Parametric waves excitation in relativistic laser-plasma interactions for electron acceleration

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Abstract. Plasma created by femtosecond laser pulse of high intensity can be used as the brilliant source of high energy electrons, ions and x- or γ-rays. In most cases, laser pulses with high contrast are used for particle acceleration. But, it has been shown, that changing parameters of pre-plasma layer on the surface of the target can significantly increase electron energies. In this work we present the results of the experimental and numerical studies of the abnormally hot electron generation mechanisms in the case of long scale pre-plasma layer subcritical density.

1. Introduction

Today many mechanisms of electron acceleration in relativistic femtosecond laser plasma are known: $\mathbf{j} \times \mathbf{B}$ and ponderomotive acceleration [1], resonant and stochastic heating [2], parametric instabilities [3], wakefield acceleration [4] etc. However, the physics of laser-plasma interactions is more complicated: several acceleration mechanisms may proceed simultaneously or even nonstandard processes may take place in some conditions. This explains the presence of the several hot electron components in the energy spectrum of the plasma or the components with abnormally high energy (if compared with the standard mechanisms in such conditions). Experimental parameters such as intensity and duration of the laser pulse, scale and density of the pre-plasma layer determine processes in the plasma. Thus changing parameters of experimental setup we can control plasma source characteristics for more efficient electron acceleration. It has previously been demonstrated that the laser contrast (ASE level) plays an important role in the electrons acceleration [5, 6]. In recent papers, additional laser pulse is used for the pre-plasma layer creation [7–9]. The similar idea was used in this work for the electron acceleration processes investigation in the long subcritical pre-plasma layer.

2. Experiment

In our experiments we used the Ti:Sa laser system (p-pol, $\lambda - 800$ nm, $\nu_{\text{pulses}} - 10$ Hz, $E_{\text{max}} - 40$ mJ, $\tau_{\text{min}} - 45 \pm 5$ fs and $I_{\text{max}} - 5 \times 10^{18} W/cm^2$, ASE $- 10^{-8}$). The Nd:YAG laser ($\lambda -$

532 nm, $E - 30$ mJ, $\tau - 6$ ns, $I - 10^{12} W/cm^2$) was used to create the controlled long and dense pre-plasma layer. This laser was locked with the Ti:Sa laser system with accuracy better than 1 ns. The experimental setup is shown in figure 1. The laser radiation was focused by off-axis parabolic mirror ($F \sim 7.5$cm) onto the target (Fe and Mo plates), creating plasma on its surface. Experiments were performed in a vacuum chamber at a pressure not higher than 10^{-2} Torr.

We performed optical and γ-ray plasma diagnostics at different delays between the pulses and the focal positions of the main pulse.
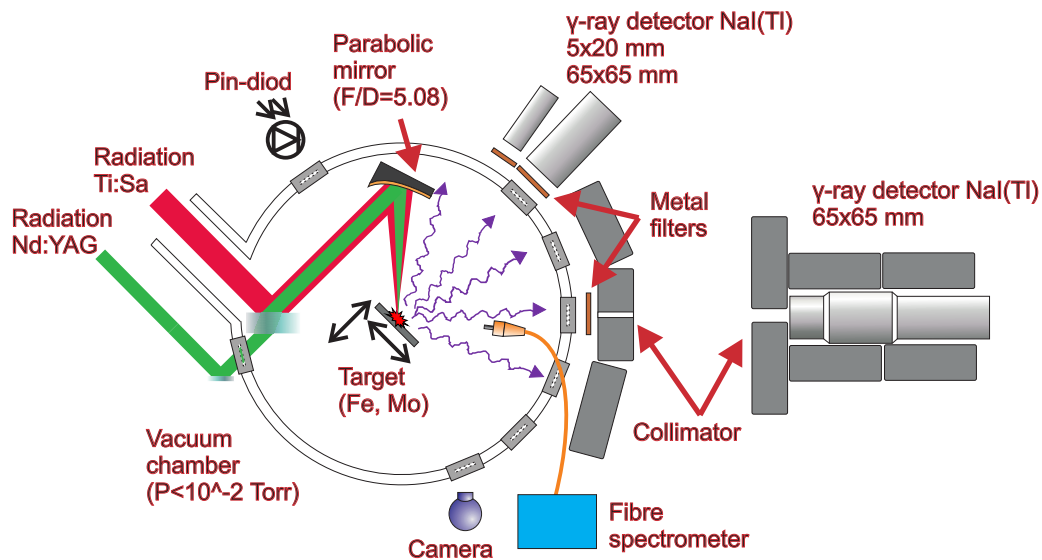

Figure 1. The experimental setup.

Bremsstrahlung of hot plasma electrons was detected by scintillation detector based on NaI crystal. We observed several laser-plasma interactions regimes. In some of them, average energies of hot electrons increases more than 7 times from 330 keV in the case of clean Ti:Sa pulse up to 2.4MeV with artificial pre-pulse. These electron energies were obtained from the measured γ-ray spectra (figure 2).
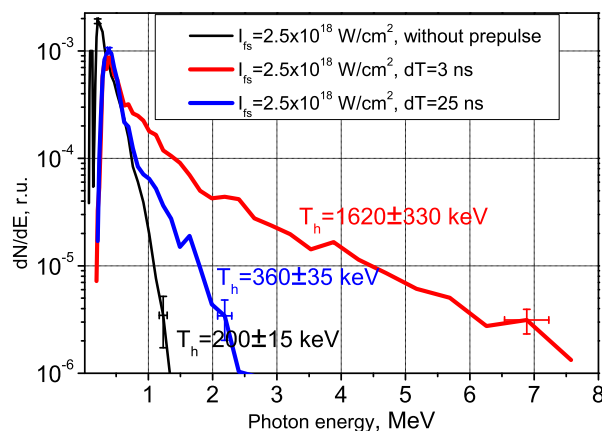

Figure 2. Bremsstrahlung γ-ray spectrum.

It should be noted that at high photon energies (E> 300 keV), spectra are strongly deteriorated during the measurement. For distortion compensation a special computer program was used which simulates the process of the photon detection [6, 10].
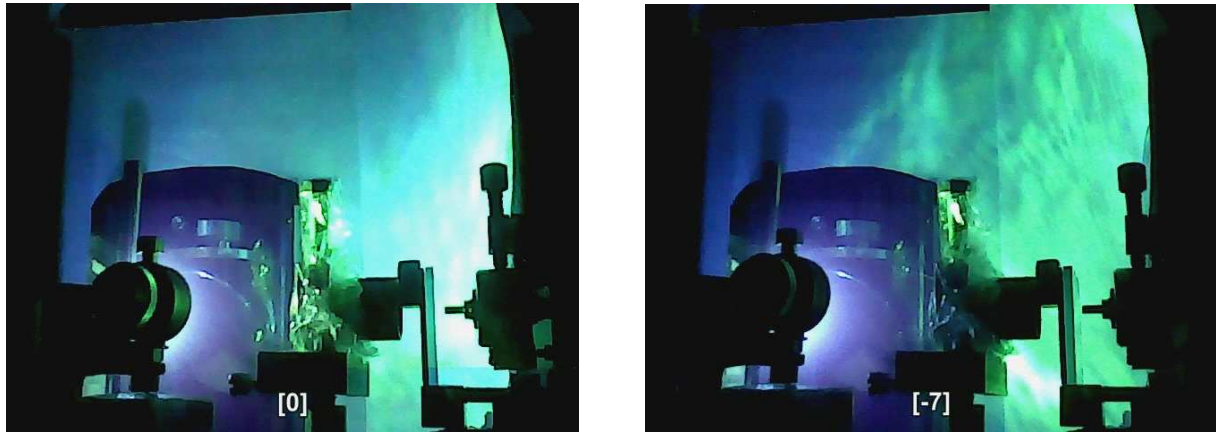

Figure 3. Changes of the three-halves harmonic generation directivity depending on the delay between pulses: directional beam at delay in 0 ns (left) and diffused radiation at -7 ns delay (right).

The fiber spectrometer was used to measure the plasma emission spectra. Directivity the plasma radiation was recorded by the camera (figure 3). Experiments showed, that there is a strong correlation between the γ-ray yield and three-halves harmonic ($3\omega_0/2$) generation. It indicates the parametric processes participation in electron acceleration [3].
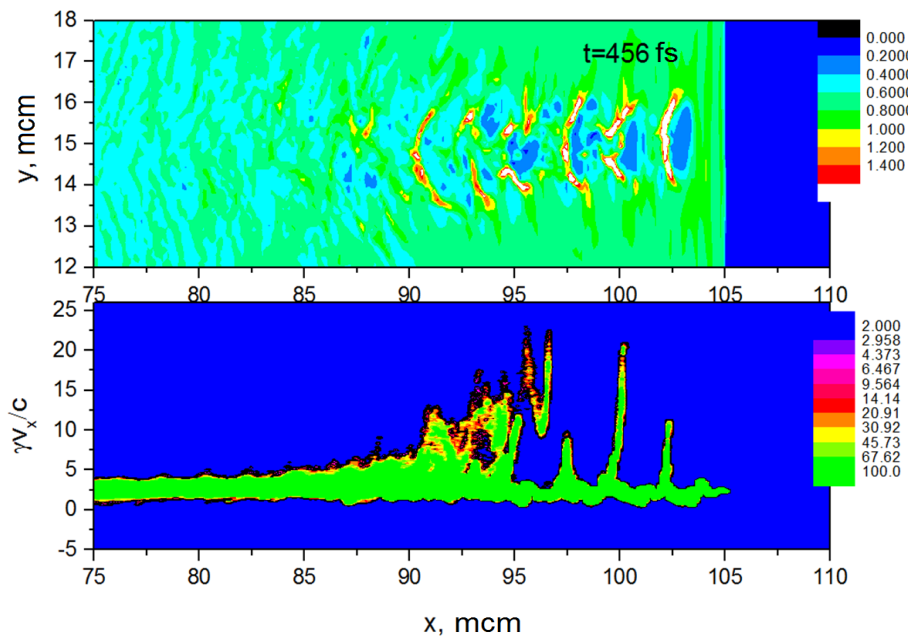

Figure 4. The electron density (top) and the longitudinal component of the momentum (down) distributions in the moment of wavebreaking.

3. Simulations

For clarification of the electron acceleration mechanisms numerical simulations were done using fully relativistic 3D3V PIC code Mandor (in 2D3V regime). The typical simulation box size was $90 \times 15 \, \mathrm{um}^2$ with periodic boundaries and spatial resolution of $\lambda/100$. A laser pulse (p-polarized, $\lambda - 1 \, \mathrm{um}, \tau - 50 \, \mathrm{fs}, I - 10^{18} W/cm^2$) was focused onto the targets with different pre-plasma layer parameters (corresponding to the experiments). For example, pre-plasma was modeled as the linear slope (1: from 0(0um) to $0.25 n_{\mathrm{cr}}$(90um)), if the delay between pulses was 0 ns. This electron density profile was obtained from the experiments on interferometry and shadowgraphy of the pre-plasma produced by the artificial prepulse.

Simulations showed, that relativistic self-focusing, parametric processes, wavebreaking, stochastic heating, its combinations and variations, define the abnormally hot electron generation. In particular, figure 4 shows the hot electrons accelerated by the longitudinal electric field of a plasma wave.

4. Conclusions

It has been experimentally shown, that energy of the hot electron component generated in relativistic laser-plasma interactions can be significantly increased if the optimal parameters of the pre-plasma layer are chosen and such parameters can be reached by long (ns) artificial prepulse. The optical plasma emission diagnostics and numerical simulations showed the key role of the parametric processes in electrons acceleration for this pre-plasma layer.

Acknowledgments

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