Role of Ionization in DLA-type Fast Electron Generation

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Abstract

We propose that field ionization can both break adiabaticity and cause significant absorption in DLA-like interactions under certain conditions. We explain the theoretical basis for this conjecture and we present some preliminary 1D PIC calculations including field ionization supporting this.

1 Introduction

In the work reported here we are concerned with the generation of fast electrons in (moderately) underdense plasmas via Direct Laser Acceleration (DLA)-*like* processes [1–3]. Specifically we consider the role that ionization injection can play in absorption in near critical plasmas. Ionization injection can lead to automatic adiabaticity breaking and it is therefore important to examine the extent to which it might contribute to absorption in preplasmas. Here we provide a preliminary report on a recent theoretical and computational study on the role of ionization in DLA-like fast electron generation. We conclude that ionization absorption may indeed be possible with circularly polarized laser pulses under a limited set of conditions.

2 Theory of Ionization Absorption

2.1 Role of Ionization Injection

The reason why ionization in the laser pulse can lead to net absorption of energy can be seen as follows: We consider the dynamics of a single electron in an essentially 1D configuration in which it interacts with an electromagnetic (EM) wave described the vector potential,

$$\mathbf{A} = [0,0,A] = [0,0,A_0\cos(\omega_L\tau)], \tag{1}$$

where $\tau = t - x/c$, and ω_L is the frequency of the field. The electric and magnetic fields are related to the vector potential via $\mathbf{E} = -\partial_t\mathbf{A}$ and $\mathbf{B} = \nabla\times\mathbf{A}$, so the electric field of this wave is polarized in the z-direction. The equations of motion of the electron that need to be considered are:

$$\frac{dp_x}{dt} = ev_zB_y, \tag{2}$$

$$\frac{dp_y}{dt} = 0, \tag{3}$$

$$\frac{dp_z}{dt} = -eE_z - ev_xB_y, \tag{4}$$

$$\frac{d\gamma}{dt} = -\frac{ev_zE_z}{m_ec^2} \tag{5}$$

From the definition of τ, one can differentiate to obtain,

$$\frac{d\tau}{dt} = 1 - \frac{v_x}{c}, \tag{6}$$

and this can then be used to write the field components as $E_z = -\partial_\tau A$, $B_y = (1/c)\partial_\tau A$. These can then be used to obtain,

$$\frac{dp_z}{dt} = e\frac{dA}{d\tau}\left(1 - v_x/c\right), \tag{7}$$

$$\frac{dp_x}{dt} = \frac{ev_z}{c}\frac{dA}{d\tau}, \tag{8}$$

and,

$$\frac{d\gamma}{dt} = \frac{ev_z}{m_ec^2}\frac{dA}{d\tau}. \tag{9}$$

In the standard treatment of a single, free electron that is at far from the laser pulse, one obtains $p_z = eA$, and $\gamma - p_x/m_ec = 1$ as the constants of motion, which means that $p_x/m_ec = a^2/2$ (where $a = eA/m_ec$ is the normalized vector potential). Note that once the laser pulse has overtaken the electron, $a \to 0$, which implies that $p_x \to 0$ which means that the electron only interacts adiabatically with the laser pulse and does not absorb any energy. This well known result is embodied in the Lawson-Woodward theorem.

Instead, consider the case where the electron is bound up until the point where it is ionized by some process in the laser pulse. Let the normalized vector potential at the point that it is freed (or injected) be a_{inj}. On being liberated, we assume the electron has negligible momentum. From eqn.s 6 and 7, we obtain,

$$\frac{p_z}{m_e c} = a - a_{inj}. \tag{10}$$

If we combine eqn.s 8 and 9 then we obtain, as in the initially free electron case,

$$\gamma - \frac{p_x}{m_e c} = 1 \tag{11}$$

If these two constants of motion are now used in eqn. 8, and we combine the second constant of motion with eqn. 6 to get $d\tau/dt = 1/\gamma$, we obtain,

$$\frac{d}{dt}\frac{p_x}{m_e c} = (a - a_{inj})\frac{da}{dt}. \tag{12}$$

If we integrate and apply the condition that $p_x = 0$ when $a = a_{inj}$ then we finally arrive at,

$$\frac{p_x}{m_e c} = \frac{(a - a_{inj})^2}{2}. \tag{13}$$

Now when the laser pulse overtakes the electron, and $a \to 0$, $p_z/m_e c \to -a_{inj}$, and $p_x/m_e c \to a_i nj^2/2$. We therefore find that, in stark contrast with the initially free electron case, that the initially bound electron case can be non-adiabatic and that ionization injection can result in the electron irreversibly gaining energy from the laser field. Furthermore the electron can irreversibly gain the highest energy that a free electron can achieve in the laser field. Also note that the electron gains both longitudinal and transverse momentum.

These analytic results can be checked by direct numerical integration of the equations of motion. Here we present results of such a numerical integration for the case where we initialize the electron at rest far from the peak of a plane wave (Gaussian temporal profile with a_0 =5 and a pulse duration of 20 fs) which corresponds to the initially free case, and the case where the electron is initially at rest at the peak of the plane wave which corresponds to the case of ionization injection at the peak of the laser pulse (note that this is the peak vector potential).

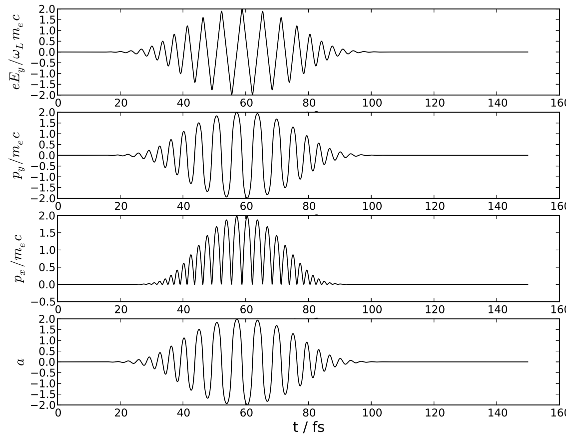

Figure 1: Results of numerical integration of equations of motion for the case of an electron initially at rest far from the laser pulse(EM wave parameters : a_0 =5, Gaussian pulse with 20 fs duration.). Note that the electron returns to rest on being overtaken, with no net energy gain.

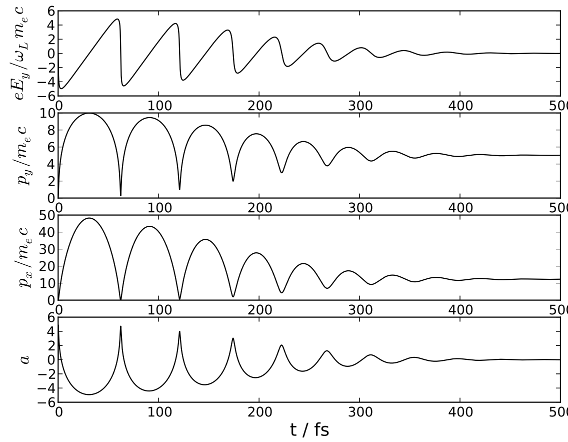

Figure 2: Results of numerical integration of equations of motion for the case of an electron injected at peak vector potential(EM wave parameters : a_0 =5, Gaussian pulse with 20 fs duration.). Note that the electron gains net longitudinal and transverse momentum on being overtaken by the laser pulse.

However we also arrive at another strangely curious conclusion. Since $\mathbf{E} = -\nabla\Phi - \partial_t \mathbf{A}$ (where Φ is the electrostatic potential), for a linearly polarized plane EM wave the peaks of a_0 correspond to nulls in $\mathbf{E}$. Therefore field ionization by the electric field of a linearly polarized EM wave cannot lead to the type of non-adiabatic absorption that we have just described. Ionization injection at peak a_0 could occur by other means though. Self-consistently generated electrostatic fields in the plasma could lead to field ionization injection at high a_0, as could collisional ionization. However it is not clear that this would produce a very strong effect. The most obvious remaining way to ensure that this means of absorption can operate effectively at the outset is, therefore, to use a circularly polarized laser pulse.

In the case of circular polarization, essentially one polarization direction can ionize atoms at the E-field nulls of the orthogonal polarization. This automatically leads to the aforementioned non-adiabatic absorption, with the acquired transverse momentum beinig in the polarization direction orthogonal to the one responsible for field ionization.

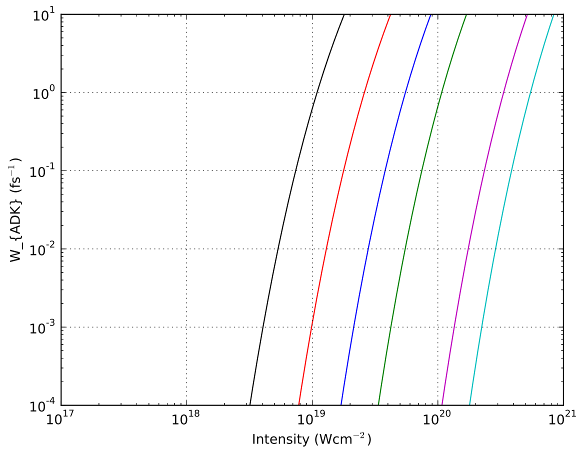

Figure 3: ADK ionization rate of hydrogen-like ion according to eqn.14 for (left to right) atomic numbers 6,7,8,9,11,12.

2.2 *Estimate of Ionization Rates*

Running meaningful simulations to examine if ionization-driven absorption and adiabaticity-breaking actually occur requires one to check that one's choice of target element is compatible with injecting electrons close to the peak of the laser pulse. In this section we will present calculations which support choices made in setting up the simulations.

For hydrogen-like ions the field ionization rate can be estimated from the oft-cited ADK formula, which we rewrite here in convenient form,

$$W_{ADK} = 124.6\frac{U_{eV}^{5/2}}{E_{GV}}\exp\left(-6.83\frac{U_{eV}^{3/2}}{E_{GV}}\right)\text{fs}^{-1}, \qquad (14)$$

where $U_{eV} = 13.6Z^2$ is the ionization energy in electron-Volts, and E_{GV} is the electric field in 10^9Vm^{-1}. In figure 3 below we plot this rate for several hydrogen-like ions with atomic numbers in the range 5–12 with respect to laser intensity. If we take 0.1 fs^{-1} as a threshold at which the ionization rate becomes significant then we can see that the requirement that ionization injection occurs at the peak of the laser pulse restricts the choice of elements depending on the peak intensity. For example, if the peak of the laser pulse corresponds to $1\times10^{20}\text{Wcm}^{-2}$, then Carbon, Nitrogen, and Oxygen will inject their final electrons before the peak of the pulse, but Fluorine should inject its final electrons closely around the peak of the pulse.

3 Simulations

A number of 1D electromagnetic Particle-in-Cell (PIC) simulations were carried out to study this potential absorption mechanism. This was done for a slab of underdense fluorine plasma (40μm thick with an ion density of $1\times10^{25}\text{m}^{-3}$). The grid has a cell size of 0.01μm and has 30000 cells in total (total length is 300μm). The front edge of the slab sat at 100μm. The incident laser pulse was a circularly-polarized Gaussian pulse of the form:

$$a_{y,z} = a_0\exp(-\frac{\eta^2}{2c^2\tau_L^2})\cos(k_L\eta), \qquad (15)$$

where $\eta = x - ct$. For these simulations, a_0 =10, and τ_L =5 fs were chosen. The wavelength used was λ_L =1μm. Ions and electrons were initialized with 100 macroparticles per cell. The version of ELPS used was a modified version of the core ELPS code in the CLF Software Repository which we have designated 'ELPS-FI'. This version of ELPS includes a field ionization subroutine based on Eq. 14, and a switch was included which could turn the E_x component of the electric field off. Simulations were carried out for two cases : (a) 'No FI' where Z_{init} =9, and (b) 'With FI' where Z_{init} =7.

The results of these two simulations were compared at 300 fs. At this point in both simulations, the amplitude of the remaining laser pulse is less than a third of its initial value. In figure 4, the $p_y - x$ phase space of the electrons is plotted for both simulations, and in figure 5 the $p_x - x$ phase space of the electrons is plotted.

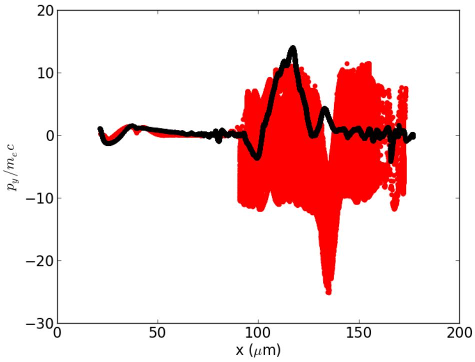

Figure 4: $p_y - x$ phase space of the electrons both 'with FI' (red) and 'no FI'(black) at 300 fs.

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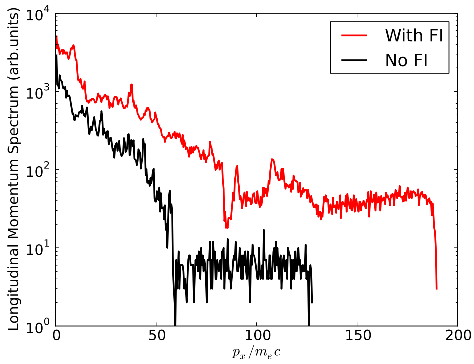

Figure 5: $p_x - x$ phase space of the electrons both 'with FI' (red) and 'no FI'(black) at 300 fs.

From 4 it is clear that many more electrons have retained significant transverse momentum in the simulation with FI than the one without. Retention of p_y without FI is possible because of the strong absorption of the laser pulse. The much greater retention of p_y in the case with FI is a strong indication of ionization absorption. In figure 5 the longitudinal momenta of the two simulations at the same time are compared as spectra. It is clear that the case with FI reaches much higher momenta with many more electrons in every energy range. In terms of overall energetics there is 4.5 times more energy absorbed in the with FI case compared to the no FI case. All three observations indicate that the inclusion of two stages of FI leads to much stronger absorption into electron kinetic energy.

There appear to be indications, however, that the pulse duration plays a special role in this. In simulations with longer (30 fs and longer) we have not observed such marked differences between the no FI and with FI cases. It has not yet been fully determined how the pulse duration plays such a determinative role.

4 Conclusion

We have proposed that intense, circularly polarized laser pulses can be subject to ionization absorption when propagating through underdense plasmas that are not fully ionized. This comes from the injection of the electrons in the middle of the laser pulse breaking adiabaticity. In principle the electrons can thus retain their energy on leaving the laser field without the need for any EM fields associated with the plasma. Circular polarization is necessary because a maximum in the vector potential is a minimum in the electric field of the laser, and we have assumed that field ionization is the dominant ionization process. We have performed some fully self-consistent, albeit 1D PIC simulations that show quite clear indications of ionization absorption occurring. Such clear results have not been obtained with other parameter sets, and thus we can only come to preliminary conclusion that ionization absorption may occur with circularly polarized laser pulses under some special conditions, one of which may be very short (< 10 fs) laser pulses.

References

[1] A.Pukhov, Z.-M.Sheng, and J.Meyer ter Vehn. *Phys.Plasmas*, 6:2847, 1999.

[2] A.V.Arefiev et al. *Phys.Rev.Lett.*, 108:145004, 2012.

[3] A.P.L.Robinson et al. *Phys.Rev.Lett.*, 111:065002, 2013.