Interaction of multi-PW class laser pulses with underdense plasmas

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Abstract

Regular electron bunches undergoing extremely high acceleration emulating the behavior of electrons near black holes are shown to occur in underdense plasma irradiated by multi-PW laser pulses with intensity over 10^{22} W/cm^2. Interaction of multi-PW laser pulses with underdense plasma, in the regime of strong relativistic wave-breaking, is investigated via fully relativistic 3D particle-in-cell simulations including ion motion and radiation reaction. The effect of a transverse cylindrical plasma wave in laser pulse wakes on the formation of regular electron bunches under extremely high acceleration, w, suitable for detection of Hawking-Unruh temperature $T_H=\hbar w/2\pi k_B c$ is shown and analyzed.

1. Introduction

Recently, the power of femtosecond laser systems has exceeded petawatt levels and has been growing continuously [1]. Such powerful lasers may open up new approaches to studying space-time, vacuum, and particle physics via creating super-strong fields. In particular, electron acceleration can exceed 10^{26} g, where g is the gravitational acceleration on the surface of the Earth. Such high instant acceleration could allow investigations of very weak Hawking-like effects [2-8] and time-resolved Compton scattering [9]. A laser pulse with its normalized vector potential being $a_0=eE_L/mc\omega$, where ω is the pulse frequency, can provide maximal instant electron acceleration $w=ca_0\omega$. Interaction of electrons undergoing such acceleration with a probe light pulse with its frequency ω_S could result in a broadening of the spectrum of the probe light as $\Delta\omega_S/\omega_S=\sqrt{(a_0 2\hbar\omega/mc^2)}$ [7,8]. Such broadening may become detectable for $a_0>100$ overcoming the common Doppler broadening in plasma if the electrons have a low energy and velocity spreads and undergo the equal instant acceleration. However, the problem is how to produce such electrons under super-strong acceleration.

The purpose of the paper is not to study electron acceleration up to high energies. In contrast, we try to find conditions for the formation of a number of electrons undergoing strong linear acceleration and having low spreads in transverse velocities. For that, we examine the propagation of femtosecond laser pulses with intensities I=10^{22}-10^{24} W/cm^2 focused in an underdense plasma with the use of fully relativistic 3D particle-in-cell simulations including all the necessary processes such as ion motion and radiation reaction. We analyze effects of pulse propagation, ion motion with the different mass-to-charge ratio, and radiation reaction on the formation of regular electron sub-systems under instant super-acceleration. The possibility of the detection of Hawking-like effects in presented regimes of acceleration with use of the Thomson scattering [8] is discussed

2. Simulation model

The interaction of multi-PW class laser pulses with underdense plasma in nonlinear regime requires kinetic simulations in a real geometry. We carry out fully relativistic 3D particle-in-cell simulation exploiting the moving window technique using a modified PIC simulation code FPLaser3Dm. The laser intensity is varied from 10^{22}-10^{24} W/cm^2, the laser wavelength λ=1 μm, and the pulse duration is τ=10 fs. The pulses have the energy of ~30 J to ~3 kJ for and their power of ~3 to ~300 PW to reach intensity 10^{22}-10^{24} W/cm^2 at the focus point. The laser intensities exceeding I= 10^{22} W/cm^2 have been already achieved; see for example Ref. [1]. In addition, the maximum laser intensity is approaching I=10^{24} W/cm^2 [10,11], which makes this range of laser intensities interesting for investigation.

3. Simulation results

We have examined the propagation of femtosecond laser pulses with intensities I=10^{22}-10^{24} W/cm^2 focused in an underdense plasma upon the use of fully relativistic 3D particle-in-cell simulations including ion motion and radiation reaction to find conditions for the formation of electron bunches with low transverse velocity spread undergoing strong linear acceleration enough for detection of the Hawking-like effect.

It has been found that classical relativistic self-focusing cannot maintain stable propagation of multi-PW class laser pulses with high intensities because pulses diffract instantly upon creating vacuum bubble in the plasma. Therefore, the acceleration $w{\sim}a_0c\omega$ can be achieved only within a few Rayleigh lengths. Due to strong wave breaking there is no regular plasma wave in the pulse wake as shown in Fig.1(a).

In addition, ion motion becomes essential, especially for M/Zm_p=1. Transverse ion motion originating from a Coulomb explosion results in the formation of a transverse cylindrical plasma wave, which has quite dense electrons and ion peaks on the laser axis as shown in Fig.1(b). The interference of longitudinal and transverse waves results in the formation of electron structures undergoing strong linear acceleration.

The observed electron bunches undergoing super-acceleration are dense enough to produce efficient Thomson scattering of a probing light with a frequency distinct from the laser pulse frequency as shown in Fig.2. However, acceleration of these bunches is still far from the maximal available $w=a_0c\omega$. We have estimated the spectral broadening of the Thomson back scattering light with an incident angle of 90 degrees for a probe pulse from the system to detect space-time effects. It gives a value of $\Delta\omega_S/\omega_S$ ~0.2-0.5%. Theoretically, such values allow detection of Hawking-like effects by the proper choice of the frequency of the scattered light, ω_S. However, rather broad transverse energy spreads in these bunches may make the experimental realization of acceleration broadening difficult.

In addition, radiation reaction effects on the electron dynamics also become strong. It dissipates about 10 % of electron energy for the case of $I=10^{24}$ W/cm^2. The radiation reaction is provoked by Compton scattering of the backward radiation by relativistic electrons; the backward radiation is a result of backward Raman scattering of laser light.

4. Conclusion

Several new physics on the interaction of multi-PW lasers with intensities $I=10^{22}$-10^{24} W/cm^2 and underdense plasmas have been found upon the use of fully relativistic 3D particle-in-cell simulations including ion motion and radiation reaction. The formation of electron bunches with low transverse velocity spread undergoing strong linear acceleration enough for detection of the Hawking-like effect has been observed.

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6. References

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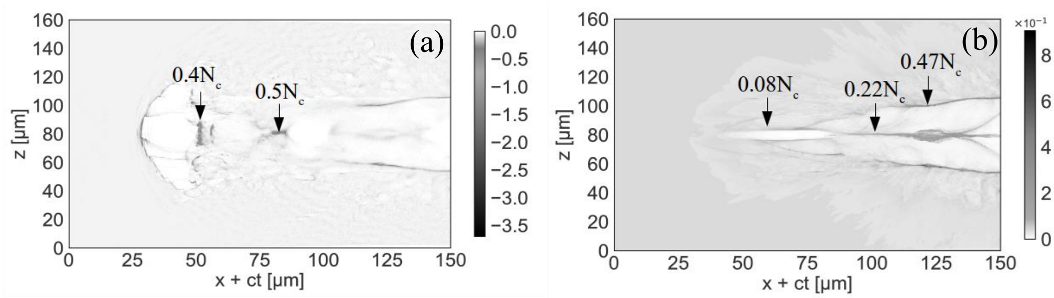

Fig.1 xz cross section of (a)the electron density and (b) ion density. The laser pulse intensity is I=10^{24} W/cm^2, and mass-to-charge ratio is M/Zm_p =1; t=625 fs. (a) The initial plasma density is N_e=5.0x10^{19} cm^{-3}. The electron densities at x=80 μm and x=120 μm are N_e=0.15N_{cr} and N_e=0.08N_{cr} respectively. (b) The initial plasma density is N_e=5.0x10^{19} cm^{-3}. The ion densities are N_i=0.08N_{cr}, N_i=0.22N_{cr} and N_i=0.47N_{cr} at indicated by arrows: x=60 μm, x=100 μm, and x=125 μm, respectively.

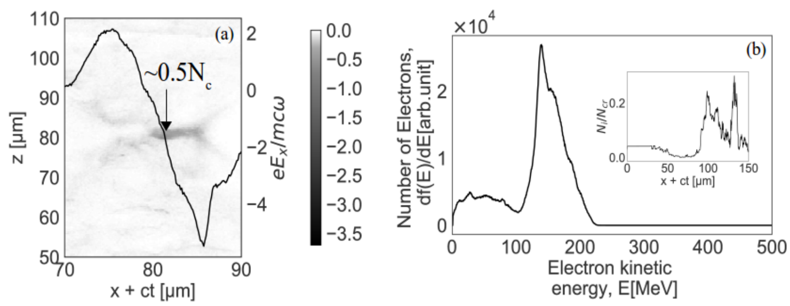

Fig.2 (a)Electron density, laser field in the p-plane, (b) energy spectrum of the bunch, and ion density for plasma density N_{e0} = 5.0x10^{19} cm^{-3}, intensity I=10^{24} W/cm^2, and mass-to-charge ratio M/Zm_p=1; t=625 fs. The average energy of electrons is about 150 MeV with the energy spread of ~20%.