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FROM DT TARGETS ILLUMINATED WITH A SHAPED LASER PULSE

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THE EFFECT OF A SUPER-THERMAL ELECTRON TAIL ON THE YIELD RATIO OBTAINED
FROM DT TARGETS ILLUMINATED WITH A SHAPED LASER PULSE*

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Abstract

The possibility of achieving super-high compression of a bare drop of thermonuclear fuel using a shaped laser pulse depends sensitively on the electron distribution produced when the laser is absorbed. Particle simulation results indicate that laser energy absorbed near the critical density by parametric decay instabilities produces a long energetic tail of electrons which can be fit by an exponential of the form $\text{EXP}(-1/2mv^2/\alpha kT_e)$ where α is typically about 12 and T_e is the temperature of the background electrons. The yield from a given size pellet is sensitive both to the energy in the tail and to the slope of the tail as determined by α . This paper presents calculations of the optimized yield ratio for various α 's and for varying fractions, f , in the tail for a target which is a 60 μm sphere of D-T. With an isotropic source of hot electrons produced in the absorption process, for $\alpha = 24$, the worst case for this target, somewhat better than breakeven is achieved with 100 Kilojoules of input energy and 30% of $\geq$ laser energy in a superthermal tail. With $\alpha = 6$, about 5 times breakeven is achieved with an input of 150KJ and all of the laser energy in a superthermal tail. For comparison, when all of the energy is deposited into an inverse bremsstrahlung spectrum, the same target yields 2.2 megajoules with an input of 45 kilojoules.

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I INTRODUCTION

When laser light is absorbed by a hot plasma, energy is transferred to electrons by a number of processes:

1. Inverse bremsstrahlung
2. Plasma decay instabilities
3. Resonant absorption

Of these, inverse bremsstrahlung results in bulk heating of the electrons and a near Maxwellian distribution while theory indicates that the other processes will produce an energetic superthermal component of electrons.

The parametric decay instability, which is excited from about .8 to 1.0 times the critical density (where $\omega = \omega_{pe}$) for sufficient intensity, is an efficient absorber of electromagnetic radiation, and will completely absorb the energy of a wave in about 10 free space wavelengths. Extensive simulations⁽¹⁾ and theoretical calculation⁽²⁾ have been done to understand the non-linear state of this instability in a couple of limiting cases.

In one dimension in the limit that an electron makes an infinite number of passes through the instability region, the electron distribution becomes $F(v) = A \exp(-1/2(1/2mv^2/KT_e)^{1/2}$. In the limit that an electron makes but a single pass through the absorption region, the distribution is given by $F(v) = B \exp(-1/2mv^2/\alpha KT)$. α depends on the size, L , and temperature of the interaction region and scales as $(\frac{L}{\lambda_D})^{2/3}$ (λ_D is the debye length). At

2 keV, and an interaction length of 10 wavelengths, $\alpha = 12$. An $\alpha = 12$ is often quoted but it is by no means a universal constant. At higher temperatures, α becomes somewhat less than 12, but then the electrons are more likely to return to the heating region before losing their energy and the distribution starts to go over to the infinite pass model. This occurs because at high energies, electrons can completely cross the low density atmosphere without significant energy loss and are reflected back into the center of the pellet by the electrostatic sheath at the outer surface of the atmosphere. Results presented below have been obtained using the single pass distribution.

When large amplitude ($\frac{\delta n}{n} \sim 10\%$), shortwavelength ($k\lambda_D \sim 1/4$) ion fluctuations are introduced into the computer calculations of the parametric decay instability, the amount of bulk heating that is done increases because of non-resonant mode coupling to the ion waves⁽³⁾ and α decreases, resulting in a softer electron spectrum. Various mechanisms have been proposed to produce the required short wavelength ion fluctuations but the work done along this line so far has been of a qualitative nature and no reliable quantitative estimate of the size of the effect is available.

The current state of knowledge about the electron spectrum produced by the parametric decay instability can be summarized as follows:

- 1) The energy will be absorbed with an effective absorption length of about 10 free space wavelengths.
2. Some fraction f of the absorbed energy is absorbed into a super-thermal tail characterized by the distribution $F(v) = B \exp(-\frac{1}{2}mv^2/kT_e)$

- 3) Some fraction 1-f of the energy is absorbed by the bulk of the electrons in something like a Maxwellian distribution.

Only superthermal electrons produced by the parametric decay instability have been included in the results below. When the non-linear states of the Raman and $2\omega_{pe}$ instability and resonant absorption are better understood, their electron spectrum can be readily included.

II LASNEX TREATMENT OF LASER ABSORPTION AND ELECTRON TRANSPORT

LASNEX is a two-dimensional, multi-fluid, laser absorption and thermonuclear burn code developed by George Zimmerman⁽⁴⁾. It has been used at LLL to study a variety of laser heated plasmas. In LASNEX, when laser light is absorbed, the energy is distributed isotropically among the electrons and it is partitioned into as many as 50 energy bins according to the prescription $F(v) = Av \exp(-\frac{1}{2}mv^2/KT_e)$ for absorption via inverse bremsstrahlung and $F(v) = Bv^2 \exp(-\frac{1}{2}mv^2/\alpha KT_e)$ for the superthermal component. The electrons are transported using a multi-group flux limited diffusion model. They lose energy to radiation by bremsstrahlung and to the background electrons by coulomb collisions. Relative to the ions, the net flow of all electrons is assumed to be zero and the electric field required to enforce this condition is calculated. The ohmic, J-E, work done by the electrons against this electric field is transferred between groups and provides an additional coupling between thermal and superthermal electrons. The treatment of this effect in the code is not very sophisticated. It does not at present allow for such effects as the possibility of a runaway current which would lower the effective resistivity of the background plasma and result in a lower coupling than predicted by our model. On the other

hand, collective effects such as excitation of the ion-acoustic instability which would increase the resistivity and coupling are not included either. The difference in yield between an assumption of zero ohmic, E-J, coupling and that used by the code is about 20%.

III QUALITATIVE EFFECTS OF SUPERHERMAL ELECTRONS ON A LASER DRIVEN IMPLSION

During an ideal implsion history, an initial weak shock is sent through the target. This shock heats the electrons and ions to temperatures of about 1 ev, gives a few fold compressions, and starts the matter moving inward at about 1 cm/ μ sec. The target material is then adiabatically compressed using a shaped laser-pulse⁽⁴⁾. Adiabatic compression is desired so that the pressure required for compression can be kept as low as possible and as near the Fermi-degen-rate pressure as practical. If nearly adiabatic compression is to be achieved, then the supersonic transport of energy into the center of the target must be small compared to the fermi energy. This means there must be strong coupling between the electrons heated by the laser and those electrons inside the critical radius. Very energetic electrons do not satisfy this criterion and can deposit their energy deep inside the pellet. This energy deposition results in a continually rising "adiabat" and is called preheat. A higher adiabat means a larger driving pressure is required to achieve a given compression and also results in a somewhat more rapid decompression of the pellet during burn.

A second effect of superhermal electrons is a lower ablation pressure for a given laser power, decoupling. This occurs because the energy coupling rate between hot and cold electrons decreases as the energy of the hot electrons goes up. Above a certain energy, the energy an electron loses to

background electrons is less than the energy it gains in each pass through the heating region and these electrons run away from the rest of the distribution. When only a fraction of the laser energy goes into a superthermal tail, one possible cure for decoupling is to increase the laser power, but this also increases the preheat. One only gains if the increase in driving pressure exceeds the increase in the pressure required for compression. If the intensity is raised to a high enough value, the background electrons in the absorption region as well as the superthermal tail will decouple. When this condition is reached, raising the intensity more will not result in a higher ablation pressure⁽⁵⁾.

IV. QUANTITATIVE EFFECTS OF PREHEAT AND DECOUPLING ON A SPHERICAL PELLET OF DT

The quantitative effects of preheat and decoupling will vary from one target design to another, but the above qualitative effects are the same. The quantitative results presented below are for a single target design, shown in FIGURE 1. This target has a 58 μ m, 400 μ m radius solid density DT core surrounded by a low density atmosphere which might be produced by a laser prepulse. The atmosphere proceeds in two steps to a density slightly greater than the critical density for 2 μ light. This is a crude approximation to the density gradient that would exist when the atmosphere is generated. The laser pulse used to drive this target was chosen so that thermal conduction could smooth $\pm 10\%$ variations in intensity from confocal laser beams whose peak intensities were separated by 18° across the surface of the drop, while at the same time giving high yields. The laser pulse is shaped in frequency as well as in intensity and proceeds in steps from 2 μ to 1 μ to 1/2 μ . The 2 μ laser is necessary to achieve the required 1% uniformity in ablation pressure, and the 1/2 μ laser is used to minimize

decoupling during the high power end of the pulse. The $1/2\mu$ laser can be replaced with a 1μ laser with only about a 10% drop in the fusion gain. This target gives a yield of 2.2×10^6 joules when imploded with 4.6×10^4 joules if all the energy is deposited into an inverse bremsstrahlung spectrum. The laser power profile used to drive the pellet is listed in Table 1.

The concomitant effects of preheat and decoupling on this target are shown in Figure 2. The curves shown are for implosions of the same target with varying fractions of energy into a superthermal spectrum and the rest into an inverse bremsstrahlung spectrum. In each case, the laser power is readjusted to optimize the yield with a given fraction of energy in a superthermal tail. The indicated fraction of the energy is put into the superthermal tail only when the instability threshold is exceeded and only between .8 and 1.0 times the critical density. The results presented are remarkably insensitive to the estimate of the threshold. This insensitivity occurs because early in time, most of the laser light is absorbed by inverse bremsstrahlung. By the time inverse bremsstrahlung has become ineffective, the laser intensity is rising very rapidly to a value far above the threshold. Varying the threshold between $0-10^{14}$ WATTS/ cm^2 for 1μ light at 1 keV only shifts the time of onset for strong instability absorption by a small increment. In fact, the difference in yield between the assumption of a zero threshold and 10^{14} W/ cm^2 is only a couple of percent.

The upper set of curves in Figure 2, is a set of pressure versus density curves for calculations in which the fraction of energy absorbed into a superthermal tail is varied from 0-40% for $\alpha = 12$. The pressure

versus density curve for DT at 10^{-5} KEV is shown for reference. The implosion with all the energy going into an inverse bremsstrahlung spectrum lies close to this and is a nearly ideal implosion. On the other hand, the implosion with 40% of the energy in a superthermal tail was very badly preheated, and barely ignited.

The lower set of curves in Figure 2 shows the ablation pressure developed as a function of laser power for the various cases. The large degradation as the superthermal energy increased is evident, and the peak power required to ignite the 40% case was a factor of 5 higher than for the 0% case.

In all the cases shown in Figure 2, decoupling of electrons in the superthermal tail could be overcome by an increase in the laser power. Figure 3 shows a case for which no power is high enough to get ignition. These runs were done with a slightly different target and laser pulse. The upper set of curves are again pressure versus density plots. The lowest of these had a peak power of 1.35×10^{15} watts. It achieved significant compression but did not ignite. The other curves are for the same target and pulse with the power increased over the last 400 picoseconds. The lower plot in Figure 3 shows that the ablation pressure continued to rise as the power increased but the pressure required to drive the pellet increased even faster as seen by the sharp kink in the pressure versus density curves.

The effects of a superthermal tail are a strong function of the hardness of the electron spectrum. Figure 4 shows the gain η as a function of the fraction f of the energy going into a superthermal tail for $\alpha = 6$ and $\alpha = 12$. Also shown is the laser energy required to achieve ignition as a function of f . With $\alpha = 6$, it is possible to stand all of the energy in a superthermal tail and gains of better than 20 are obtained with 50% in superthermal tails. However at $\alpha = 12$, 40% of the energy in a superthermal tail causes severe degradation and gains of 20 are achieved with 20% of the energy in the tails.

The fraction of energy in superthermals that can be tolerated levels off as α is increased much beyond 12 as seen in Figure 5 for $f = .1$ and 3. The gain reaches a minimum, at $\alpha \approx 24$ and rises slightly thereafter. The gain at very large α 's occurs because the very energetic electrons produced cannot couple to the fuel in the time it takes for the implosion to occur and less preheat results. In the limit of infinite α , there would be no preheat and one would only have to contend with decoupling. From Figure 5, one sees that with the most pessimistic choice of α one can achieve breakeven at about 100kJ with 30% of the energy in a superthermal tail.

V CONCLUSIONS

The performance of solid spheres of D-T is sensitive to the production of superthermal electrons when the laser light is absorbed above the threshold of the parametric decay instability. However, the targets can be successfully imploded to give better than a breakeven yield of thermonuclear energy with a significant fraction of the laser energy in such a tail. These tails are

characterized by a distribution of the form $F(v) = Bv^2 \exp\left(\frac{-1/2mv^2}{\alpha kT_e}\right)$. If $\alpha = 6$, then 5 times breakeven can be achieved at 150 KJ with all of the energy being dumped into a superthermal tail, and gains of better than 20 achieved at 70KJ with 50% of the energy in tails. In the worst case, with $\alpha = 24$, breakeven at 100 KJ is possible with 30% of the energy in superthermal tails.

No attempt has been made to stay below threshold in these calculations, and indeed, the peak intensities of about 10^{17} WATTS/CM² are several orders of magnitude above the threshold for the parametric decay instability. If it turns out to be impossible to limit α to 6 or f to .3 - .4, then one still has the choice of modifying the target and laser pulse to stay below threshold. This can be done by seeding the pellet to increase the effective Z , by decreasing the laser wavelength, and by making various optimistic estimates about the threshold intensity at which significant energy is dumped into superthermal tails. Calculations done by Ron Thiessen at LLI indicate that one can implode a target below threshold by seeding to get an effective $Z \sim 10$, using $1/5\mu$ light and assuming that one can go a factor of 10 above the linear threshold before producing energetic tails. In addition, his calculations assumed the effective threshold intensity could be raised a factor of 10 by about a 5% F.M. modulation of the laser beam. One can also greatly reduce the required intensities by use of hollow pellets. However, stability and symmetry requirements are then more severe.

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TABLE 1

LASER POWERS AND WAVELENGTHS USED TO IMplode THE D-T TARGET WHEN ALL THE LASER ENERGY IS DEPOSITED IN AN INVERSE BREMSTRAHLUNG SPECTRUM

WAVELENGTH λ (microns)	INITIAL POWER ϵ_1 (WATTS)	FINAL POWER ϵ_2 (WATTS)	INITIAL TIME t_1 (NS)	FINAL TIME t_2 (NS)	M
2	10^{13}	10^{13}	0.0	10^{-3}	-1
2	10^{10}	4.0×10^{12}	0.0	28.0	2.05
1	4.0×10^{12}	1.65×10^{13}	28.0	28.6	2.05
1/2	10^{13}	8×10^{14}	28.6	29.0	2.05

$$\epsilon(t) = \epsilon_1 \left[\frac{(t_1 - t_2)}{R(t_1 - t_2) - (t_2 - t)} \right]^M ; \quad R = \left(\frac{\epsilon_1}{\epsilon_2} \right)^{\frac{1}{M}}$$

**SECTION OF THE D-T TARGET WHOSE
IMPLOSION and THERMONUCLEAR BURN
WAS TESTED FOR SENSITIVITY TO
SUPERHERMAL ELECTRONS**

Figure 1

Figure 2

Figure 3

GAIN and INPUT ENERGY as A FUNCTION OF THE FRACTION, ξ , OF THE ENERGY DEPOSITED IN A SUPER-THERMAL TAIL

Figure 4

GAIN and INPUT ENERGY as A FUNCTION OF THE SLOPE, d , OF THE SUPERHERMAL DISTRIBUTION

$$F(V) = BV^2 \exp(-\frac{1}{2} m V^2 / a K T_e)$$

Figure 5