Transition from nonlocal electron transport to radiative regime in an expanding blast wave


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We have investigated formation, evolution and late-time propagation of a laser-generated cylindrical blast wave. The whole blast wave evolution over timescales of several nanoseconds was reconstructed experimentally (via temporally-resolved interferometric measurements) and via hydrodynamic simulations that included modeling of nonlocal electron transport and radiation diffusion. Comparison between the experimental results and the simulations indicates that the early expansion phase is characterised by nonlocal electron heat transport causing energy spread on times shorter than the typical timescales for hydrodynamic expansion. Nonlocal electron transport ionizes the gas ahead of the plasma front and gives rise to a smooth radial density gradient. At later times, once the shock is launched and the BW is formed, radiation results in reduced shock velocity compared to the adiabatic case. These investigations provide a suitable and effective platform to benchmark the inclusion of kinetic and radiative effects in fluid modeling of the plasma dynamics over timescales that may be unaccessible to fully kinetic simulations.

We present a detailed investigation of laser-driven blast waves (BWs), which offer a chance to study high Mach number shock waves in the laboratory. In particular, we study the effects of nonlocal electron transport and radiation diffusion on BWs evolution. These fundamental properties are relevant to plasma applications, such as Inertial Confinement Fusion and astrophysics. BWs have been studied both theoretically and experimentally. Experiments have shed light on a variety of aspects, including radiative dynamics and radiative properties of secondary shocks at latetimes, self-induction of magnetic fields, effects of nonlocal heat conduction at early evolution times, thermal plasma instabilities. Collisions between two BWs have also been investigated. In this letter, we report on the early effects played by nonlocal heat transport in BW formation and launching, when fast, free-streaming particles cause an energy spread on times shorter than the typical timescales for hydrodynamic expansion. Nonlocal heat conduction ionizes the gas ahead of the plasma front giving rise to a smooth density profile. At later times, once the BW is formed, radiation results in reduced shock velocity compared to the adiabatic case.

Gave their broad relevance in various contexts, electron and radiation transport mechanisms have been extensively investigated for laboratory astrophysics scenarios or in relation to ICF problems. Modelling nonlocal heat transport is however a non-trivial task, and a number of different approaches have been developed. Electron heat transport is in fact a kinetic process intrinsically related to the deformations of the electron energy distribution function. According to the classical treatment of thermal conduction, based on first-order perturbation theory applied to the Fokker-Planck equation, the thermal flux is given by \( Q_{\text{SH}} = -\kappa_{\text{SH}} \nabla T_e \) with \( \kappa_{\text{SH}} \) the Spitzer-Härm (SH) electron conductivity and \( T_e \) the electron temperature. However, it has been shown that as soon as the electron mean-free-path (mfp) exceeds about \( 2 \times 10^{-3} \) times the temperature gradient scale-length, this expression breaks down, and long-range electron corrections need to be taken into account.

In the investigated case, the electron mfp \( \lambda_e, \pi/2 = T_e^2/4\pi ne^4(Z\Lambda_{ei} + \Lambda_{ee}) \) (with \( n \) the electron number density, \( e \) the fundamental charge, \( Z \) the ion charge and \( \Lambda \) the Coulomb logarithms) becomes as large as the density gradient scale-length at the boundary of the laser-heated region. While a kinetic treatment is in principle required, performing fully kinetic simulations on hydrodynamic timescales may be computationally challenging. It is therefore necessary to rely on a fluid or weakly-kinetic approach, where suitable schemes to treat electron thermal transport must be implemented. In the simplest approach the limitation of thermal conductivity due to nonlocal effects is mocked-up by introduc-
The temporal evolution of the plasma spanning for tens of nanoseconds was reconstructed by varying the relative delay of the CPA₂ probe with respect to CPA₁. Typical examples of the interferograms with the Abel-inverted electron density radial profiles are shown in Fig. 2 (additional time frames are shown in Fig. 3). The Abel-inverted density profiles indicate that, within the error bar associated with the deconvolution process, at the earliest probing times (0.03 ns) a plasma filament is created with relatively smooth radial gradients and long-extending wings. As the plasma expands radially, it accumulates at the expanding front while a density depression progressively forms on axis (0.3 ≤ t ≤ 2.7 ns). At t ∼ 2.7 − 5.2 ns the density gradient at the plasma front has steepened, and a shock front with a radiative precursor (indicated by the arrow in Fig. 2 (c)) has formed. As the shock propagates radially, its amplitude initially increases, eventually reaching a maximum at t ∼ 5.2 ns, and subsequently decreases with a width increase.

To gain insight into the physical processes determining the evolution of the plasma, simulations were performed with the hydrodynamic code DUED³² running in one-dimensional cylindrical geometry. DUED is a two-temperature Lagrangian fluid code including flux-limited multigroup radiation diffusion. The radiation package is run with 33 fixed energy photon groups and the relevant Argon opacities, the energy groups are distributed to account for temperature lowering. (The non-dynamical group re-distribution can be source of some uncertainty.) Opacities are provided by the SNOP code³³. Electron thermal conduction is either treated with a flux-limited model or a nonlocal model²²,²⁵. In our simulations energy deposition by the laser pulse was modeled by imposing an initial spatial temperature distribution over a uniform density Argon background gas. The background gas density was taken equal to the experimentally measured value of ∼ 10¹⁸ cm⁻³. An initial Gaussian temperature profile with a 1 keV peak temperature and a full-width half-maximum of 235μm was chosen in such a way to best reproduce the radial plasma density profile at the earliest available experimental probing time, with the additional condition that total energy initially stored in the system equals the laser absorbed energy. Given these constraints, the initial parameters for the simulation were rather univocally determined. The employed setup creates a relatively hot plasma with pronounced thermal gradients, which readily reduce under the effect of nonlocal electron transport¹⁶. Simulations show that nonlocal transport effects influence the thermal wave evolution for a time interval of no more than 200 ps (see the red box in Fig. 4). Once the gradients smooth out, an

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**FIG. 1.** Schematic experimental setup.
electron thermal wave is formed. The energy, still stored mostly in the electrons, is partly converted into ion kinetic energy seeding the shock formation. This phase spans from 0.3 to 5.2 ns [see frames (c)–(f) Fig. 3 and the blue shaded area in Fig. 4]. During this stage, the evolution of the shock-front radius is fitted by the power law \( R \propto t^{0.22} \). When the rarefaction wave reaches the shock front (Fig. 3 (f)) a BW is launched [Fig. 3 (g)–(l)]. From this time on, the BW evolves in a radiative phase and the thin shell continuously radiates energy received from the hot remnant\(^{11}\). The radiative BW trajectory is fitted by the power law \( R \propto t^{0.41} \). Figure 4 also shows the adiabatic and fully radiative snowplough cases for comparison. The effect of nonlocal heat conduction is the fast removal of energy from the hot filament, due to the the long-range electrons. As a consequence the electron-ion energy exchange is less efficient and the shock formation is delayed. Eventually, a heat conduction flux-limiter technique constraints the energy over a smaller volume seeding the almost immediate shock formation, (Fig. 5, Fig. 6). The effects of the removal of energy by radiation are also visible during the self similar phase as a reduced shock front velocity. At early times \( t \lesssim 2.7 \) ns the plasma front exhibits a weaker density gradient than the simulations [Fig. 3 (a)–(e)], as well as wings, probably due do hard-photon preheating, that are not reproduced by simulations. However, the front position at different times is approximately well described by the simulation at all times (Fig. 4). To best match the early time profiles the use of the nonlocal model is necessary, as shown in Fig. 5 and Fig. 6. From Fig. 5 a)-b). When the BW has fully formed, quantitative agreement is found between the simulation and the experiment both in terms of shock amplitude and shock front trajectory (Fig. 3 (f-l) and Fig. 4). Consistently with the experimental findings, a density precursor is observed in the simulations ahead of the shock front [see the arrow in Fig. 3 (f)]. A Sedov-Taylor scaling is also plotted for comparison in Fig. 4 (b), showing that the late-time BW trajectory is well reproduced by a power law \( R \propto t^\alpha \) with a coefficient \( \alpha \sim 0.41 \). While a value of 0.5 is expected for an adiabatic cylindrical BW\(^{19,20}\), a lower value for the exponent is a typical signature of radiative losses. Consistently, during this stage the observation of the density precursor can be attributed to preheating and ionization of the upstream gas by radiation emission from the thin shell. To address the question of the relative importance of the different physical processes at play, and to
FIG. 4. Blast wave radius versus time: experimental data (blue dots) vs DUED simulations (solid red curve). A Sedov-Taylor power-law exponent $\alpha = 0.41$ is inferred for the radiative phase (yellow background), while $\alpha = 0.22$ is inferred for the thermal wave phase (blue background). The red background box highlights the time window where simulations predict nonlocal heat conduction major effects.

FIG. 5. Comparison of electron density profiles from experimental interferograms and DUED simulations for two selected times (a) $t = 0.7$ ns, (b) $t = 31.5$ ns and four different simulation conditions, i.e. with nonlocal transport (NL) or with a flux-limiter (FL), radiation (RAD) on and off.

FIG. 6. Electron number density profiles at two selected times, for different flux-limiter values.
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Cluster-Gas
Nozzle
Interaction Laser 2
\( \text{CPA}_1 \)
\( \text{CPA}_2 \)

optical probe
to calorimetry

Cluster-Gas
Nozzle
Radius (mm) vs. time (s) graph showing the radius of different phenomena.

- Adiabatic: $\alpha = 1/2$
- Pressure driven: $\alpha = 0.41$
- Snowplow: $\alpha = 1/3$

Key points:
- $\alpha = 0.22$
(a) $t=0.7$ ns

- experiment
- NL on, RAD on
- NL on, RAD off
- FL on, RAD on
- FL on, RAD off

(b) $t=31.5$ ns

$\eta_e \text{ (10}^{19} \text{ cm}^{-3})$
(a) $t=0.7$ ns

- experiment
- NL on
- $FL=0.24$
- $FL=0.08$
- $FL=0.02$

(b) $t=31.5$ ns