Analyzing the Structure of Shell Modulations Around Peak Compression of Spherical Implosions

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Abstract

Programs were created to analyze the structure of shell modulations at peak compression of spherical implosions. Measurements of the modulations were taken by using absorption of titanium-doped layers placed at distances 1,5,7, and 9 μm from the inner surface of 20 μm-thick plastic CH shells filled with 18 atm of D^3He gas. These nonuniformities were measured using ratios of monochromatic target core images taken inside and outside the titanium 1s-2p absorption spectral regions. The results show that the peak-compression, time-integrated areal-density modulations are higher at the inner shell surface, unstable during the deceleration phase of implosion, with the modulation level of 59 ±14%. The nonuniformities are lower in the central part of the shell, having a modulation level of 18±5%. The outer surface of the shell, unstable during the acceleration phase of the implosion, has a modulation level of 52±20%.

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Introduction

In direct-drive inertial confinement fusion, the type attempted at the Laboratory for Laser Energetics (LLE), the deuterium and tritium react to produce neutrons, helium, and excess energy as byproducts. The goal of LLE is to find a way to gain as much excess energy output as possible through the fusion process. LLE achieves this by using laser-driven inertial confinement fusion when the laser heats and compresses spherical targets filled with deuterium and tritium. As the target shell implodes from the force of the laser, the shell compresses the core (using Newton's third law) forcing the deuterium and tritium to react. If there are instabilities and modulations in the target shell, then the fusion reaction won't be as efficient as possible. In fact, one of the greatest factors limiting target performance in spherical implosions is the growth of shell perturbations. This is why assessing the structure of the shell modulations near peak compression is necessary.

One can determine the shell structure during peak compression by placing diagnostic titanium-doped layers inside the shell. At around peak compression when the maximum density and temperature occur, the compressed core and inner surfaces produce strong x-ray emissions which can be used as a backlighter to probe the outer, colder shell.[1] The x rays can be imaged through the titanium-doped layers and captured by a GMXI camera. These images can be used to assess what is going on inside the core.

Initially, the nonuniformities come from target imperfections and the irradiation from the laser. These perturbations grow at the outer shell during the laser-driven part of the experiment due to the Raleigh-Taylor instability and convergent Bell-Plesset effects. During the acceleration of the shell, these perturbations feed through the shell seeding the

Raleigh-Taylor instability on the inner surface. The modulations on the outer shell are not of great concern because they become stable when the laser is turned off. What is of great concern are the modulations caused on the inner surface. As the shell starts to decelerate, the perturbations on the inner surface of the shell now become the subject of Rayleigh-Taylor instability. As a result, the modulations from the inner shell can penetrate deep, causing the shell and the fuel to mix.[2] This mixing inhibits the achievment of high compression and high temperature necessary to sustain an efficient fuel burn.

Present shell-integrity measurements have been made using imaging at photon energies in and out of the sensitive (1s-2p) titanium absorption regions. The images captured out of the 1s-2p absorption region (energies not absorbed by the shell) provide the spatial shape of the core, while core images taken in the 1s-2p absorption region (energies highly absorbed by the shell's titanium) contain information about the structure of the shell areal-density modulations in the titanium doped layer. Computer programs were written to filter out the background noise from the images and to calculate the optical depth modulations of the target shell.

Earlier experiments were limited,[1,3] because the results only measured the perturbations at the shell inner surface. The titanium-doped layers placed at the central and outer parts of the shell were not sufficiently sensitive to detect the instabilities and modulations. That is because previous images were taken at energies around the titanium K-edge. This particular experiment extends the idea of differential imaging into the much more sensitive titanium 1s-2p region. Thus, the titanium in the layer can absorb not only above 4.966 keV (which is what the previous K edge experiments did) but also in the 1s-2p absorption region with the photon energies of ~4.5-4.7 keV. The mass absorption rate at any absorption line in the titanium 1s-2p spectral region is about one order of magnitude higher than at photon energies above the K edge. This means that the differential imaging can be extended to the central and outer parts of the shell where the compression and the modulations are smaller. For the first time, measurements of the compressed shell modulation structure were conducted.

Experimental Conditions

Figure 1(a) shows the schematic representation of the target shell. The shell is a sphere with a ~450 μm initial radius filled with 18 atm D^3He gas. The target shell is made of a 20-μm-thick plastic CH. The titanium-doped layers are placed at the distances of 1,5,7, and 9 μm from the inner surface of the shell. The thick solid lines in figure 1(b) represent those layers. Figure 1(b) also shows the profile of what the target looks like around peak compression. The thick line represents the mass density and the thin line represents the electron temperature vs. the radius. Those two profiles were calculated using the 1-D code LILAC.[4] One can see that the 1 μm layer is where there is high temperature and high density; this represents the inner part of the shell. The 9 μm layer, where there is low temperature and low density, represents the outer part of the shell. The 5 and 7 μm layers represent the central part of the shell. Each of the layers was 1 μm thick. These titanium-doped layers absorbed the x rays which were then used to analyze the density shell modulations at the inner, central, and outer parts of the surface.

Each of these targets with the titanium-doped layers was imploded by 351 nm laser light using the 60-beam OMEGA laser system[5] with a 1-ns square pulse shape at a total energy of ~23 kJ. All the shots were taken with laser beams smoothed by distributed phase plates (DPP's)[6]; 1-THz, two-dimensional smoothing by spectral dispersion (2-d

SSD)[7]; and polarization smoothing (PS)[8] using birefringent wedges. The average beam-to-beam imbalance was ~3%.

A monochromatic x-ray imager known as the GMXI[9] camera captured the core images. One channel of the GMXI recorded monochromatic images at ~4.60 keV (in the titanium 1s-2p absorption region) and another channel was set up at ~4.87 keV (outside the titanium absorption region). The core images were taken at two different channels. Figure 2 shows the images that were captured after Wiener filtering[10]. There is a lot of background noise due to light during the implosion. Therefore, it was necessary to write programs using Wiener filtering to filter out all of this extra noise.

The principle of the Wiener filter program was to use a noise level constructed from the differences in the two images (one in the 1s-2p region and one not) in the shot 26633 without titanium. Taking this and the measured GMXI modulation transfer function (MTF), one was able to assess what the exact noise level in each image was. For more details of the image processing one can see References 1,3, and 10.

To get a better idea of where exactly the images were taken, one can look at Figure 3(a). The spectral intensity vs. the energy $S_{meas}(E)$ is shown by the thin solid line (for shot 26625). The first channel of the GMXI camera was set up in the 1s-2p absorption region at the dashed spectral response. The second channel was set up at the dotted spectral response.

After filtering out those two images, the shell optical depth (OD) was calculated. A program was written that took the natural logarithm of the ratio of intensities of the two images at photon energies in the 1s-2p region, below the K edge (weakly absorbing by the shell), $I_{<K}(r)$, $\delta[OD(r)] = \delta\{\ln[I_{1s\text{-}2p}(r)/I_{<K}(r)]\}$. In Figure 3(a), the thick solid line

represents the estimated continuum level $S_{con}(E)$ of core x rays used to calculate the average titanium optical depth, $OD=\ln[S_{con}(E)/S_{meas}(E)]$ at a photon energy of E=4.6 keV. The average titanium optical depth, OD, is used to determine the relative optical depth modulations (which are approximately the relative areal-density modulations), $\delta[OD(r)]/OD=\delta[\rho R(r)]/\rho R$, to compare levels of the modulations in the different areas of the shell.

This measured spectrum in Figure 3(a) is used to also calculate the spatial variations in the images due to the small variations of the spectral response across the horizontal axis of the images. A program was written so that the resulting correction function for each shot used the corresponding spectra. Why is there a correction factor? Look for example at the central part of an image of Fig. 2, which is set up at 4.6 keV. When it goes through the camera, it is reflected in the GMXI multilayer mirror at an angle of 5.88 ±.01 degrees. The x rays that originated from the vertical line at 100 μm off the image center are reflected from the mirror at a slightly different angle of 5.91±.01 degrees, corresponding to a photon energy of 4.58 keV. The program takes into account the different angles at which the light hits the camera and then corrects the image accordingly. For the images at the 1s-2p absorption channel, the resulting correction function is proportional to the convolution of the measured spectrum, $S_{meas}(E)$ with the spectral response function $R_{1s\text{-}2p}(E)$.

Figure 3(b) shows the correction functions for the shot 26625 in (dashed line) and out of (dotted line) the 1s-2p-absorption channel. For each Wiener-filter image the x-ray intensity was divided by the corresponding correction function to compensate for these spatial variations.

Experimental Results

Figure 4 shows the images of the optical depth modulations in the titanium-doped layers offset by 1,5,7, and 9 μm. The more bumpy and darker the image is, the more instabilities and modulations are occurring at that area. Figure 5(a) presents the power per mode spectra of these modulations as functions of spatial frequency. The modulation levels are highest at the spatial frequency of ~20mm^{-1} which corresponds to the wavelength of ~50μm. It was determined that the absolute values of the optical depth modulations decrease monotonically from 0.30±0.06 at the inner surface as shown by the solid line in Figure 5(b). The relative areal-density modulations are 59±14%, 18±5%, 26±10%,and 52±20%, in the layers offset by 1,5,7, and 9 μm respectively, as shown by the dashed line in Figure 5(b). This implies that the modulations and the instabilities are the highest at the inner part of the shell (where the 1 μm titanium-doped layer was located). As expected, the modulations decrease at the central part of the shell (in the 5 and 7 μm layers) and increase again at the outer part of the shell (at the 9 μm layer). Recall that the modulations that occur at the outer part of the shell are due to the perturbations that grow when the laser is hitting the target, and the shell is about to implode. When the laser is turned off, however, the perturbations stop growing and stabilize. So these measured modulations are not of that great concern. What is of concern is the high modulation level due to the Raleigh-Taylor instability that is occurring at the inner shell surface, The areal-density modulations are dominated by these nonuniformities.

In the future, the time-integrated measurements of modulations will be extended to time-resolved measurements, using the same titanium 1s-2p absorption technique. In addition, data will be analyzed not only for titanium-doped filters but for other ones such as argon. This way, scientists will be able to get a clearer picture of what exactly occurs inside the target shell.

Conclusion

For the first time, the structure of the inner, the central, and the outer parts of the shell could be analyzed. Instabilities and nonuniformities were measured using titanium-doped layers placed at the 1,5,7 and 9 μm points from the shell inner surface. The shell modulations were obtained using the ratio of images in and out of the titanium 1s-2p absorption region and various other programs. The inner part of the shell had more modulations (~59%) than any other part of the shell. The outer surface had a high modulation level of ~52%, but its contribution to the modulations in the whole shell is small due to the fact that these instabilities stabilize once the laser is turned off. The central part of the shell was the most uniform.

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FIGURES

Figure 1

(a) Schematic of spherical targets with diagnostic titanium-doped (2% by atom) layers offset by 1, 5, 7, and 9 μm of pure CH from the inner surface. (b) *LILAC*-simulated profiles of target density and temperature at peak compression of the implosion. The locations of titanium-doped layers are shown by the gray areas.

Figure 2

(a) Measured time-integrated spectrum $S_{\mathrm{meas}}(E)$ as a function of photon energy for shot 26625 (thin solid line). Estimated continuum level $S_{\mathrm{con}}(E)$ as a function of photon energy (thick solid line). The instrumental spectral responses as functions of photon energy of GMXI channels inside [$R_{1s-2p}(E)$, dashed line] and outside of [$R_{<K}(E)$, dotted line] the titanium $1s$–$2p$ absorption region. (b) The spatial correction functions as a function of distance in the vertical axis for images inside (dashed line) and outside (dotted line) the titanium $1s$–$2p$ absorption region.

Figure 3

Wiener-filtered core images around peak compression at energies inside (~4.60 keV, upper row of images) and outside (~4.87 keV, lower row of images) the titanium $1s$–$2p$ absorption spectral region for shots with 1-μm- (shot 26625), 5-μm- (shot 26630), 7-μm-

(shot 26631), and 9-μm-offset (shot 26632) titanium-doped layers, and for the shot without titanium (26633).

Figure 4

Optical-depth modulation images at peak compression for shots with 1-μm- (shot 26625), 5-μm- (shot 26630), 7-μm- (shot 26631), and 9-μm-offset (shot 26632) titanium-doped layers integrated over ~200 ps of x-ray emission.

Figure 5

(a) Power per mode as a function of spatial frequency of relative areal-density modulations at peak compression for shots with 1-, 5-, 7-, and 9-μm-offset titanium-doped layers. (b) Peak compression optical-depth modulation σ_{rms} (solid line) and relative areal-density modulation σ_{rms} (dashed line) as a function of the layer offset.

Figure 1

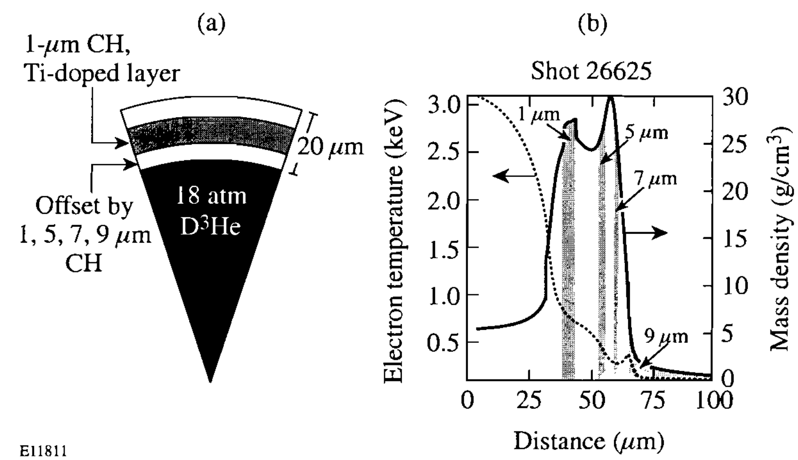
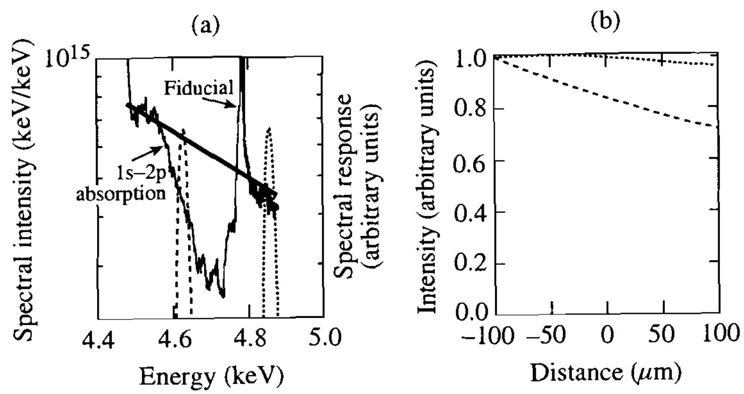
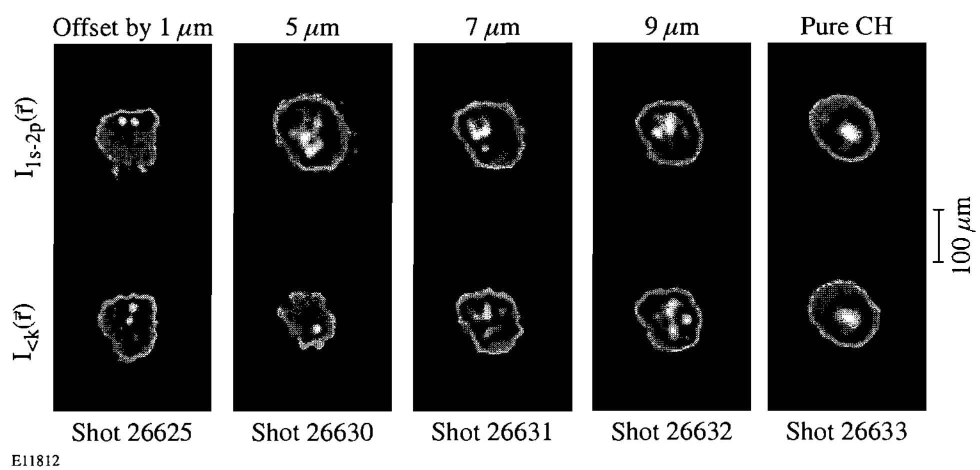

(a)
1-μm CH,
Ti-doped layer
20 μm
Offset by
1, 5, 7, 9 μm
CH
18 atm
D3He
(b)
Shot 26625
1 μm
5 μm
7 μm
9 μm
3.0
2.5
2.0
1.5
1.0
0.5
0
25
50
75
100
30
25
20
15
10
5
0
Electron temperature (keV)
Mass density (g/cm3)
Distance (μm)
E11811

Figure 2



E11813

Figure 3



Offset by 1 μm
5 μm
7 μm
9 μm
Pure CH
I1s-2p(r)
I<k(r)
100 μm
Shot 26625
Shot 26630
Shot 26631
Shot 26632
Shot 26633
E11812

Figure 4

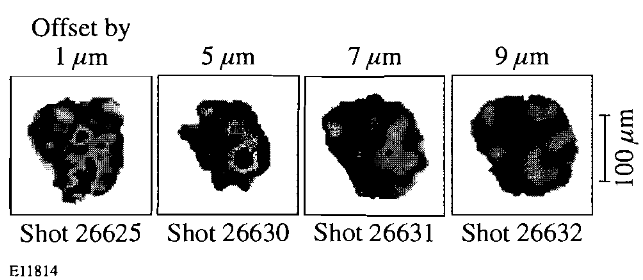
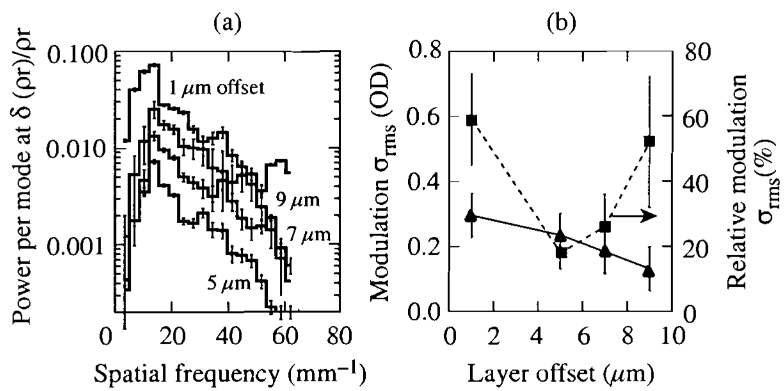

Offset by
1 μm
5 μm
7 μm
9 μm
100 μm
Shot 26625
Shot 26630
Shot 26631
Shot 26632
E11814

Figure 5



E11815