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論文内容の要旨

The interaction of intense laser electromagnetic (EM) wave with plasma has become a basic and important problem in plasma physics due to its potential applications, ranging from astrophysics to fusion science. Inertial confinement fusion (ICF) has been considered as an attractive energy source, which motivates many scientists to pay much attention to the research of intense laser-plasma interactions. On the other hand, the particle acceleration by intense laser interacting with plasma also became a very attractive research topic because of its widespread applications, such as laser-induced nuclear reaction, particle acceleration, medical treatment, radiography and so on.

Intense laser pulse interacting with plasma is a source of various electronic instabilities. When an laser EM wave propagates in an underdense plasma, many electronic instabilities, such as stimulated Raman scattering (SRS) instability and stimulated Brillouin scattering (SBS) instability then can be excited and developed. These instabilities do not appear isolated but are often interconnected in the real intense laser-plasma interaction. In the past years, large efforts have been put into the studies of SRS and SBS, which produce energetic particles to preheat the core of a fusion pellet. Recently, a new type of stimulated scattering on the so-called Stimulated Electron-Acoustic Wave Scattering (SEAWS) instability was proposed by Montgomery et al., to reinterpret a underdense plasma data from the Trident laser facility. This novel SEAWS induced by relativistic laser interacting with a subcritical density plasma layer has been studied by Nikolić et al. by means of one-dimensional fully relativistic EM Particle In Cell (1D-PIC) simulations.

When an ultra-intense laser pulse propagates in a plasma, a dispersion effect comes to play an important role due to the finite inertia with which plasma particles respond to the high laser EM field, while plasma density redistribution is caused by the ponderomotive force that pushes the plasma particles away from the region of maximum EM field. These effects can lead to well-known nonlinear phenomena such as self-focusing, transparency of an overdense plasma and the generation of EM soliton. Relativistic solitons are EM structures self-trapped by locally modified plasma refractive index through the relativistic plasma particle mass increase and the plasma density redistribution by the ponderomotive force of an intense laser pulse. These solitons are generated behind the front of the laser pulse and are made of nonlinear, spatially localized low-frequency EM fields with a close to zero group velocity. A fairly large part of the laser pulse energy can be transformed into EM solitons. The formation mechanism and spatial structure of EM soliton have been investigated by theoretical analysis and Particle-In-Cell (PIC) simulations. The solitons found in previous particle simulations consist of slowly or non-propagating electron density cavities inside which EM fields are trapped and oscillate coherently with frequencies below the unperturbed electron plasma frequencies. In homogeneous plasmas, solitons have been found to exist for a long time, close to the regions where they are generated and eventually decay due to their interaction with fast particles; as a result, the soliton energy is transformed into the fast particle energy. In inhomogeneous plasmas solitons are accelerated with the acceleration proportional to the plasma density gradient toward the low density side. When a soliton reaches some critical region, for example, the plasma-vacuum interface, it radiates away its energy in the form of a short burst of low-frequency EM radiation.

Particle acceleration by laser pulse propagating in plasmas has also become a very attractive research topic due to the advent of short-pulse, high-intensity lasers and their many potential applications. Various concepts of laser accelerators in a plasma, such as, beat-wave accelerator, laser wakefield accelerator, etc., are presently under discussion and investigation as possible approaches to accelerate to ultra-high energies. When an intense laser pulse propagates in underdense plasma, by backward and forward SRS, and other nonlinear processes e.g., the ponderamotive force of an intense laser pulse, a large amplitude electron plasma wave can be excited. This large amplitude plasma wave has a very high phase velocity close to the group velocity of a laser pulse, and can be used to accelerate electrons, protons or ions to high energies.

My research motivations come from inertial confinement fusion and particle acceleration. In the thesis, the researches are mainly concentrated on instabilities, relativistic EM soliton and electron acceleration, induced by linearly-polarized intense laser interacting with underdense plasmas, by means of fully relativistic EM 1D-PIC simulations.

The first part is the generation of accelerated large amplitude relativistic EM solitons in a long underdense homogeneous plasma. In simulations, ions are initially placed as a neutralizing background and are kept immobile. When laser enters the plasma layer, the first stage is dominated by SRS interactions. In our low density and long plasma condition, Stimulated Backward Raman Scattering (B-SRS) has shorter growth time than Stimulated Forward Raman Scattering (F-SRS). A nonlinear interplay between B-SRS and F-SRS produces a strong spatial modulation of the laser pulse. After that, there is typically the stimulated Raman cascade in the EM frequency spectra and wavenumber spectra both for backscattered and transmitted EM waves; which effectively scatter incident laser energy to higher order (Stokes and anti-Stokes) EM modes. In the later time, the continuing instability growth through stimulated Raman cascade down-shifts the power maximum from the fundamental to the bottom of EM wave spectra. They clearly reveal a tendency of a transition from the stimulated Raman cascade regime to the regime of energy accumulation at the about electron plasma frequency, the so-called photon condensate. The cascade-to-condensate transition becomes more pronounced with increasing laser intensity. After the photon-condensate process, the standing, backward- and forward-accelerated large amplitude relativistic EM solitons are observed. As a new research results, we found that the acceleration of EM soliton depends upon the incident laser intensity in a homogeneous plasma. The accelerated solitons are accelerated toward the plasma-vacuum interfaces and it radiate their energy in the form of low-frequency intense EM bursts. The frequency of the EM wave trapped inside soliton region is about the half of the unperturbed electron plasma frequency, while the corresponding ES frequency is about four and half times the unperturbed electron plasma frequency. The transverse electric and magnetic field have half- and one-cycle structure in space, while the corresponding ES field has one-cycle structure in space, respectively.

The second part is the generation of ion-vortices in phase-space in subcritical density plasmas ($n_{cr}/4 < n/\gamma < n_c$, γ - relativistic factor). When intense laser light enter a subcritical plasma, a stimulated trapped electron-acoustic wave scattering (T-SEAWS) instability takes place. It can be well-explained by a resonant three-wave parametric decay of the relativistic laser pump into the slowed Stokes EM wave with $\omega_s \sim \omega_{pe}$ and the trapped electron-acoustic wave (EAW) with $\omega_{eaw} < \omega_{pe}$ in the early stage, where ω_{pe} is the electron plasma frequency. There appear a rapid growth and strong localization of the Stokes wave by forming narrow intense EM soliton-like structures with downshifted laser light. The train of EM soliton-like structures get irradiated through the front vacuum-plasma boundary in a form of intense coherent reflection of the downshifted laser light. Large trapped EAW quickly heats up electrons to relativistic energies, which eventually suppresses the T-SEAWS instability. The ion dynamics does not play a significant role on the early physics behaviors of T-SEAWS. However, the ion wave created in the upstream region breaks in time and generates a large amplitude relativistic EM soliton in its breaking place. Thus this forms a large ES field inside. As a new phenomenon, we found that an ion-vortex (ion-hole) structure in phase-space is created because the large part of ions are accelerated and trapped by the regular EM and ES fields inside soliton. As this large amplitude EM soliton is accelerated in the backward direction, several ion-vortices in phase-space are generated due to the continuing ion acceleration and trapping.

In the third part of this thesis, the formation of high-quality and well-collimated return relativistic electron beam in long underdense homogeneous plasma is studied. A short ultra-relativistic electron beam acceleration by an intense laser pulse in a finite plasma is examined by 1D-PIC simulations. The mechanism is the combined effect of the electron acceleration by longitudinal field: synchrotron radiation source (SRS) and driven oscillatory relativistic electron plasma wave and the electrostatic (ES) Debye sheath field at the plasma-vacuum interface. The standard dephasing limit and the electron acceleration process are briefly discussed. The novel point is that, at relativistic laser intensities, a phenomenon of pushed short high-quality and well-collimated return relativistic electron beam with thermal energy spread in the direction opposite to laser propagation, is observed. It operates like a two-stage accelerator. In the initial phase: rapid electron heating by the SRS driven relativistic plasma wave allows a massive initial electron blow-off into a vacuum. Large potential Debye sheath fields are created which further accelerate electrons (second stage) to ultra-relativistic beam energies. The mechanism of the beam formation, its characteristics and the time history in x and p_x space for selected test electrons in a beam, are analyzed and clearly exposed.

論文の審査結果の要旨

本学位論文は、慣性核融合研究、天体プラズマ研究、X線源、粒子加速などで重要となる、高強度電磁波とプラズマの相互作用における非線形過程を相対論的電磁粒子モデルに基づく計算機シミュレーション手法を用いて解明したものである。本論文ではプラズマ密度、空間スケール、入射電磁波強度などに関して、これまでの研究にない広いパラメータ領域での長時間にわたる詳細なシミュレーション及び精密な解析を行った結果、レーザーと低密度プラズマ相互作用により形成されるソリトンの加速が入射レーザー強度に依存すること、レーザーと亜臨界密度プラズマの相互作用により形成されるソリトンにより、イオンの位相空間上に渦構造が形成されること、低密度プラズマと高強度レーザーの相互作用によりエネルギーが狭い領域に集中した高エネルギー電子ビームが生成するといった新しい知見を得ている。

第 2 章では、低密度で非常に長い一様プラズマに超高強度電磁波を入射した際の物理過程を空間一次元速度空間三次元の相対論的電磁粒子シミュレーションにより詳細に調べている。用いたシミュレーションモデルでは、系の中央部にプラズマを、その両側に真空領域を配置し、真空領域に置かれたアンテナから電磁波を発生させている。ラマン散乱過程、ラマンカスケード過程、光子凝縮などの物理過程を経た後に、電磁エネルギーが狭い領域に局在する電磁ソリトンが生成されることを観測した。これ以前の研究では、密度勾配のないプラズマ中ではこのような電磁ソリトンは定在するとされてきたのに対し、入射レーザー強度を大きくするに従って、定在する場合、入射レーザー進行方向と逆の方向に加速され強い散乱波を発生する場合、レーザー進行方向に加速され強い透過波として現れる場合があることを見いだした。さらに、この加速の原因を電子の分布関数及び電磁力のバランスから考察している。

第 3 章では、ラマン散乱不安定性の臨界密度より大きい密度の一様プラズマ中に超高強度レーザーを入射した際、電子音波散乱過程を経た後、電磁ソリトン状の構造が形成されることを空間一次元速度空間三次元の相対論的電磁粒子シミュレーションにより観測した。シミュレーションモデルの空間的配位は第 2 章の場合と同じであるが、プラズマ密度が大きいことと、系のイオンの運動も取り入れていることが異なっている。ここで現れたソリトン状の構造は時間と共にレーザー進行方向の逆方向に移動し、プラズマ境界を通過し、強い散乱波として真空中を伝播し、強い反射波として観測される。このソリトン状の構造により、イオンの座標、運動量位相空間上に渦構造が形成され、その渦構造は電磁ソリトン構造が伝播した後もプラズマ中に存在することを見いだした。

第 4 章では、低密度プラズマへの超高強度レーザーの入射によるラマン散乱過程に伴う電子加速を詳細に調べている。ここで用いたモデルは第 2 章と同じであるが、プラズマ密度、温度、プラズマ長などのパラメータが異なっている。レーザー強度及びプラズマ密度を適切に選ぶことによって、ラマン散乱過程によって励起された静電電子波により、電子波伝播方向に電子が加速され、プラズマ境界で時間的に変動するシース電場によるそれらの電子の反射過程を経て、レーザーの入射方向と逆方向に進行するエネルギーが狭い領域に集中した電子ビームが形成されることを見いだした。その加速及びビーム形成過程、性質、座標と運動量の位相空間上での典型的粒子の振る舞い等を詳細に解

析し、明らかにした。

以上の研究成果は、これまでにない新しい結果であるとともに、レーザープラズマ相互作用の研究、さらにはエネルギー開放系におけるプラズマ自己組織化などの複雑性科学の研究に大きな貢献をするものといえる。　従って、本審査委員会は、本論文が博士学位論文として十分な水準にあり、本専攻にふさわしい内容を持つものであると結論した。