A new mechanism of direct coupling of laser energy to ions

Ayushi Vashistha$^{1,2,*}$, Devshree Mandal$^{1,2}$, Atul Kumar$^{1,2}$, Chandrasekhar Shukla$^{3}$, Amita Das$^{4}$

$^1$ Institute for Plasma Research, HBNI, Bhat, Gandhinagar - 382428, India
$^2$ Homi Bhabha National Institute, Mumbai, 400094
$^3$ Samspra Aerospace Systems Pvt. Ltd. Bengaluru, 560008 and
$^4$ Physics Department, Indian Institute of Technology Delhi, Hauz Khas, New Delhi - 110016, India

The well-known schemes (e.g. Brunel, resonance absorption, JxB heating etc.) couple laser energy to the lighter electron species of the plasma. In this work, a fundamentally new mechanism of laser energy absorption directly to the heavier ion species has been proposed. The mechanism relies on the difference between the ExB drifts of electron and ions in the oscillating electric field of the laser and an external magnetic field to create charge density perturbations. The proposed mechanism is verified with the help of Particle - In - Cell (PIC) simulations using OSIRIS4.0.

**INTRODUCTION**

There are many well-known schemes by which the laser energy can get absorbed in the plasmas [1, 2]. For instance, resonance absorption, Brunel, JxB heating schemes etc. [3, 4, 5]. All these schemes rely on the dynamical response of the lighter electron species in the presence of the oscillating field of a high frequency laser. Consequently, the dominant transfer of energy from laser occurs in electron species. However, there are many applications (e.g. fast ignition, medical therapy etc.) where it is desirable to have energetic ions. This has led to efforts seeking efficient mechanisms of ion heating and/or acceleration [6, 7, 8, 9, 10]. In many previous studies, a two step approach has been envisaged for this particular objective. The laser energy is first absorbed by electrons and its transfer to ions depends on the electron-ion classical collisional and/or anomalous processes. Since Rutherford’s collision cross section decreases with increasing electron energy, this process is inefficient at high energies [11].

Many ideas of anomalous transfer of energy from electron to ion have also been proposed [12, 13, 14, 15, 16]. In this work, we propose a novel scheme by which direct transfer of laser energy to ions is possible.

The new mechanism relies on the application of a strong external magnetic field normal to the laser propagation and the polarization direction. The strength of the magnetic field is chosen such that it restricts the motion of electrons which are tied to the magnetic field lines but the heavier ion species remain unmagnetized and are relatively free to move in response to the laser electric field. This happens when the electron gyroradius is much smaller than the laser wavelength whereas ion gyroradius is longer compared to it, as depicted in the schematic of Fig.1. The frequency condition $\omega_{ce} > \omega_l > \omega_{ci}$ needs to be satisfied. This requires that the applied external magnetic field strength $B_0$ should be greater than $m_e c \omega_l / e$.

The $E \times B$ drift velocity in the presence of an externally applied magnetic field and an oscillating electric field is given by

$$\vec{V}_{E \times B}(t) = \frac{\vec{E}(t) \times \vec{B}}{\omega_{ci}^2 - \omega_l^2} \frac{\omega_{ce}^2}{B^2}$$  \hspace{1cm} (1)

as $\omega_{ce} > \omega_l > \omega_{ci}$, the drift velocity of the two species differ [13]. Here, the suffix $s = e, i$ represents the electron and ion species respectively. Thus, $\omega_{ce}$ and $\omega_{ci}$ stands for the electron and ion cyclotron frequency respectively.

Furthermore, $\omega_l$ stands for the laser frequency. The difference in the drift velocities of electron and ions gives rise to a current. Since, the laser electric field and the externally applied magnetic field, both are perpendicular to the propagation direction, this drift is along the laser propagation direction. This current has a spatial variations at the laser wavelength due to its dependence on the electric field of the applied laser. This spatial variation leads to a finite divergence of the current which drives a charge density fluctuation given by the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \vec{j} = 0$$  \hspace{1cm} (2)

This generates electrostatic plasma mode in the system, thereby, the energy of the laser gets transferred to plasma. This is the underlying main principle on which our new mechanism has been proposed. It should be noted when the applied magnetic field is zero, $\vec{V}_{E \times B} \approx 0$ (as $\omega_{cs} = 0$) for both the species, and no charge separation will be created in the plasma. In the other limit of a very large magnetic field, $\vec{V}_{E \times B} \approx 0$ for both ions and electrons will become same and hence in this limit also one should expect no creation of number density fluctuation. Thus, in both the limits the proposed mechanism of laser energy absorption will be inoperative. We have carried out PIC (Particle - In - Cell) simulations through OSIRIS4.0 to support our mechanism presented in this work.

The experimental implementation of this mechanism requires an application of an external magnetic field of magnitude $B_0 > m_e c \omega_l / e$. For a typical laser of $1 \mu m$ wavelength this translates to a requirement of magnetic...
field of the order of $10^4$ Tesla. The CO$_2$ lasers which have a 10$\mu$m wavelength, reduces the requirement by ten times. Lately, there has been a rapid technological progress in achieving high magnetic field in the laboratory. The value of 1.2 Kilo Tesla$^{[22]}$ at Institute for Solid State Physics at the University of Tokyo, Japan has already been achieved. Thus, it is only a matter of time before the requirement for carrying out experiments in this domain would be possible.

**SIMULATION DETAILS**

We use OSIRIS-4.0 framework$^{[19,21]}$ for our Particle-in-Cell (PIC) studies. The schematics (not to scale) in Fig.1 shows the field configuration used in the simulation. The $\hat{z}$ is the propagation direction of the laser. The laser electric field is along $\hat{y}$ and the applied external magnetic field is along $\hat{z}$ as shown in the figure. A 2-D rectangular simulation box with dimensions $L_x = 3000c/\omega_{pe}$ and $L_y = 100c/\omega_{pe}$ has been chosen. The plasma boundary starts from $x = 500c/\omega_{pe}$ onwards. There is vacuum between $x = 0$ to $x = 500c/\omega_{pe}$. The spatial resolution is taken as 10 cells per electron skin depth corresponding to a grid size $\Delta x = 0.1c/\omega_{pe}$ and time step for calculations is taken to be $\Delta t = 0.02\omega_{pe}^{-1}$. There is a sharp plasma-vacuum interface and laser is incident from left side on the plasma target. We consider a p-polarized, plane short-pulse laser of wavelength $\lambda_l = 9.42\mu$m corresponding to CO$_2$ laser. The choice of long-wavelength laser is simply for the sake of definiteness and is motivated by the fact that it reduces the requirement of the externally applied magnetic field. The mechanism, however, is independent of the laser wavelength. The normally incident laser is propagating along $\hat{x}$, centred at $x = 250c/\omega_{pe}$ and has a pulse length ranging from $x = 0$ to $500c/\omega_{pe}$. The number density of the plasma is taken to be $n_0 = 3 \times 10^{20}$ cm$^{-3}$ for which the electron plasma frequency is equal to $10^{12}$ Hz. Hence the plasma is overdense for the incident laser pulse.

We have followed the dynamics of both electrons and ion species. The simulations are, however, carried out at a reduced mass of ions which is taken to be 25 times heavier than electrons (i.e. $m_i = 25m_e$, where $m_i$ and $m_e$ denote the rest mass of the ion and electron species respectively). This mass ratio has been chosen to reduce the computational time. (The computational resources being meagre at our disposal.) We use normalized units henceforth, unless otherwise stated explicitly. The time is normalized by the inverse of electron plasma frequency corresponding to the chosen plasma density of $n_0$. The laser frequency is $\omega_l = 0.2\omega_{pe}$. The length is normalized by electron skin depth $c/\omega_{pe}$ and the magnetic field by $m_e\omega_{pe}/e$. The external magnetic field has been chosen in such a way that $\omega_{ce} > \omega_l > \omega_{ci}$. To satisfy this condition the value of magnetic field is chosen to be $B_0 = 2.5$. For this field, the electrons gyrate at a frequency $2.5\omega_{pe}$. The number of particles per cell are taken to be 4. Boundary conditions for fields and particle are periodic in transverse direction and absorbing in longitudinal direction. The laser is taken to be infinite in y-direction.

The observation geometry is specifically chosen to avoid the possibility of any well-known absorption schemes to be operative. The laser frequency being 0.2 is much smaller than the electron plasma frequency (unity here). The laser is incident normal to the sharp plasma interface. This ensures the absence of resonance and vacuum heating schemes. Also, the role of $\vec{J} \times \vec{B}$ electron heating is made negligible by choosing the laser intensity to lie in the non-relativistic domain of $a_0 = eE/m_e\omega_l c < 1$. Thus the peak intensity of laser in simulation is taken to be $I = 3.5 \times 10^{15}$ W/cm$^2$ with a rise and fall time of $205\omega_{pe}^{-1}$ each.

**OBSERVATION**

We first provide a comparison between two cases, namely (A) for which the applied magnetic field $B_0 = 0$ and (B) for which $B_0 = 2.5$. The choice of $B_0 = 2.5$ ensures that the condition $\omega_{ce} > \omega_l > \omega_{ci}$ is satisfied. The simulation configuration being symmetric in the y coordinate, we choose to depict the fields as a function of the coordinate $x$ in the figures.

In Fig.2 the three subplots in the first row depict the plot of the time-dependent magnetic field associated with the laser and the self-consistent response of the plasma medium as a function of $x$ at three distinct time (i) $t = 0$ showing the initial laser pulse field when it does not touch the plasma surface, (ii) $t = 350$ when the laser has touched the plasma and (iii) $t = 700$ when the laser pulse has been reflected from the plasma surface and the plasma is left with the remnant self-consistent excitations. The dashed red line denotes the case (A) for which $B_0 = 0$ and the solid blue line corresponds to case (B) with $B_0 = 2.5$. It can be observed from the figure that in case(A) there is no penetration of the laser magnetic field in the plasma and almost a complete reflection of the pulse occurs. However, for case (B) when the external applied field $B_0$ is finite and equal to 2.5, a part of the laser field shows clear penetration in the plasma medium. In the same figure the next row of three subplots show the plasma current $J_x$ as a function of $x$ for the two cases. The third and the last row depicts the electrostatic field $E_x$ generated in the plasma medium. It is clear from the plots of $J_x$ and $E_x$ that while the plasma gets stirred significantly by the laser field in the presence of applied external magnetic field in case(B), for case(A) the plasma continues to remain quiescent even after interacting with the laser pulse. This is as expected by our proposed mechanism.
We now compare the evolution of various energies for the two cases in Fig. 3. We indicate distinct time incidents by vertical lines in this figure. The first two solid black vertical lines denote the times \( t_1 = 100 \) and \( t_2 = 380 \), where \( t_2 - t_1 \) region indicates the time interval during which the laser interacts with the plasma. Thereafter, laser field gets reflected from the plasma surface. At around \( t_3 = 500 \) denoted by the black dashed line, the laser reflects from the plasma surface and at \( t_4 = 780 \) indicated by black dotted line the laser field leaves the simulation box. The evolution of the electromagnetic field energy has been shown by the blue dashed and solid lines for case(A) and case(B) respectively. The left side of the \( y \)-axis in the figure represents the scale for this particular energy. The electromagnetic field energy remains constant associated with the laser pulse till \( t_1 \). At \( t_1 \) the laser pulse interacts with the plasma surface. There is a fall of electromagnetic energy from \( t_1 \) to \( t_2 \), the time for which the laser pulse interacts with the plasma medium. It is evident from the figure that the electromagnetic energy decreases more in case(B) than in case(A) during this period. From \( t_2 \) to \( t_3 \) when the laser pulse reflects from the plasma surface but remains within the simulation box the electromagnetic energy remains constant. At \( t_3 \) the left edge of the reflected laser pulse touches the left boundary of the simulation box. Thereafter there is a continuous decay in the field energy till \( t_4 \) at which the pulse completely leaves the simulation box. Thus, while the first fall of the electromagnetic field energy between \( t_1 \) to \( t_2 \) is associated with the laser pulse interacting with the plasma medium, the second fall of the electromagnetic energy between \( t_3 \) to \( t_4 \) is due to the laser pulse leaving the simulation box. The laser energy transfer, therefore, essentially occurs between \( t_1 \) to \( t_2 \). Further, it should be noted that the energy transfer to plasma medium is more in case(B) with externally applied magnetic field. Clearly, this energy transfer to plasma would be in the form of field and kinetic energies. Another interesting thing to observe is that even after the laser pulse leaves the system, the electromagnetic energy for case(B) remains finite in contrast to case(A) where it falls off to zero. This shows that the laser interaction creates some electromagnetic field fluctuation in the plasma medium in case(B).

The evolution of the kinetic energy of electrons and ions are shown by green and red color line plots respectively in the same Fig. 3. The dashed and dotted lines are for case(A) and the solid line with dots correspond to case(B). For these kinetic energy plots, the right \( y \)-axis defines the scale. In the absence of applied magnetic field in case(A) the gain in ion energy is much smaller compared to that of electrons. However, for case (B) in the presence of magnetic field the kinetic energy of ions is much higher than that of electrons. The total energy absorbed by plasma in this case is higher. It is clear that the laser interacts with plasma in case (B) in a more efficient fashion and excites certain disturbances in the plasma. The disturbances excited in case(B) do have an electrostatic characteristic as evidenced from the evolution of the \( x \) component of the electric field \( E_x \) shown in Fig 3(a) at a location \( x = 540c/\omega_{pe} \) (which is deep in the bulk region of the plasma medium). For case(A) the amplitude of the electrostatic field \( E_x \) is negligible. The frequency associated with the regular oscillation in the electric field \( E_x \) is identified by carrying a Fourier transformation which is shown in Fig 3(b). The peak in the Fourier transform for the two cases appear at very distinct frequencies. In case(A) the spectrum shows a peak at \( \omega = 1 \) which is the electron plasma frequency. On the other hand, for Case(B) the peak in the frequency is shifted at a lower side (corresponds to a value close to \( \sim 0.2 \)) which indicates towards presence of an ion dominated mode.

The oscillations in the electrostatic field are a result of space charge fluctuations excited in the plasma. The number density and the velocity fluctuations associated with the two species have been shown in the first and second row of the figure for the two species of electron and ions by blue and red color lines respectively as a function of \( x \) at three different times (Fig. 4). The third row of subplots shows the current density fluctuations. It is clear from the plot that except for the short distance near the plasma boundary at \( x = 500 \), the ion and electron density oscillations and their \( x \) component of the velocities are in tandem. These oscillations propagate deeper in the plasma with time. The laser interacting at the plasma boundary excites a space charge fluctuations at the boundary which then travels in the bulk region of the plasma.

In Fig. 6 we show a plot of the velocity and density fluctuations of the two species as a function of time for \( x = 540 \) (a point in the bulk region of the plasma). The plots correspond to six different values of the magnetic field. From the plots it is clear that at low values of the magnetic field the velocity fluctuations are small. At an intermediate value of the magnetic field \( B_0 = 2, 2.5, 3.0 \) the velocity fluctuations increase and the difference between electron and ion velocity is also high. The number density fluctuations are also high for these cases. However, at very high value of magnetic field of \( B = 10 \) the electron and ion velocities are almost similar and the number density fluctuation is small. It should be noted that at the intermediate value of \( B = 2, 2.5, 3.0 \) only the required condition of \( \omega_{ce} > \omega_l > \omega_{ci} \) is satisfied. For \( B = 10 \) even the ions get magnetized. This is consistent with our proposed mechanism in which the number density fluctuation are supposed to be excited by the difference in the \( E \times B \) velocity of the two species. The difference in the drift velocity of the two species vanishes in both the limits of low and high magnetic fields.

These number density fluctuations associated with ion time scale of response peak at an intermediate value of
$B_0$ the applied magnetic field. The mode disappears both at the low magnetic field and also at the higher values of the magnetic field. To understand the role of magnetic field on laser absorption, we show in Table I the total energy absorbed by the two species electrons and ions from the laser for various values of the applied magnetic field. From this table, it is clear that the energy absorption in ions is low both at the low value of magnetic field and also at the high value of the magnetic field. This has also been depicted in the plot of Fig. 7 showing the total energy absorption by electrons and ions at various values of the external magnetic field. We have also shown total current $J_x$ in the system. The ion absorption follows the profile of the current as a function of the applied magnetic field.

The particle count of the two species as a function of energy has been shown in Fig. 8 for the two cases of (A) and (B). From this figure also one can infer clearly that energy absorption by ions in the presence of external magnetic field is higher.

**CONCLUSION**

In conclusion, the results of the previous section clearly demonstrate that the laser energy gets preferentially coupled to ions in the presence of external magnetic field. The space charge fluctuations created by the difference in the $E \times B$ velocity of the two species in presence of oscillating electric and static external magnetic field appears responsible for the excitation of the electrostatic mode in the plasma medium.

While we have primarily focused here on the illustration of a fundamentally new concept, it should be realised that in recent years there has been rapid progress in the creation of high magnetic fields in the laboratory. Magnetic field of the order of 1.2 kilo Tesla has already been produced in laboratory. One expects that in near future this limit will increase. We feel that it is only a matter of time when we will witness magnetic field of the order of 10s of kilo Tesla at which the mechanism presented in this manuscript can be experimentally verified in laboratory with a long wavelength CO$_2$ lasers which have now already been made to operate in the pulsed high-intensity mode.

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* Electronic address: ayushivashistha@gmail.com, amitadas3@yahoo.com

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FIG. 1: Schematic (not to scale) showing that under the condition \( \omega_{ce} > \omega_l > \omega_{ci} \), the electrons are tightly bound to the external magnetic field (along \( \hat{z} \)) whereas ions are free to move under the effect of laser. The direction of oscillating electric field due to laser is along \( \hat{y} \) and that of laser magnetic field along with a static external magnetic field is along \( \hat{z} \) and the laser propagation is along \( \hat{x} \) direction. \( \mathbf{E} \times \mathbf{B} \) drift due to oscillating electric field is acting along \( \hat{x} \).

FIG. 2: Time evolution of spatial variation of \( B_z \), x-component of total current \( J_x \) and x-component of electric field \( E_x \) along \( \hat{x} \), averaged over \( \hat{y} \), showing that as laser interacts with plasma (t=350), there is a finite magnitude of perturbed \( B_z \), \( J_x \) and \( E_x \) in case(B) which is absent in case(A). From these plots, we can infer that a part of laser energy has been coupled into plasma.
FIG. 3: Time variation of mean of Electromagnetic field (Emf) energy density of the system (left y axis) and kinetic energy density of both the species (right y axis) showing that laser energy is mainly gained by electrons in case(A) and by ions in case (B). The decrease in Emf energy of the system between the two solid lines is due to the interaction of laser with plasma (there is gain in Kinetic energy of electrons in case (A) and ions in case(B) at the same time). Between dashed and dotted line, the laser reflects back and moves out of the simulation box and as a result, we observe a drop in Emf energy of the system. There is also generation of some electrostatic mode in plasma in case (B) contributing to emf energy of the system even after the laser has been reflected out of the simulation box (beyond dotted line).

FIG. 4: (a) Time variation of x-component of electric field $E_x$ for both the cases at $x=540$ $c/\omega_{pe}$, averaged over $\hat{y}$, showing generation of electrostatic mode in the bulk plasma in case (A) and case(B). (b) Fast fourier transform of $E_x$ showing peak at electron plasma oscillation for case (A) and at a lower frequency for case (B). The shift in the frequency towards lower end in case (B) indicates presence of an ion dominated mode.
FIG. 5: Figure shows the spatial variation of density \((n)\), \(x\)-component of velocity \(V_x\) and \(x\)-component of total current \(J_x\) averaged over \(\hat{y}\) at different times. At a particular time we observe that the density perturbations created and the difference in \(V_x - V_{ce}\) are at the same position, indicating the correspondence between them.

| \(B_z\) | % of laser energy absorbed by electrons | % of laser energy absorbed by ions | % of laser energy absorbed by plasma |
|--------|-------------------------------------|----------------------------------|----------------------------------|
| 0      | 6.06                                | 2.40                             | 8.46                             |
| 1.5    | 0.42                                | 2.76                             | 3.18                             |
| 2      | 0.42                                | 9.68                             | 10.10                            |
| 2.5    | 0.58                                | 14.52                            | 15.10                            |
| 3      | 1.22                                | 31.12                            | 32.34                            |
| 3.5    | 1.41                                | 44.60                            | 46.01                            |
| 4      | 0.22                                | 10.98                            | 11.2                             |
| 5      | 0.003                               | 0.61                             | 0.61                             |
| 7      | 0.002                               | 0.002                            | 0.004                            |
| 10     | 0.002                               | 0.005                            | 0.007                            |

TABLE I: Table showing that laser energy absorbed by ions increases as applied external magnetic field increases. It can also be noted that the ion energy is significant for the case only when \(V_{ix} - V_{ce}\) is finite (Fig 6) which is only true if \(\omega_{ce} > \omega_i > \omega_{ci}\) is satisfied.
FIG. 6: Figure showing the effect of varying external magnetic field on $V_x(t)$ and density perturbations of both the charged species at a particular $x$ (here, $x=540$), averaged over $\hat{y}$. With increasing applied magnetic field, $V_{ix} - V_{ex}$, when $\omega_{ce} > \omega_l > \omega_{ci}$ is satisfied. As soon as $\omega_{ce} > \omega_l > \omega_{ci}$ is not satisfied ($B_z = 10$), $V_{ix} - V_{ex}$ again decreases. Similar trend is observed in density perturbations of both the species as well.
FIG. 7: Figure shows the effect of varying external magnetic field on the total current generated in the system (left y axis) and energy absorbed by electrons and ions (right y axis). It can be observed from the graph that the energy absorbed by ions follow the total current in the system. Also, total current as well as energy absorbed by ions increase only when $\omega_{ce} > \omega_l > \omega_{ci}$.

FIG. 8: Energy distribution of ions and electrons for case(A) and (B) showing the maximum energy gained by them in both the cases.