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X-RAY BACKLIGHTING REQUIREMENTS FOR THE
DOUBLE-SHELL TARGET

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Introduction

Attainment of DT fuel ignition is one of the goals of the NOVA laser facility. Prior to this achievement, the facility will be used extensively for obtaining a detailed understanding of implosion dynamics. The double-shell target design will be studied exhaustively and developed for attainment of the programmatic goals.

A successful target design is the result of many implosion experiments and computer simulations of these experiments. Information learned from simple target designs is of great importance in the design and construction of the more sophisticated targets needed for high gain performance. An important laboratory measurement which is easily compared to numerical simulations is one that can trace the implosion history of one or more parts (shells) of a target. In particular, it is necessary to know some temporal and spatial information about the outer shell of a double-shell target design. The only method available for these measurements is x-ray flash photography, commonly known as x-ray backlighting.

X-ray backlighting is, in itself, a simple concept. The difficulties arise in providing the correct x-ray source and required resolutions. Figure 1 is a schematic of the technique in which one or more dedicated laser beams are directed towards a material which will produce the required x-ray energies, intensities, spatial extents and temporal durations for probing the target. The exact specifications for the x-ray source are very target dependent in that the x-ray energies are dictated by the target opacities and areal densities, the intensity requirement is determined by the self-emission level of the target in the energy window viewed by the detector, and the spatial and temporal requirements are set by the accuracies to which the measurements are to be made. These quantities are not all constant during the course of the implosion and thus it may be necessary for some target designs to have multiple x-ray sources. Placement of the x-ray source will be in the immediate vicinity of the target, while the x-ray imaging device is, in general, at some large distance. Of course, there is a minimum x-ray flux constraint placed upon the probe source by the sensitivity and dynamic range of the specific detector.

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X-Ray Backlighting Sources

Two sources of intense x-rays of the proper frequencies are possible. One source uses the x-ray continuum generated by free-bound transitions and bremsstrahlung and the other exploits specific bound-bound transitions.

The most promising candidate for an intense x-ray source is the narrowband one based upon one or more discrete transitions in the x-ray producing material. A distinct advantage of this method is the large concentration of energy in a very narrow frequency window that can be "tuned" to the target by the proper choice of material. (An ideal source/detector combination would employ a narrow-band detector matched to that of the source.) These hot x-rays have been measured under conditions similar to that needed for a backlight source. Figure 2 shows the experimental results from a titanium disc irradiated at the Shiva laser facility with about 3 kJ of laser energy in 600 ps. Both the background continuum and line structure are shown. An intense He- α line is seen at about 4.7 keV, which gives a radiance of about 6.2×10^6 watts/cm² cm⁻¹, assuming the emission spot size is the same 450 μ m diameter as the laser spot size and its duration is also 600 ps. The equivalent blackbody temperature which would give this radiance is about 340 eV. Note that the narrow band source, whose width is about 5 eV, has an intensity many times greater than the continuum. Another distinct advantage in using a narrowband (monochromatic) source is in the interpretation of the backlight data. As will be seen in a following section, the opacities of the materials vary rapidly with frequency. Hence, it simplifies the analyses if only one frequency is propagated through the target.

For the purposes of this study, we assume an external narrowband source will be employed, and we seek to define the frequencies, intensities and durations which are required to probe a double-shell target. Figure 3 is a schematic of one particular target for which there has been an extensive analysis using LASNEX and its postprocessor code TDG.

Structure of the Double-Shell Target

The target capsule used in this study was adapted from the work of Lindl. His 300 kJ double shell geometry was scaled to the 100 kJ NOVA-I

size by noting that the dimensions scale as $E^{1/3}$, the laser peak power scales as the dimensions squared, and the pulse history goes linearly with the dimensions.

Along with the pie-diagram in Figure 3 is the applied laser power history. The physics model used for the calculations is the same as for Lindl's target, which is nearly all inverse bremsstrahlung absorption. The small contaminant of suprathermal electrons does not affect the target's performance. Subsequent calculations have been performed to ascertain the sensitivity of the target to modifications in the physics model. Some results from a high suprathermal content calculation are presented later.

Figure 4 is the radius history of the two pushers from the nominal calculation. The first 12 ns are relatively uninteresting. By a time of 13 ns the outer pusher has moved about 10%. As this pusher is accelerated inward, the shell thickens by spherical convergence. There is a slight pre-heating of the inner shell at about 15 ns, but this is of little consequence. Contact between the two shells takes place at a time of about 16.6 ns resulting in the inner pusher being rapidly accelerated. Compression of the DT fuel to ignition conditions has been completed by a time of 17.4 ns.

Analysis of the Inner Pusher

One of the initial purposes for developing the backlighting capability was to measure the compressed fuel volume. However, for any target which will get to a significant final fuel density, this is nearly an impossible task. The difficulty arises from the large $\rho\Delta R$ of the inner pusher together with the opacity of the U+Au material at the temperatures and densities encountered at burn time. Figure 5 shows the cold opacity data for gold. From Figure 6, which is the temporal behavior of the radial $\rho\Delta R$ for the different materials, we see the inner pusher achieving $\rho\Delta R$ values in excess of one. The opacity varies from about $10^3 \text{ cm}^2/\text{gm}$ at 4 keV to about 10^2 at 10 keV. Hence, we see that $2K\rho\Delta R \approx 4.6$ using the initial radial ρR and the 10 keV opacity. In order to radiograph the final state, it would be necessary to have x-rays of more than one hundred keV energy!

The second difficulty is achieving a sufficient contrast ratio between a line of sight along the edge of the fuel to that of one through a

diameter so as to be able to define a fuel boundary. This is demonstrated in Figure 7 for a 100 keV backlighting source. The x-ray transmission as a function of radius shows only a small amount of detail in the vicinity of the compressed fuel; the compressed radius is about 10 μm and the outside of the inner pusher is near 33 μm .

The third difficulty is providing sufficient spatial resolution to allow the fuel density to be determined to within a factor of two. Since the density is inversely proportional to the cube of the radius, the position of the interface must be accurate to about 20%, or an accuracy of 2 μm out of about 10 μm . This assumes the exposure is sufficiently short in time so that there is no temporal smearing. Again, if we require an accuracy of about 2 μm and the interface's average velocity is about 0.1 $\mu\text{m}/\text{ps}$ just before and after the "bounce", the exposure time must be somewhat less than 40 ps.

A fourth difficulty is in the timing accuracy of the x-ray flash relative to the pusher motion. A precision of about ± 20 ps relative to the laser pulse is necessary to "stop the action" at peak compression.

It is virtually impossible to obtain by the backlight technique any information about the condition or size of the DT-fuel contained within the inner pusher.

Background Emission From the Capsule

The background signal is generated by the high-Z materials used in the fabrication of the shell. Since these shells' temperatures change with time, there will be a time varying spectrum of x-rays. This signal must be overcome by any backlighting technique. Figure 8 shows the expected x-ray emission rate as a function of time from the capsule for representative energy windows at 4.5 and 9.0 keV. The window is assumed to be 0.1 keV wide. As will be seen shortly, these emissions appear to be coming from the outer TaCOH pusher. At the stagnation and ignition time near 17.4 ns, the high-energy emission becomes very large due to the sudden heating of the target interior resulting from the burning of the DT. Figure 9 shows the late time emission in the 9 keV window. Hence, even though there may be a negligible background problem during the majority of the implosion, the late time signal could wipe out the earlier

recorded information. The detecting instrument will have to safe-guard against this from happening.

With regards to the probing of the inner pusher at the time of pre-heat, a 9 keV source strength greater than about 3×10^{14} keV/keV/sh/cm²/sr will be required. We note for comparison purposes, the 4.5 keV titanium He- α source mentioned earlier would have a source intensity equivalent to 4.8×10^{18} keV/keV/sh/cm²/sr, assuming it was a point source located 1 cm behind the capsule.

Analysis of the Motion of the TaCOH Pusher

The success of this target giving a significant gain is highly dependent upon the performance of the outer pusher. This shell is made of TaCOH and is designed to provide a measure of preheat shielding as well as delivering the impulse to the inner shell. A determination of the history of this shell's motion is the most important measurement to be made with the x-ray backlighting capability. It will also be necessary to understand any asymmetries and/or fluid instabilities that may appear during the motion of this shell.

We note first that the emission in the 4.5 keV region is large (see Figure 8) and is coming entirely from the TaCOH pusher where $K\rho\Delta R$ is greater than one. The self-emission in the 9 keV window is down by about an order of magnitude compared to the 4.5 keV channel. Since the TaCOH opacity drops a factor of about six in going from 4.5 to 9 keV, the apparent emitting surface is further into the shell. Figure 10 demonstrates this at a time of 16 ns. Note that there is a peak in the self-emission at a radius of about 450 μ m at both energies. This is due to the ablation surface just reaching the LiD-TaCOH interface at this time; the outside of the TaCOH has an outside radius of about 415 μ m at this time. The outer edge of the gold alloy pusher can clearly be seen at a radius of about 135 μ m in the 9 keV channel, but is not visible in the 4.5 keV channel. Even though the radial distributions of Figure 10 are plotted together, the self-emission in the 9 keV window is about a factor of 50 less than that in the 4.5 keV window.

As the implosion progresses we see, from Figure 6, that the TaCOH shell thickens and just prior to contact with the inner shell at 16.6 ns has increased its $\rho\Delta R$ by a factor of ten compared to its initial value.

Hence, it is not possible to obtain any information about the contact at these low x-ray energies. At contact, $\rho\Delta R$ of the TaCOH is about $6 \times 10^{-2} \text{ g/cm}^2$, and we need an x-ray energy where the opacity is $K \leq (2\rho\Delta R)^{-1} = (1.2 \times 10^{-1})^{-1} \approx 8$, which occurs for x-rays of energy greater than about 25 keV. A good determination of the collision between the shells is of sufficient importance to encourage the development of more than one x-ray energy for probing purposes.

We turn now to a demonstration of what might be seen as the outer pusher converges toward contact with the inner pusher. We are assuming there is a sufficiently strong x-ray source to overcome the background self-emission as shown in Figure 8.

Figure 11 is a series of intensity profiles simulating a 100 ps exposure using the aforementioned 4.5 keV line source. The x-ray window is taken to be 0.1 keV wide. Exposure times are at 10, 12, 14, and 15 ns. One immediately sees the TaCOH pusher to be relatively opaque at these frequencies in that the inside surface is quite dark. This is of marginal quality in that it is best to have a "non-zero" signal at the interface position. Figure 12 shows a similar series of x-ray emission profiles as in Figure 11 but using a 9 keV x-ray line source. Clearly, the inside edge of the TaCOH pusher can be defined.

The 4.5 keV line source appears to have a limited capability for this particular target.

In studying the radial profiles for the 9.0 keV source (see Figure 12), we easily identify the positions of the two surfaces of the TaCOH shells as well as that of the outer surface of the inner pusher. As the implosion proceeds, the cushion gas between the two shells thickens until the surface of the inner pusher disappears just before the contact time at about 16.6 ns. The 9.0 keV line source is ideal for probing this target.

Analysis of a Severely Heated Target

In this section we present the results from a calculation using an extreme physics model: all of the absorption is into a hot electron spectrum which has a maximum electron temperature of about 60 keV. This represents a severely preheated environment for which the target performance is dismal. Figure 13 shows the radial history of the two shells for this calculation. The inner pusher thickens from a time well

before 10 ns. This is due to electron preheat primarily by the coupling from the suprathermal electrons generated near the end of the laser pulse. Figure 14 is the calculated hot electron temperature as a function of time. The penetration mean-free-path for an electron goes as the square of the energy.

The x-ray emission from the capsule as a function of time is shown in Figure 15 for the 4.5 and 9 keV channels. This is to be compared to that of Figure 8; the emission for the suprathermal preheat calculation is substantially less than for the nearly pure inverse bremsstrahlung driven case. Thus, it appears that the requirements outlined above for the high performance capsule will be sufficient for any performance level this particular target design achieves. In case a large preheat exists, the $K\alpha R$ of the various shells is smaller and thus it is easier to see into the target interior. Of course, the penetration of the inner pusher is just as difficult as in the optimal case first discussed.

Space and Time Resolution Requirements

Achievement of a successful implosion depends, in part, on the spherical and symmetrical contact of the outer pusher with the inner pusher. This places an early time constraint on the pressure variations at the ablation surface which can be tolerated. Typically, this value is 1%. Hence, the motion of the TaCOH pusher must be detectable to about 1% at a time of 13 ns (see Figure 4). This is about 8 μm spatial resolution.

It is desired to measure the "contact" between the shells to a spatial accuracy of 5%. As the outer pusher has an appreciable velocity at contact time there is another point to be considered; namely, the resolution determined by the temporal smearing. This constraint is in addition to that of the instantaneous spatial resolution of the "camera." From the calculation it is found that at the time of shell contact ($t \approx 16.6$ ns) $r \approx 160$ μm and the velocity is about 0.16 $\mu\text{m}/\text{ps}$. Hence, we must be able to determine the position to about 5% of 160 μm or about 8 μm . This necessitates a shutter speed of $t \leq \Delta R/v$ which is about 50 ps, for an infinite resolution "camera."

Summary

We have analyzed one specific NOVA double-shell target design and have determined the x-ray energies required for probing the performance of the implosion. It is virtually impossible to study the compression of the fuel or the motion of the inner pusher. An x-ray energy of about 9 keV appears to be ideal for measuring the behavior of the outer TaCOH shell for the majority of its travel. However, it would be advantageous to have an x-ray source of about 25 keV to measure the contact between the two shells. Development of narrowband x-ray line sources are more desirable than broadband continuum sources since the intensity per keV is many times greater in the line. Intensities of the probes is determined by the self-emission levels of the target capsule. For the 9 keV line source, an intensity of upwards to 10^{15} keV/keV/sh/cm²/sr is required with a source area of about 0.01cm².

Temporal and spatial resolution requirements are determined to be less than 8 μ m and 40 ps with a probe beam timing accuracy of about ± 20 ps. It would be advantageous to be able to record at least four images separated by 1/2 to 1 ns during the course of the implosion.

We strongly urge the development of such a capability and suggest a series of preliminary experiments be conducted at the SHIVA laser facility leading to the recording of an implosion at that facility.

Figure Captions

1. Schematic of the NOVA double-shell target with x-ray backlight source. X-rays generated from the source disc irradiate the target in a nearly collimated beam. X-rays are attenuated in different amounts by the two shells of the capsule and emerge from the target where they are imaged by a suitable detector.

2. Helium-like titanium is an excellent emitter of 4.7 keV x-rays. The SHIVA experiment was performed with a 3 kJ pulse delivered in 600 ps; intensity was about $3 \times 10^{15} \text{ w/cm}^2$. The line intensity was about $3 \times 10^{17} \text{ keV/keV}$, and the contrast ratio was more than 100.

3a. The pie-diagram for the double-shell capsule shows the two shells. An inner pusher of a gold alloy contains the DT at liquid density ($\rho = 0.21 \text{ g/cm}^3$). The outer shell is composed of a TaCOH pusher with a LiD ablator. The shells are separated by helium gas which acts as a cushion to provide some pressure pulse shaping of the impulse delivered to the inner shell.

3b. The laser power history consists of a low power foot which conditions the plasma formed from the ablation of the LiD; a small shock ($\sim 1 \text{ Mbar}$) is generated, slightly compressing the TaCOH. Near the mid-point of the laser history an exponential rise in about 5 ns to the peak power increases the temperature and ablation pressure, where it remains constant for the remainder of the implosion.

4. The R-T diagram for the two pushers shows little motion of the TaCOH pusher in the first 13 ns. The outer (TaCOH) pusher reaches a velocity of about $0.13 \text{ } \mu\text{m/ps}$ with the inner surface moving slightly faster because of spherical convergence. Contact between the two shells is made at about 16.6 ns. A slight pre-heating of the inner shell is seen to occur near 15 ns. Ignition time is at 17.4 ns; the inner pusher reached a velocity in excess of $0.20 \text{ } \mu\text{m/ps}$.

5. Cold gold opacities: Photon energies of more than 100 keV would be required to penetrate the inner pusher, while ~10 keV photons will provide a good definition of its outer surface.

6. Radial density-thickness products increase with time as spherical convergence of thin shells takes place; the TaCOH outer pusher's ρR is continually increasing while the inner gold alloy pusher thickens rapidly after shell contact at $t = 16.6$ ns. This information is used in conjunction with opacity values of the different materials (see Figures 5 and 8).

7. A plot of the transmitted x-ray intensity as a function of radius at the DT ignition time is shown. The backlight energy is 100 keV. The large ρR of the gold alloy pusher makes the contrast at the fuel/pusher interface poor; the thickness of the pusher is comparable to the radius of the compressed fuel. Demarkation of the outer surface is much easier than for the inner surface.

8. Intensity requirements for the x-ray probe are determined, to an extent, by the self-emission of the capsule. The figure shows the temporal behavior for two x-ray energies representative of the region of interest. These background intensities follow the laser pulse and are emitted from the outer surface of the TaCOH pusher (see Figure 11).

9. As spherical convergence drives the fuel to ignition, a burst of higher energy x-rays is emitted coincident with the release of thermonuclear energy. This figure shows the intensity of 9.0 keV x-rays escaping from the capsule. Hence, at late times the "background" signal becomes appreciably larger, if not comparable to, the probe intensity. Care must be taken to isolate this late time flux from obscuring earlier recorded information.

10. Self-emission from the target capsule depends upon the x-ray energy. Opacity effects limit the apparent depth from which the x-ray emission is coming. Higher energy x-rays have a lower opacity (not

including electronic shell edge effects) and thus appear to come from deeper within. This snapshot of x-ray emission as a function of radius is taken at a time of 16 ns. The relative emission scale for the 4.5 keV window is 50 times that for the 9 keV window. Approximate material boundaries are shown. Emission peaks at the ablator/outer pusher interface since the ablation surface has penetrated to this point at the end of the laser pulse.

11. Transmitted x-ray profiles are shown for several times during the implosion. The photon energy of the probe is 4.5 keV. Calculated positions of the inside and outside surfaces of the TaCOH pusher are indicated.

12. A similar set of transmitted profiles as in Figure 11 but with an x-ray energy of 9.0 keV. This high-energy probe appears to be more satisfactory for locating the inner edge of the TaCOH pusher.

13. An implosion with a high suprathermal electron content severely preheats both shells. The inner shell behaves as an exploding pusher while the outer shell has an ablative nature. The trajectory of the pusher/fuel interface is such that the fuel is never rapidly heated.

14. Preheat is generated by the long-mean-free-path electrons from collective plasma processes. The calculated hot electron temperature scales nearly with the square root of the laser power and thus tracks the laser pulse in time. Suprathermal electrons have a mean-free-path which scales as the square of the electron energy.

15. Background emission from the capsule in the 4.5 and 9.0 keV region behaves differently from that of Figure 9. Preheat, in general, decompresses material which results in a lower x-ray emission intensity. Opacity effects play a small role in the apparent depths of emission.

Figure 1

Radius, cm

(a)

(b)

Figure 3

Figure 4

X-RAY ABSORPTION COEFFICIENT OF GOLD (COLD MATERIAL)

Figure 5

50-60-0780-2120

Figure 6

Figure 7

Figure 9

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15