The influence of a strong external magnetic field on laser-plasma interaction

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Introduction

In August 2021, National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in the USA made a great stride bringing the fusion energy much closer to reality [1]. For the energy production, the gain has to be further increased by about 2 orders of magnitude [2]. Application of a strong external magnetic field is being explored recently to improve the confinement of the fuel and thus help to increase the overall energy gain [3]. The question whether a strong magnetic field may also influence the interaction of the laser beam with the underdense plasma is not fully explored so far. For example, a recent study [4] demonstrates that the magnetic field strength of 12 T has already a significant influence on laser propagation and interaction with the plasma.

In this paper, the interaction of a sub-relativistic multi-picosecond laser beam with the wavelength ~ 1 μm and intensity 10^{16} W/cm^2 with an underdense plasma is investigated via 2D Particle-in-cell (PIC) simulations using the code EPOCH [5]. External magnetic field with the field strength of the order of a few tens of Tesla is included in the simulation box and the simulations concentrate on the interaction in front of and around quarter critical density and on the laser absorption and hot electron generation due to parametric instabilities.

Magnetic fields strength and geometry

A typical timescale associated with the magnetic field is the cyclotron frequency (ω_C) at which a charged particle such as an electron gyrates around a magnetic field B. Let us first compare this timescale for the field strength B=30 T with other timescales in the laser produced plasma (assuming the wavelength $\lambda = 1.3$ μm and the intensity of 10^{16} W/cm^2) around the quarter critical density and for the plasma at a temperature of 1 keV. Comparing the cyclotron and the laser frequency (ω_L), one may conclude that the laser wave propagation is not significantly influenced by the magnetic field as $\omega_L = 270\omega_C$. On the other hand, the intense laser plasma interaction may be significantly influenced by parametric instabilities and their typical timescale is given by the growth rate. Indeed comparing the growth rate for the Stimulated Raman Scattering (SRS) γ_{SRS} or the Stimulated Brillouin Scattering (SBS) $\gamma_{SBS}$with the cyclotron frequency, the order of magnitude difference disappears and the timescales become comparable ($\gamma_{SRS} \simeq 8\omega_C$, $\gamma_{SRS} \simeq 4\omega_C$). Thus it can be seen that these processes may be influenced by the magnetic field with the strength of several tens of Tesla.

The geometry of the magnetic field with respect to the laser propagation and polarization direction (assuming linear polarization) plays also an important role. Let us assume a linearly polarized plane laser wave with the electric field in the y-direction (E_y) propagating along the x-axis (k_x) with the normalized potential $a_0 \ll 1$. An electron exposed to this laser beam is oscillating with the high frequency in the y-direction with the amplitude of the velocity $v_y \sim a_0$ while it will slowly propagate in the x-direction due to the ponderomotive force of the finite laser pulse. The oscillatory motion combined with a static external field does not result in a significant deviation of the trajectory. However, the slowly varying component of the velocity associated with the ponderomotive force (v_x) may have some influence on the trajectory if the strength of a transverse external magnetic field is sufficiently high. If a finite focused beam is taken into account, the transverse ponderomotive force combined with the longitudinal external magnetic field may be important slowing down the expansion due to ponderomotive force. At this moment, let us point out that our two dimensional simulations presented in this paper do not take into account the variation of the laser field in the z-direction and thus the influence of the magnetic field components B_x and B_y is described in a simplified way.

Simulation setup

The simulations are performed in 2D geometry (x-longitudinal, y-transverse with respect to the laser propagation) with a linearly polarized laser beam having the electric field in the simulation plane. The laser pulse has a wavelength $\lambda \sim 1.3$ μm and the intensity 10^{16} W/cm^2. The pulse is focused to the spot size of 10λ FWHM and it has a 1 ps long up-ramp followed by a constant intensity. The external magnetic field is applied as initial condition in the whole simulation box with the field strength 0, 30 or 100 T. The simulation box size is $135\lambda \times 40\lambda$ with the resolution of 50 cells per λ and the boundary conditions are periodic in the y-direction and absorbing in the x-direction. The plasma consists of protons and electrons with the temperature of 1 keV and 0.5 keV respectively and it has a linear density profile with the scale length L=300 λ and the maximum density 0.35 critical density (n_c).

Results

In this paper, we typically simulate 7-9 ps of the interaction, which can be divided into two phases as seen in Fig. 1. In the first phase, which is about 3 ps long, the reflectivity reaches a very high value and the dominant role is played by processes related to electron plasma waves,

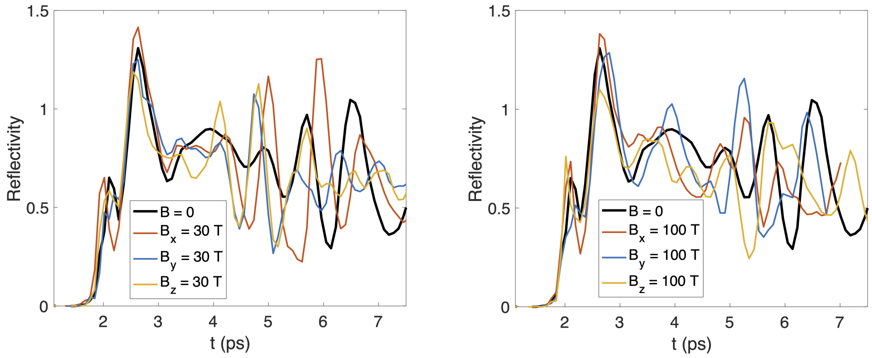

Figure 1: *Temporal evolution of reflectivity in 2D PIC simulations with different geometry of the external magnetic field of the strength 30 T compared with the simulation, where the field is not included.*

in particular SRS and two plasmon decay (TPD). The growth of these processes is influenced by the relatively steeply rising intensity of the laser pulse, which is however necessary due to computational constraints. As we are mainly interested in answering the question whether a few tens of Tesla strong external magnetic field may influence these processes the effect of the steeply rising intensity is not important.

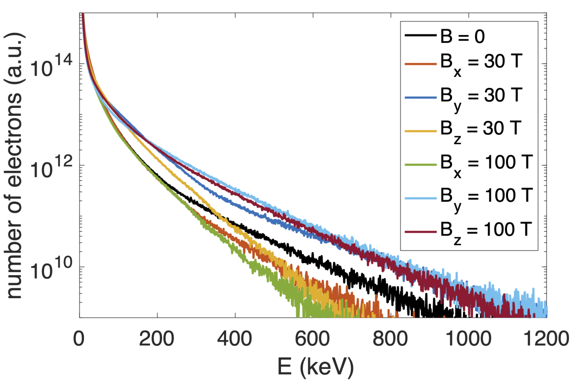

Figure 2: *The energy distribution of electrons in the simulation box averaged over time during the second stage of simulation starting at 3.5 ps. The number of electrons is in arbitrary units.*

The second phase of interaction starts at about 3 ps and lasts until the end of the simulation. In this phase, ions start to move and backscatter the laser beam due to strong SBS which develops in a less dense plasma in front of quarter critical density. Overall, one can say that the average reflectivity does not significantly change due to the external magnetic field. Nevertheless, there are some differences. With the application of external magnetic field, the reflectivity is oscillating earlier due to Brillouin backscattering while without the magnetic field the oscillations start only later. These oscillations are suppressed when the intensity of the magnetic field is increased to 100 T (in the case of B_x and B_z) and the initial spike in the reflectivity is also significantly lower with $B_z = 100$ T.

Although the overall difference in the reflectivity is not too large, the hot electron distribution associated with parametric instabilities is influenced by the field significantly. This can be seen in Fig. 2 which shows the energy distribution of hot electrons averaged over the second phase of the interaction. Based on these spectra one can draw several conclusions. First of all, even the field with the strength 30 T has some influence on hot electron generation/transport and this influence increases with the field strength. Second, there is a strong dependance on the orientation of the magnetic field. While for the longitudinal magnetic field (B_x) the number of hot electrons as well as their temperature are both reduced, the distribution in the case of the transverse field includes significantly higher number of hot electrons. This is particularly significant with the magnetic field strength 100 T, while the case of B_z = 30 T is an exception. There are two hypothetical explanations of this effect. The magnetic field reduces the generation of plasma waves associated with the absorption process in the transverse direction with respect to the field lines or the field can also reduce the flux of hot electrons outside the simulation box or even outside the region of their generation. For example, the gyro-radius of relativistic electron in the field with the strength 100 T is about 13 λ which is significantly less than the simulation box size. Although the simulation is 2D, the particles have 3 velocity components so the gyration in the x-z or y-z plane is possible too. The results from the simulation with $B_z = 100$ T indicate that the gyration is indeed important. However, a large 3D simulation might be necessary to conclude whether such process is important for weaker magnetic fields and different geometries.

Conclusions

In conclusion, we have demonstrated that the magnetic field strength of several tens of Tesla may have influence on the parametric instabilities and hot electrons in the laser-plasma interaction volume. The number of the hot electrons is reduced when a strong longitudinal magnetic field is applied. The magnetic field may also reduce the transport of hot electrons from the region of their generation (mostly around quarter critical density) by forcing them to gyrate around the field lines. Larger 3D simulations might be needed to give a conclusive answer about the influence of tens of Tesla field in different geometries.

Acknowledgments

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