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Recent progress in high field physics research at the Institute of Physics, Chinese Academy of Sciences

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Abstract. We report firstly a homemade femtosecond laser system (XL-III) developed in our institute, which can reach a peak power of 355TW. Then some of our recent results on the fast electron generation and transportation during laser-solid interactions, ion acceleration by collisionless electrostatic shocks waves are introduced briefly.

1. Introduction

With the advent of the chirped-pulse amplification (CPA) technique, there has been rapid progress in the development of high-peak, ultra-short laser systems. To date, Ti:sapphire CPA laser systems with peak power of multi-hundred TW and pulse duration of tens femtoseconds have been constructed. These systems are opening new research frontiers in high-field laser-matter interactions, which result in numerous potential applications, such as particle acceleration, novel radiation sources, fast ignition of fusion targets, high energy density physics, and some fundamental physics, etc.

Since 1999, we have been focusing our attention on the ultra-intense ultra-short (UIUS) laser system construction, particle acceleration and transportation during the interaction of UIUS laser pulses with all kinds of materials, such as solid and gaseous targets.

In this paper, we review some our recent progress in the above aspects. Firstly the homemade 355 TW femtosecond Ti:sapphire laser system with only three stage amplifiers is introduced. Then we discuss the fast electron generation and transportation during laser solid interaction and ion acceleration by collisionless electrostatic shock waves, which are related to the fast ignition scheme of inertial confined fusion.

2. Multi-hundred TW femtosecond laser system: XL-III

In general, more than four stage amplifiers are necessary to boost the laser peak power to higher than 100TW, which need large space and a lot of pump resources. Recently, we have developed a compact multi-hundred TW femtosecond Ti:sapphire facility with only three stage amplifiers. The final amplifier was pumped by an energetic single-shot Nd:glass laser system. With 80J/15ns pump energy at 527nm, 700mJ/600ps chirped pulse was amplified to 21J by reducing the effects of parasitic lasing (PL) and amplified spontaneous emission (ASE). By spectrum shaping with an acoustic optics

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modulator (AOM) and chirp compensating with a vacuum compressor, the laser output at 11J/31fs was obtained with a corresponding peak power of 355TW.

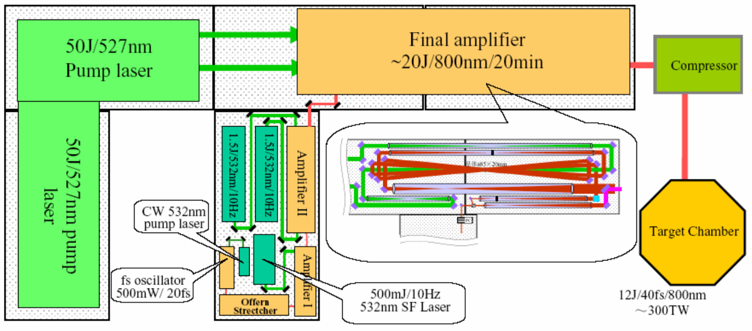


Figure 1. The schematic layout of 355TW laser system

The Ti:sapphire laser system consists of a home-made Ti:sapphire oscillator, an Öffner stretcher, a regenerative amplifier, two multi-pass amplifiers, and a vacuum compressor. Figure 1 is the schematic layout. Seed pulses were derived from a Ti:sapphire Kerr-lensing mode-locked oscillator pumped by a 5W frequency-doubled CW diode-pumped Nd:YVO4 laser (Spectra-physics Ins.). The oscillator generates the train of pulses with 20fs duration at the repetition rate of 82MHz, single pulse energy is about 6nJ and operates on 800nm center wavelength with 50nm FWHM bandwidth. After passing through a Faraday isolator, the pulse train was stretched by a typical all reflective Öffner-triplet stretcher. Our stretcher consists of a single 1480-grooves/mm gold-coated grating, one concave spherical mirror and one convex spherical mirror. In our design, the large size of optical elements and careful alignment could minimize the spectral clipping and spatial chirp in it. The stretched pulses were then amplified in a regenerative amplifier, which was pumped by 50mJ pulses of 532nm at 10 Hz. The amplifier provided a net gain of approximately 10^7, which led to 4mJ output with 600ps pulse duration (FWHM). To reduce the gain narrowing effect in pre-amplifier, we used a commercial acoustic optics modulator (DAZZLER™ WB-800, Fastlite Inc.) to shape the spectrum. In order to minimize the prepulse, two good-quality crossed Glan-laser prisms and a pockels cell were used as a single pulse selector after regenerative amplifier. Then the beam was enlarged to 14mm and sent into the second stage amplifier for further amplification.

The second stage amplifier is designed as a 6-pass one. In this amplifier, a Φ 25x15mm Ti:sapphire crystal was pumped from both sides by 2.6J of energy at 532nm, and about 700mJ of energy was got with ideal beam quality. Before injected into the final amplifier, the beam size was expanded to 60mm with a telescope, which was set in a vacuum chamber. And the design of image relay could eliminate the ASE of the chirped laser pulse and restore the original beam quality.

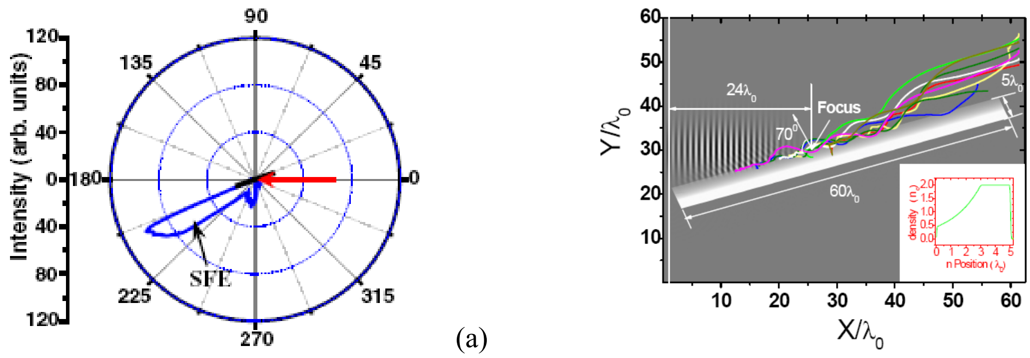
The Ti:sapphire disk used in the final amplifier has a size of 85x20mm with antireflection coating on both surface. In order to eliminate the PL and ASE, the crystal was cut into V shape and held with the absorptive polymer thermoplastic (Cargille Laboratories, Inc.) around. The pump source was a single shot Nd:glass laser with two outputs, each output beam can supply 50J energy at the SHG wavelength of 527nm per 20min. In the experiment, the optimized output energy cannot be obtained under full pump energy. We think that the high pump will generate strong PL and ASE, which consumed the gain and led to the decreasing of laser output energy. In addition, the injected energy was just 700mJ, so the saturated output energy in the final amplifier need more pass amplification. After a lot of optimized experiments, the stable output energy of around 21J was obtained with 9 pass amplification under 80 J pump energy, and the stability was about 1% for three shots within 1.5hous. By replacing the crystal with a thicker one to reduce the PL and ASE, we expect that the output energy can be further increased.

After the amplifier, the output beam was up-collimated with a telescope and sent into the compressor. The beam size was expanded to 120mm. The compressor consists of four gold coated holographic gratings (Jobin-Yvon Inc.) with groove of 1480 lines/mm, the size of grating 1 and 4 was

230x180x30mm, one of grating 2 and grating 3 was 460x210x50mm. The total transmission of the telescope and compressor system was about 52.3%, yielding compressed output pulse energy of 11J with pulse duration of 31fs, which implied a peak pulse power of 355TW.

3. Fast electron generation and transportation

Fast electron generation and transportation are hot topics in the high field physics for their relevance with the fast ignition scheme. In our recent laser solid interaction experiments with a large laser incidence angle (>60°) conducted with our laser system XL-II, we find a new electron emission direction which is along the target front surface [1]. This observation experimentally demonstrates the electron guiding during the cone guided fast ignition scheme proposed by Kodama in 2001 [2].



(a) (b)

Figure 2. (a) The angular distribution of the electrons with energies >300keV for the incidence angle of 70°; (b) Schematic of 2D PIC simulation and selected electron trajectories along the target surface. The inset illustration shows the plasma density profile along the target normal.

Figure 2(a) shows the angular distribution of the electrons in one of our experiments. The laser pulse is p-polarized with an energy up to 0.6J in 30fs at 800nm, the incidence angle is 70°, the target is a 30μm thick aluminum foil, and the diameter of the focus is 10μm. As figure 2(a) shows the electrons are mainly emitted along the target surface. This is quite different from the earlier reports, usually in the target normal or laser reflected direction. We check the dependence of the surface emission on the laser and target parameters and find it can only appears in the condition of large incidence angles and a target with short pre-plasma scale length. To explain the new feature of this emission, we have made two-dimensional PIC simulations as shown in figure 2(b), where most of the parameters are the same as the experiment. We find electrons are really oscillating and moving along the target front surface. This is because of the static electric and magnetic fields, which tend to confine some energetic electrons at the target surface and make them to do betatron oscillations. Further studies show electrons can even resonant with the reflected laser pulse and be accelerated when the oscillating frequency is the same as the laser frequency seen in the moving frame of the electrons [3].

When we decrease the incidence angle (<60°), four groups of collimated emissions of fast electrons along the front and rear target surfaces are observed. This multi-peak characterization is found to be independent of the polarization states. Numerical simulations reveal that the electron beams are formed due to the deformation of the target surface and then guided by the induced quasistatic electromagnetic fields [4].

4. Ion acceleration by collisionless electrostatic shock waves

In recent years, ion acceleration has received extensively attention. This has been motivated by the wide potential applications of the ion beams in laser fusion, proton therapy, radioisotope production, etc. Usually ion acceleration results from the large space-charge fields set up both at front and rear surfaces of the target irradiated by an UIUS laser pulses. Here we report an ion acceleration mechanism related with the collisionless electrostatic shock wave, by which ions can be accelerated inside the solid density target and the energy spectrum is monoenergetic.

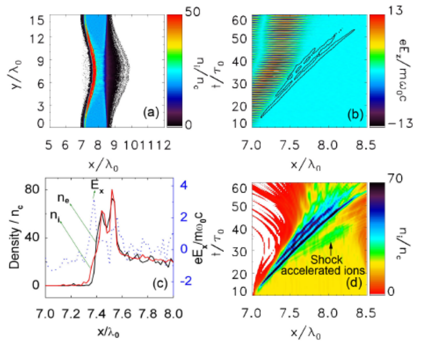


Figure 3. (a) Snapshot of the ion density in 2D space at t=40T_0; (b) The space-time evolution of the laser fields. The ion density contour lines of 45 n_c are also overplotted; (c) The longitudinal density distributions of the ions and electrons, and the longitudinal electric field on the laser axis at t=30T_0; (d) The space-time evolution of the ion density distribution on the laser axis. Here the normalized laser electric field is a_0=5, and the target density is 20n_c.

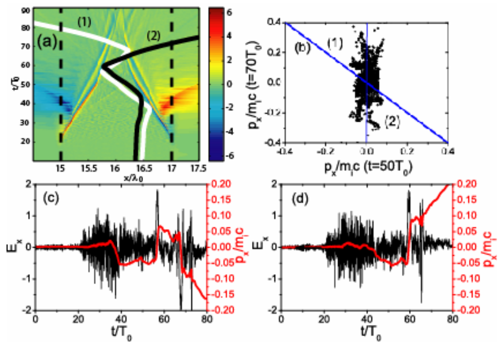


Figure 4. (a) Two typical trajectories of ions accelerated in two colliding electrostatic shocks waves driven by two laser pulses from two sides. The background shows space-time evolution of the longitudinal field. (b) Longitudinal momentum distribution of the ions at different time. (c) and (d) show the evolution of the longitudinal momenta and the fields experienced by the ions with the white and black trajectories shown in (a), respectively.

We have done 2D PIC simulations as shown in figure 3(a)-3d) [5]. Usually when the laser irradiates a target, its pondermotive force accelerates the electrons and then ions are accelerated by the space-charge field. If the speed of the ion beam in front of the target is larger than the ion acoustic speed, shock wave can be generated. When the shock wave propagates in the target, its bipolar field can accelerate the ions in front of it to the speed of twice the shock speed. Parameter scan simulations show, shock waves can be formed in a large laser plasma conditions, even the laser intensity is 10^{18}W/cm^2. However it is sensitive to the pre-plasma scale-length, which should be short enough [5].

We further studied multiple species of ions acceleration in two colliding shock waves [6]. One-dimensional PIC simulation shows ions with higher ratio of charge to mass (higher R) can be reflected many times in the shock waves composed of ions with lower R. In figure 4(a) we have shown the two typical ion trajectories, which show the light ions reflected many times by the two shock waves. Figure 4(c) and 4(d) shows the evolution of their longitudinal momenta. As we can see, ion energy increases once they are reflected by the shock. This affords a new method to increase the final energy by the shock acceleration and such kind of mechanism may also happen in space plasmas.

Acknowledgments

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