ_{rms} profiles for slow-freeze experiments. (a) Temperature evolution during each freeze cycle with a cooling rate of 0.003 K per minute. This graph shows the D-T cell temperature as measured at the times indicated. (b) A 19.45 K D-T solid layer equilibration profile, with σ_{rms} averaged over five experiments. These layers

were also thermally stressed by first reducing the temperature to 18 K for 3 hours, then increasing the temperature to 19.2 K. The temperature profile is shown by the dotted line at the top of the graph.

6. Temperature dependence of σ_{rms} for slow-freeze experiments. Each data point is an average of all the experiments performed at the selected temperature, with error bars indicating ± 1 standard deviation. Average layer thickness data for each of the selected temperatures is shown at the top of the graph.

7. Evolution of the average σ_{rms} for solid layers equilibrated by beta-layering at 19_K followed by subsequent abrupt temperature changes. (a) Average σ_{rms} following rapid freezing at 19 K and during subsequent temperature steps of 0.1 K. Temperature steps and duration profiles are indicated by the dotted line. (b) Average σ_{rms} following slow freezing at 19_K and during subsequent abrupt temperature changes to 18 K and to 19.35 K.

8. σ_{rms} response to sudden temperature steps for DT layers. Arrow direction indicates either a decrease (down) or an increase (up) in σ_{rms} as a result of the temperature step. (a) Average σ_{rms} for rapid-freeze experiments. The circular symbols show σ_{rms} at the end of the beta-layering equilibration, while the diamond symbols show the final σ_{rms} several hours after the temperature step. (b) Same as 8a, but for slow-freeze experiments.

9. (a) σ_{rms} for a single cycle slow-freeze to 19 K, followed by abrupt temperature changes to 18 K and to 19.35 K. (b) Accumulative σ_{rms} spectrum for the last data point in each

of the constant temperature series shown in (a). These curves are the result of a running quadrature summation modes 1 to l (plotted vs. l) of the power spectrum.

10. (a) σ_{rms} vs. time for a beta-layering equilibration at 19.45 K, followed by abrupt steps to 18 K and to 19.2 K. (b) Accumulative σ_{rms} spectrum for the last data point in each of the constant temperature series shown in (a). The higher equilibration temperature used here (19.45 K vs. 19.0 K in Fig. 9), results in a substantial gravity-induced distortion, as shown by the high values of the lower l -modes.

FIG 1

Empty Torus

D-T Liquid Fill @ 20 K

80 μ m Solid Layer @ 19 K

(a)

(b)

(a)

(b)

FIG 6

(a)

(b)

(a)

(b)

(a)

(b)

(a)

(b)