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Front Edge of High Energy Density Science with High Power Laser
パワーレーザーによる高エネルギー密度科学

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High Energy density states created by high power lasers cover a variety of attractive fields of sciences and technologies such as particle acceleration, laboratory astrophysics, and material science, nuclear science including medical applications and laser fusion.　Two novel states with high energy density are now being explored in both vacuum and sold with high power lasers, i.e. nonlinear optics in vacuum and high energy density solid matter such as solid metallic hydrogen.　These new fields will be opened by well controlling of high energy density plasmas.

1. Introduction

High power laser technologies are now opening a variety of attractive fields of sciences and technologies using high energy density plasmas. The high energy density plasmas created by high power lasers include a lot of states of plasmas as shown in Fig.1, e.g. warm dense matter, high pressured plasmas, radiative plasmas, fusion burning plasmas, relativistic plasmas and electro-positron plasmas. These broad areas of plasmas enable us a lot of applications of high energy density plasmas such as particle acceleration, laboratory astrophysics, material science, nuclear science including medical applications and laser fusion, which are "High Energy Density Science (HEDS). These applications are well in progress with technologies on high power lasers and related plasma devices [1-4].

On the other hand, novel states with high energy densities are now being created in vacuum or as a solid by controlling of high energy density plasmas as well as high power lasers.　These states are shown in the areas out of the plasma states as show in Fig.1, which would be key elements to open new fields of sciences. The nonlinear optics in vacuum will be experimentally realized with development of novel focusing optics or a spheroid plasma mirror [5] as well as 100PW lasers.　Calculating Lagrangian densities of electromagnetic fields with quantum electromagnetic dynamics (QED) and wave optics, feasibility of experiments are discussed on nonlinear optics in vacuum.　Other interesting topics are creation and freezing of high energy density solid states with high power lasers. A metallic state of Silicon existing at an ambient pressure has been created at a few 10GPa with a fast compression scheme using high power lasers, for the first time. In the TPa regime of pressures at temperatures of less than 8000K, we have demonstrated creation of a super diamond or BC8 carbon, which must have twice of densities of diamond.　As an ultimate goal of exploring of the high energy density solid matter and material, element technologies are being developed to create a solid state of metallic hydrogen at temperatures of less than a few 1000K with pressures of around TPa.

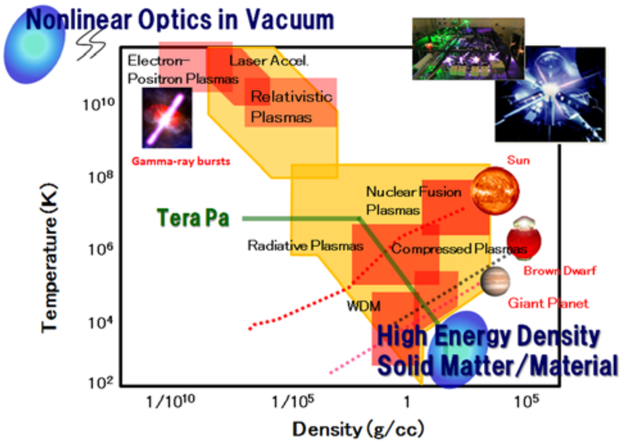

Fig.1. Phase diagram showing high energy density plasma states accessible with high power lasers. The circles i.e. high energy density solid and nonlinear optic in vacuum are now being explored by control of the high energy density plasmas.

2. Nonlinear Optics in Vacuum

According to the uncertainty principle, vacuum has quantum fluctuations and photons can interact with vacuum.　Classical analogy of the quantum fluctuation with special relativity may allow us to imagine virtual particles for a short time in vacuum. Intense laser light could interact with the virtual particles, resulting in nonlinear optics in vacuum and vacuum breaking with avalanche phenomena. The nonlinear optical properties before break of vacuum or creation of real particles can be treated with QED and perturbation theory. From this analysis, dipoles in vacuum are excited by both of electric field and magnetic field. The polarization and beam pattern after the interaction in vacuum are totally different from those in matter. As other interesting points different from the interaction with mater, the interaction rate significantly depends on the angle of the laser beams or a focusing cone angle [6]. To realize experiments on the nonlinear optics in vacuum, we have developed a novel geometry of a plasma mirror [5], which realizes fast focusing of laser light with cone angles of more than 100deg in a large laser system. By using such a plasma photonic device, we would open nonlinear optics in vacuum at laser powers of less than 100PW.

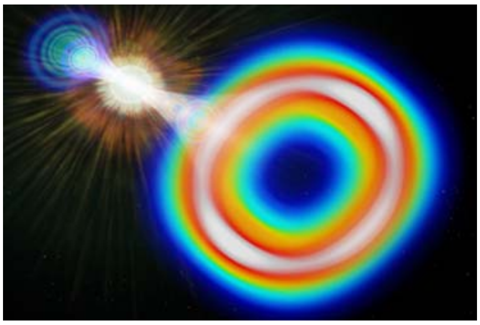

Fig. 2. Image of laser interaction with vacuum

3. High Energy Solid States

High power lasers also easily generate high pressures of more than TPa. This high pressure condition creates a strong shockwave in matter. The shockwave followed by a Hugoniot relation has been a useful tool to investigate EOS of high-pressured matter. The pressures of more than 0.1TPa is the energy density corresponding to the chemical bonding energy, resulting in expectation of dramatic changes in the chemical reactions. At pressures of more than TPa, most of material would be melted on the shock Hugoniot curve. However, if the temperature is less than 1eV or lower than a melting point at pressures of more than TPa, novel solid states of matter must be created through a pressured phase transition. One of the interesting materials must be carbon. The structure of the carbon is well known as a diamond at pressures of more than about 10GPa. At pressures of more than TPa, the diamond structure changes to BC and cubic at more than 3TPa. The band gap of the cubic structure carbon could disappear and diamond semiconductor changes to a metallic. On the other hand, the BC8 carbon will be still semiconductor and harder than the conventional diamond. Then it is called as “Super-diamond”.

To create such novel states of matter, several kinds of isentropic-like compression techniques are being developed with high power lasers, e.g. impedance matching, pulse tailoring, static-dynamic coupling compression and hybrid compression. The super diamond phase has been realized with a ns high-power laser using the impedance matching technique for the first time. One of other important compression techniques is non-equilibrium compression or fast compression. Using this technique, high pressured states of Si, which was metallic state, was kept at ambient pressures. Detail mechanisms of the freezing of the high pressured states have been not yet cleared but metallic Si confidentially exists on our hand at ambient pressures. This result indicates that more kinds of matters, which had been realized only at high pressure conditions, would be expected as novel material.

Extending the metallization of the material with the isentropic compression, superconductive metallic hydrogen must be the ultimate. Once the solid metallic hydrogen was generated, the Deby temperature was extremely high and it would be strongest material against thermal fluctuations. This is because the monatomic solid hydrogen can possess high number density due to no closed shell electrons and nuclear mass is much lighter than other material.

4. Summary

High energy density plasmas are being explored with high power lasers. Novel states with high energy densities i.e. nonlinear optics in vacuum and high energy density solid matter/material are now being created by well control of high energy density plasmas as well as high power lasers.

Acknowledgments

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