LASER DRIVEN ISOTHERMAL IMPLOSIONS

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Laser initiated, inertially confined, thermonuclear burn has been described in the literature$^{1,2}$ for lasers that produce on the order of 10 kilojoules in an optimally programmed temporal pulse. The essential characteristics of this process are compression of the thermonuclear fuel to densities on the order of 1000 g/cc, shock heating of the ions at the center of convergence to temperatures of 10 keV and thermonuclear bootstraping of the fuel by redeposition of the burn produced alpha particles to propagate the reaction from the center of convergence. The principle difficulties that are anticipated in achieving these conditions are due to plasma instabilities that may tend to preheat the pellet and make the DT more difficult to compress; and due to hydrodynamic instabilities such as the Rayleigh Taylor instability that tend to destroy the symmetry of the implosion.

Compressions to on the order of 1-10 g/cc and to thermonuclear temperatures can be achieved in systems that are essentially Rayleigh Taylor stable with present day laser systems. In these systems an optimally chosen, low density DT fuel ($\sim 10^{-2}$ g/cc) is confined by a spherical shell of a low Z material that is at a considerably higher density than the fuel. This

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configuration is illustrated in Fig. 1. The primary purpose of the shell is to do hydrodynamic work on the ions of the fuel and simultaneously compress and heat them.

There are several loss mechanisms operating in the fuel that tend to cool the ions. In order to overcome these mechanisms and heat the ions to thermonuclear temperatures, a certain minimum implosion velocity must be achieved. These mechanisms are illustrated in Fig. 2.

The minimum implosion velocity implies two things. First, the velocity sets the time scale for the implosion and thus the time scale for the laser pulse (\( \tau_v \approx v/r_0 \), where \( r_0 \) is the initial radius of the system). Secondly, the velocity implies a minimum energy that must be supplied to the target since the velocity achieved in roughly proportional to the square root of the temperature of the pusher. Figure 2A is a plot of the specific neutron yield as a function of the specific energy of the target as computed by LASNEX. The curve rises rapidly at the low specific energy end since the fusion temperature (\( T_f \)) is increasing, thereby increasing the neutron yield roughly as \( T_f^5 \) power, (which is the rate of increase of the Maxwell averaged thermonuclear cross section [\( \sigma V \)] in the region of 1 keV). At the high end the specific yield drops off since \( \sigma V \) is less steep and since conduction and hydrodynamic disassembly decrease the efficiency. A good rule of thumb is that one needs on half of a joule for each nanogram of target in order to drive it efficiently. For example, the target shown in Fig. 1 has a mass on the order of 100 ng, so 50 joules of absorbed energy should drive it efficiently.
If the above conditions are met, then the problems of Rayleigh-Taylor hydrodynamic instability are alleviated. The thermal electron conduction wave penetrates the shell supersonically thereby causing the pusher to everywhere become less dense and the situation where a low density hot plasma is accelerating a dense shell for a substantial portion of the laser pulse never occurs. The electron mean free path at the critical density for silicon is on the order of $2 \mu$ and $\lambda \sim \frac{1}{\rho Z}$. If the temperature in the region of the critical density gets as high as 10 keV then the electron mean free paths become comparable to the scale of the system. Hence, symmetry can be achieved using one laser through electron conduction. In fact, under these conditions, the electron temperature can become essentially isothermal throughout the target. Intensities on the order of $10^{17}$ w/cm$^2$ are necessary to achieve this. Low density, low Z materials such as plastic can be added to the outside of the pusher to substantially increase the mean free paths (50 fold) between the region of the critical density and the pusher and smooth spatial variations in the laser source. I have a movie here that was made in 1970 when John Nuckolls conceived of the possibility of this kind of implosion. A four hundred joule, 10 ps laser impinges on the target from the left side. One electron temperature approximations are used (show movie).

Present laser systems are not sufficiently powerful to achieve true isothermal performance. Figure 3 shows the electron and ion temperatures
as a function of radius at three different times during an implosion of a target like that in Fig. 1. The source was a 100 ps FWHM Gaussian pulse of 50 joules. At $t = 140$ ps 10 joules of the energy has been absorbed and the electron temperature around the critical density at 80 $\mu$ is approaching 2 keV. In the low density exterior the ions are decoupled, and as one gets into the high density area of the pusher ($\rho \sim 1.1$ g/cc) the electrons and ions are coupled together. In the fuel, a shock is heating the ions ahead of the pusher. Since the DT is at a low density the ions are decoupled from the electrons.

At 180 ps, the laser intensity is a maximum and the pusher has moved into 15 $\mu$ and has a density of .9 g/cc. The initial shock has arrived at the center and set a temperature of 2 keV throughout most of the fuel. The remaining motion of the pusher will compress this gas so at 210 ps the ions are heated to $\sim 7$ keV and the pusher has imploded to 5 $\mu$ and 1.3 g/cc which represents a compression ratio of 500. Only at the end of the implosion does the electron temperature become nearly isothermal.

Several options are available for the illumination of the target in Fig. 1. In Figs. 4-9 (which are frames from a movie) a spherically symmetric target is illuminated by a confocal ellipse system with f/1 optics. Geometrical optical calculations with normal incidence show that the intensity rises from a relative value of .25 on the pole to a maximum of .28 around 40°. The profile then rolls off to .14 at 54° and to zero at 67°. The entire target can be illuminated by moving the focal point over 25 $\mu$ or so from the center. The top of the target is then illuminated with non normal
incident rays. The effect of the non normal incidence can be investigated using the ray optics package now available in Lasnex. The Figs. 4-9 show a fair lag in the top of the pusher near the end of the implosion. The final state achieved has a ion temperature of 5 keV and a density of .6. This is a three fold reduction in the compression from that achieved in one dimensional calculations. If one uses faster lenses the intensity distribution becomes more peaked at higher angles and the implosion becomes more symmetric. Unfortunately implosions of this kind do not achieve breakeven until the laser energies are in the megajoule range. This is essentially due to the fact that the compression does not follow the Fermi Degenerate adiabat.

This does not make these experiments uninteresting, however, since they demonstrate the essential features of laser induced compression to thermonuclear temperatures ($h\pi - 10^{13}$) and serve as a valuable check on the computer codes that are being used to investigate laser fusion.
Figure 10 illustrates a geometrical arrangement of the target that is suitable for illumination using six separate laser beams. Calculations indicate that substantial symmetry can be achieved using this arrangement.
In Figure 11 the target is irradiated using axicon symmetry with lasers also illuminating the end of the target. Since LASNEX calculations are two-dimensional, this is the arrangement that was used to approximate the six-sided illumination in Figure 10. Substantial compression can be achieved using only the axicon portion of the laser. In this case, the implosion becomes cylindrical in character and one loses a factor of \( r \) in the convergence ratios. Figure 11a shows a step in the manufacture of the target shown in Figures 10 and 11. The mixture of plastic and gas-filled microbaloons is extruded through a hypodermic needle. Then the encapsulated target is cut out.
SPHERICAL NAAPA

Low Z, low density (~0.1) plastic for electron conduction symmetry

Low Z medium density (~2) material for containment and to compress fuel

Low density DT (~0.01) fuel

Silica stalk for support

50 μ
MAJOR LOSS MECHANISMS

Brom

\[ \frac{\dot{\varepsilon}_h}{\dot{\varepsilon}_b} \approx A \frac{T^{1/2}}{\rho r} \rightarrow r \geq 0.1 \mu m / \mu s \]

Electron cond

\[ \frac{\dot{\varepsilon}_h}{\dot{\varepsilon}_{ce}} \approx 3 \times 10^3 \frac{\rho r}{T_e^{3/2} \nabla T_e} \rightarrow (r / \nabla T_e) \geq 0.03 \]

Ion cond

\[ \frac{\dot{\varepsilon}_h}{\dot{\varepsilon}_{ci}} \approx 10^3 \frac{\rho r}{T_i^{3/2} \nabla T_i} \rightarrow (r / \nabla T_i) \geq 0.01 \]

Hydro of expansion

\[ \dot{\varepsilon}_1 = \rho T^{3/2} r^2 \]
YIELD VS. SPECIFIC ENERGY

![Graph showing yield vs. specific energy with logarithmic scales on both axes.]
ELECTRON AND ION TEMPERATURE VS. RADIUS

The graph shows the variation of electron and ion temperatures with radius, measured in micrometers (µm). The temperature is plotted on a logarithmic scale from $10^{-1}$ to $10^{1}$ KeV. The data is presented for different time points: $t=140$ ps, $t=180$ ps, and $t=210$ ps. The graph indicates a peak temperature and a peak radius for both electrons and ions at different time intervals.
0.1 g/cc plastic
10µ thick

DT gas at 10^{-3} g/cc

1 µ Silica balloon
80 µ diam

2 µ diameter glass support stalk
CYLINDRICAL NAAPA

- Laser light
- Pusher and DT fuel
- Low density, low Z plastic for electron conduction symmetry
- Support

100 μ
REFERENCES

