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学 位 論 文 題 目	Study of ultra-high gradient wakefield excitation by intense ultra short laser pulses in plasma
論 文 審 査 委 員	主　　査　教授　　井元　信之 教授　　平田 光司 助教授　　中島　一久 助教授　　佐藤　國憲

論文内容の要旨

Recently laser-driven plasma accelerators using laser wakefields have been conceived to be the next-generation particle accelerators, promising ultrahigh field particle acceleration and compact size compared with conventional accelerators. For this purpose, it is first important to investigate the mechanism of the nonlinear optical phenomena in laser-plasma interactions; optical field ionization (OFI), self-channeling, ionization induced spectral shift, and excitation of laser wakefield. These phenomena are deeply related to laser wakefield acceleration of particles. We investigate the laser wakefield excitation and acceleration of bright electron beams due to laser-plasma interactions to clarify the feasibility of a laser wakefield accelerator (LWFA). We present the results of studies on the nonlinear optical phenomena and the laser wakefield excitation.

Generation of intense laser pulses and measurements of the nonlinear optical phenomena induced laser-plasma interactions are presented. OFI and self-focusing depend on the gas density are observed in the measurement. Measurements of side and forward scattered radiations indicate self-channeling which is filamentation and a long propagation of the intense laser pulse. The gradient of a refractive index in an ionization front causes a spectral frequency shift of the short pulse laser. The spectral blueshift has been observed experimentally in the propagation of intense ultrashort laser pulses through a gas medium. This generic blueshift strongly depends on the laser intensity and the gas density. In our experiments, a different type of blueshift has been discovered. In this blueshift, a whole spectrum of the laser pulse shifts to a fixed value without regard to the laser intensity and the gas density. We call this effect an "anomalous blueshift". We present a physical interpretation of this puzzling effect.

The gas density measurements and the laser wakefield measurement are presented. The gas-jet has been used for many applications to supply a plasma source in the vacuum chamber. Since a gas adiabatically expands through a nozzle at a sound speed, the density distribution changes in space and time at the same rate as the sound velocity of the gas. Therefore it is necessary to measure the time-dependent spatial distribution of gas density for controlling the plasma precisely. For this purpose, we have made a time-resolved measurement of the gas density distribution produced by the gas-jet. These results visualize dynamics of a neutral gas ejected from the gas-jet nozzle.

Following the gas density measurements, a direct measurement of the plasma density oscillation can be performed by means of the ultrafast time-resolved frequency domain interferometry (FDI). The FDI measurement is based on the pump-probe technique consisting of an intense ultrafast pump pulse and two ultrafast probe laser pulses. In FDI, the plasma electron density oscillations excited by the pump pulse can be detected as a phase shift of the frequency domain interferogram in the spectrum produced by two probe pulses. The measurement of the phase shift as a function of time gives direct information of the amplitude and phase of the wakefields. Several measurements have been made with FDI to demonstrate wakefield excitation by ultrashort laser pulses in an underdense plasma. These measurements have been done for a relatively low density plasma in a gas filled chamber using laser pulse durations around 100 fs and pump peak powers less than 1 TW. In these measurements the probe pulse width limits the highest measurable density to $\sim 4 \times 10^{17}$ cm^{-3}, and the pump pulses were tightly focused to enhance the plasma wave excitation due to 2D effects. In the 2D dominant regime, where the pulse width is longer than the spot size, the radial wakefield is higher than the longitudinal one. Therefore a shorter pulse is preferable to generate a more 1D coherent planar wakefield at the higher resonant plasma density. The measurement of laser wakefields has been made in less 2D dominant regime. The measured wakefield is compared with 1D Particle-in-Cell simulation results.

Hence, from the point of view of applications for particle accelerators, it is crucial that an ultrashort particle bunch with an energy higher than the trapping threshold should be injected with respect to the correct acceleration phase of the wakefield to produce a high quality beam with small momentum spread and good pulse-to-pulse energy stability. The trapped phase space of the wakefield accelerations are typically less than 100 fs temporally and 10 μm spatially, respectively. Therefore it is essential to inject a very short pulse and a low emittance electron beam into the wakefield. Electron beam injection triggered by an intense ultrashort laser is proposed to an injector of ultrashort electron beams as "optical injection". We present the numerical simulation an optical injection scheme based on the FDI system and the anomalous blueshift.

In conclusion we have investigated the extraordinary nonlinear phenomena manifested via interactions of ultrashort laser pulses with gas and plasma; optical field ionization, ionization induced self-focusing and filamentation, an anomalous spectral shift and a large amplitude wakefield excitation. This study reveals that these phenomena occur in a consecutive strong field process through mutually correlated mechanism generated above a certain threshold intensity and that they can be controlled with femtosecond optical pulse technique in order to generate a relativistic bright electron beam with high quality in a laboratory table-top scale. As a result of particular observations of nonlinear optical phenomena in strong field, we found the anomalous blueshift that shows a coherent frequency upshift of the whole laser pulse to a fixed frequency independent of the plasma density and the laser power. We clarify that this phenomenon results from a complex mechanism of the ultrafast optical field ionization and filamentation to cause acceleration of the whole laser photons due to a steep gradient of the refractive index change from neutral gas to plasma. In the wakefield measurement, we have made the first direct observation of 20 GeV/m of coherent ultrahigh gradient wakefields excited by an intense ultrashort laser pulse in a gas-jet plasma. The experimental results agree with the 1D PIC simulation results and the linear theory. In the numerical simulations based on the results of these measurements, we verify generation of a relativistic electron beam accelerated by laser wakefields to be optically controlled with two colliding injection pulses of which one pulse can utilize a frequency up-shifted pulse due to the anomalous blueshift effect. This synthetic study on laser wakefield excitation illuminates physical mechanisms of complex ultrafast nonlinear phenomena generated by interaction of ultraintense laser pulses with plasma and gives prospects of next generation particle accelerators for applications to a wide range of sciences; such as material science, nuclear science, high energy physics, chemical science, biological science, and medical science.

論文審査結果の要旨

本論文は、超高強度超短パルスレーザーとプラズマとの相互作用により励起される大振幅プラズマ波振動（レーザーウェーク場）の発生現象に焦点をあて、気体中を伝播する高強度レーザーパルスがイオン化する過程で引き起こす強い非線形光学現象とともに、様々な光学測定実験とその詳細な結果について述べ、それら超高強度場現象の解明を試みた。さらにそれらの現象を応用、制御することにより高品質相対論的電子ビームを発生するレーザー粒子加速器が構築可能であることを検証する研究を述べた。

高強度超短パルスレーザー技術の進展によって超高強度場と物質の相互作用を扱う研究分野が注目されており、従来の伝統的な研究手法に変革を起こそうとしている。このひとつとしてレーザープラズマ相互作用によって発生するレーザーウェーク場の粒子加速機構を用いる粒子加速器が提案されている。本研究は、このレーザープラズマ相互作用によるウェーク場の発生とその粒子加速機構の解明を主題として超高強度ウェーク場の直接観測に成功すると共に、高強度光子場による気体原子の超高速プラズマ生成（トンネルイオン化）に起因する新しい非線形光学現象を発見し、その明快な発生機構の解明に成功した。

強光子場イオン化現象にともなう非線形光学現象の研究では、プラズマからの発光、トムソン散乱光を様々な条件のもとで詳細に観測することにより、自己集束、フィラメント化、異常ブルーシフト（波長青方変位）という興味ある現象を一連の実験で観測した。とくに異常ブルーシフト現象は、従来から知られているブルーシフト現象とは異なりレーザーのスペクトルがある光強度以上で一定の波長にパルスごと青方変位する現象で、その変位量は気体密度、レーザー強度によらないことを発見した。さらにその発生機構をイオン化、自己集束、フィラメント化現象の観測結果から、これら高強度場現象が複合しておこる光子の自己加速機構であるという考察を与えた。

ポンププローブ法を用いたレーザーウェーク場の直接観測は、すでにいくつか実験例があるがより短パルスレーザーとガスジェットプラズマを用いることにより、実際に粒子加速が起こるより高密度プラズマ状態のもとで、20Gev/mに達する加速電場をもつコヒーレントなウェーク場を精密に直接測定することに初めて成功し、ウェーク場による高エネルギー電子加速機構を直接解明した意義は大きい。また論文ではこのポンププローブ法と異常ブルーシフト効果を応用し、プローブパルスをウェーク場へのプラズマ電子の入射を制御する光パルスとして用いるユニークな電子加速法を提案し、詳細な数値シミュレーションの結果、従来の高周波加速器では得られない超短パルス高品質電子ビームが実現できることを明らかにした。

以上申請者の研究は、次世代粒子加速器の加速機構として研究がさかんになっているレーザープラズマ粒子加速機構として注目されているレーザーウェーク場の発生とその直接観測実験を主題に、それに伴う超高強度場非線形光学現象について詳細な実験観測をもとにその解明を試みたもので、その研究結果は、レーザープラズマ加速器の開発における重要な到達点となる成果である。また加速機構を含む複合的な超高強度場現象を場の自己組織化という新しい物理過程で統合的に解明する可能性が期待でき、本研究はその端緒となる研究成果として評価できるので学位授与に値すると判定した。