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Stochastic heating in ultra high intensity laser-plasma interaction: theory and PIC code simulations.

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Introduction

A large number of issues remain open in the study of laser-matter interaction at very high intensities. Recently, particle-in-cell (PIC) code simulations results published by Tajima *et al.* have shown that the irradiation of very high intensity lasers on clustered matter leads to a very efficient heating of electrons [1]. They have shown that chaos seems to be the origin of the strong laser coupling with clusters. Therefore, the conditions for the onset of stochastic heating in laser matter interaction have to be explored. In a first part, the theoretical model is presented briefly [2]. PIC code simulations results obtained with the code CALDER [3], for experimentally relevant parameters, are presented in order to confirm the acceleration mecanism predicted by the one-particle theoretical model.

Theoretical model for the onset of stochastic heating

A charged particle interacting with two electromagnetic planes waves is considered. One has a high intensity $\overrightarrow{a_0}(\overrightarrow{r},t) = a_0 \cos(t-z)\overrightarrow{e_x}$, the second one a_1 is in the same polarisation plane propagating at some angle α with respect to a_0, a_1 is considered as a perturbation ($a_1 \ll a_0$) $\overrightarrow{a_1}(\overrightarrow{r},t) = a_1[\sin\alpha\overrightarrow{e_z} - \cos\alpha\overrightarrow{e_x}]\sin(\omega_1 t - k_{\|}z - k_{\perp}x)$, with $k_{\|} = k_1\cos\alpha$ and $k_{\perp} = k_1 \sin\alpha$, where $k_1 = \|\overrightarrow{k}_1\|$. In the following we will use $e = m = c = 1$.
The Hamiltonian of an electron interacting with both the $\overrightarrow{a_0}$ and $\overrightarrow{a_1}$ waves is $H(\overrightarrow{r},t,\overrightarrow{P},-\gamma) = 1+\left[\overrightarrow{P}+\overrightarrow{a_0}(\overrightarrow{r},t)+\overrightarrow{a_1}(\overrightarrow{r},t)\right]^2 - \gamma^2$. We have let $H = H_0 + H_1$, were H_0 is the integrable part and H_1 a perturbation. H_1 has been expressed in terms of the action angle variables $\left(P_{\perp}, P_{\|}, E, \theta, \varphi, \phi\right)$ of H_0 [4]. One has $H_0\left(P_{\perp}, P_{\|}, E\right) = 1 + \frac{a_0^2}{2} + P_{\perp}^2 + P_{\|}^2 - E^2$ and neglecting the a_1^2 term
$H_1\left(P_{\perp}, P_{\|}, E, \theta, \varphi, \phi\right) = a_1 \sum_N V_N \cos\left[k_{\|}\varphi + k_{\perp}\theta + \omega_1\phi + N(\varphi+\phi)\right]$,where
$V_N = V_N\left(P_{\perp}, P_{\|}, E\right)$ is the amplitude of the Nth resonant term.
The resonance condition is found by using the standard perturbation technics [2] [4]:

$$k_{\|}P_{\|} + k_{\perp}P_{\perp} - \omega_1 E - N(E - P_{\|}) = 0 \qquad (1)$$

As $H_0 = 0$, one has $E\left(P_{\perp}, P_{\|}\right) = \sqrt{1 + \frac{a_0^2}{2} + P_{\perp}^2 + P_{\|}^2}$.

Using this equation and equation (1) allows to calculate $P_\perp$ versus $P_\parallel$. Figure 1 displays the resonance lines for $\alpha = \pi/6$, the resonance lines ar quite far from each other in this case. In order to satisfy Chirikov criterion [5] for more resonances, resonance lines should be closer. It is the case in figure 2 where $\alpha = 5\pi/6$. Then the criterion is better satisfied as the widths of resonances decrease slowly with α. Figure 3 shows the particle energy γ versus time calculated

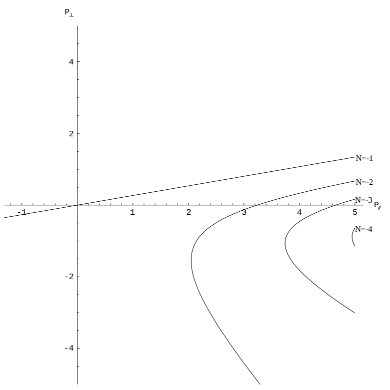

Figure 1: Resonance in the $(P_\parallel, P_\perp)$ plane, $a = 2$, $\omega_1 = k_1 = 1$ et $\alpha = \pi/6$.

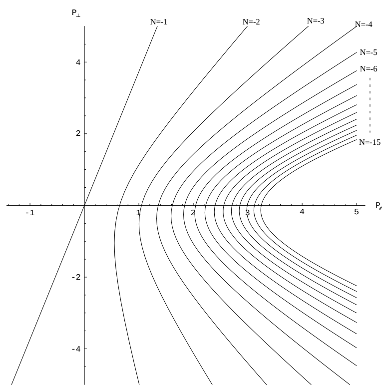

Figure 2: Resonance in the $(P_\parallel, P_\perp)$ plane, $a = 2$, $\omega_1 = k_1 = 1$ et $\alpha = 5\pi/6$.

through the Hamiltonian one-particle model in two cases, one curve corresponds to the case when the particle interacts with one wave only (integrable case, black curve), the other one corresponds to the case when two counterpropagating waves are considered (non-integrable case, red curve). In the second case, the particle has a chaotic motion, its energy is higher due to the stochastic heating.

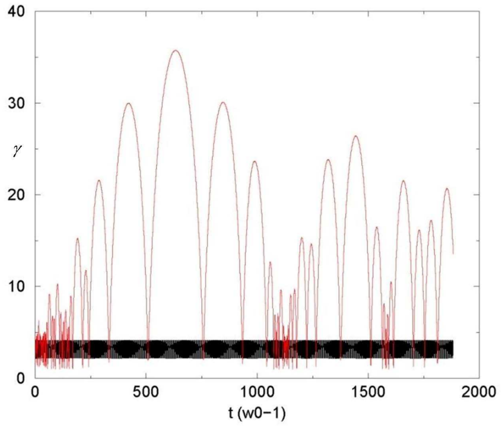

Figure 3: Energy versus time. $\alpha = \pi$, $\omega_1 = k_1 = 1$. $a_0 = 4.02$: black curve (one wave). $a_0 = 4.0$ and $a_1 = 0.4$: red curve (two waves)

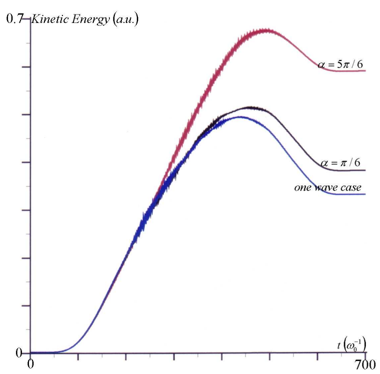

Figure 4: Kinetic energy versus time in three case: $\alpha = 5\pi/6$: red curve; $\alpha = \pi/6$: black curve; $\alpha = 0$: blue curve.

PIC code simulations

Simulations were performed using the code CALDER [3]. First, only one cell was considered with one particle in it. The curves obtained are similar to those shown in figure 3.
Concerning the conditions for the onset of stochastic heating, the PIC code simulations results are in good agreement with the theoretical model.

Influence of the angle between the waves

In this part, the stochastic heating is shown to be more efficient when the waves are counterpropagating. According to the theoretical model, the Chirikov criterion [5] is achieved more easily when $\alpha \rightarrow \pi$. Figure 4 shows the evolution of the kinetic energy of the electrons when $\alpha = 5\pi/6$, $\alpha = \pi/6$ and $\alpha = 0$. Figure 4 shows that the highest energy transferred to the electrons is when α goes to π.

Influence of ω_1

The 2D simulation parameters are $a_0 = 3.922$, $a_1 = 0.784$, $n = 10^{-2} n_c$, $\tau_0 = \tau_1 = 0.3\ ps$ and $\alpha = 5\pi/6$. Figures 5 and 6 show that the gain is inversely proportional to ω_1.

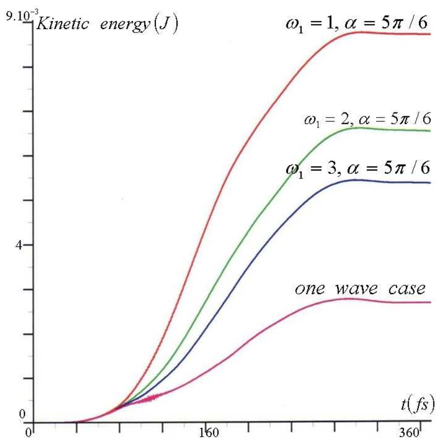

Figure 5: Kinetic energy of the plasma.

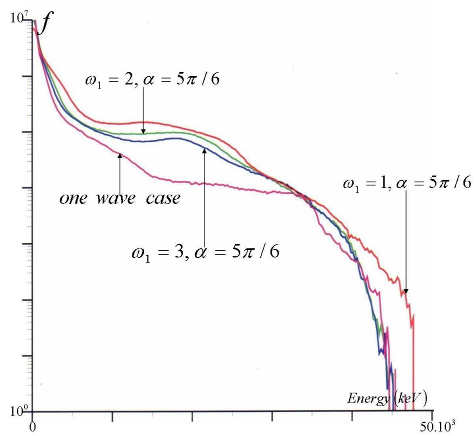

Figure 6: Electron energy distribution.

Influence of $q = a_0/a_1$ for a given laser energy

The physical parameters of the 1D-simulations are $n = 10^{-2} n_c$, $\sqrt{a_0^2 + a_1^2} = 4$, $\omega_1 = 1$, $\tau_0 = \tau_1 = 0.5\ ps$ and $T_e = 0.1\ keV$, where n is the density of the plasma, τ_0 and τ_1 are the length of the two pulses and T_e is the initial temperature of the electrons. The gain is defined by $Gain = \left(\frac{Ek_{2\ waves,\ f} - Ek_{1\ wave,\ f}}{Ek_{1\ wave,\ f}}\right) * 100$ where $Ek_{2\ waves,\ f}$ (resp. $Ek_{1\ wave,\ f}$) is the kinetic energy of the particles at the end of the simulation for the two waves case (resp. one wave case). The kinetic energy of the electrons is compared to the case when there is only one wave with the same laser energy (i.e. with an a equal to $\sqrt{a_0^2 + a_1^2}$). $Ek_{1\ wave,\ f} = 6.03 \times 10^{-4}$. The gain

a_1/a_0	1%	15%	20%	80%	100%
a_0	3.999	3.955	3.922	3.123	2.828
a_1	0.039	0.593	0.784	2.498	2.828
Gain (%)	128	2258	2398	1390	1291

Table 1: Gain for different value of a_0/a_1

reaches a maximum when the counterpropagating wave amplitude ratio is 20%. These results are impressive, but are 1D simulations results only. 2D simulations might give a lower gain as they take into account the transverse motion. A preliminary study with 2D simulations gives a lower gain.

Influence of the density

The simulation's parameters used in the simulation are $a_0 = 2$, $a_1 = 0.1$ and $T_e = 0.1$ keV. The density is varied from $10^{-6}n_c$ to $10^{-1}n_c$. There is an optimum for $n = 10^{-2}n_c$ (*cf* table 2).

Densité (n_c)	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Gain(%)	7.9	300	-25	-6	37	-34

Table 2: Gain for $a_0 = 2$

An explanation for this result is still lacking.

Conclusions

In this work, the laser-plasma interaction at very high intensities has been studied, here, within the framework of Hamiltonian analysis. Stochastic heating was evidenced by considering single trajectories and calculating the energy of the charged particle. PIC code simulations were performed to confirm and optimize the occurrence of stochastic heating. The PIC code results highlight the fact that an optimum, for the energy deposit, seems to exist for each set of experimental parameter.

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