Research on Structure Formation of Plasmas Dominated by Multiple Hierarchical Dynamics

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We have developed a three dimensional extended particle based integrated code (EPIC3D) in order to simulate complex plasma states where multiply charged ions and free electrons, polarized neutral atoms and molecules, external fields like lasers and induced fields with various frequencies, etc, coexist. The code was parallelized on the Earth Simulator (ES) during FY2003 based on a domain decomposition technique in two dimensional directions in real space. Using the EPIC3D, we successfully performed large scale simulations of high power laser-matter (solid carbon) interaction and found a new ionization dynamics and associated heat transport, which develops in fast time scale of the order of light speed. We investigated the underlying physical mechanism and found that the Cherenkov emission of plasma waves by laser induced fast electrons leads to the ionization. The process may play an important role in various applications utilizing laser-matter interaction such as laser driven particle accelerator, high power X-ray generation using laser-cluster interaction, and fast ignition of laser inertia fusion, etc.

Keywords: multiple hierarchical phenomena, laser-matter interaction, heat transport, Cherenkov emission

1. Introduction

In the present research subject, we aim to understand nonlinear interactions between electromagnetic (EM) fields including coherent lasers and complex material state in which various atoms and molecules, multiply charged ions and electrons are mixed. For simulating such plasmas, we have developed a code EPIC3D (Extended Particle based Integrated Code) based on plasma approach by taking into account various new effects such as ionization due to EM fields and electron impact, and also Coulomb collision and relaxation among charged particles [1, 2]. The physics of laser-matter interaction plays a central role in applications utilizing high power lasers, such as laser fusion, laser driven particle accelerator, and laser driven X-ray and neutron sources [3, 4]. However, an ideal plasma state has been usually assumed and the study taking into account atomic and relaxation processes by which the plasma state is established is rare. In order to understand the underlying physical process, here we studied short pulse laser-solid (or thin-film) interactions utilizing the EPIC3D and investigated the ionization dynamics in detail.

2. Turbulence excitation in laser-sold interaction and propagation of ionization waves

Using the EPIC3D on Earth Simulator, we performed simulations of interaction between a solid carbon (Z=6) and a short pulse laser with focused intensity of 2×10^{18}w/cm^2 (normalized amplitude a_0~1), wavelength of 820nm, pulse length of 100fsec (Gaussian shape). Figure 1 illustrates the time history of (a) laser energy, and electron and ion kinetic energies, and (b) ion number (PIC particle) with different charge state q, i.e. C^{+q}. In the first half of the interaction with the laser pulse, C^{+1} and C^{+2} are produced, whereas in the latter half, C^{+4} appears through C^{+3} from t=90fsec at which the laser intensity becomes maximum. C^{+5} and C^{+6} are also produced, but the generation rate is low.

Figure 2 shows the ion density distribution, where all charge states are summed up. In the beginning of the interaction, a localized high density distribution is formed in a narrow region near the surface and from this region, ionization convectively develops toward the inside of the solid. A flat density distribution which originates from C^{+2} ions is found to be formed around t=90fsec. This process corresponds to the propagation of the ionizing wave front of C^{+2} ions and

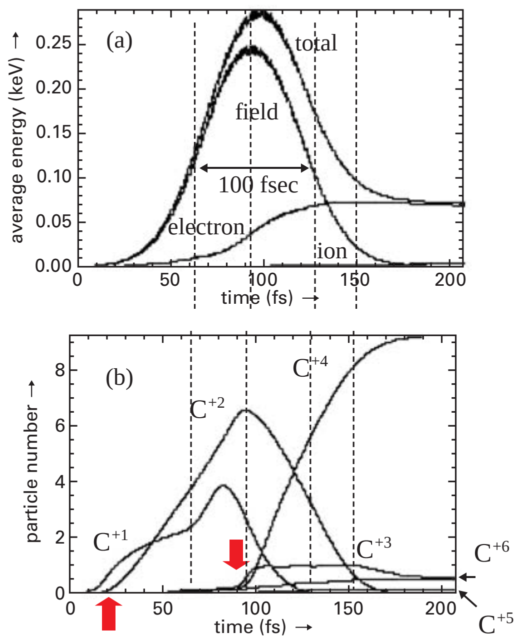

Fig.1 (a) time history of laser, and electron and ion kinetics energy. (b) time history of ion density with charge state C^{+q} (q=1-6).

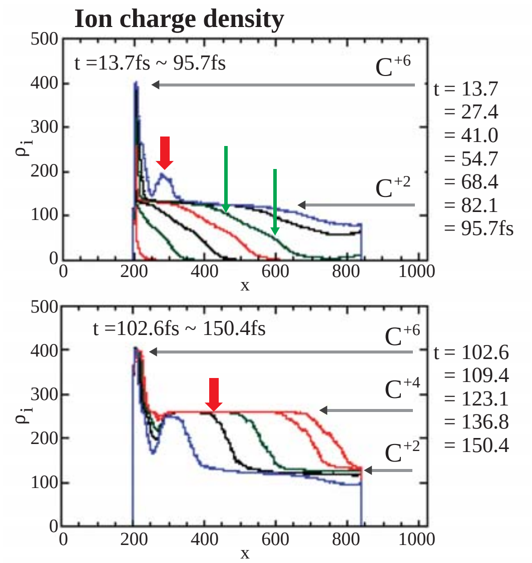

Fig.2 Ion density distribution for different times. Three arrows corresponds to the density for q=2, 4, and 6 (fully ionized state), respectively.

the propagation speed is relatively high, which is approximately 0.7×10^8m/sec. Furthermore, around t=95.7fsec, a density hump appears around 1.2μm inside from the left-hand side of the solid surface. The corresponding front also convectively propagates toward the inside of the solid, which is similar to that happened in the C^{+2} ionization dynamics. Around t=150fsec where the direct interaction with the laser pulse is finished, a flat density profile originating from C^{+4} ions is formed. This process corresponds to the propagation of the ionization wave front of C^{+4} ions and the propagation speed is a little higher than that in the case of C^{+2}, i.e. which is roughly given by 0.9×10^8m/sec. Thus, the ionization to the C^{+2} and C^{+4} states is successively triggered and the front propagates with avalanche-like nature.

Figure 3 illustrates the 2-dimensional distribution of ion density which corresponds to those in Fig. 2. The propagation of ionizing front of C^{+2} is seen in Fig. 3(a) (t=68.4fsec). Micro-scale complex spiky structures are seen around the propagation front. The region around x=300 in Figure 3(b) shows a density hump due to the generation of C^{+3} and C^{+4} ions, which propagates keeping prominent spiky structures as seen in (c) and (d).

Figure 4 shows the spatial distributions of (a) longitudinal (x-direction) electric fields and (b) corresponding ion density [region indicated by square in Fig. 3(b)]. In Fig. 4(a), a spiky structure similar to wake fields is seen ahead of the density hump due to C^{+3} and C^{+4} ions. The field is oscillating with a wavelength around 50nm. Since the oscillation satisfies a relation $\omega_p \cong kv_e$, where v_e is the typical velocity of heated fast electrons and ω_p is the plasma frequency. Therefore, the fields may result from the Cherenkov emissions of plasma waves induced by the fast electrons. In particular, it is found that the excited plasma waves develop to a turbulent state as seen in Fig. 4(a) and ionizations are triggered by the electric fields. The domain of the turbulence and corresponding ionization front propagate in the x-direction. The high density region near the surface which corresponds to C^{+5} and C^{+6} ions is also found to propagate with a slower time scale than that of the C^{+4} ionizing front.

In order to understand the interaction between such a turbulent excitation and ionizing plasma in detail, we investigate (a) electron density and (b) electron temperature, and also (c) ion temperature in Fig. 5 at t=64.8fsec in the case of a_0=5. The spatial distribution of E_x is also shown in Fig. 5 (a). It is found that the ionization to C^{+4} is quickly developed in the region (A) where the plasma is in a turbulent state. On the other hand, the turbulent fields are found to disappear in the region of the upper stream (B), where electrons are heated and the electron temperature increases. This is due to the fact that the turbulent energy is converted to that of electrons via wave-particle interaction. Furthermore, a sheath electric field originating from the thermal conduction due to the formation of electron temperature gradient is established in the x-direction. In addition to the electron heating, ions are also heated as seen in Fig. 5(c) in a fast time scale through collisional process between electrons and ions.

3. Summary

A plasma wave turbulence is caused by the Cherenkov process in the solid where the laser field does not penetrate and the turbulent electric fields dominate the ionization dynamics. Such an elementary process may play an important role in various studies utilizing high power lasers.

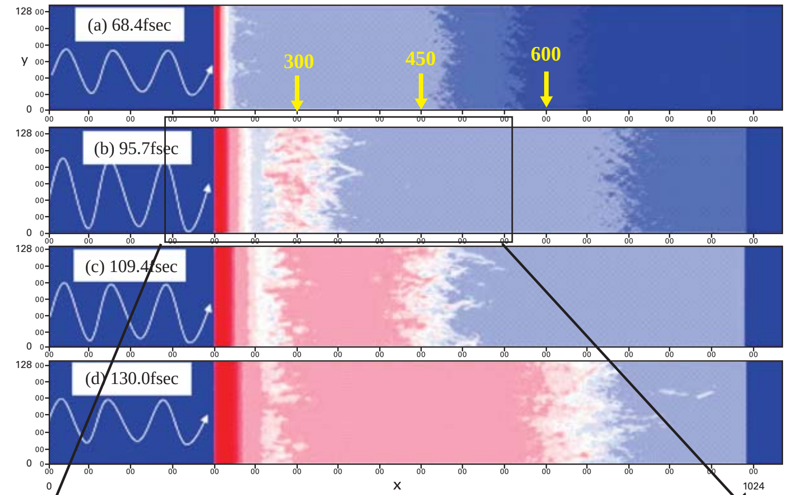

Fig. 3 Ion density dis- tribution in 2 dimensional simulation domain at four different times. Propagation of the ionization front of charge state 4 is seen having a complex finger-like structure

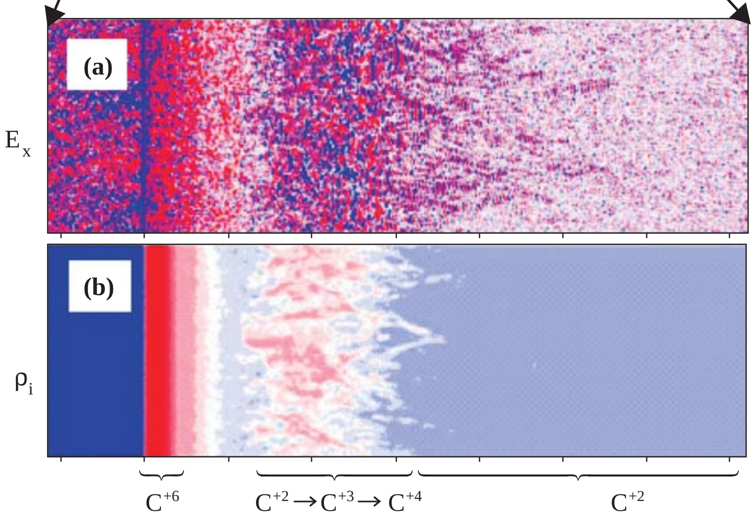

Fig. 4 Distribution of longitudinal electric field E_x and corresponding ion density at t=95.7fsec. Micro-scale finger-like structure at the ionization front corresponds to Cherenkov emission of plasma waves induced by fast electrons.

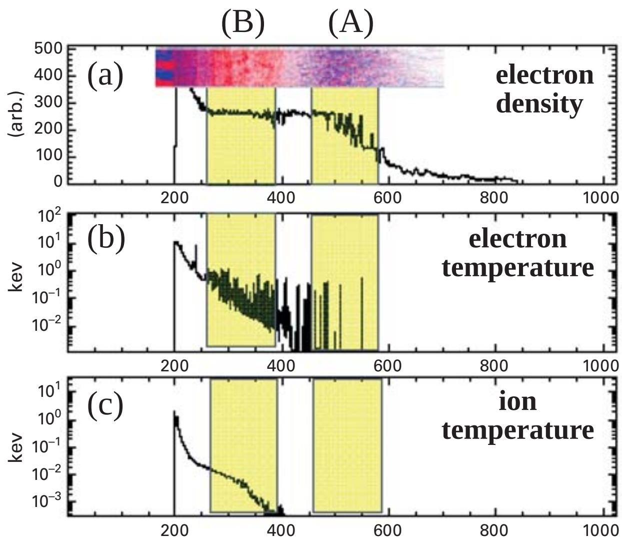

Fig. 5 (a) electron density, (b) electron temperature, and (c) ion temperature at t=68fsec in the case of a_0=5. The figure in (a) shows the distribution of E_x.

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多階層ダイナミックスが支配するプラズマの構造形成に関する研究

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本研究課題では、コヒーレントなレーザー場をはじめとした様々な波長領域の電磁場と、中性原子や分子、多価イオンや電子が混在した複雑な物質状態との非線形相互作用を理解することを目的に、マクロないしセミマクロな構造の解析に適したプラズマ手法を基礎に、電磁場や粒子衝突による物質の電離・再結合過程、生成された荷電粒子間のクーロン衝突や緩和過程等の様々なミクロ過程をモデル的に導入したシミュレーションコードEPIC3D（Extended Particle based Integrated 3-dimensional Code）の開発を系統的に進めている。レーザーと物質との相互作用の物理は、レーザー駆動の加速器やレーザークラスター相互作用を利用した高パワーX線源や中性子源、レーザー核融合の高速点火等の様々の応用研究に重要な役割を果たす。しかし、これまでの多くのプラズマ粒子シミュレーションは初期に理想的なプラズマ状態を仮定しており、原子過程や緩和過程を正確に取り扱った例は少ない。本コードは、2003年度中に、領域分割法を用いることにより、地球シミュレータ上において実空間の2次元方向に対して並列化されている。このEPIC3Dを用いて、高パワーレーザーと物質（炭素固体）との相互作用のシミュレーションを実施し、光速のオーダーの速い時間スケールで進行する新しい電離ダイナミックスとそれに伴う熱伝導過程を見出すことに成功した。この物理機構を詳細に調べ、レーザーによって生成された高速電子によるプラズマ波のチェレンコフ放射とそれによるプラズマ波乱流がこの電離過程を引き起こしていることを見出した。

キーワード：多階層現象，レーザー物質相互作用，熱伝導，チェレンコフ放射