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## Comment on “Electron Temperature Scaling in Laser Interaction with Solids”

Very strong assumptions are used in Ref. [1], but their validity is never checked using particle-in-cell (PIC) simulations. In particular, it is implicitly and incorrectly assumed that the injection of electrons into the laser field and their return to the plasma are uniform in time. Ultrashort laser pulses interacting with sharp-edge overdense plasmas drive coherent electron motion, as proven by the generation of high order harmonics [2]. During each optical cycle, 1 or 2 as electron bursts are pulled out of the plasma. Electrons are then accelerated in the laser field before returning to the plasma with an energy which is a function of their return time. To estimate correctly  $\langle \gamma \rangle$ ,  $t$  in Eq. (3) of Ref. [1] should be considered as the return time and  $\gamma(t)$  as the return energy. These corrections lead to a  $dN/dt$  which is not proportional to  $1/\gamma$ , as illustrated by PIC results in Fig. 1(a). It follows that the scaling laws of Eq. (5) and Ref. [1] are irrelevant.

To confirm this, the scalings are compared in Fig. 1(b) with PIC simulations. Following Ref. [1], the laser is considered to be a plane wave of constant intensity. The electron density is  $n_e = 100n_c$ , and ions are fixed. In contrast with Ref. [1], the density is the same for all values of  $a_0$ . Instead of plotting the mean plasma energy which depends on the plasma size and numerical heating,  $T_{\text{hot}}$  is computed by fitting the hot electron distribution by a Maxwellian. For an infinitely steep density gradient ( $L = 0$ ) and an incidence angle  $\theta = 0$ , simulations predict much lower  $T_{\text{hot}}$  than Eq. (9) of Ref. [1], which should apply in this case. In the nonrelativistic limit  $a_0 \ll 1$ , electrons are mainly driven by the transverse component of the laser field (sum of incident  $E_i$  and reflected field  $E_r$ )  $E^\perp \propto 2a_0 k_0 \delta (1 + k_0^2 \delta^2)^{-1/2} \approx 2a_0 \omega_0 / \omega_p$  on the plasma surface, with  $\delta \approx c/\omega_p$  the skin depth. Electrons acquire a quiver velocity  $\propto E^\perp$  and are injected by the  $\mathbf{v} \times \mathbf{B}$  force into the plasma bulk, where they do not interact any more with  $E$ . Therefore,  $T_{\text{hot}} \propto a_0^2$ , which is consistent with ponderomotive models. However, because  $E^\perp \ll E_i$ , the temperature is greatly overestimated by the models. For  $a_0 \gg 1$ ,  $T_{\text{hot}}$  grows steeper with  $a_0$  because the relativistic skin depth, and hence  $E^\perp/a_0$ , increase with  $a_0$ . This important trend cannot be captured by Kluge’s model.

Equation (11) of Ref. [1] is supposed to address a more realistic case including a preplasma. Figure 1 shows that  $T_{\text{hot}}$  is much larger when the plasma has a short exponential gradient of scale length  $L = 0.1\lambda_0$  than for  $L = 0$ . Two main reasons can explain this. First,  $\delta$  is larger when  $L > 0$ , resulting in a larger  $E^\perp$ . Second, during their oscillations in the gradient along the  $z$  axis (perpendicular to the surface), electrons experience a charge separation

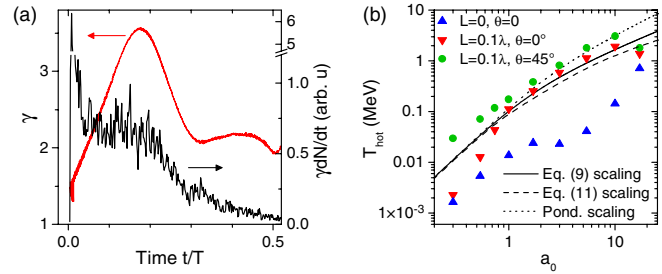


FIG. 1 (color online). (a) Evolution of  $\gamma$  and  $\gamma dN/dt$  as a function of the electron return time, in a PIC simulation for  $a_0 = 3$  and  $L = 0.1\lambda_0$ . The quantity  $\gamma dN/dt$  is not constant, in contradiction with Ref. [1]. (b) Temperature scalings from Ref. [1] (solid and dashed lines), the ponderomotive model (dotted line), and PIC simulations in different cases (circles). Simulations were performed with the two-dimensional in space and three-dimensional in velocities PIC code CALDER.

field that accelerates them towards the plasma. For  $a_0 \ll 1$  and  $\theta = 0$ ,  $T_{\text{hot}}$  is, however, almost the same as for  $L = 0$ . In this case, the amplitude of the electron oscillations along the  $z$  axis is  $z_0 \sim 4a_0^2 c/\omega_0 \ll L$ . Hence, many electrons can oscillate in the field without being injected into the plasma bulk, leading to low temperatures. The efficiency is much improved for  $\theta = 45^\circ$ . In this case, the electron dynamics for  $a_0 \ll 1$  is dominated by the component of the electric field perpendicular to the surface, which drives electrons much more efficiently than the  $\mathbf{v} \times \mathbf{B}$  force, resulting in a larger  $z_0 \sim 2a_0 \sin\theta c/\omega_0$  and in a better heating. Reference [1] scalings which neglect the plasma and the reflected fields and assume uniform injection cannot capture this physics.

Figure 1 shows that a correct temperature scaling should take  $L$  and  $\theta$  as input parameters. The model presented in Ref. [1] is based on wrong assumptions and does not fulfill this requirement.

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