Developments of electron and proton acceleration using Laser-plasma Interaction

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Abstract

With the development in ultra-short, ultra-intense laser technology, the potential of inventing novel table-size charged particle accelerators using laser-plasma interaction has attracted a lot of attentions due to its advantages comparing to classical accelerators. The accelerators have broad application aspects, such as medical imaging, cancer therapy, fast ignition in inertial fusion, and protons with TeV energies are relevant to high-energy physics and astrophysics. In this paper, we introduce some new progresses in the laser-plasma electron and proton accelerations.

Keywords

laser plasma interaction; electron accelerator; proton accelerator.

1. Introduction

With the invention of laser in 1960s, the idea of using laser to accelerate electron and proton had been proposed. But the energy intensity was not high enough until the invention of Kerr-lens mode-locking[1] and Chirped-pulse amplification (CPA)[2] technologies. With ultra-short, ultra-intense laser, this field has revived and have attracted lots of interest from the scientists all over the world due to its advantages comparing to electromagnetic accelerators. While, studying the laser and plasma interaction which contains many physical processes could lead to a lot of applications. Figure1 shows parts of the physical processes that involved in the laser plasma interaction when the laser pulse focus intensity exceeds 10^{18} W/cm^2.

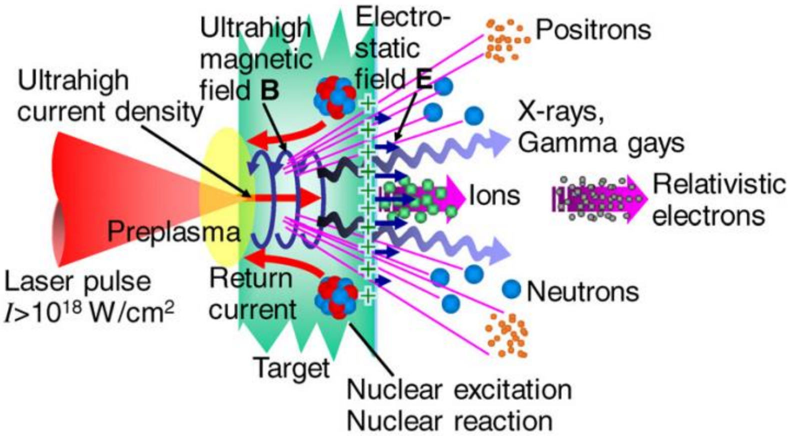

Fig.1 Sketch of the ultra-high intensity laser interacting with a plasma[3]

With the development of CPA , laser technology comes into a new field. Figure 2 shows the principle of CPA. The working principle of CPA is as follows: Firstly, the laser is broadened; secondly, the broadened laser is amplified in the amplifier; then the laser is compressed in the compressor; finally, the ultra short laser pulse with high intensity is achieved. Currently, many countries are developing the laser fast ignition system using the CPA technology which could be the best way to achieve self-sustaining fusion. Many laboratories have successfully built laser systems with intensities as high as multi-pet Watt using CPA technology, such as LLNL has achieved laser pulse with 450 fs, 1.5 PW using Nd: glass system[4]; Chinese Academy of Sciences Research Institute has got the laser pulse with intensity reached 1.16 PW[5]. With the assists of this technology, people can extract energy effectively from the high energy storage medium and get ultra-short pulses. As the laser pulse shorting, the effect of laser and plasma showing new physical phenomena. Ultra-short laser pulse can accelerate the initial static electron to relativistic energy easily, and what more important is the ultra-short laser pulse can stimulates the large amplitude of plasma wave through the ponderomotive force, and speeds up the electron to higher energy, which the accelerating gradient can be achieved as high as 100 GV/m which is 1000 times comparing to typical electromagnetic accelerators.

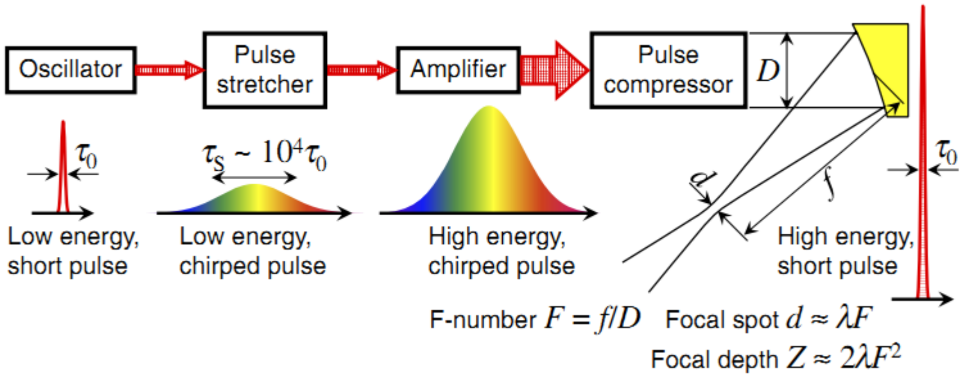

Fig.2 Schematic diagram of a CPA system[2]

The bulky size and the high running cost of the traditional electron and proton accelerators have prevented the build and the applications of such device, so in the past 30 years, great efforts have been made to find new scheme for particle acceleration, *i.e.*, looking forward to accelerate the particles to very high energy in the short distance. In 1979, T. Tajima and J. M. Dawson proposed the idea of the plasma accelerator based on plasma wave theoretically[6-8]. They suggested that the strong electric fields formed within the laser-driven plasma waves could make the charged particles accelerate to relativistic energies. Here we summarize some of the key schemes for laser plasma acceleration to nowadays.

2. Overview of main electron acceleration schemes

According to the way that the plasma wave is generated, the main schemes for laser plasma acceleration can be classified as the Laser Wakefield Acceleration (LWFA), the Plasma Beat-wave Acceleration (PBWA), the Self-modulated Laser Wakefield Acceleration and the Bubble regime.

The principle of LWFA is that the excitation of relativistic plasma waves by a single, intense laser pulse with a duration less than the plasma period. Figure 3 shows a schematic experimental setup of LWFA.

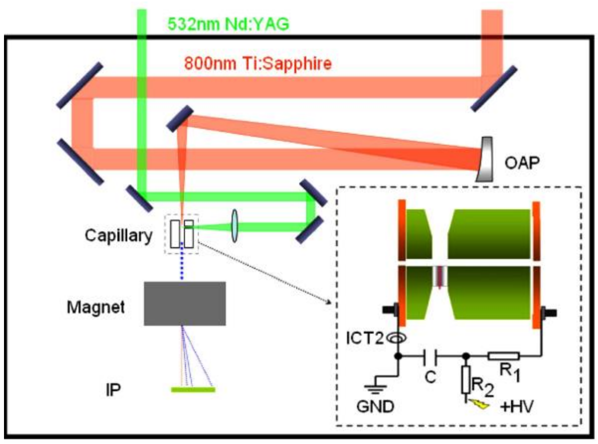

Fig.3 Schematic experimental setup of LWFA[9]

Plasma beat frequency wave acceleration (PBWA)[10] using two long laser pulse incident at the same time (at the level of ns), set the two frequencies to be ω_1 and ω_2 respectively, when the frequencies of the two meet $\omega_1 - \omega_2 = \omega_p$, two laser phase in space formed by the wavelength of standing wave cycle is λ_p, through these standing waves can effectively drive up the large amplitude of the plasma wave to accelerate electrons.

The PBWA scheme suffers from an intrinsic limitation: when the amplitude of the plasma wave is increased, due to the relativistic effects, the corresponding plasma oscillation frequency is reduced; In addition to the effects of resonance disorders, the plasma wave amplitude also become unstable[11].

To avoid difficulties of PBWA, Andreev et al.[12] and Krall et al .[13] put forward a new scheme--Self-modulated LWFA. This approach is of single beam laser pulses, which laser pulse length is about several times of the plasma wavelength. When the laser pulse propagating in low density plasma, due to the effect of stimulated Raman scattering, it will be modulated by the plasma density wave, then the pulse is split into intervals with the space of about λ_p, these pulses fragments can stimulate the plasma wave to accelerate electrons.

With the development of CPA, people consider driving a plasma wakefield with a single intense laser pulse. In 2002, Pukhov and Merter[7] using three dimensional Particle-in-Cell (PIC) simulation found that when the laser pulse is strong enough, the laser ponderomotive force can make the electrons line up off-axis and forming a vacuum of electrons, thereby forming a sphere solely consists of ions in the tail of the laser, while the electrons in the cavity region only exist at the end of the surface. At the same time, the first experimental results in bubble regime were reported in 2004[14]. The experimental setup was shown in Fig. 4.

In 2013, the United States Austin Wang X M, et al in more than 100J PW laser system, through the self injection mechanism has obtained energy more than 2 GeV quasi monoenergetic electron beam (higher energy spread is 5%) through self injection mechanism[15].

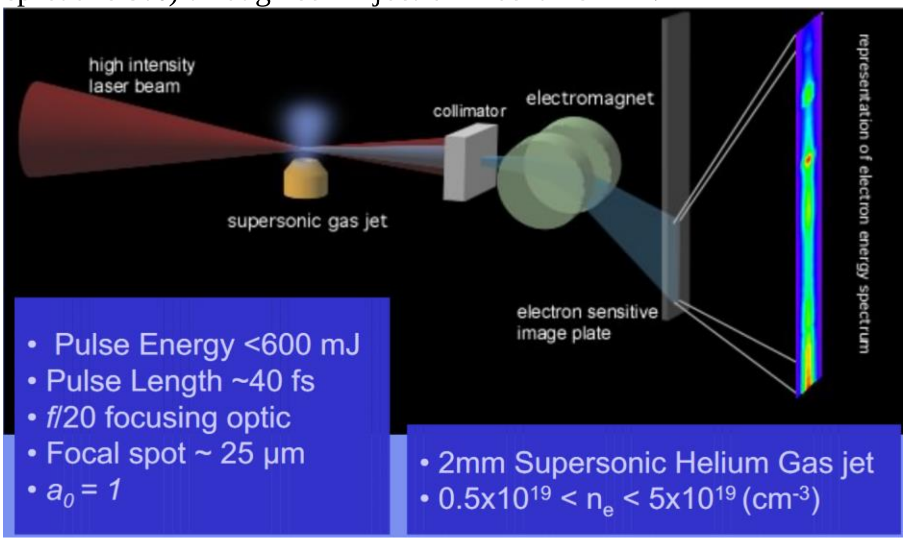

Fig.4 Experimental setup of Bubble regime[14]

3. New development of proton acceleration schemes

The applications of high energy proton beam generated by femtosecond relativistic laser and plasma interaction is also very broad. For example, in the medical treatment of tumor, compared with other means of chemotherapy, energetic proton beam energy deposition has a pronounced Bragg peak. That is to say, the proton deposits most of its energy in the diseased cells without affecting the healthy cells, so proton cancer therapy in medicine has great advantage. But the mass of the proton is much larger than the mass of the electron, to accelerate proton or heavier particles is more difficult than accelerating electron.

In order to obtain high energy ion beam with different energies, several accelerating mechanisms have been proposed. The main acceleration mechanisms include Target Normal Sheath Acceleration (TNSA), Break Out Afterburner (BOA), Radiation Pressure Acceleration (RPA), Collisionless Shock Acceleration(CSA) and so on.

In 2000, Hatchett *et al.* proposed the target back to sheath acceleration mechanism (TNSA), the mechanism theoretically illustrates why the high-energy protons are observed at the back of the target experimentally, and this mechanism is now the most widely used theoretical interpretation[16]; In 2003, P. Mora presents the plasma from expanding toward the half space model[17], and later it was discovered that such a plasma model can also be used to explain the super laser and solid target interaction emission mechanism of proton.

In 2012, F. L. Zheng *et al.* [18] proposed a two-phase proton acceleration scheme. This scheme using an ultra-intense laser pulse to irradiate a proton foil with a heavier-ion plasma behind it. They considered that the pre-accelerated protons by radiation pressure acceleration (RPA) can be further accelerated over a long distance by the front positive wakefield as long as they are trapped in the acceleration field. Their thoughts were verified by 1D and 2D PIC simulations. Sub-TeV quasi-monoenergetic proton bunches can be generated by a centimeter-scale accelerator with a laser pulse of intensity 10^{23} W/cm^2 and duration 116 fs. The length of proton beam is shorter than 100 um.

In 2014, A. A. Sahai and T. C. katsouleas proposed a new scheme named “The Chirp Induced Transparency Acceleration (ChITA)” [19]. In this scheme, the protons acceleration is achieved by reflecting them off of a continuously driven acceleration structure. They use OSIRIS 1D PIC to simulate a chirped laser pulse interacting with plasma. And through the simulation, they found that the ChITA snowplow for the laser-plasma conditions propagates at the analytically predicted velocity 0.066c, and gaining a momentum of 0.132 m_pc.

4. Summary

Laser plasma acceleration has made enormous achievements in recent years. With the development of both the theoretical and experimental research, a lot of progresses have been made to design the laser-plasma electron and proton accelerator. But a lot of theoretical and experimental questions for laser-plasma interaction are still unknown, that more efforts need to be made to understand the processes. With the advancing of laser technology and material science, the new table-size accelerator would be realized in the near future.

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