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Generation of shock waves in dense plasmas by high-intensity laser pulses

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Abstract. When intense short-pulse laser beams ($I > 10^{22}$ W/m², $\tau < 20$ ps) interact with high density plasmas, strong shock waves are launched. These shock waves may be generated by a range of processes, and the relative significance of the various mechanisms driving the formation of these shock waves is not well understood. It is challenging to obtain experimental data on shock waves near the focus of such intense laser–plasma interactions. The hydrodynamics of such interactions is, however, of great importance to fast ignition based inertial confinement fusion schemes as it places limits upon the time available for depositing energy in the compressed fuel, and thereby directly affects the laser requirements. In this manuscript we present the results of magnetohydrodynamic simulations showing the formation of shock waves under such conditions, driven by the $\boldsymbol{j} \times \boldsymbol{B}$ force and the thermal pressure gradient (where $\boldsymbol{j}$ is the current density and $\boldsymbol{B}$ the magnetic field strength). The time it takes for shock waves to form is evaluated over a wide range of material and current densities. It is shown that the formation of intense relativistic electron current driven shock waves and other related hydrodynamic phenomena may be expected over time scales of relevance to intense laser–plasma experiments and the fast ignition approach to inertial confinement fusion. A newly emerging technique for studying such interactions is also discussed. This approach is based upon Doppler spectroscopy and offers promise for investigating early time shock wave hydrodynamics launched by intense laser pulses.

Key words: shock waves • radiation hydrodynamics • laser–plasma interactions • fast ignition • inertial confinement fusion • Doppler spectroscopy

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Introduction

When high-intensity laser pulses interact with matter, they can generate strong shock waves. This article is particularly concerned with the case in which a high-intensity laser pulse interacts with plasma that is over-dense to the laser. That is to say that the electron gas density is sufficiently high, in the media, that the bulk of the material lies beyond the relativistic critical surface. The relativistic critical surface is the surface at which the relativistically corrected electron plasma frequency is equal to the frequency of the laser radiation. The electron number density at which this occurs is given by the equation

$$n_{c\gamma} = \frac{\langle\gamma\rangle m_e \varepsilon_0 \omega_L^2}{e^2} = \langle\gamma\rangle n_c \qquad (1)$$

where $<\gamma> = (1 + a_0^2/2)^{1/2}$ is the relativistic gamma factor introduced by the oscillation of the electrons in the electromagnetic field of the laser beam, while $a_0 = eA_0/m_e c^2$ and ω_L are the relativistically normalized laser amplitude and the laser frequency, respectively.

At such high densities, the laser beam cannot propagate. Hydrodynamics is driven directly by the light pressure, but also at depth within the plasma by the relativistic electron beam that is accelerated by the action of the laser near the critical surface. This electron beam can accelerate the plasma by non-uniform Ohmic heating and consequent introduction of pressure gradients, as well as by the $\boldsymbol{j} \times \boldsymbol{B}$ force induced.

In this paper we will firstly put our work on short-pulse laser generated shock waves into context by summarizing the fast ignition approach to inertial confinement fusion and the role of fast heating effects. Secondly we will describe our theoretical investigation of the hydrodynamic processes caused by the rapid heating of plasma by a fast electron beam. Finally, we will report on a recent experiment in which detailed measurements of a shock wave generated by a short-pulse laser were made.

Fast ignition

In the fast ignition approach [1] to inertial confinement fusion (ICF) [2] a laser with a focused intensity on the order of 10^{25} W/m^2 and a pulse length on the order of 10 ps interacts with a dense plasma target containing fusion fuel. The dense target is formed by the implosion of a spherical shell containing cryogenically frozen deuterium–tritium (DT). The implosion is driven by a pulse of radiation lasting approximately 10 ns. This radiation may be in the form of either soft X-rays or focused laser beams. The incident intensity at the surface of the capsule is roughly 10^{18} W/m^2. At the end of the implosion process, when the fuel 'stagnates' up against itself at the centre, the DT is compressed to thousands of times its normal solid density of 220 kg/m^3.

A range of variants upon the fast ignition principle have been thought of [3–7] however, the basic principle is similar in all cases. The secondary laser acts, by some means, to heat a small portion of the imploded DT fuel to the conditions required for thermonuclear ignition.

Ignition in the context of ICF takes place in a hot spot. The hot spot is a region of fuel in which, as the name suggests, the temperature is significantly higher than in the bulk of the DT fuel. This hot spot may be formed by compression, as in the case of conventional ICF, or by means of a secondary driver, as in the case of fast ignition. Ignition occurs when the hot spot is able to self-heat from the conditions in which it is left by the driver ($T_{\text{ion}} \approx 10$–12 keV) to a much higher temperature of around 70 keV. Once the hot spot is burning vigorously, the power radiated into the surrounding 'cold' fuel in the form of thermonuclear alpha particles is sufficient that the burn readily spreads. It is important that the bulk of the fuel is heated to ignition temperatures by the spreading thermonuclear burn wave rather than by the driver. If this were not the case then the driver would have to be excessively large and the available energy gain insufficient for the purposes of electrical power production.

In the case of fast ignition, the hot spot is formed in a region near the surface of the compressed fuel mass. The hot spot is surrounded by lower density material of similar temperature on one side, and by material of similar density and much lower temperature on all others. This means that during its formation the hot spot is far from being in pressure equilibrium with the surrounding plasma and will tend to expand rapidly. Where the hot spot faces the cold dense fuel, this expansion is led by strong shock waves.

In order that we can properly formulate the ignition problem, it is critical to quantify both the hot spot expansion and shock wave generation and propagation processes. The driver must deposit its energy in a hot spot that is continuously evolving in size and density, and the thermonuclear burn rates at any point in time are a strong function of the density profile of the DT fuel. The situation is complicated by the fact that in fast ignition the intense laser pulse acts to drive enormous currents as well as ultra-strong magnetic and electric fields. In order to tackle the evolving hydrodynamics therefore we must take into account the possibility of magnetohydrodynamic effects such as the $\boldsymbol{j} \times \boldsymbol{B}$ force on the fluid.

In addition to the evolution of the hot spot there is also the issue of hydrodynamic motion in other regions of the target. The fast electrons will heat any material present between the point of laser absorption and electron deposition in the hot spot. The heating duration (10–20 ps) is sufficient for some regions to experience significant hydrodynamic motion during this time, which in turn can affect the transport of fast electrons to the hot spot. This effect has not been thoroughly studied.

To summarize, the pursuit of fusion energy via fast ignition ICF requires one to consider a situation where shock wave generation by rapid heating of a plasma with a high energy relativistic electron beam is important and impinges on many facets of the whole problem. This largely motivates our current efforts to study this form of shock wave generation.

Modeling of shock waves generated by intense laser–plasma interaction

When a laser of focused intensity 10^{22}–10^{25} W/m^2 interacts with a dense fuel, it accelerates electrons from the plasma background to approximately MeV energies. These electrons propagate forward into the dense fluid beyond the critical surface. These high energy electrons have relatively long mean free paths and, to a fair approximation, propagate ballistically. However, in order to conserve charge, a so-called return current is drawn from the plasma background. This return current is collisional and is therefore subject to the resistivity of the medium. We can therefore write,

$$j_{\text{fast}} + j_{\text{return}} \approx 0 \tag{2}$$

and thence,

$$E = \eta j_{\text{return}} = -\eta j_{\text{fast}} \tag{3}$$

where η is the resistivity of the background plasma. For plasma at temperatures in excess of 100 eV (11.8 million K), at solid densities, the resistivity is given approximately by the Spitzer formulation as:

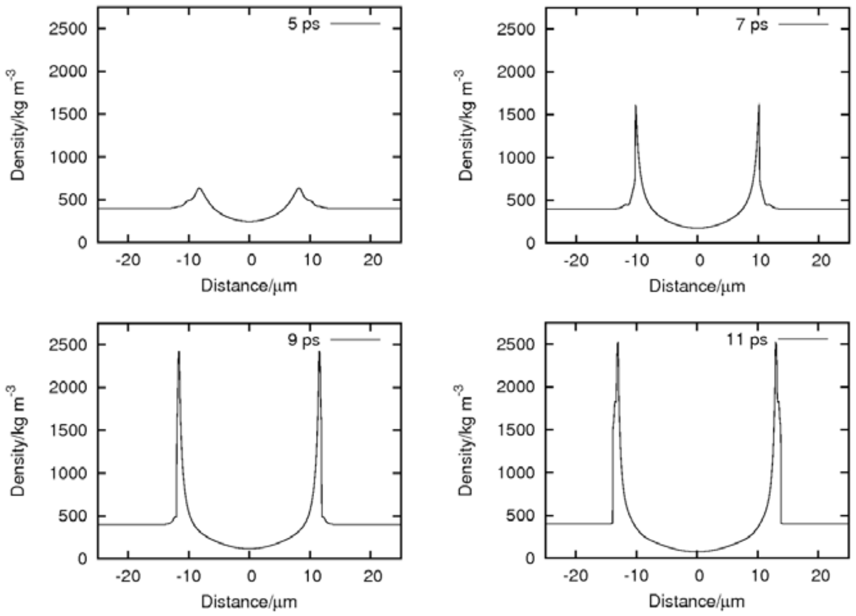

Fig. 1. Formation of strong shock waves driven by a cylindrically symmetric continuous current profile with an amplitude of 6×10^{17} Am^{-2} and a Gaussian distribution about the cylinder axis with a full width at half maximum (FWHM) of 7 mm. The density of background hydrogen is 400 kg/m^3. The heated region is centered on $r = 0$. The outward propagating density features clearly show the rapid formation and propagation of strong shock waves from the periphery of the heated region.

$$\eta = 10^{-4}\frac{Z \ln \Lambda}{T_{\mathrm{eV}}^{2}}\ \Omega\mathrm{m} \tag{4}$$

where Z is the atomic number and $\ln \Lambda$ is the dimensionless plasma parameter. The background plasma is heated such that,

$$\frac{\partial T}{\partial t} = \frac{\eta j^2}{k_B n_e C} \tag{5}$$

where C represents the heat capacity, since the current is not uniformly distributed throughout the plasma, this Ohmic heating leads to pressure gradients that drive expansion and shock wave formation. Furthermore, by combining Faraday's law and Ohm's law, it can be seen that the growth of the magnetic field in the plasma (assuming current flowing along the y-axis) is given by:

$$\frac{\partial B_Z}{\partial t} + \upsilon_x \frac{\partial B_Z}{\partial x} = -\frac{\partial(\eta j_y)}{dx} \tag{6}$$

This results in a $\boldsymbol{j} \times \boldsymbol{B}$ force on the background plasma in addition to the influence of the kinetic pressure.

Magnetohydrodynamic simulations of laser-generated electron beam driven strong shock waves

A magnetohydrodynamic (MHD) simulation code has been written [8], based upon the methods described by Ziegler in Ref. [9]. As can be seen from Fig. 1, the generation of strong shock waves is anticipated on timescales of only a few picoseconds.

A wide ranging parameter scan was performed in order to determine the timescales for the shock wave formation with a range of background plasma densities and drive currents. It is important to consider a wide ranging parameter space, since, even in the case of fast ignition, electrons must traverse a wide range of plasma densities between the point where they are generated by the laser and their being absorbed in the dense fuel. The results of this study are shown in Fig. 2. Here it is assumed that shocks are formed whenever material is accelerated to above the sound speed in the background plasma.

In fast ignition it is necessary to heat a region of fuel with a ρr of approximately 5 kg/m^2 to a temperature of around 12 keV. Assuming a cylindrical hot spot with initial density of approximately 3×10^5 kg/m^3 and given that the heat capacity of DT is around 100 GJ/kg/keV, this implies heating of 8.73 mg of DT to the temperature of 12 keV. This requires approximately 10.5 kJ of energy to be deposited. Presuming a time scale for depositing the energy of around 20 ps, this implies that a heating power of around 0.5 PW must be supplied to the cylinder. Assuming the energy enters the cylinder from one end, the power density must be around 6×10^{23} W/m^3. In order that the heating be limited

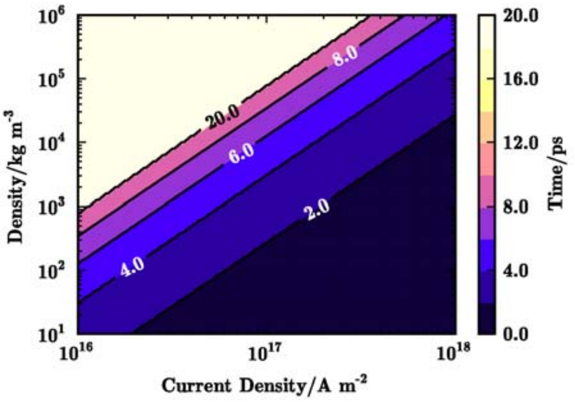

Fig. 2. Timescales for shock wave formation in a variety of different current and plasma density regimes.

to the hot spot, electrons with the energy of around 1 MeV must be employed. This gives a total minimum beam current of around 6×10^{17}A/m^2. The data shown in Fig. 2 suggests that shock waves would form around 6 ps into such a 20 ps ignition pulse. Therefore at the moment of ignition the hot spot would be rarefied and bounded by strong shock waves where it interfaced with the cold dense fuel mass. It is clear, therefore, that in modeling fast ignition it is important to properly take into account the effects of such shock waves upon the ignition process, and also in the deposition of energy by the driver.

These calculations also suggest the utility of short pulse lasers for generating extremely strong shock waves for laboratory investigation. For instance, the shock wave in Fig. 1 is propagating at approximately 900 km/s. Furthermore, the results of the simulations taken together with other analyses presented in Ref. [8] clearly demonstrate that MHD effects play no significant role in the parameter range explored here, and that the driving of shock waves is due entirely to the steep kinetic pressure gradients accelerating the fluid.

Experimental measurement of shock waves generated by intense laser–plasma interaction

Experimental investigations of extremely strong shock waves generated by application of ultra-high intensity short-pulse laser pulses are complicated by three factors. Firstly, shock waves weaken rapidly once the laser pulse has ended and therefore persist only fleetingly at a maximum strength. Secondly, there is an issue of spatial scale: the shock waves form around the focus of the laser. In order to achieve such high intensities as we have discussed earlier the laser is typically focused to a spot of around 5 μm diameter. Finally the interaction between the laser and the dense plasma generates a range of energetic particles including relativistic ions and electrons, as well as electromagnetic radiation over an exceptionally broad spectrum, ranging from radio to gamma rays. This calls for a diagnostic that has exceptionally high temporal and spatial resolution, and which can discriminate the desired signal from a bright background. Such diagnostic must also be capable of functioning in the environment of the target chamber, where electromagnetic pulses (EMP) generated by the laser–plasma interaction can disable some devices.

In addition to the difficulties of making measurements on such shock waves, the short-pulse laser based method for shock wave generation renders the shock waves produced in this way inappropriate for some applications. The material ahead of the shock wave may be preheated by energetic particles and hard X-ray radiation generated by the interaction. Furthermore, at early times, the shock waves will tend to be irregular and non-planar in character. This renders them poor candidates for equation of state studies, and for drawing inferences about more general strong shock physics; it may, for example, be challenging to determine whether preheating is driven by thermal radiation from behind the shock front or by radiation generated directly by the laser–plasma interaction.

Most measurements of shock waves generated by short-pulse laser systems have therefore focused upon measuring blast waves that have evolved for many tens of picoseconds, or even nanoseconds, after the laser–plasma interaction has occurred [10, 11]. Measurements of shock wave dynamics at earlier times are scarce. Some information may be gleaned from X-ray spectroscopy [12], however such data are challenging to analyze and rely on substantial modeling for interpretation.

It is clear that in order to better understand the hydrodynamics associated with the short-pulse laser interaction that takes place in a fast ignition target additional measurements and more detailed simulations will be required. Experimental data is particularly scarce at early times, for the reasons already mentioned. In this section we discuss a promising new diagnostic approach which might allow to extract substantial data on the process of shock wave formation and propagation in the first few picoseconds of an intense short-pulse laser–plasma interaction. This in turn will support modeling efforts by providing data suitable for benchmarking of simulation codes, for instance codes like the one described in the preceding section.

The Doppler spectroscopy diagnostic

A recent experiment performed at the Tata Institute for Fundamental Research (TIFR) in Mumbai demonstrated a novel diagnostic approach to investigating short-pulse laser-generated shock waves [13]. This approach, illustrated alongside sample data in Fig. 3, relies upon the Doppler shift of a short-pulse of probing laser light reflecting off the shock generated by a higher energy ‘pump’ pulse at earlier times. In this case the focused intensity of the pump laser was 5×10^{18} W/cm^2, at a wavelength of 800 nm, with a pulse length of 30 fs and the target in the form of

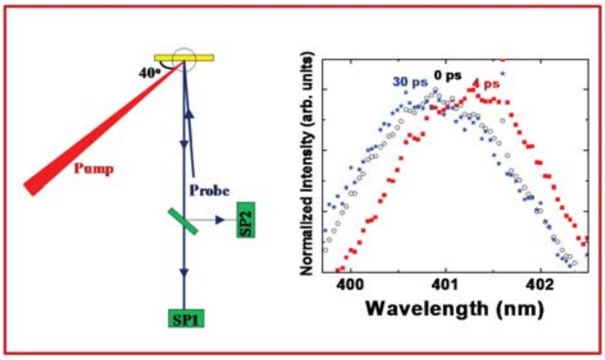

Fig. 3. The layout of the Doppler spectroscopy experiment described in Ref. [13]. The 5×10^{18} W/cm^2, 800 nm, 30 fs pump pulse drives hydrodynamics in the aluminum target. A 400 nm probe pulse penetrates the region illuminated by the pump pulse. The reflected probe light is then directed onto two spectrometers which record the Doppler shift of the probe due to the motion of the target plasma as induced by the pump pulse.

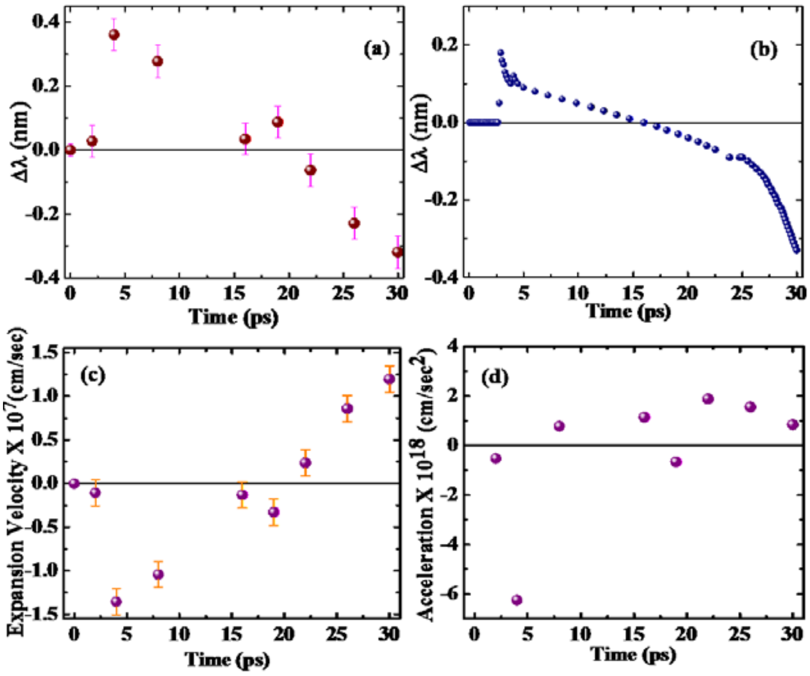

Fig. 4. The experimental data (a) and a hybrid simulation (b) that uses a 1D electromagnetic PIC simulation for the initial evolution and a hydrodynamic code for later times, together with the calculated expansion velocity (c) and the acceleration obtained from the Doppler shift (d). The strong negative acceleration and associated high velocity around 4 ps corresponds to the passage of the shock wave into the target launched by the high-intensity laser–plasma interaction.

a 0.5 mm thick optically polished aluminum. By selecting a probe wavelength shorter than that of the laser which drives the shock it is possible to view the dynamics in plasma that is overdense with respect to the pump pulse. In this experiment we chose to use a second harmonic probe (400 nm). Using a probe of a different wavelength also allows for easier disambiguation from the scattered light of the pump pulse. As may be seen in Fig. 3, the frequency doubling results in a probe beam with a spectral width of around 2 nm.

This diagnostic has a number of interesting advantages. The probe laser pulse can have a very short duration, and be timed precisely with respect to the pump pulse, enabling plasma dynamics to be resolved at very early times. The probe laser is also bright enough for the self-emission from the background plasma to be readily overcome, yielding a clean signal. Furthermore, the probe laser can be focused down to dimensions similar to that of the pump laser, thereby effectively achieving spatial resolution on the scale of a few microns. Using multiple shots on similar targets enables excellent resolution of comparatively small Doppler shifts; in this experiment data from around 100 shots was averaged at each time point. A major drawback is that the diagnostic can only function when the shock wave is moving in plasma that is underdense with respect to the probe.

Since this diagnostic relies upon the Doppler effect, it provides an unambiguous measurement of the shock wave velocity. The degree of frequency shifting corresponds exactly to the velocity at which the critical surface for the probe pulse is moving through the plasma. As shown in Fig. 4 the match between measurements made using this diagnostic at TIFR and a coupled 1D PIC-hydrodynamic simulation of the experiment is impressive. The diagnostic provides detailed time resolved information about the plasma dynamics that can be readily compared with simulation output. This makes it possible to accurately constrain computational models used in this and other computational modeling codes.

The experimental results combined with the simulations suggest that the pump pulse induces rapid heating of the intermediate density plasma blow-off that had been previously created by the laser prepulse. This heating rapidly launches a pressure disturbance, which is observed shortly thereafter propagating into the target by the Doppler spectrometry diagnostic. After this pressure disturbance (which it is expected would take the form of a strong shock wave) has passed, the rarefaction wave that must follow it causes the fluid motion to reverse.

Summary and conclusions

Intense short pulse laser–plasma interactions with dense plasmas provide the strongest shock waves available in the laboratory setting. These shock waves are accompanied by intense currents of relativistic electrons, and the preheating of the material ahead of the shock by laser-generated particle and electromagnetic radiation is inevitable. While this may render such early-time shock waves non-ideal for the study of fundamental radiation-hydrodynamics and material properties, the understanding of such shock waves is critical to the development of the fast ignition approach to inertial confinement fusion. In this manuscript we have discussed several ongoing studies which aim to provide further insight into the generation of shock waves in fast ignition targets. Magnetohydrodynamic simulations have been performed which indicate that the presence of strong shock waves must be taken into account by models of fuel heating by relativistic electron beams. Preliminary experimental studies had also been performed which have facilitated unique insights into the behavior of shock waves within a few picoseconds of an intense laser plasma–interaction in a solid material. In the future these experimental studies will be extended and used to benchmark simulations of higher dimensionality with the goal of enabling accurate modeling of fast ignition targets.

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