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Absorption of Ultra-Short Laser Pulses and Particle Transport in Dense Targets

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The interaction of short laser pulses with solid density targets has been studied in numerous experiments and by theoretical and computational modelling. The absorption of laser energy and transport of heat into dense plasmas is central to the understanding of such interactions. For moderate laser intensities, $I\lambda^2<10^{17}$ Wμm^2/cm^2, hydrodynamic simulations [1,2] have properly reproduced experimental results. At higher laser fluxes collisionless absorption mechanisms and the generation and transport of relativistic electrons become important and therefore kinetic models have to be used to describe laser plasma coupling. We report in this paper on the test case study of laser pulse absorption by a steep density profile plasma using the new kinetic code, KALOS [3]. We have modelled absorption and electron transport at normal laser incidence and maximum intensity $I_0=10^{15}$ W/cm^2 in a high density Al plasma. Several kinetic effects related to the non-Maxwellian electron distribution function (EDF) and reduced thermal transport have been observed in the simulations already at this moderate intensity which was previously considered in the hydrodynamic description [2].

So far, absorption has been studied primarily with Particle-In-Cell codes [4] which lack the ability to realistically model particle collisionality, due to the high computational cost of both the collision algorithms themselves and the need to resolve the tail population of the distribution function (i.e. many times the thermal speed). Although the laser field may be of sufficiently high strength near the front of the target to render collisional absorption negligible, collisions always play an important role in determining absorption indirectly, since they determine the strength of the cold return current inside the target as well as the transport of heat into the target. The cold return current regulates the fast electron propagation [3] while transport of heat away from the front surface modifies the absorption. Thus, absorption and transport are interrelated processes and any attempt to model the absorption must include the effects of collisional transport. Fokker-Planck codes based on a spherical harmonic expansion of the EDF have proved ideal for modelling transport when f is close to isotropic, since in this case only a few terms in the expansion are required. In order for a similar approach to be employed to model absorption, it is necessary to incorporate many terms in the spherical harmonic expansion, since f is not close to isotropic in the presence of strong fields. The numerical code KALOS solves the Vlasov-Fokker-Planck equation for f, with f being represented by a spherical harmonic expansion of arbitrary order. The full electron-ion Fokker-Planck collision operator is solved for cold ions, while electron-electron scattering is carried out only for the isotropic component of the EDF. The code has already been successfully used to model anisotropic transport processes such as the resistive collimation of electron beams in solid targets [3]. We have coupled the basic KALOS algorithm with Maxwell's equations to model the EM pulse. No temporal averaging of the EDF is performed, allowing processes which occur on the timescale of the laser period to be fully resolved.

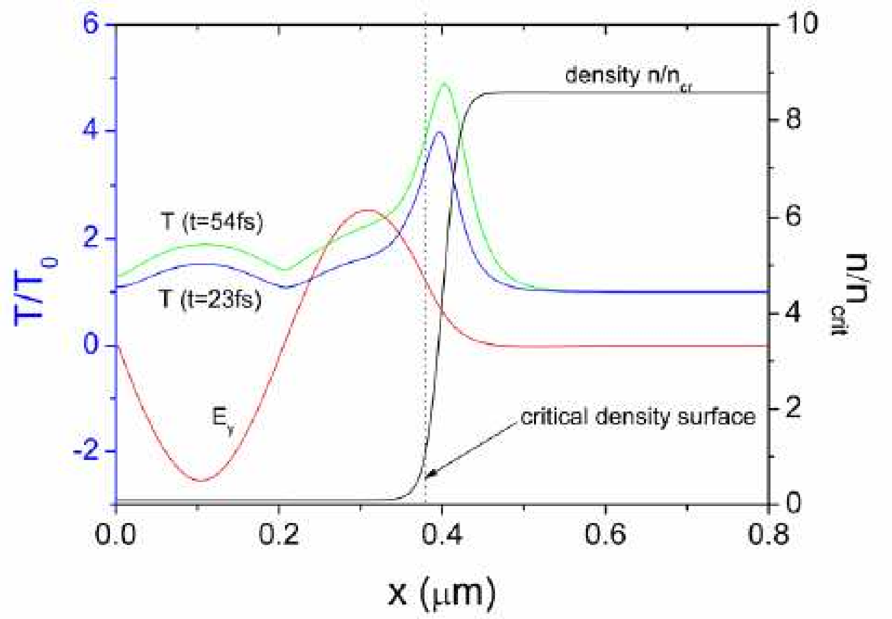

Fig.1 The electron density density profile (black) and the transverse laser field (red). Electron temperature profiles are also shown at 23fs (blue) and 54fs (green).

Fig. 1 illustrates the main physical processes which are included in our model. Laser light propagates from the lefthand boundary with constant intensity and is reflected at the critical density surface. The standing wave profile is illustrated by the y-component of the electric field, which penetrates the dense plasma by the skin depth. Collisional absorption and plasma heating take place predominantly in the skin layer as seen in the temperature profiles at t=23fs and t=54fs. Heat conduction is responsible for the extension of the temperature profiles into the overdense region.

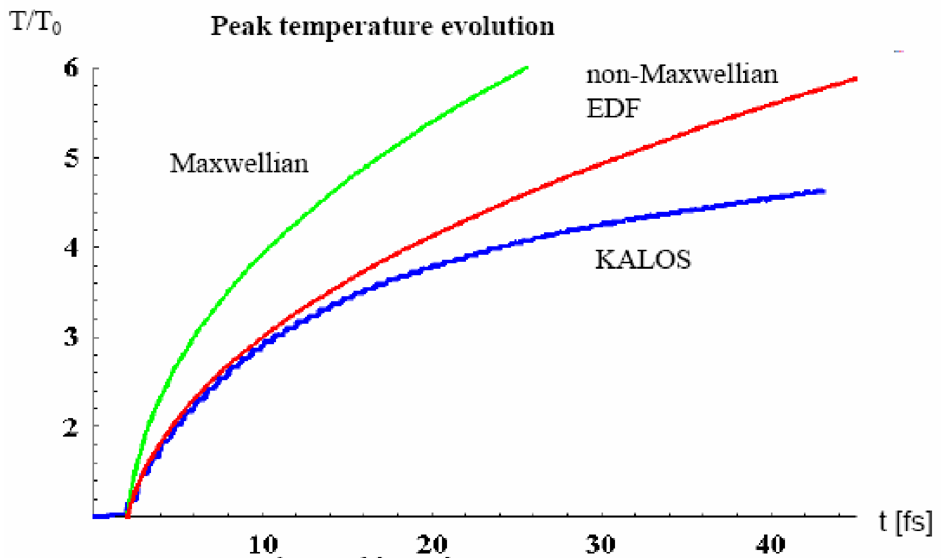

Fig. 2 *Time evolution of the peak temperature – comparison of KALOS results, solution to the homogeneous heating model with Langdon effect and heating of Maxwellian plasma.*

Fig. 2 shows the growth of the peak temperature in the absorption region. The temperature is uniformly initialised at 50 eV . Until approximately t=15fs heating takes place in the skin layer without conduction losses [5]. The initial increase of the temperature is well reproduced by homogeneous plasma heating theory which accounts for the change in the EDF (the so called Langdon effect) [6]. The large initial value of the parameter $\alpha=Z(v_0/v_{th})^2 \sim 10$ (v_0 - oscillatory velocity amplitude, v_{th} - thermal velocity, Z=13) leads to strong inverse bremsstrahlung heating which dominates electron-electron collisions and leads to the following isotropic EDF in the heating region [7]:

$$f_0 = \frac{\mu}{4\pi u^3 \Gamma(3/\mu)} \exp\left[-\left(\frac{v}{u}\right)^{\mu}\right], \quad \mu = 2 + \frac{3}{1+1.66/\alpha^{0.724}}, \; u = v_{th}\left[\frac{3\Gamma(3/\mu)}{\Gamma(5/\mu)}\right]^{1/2}. \qquad (1)$$

This time-dependent fit is matched to homogeneous Fokker-Planck simulations but has also been obtained analytically [8]. Fig. 3a shows the EDF from KALOS simulations at the peak of the temperature profile at t=19fs, displaying the characteristic features of eqn(1), i.e. a reduced number of slow electrons and a reduced tail of energetic particles. For comparison we also show a Maxwellian EDF at the same temperature. If a local Maxwellian EDF is assumed during the heating process the temperature increase will strongly deviate from the predictions of KALOS (cf. Fig. 2). At later times the homogenous heating model overestimates the peak temperature because of the transport losses due to heat conduction into the dense plasma. We show in Fig. 3b the EDF at t=54fs outside the skin layer, where the temperature increases due to the heat flow rather than absorption. In spite of the high collisionality the heat conductivity is slightly reduced as compared to Spitzer-Harm theory for the same temperature gradient. The KALOS EDF in this region is closer to a Maxwellian (at the same temperature) as compared to that in the absorption region (Fig. 3b). The heating and EDF calculated by KALOS are reminiscent of the results obtained in the hot spot heating problem [9], except that we have present a strong density gradient.

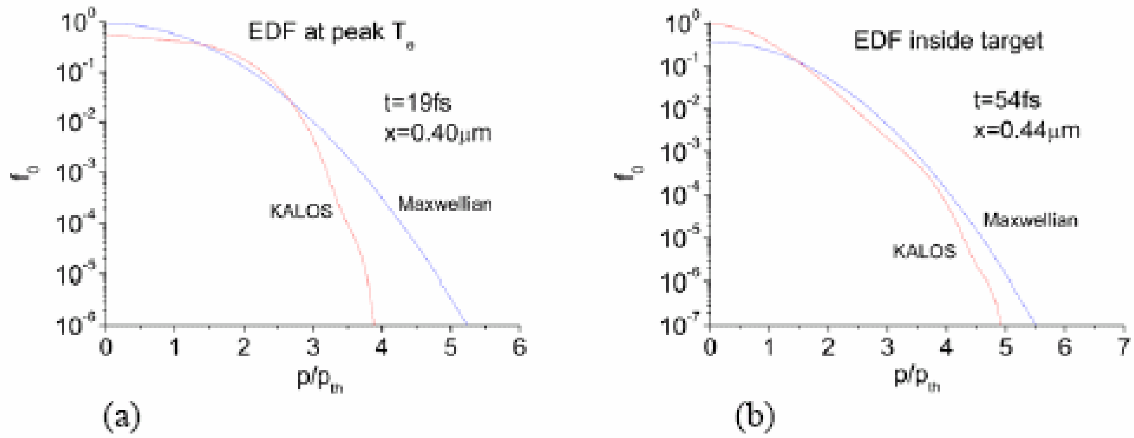

Fig.3 The EDF at 54fs as computed by KALOS at (a) x=0.40μm, where absorption occurs and the temperature peaks and (b) at x=0.44μm, where the field cannot penetrate but the plasma has been heated by heat flow.

In conclusion, we have demonstrated that kinetic effects are important for absorption and transport at moderate laser intensities ($\sim 10^{15}$Wcm^{-2}). The model is currently being extended to study higher intensities and obliquely incident light.

References

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