A coupled two-step plasma instability in Petawatt laser plasma interaction

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Recently, there has been a considerable progress on fast ignition. In particular, there is now a growing body of evidence for anomalous ion bulk heating in laser plasma interaction experiments, when the laser power approaches the PetaWatt (PW) regime, both from experiments[1,2] and from hybrid code simulations[3]. Anomalous processes are an important ingredient of fast ignition, because the typical mean free path of the fast electrons moving across the dense plasma core is much larger than the pellet dimensions, which means that the energy absorption cannot simply rely on particle collisions.

Here we propose a possible explanation for the observed anomalous resistivity. Our model[4] is based on the existence of two coupled processes. First, the fast electrons created by the laser pulse interact with the resulting return current[5] and produce an intense electrostatic field, by means of a two stream instability. Second, the resulting electrostatic waves become modulationally unstable and decay resonantly into ion-acoustic waves. This mechanism is not efficient for electron heating but leads to an efficient ion heating which could explain the observations.

The energy cascading in the solid target takes the following form: the intense laser pulse hits the surface of the solid target and transfers a significant amount of its energy to a relativistic electron beam. This beam of energetic electrons produces a return current and the resulting counter-streaming electron beams excite an electron two-stream instability. The resulting plasma waves have relativistic phase velocities and can easily become modulational unstable by decaying into heavily damped ion acoustic oscillations. This results in the occurrence of anomalous ion heating process which efficiently dissipates the energy transferred to the ion oscillations.

In order to establish our two-step model for anomalous ion heating, we consider the various beam instabilities that can occur in laser produced plasmas and establish their relevance to ion heating in the fast ignition scenario. We will restrict our discussion to the electrostatic case. This will involve ion and electron instabilities in a plasma with the following constituents: i) a fast electron beam, ii) a return current, iii) an ion background and iv) a broad band plasmon spectrum. In our analysis, we will extend our previous work[6] in several directions, namely by including relativistic particle beams, instability growth of the plasmon turbulence and particle collision frequencies.

In what concerns plasma stability analysis, in the overdense region beyond the critical density, we will consider the plasma as a medium composed of several types of particles and quasi-particles. The different particle populations are: the fast electrons of the intense electron beam created by the incident laser pulse and moving in the overdense region (f), the background plasma electrons that move in the backward direction in order to maintain a return current (e), the plasma ions that are stay at rest (i), and the plasmons that are created by the electron two stream instability. In such a plasma, the dispersion relation of low frequency electrostatic waves, with frequency $\omega << \omega$ pe and wavenumber $\vec{k}$ can be written as

$$1+\sum_{\alpha=i,e,f}\chi_\alpha\left(\omega,\vec{k}\right)+\chi_{pls}\left(\omega,\vec{k}\right)=0 \qquad (1)$$

where $\chi_\alpha\left(\omega,\vec{k}\right)$ are the electric susceptibilities of the different particle species, and $\chi_{pls}\left(\omega,\vec{k}\right)$ is the electric susceptibility of the plasmons or quasi-particles of the high frequency turbulence. Therefore, or description introduces a symmetry between particles and quasi-particles in the turbulent plasma[7].

Initially, our plasma is made of a background population of ions, a fast electron beam and a return current. Assuming that the net current is nearly equal to zero, we can establish a relation between the velocities of the two electron populations

$$\vec{J}=-e\left(n_{0e}\vec{u}_e+n_{0f}\vec{u}_f\right)\simeq 0 \qquad (2)$$

where the subscripts *e* and *f* refer to the return current and to the fast electron beam respectively.We can conclude that $\simeq\left(n_{0f}/n_{0e}\right)u_f$, with $u_f\simeq c$.

Due to the electron two stream instability, a broadband plasma turbulence is excited. The plasmon gas can be described by a kinetic equation, which is the equation of conservation of the number of plasmons, plus a source term, as given by

$$\frac{d}{dt}N_{k'}=2\Gamma_{k'}N_{k'} \qquad (3)$$

where $N_{k'}=W_{k'}/\hbar\omega_{k'}$ is the plasmon occupation number, $W_{k'}$ is the electrostatic energy density and

$$\omega_{k'}=\left(\omega_{pe}^2+S_e^2K'^2\right)^{1/2}\simeq\omega_{pe} \qquad (4)$$

is the plasmon frequency, and $S_e=\left(3T_e/m_e\right)^{1/2}$ is the electron thermal velocity. We have also used the plasmon growth rate $\Gamma_{k'}$. The total derivative in equation (3) can explicity be written as

$$\frac{d}{dt}\equiv\left(\frac{\partial}{\partial t}+\vec{v}_{k'}.\frac{\partial}{\partial\vec{r}}+\vec{F}_{k'}.\frac{\partial}{\partial\vec{k}'}\right) \qquad (5)$$

where $\vec{v}_{k'}=S_e^2\vec{k}'/\omega_{k'}$ is the plasmon group velocity, or identically, the group velocity of the electron plasma waves, and $F_{k'}=-\left(e^2/2\varepsilon_0 m_e\omega_{k'}\right)\nabla n_e$, where n_e is the electron plasma density, is the force acting on the plasmons.

Let us now study the plasma stability in the present of the plasmon field that results from the electron two-instabilities. We have to use the relativistic fluid equations for the fast electrons, the return current and the plasma ions $\left(\alpha=f,e,i\right)$

$$\frac{\partial n_\alpha}{\partial t}+\nabla.n_\alpha\vec{v}_\alpha=0$$

$$\frac{\partial\vec{p}_\alpha}{\partial t}+\frac{\vec{p}_\alpha.\nabla\vec{p}_\alpha}{m_\alpha\gamma_\alpha}=-q_\alpha\nabla\varphi-\frac{\nabla P_\alpha}{n_\alpha}-\nu_\alpha\vec{p}_\alpha \qquad (6)$$

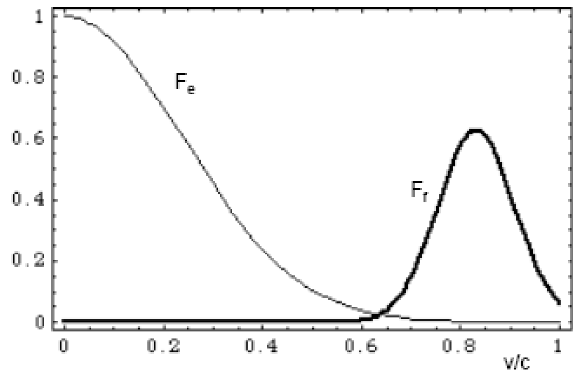

Figure 1. Electron distribution functions, showing both the fast electron beam (f) and the background plasma electrons. This unstable beam plasma interaction creates electron plasma waves, or plasmons.

where $n_{\alpha,}\vec{v}_\alpha$ and P_α represent the density, velocity and pressure of the various particle populations α, and ν_α their collision frequencies. We also have $\gamma_\alpha = \left(1 - v_\alpha^2/c^2\right)^{-1/2}$. In this equation we have also used the electrostatic potential φ, determined by the Poisson's equation.

Let us first consider the electron two stream instabilities. Neglecting the thermal effects $\left(S_\alpha^2 = 0\right)$ and the collisions $\left(\nu_\alpha = 0\right)$, the dispersion relation is

$$1 - \frac{\omega_{pe}^2}{\left(\omega + g\vec{k}.\vec{u}_0\right)^2} - \frac{\omega_{pf}^2}{\gamma_0^3\left(\omega - \vec{k}.\vec{u}_0\right)^2} = 0 \qquad (7)$$

Here we have used for the mean velocity of the return current the value $\vec{u}_e = g\vec{u}_0$, where $\vec{u}_0 \equiv \vec{u}_f$ is the fast electron beam velocity and the factor $g = n_{of}/n_{oe}$ is smaller than one. This equation can be found in reference[8)], written in a different notation. Assuming that the oscillating frequency $\omega = \vec{k}.\vec{u}_0 + \eta$, where η is much smaller than the first term, and considering the quasi-resonant conditions such that $\vec{k}.\vec{u}_0 \simeq \omega_{pe,}$ we obtain an expression for the maximum growth rate of the electron two-stream instability, which can be written as if

$$\Gamma = \frac{\sqrt{3}g^{1/3}}{2^{4/3}\gamma_0}\omega_{pe} \qquad (8)$$

With $\eta = i\Gamma$. If we are considering overdense plasma, where $\omega_{pe}^2 >> \omega_{laser}^2$, the value of this growth rate can be very significant, especially for ultra intense laser beams in the Petawatt domain where the factor $g^{1/3}$ can approach one, even

these high energies imply that the fast electron beam is also highly relativisitic, $\gamma_0 >> 1$ [8,9)]. This instability will create electron plasma waves (or plasmon turbulence) with relativistic phase velocities, such that $\omega \sim ku_0 \simeq kc$. This means that he associated plasmons will have a very low group velocity $v_k = S_e^2 k/\omega \simeq S_e^2/c << S_e$. Therefore, they are well suited to decay into ion acoustic waves, as shown below.

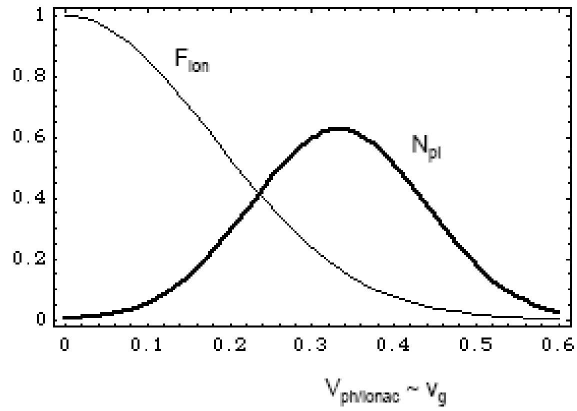

Figure 2. Ion and plasmon distribution functions showing both the plasmon beam (f) and the background plasma ions. This unstable beam plasma interaction excites ion acoustic waves.

On the other hand, the dispersion relation for ion acoustic waves in the presence of a plasma beam can be written as

$$\left(2\eta + i\nu_i\right)\left(\eta - i2\Gamma_0\right)^2 = \Omega^2\omega_s \qquad (9)$$

where Γ_0 is here the growth rate of the unstable plasmon spectrum and $\Omega^2 = \left(ZW_0/n_0 m_e c^2\right)\left(k^4 S_e^2 c^2/\omega_0'^2\right)$. It is clear that Ω has the dimensions of a frequency, which can be seen as an effective plasmon beam frequency. We have used here the energy density of the plasmon beam, as defined by $W_0 = \hbar\omega_0' N_0$.

In the absence of dissipation, this would simply lead to $\eta = i\Gamma$ where the growth rate of the ion acoustic waves would be given by[6)]: $\Gamma = \sqrt{3}\left(\omega_s\Omega^2/2^4\right)^{1/3}$. This upper limit of the growth rate is illustrated in Figure 2. Notice that the quantity $Y_s = \Omega/\omega_s$ can be approximately written as $Y_s = \left(Z_{\gamma 0 g}\right)^{1/2}\left(\omega_s/\omega_{pe}\right)\left(c/S_e\right)$, where we have assumed that the plasmon energy is of the order of the fast electron beam energy. It is obvious that, for large γ_0 and low electron temperature, this quantity can be in the range of 0.1-1, thus leading to very high growth rates comparable to those of the electron two-steam instability, which is in the range of $10^{-1} - 10^{-2}\omega_{pe}$.

For a dissipative and unstable system, we obtain the approximate expression

$$\Gamma = \frac{\sqrt{3}}{2^{4/3}}\left(\omega_s\Omega^2\right)^{1/3} + \frac{4}{3}\Gamma_0 - \frac{\nu_i}{6} \qquad (10)$$

We see that, for a moderate level of the electron two-stream instability, such that $\Gamma_0 > \nu_i/8$, the ion acoustic waves will always become unstable, even for a very small value of the plasmon turbulence. The electron two-steam instability will then be saturated by the fast energy transfer to the ion-acoustic wave spectrum, which in turn will be heavily damped due to the high rate of ion collisions. Such a two-step proves will then efficiently transfer energy from the fast electron beam (in reality, from the incident laser beam) to the ion thermal energy without heating the electrons. The electrons only mediate the transfer, without being significantly heated, because they have high mean velocities (which corresponds to low collision frequencies) and support high frequency plasma wave oscillations which are not significantly affected by collisions. In the end, these physical processes could result in a scenariou where the bulk ion heating is greater than the electron heating if the ion growth rate exceeds the rate at which the energy in the electron oscillations is eventually converted to electron heating. The condition for preferred ion heating, expressed in terms of the laser beam intensity, can be written as

$$I > \frac{2^4}{3^{3/2}} \frac{n_{0e} m_e c^3}{f_{abs}} \gamma_0^4 \left(\frac{v_e}{\omega_{pe}} \right)^3 \qquad (11)$$

where f_{abs} is the laser absorption factor into fast electrons. Notice that the relativistic gamma factor γ_0 and the electron return velocity u_{0e} are typically proportional to $\sqrt{I}$, and the collision frequency goes with u_{oe}^{-3}. This means that the right hand side of this inequality varies with the laser intensity as $I^{-5/4}$. For a typical laser target experiment with $n_{0e} \sim 10^{23} cm^{-3}$, this threshold criterion can only be satisfied for laser intensities in excess of $10^{20} Wcm^{-2}$.

In conclusion, we have proposed a new mechanism for anomalous ion heating in ultra-intense laser plasmas. This mechanism is based on the excitation of two coupled instability processes that drive the laser energy down to the ion population and provides a simple explanation for the preferential heating of the bulk ion population observed in recent laser experiments in the Peta-Watt regime.

References

1. R. Kodama *et al.*,
   Nature, 412, 798, (2001)
   R. Kodama *et al.*,
   Nature, 418, 933, (2002)
2. P. A. Norreys *et al.*,
   Phys. Plasmas, 11, 2746, (2004)
3. R. B. Campbell *et al.*,
   Phys. Rev. Lett. 94, 245002, (2005)
4. J. T. Mendonca, P. Norreys, R. Bingham and J. R. Davies,
   Phys. Rev. Lett. 94, 245002 (2004)
5. J. R. Davies,
   Phys. Rev. E, 69, 065402(R), (2004)
6. J. T. Mendonca and R. Bingham,
   Phys Plasmas, 9, 2604 (2002)
7. J. T. Mendonca, R. Bingham and P. K. Shukla,
   Phys. Rev. E, 68, 0166406 (2003)
8. F. Califano, F. Pegoraro and S. V. Bulanov,
   Phys. Rev. E, 56, 963 (1997)
9. T. Haruki and J.-I. Sakai,
   Phys Plasmas, 10, 392 (2003).