The laser fusion program at KMS Fusion has been directed toward achieving high density compressions. The limitations in this endeavor have been caused by the small amount of energy which is deposited in the fuel before the implosion occurs. This preheat energy is associated with radiative transport from the conduction front and with the athermal conditions existing in the corona which allows a portion of the high energy electron distribution to penetrate through the target. Targets have been designed and tested which minimize the effect of the electron preheat but since they increase the mass of the target they penalize the laser fusion experiment by requiring much larger laser drivers.

The approach taken by KMS Fusion is to attempt to minimize the source of the electron preheat through broadening of the laser bandwidth and operating at shorter wavelengths. In addition, the design of the target has incorporated a cryogenic fuel layer so that the target implosion will reach higher densities if it is not preheated. As an additional benefit, it has been found that the absorption of the laser light is significantly improved with the broadened bandwidth and shorter wavelength which reduces the power requirements on the laser driver.

Laser Absorption Experiments

A schematic of the plasma spatial filter used in these experiments is shown in Figure 1. The main feature which needs to be indicated is that the incident beam has a bandwidth of several angstroms before it strikes the target, and the backscattered light from the target is broadened in bandwidth and smoothed in the beam profile. The beam then passes through the Faraday rotator and the reflection off the polarizer is directed to the rest of the laser amplifiers. The result is an output laser beam that has a considerably broadened bandwidth and a laser beam profile that is much smoother than without the plasma filter. The near field photographs obtained at the output of the laser are shown in Figure 2. The equivalent plane images are not as smooth as the near fields, but they are significantly better than images obtained without the plasma filter. It is
anticipated that any hot electron generation associated with higher laser intensities will also be decreased while using the plasma spatial filter. The spectrum of the laser operated with the plasma filter not in the system is shown in Figure 3 and it has a bandwidth of 3.4 angstroms. With the plasma filter in place, the bandwidth is measured to be 37 angstroms. The bandwidth of the laser is not controlled since the backscatter is intensity dependent and the plasma filter is physically located in the rod amplifier section of the laser. The other spectrum shows that the bandwidth can be broadened for green experiments.

An experiment was performed to show the influence of the target interaction in broadening the bandwidth of the back-reflected laser light. These experiments used spherical shell targets. The laser power was varied. The incident laser light on the target was narrowed since the plasma filter was not in the system. The reflected spectra are shown in Figure 4 for two different laser intensities. The arrow is the location of the 1.06-μm wavelength and there is a slight blue shift in the reflected light as a result of the expanding plasma. The Brillouin scattering is shown to increase as the laser intensity becomes higher. These spectra were obtained in long pulse (-1 nsec) experiments with the laser power on target of 0.5 TW. Target absorption is shown as a function of laser intensity in Figure 5 for experiments with and without the plasma filter. The data can be explained on the basis of Brillouin scattering for these long pulse-length (-1 nsec) experiments. Measurements of the corona temperature, using x-ray spectra, are shown in Figure 6 as a function of the laser irradiance for the same set of experiments. The closed symbols are data taken without the plasma filter and the open symbols with the plasma filter. It was found that the corona temperature is approximately 6 keV when the plasma filter was in place and there does not appear to be a strong intensity dependence. It should also be pointed out that typically for "exploding pusher" target experiments the intensities are 5 x 10^{15} watts/cm² and the corona temperatures are in the 10 to 20 keV range. Data from experiments using green light in which the plasma filter was used is shown in Figure 7. The absorption data are shown as a function of laser pulse-length and the increase in absorption at the longer pulse-lengths with the plasma filter in place suggests that the broadened bandwidth of the laser suppresses Brillouin backscatter as expected theoretically. These experiments have shown improved performance of target response when short wavelengths and broadened bandwidths for the laser are employed.
Cryogenic Target Experiments

The high compression experiments at KMS Fusion have used cryogenic targets and the laser configured with the plasma spatial filter in place. In order to measure the fuel density, it is necessary to develop diagnostics which do not perturb the fuel as listed in Figure 8. At KMS Fusion, the two principal diagnostics that have been used are alpha particle emission and space resolved x-ray photography. The alpha particle spectra are downshifted and broadened in high density compressions as a result of the $<pR>$ in the fuel and the tamper. The x-ray photography provides a direct measurement of the compressed fuel region. X-ray streak photographs are used to verify that the implosion occurs after the laser pulse and therefore the alpha particles are not influenced by electrostatic fields in the corona. In addition to these diagnostics, the use of radiation chemistry will be used to determine the $<pR>$ of the tamper and it is determined that a $<pR>$ of $10^{-3}$ g/cm$^2$ in the tamper requires a neutron yield greater than $10^8$ for an accurate measurement. With this information, it is possible to determine the fuel density, the fuel $<pR>$, the tamper $<pR>$, and the ion and electron temperatures which completely describes the conditions in the imploded core. A schematic of the imploded core is shown in Figure 9. This happens to be for a case with high fuel density and although the alpha particles do not escape the fuel region in this example, the neutrons will collide with the fuel and fast deuterons and tritons will be emitted and their spectra can be measured. A deuteron detector will be used to measure the number of fast deuterons emitted. The fast deuterons have an energy peak at 12.5 MeV which will be downshifted and the amount of the downshift will be related to the $<pR>$ in the fuel and tamper.

A schematic drawing of the fuel and tamper regions is shown in Figure 10. In this figure the $g$ refers to the thickness of the glass tamper which is located around the fuel at peak compression. Alpha particles generated at the point $P$ will go a distance $f$ in the fuel plus a distance $g$ in the glass. The energy loss of an alpha particle will occur because of both of these regions. Alpha particles, depending on the angle $\theta$, will come out through different amounts of material. It is then possible to integrate over angle to obtain an alpha particle energy spectrum. After performing this calculation, it is found that there is a significant broadening of the alpha spectrum as a result of the fuel portion of the core. A calculation of the amount of alpha particle energy loss
for a uniform planar distribution of DT fuel is shown in Figure 11. It is shown that for DT fuel with a $\rho R$ of $2 \times 10^{-2}$ and an electron temperature of 1 keV, almost all of the alpha particles will be stopped by the fuel. Using this information about the energy loss, as well as the previous spherical geometry of the fuel and the tamper it is possible to calculate the alpha particle energy spectrum for a given electron temperature as shown in Figure 12. The downshift between the no-loss condition and the high energy end of the spectrum is caused by the $\rho R$ in the tamper and the width of the spectrum is caused by the $\rho R$ in the fuel. By increasing the relative density of the fuel to that of the tamper it is observed that the profiles are skewed toward the high energy region. This effect will be very useful, provide the spectra can be measured accurately, because one of the parameters not easily measured is the ratio of relative values of the densities in the fuel and the tamper. A typical calculation of the radiochemistry involved in determining the $\rho R$ of the tamper is shown in Figure 13.

For the cryogenic experiments, we use a target filled with 100 atm of DT gas. At 19°K the fuel freezes and forms a liquid spheroid at the bottom of the glass shell as shown in Figure 14. These glass spheres are typically 80-90-μm in diameter with a wall 1-μm thick. The condensed fuel is approximately 1.5-μm thick when evenly distributed on the inside of the shell. The location of the target within a shroud is shown in Figure 15. Helium gas flows past the target in order to maintain a cold environment. There are sapphire windows in the shroud which allows a YAG laser to heat the glass to vaporize the fuel. When the laser is turned off the fuel will freeze very quickly and uniformly on the inside of the shell. The shroud surrounding the target is launched using a retraction device shown in Figure 16. The entire shroud has to be out of the focal volume before the laser beam arrives at the target and the retraction begins approximately 3 milliseconds before the target shot. The retraction device is attached to the ceiling and it must still be in motion when the laser hits the target or the vibration when it stops will cause the target to move. In Figure 17 an interferogram of a cryogenic target is shown. A noncryogenic target would not have any of the fringes shown here. There is a slight nonuniformity of the cryogenic layer in the target shown in this figure but the variation is less than 10% in fuel thickness.
One of the features that it is very important to understand in high compression experiments is why cryogenic targets achieve higher densities than gas-filled targets. A computer simulation of target experiments in which cryogenic to noncryogenic fuels are used is shown in Figure 18. It is found from the motion of the interface between the fuel and the pusher that the cryogenic targets implode to a small diameter when preheat energy is not deposited in the fuel. It should be noted that the cryogenic layer reaches the center of the target just before the time of peak compression. In the early time, corresponding to the original target position the pusher has more fuel mass to accelerate so the velocity is not as great but later there is less back pressure from the cryogenic layer which causes it to reach a higher asymptotic velocity and when implosion occurs to the center in the noncryogenic case there is considerably more backpressure and hence less compression. The fuel adiabats for the two different cases is shown in Figure 19. The noncryogenic target experiment has an adiabat typical of gas-filled microballoons. There is a strong shock which causes it initially to reach an adiabat which is relatively high which is then followed into the implosion phase. The slopes are all 5/3 in the figure as anticipated for an ideal gas. The second curve, for the cryogenic layer calculation, shows the shock raising it to a high adiabat initially. However, the fuel then decompresses because the inside edge of the cryo layer begins to move faster than the outside edge. At about 60 psec into the laser pulse, the pusher begins to move faster than the inside edge of the fuel which forces the fuel to compress into a smaller fuel volume. These calculations are both done using the same input conditions with no preheat energy deposited in the fuel. It is found that for the cryogenic calculation the fuel reaches a higher pressure by a factor of eight corresponding to the same ratio in the volume factor. This means that the internal energy of the fuel is equal to the same value in both cases. The effect of the cryogenic layer in achieving the higher density is shown in Figure 20. The cryogenic simulation shows that the compressed fuel was contained within a region of 7.6-μm radius, and for the non-cryogenic case the compressed fuel radius was 14-μm. The ion temperature is lower in the cryogenic case since the internal energy is approximately the same. Although higher fuel densities and lower fuel temperatures were calculated for the cryogenic case, the neutron yields turn out to be very similar in both target configurations.
Conclusion

The target experiments have shown that it is possible to improve the target response by using broadened bandwidth and short wavelength. This also results in lowering of the corona temperature to permit experiments that are further removed from exploding pusher type experiments. By minimizing the preheat, simulations of cryogenic and noncryogenic target experiments show that the cryogenic targets reach higher densities as a result of lowering the fuel adiabats.
Fig. 4.

Fig. 5.

Fig. 6.

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NUCLEAR REACTION OF INTEREST

\[ n + \text{Si}^{28} \rightarrow \text{Al}^{27} + p \]

\[ \frac{1}{\text{p}} \times 2.3 \text{ min.} = \text{Si}^{28} \]

\[ \beta^- (2.55 \text{ MeV}) \]

\[ \gamma (1.76 \text{ MeV}) \]

NUMBER OF ACTIVATED NUCLEI

\[ N_a = \int \frac{dN}{dt} \int p(r,t) dt = N_{ne} \sigma_{\text{act}}(t) \]

WHERE

\[ N_{ne} = \text{NEUTRON NUMBER} \]

\[ p_r = \text{TAMPER NAIL DENSITY} \]

\[ n_{st} = \text{SILOCA NUMBER DENSITY} \]

\[ t_s = \text{TAMPER THICKNESS} \]

\[ N_a = 4 \times 10^3 \times \int n < p > \]

Fig. 13.

Fig. 14.

Fig. 15.
Fig. 19.

Fig. 20.