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DIRECT-ILLUMINATION SPHERICAL-TARGET EXPERIMENTS

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INTRODUCTION

A substantial effort at KMS Fusion is in the area of Direct Illumination Spherical Target Experiments with the recent emphasis in understanding thermal and superthermal transport and the mechanisms which can limit high convergence ratio implosions. These processes must be well understood in order to do effective target design calculations needed for larger ICF facilities.

The spherical target experimental campaigns cover the full spectrum of theoretical and experimental capabilities. These include the initial concept that proposes the method to determine the physics effect of interest. Target design then follows based on the state-of-the-art hydro and plasma codes. Target fabrication with complete characterization is required to ensure that the target experiments are not influenced by extraneous parameters. Knowledge of the quality of the laser and optics characteristics are essential in order to adequately model the experiments. Advanced diagnostic techniques must be employed since the observables from the experiment are generally low level resulting in poor signal to noise ratios. After the experiments have been performed, it is necessary to provide good theoretical modeling to arrive at the correct interpretation of the results.

For future reactor scale concepts, indirect-drive (radiation) targets are considered superior to direct-drive (electron) targets, and constitute the main line thrust of the US ICF program. With small scale lasers (≤ 100 kJ), however, direct drive targets may have an advantage. Consequently, experiments using uniformly illuminated spherical targets have played a significant role in US

laser fusion research. It was recognized very early that direct-drive laser fusion would require highly uniform target irradiance (of order 1%) to achieve the necessary high convergence-ratio implosions. In addition, spherical geometry has some unique advantages in laser-plasma interaction experiments. Spherical symmetry can avoid two-dimensional geometric effects, such as lateral heat conduction, that complicate interpretation, while also simplifying certain measurements because angular distributions of particle and x-ray emissions are nearly isotropic.

A set of spherical target experiments was designed to evaluate the effectiveness of three techniques for achieving higher convergence implosions. They are 1) cryogenically frozen fuel layers, 2) submicron wavelength laser light, and 3) temporally tailored pulse shapes. A second set of experiments provides information about energy transport by thermal and suprathermal electrons and uses multilayered targets as an integral component of the diagnostics. These results, in conjunction with existing laser-target coupling data, provide a more comprehensive test of our understanding of laser plasma interaction, energy transport, and hydrodynamic response of small scale spherical laser fusion experiments.

EXPERIMENTAL FACILITIES

The 20 cm diameter, two beam Chroma laser can produce up to 2 TW of infrared energy in a 100 psec pulse. It is capable of operating at 1.05 μm , 0.53 μm and 0.35 μm with the flexibility of shaping the laser pulse to any predetermined pulse form from 100 psec to a few nsec. The coherent pulse stacker is generally configured to form a trapezoidal shaped pulse with a FWHM of 0.5-1 nsec, but other pulseshapes are available. For example, cryogenic implosion experiments at 1.05 and 0.53 μm used a variety of pulseshapes as shown in Fig. 1.

For spherical target campaigns, KMSF uses a unique all-reflective triple bounce ellipsoidal mirror system that focuses the laser light onto spherical targets with nearly uniform 4π illumination. This system is achromatic so that changes in the wavelength of the driver can be routinely implemented.

KMSF emphasizes optical diagnostic techniques and with the laser plasma interaction capabilities available, it is possible to study the nonlinearly generated harmonic emission from the laser plasma interaction process as well as the light scattered by the Raman and Brillouin instabilities by spatially and temporally resolving this emission with submicron and picosecond resolution. A 0.26 μm holographic probe with 20 psec time resolution allows simultaneous probing of electron plasma distribution in the targets

both normal to and along the main laser axis. Using automated general purpose Abel inversion codes, electron densities up to 10^{21} cm^{-3} can be analyzed with $1 \mu\text{m}$ spatial resolution, from double-pulse interferometric measurements.

In addition to these diagnostics and the standard optical diagnostics monitoring the energy and power distributions delivered to the target, KMSF has an extended suite of x-ray and particle diagnostics to monitor the partitioning of the energy from the laser target interaction, as well as any fusion reaction products. X-rays from 0.1 to 100 keV are measured with a range of instruments providing temporal, spatial and energy resolution. Charged particles and neutrons are measured with a variety of fusion product spectrographs, charge collectors, plasma calorimeters, activation detectors and time-of-flight systems.

DIRECT ILLUMINATION CRYOGENIC IMPLOSION EXPERIMENTS

In an idealized laser fusion target, there is an energetic advantage to having the thermonuclear fuel in the form of a solid spherical shell with a void in the center of the sphere. Compared to a uniform gaseous fill, the solid layer configuration starts the implosion of the fuel at a higher initial density, resulting in the early stages of the implosion proceeding along a lower adiabat. At the peak of the implosion, the target should have a higher density than an initially gas filled one. Ultimately this translates into more thermonuclear output at fixed laser input for the target with the fuel in a solid shell.

Previous experiments with infrared lasers have generated copious quantities of high energy electrons. Because inverse bremsstrahlung is not very efficient at high intensities a substantial amount of laser light reaches the critical surface where it is absorbed by resonant processes. These long mean-free-path electrons are capable of penetrating into a solid fuel shell and vaporizing it very early in the implosion event. This preheat by fast electrons tends to eliminate the difference between solid-layer and gaseous fuel targets. It is now possible to substantially reduce fast electron preheat by using shorter wavelength laser light obtained from frequency multiplication of $1 \mu\text{m}$ glass lasers. In addition, absorption via the collisional mechanism has been shown to be more efficient at shorter ($0.53 \mu\text{m}$ and $0.35 \mu\text{m}$) wavelengths.¹ The rapid heat penetration possible at shorter wavelengths potentially can give a higher driving (ablation) pressure. The closer proximity of the absorption and ablation surfaces also results in more efficient energy transfer to the target, perhaps at some expense of the benefit of thermal conduction smoothing at the ablation front.

The techniques for producing uniform solid DT layers were demonstrated in 1978.² The basic concept is to cool the target under a shroud with flowing low temperature helium gas. The frozen DT layer is observed with a high resolution optical interferometer. If the frozen layer is nonuniform, it can be melted by heating it with a CW laser. When the DT refreezes, the layer uniformity can be improved, as described in Ref. 2 and demonstrated in Fig. 2. When an acceptable layer is formed, the main laser firing sequence begins, with the cooling shroud retracted a few milliseconds before the laser is triggered. Test shots were conducted to verify the ability of a cryo-layer to survive the amplified spontaneous emission generated prior to the high power laser pulse.

The output of the CHROMA laser is focused by the illumination system which provides reasonably uniform irradiance (1.2:1 for a smooth laser pulse) over the entire spherical surface. The laser pulse length was varied by changing the number of individual 100 psec pulses combined in a coherent pulse stacker. Most of the data were taken with constant-power pulses up to 500 psec long and at on-target power levels of 0.6 to 1.0 TW. However, a few experiments were performed with shaped pulses in which the power was varied linearly with time, as t^2 , t^3 or in a stepped fashion. Fig. 1 showed a few examples of these pulse shapes.

The targets for these experiments were simple glass shells of 115-120 μm diameter. The wall thickness was varied from 1.8 to 5 μm . The shells were filled with 100 atm (20 mg/cm^3) of DT, which forms an ~ 2 μm thick layer when frozen. The principal diagnostics that provide information about compressed core conditions are 1) an x-ray streak camera (on loan from LLNL) coupled to an x-ray pinhole to measure implosion times and compressed core dimensions, 2) x-ray pinhole cameras that measure the symmetry of the implosion and the size of the compressed core, 3) neutron yield monitors, 4) an alpha particle time-of-flight system that measures the energy downshift of fusion alpha particles, and 5) x-ray crystal spectrographs to measure a high atomic number seeded fuel density and temperatures and compressed-glass temperature from x-ray line widths and line ratios.

Interpretation of data obtained using 1.05 μm laser light in a flat-topped pulse and targets with various wall thicknesses show a factor of 2 increase in neutron yield and a 20% reduction in compressed core size for cryogenic targets compared to identical targets at room temperature as shown in Figs. 3 and 4. Fig. 3 shows the neutron yield normalized by the incident laser power to the fifth power as a function of wall thickness for gas and cryogenic targets. There appears to be a distinct difference in target performance as long as the cryogenic target layer was uniform prior to laser irradiation. Fig. 4 compares the size of the compressed core

as measured from x-ray pinhole and x-ray pinhole/streak camera data. The dimension of the core is defined as the diameter of the central image in the x-ray photographs as extrapolated to the background (fog) level on the film (corrected for pinhole image convolution). Use of this diameter as an indication of compression provides a conservative lower bound for the final fuel density. A more realistic estimate would be found by assuming the DT fuel to be contained within the diameter corresponding to the peak-to-peak x-ray emission from the compressed core. (The peak-to-peak feature was not clearly discernible in all of the pinhole pictures, but the ratio of the two dimensions was typically $D(\text{core})/D(\text{peak-to-peak}) > 1.3$.) Fig. 5 shows this estimate of compressed fuel density plotted as a function of target wall thickness and compared with computer simulations. There is, approximately, a factor of two increase in the final fuel density (especially for the thicker walls) when going from a gaseous fill to a cryogenic layer. Implosion times are determined from x-ray streak records (shown in Fig. 6) for gas and cryogenic targets as a function of wall thickness. Fig. 7 shows the experimental results for both types of fuel conditions. The lack of an implosion time dependence on fuel conditions is easily understood in that the majority of the mass of the target is in the glass shell which has the same configuration in all experiments. The increase in implosion time with increasing wall thickness is expected since the specific energy absorbed decreases as does the driving pressure and hence implosion velocity and is consistent with the corresponding decrease in neutron yield and core size.

The alpha particle spectrometer measures the velocity distribution of the fusion products from which a mean energy may be deduced. Fig. 8 shows the mean alpha particle energy as a function of wall thickness. A gas/cryo difference is not expected since most of the energy loss takes place in the pusher.

By using green ($0.53 \mu\text{m}$) light, the number of hot electrons can be substantially reduced. With the concomitant lower preheat and weaker shockwaves penetrating the pusher and fuel, we would expect even flat-top driven, green light, cryogenic targets to stay on the high density adiabat for a longer time than was possible with $1.05 \mu\text{m}$ irradiation. This effect is demonstrated in Fig. 9 which compares the size of x-ray images at stagnation for two $0.53 \mu\text{m}$ experiments with the $1.05 \mu\text{m}$ results from Fig. 4. The data imply four times higher final compressed fuel density for thin-walled targets irradiated at $0.53 \mu\text{m}$. Pinhole images of silicon x-ray emission were only available from a few experiments since the damage level of optical coatings limited the peak power in target to about 0.3-0.5 TW ($\leq 50 \text{ J}$ in 100 ps, $\leq 130 \text{ J}$ in 300 ps).

The low energy-on-target did not drive the implosion to sufficient temperatures to produce a large number of neutrons or significant silicon x-ray emission to allow pinhole photography to be used as a routine diagnostic. However, most targets were seeded with a few atmospheres of argon gas whose x-rays could be thermally excited. This x-ray emission was sufficient to allow pinhole photography as well as x-ray line spectroscopy. Fig. 10 shows x-ray pinhole images from two green light implosions. The image on the left is from a target filled only with Argon while the one on the right is from a target filled with 20 mg/cm^3 of D_2 and 3.6 mg/cm^3 of Argon as a tracer. Both were room temperature targets, had $\sim 1 \text{ }\mu\text{m}$ wall and were irradiated with $\sim 50 \text{ J}$ in 100 ps . With the exception of initial fuel temperature, the DD/Ar target and laser conditions were nearly identical to the two $0.53 \text{ }\mu\text{m}$, DT only targets from Fig. 9. Spatial imaging of x-ray emission from Argon tracer gas has been used at many laboratories as a compression diagnostic. For a cryogenic target there is some concern that Argon and DT (or D_2) will freeze out in separate layers and imaging the Argon emission would therefore give an ambiguous density measurement. For the room temperature target of Fig. 10 this separation would not take place, and we would expect the size of the central spike to compare well with the Silicon x-ray emission data from Fig. 9. This, however, is not the case. The final imploded density from the two figures differ by nearly a factor of two. The density inferred from Stark broadening of the helium-like Argon beta line is in good agreement with the Silicon x-ray image. The experimental spectrum and the theoretical line profile are shown in Fig. 11. The line is nearly optically thin so that its Stark broadening is a good measure of the density. The pinhole picture suggests a density of about 4.4 g cm^{-3} as an upper limit, assuming all of the compressed gas is emitting uniformly. The Stark broadening measurement shows a lower value, about 2.7 g cm^{-3} , which is more realistic. The discrepancy is due to a large temperature gradient across the fuel. This will be further discussed below.

Even though care must be taken before final density can be quantitatively extracted from images of seed-gas x-ray emission, such data can give us useful qualitative information and trends. This is shown in Fig. 12, which compares the size of the central x-ray image for 1.05 and $0.53 \text{ }\mu\text{m}$ experiments. For $1.05 \text{ }\mu\text{m}$ irradiations of $1\text{--}2 \text{ }\mu\text{m}$ thick targets we observe that increasing the pulse length (and thus the incident energy) does not produce any change in the central x-ray image (and by implication, the final fuel density). Although not explicitly stated previously, the long pulse (thin walled) experiments did not produce a higher neutron yield either. This behavior is consistent with the picture of a hot-electron dominated implosion. The early preheat and hot electron generated shockwaves essentially decouple the implosion of these targets from laser energy delivered after the first $\sim 100 \text{ ps}$. Fig. 12 indicates

that this is not the case for $0.53\ \mu\text{m}$ implosions of the same targets. The lower initial preheat allows the targets to effectively use a larger fraction of the longer laser pulses.

NUMERICAL SIMULATIONS AND INTERPRETATION

We have performed numerical simulations on many of the cryogenic and gas-fill implosion experiments discussed above. The one-dimensional hydrodynamics code TRHYD includes radiation, a realistic equation of state, and a multi-group diffusion treatment for non-thermal electrons. The calculations indicate that the $1.05\ \mu\text{m}$ temporally flat-topped cryogenic implosion experiments are dominated by hot electrons. This is clearly demonstrated by the implosion history for a cryogenic, $1.05\ \mu\text{m}$ irradiated target shown in Fig. 13. The rapid hot electron generated thermalization of the pusher causes the half-mass position of the shell to remain very nearly at its original position during the implosion providing no ablative acceleration of the pusher. The hot electron generated shockwave penetrates the pusher and DT fuel early in the implosion, destroying the integrity of the cryogenic layer and very rapidly moving the compression away from the favorable, high-density adiabat the implosion was on initially. This effect is clearly seen in Fig. 14 where the pressure-density history for an average element of the fuel is shown for both a gas-fill and a cryogenic target. Also shown is an adiabat for an identical cryogenic target illuminated with temporally flat-topped $0.53\ \mu\text{m}$ light.

Preheat of the DT fuel consists of two types: direct collisional and shock. The former is due to the coulomb collisions of the hot electrons which penetrate the glass shell and undergo interactions with the thermal electrons of the fuel. This heating is most evident for the first 75 ps or so in which the pressure rises with no change in the fuel density (see Figs. 13 and 14). For the cryogenic configurations there follows a small amount of compression along a $\gamma = 5/3$ adiabat until the shock wave penetrates the cryogenic shell at about 100 ps. The shock wave is generated by the explosive heating of the pusher by the hot electron population. Upon the passage of the shock wave through the fuel it begins to irreversibly decompress the cryogenic layer resulting in its partial return to the homogeneous gaseous state. This decompression is slowed and finally reversed by the inward motion of the pusher; again adiabatic work is done on the gas until its final compressed state is achieved.

To a large extent, determination of the final fuel densities achieved relies on a measurement of the spatial extent of the pusher x-ray emission. Numerical simulations for a wide variety of target and laser parameters show this (for these intermediate

densities) to be a reasonable method providing there has been no mixing of fuel and pusher. Fig. 15 presents the radial profiles of electron temperature and density for a specific experiment. The silicon free-bound emission is sharply peaked at the pusher/fuel interface where the glass density is maximum. It is also important to note the temperature gradient in the fuel. Not only are the neutrons produced in this small amount of fuel but so are most of the argon x-rays. Hence, a pinhole picture dominated by the argon free-bound emission is not seeing the majority of the fuel, and must be carefully analyzed before quantitative information can be obtained. This point is further emphasized by the data shown in Fig. 16. Indiscriminate use of this pinhole image would imply a final density a factor of 5 to 6 greater than that given by x-ray spectroscopy.

SHAPED-PULSE EXPERIMENTS

Achievement of an even higher final fuel density is possible by starting on an adiabat of lower preheat. This may be accomplished by modifying any one (or a combination) of three parameters: laser wavelength, laser intensity, or shell thickness. Fig. 17 shows the range of hot electron energy penetration into the fuel for the infrared and green illuminations done at KMSF. One additional method for reducing both the collisional and shock preheat is to shape the laser pulse in time. Slowly rising pulses, when properly matched to target parameters, are calculated to drive targets to higher density than would fast rising, flat-topped pulses. Achievement of another factor of ten in preheat protection should be possible.

A few experiments were conducted with slowly rising and stepped-pulse shapes at $1.05 \mu\text{m}$. Several different pulse shapes were attempted. The most complicated was an eight-pulse-stack with power increasing at t^3 as shown in Fig. 1. Three and four pulse linear and t^2 ramps and a number of single step-pulses were also tried. In the stepped-pulses the first pulse in the stack had half the amplitude of the succeeding pulses.

Neutron yields on the t^3 ramps were less than 10^6 , and in only one case was there a signal above threshold. Neutron yields in the 10^6 range were measured on linear ramp and step-pulse shots. At best, the shaped pulse yields (normalized by the average input power) are a factor of 10 below the best flat-top yields. In most cases the yields were even lower. The highest yields came from the step-pulses, which rise quickly to half power. Some of these results are shown in Fig. 18.

Qualitatively, the most striking feature of the x-ray images from the shaped pulse shots is the strong reduction in core emission compared to the flat-top pulses. No core emission was observed on any of the t^3 pulse shots, even at energies up to 380 J. Weak core emission was visible in most of the linear-ramp and step-pulses.

There is a systematic difference in the outer-ring x-ray image between the t^3 and the shorter linear ramp and step-pulses. On the longer t^3 ramps, the peak x-ray emission is at or just inside the original target diameter, rather than 10 to 20 μm outside the original wall position as is typical of the flat-top and stepped pulse data. The radial width of the emission region was consistently 30 μm for the t^3 pulse shots, but only 10 to 20 μm for the other pulse shapes, even though the high-power portions of the laser pulse are of comparable duration. This is to be expected for a more ablative implosion in which the most dense part of the pusher, which is emitting the x-rays, is slowly accelerated inward by the reaction to the ablating material.

Implosion times were obtained for all of the step-pulse shots (where core emission is brightest). Core diameter measurements were also obtained on a few step-pulse shots. Implosion times were of the order of 20% longer for the step-pulse shots.

Fig. 19 compares core diameter measurements for flat-topped and stepped cryogenic target experiments. The three data points for the step pulses suggest that these targets produced somewhat smaller core sizes and correspondingly higher compressions than those with flat-top pulses.

TRHYD simulations of a stepped-pulse experiment investigated the sensitivity of target performance on details of the laser pulse profile. A slight variation in the peak power of the "front porch" and/or its duration can affect the overall compression, implosion time and neutron yield. This was demonstrated with a stepped-pulse used in the calculation as well as a calculation with a flat-topped pulse. Clearly, the target performance is sensitive to the leading edge of the laser pulse with the stepped-pulse results producing higher density lower temperature implosions.

The results of the shaped-pulse experiments are all generally consistent with much lower temperatures in the imploded core, leading to lower yield, less x-ray emission, smaller core size, and probably higher fuel density.

Numerical studies show that by combining shorter wavelength illumination, cryogenic fuel layers and properly shaped laser pulses, we can approach the ideal Fermi degenerate adiabat in our experiments. Fig. 20 shows the typical fuel adiabat that we expect

to achieve. In Fig. 21, the comparison between the flat-topped experiment (discussed earlier) and the ideal shaped-pulse calculation is made. Again, we expect the performance of this target to be critically dependent upon matching the laser pulse to the target implosion time and the details of the laser pulse during the very early phase of the implosion. Even weak shock waves caused by too high a power level; or local temporal spikes in the laser pulse during this phase would take the implosion off the favorable adiabat and severely reduce the final compressed fuel density.

TRANSPORT EXPERIMENTS

The absorption of laser energy is primarily into two distinct electron populations, the thermal and superthermal groups. The exchange of energy among the laser, the directly heated electrons, and the remainder of the target is not well understood. Two sets of experiments are being performed to study the transport of energy in spherical targets. One set emphasizes transport by thermal electrons; the other emphasizes transport by superthermal electrons.

Fig. 22 shows the pie-section of the target used to study thermal transport. The experimental technique infers the ablation rate of the low-Z layer by observing the time delay between x-ray emission of the titanium and aluminum layers. Similar layered spherical target experiments at the Rutherford Laboratory have shown marked differences from several layered planar target experiments. Our measurements extend the scaling of spherical ablation rate with absorbed intensity up to 8×10^{14} W/cm², as shown in Fig. 23. Preliminary results from our transport experiments do not follow an extrapolation of the results from Rutherford to higher intensities. From the data it is clear, however, that thermal transport (as measured by mass ablation rates) is more efficient in spherical geometry.

Different targets are used to investigate the penetration of superthermal electrons into spherical targets. An example is shown in Fig. 24. The inner metallic layers will emit K_α x-ray radiation as the superthermal electrons penetrate into the target. The K_α yield from each layer will be measured as the laser intensity and inner polymer layer thickness are varied.

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THE COHERENT PULSE STACKER PROVIDES A WIDE VARIETY OF SHAPED LASER PULSES FOR THE IMPLOSION EXPERIMENTS

fusion
kms
INC.

For the high density, cryogenic experiments planned at $0.53 \mu\text{m}$ code simulations indicate that a laser pulse having a t^3 temporal shape provides optimal target performance.

By adding 3 gaussian, 100 ps pulses we can create a flat-topped laser pulse.

By adding two pulses of different amplitude, we can create a "front-porch" laser pulse.

ACHIEVING A UNIFORM CRYOGENIC FUEL LAYER IS SENSITIVE TO THE COOL DOWN PROCESS

fusion^{lms}
INC.

The uniformity and quality of the glass shell is demonstrated by this interferogram of the target taken at room temperature. The interferograms below are of the same target at cryogenic temperatures.

A good cryogenic layer is provided by heating the cryogenic fuel a short time and then letting it refreeze rapidly.

A non-uniform cryogenic layer occurs if the refreezing process is allowed to occur too slowly

Fig. 2

NORMALIZING NEUTRON YIELD WITH INCIDENT POWER ENHANCES THE DIFFERENT SCALING FOR CRYOGENIC AND GAS TARGETS

kms
fusion
Inc.

- NEUTRON YIELDS SCALE $\sim$ AS ION TEMPERATURE TO THE 5th POWER IN THIS TEMPERATURE RANGE (0.6 – 1.2 keV)
- TARGET SHOTS WITH NON-UNIFORM CRYO LAYERS HAVE LOWER NEUTRON YIELD

Figure 3

FINAL COMPRESSED STATE IS IMPROVED FOR THICK WALLED CRYOGENIC TARGETS

kms
fusion
Inc.

- THICKER WALLS PROVIDE BETTER PROTECTION AGAINST HOT ELECTRON PREHEAT.
- THE CRYOGENIC DT SHELL GETS TO A DENSER FINAL STATE FOR THE SAME DRIVER CONDITIONS

EKS-0482-067

Figure 11

FUEL DENSITIES INFERRED FROM X-RAY PINHOLE IMAGES ARE IN GOOD AGREEMENT WITH SIMULATIONS

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inc.

X-Ray Pinhole Image
For Cryogenic Target
With $3.2 \mu\text{m}$ Wall

29 μm Peak-To-Peak
X-Ray Dimension

Initial Target
Diameter

113 μm

- FUEL DENSITIES AT STAGNATION ARE FOUND FROM THE EXPERIMENT BY ASSUMING ALL THE DT FUEL IS CONTAINED WITHIN THE VOLUME DEFINED BY THE CENTRAL PEAK-TO-PEAK X-RAY EMISSION.

Figure 5

THE X-RAY PINHOLE/STREAK CAMERA PROVIDES TARGET IMPLOSION TIMES AND THE SIZE OF THE IMPLODED CORE

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Shot 5451
 $\lambda = 1.05 \mu\text{m}$
 348 J
 350 ps Flat-Top Pulse
 Diameter $115 \mu\text{m}$
 Wall Thickness $3.2 \mu\text{m}$
 Cryogenic Fuel
 Neutron Yield 5.3×10^7

Implosion Time = 250 ps

Figure 6

IMPLOSION TIME FOR CRYOGENIC AND GAS TARGETS INCREASES WITH WALL THICKNESS

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IMPLOSION TIME DEFINED AS THE TIME FROM THE FIRST RECORDABLE X-RAY EMISSION, UNTIL THE PEAK OF THE X-RAY SIGNAL AT STAGNATION.

Figure 7

ALPHA-PARTICLE ENERGY LOSS INCREASES WITH TARGET WALL THICKNESS AND IS CONSISTENT WITH HIGHER COMPRESSION FOR INCREASING WALL THICKNESS

lms
fusion
inc

- CRYO/GAS DIFFERENCE IS NOT EXPECTED SINCE MOST OF THE ENERGY LOSS TAKES PLACE IN THE PUSHER.

Figure 8

FINAL COMPRESSED STATE IS IMPROVED FOR CRYOGENIC TARGETS IRRADIATED AT $0.53 \mu\text{m}$

fusion
Inc.

- THICKER WALLS PROVIDE BETTER PROTECTION AGAINST HOT ELECTRON PRE HEAT.
- THE CRYOGENIC DT SHELL GETS TO A DENSER FINAL STATE FOR THE SAME DRIVER CONDITIONS.

GREEN LIGHT IMPLOSIONS WERE DIAGNOSED BY IMAGING THE ARGON X-RAY EMISSION FROM THE CORE

fusion^{lms}

3.6 mg/cm³ Ar

$\rho_{\text{final}} \sim 1.2 \text{ g/cm}^3$

**3.6 mg/cm³ Ar
20 mg/cm³ D₂**

$\rho_{\text{final}} \sim 4.4 \text{ g/cm}^3$

DATA FROM STARK
BROADENING GIVES
DENSITY OF 2.7g/cc

$\lambda = 0.53 \text{ μm}$

Wall Thickness = 1 μm

50 J/100 ps

STARK BROADENING OF Ar He β GIVES A FUEL DENSITY LESS THAN THAT FROM IMAGING THE Ar EMISSION

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fusion

Figure 11

LONGER PULSELENGTHS ARE MORE EFFICIENTLY COUPLED TO THE IMPLOSION FOR 0.53 μm LIGHT

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(Initial Diameter)
(Size of X-Ray
Emission)

0.53 μm

1.05 μm

DT

DT/Ar, DD/Ar

Wall Thickness 1 - 2.5 μm

~ 0.5 TW for 0.53 μm

~ 0.8 TW for 1.05 μm

Implosion Times

Exceeded 200 ps for All Targets

Pulse length, ps (Flat-top)

FOR 1.05 μm LIGHT HOT ELECTRON PREHEAT CAUSES UNCOUPLING OF THE IMPLOSION AND ABSORPTION DURING THE LATER PART OF THE LASER PULSE.

Fig. 12

IN RECENT INFRARED CRYOGENIC EXPERIMENTS SUPER-THERMAL ELECTRONS UNIFORMLY PREHEAT THE PUSHER

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EKS-0482-071

TIME, ps

Fig. 13

HOT ELECTRON PREHEAT RAISES IMPLOSION ADIABAT BY COLLISIONAL AND SHOCK PROCESSES

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Figure 14

X-RAY EMISSION AT TIME OF PEAK COMPRESSION ($t = 250$ ps) COMES FROM INSIDE OF GLASS PUSHER

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fusion
Inc.

EKS-0472-066

Figure 15

SPATIAL IMAGING OF EMISSION FROM THE CORE IS A USEFUL DIAGNOSTIC TOOL — BUT REQUIRES CAREFUL INTERPRETATION

^{kms}
fusion

Shot 5531
 20 mg/cm³ DD
 3.6 mg/cm³ Argon
 119 μm Diameter
 2 μm Wall
 84 J of 0.53 μm
 200 ps

- Simulations show a temperature and density gradient in the compressed volume.
- X-ray emission is sensitive to ρ and T and is most intense at the center of the compression.
- Interpretation depends upon:
 - ✓ Identification of radiating species
 - ✓ Degree of mixing
 - ✓ The time of x-ray emission

Fig. 16

PREHEAT FROM HOT ELECTRON PENETRATION IS DICTATED BY THICKNESS OF GLASS SHELL

kms
fusion

15 - 50% OF HOT ELECTRONS REACH FUEL
FOR $\lambda = 1.05$

$$X = \left[\frac{5.29 \Delta R_{\mu}}{(I_{16} \lambda_{\mu}^2)^{.84}} \right]^{1/2}$$

Figure 17

TARGET PERFORMANCE IS CRITICALLY DEPENDENT UPON THE PULSE SHAPE DURING THE EARLY STAGE OF THE IMPLOSION

kms
fusion
Inc

- ALL TARGETS WERE CRYOGENIC; DIAMETER $\sim 115 \mu\text{m}$; WALL $\sim 3 \mu\text{m}$
- POWER LEVEL OF STEP WAS TYPICALLY $\frac{1}{2}$ OF PEAK POWER
- FOR SIMILAR ENERGY ON TARGET, TARGET IMPLOSION TIMES INCREASED FOR STEPPED PULSES.

Figure 18

30

**CRYOGENIC TARGETS IMPILODED WITH SHAPED (STEPPED)
LASER PULSES APPEAR TO ACHIEVE A HIGHER COMPRESSION**

kms
fusion
Inc.

TARGETS IRRADIATED WITH STEPPED TEMPORAL PULSES ALSO HAD

- ✓ LOWER NEUTRON YIELDS AND COLDER FUEL
- ✓ LONGER IMPILOSION TIMES

THAN TARGETS IRRADIATED WITH FLAT-TOPPED PULSES.

CALCULATED FUEL ADIABATS APPROACH THE IDEAL BY REDUCING PREHEAT WITH SHAPED PULSES

kms
fusion
inc.

Figure 20

A SHAPED GREEN LASER PULSE PRODUCES AN IMPROVED IMPLOSION

$E_{\text{LASER}} = 270 \text{ J}$

DIAMETER = $115 \mu\text{m}$, WALL = $3.2 \mu\text{m}$

fusion
kms
Inc.

- COMPUTER SIMULATION FOR INFRARED FLAT-TOP PULSE AGREES WELL WITH EXPERIMENTAL RESULTS
- PREDICTED INCREASED COMPRESSIONS FOR A SHAPED, GREEN PULSE ARE SENSITIVE TO PREHEAT, HYDRODYNAMIC INSTABILITIES. THE DETAILS OF THE PULSE SHAPE DURING THE VERY EARLY PHASE OF THE IMPLOSION AND MATCHING OF LASER PULSE TO IMPLOSION TIME

Figure 21

THERMAL TRANSPORT EXPERIMENTS USE TIME DEPENDENT X-RAY EMISSION AS THE MAIN DIAGNOSTIC

kms
fusion
inc.

SHOT #5498

$\lambda_L = 1.05 \mu\text{m}$

$P_L = 0.39 \text{ TW}$

$I_L = 1.2 \times 10^{15} \text{ W/cm}^2$

- THE TIME DELAY BETWEEN X-RAY SIGNALS IN SPHERICAL GEOMETRY WILL BE MODELED BY THE I-D CODE

Figure 22

ABLATION RATES OF SPHERICAL TARGETS ARE INTERMEDIATE TO RESULTS FROM OTHER LABORATORIES

kms
fusion
inc.

- HEAT FLOW APPEARS TO BE MORE EFFICIENT FROM UNIFORM ILLUMINATION.

Figure 23

SUPERTHERMAL ELECTRON TRANSPORT EXPERIMENTS ARE IMPORTANT FOR MODELING THE HIGH DENSITY, CRYOGENIC IMPLOSION EXPERIMENTS

kms
fusion
Inc.

- THE TRANSPORT OF ENERGY BY SUPRATHERMAL ELECTRONS IS NOT WELL MODELED IN PRESENT CODES.

$$\lambda = 1.05 \mu\text{m} \text{ and } 0.53 \mu\text{m}$$

$$I = 5 \times 10^{14} - 5 \times 10^{15} \text{ W/cm}^2$$

$$t = 100 - 200 \text{ ps}$$

- K-EDGE, X-RAY SPECTRA FROM TITANIUM AND VANADIUM WILL INDICATE HOW MANY FAST ELECTRONS ARE PRODUCED AND HOW FAR THEY PENETRATE.
- 1-D GEOMETRY WILL ALLOW CODE SIMULATIONS TO PARAMETERIZE ANOMALOUS TRANSPORT.