Preheat Studies for Foils Accelerated by Ablation due to Laser Irradiation

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Laser fusion requires the inward acceleration of pellet shells to very high velocity without excessive preheat of the pellet fuel. In a study of ablatively accelerated thin planar Al foils, the complete time history of the rear-surface temperatures has been determined, and the energy transport mechanisms that contribute to the heating have been evaluated.

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In current laser-fusion studies, it is recognized that preheat of the target fuel of more than a few electron volts can significantly reduce the degree of compression and pellet yield that can be achieved.[1] Therefore, it is of considerable importance to know the temperature on the inside of the target shell. Such knowledge will allow one to choose the proper isentrope for compression calculations as well as to check the predictions of detailed numerical simulations of laser-driven implosions. Using laser-driven ablation we have accelerated thin planar foils, which simulate the early behavior of an imploding pellet shell, to velocities of 1.5×10^7 cm/sec for CH targets and 3×10^6 cm/sec for Al targets.[2] Here we report measurements of rear-surface temperatures of accelerated Al targets which remain below 3 eV through the bulk of the laser pulse. These targets achieve a directed kinetic energy per particle greater than 40 times the thermal energy. The temperatures are inferred by measuring the absolute rear-surface continuum emission with monochromators and then using blackbody emission assumptions, which we verify.[3] These are the first time-resolved temperature measurements for these conditions. Similar techniques have been used elsewhere to measure temperatures and velocities associated with high-pressure shock phenomena.[4,5]

The experiments were performed with use of one beam of the Naval Research Laboratory Pharos II Nd:phosphate-glass laser system (1.05 μm) with up to 200 J on target in a 4-nsec full width at half maximum pulse. Irradiation uniformity is improved and edge effects are minimized by placing the target off focus to obtain large focal-spot diameters (typically 1 mm) at irradiances of $(1-6)\times10^{12}$ W/cm^2. Measurements were made on 3-mm-wide Al foil targets ranging in thickness from 4 to 23 μm. The experimental setup consisted of a lens, a beam splitter, and two $\frac{3}{4}$-m monochromators equipped with 1-nsec-rise-time photomultipliers[6] to measure continuum intensity normal to the rear surface of the target at two wavelengths simultaneously. Good shot-to-shot reproducibility allows a parameter study in target thickness, target material, and wavelength of observation. The spectrograph slit samples only a central portion of the focal-spot area and typical slit widths observe a 17–33 Å bandwidth. An absolute calibration of the optics, the spectrographs, and the photomultipliers is made *in situ*.

Several experiments were done to check the assumption that the rear surface radiates as a blackbody. Figure 1 shows peak intensity versus wavelength data for Al foils of 4, 7, and 12 μm thickness. The wavelengths of the data points were chosen where no spectral lines occur. This figure demonstrates the magnitude of shot-to-shot scatter and calibration errors. The intensity data have the magnitude and approximate wavelength dependence expected from a blackbody. In addition, even though a small number of spectral lines had been seen on time-integrated photographic spectra, the peak intensity of a time-resolved strong Al line was found to be the same (± 20%) as the neighboring continuum. (It is assumed that most of the spectral line intensity oc-

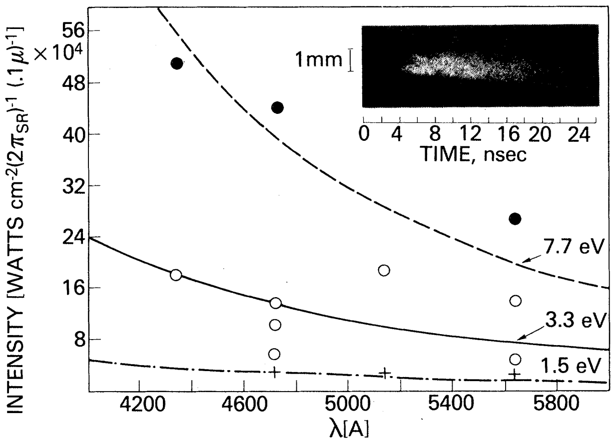

FIG. 1. Rear-surface continuum intensity vs wavelength for 3 Al-foil thicknesses at 5×10^{12} W/cm^2. Curves are blackbody intensities at the given temperatures. Solid circles, 4-μm Al foil; open circles, 7-μm Al foil; plusses, 12-μm Al foil. Inset shows streak photograph of rear-surface luminosity across a diameter of the focal spot.

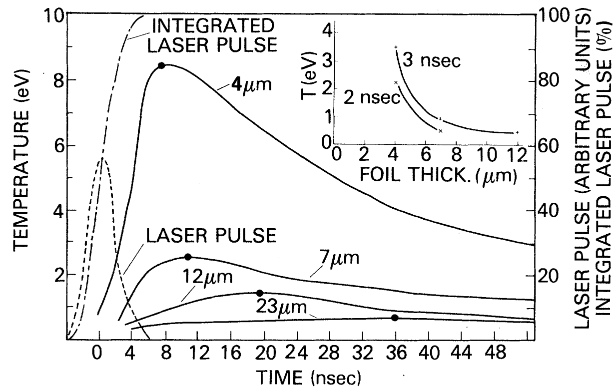

FIG. 2. Rear-surface temperature vs time for four Al-foil thicknesses at 5×10^{12} W/cm^2, 1-mm spot, $\lambda = 4717$ Å, and $\Delta\lambda = 33$ Å. Dots mark the curve peaks. Dotted curve is the time history of the laser pulse and the dashed curve is the integrated laser pulse. The time $t = 0$ corresponds to the peak of the laser pulse. Inset shows rear-surface temperature vs Al-foil thickness at two times at the end of the acceleration process.

curs later in time in the lower density region.) Since the line and continuum intensity was the same, it can be concluded that the radiation was emitted from an isothermal, optically thick, local-thermal-equilibrium plasma, i.e., a blackbody. Also, a pulsed optical probe beam directed perpendicularly to the rear target surface was strongly absorbed when the temperature reached a few tenths of an electron volt. We conclude that the blackbody assumptions are justified.

Interferometric density measurements with a tangential laser (5270 Å) probe beam gave a gradient scalelength of 50 μm to densities of approximately 10^{19} cm^{-3}, at which point absorption and refraction limit this diagnostic. Opacity calculations[7] assuming this gradient scalelength show that, at the emission wavelengths observed and at a temperature of 1–2 eV, the plasma has an optical depth of 1 for a density of order 10^{20} cm^{-3}. We infer that the temperatures we are measuring characterize this region.

Figure 2 shows the time history of the rear-surface temperatures obtained from continuous observation of the luminosity of Al-foil targets of several different thicknesses. Overall accuracy of the temperature determination is better than a factor of 2 for $T > 2$ eV and improving to ± 20% at $T_e = 0.4$ eV. In each case, heating occurs during the period of the laser pulse but the temperature continues to increase for several nanoseconds thereafter. The peak temperatures shift to later times and lower values as the target thickness increases. Figure 2 (inset) shows the dependence of temperature on target thickness just after the acceleration (which is over by about +2–3 nsec). Additionally, the peak rear-surface temperature was found to increase linearly with increasing irradiance (or energy) over the irradiance range $(2-6)\times10^{12}$ W/cm^2.

Possible mechanisms for energy transport to the rear of targets include fast electrons, x rays, thermal conduction, and shocks. The contributions of these various phenomena have been evaluated by separate measurements and by considerations of the time history and parametric behavior of the measured temperature.

First, the lack of measurable x-ray emission (< 0.1 erg) in the energy range 20–50 keV (corresponding to radiation from electrons with ranges comparable to target thickness) from the front side of the foils[8] demonstrates that there is insufficient fast electron energy ($< 5\times10^{-5}$ J) to cause appreciable heating of the rear target surface.

Second, time-resolved studies have shown that the x-ray emission (> 1 keV) closely follows the time history of the incident-laser irradiance, so that x-ray preheat effects should closely follow the time-integrated laser pulse (Fig. 2). Based on the known range and measured intensities of 1.6–50-keV x rays emitted from the front side of Al targets, the important x rays for the purpose of preheating the rear target surface are the line and continuum radiation between 1.6 and 2.3 keV. (The much-lower-intensity continuum emission just below the K edge at 1.56 keV, as yet unresolved, may also be an important preheat agent.) The time-integrated x-ray line spectrum was measured on an absolute basis (to an estimated accuracy of a factor of 2) and the x-ray energy deposited throughout the target was calculated, assuming spatial uniformity of the x-ray source and using cold material absorption coefficients. A knowledge of the equation of state is necessary in order to convert preheat energy deposition to temperature. We assume the target-foil material remains near solid density for the times of interest, and use tabulated heat-capacity data[9] to determine the temperature resulting from the calculated local x-ray deposition (curve at 3 nsec, Fig. 3). We find that the rear-side temperature rise during the laser pulse is consistent with the measured 1.6–2.3-keV x-ray deposition.

Third, with use of formulae and tabulated data for thermal conduction and radiative diffusion[9] and the tabulated data for heat capacities, numerical calculations which assume a fixed temperature at a point 1 μm in from the front surface and no losses from the rear surface (curves at 6 and 12 nsec, Fig. 3) show that thermal conduction may explain the upward drift in temperature after termination of the laser pulse.

Fourth, the contribution to the heating of the target due to shock waves that may be present is

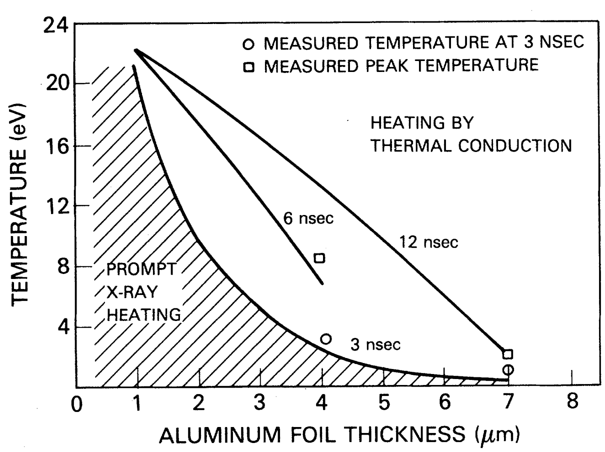

FIG. 3. Rear-surface temperature vs Al-foil thickness showing the prompt x-ray heating at 3 nsec, and prompt plus thermal conduction heating at 6 nsec for the 4-μm foil and at 12 nsec for the 7-μm foil. The square data points are measured temperature values at 6 nsec for the 4-μm Al foil and at 12 nsec for the 7-μm Al foil.

difficult to evaluate precisely. From measurement of ablation and acceleration parameters we infer a peak ablation pressure of ~2 Mbar at 5×10^{12} W/cm^2 on Al. A single 2-Mbar shock propagating into cold Al will produce a 75% density increase, a 0.8-eV temperature rise, and a shock velocity of 1.3×10^6 cm/sec.[9] In fact, the small early temperature rise for the thicker Al targets (12–23 μm) appears consistent with such a model. For thin targets, however, one must use a hydrodynamic code to evaluate the magnitude of shock wave heating; multiple reflections occur because the rise time of the pressure pulse is longer than the shock transit time through the target. Two different hydrodynamic codes, which have been run for our experimental conditions, indicate that the x-ray deposition is the major contributor to the rear surface heating for 4–12-μm Al targets. The codes agree within a factor of 2 with the observed temperature and closely match the temporal behavior for these targets.

The late-time heating and cooling of the rear surface can be understood in terms of an energy transport balance into and out of the rear surface. Thermal conduction calculations similar to those previously mentioned suggest that ordinary axial thermal conduction can account for the slow upward drift of the rear-surface temperature that is seen on the thicker targets. The importance of lateral thermal conductivity is indicated by measurements that show a lower peak temperature and more rapid temperature decay when the focal-spot size is reduced from 1 to $\frac{1}{4}$ mm diameter at constant irradiance.

We have examined the possibility of energy flowing around our target foil, which has been reported on disc targets with higher-irradiance CO_2 lasers.[10] By increasing the width of the foil from 3 mm to 1 cm, we see less than 10% change in the rear-surface temperature, and conclude that the effect of energy flowing around the target, if present, is small. There is also the possibility of energy flowing around the edges of the slug of accelerated material ("cookie-cutter" model).[11] Streak photography of the rear-surface visible emission (Fig. 1, inset), as well as time-integrated photography, shows no sign of either of these effects.

In conclusion, we have measured the time history of the rear-surface temperature of foils accelerated by laser ablation. The relative effects of x rays, shocks, thermal conduction, and fast electrons upon preheating this surface have been evaluated. It is concluded that for our conditions direct heating by soft x rays followed by thermal conduction appears capable of explaining most of the heating observed in thinner foils. Shock waves are more important for the thicker targets. The energy flows through rather than around the targets, providing a close analogy to the laser ablative implosion of pellet shells.

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Steady-State Magnetic Diffusion from Resistive Interchange Modes in a Plasma

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It is shown that a likely nonlinear state for resistive interchange modes is one where stabilization is achieved by flow-induced plasma compression and in which velocity vortex structure is balanced in Ohmic dissipation. Macroscopically this is manifested as magnetic diffusion and anomalous energy transport. The results are discussed and compared with recent experiments.

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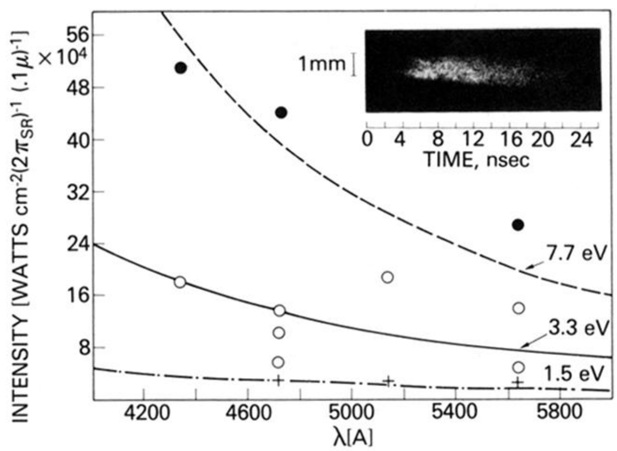
It is now generally assumed that reversed field pinches (RFP's) can exist neither in states which are magnetohydrodynamically unstable nor in states which are tearing-mode unstable. Indeed, diffuse pinch profiles which are stable to all of these have been calculated.[1-3] It seems reasonable that this conclusion also applies to spheromaks. The remaining problem is the effect of resistive interchange modes. The simplest theory, which mocks up pressure gradient in slab geometry with an effective gravity, indicates that any pressure gradient drives these modes unstable.[4-6] Apparently the plasma must either exist in such an unstable state, or else be driven to the Taylor configuration with zero pressure gradient.[7] This seems to be a crucial issue and one can examine it in two ways. First, one can do the linear theory more accurately, modeling geometry and/or kinetic effects more realistically, and hope that stable regimes emerge. Second, one can examine whether the plasma can exist in the presence of these modes. This report follows the second approach. It finds that the plasma can indeed exist (but has anomalous transport), with a spectrum of nonlinearly saturated resistive interchange modes. The anomalous magnetic diffusion, which arises from a resistivity-induced phase shift between $\tilde{\vec{v}}$ and $\tilde{\vec{B}}$, is calculated in terms of the fluid velocity fluctuation. The velocity fluctuation is estimated nonlinearly by calculating the



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