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Reducing Deuterium-Tritium Ice Roughness by Electrical Heating of the Saturated Vapor

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High gain targets for inertial confinement fusion (ICF) contain a layer of deuterium-tritium (DT) ice which surrounds a volume of DT gas in thermal equilibrium with the solid. The roughness of the cryogenic fuel layer inside of ICF targets is one of the sources of imperfections which cause implosions to deviate from perfect one dimensional performance. Experiments at Lawrence Livermore National Laboratory have shown that applying a heat flux across the inner surface of a hydrogen layer such as that inside of an ICF target reduces the intrinsic roughness of the surface. We have developed a technique to generate this heat flux by applying an electric field to the DT vapor in the center of these shells. This vapor has a small but significant conductivity due to ionization caused by beta decay of tritium in the vapor and the solid. We describe here experiments using a 1.15 Ghz cavity to apply an electric field to frozen DT inside of a sapphire test cell. The cell and cavity geometry allows visual observation of the frozen layers.

All high gain target designs for inertial confinement fusion employ uniform layers of condensed DT to achieve efficient ignition of the fuel. Various routes to the formation of these layers within target shells have been investigated[1], and the most promising method relies on the radioactive self heating of condensed DT to redistribute the solid along the isotherms in the structure containing the fuel[2,3,4]. The resulting roughness of the ice surface has been characterized optically and been found to be in the range of 1 - 1.5 μm rms for cylindrical layers approximately 100 μm thick and 2 mm in diameter. It is desirable to decrease this roughness to reduce the effects of mix during the implosion of an ICF capsule and increase the drive flexibility available to experimental designers.

Electrical Conductivity of DT

The electrical properties of DT gas are only roughly known but measurements have been made by Souers[5,6]. This data may be used to estimate the free electron density in the DT gas to be 4 x $10^{13}/m^3$ at 20 K in 100 $mole/m^3$ density DT. However, these measurements were done on the gas alone without the additional radiation load of the surrounding DT solid found in an ICF target. Souers[7] estimates the fraction of beta particle energy escaping from a surface layer of hydrogen of areal density 1.4 moles/m^2 as 0.11. This is about five times the beta energy generated in the vapor of an ICF target. Since the free electrons are only about one percent of the charged particles in the gas[5,6], their recombination rate is approximately independent of density and we can estimate the free electron density in the gas as 2 x $10^{14}/m^3$. The electron mobility can be estimated from electron mobilities measured in 76.8 K D_2 gas[8] and from ref. 7. For a field of 5.0 x 10^4 V/m and a density of 100 moles/m^3 these give μ_e=0.1 m^2/V-s.

A high gain NIF target has a DT ice layer approximately 2.2 mm in diameter and 0.1 mm thick. This surrounds a gas volume of V=4.2 x 10^{-9} m^3 with an inner ice surface area of S=1.26 x 10^{-5} m^2. The power coupled into this gas volume is:

$$P = e\,\mu_e\,n_e\,E^2\,V,$$

where E is the root mean squared electric field and e is the electron charge. To reach a heat flux equivalent to the bulk heat produced by DT requires P=SqL=63 μWatts, where q is the bulk heating rate of DT or about 0.05 Watts/m^3, and the ice thickness, L is 100 μm. The corresponding field is E=6.9 x 10^4 V/m. Given the electron mobility above and the interior diameter of 2 mm, the electron transit time through the DT gas space is 0.3 μsec. In order to avoid the loss of electron mobility as they drift into the DT ice we choose to work at a frequency much higher than this. The desired field can be generated using a resonant cavity with reasonable rf power. For practical reasons concerning the size of the cavity, we choose to apply the field at about 1 Ghz.

Sample Cell

In order to facilitate the imaging of the DT ice our sample cell is roughly cylindrical with flat windows sealing the ends. The portion of the sample cell inside of the rf field was made entirely from sapphire parts. A 5 mm diameter sapphire rod has a 3 mm hole bored through the center perpendicular to the rod axis. Flats are ground on either side of the 3 mm hole to provide a flat surface on which windows are epoxied. A sapphire ring 3 mm in diameter and 1 mm wide with a 2 mm inner diameter is positioned in the center of the 3 mm bore and epoxied in place. The inner edges of this ring are beveled to provide a 500 μm wide surface on the inside of the ring. Then the ends of the 3 mm bore are sealed with sapphire windows. A 100 μm hole in the top of the cell provides access for the DT gas. The function of the ring is to provide a surface on which to image the DT ice which is not vignetted by the outside edge of the 3 mm bore. The assembled sapphire cell is epoxied to a sapphire tube which holds it in the center of the microwave cavity.

Data collection and Analysis

The roughness of the DT ice surface is characterized optically. A long range microscope looks through windows in the cryostat and the cavity, and is focused on the ring centered in the sapphire cell. Images are taken with a Photometrics camera using a Kodak KAF-1400 CCD array , and downloaded to a personal computer for analysis. Images are saved using a 1024 x1024 subarray of pixels on the CCD. Each 6 μm pixel at the CCD corresponds with 2.15 μm at the focal plane.

Raw images such as that shown in figure 1 have a bright central region which makes a transition to a dark outer region where the ice surface blocks the light. Analysis of the images consists of locating the center of the transition from light to dark as a function of angle. This is done by initially guessing the coordinates of the center of the bright region and sampling the image along radial lines emanating from the center estimate. Image intensity along the radial line is estimated at one pixel increments using a bilinear interpolation scheme. The resulting linear array of intensities is scanned to find the point of maximum derivative in intensity as an initial estimate of the location of the edge. The linear data is then fit to an error function using a Levenberg-Marquardt method allowing the center, height, baseline, and width of the fit function to vary. This procedure is repeated as a function of angle to produce an array of edge radii versus angle. The center is recalculated and the entire procedure in repeated until the center estimates converge. At this point the roughness of the surface is computed by calculating the root mean square fluctuation of the edge estimates from their average, and a power spectrum of the surface fluctuations can be calculated in the usual way.

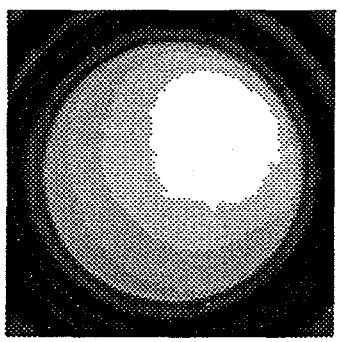

Figure 1. Image of DT ice

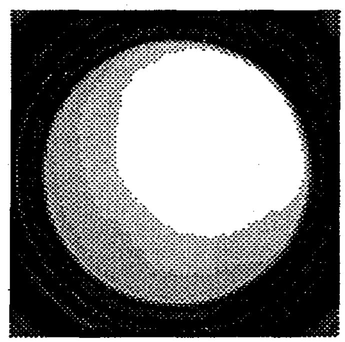

Figure 2. DT ice after E Field smoothing

Experimental Results

Application of the rf field results in a rapid decrease in the apparent roughness of the DT ice in the cell. Figure 2 shows the surface resulting after applying 350 mWatts (6.0×10^4 V/m) of rf power to the cavity for 300 secs. The rms roughness of the surface was initially 2.6 μm and the final rms is 0.8 μm. The initial roughness is exaggerated due to the roughness of ice on the front window. The final roughness includes contributions at low frequencies which are due to anisotropy in the electric field inside the sapphire cell. Sapphire has a dielectric constant of about 10 so the complex shape of this cell produces variations of the field in the interior of the cell. This effect is much reduced in the plastic shells used for ICF targets.

In order to evaluate the coupling of the electric field to the gas we measure the rate at which freshly frozen liquid in the cell forms a uniform layer as a function of rf power into the cavity. At each rf power value we allow the ice to evolve into a uniform layer, photographing the layer in the cell at a constant rate. Each photo is analyzed as described above and the fourier transform of the surface fluctuations is computed. The decay of the second harmonic is plotted for each power and fit to an exponential decay. The layering rate at that power is then taken as the time constant of the exponential. These fit results are plotted in figure 3 as a function of rf power into the cavity. Since heat flux through the surface is proportional to the square of the electric field which is proportional to the power into the cavity, we find that the layering rate is proportional to the power into the cavity.

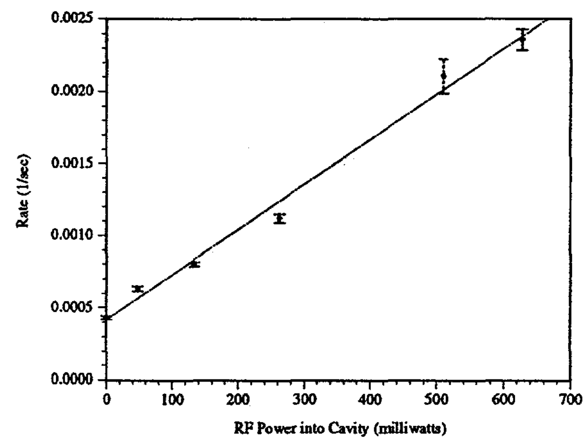

Figure 3. Layering rate versus rf power into the cavity

The improved surface finish and the increase in the layer rate to a value about six times the natural beta layering rate confirm that the electric field couples sufficiently strongly to the DT to provide a useful technique for modifying DT surface roughness.

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