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論文内容の要旨

The majority of known universe consists of the plasma. Stars, stellar and extragalactic jets and the interstellar medium are examples of astrophysical plasmas. Moreover, a wide variety of plasma experiments have been performed in the laboratory. Since the particle dynamics in a plasma is governed by internal fields due to the nature and motion of particles themselves and by externally applied fields, it is very difficult to describe dynamics and predict behavior of real plasma systems. Complexity in plasmas is predominately characterized by the nonlinear excitation of an enormous variety of collective dynamical modes. In a plasma system there can be a rich interplay and coupling of these modes. It is possible to have modes with growing amplitudes, as a result of instabilities. Instability phenomena are important in a wide variety of physical situations involving dynamical processes in a plasma

During a large amplitude electromagnetic (EM) wave propagation through a plasma, a large number of nonlinear processes may occur. Some applications are based on processes that occur during intense EM wave-plasma interaction, on the other hand, for certain applications many of these processes play a destructive role. In both cases, however, there is an interest to control and optimize responses of plasmas. There exist considerable interest in the study of relativistic laser plasma interaction relevant to a number of potential applications. These include: inertial confinement fusion (ICF), the simulation of astrophysical processes in laboratory, X-ray sources, nuclear reactions, properties of matter at very high density and pressure, acceleration of particles (relativistic electrons, MeV protons) , RF plasma heating and current drive in tokamaks, etc. Laser fusion represents one of the most challenging goals in current energy research. An intense laser beam which penetrates a plasma is a source of free energy, and a plasma is able to efficiently convert laser energy into its modes. Some of the processes in a plasma can seriously affect laser beam and change the performance of laser-fusion target. Since fusion pellets are surrounded by large regions of coronal plasma, a general issue in laser fusion that has been of considerable interest in past decades is growth of instabilities in underdense plasmas. Experiments, theory and computer simulations agree on a possible complex interplay between various laser-plasma instabilities.

The study of parametric instabilities in laser plasmas is of vital importance. Most of these instabilities represent the resonant coupling of the intense EM wave to two other waves, in particular scattered EM wave and electrostatic (ES) wave (scattering instabilities). The excitation of scattering instabilities is through a positive feedback loop by which the beating between the EM field of the laser and scattered light matches the frequency of longitudinal ES mode of the plasma. These instabilities are nonlinear wave-conversion mechanisms and can be very efficient in a plasma. Stimulated Raman and stimulated Brillouin scattering (SRS and SBS, respectively) are known as major processes that can bring about high reflectivity and undesirable target preheat to prevent efficient compression of the fuel. Quantitative prediction of the onset and saturation of these instabilities under given laser and plasma conditions is an important goal of laser-plasma research. However, although much effort has been devoted to this subject, observations and theoretical models are rarely in good agreement. Not surprisingly, any process that occurs in a plasma can alter substantially the dynamics of the nonlinear system and the behavior of instabilities.

In efforts to obtain deeper insight into nonlinear processes, computer simulations serve as a powerful research methodology and the present-day supercomputers offer a good base for investigating complexity from first principles. By creating mathematical models and running computer simulations one is able to explore a large number of possible initial conditions and to analyze the common features of the results. Although simulation systems are on space and time scales smaller than real ones, it can be sufficient to discover important plasma properties and to come to conclusions applicable to real systems.

Motivated by plasma complexity in the laser-fusion research, the goal of this thesis is to examine properties of a large-amplitude wave propagation in an underdense plasma by using relativistic theory and computer simulations.

As an illustration of laser parametric instabilities in underdense plasmas a standard model of large amplitude EM wave propagation through an unmagnetized cold electron plasma has been analytically considered. The relativistic hybrid dispersion equation that couples laser wave with two sidebands has been derived and solved for real values of the wave number in a broad range of electron densities and laser strengths. The dispersion equation predicts forward and backward stimulated Raman scattering instabilities (F-SRS and B-SRS, respectively) and relativistic modulational instability (RMI). In general RMI has lower growth rate than B-SRS and F-SRS instabilities. In contrast to SRS instability, RMI does not have a density restriction, i.e. it can appear in a whole underdense plasma. However, for large amplitude waves, Raman instability can be relativistically shifted to plasma densities beyond $0.25n_{cr}$ (here n_{cr} is the critical (EM wave cutoff) density). For high intensity EM waves RMI, B-SRS and F-SRS instability branches can merge.

Further, one-dimensional EM relativistic particle-in-cell simulations have been performed to study high intensity laser wave-plasma interaction in a bounded plasma. The homogeneous plasma layers which are overcritical for SRS instability, placed in vacuum and driven by an intense laser light have shown some unexpected features. Namely, a strong reflection near the electron plasma frequency has been observed. It has been shown that the intense reflection and heating of the plasma layer are due to the novel electronic instability (Stimulated Electron-Acoustic Scattering (SEAS) instability) that excites an electron-acoustic ES wave. The key features of SEAS can be summarized as follows:

- SEAS can be described as a three-wave parametric decay of the laser light (ω_0, k_0) into a scattered light (ω_s, k_s) and an electron-acoustic ES wave (ω_a, k_a).

- The scattered wave is driven near critical, i.e. $\omega_s \approx \omega_p$ which implies $k_s \approx 0$ and $V_s \approx 0$ ($V_s \approx 0$ is the group velocity). Therefore, the scattered wave is a slowly propagating(almost standing) EM wave. The dominant propagation of scattered EM waves is observed to be in backward direction.

- Since $\omega_s \approx \omega_p$, the frequency and wave number of the electron-acoustic wave are $\omega_a = \omega_0 - \omega_s \approx \omega_0 - \omega_p$ and $k_a = k_0 + k_s \approx k_0$, respectively. Therefore the phase velocity of this wave is $v_{ph} \approx \frac{\omega_0 - \omega_p}{k_0}$.

There is an evidence that SRS instability can assist (mediate) SEAS instability excitation and growth. Near the threshold intensity for SEAS instability, high electron temperatures can be essential for the instability growth. There is an optimum temperature when resonant SEAS instability gives a large reflectivity response. In general, SEAS instability produces strong heating and high reflectivities that exceed SRS reflectivities. A possibility of exciting intense trapped electron-acoustic ES waves in large inertial fusion experiment targets deserves more attention.

To further investigate SEAS features and clarify background of this instability, deeper considerations of relativistic nonlinear properties of electron-acoustic waves as well as nonlinear effects of EM wave condensation at the plasma frequency are expected. The slowly propagating backscattered wave which serves as an "attractor" to this instability, as it has been shown, seems to be a key factor for SEAS growth as an absolute instability.

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。特に、これまで知られていなかった新しい 3 波過程により非常に強い散乱電磁波が現れることを見いだし、その物理過程や発生条件を明らかにしたものである。

論文では、まず、電磁波とプラズマの相互作用における典型的な不安定性であるパラメトリック不安定性（ラマン散乱不安定、相対論的変調不安定）の相対論的領域における分散関係を、ゼロ温度近似の下で摂動展開を用いて求め、プラズマ密度、電磁波強度に対する依存性や物理特性を明らかにしている。次に、第 3 章では高強度電磁波をプラズマに入射した際の振る舞いを 1 次元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。ラマン散乱不安定性の臨界密度より十分大きい密度のプラズマにある臨界強度を越える高強度電磁波を入射させた際、これまでの研究では予想されていなかった非常に強い後方散乱電磁波が現れることを見いだした。後方散乱電磁波の周波数は相対論的補正をしたプラズマ周波数近傍にあり、またプラズマ中には電子プラズマ周波数より小さい周波数の静電電子波が存在することを確認した。詳細な解析の結果、この現象はこれまでに知られていなかった新しい 3 波過程、即ち、入射波である高強度電磁波と後方散乱電磁波、および電子プラズマ周波数より小さい周波数領域での静電電子波である電子音波の 3 つの波が関与した誘導電子音波散乱によって引き起こされたものであることを示した。電子音波は線形の範囲ではきわめて減衰が大きく、通常は存在し得ないが、捕捉粒子が存在する場合などには安定に存在しうる。この誘導電子音波散乱においては、後方散乱電磁波の周波数はプラズマ周波数に近く、そのためプラズマ中では小さい波数を持ち、群速度はきわめて小さい。この後方散乱電磁波はプラズマ中でゆっくりと進行しながら成長し、プラズマ領域から真空中へと伝播する。この特性が電子音波の発達を促進し、強いパルスとして観測される。3 章の後半においてはこの誘導電子音波散乱に対するパラメトリック不安定のモデルを導入し、その物理特性を考察している。

4 章では密度勾配があるような現実的な系での励起過程を明らかにするために、ラマン散乱が起こりうる低密度層と、起こりえない高密度層からなる 2 層プラズマに 3 章で得られた臨界強度以下の電磁波を入射した場合の振る舞いを調べている。初期にラマン散乱による反射波のピークが何度か観測された後、反射の低いレベルが長時間続き、そのあと突如としてラマン散乱のピークの数倍の大きさを持つ強い散乱波が現れることを見出した。この現象は、低密度層で発生したラマン散乱により加熱された電子が高密度層に流入することにより、誘導電子音波散乱に対する入射電磁波強度の臨界値を下げ，高密度層において誘導電子音波散乱を励起したために発生したものであることを明らかにした。本論文では、さらに、誘導電子音波散乱の電子温度依存性を明らかにするために、ラマン散乱不安定性の臨界密度より大きい密度のプラズマにおいて、電子温度をパラメータとして変化させた一連のシミュレーションを実行し、電子音波散乱の強度、散乱電磁波パルスの現れる

までの時間などの電子温度依存性を明らかにしている。

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に関するこれまでの実験結果の解釈に示唆を与えるものであり、レーザープラズマ相互作用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。