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Laser-driven electron acceleration in hydrogen pair-ion plasma containing electron impurities

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Research Article

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Abstract

In this paper, the intense laser heating of hydrogen pair-ion plasma with and without electron impurities through investigation of related nonlinear phenomena has been studied in detail, using a developed relativistic particle-in-cell simulation code. It is shown that the presence of electron impurities has an essential role in the behavior of nonlinear phenomena contributing to the laser absorption including phase mixing, wave breaking, and stimulated scatterings. The inclusion of electron into an initial pure hydrogen plasma not only causes the occurrence of stimulated scattering considerably but also leads to the faster phase-mixing and wave breaking of the excited electrostatic modes in the system. These nonlinear phenomena increase the laser absorption rate in several orders of magnitude via inclusion of the electrons into a pure hydrogen pair-ion plasma. Moreover, results show that the electrons involved in enough low-density hydrogen pair-ion plasma can be accelerated to the MeV energy range.

Introduction

Pair-ion plasmas consisting of the positive and negative charged particles of equal mass have attracted special attention in the recent years due to the exhibition of the new state of the matter with unique thermodynamic properties different from ordinary electron-ion plasmas. These plasmas are found in some astrophysical environments (Yu *et al.*, 1986) such as in galactic nuclei. On the other hand, in the laboratory, some pair-ion plasmas such as positron–electron pair plasma is produced in large tokomaks and in the next generation laser–plasma interaction experiment. Moreover, several experimental efforts have been made to produce pure pair-ion plasmas (Zank and Greaves, 1995; Oohara and Hatakeyama, 2003; Oohara *et al.*, 2007). There are some different schemes for producing electron–positron pair plasma in the laboratory. The electron–positron pair plasma can be experimentally generated by injection of a low-energy electron beam into a positron plasma (Oohara and Hatakeyama, 2003). Moreover, according to the academic reports the electron–positron pair plasma is produced via the collision of a wakefield-accelerated electron beam with a multi-petawatt laser (Lobet *et al.*, 2017). In addition, the electron–positron plasmas with unique characteristics can be produced by using a compact laser-driven setup (Lobet *et al.*, 2015; Sarri *et al.*, 2015; Gu *et al.*, 2016; Ribeyre *et al.*, 2016). Since the electron–positron pair plasma generation and maintenance are not easy for longer times due to annihilation, the study of the collective modes in pair-ion plasmas is done in the pair-ion fullerene plasma produced in the laboratory. Recently, making use of a preparation of pair fullerene populations consisting of C_{60}^{+} and C_{60}^{-} in equal numbers, the pair-ion plasmas were created in the laboratory. In this regard, Oohara *et al.* (2005) presented a novel method to generate a pair-ion plasma consisting of only the positive and negative ions of equal mass, using fullerene. Since in the case of fullerene pair-ion plasmas the frequency range of the collective phenomena is limited to the low frequencies due to the massive ions, the light pair-ion plasmas generated in the high-frequency range are suitable for studying the novel collective phenomena. The best example is the parametric scattering of high power laser from these environments studied in the present work. In this regard, since hydrogen is the most fundamental element of the periodic table, the pair-ion hydrogen plasmas consisting of $H^{+}$and H^{-} ions (Oohara *et al.*, 2007) having small mass have been considered in this research. Hydrogen-containing plasmas can be found in a variety of environments including planetary ionospheres, interstellar media (Mendez *et al.*, 2006), and in different industrial processes (Darwiche *et al.*, 2007; Rico *et al.*, 2009) such as surface cleaning and controlled fusion devices (Curran *et al.*, 2000). In these plasmas, the dissociative attachment of low energetic electron (0.75 eV) with an excited hydrogen molecule is the main process of the formation of negative hydrogen ion as

$$e + H_2 \rightarrow H_{-} + H \qquad (1)$$

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So far, a great deal of theoretical work has appeared on the pair-ion plasmas in the literature (Moslem *et al.*, 2007; Saleem *et al.*, 2008; Vranjes *et al.*, 2008; Khan *et al.*, 2014). An analysis of waves and instabilities in the created pair-ion plasma has been presented by Vranjes *et al.* (2008). Moreover, the electrostatic modes propagating along the magnetic field lines in a fullerene pair-ion plasma and also the collective motion of pair-ion plasma in the range of high frequencies in a hydrogen pair-ion plasma were proposed as a reference by Mahmood *et al.* (2009). The space-time evolution of the cyclotron and upper hybrid modes of a warm pair-ion plasma has been studied in the presence of a constant magnetic field (Pramanik *et al.*, 2016). Recently, a number of scientists have been interested in studying the evolution of the linear and nonlinear electrostatic shocks in the pair-ion plasmas (Misra, 2009; Masood and Rizvi 2011, 2012). Meanwhile, Thomson scattering of a pair-ion plasma interacting with an incident electromagnetic wave (EMW) in the collision and collisionless limits has been investigated by Jian (2006). Recently, a number of theoretical investigations have been focused on the phase-mixing phenomenon in the magnetized and un-magnetized pair-ion plasmas (Pramanik *et al.*, 2014, 2015). In addition to above-mentioned works, the linear and nonlinear electrostatic waves were studied in impure pair-ion (pair-ion-electron) plasmas (Saleem *et al.*, 2008; Mahmood *et al.*, 2009). The presence of electrons in these systems has been discovered through observation of ion acoustic wave in recent experiments with fullerene plasmas. Also, as shown recently, the presence of electrons causes the electrostatic solitons to appear in the pair-ion plasma. The excitation of ion sound waves in a pair-ion plasma, through electron beam induced Cherenkov instability, has been also investigated (Ehsan *et al.*, 2016). Although various properties of the pair-ion and electron-pair-ion plasmas have been extensively investigated so far, to the best of our knowledge, the stimulated scatterings from these environments as well as the energy absorption of EMWs in these plasmas have not been addressed yet. So, the goal of the present paper is to study the laser scattering and absorption in both pure and impure hydrogen pair-ion plasmas.

In this paper, a developed fully kinetic electromagnetic particle-in-cell (PIC) simulation code (Mehdian *et al.*, 2015) has been employed to investigate the nonlinear interaction of high power laser with pure and impure hydrogen pair-ion plasmas in detail. For this purpose, the excited modes behavior in these plasmas in the interaction with an intense short-pulse laser relying on the nonlinear phenomena such as wave-breaking and phase-mixing has been studied, and the results have been compared with the behavior of an electron-hydrogen plasma. We have studied the nonlinear laser energy absorption in impure pair-ion plasma varying the electron density number. We have also shown in a characteristic range of plasma density a considerable amount of laser energy is transmitted to the plasma particles in the laser direction. Knowing how the energy of high power laser can be converted to the directed kinetic energy or thermal energy of the plasma particles is important in various applications including the laser fusion schemes, plasma-based particle acceleration, and high-energy electron production.

This paper is organized as follows: In the section 'Modeling and simulation method', the modeling and simulation used in the paper have been presented. In the section 'Nonlinear plasma modes in the pure andimpure hydrogen pair-ion plasmas', the phase-mixing phenomenon in both pure and impure hydrogen pair-ion plasmas has been spatiotemporally scrutinized. The section 'Nonlinear laser absorption in pure and impure hydrogen pair-ion plasmas' is devoted to the investigation of the laser energy absorption rate in the finite-size electron-ion plasma and pure and impure hydrogen pair-ion plasmas relying on the nonlinear phenomena related to the laser absorption. Finally, the conclusion is given in the section 'Conclusion'.

Modeling and simulation method

A quantitative description of laser-driven electron acceleration requires numerical simulations. For this purpose, we now employ a relativistic electromagnetic 1D3V code to focus on the interaction of a short high-intensity laser pulse with the pure and impure hydrogen pair-ion plasmas consisting of the cold ions ($T_{\mathrm{i}} \ll eV$) and the warm electron impurities ($T_{\mathrm{e}} \sim eV$). In the considered configuration, the cold-ion assumption (equivalently the condition of $T_{\mathrm{i}} \ll T_{\mathrm{e}} \sim eV$) has been made to eliminate the heavily damp of the excited electrostatic waves in the system due to ion-landau damping phenomenon. For this purpose, these necessary conditions have been worked out in the considered system by typically choosing the ion temperature in the cold regime, $T_{\mathrm{i}} = 10^{-3} eV$, and the electron temperature in the warm regime, $T_{\mathrm{e}} = 10\ eV$. The other simulation parameters are as follows:

The plasma with a step-like density profile is located in the interval of $80\,\mu\mathrm{m} < x < 200\,\mu\mathrm{m}$ (simulation box with the length $250\,\mu\mathrm{m}$). Simulation is carried out for a laser pulse with wavelength $\lambda_L = 1.6\,\mu\mathrm{m}$, pulse duration $\tau = 50$ fs, and intensity $I = 2.14 \times 10^{18}\, W/\mathrm{cm}^2$ whose electric and magnetic field components are along the y and z directions, respectively.

This normally incident laser pulse has a Gaussian profile with the normalized peak amplitude a which is related to the laser intensity by $I = 1.37(a^2/\lambda_L^2) \times 10^{18}\ \mathrm{W/cm^2\,\mu m^2}$. Forty-eight super-particles are used as per cell in the simulation box where the time and space steps have been chosen $dt = 0.03$ fsand $\delta x = 0.01\,\mu\mathrm{m}$, respectively. It is worth mentioning that all selected parameters used in this paper are normalized as $\tau = t\omega_l$, $P_{x,y} = p_{x,y}/m_{\mathrm{e}}c$, $E_{x,y} = E'_{x,y}e/m_{\mathrm{e}}c\omega_l$, $B_{x,y} = cB'_{x,y}e/m_{\mathrm{e}}c\omega_l$. Here, λ_l and ω_l are laser wavelength and frequency, respectively.

Nonlinear plasma modes in the pure and impure hydrogen pair-ion plasmas

The interaction of short intense laser pulse with plasmas is a challenging area of applied physics including plasma heating (Honda *et al.*, 2000), electron acceleration (Kumar *et al.*, 2010; Mehdian *et al.*, 2014a, 2014b), laser fusion (Klimo *et al.*, 2011; Yan *et al.*, 2012), and astrophysics laboratories (Farley *et al.*, 1999). The comprehensive concepts of this area of physics rely on a thorough understanding of nonlinear phenomena excited in the system, particularly phase mixing and wave breaking. We consider an ultra-intense laser pulse irradiated on a plasma. In this system, the nonlinear effects cause the excited electrostatic waves to become non-periodic and then wave-breaking process appears (Bulanov *et al.*, 2006). Physically, when the fluid speed along the crest of the wave exceeds the wave phase speed the wave-breaking amplitude is reached, consequently the wave starts to break (Modena *et al.*, 1995; Verma *et al.*, 2012). A plasma wave can also break at an amplitude well below its wave-breaking amplitude via mixing of phases. This phenomenon is attributed to the space dependence of the wave characteristic frequency. In this state, the space dependency of the frequency causes the different oscillators (e.g., electrons) to oscillate with their local

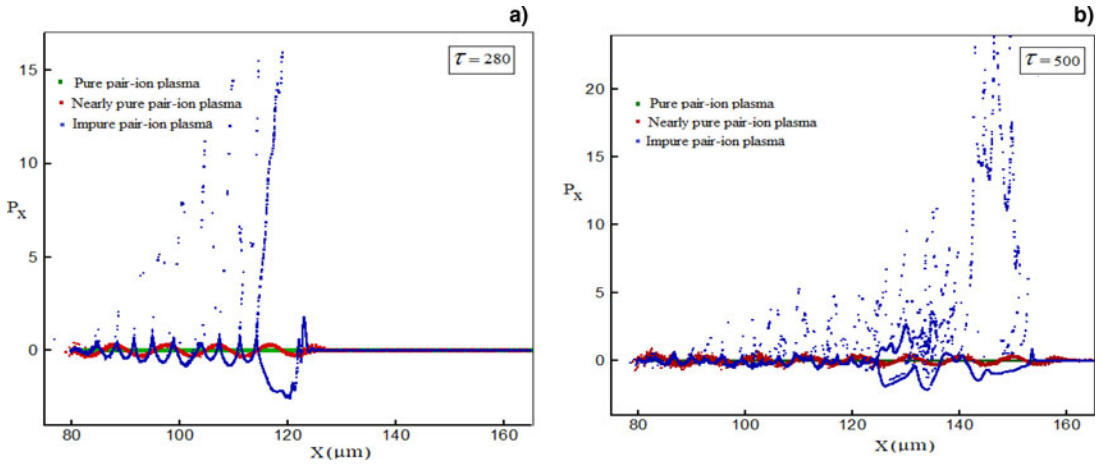

Fig. 1. Longitudinal phase-space associated with the oscillation modes in highly pure ($n_{\mathrm{H}_-}/n_{\mathrm{H}_+} = 1$, green plot), nearly pure ($n_{\mathrm{H}_-}/n_{\mathrm{H}_+} = 0.98$, red plot) and impure hydrogen pair-ion plasmas ($n_{\mathrm{H}_-}/n_{\mathrm{H}_+} = 0.2$, blue plot) at two different times (a) $\tau = 280$ and (b) $\tau = 500$ with $a = 2$ and $n_{\mathrm{H}+} = 0.1$.

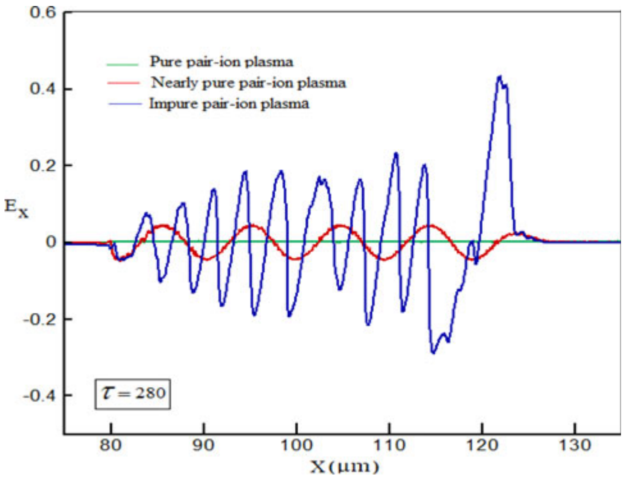

Fig. 2. Space-time evolution of normalized electric field associated with the excited electrostatic wave at $\tau = 280$ for a highly pure (green line), nearly pure (red line), and impure (blue line) hydrogen pair- ion plasma with $a = 2$ and $n_{\mathrm{H}+} = 0.1$.

frequencies. As a result, the phase difference among the adjacent oscillators increases as time elapses and finally a moment comes when the neighboring oscillators' trajectories start to cross one another, leading to a complete destruction in the wave structure and hence the phase-mixing phenomenon occurs (Sengupta *et al.*, 2009; Sarkar *et al.*, 2013; Mehdian *et al.*, 2014a, 2014b). Signatures of phase-mixing have often been seen through the loss of periodicity of wave and through the appearance of density bursts. Moreover, other physical effects such as plasma inhomogeneity, relativistic mass variation, and motion of background massive ions have been recognized as possible sources of phase mixing phenomenon (Maity *et al.*, 2012; Kargarian *et al.*, 2016). Phase mixing or wave breaking phenomena of various normal modes of plasmas are being extensively reported in different plasma contexts theoretically. Recently, the phase mixing phenomenon has been theoretically studied by several authors in different plasma contexts including electron–positron plasmas (Maity *et al.*, 2013a, 2013b), multispecies electron–positron-ion plasmas (Maity, 2014), and pair-ion plasmas (Pramanik *et al.*, 2015). Here, we investigate the phase-mixing of the excited electrostatic modes in a pure pair-ion plasma comprising negative- and positive-hydrogen ions and in an impure pair-ion plasma consisting of negative- and positive-hydrogen ions and electrons, using the mentioned simulation method in the previous section.

Here, in the following simulations, the positive ion number density (n_{i+}) is obtained from $n_{i+} = n_{H+} n_{cr}$. where n_{H+} is a dimensionless constant value considered in the paper as $n_{H+} = 0.1$, 0.03, and n_{cr} is the critical density related to the laser frequency, ω_l, with the relation $n_{\mathrm{cr}} = \varepsilon_0 m_e \omega_l^2/e^2$. In these simulations $\omega_l = 1.17 \times 10^{15}\,\mathrm{s}^{-1}$ so the critical density becomes $n_{cr} = 0.42 \times 10^{27}\ 1/\mathrm{m}^3$. Calculating the positive ion number density for each case from the above relation, the negative ion and electron number densities are obtained using the values $n_{H-}/n_{H+} = \beta$ and $n_{el} = (1 - \beta) n_{H+}$, respectively, where $0 \leq \beta \leq 1$ is a constant value.

The simulation results of the longitudinal phase-space associated with the oscillation modes in highly pure ($n_{\mathrm{H}_-}/n_{\mathrm{H}_+} = 1$), nearly pure ($n_{\mathrm{H}_-}/n_{\mathrm{H}_+} = 0.98$), and impure hydrogen pair-ion plasmas ($n_{\mathrm{H}_-}/n_{\mathrm{H}_+} = 0.2$) with number density $n_{H+} = 0.1$ (n_{H+} is normalized to the critical density, n_{cr}) and laser intensity $a = 2$ have been indicated in Figures 1a and 1b, respectively, for normalized times $\tau = 280$ and $\tau = 500$. One can see that in the impure pair-ion plasma, the excited oscillation modes have considerably lost their periodicity with time, signifying the wave-breaking and the mixing of phases. While, in the nearly pair-ion plasma ($n_{\mathrm{H}_-}/n_{\mathrm{H}_+} \to 1$) the excited oscillation modes with the small amplitude, preserve their form as sinusoidal by time lapse. This is because in the presence of considerable light negative species, namely electrons, in an impure pair-ion plasma, the mixing of the excited modes occurs at a shorter time. Moreover, as we expected, in the highly pure pair-ion plasma ($n_{\mathrm{H}_-}/n_{\mathrm{H}_+} = 1$) there are no excited longitudinal oscillation modes in the system. As a result, for the fixed value of ion-positive number density, by increasing the ratio of the negative ion to positive ion density number, the phase-mixing time increases.

The spatiotemporal evolution of the electric field profile associated with the electrostatic oscillations in the phase-mixing region is illustrated in Figure 2. Here, E_x component refers to the excited electrostatic modes in the system. This component arises due to the space-charge distribution of the plasma species namely electron, negative and positive hydrogen ions. As can be seen in this figure, in a highly pure pair-ion plasma ($n_{\mathrm{H}_-}/n_{\mathrm{H}_+} = 1$) an electrostatic field cannot be excited in the

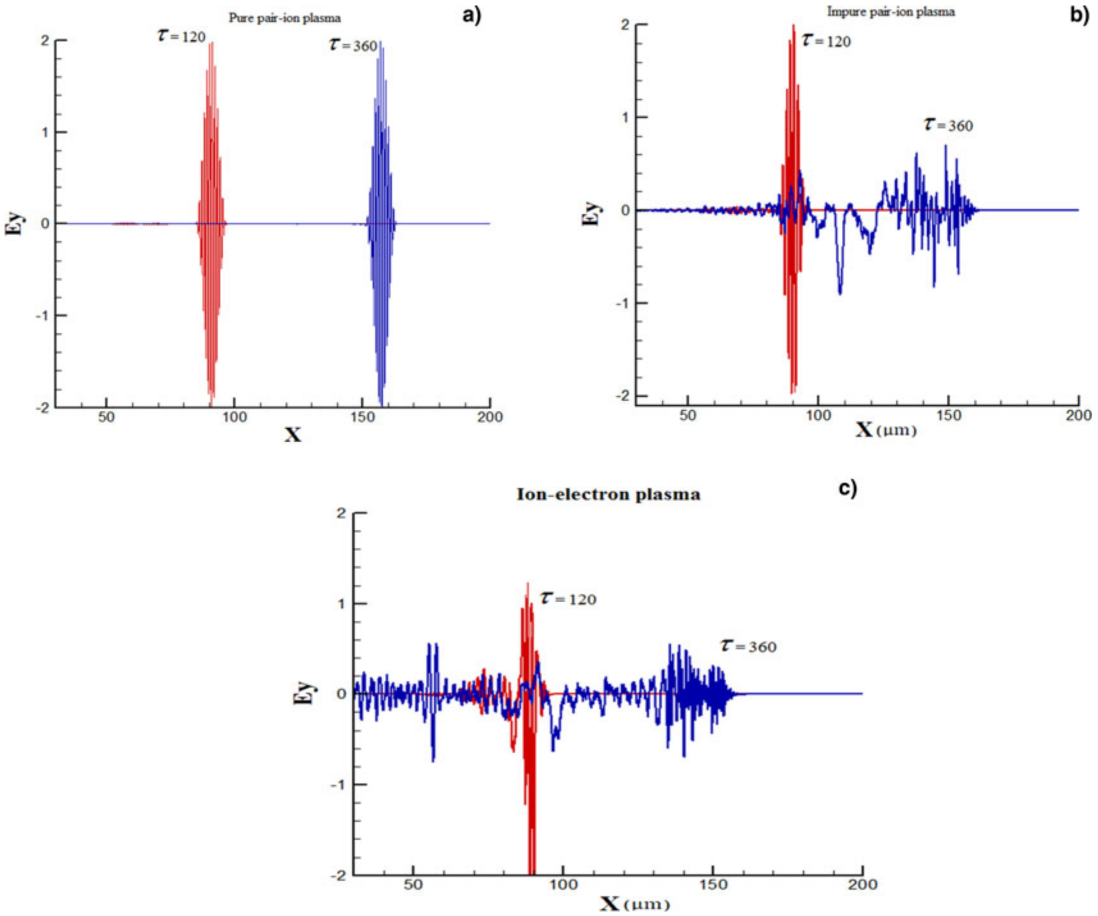

Fig. 3. Space evolution of the transverse electric field at two different times τ = 120 and τ = 360 in the interaction of laser pulse ($a = 2$) with (a) pure hydrogen pair-ion plasma, (b) impure hydrogen pair-ion plasma, and (c) ion-electron plasma. In these figures, the normalized positive hydrogen number density is $n_{H+} = 0.1$.

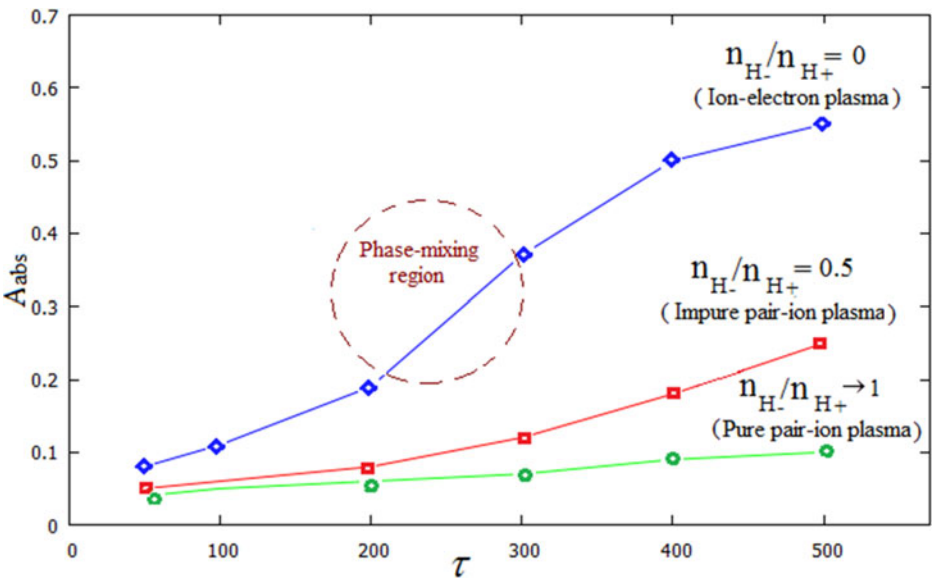

Fig. 4. Variation of the absorption rate of laser pulse ($a = 2$) versus time for interaction with nearly pure pair-ion plasma (green curve), impure pair-ion plasma (red curve), and hydrogen ion-electron plasma (blue curve). In this figure, the normalized positive hydrogen number density is $n_{H+} = 0.1$.

environment due to the approximately equal-mass of the two species while in a nearly pure pair-ion plasma ($n_{H_-}/n_{H_+} = 0.98$) the weak wakefield with a regular electric field can be excited in the presence of electrons. Whereas, in the impure hydrogen pair-ion plasma with $n_{H_-}/n_{H_+} = 0.2$ the excited electric field profile is not regular anymore (non-sinusoidal profile) and the steepening and dips in the peaks of the profile in the phase-mixing region confirm that the wave breaking occurs at the shorter time for this plasma, comparing with the nearly pure pair-ion plasma.

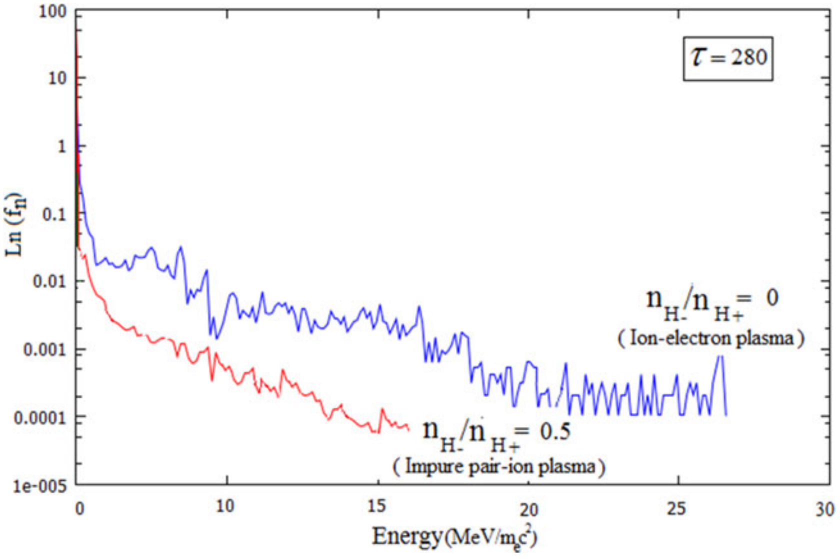

Fig. 5. Logarithmic spectrum for electrons in impure pair-ion plasma (red curve) and hydrogen ion-electron plasma (blue curve) with $a = 2$ and $n_{H+} = 0.1$. The energy axis has been normalized to $m_ec^2 \cong 0.51$ Mev.

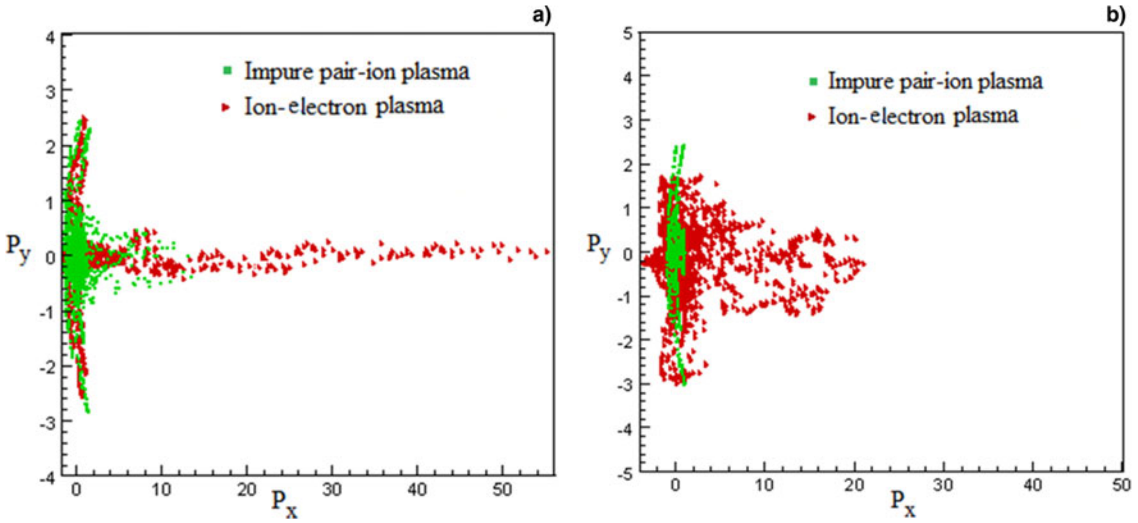

Fig. 6. Snapshots of the electron distribution function in impure pair-ion plasma (green dots) and in ion-electron plasma (red dots) for (a) $n_{H+} = 0.03$ and (b) $n_{H+} = 0.1$ at $\tau = 500$.

We close this section by an investigation into the laser scattering from the finite-size pure and impure pair-ion plasmas. For this purpose, the space evolution of the transverse electric field of high power laser, $a = 2$, interacting with the pure hydrogen pair-ion plasma, impure hydrogen pair-ion plasma, and ion-electron plasma at two different normalized times is illustrated in Figures 3a–3c. As can be clearly seen in these figures, in the interaction of laser with pure pair-ion plasma (Fig. 3a) the laser scattering is negligible and in this case, the laser passes through the medium without any considerable change. While, in the interaction with impure pair-ion plasma (Fig. 3b) at the presence of the electrons, an un-ignorable amount of laser light starts to leave the plasma environment in a long time due to the stimulated scattering. Figure 3c shows that in the interaction of laser with an ion-electron plasma, a significant amount of the scattered light leaves the plasma environment at $\tau = 360$ and so cannot be absorbed any further by the plasma particles.

Nonlinear laser absorption in pure and impure hydrogen pair-ion plasmas

In the interaction of intense short-pulse laser with the finite-size plasma environment, there are some nonlinear phenomena that drastically affect the laser energy absorption rate by the plasma particles. Evidently, the phase-mixing or wave-breaking phenomenon described in the previous section has an important role in the plasma heating and particle energization (Maity *et al.*, 2013a, 2013b). In this section, we will show how these nonlinear phenomena have a substantial role in the conversion of laser energy to the directed kinetic or thermal energy of the charged plasma particles. For this purpose, using the obtained results in the previous section, the behavior of laser absorption rate ($A_{abs} = (W_t - W_{t=0}/W_{t=0})$ where $W_t = \sum_{\alpha=1}^{N}((\gamma_\alpha - 1)m_\alpha c^2)$ is the kinetic energy of all species in each time step with N the total number of the particles, γ_α the relativistic factor, and $W_{t=0}$ the

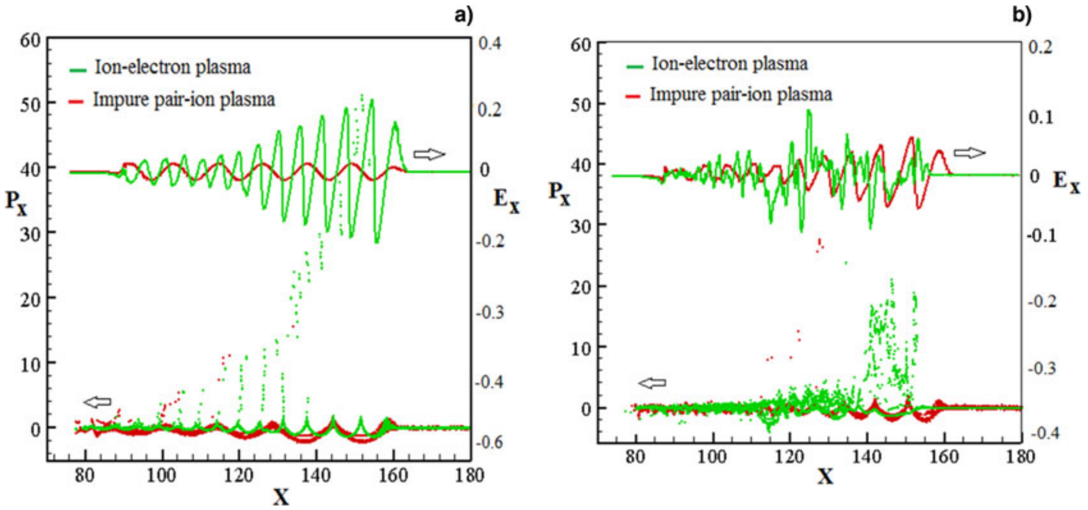

Fig. 7. Evolution of the normalized electric field and longitudinal phase-space for ion-electron (green line and dots) and impure pair-ion (red line and dots) plasmas for (a) low and (b) high plasma densities.

initial kinetic energy of particles) in a finite-size nearly pure pair-ion plasma, impure pair-ion plasma, and ion-electron plasma versus normalized time (τ) for $a = 2$ and $n_{H+} = 0.1$ has been indicated in Figure 4 for a fixed value of the positive ion density. As can be seen in this figure, in the hydrogen ion-electron plasma (topmost curve) the absorption rate increases with time until saturation is reached. With increasing time some nonlinear phenomena such as laser scattering from the finite-size plasma are underway, therefore, a considerable amount of laser energy is reflected from the plasma environment (see Fig. 3c) and cannot be absorbed any further by the plasma particles, resulting in the saturation of energy absorption. Investigation of the absorption curve for such a plasma shows a steeper slope in the absorption curve when the wave-breaking or phase-mixing phenomenon occurs, as shown on the topmost curve, while the absorption curve related to the nearly pure pair-ion plasma (lowest curve) shows that the phase mixing has not yet occurred in this system at the considered time. The absorption curve of impure pair-ion plasma ($n_{H_-}/n_{H_+} = 0.5$) shows that the phase mixing just starts to occur at the maximum time. A comparison of the three curves illustrates that in a nearly pure pair-ion plasma, the least amount of laser energy is transferred to the plasma. This can be attributed to the absence of the considerable amount of electrons (compared with the two other plasmas) playing the essential role in the laser energy transition in this plasma. In other words, in a nearly pair-ion plasma the coupling between the excited modes and plasma particles is loose due to the weak electric field and low amplitude oscillation modes in this system. For the more precise investigation, the logarithmic spectrum of the electrons related to the impure pair-ion plasma and ion-electron hydrogen plasma at $\tau = 280$ is shown in Figure 5. As can clearly be seen in this figure, the excited strong wakefield in these systems can accelerate the electrons to energies in the range of several MeV at $\tau = 280$. Meanwhile, in the ion-electron plasma, the electrons obtain more energy than in the impure pair-ion plasma.

The snapshot of the electron distribution function at $\tau = 500$ for hydrogen ion-electron plasma and impure pair-ion plasma is shown for plasma densities $n_{H+} = 0.03$ and $n_{H+} = 0.1$ in Figures 6a and 6b, respectively. As we expressed, the plasma particles can acquire further energy from the laser in a hydrogen ion-electron plasma than an impure pair-ion plasma. As an interesting result, investigation of the distribution functions shows that for low plasma densities (Fig. 6a) a large amount of laser energy is transferred to the electrons as directed kinetic energy (in the laser direction) to produce the electron beam in the MeV energy range. While for high densities (Fig. 6b) the laser energy is transferred to the particles as thermal energy due to the faster breaking of relativistic electron oscillations (wake wave breaking).

Finally, the longitudinal electric field profile combining with the phase-space of the particles in the x-direction (longitudinal phase-space) have been plotted for both ion-electron and impure pair-ion plasmas in low and high plasma densities in Figures 7a and 7b, respectively. For low density (see Fig. 7a) the acceleration of electrons in an ion-electron plasma by trapping process has been shown well, while this nonlinear process for the low-amplitude excited electric field in an impure pair ion plasma cannot a considerable role to accelerate the particles. However, in high density (see Fig. 7b) the excited electric field starts to break due to phase mixing or wave breaking and so, the transferred laser energy to the plasma particles is mostly as thermal energy. This is because the electrons do not move further in the trapping wave bubbles due to the breaking of these excited longitudinal waves.

Conclusion

In summary, using the PIC simulation method, the laser energy absorption in both pure and impure hydrogen pair-ion plasmas containing electron impurities has been studied relying on the investigation of nonlinear phenomena contributing to the laser absorption such as the wave breaking, phase-mixing, and stimulated scattering. A careful scrutiny of the space-time evolution of the longitudinal space-phase and the fields associated with the laser and excited waves in the system shows that the inclusion of electron impurities into an initial pure pair-ion hydrogen plasma not only causes the occurrence of considerable stimulated scattering but also leads to the faster phase-mixing and wave breaking of the excited electrostatic modes in the system. Moreover, an investigation into the behavior of laser absorption rate in a finite-size pure and impure hydrogen pair-ion plasma demonstrates that the obtained nonlinear phenomena behaviors result in increasing the laser absorption rate in several orders of magnitude via inclusion of the electrons into a pure hydrogen pair-ion plasma target. Finally, as an interesting result, the distribution function of the involved species displays that the laser energy can be transferred to the included electrons to accelerate them in the laser direction in a specific range of the plasma density and an increase in this energy is directly proportional to the contribution of the electron impurities.

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