High energy electrons accelerated in the field of tightly focused relativistic laser pulse for peak intensity evaluation

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Abstract. The action of relativistic femtosecond laser pulse with peak intensity over $10^{19}$ W/cm² onto low density plasma is studied experimentally and numerically. It is demonstrated that electrons may be accelerated up to the relativistic energy (>500 keV) directly by the strong field of tightly focused laser radiation. In dependence on the peak laser intensity a dominant angle of high energy electrons is observed, which is around 45 degree for experimental intensity. On the basis of particles energy and angular distribution the laser pulse peak intensity may be evaluated.

1. Introduction

The progress of the laser technologies within the last decade allowed to reach the tera- and petawatt level of peak power of the ultrashort pulses opening for researchers the experimental investigation of a promising field of high intensity laser interaction with matter and plasma [1,2]. Among various scientific tasks and applications, the area of laser acceleration of electrons is one that has been intensively studied both theoretically and experimentally. With the access to the relativistic regime of laser interaction (when the peak intensity exceeds $10^{18}$ W/cm²), a myriad of new concepts of particle acceleration to relativistic energy in the low density plasma have been demonstrated: wakefield acceleration [3], direct laser acceleration [4,5], in vacuum energy gain [6], electron acceleration in the presence of magnetic field [7] etc. Together with the precise control of key beam parameters, such as phase, polarization, transverse intensity distribution in the beam waist the efficient energy gain up to a GeV level may be achieved [8,9]. At the same time, the interaction of strong laser field with low density plasma may be also utilized for studying the complex particles dynamics, non-linear physics, atoms ionization [10-12]. One of the challenging tasks is the laser beam parameters evaluation, especially for ultrahigh peak power machines. The measurements of particles momentum and spatial distribution, ionization state may serve as a foundation for intensity estimation and focal energy distribution of the beam [13-16]. Since the collective plasma effects may be neglected (due to low plasma density), the energy and angle of scattering of the outgoing particles are the result of the net motion in the laser field.

In this paper we experimentally demonstrate, that electrons may be accelerated to the energy over 500 keV in the waist of tightly focused linearly polarized femtosecond laser pulse with an estimated
peak intensity around $10^{19}$ W/cm$^2$. The particles are born via field ionization of noble gas (Argon) at a pressure of $\sim10^{-1}$ Torr. Measurement of angular distribution in the polarization plane of outgoing electrons revealed the dominant direction of about 45 degree from the laser wavevector $k$ for the high energy electrons. At the same time, the larger number of slow particles (<200 keV) is detected along the polarization direction. Numerical 2D3V PIC simulations show that the electrons are accelerated in the high intensity region and mainly scattered from the caustic at an angle between the polarization direction and the $k$-vector in accordance with the theory of single electron motion in a planar wave. On the basis of angular-energy electrons distribution a simple model for peak intensity evaluation may be developed.

2. Experimental results
The experiment was made on the Ti:Sa laser system of the International Laser Center of M.V. Lomonosov Moscow State University, capable to deliver pulses of 50±5 fs duration and energy after the compressor 50±5 mJ at 10 Hz repetition rate. The central wavelength is 805 nm. The horizontally polarized beam was focused by a 90° off-axis parabola (F/D=3) mounted inside a gas filled vacuum chamber, see Fig.1(a). The residual pressure of the air was $10^{-5}$ torr (achieved by a turbopump). A gas leak was used to add pure Argon into the chamber and maintain its pressure on the level of $10^{-2}$-10$^{-1}$ Torr, enough to make the collective plasma effects negligible [17].

Using a microobjective (NA=0.3) with optical resolution of $\sim1$ μm we measured the diameter of the focal spot, which is found to be 2.2±0.1 μm (FWHM). Approximately 30% of laser pulse energy is contained in the main peak, see Fig.1(b). Hence the estimated peak vacuum intensity in our experiment was $\sim1.5x10^{19}$ W/cm$^2$.

To accumulate electron spectra for a long time (at 10 Hz), we used a simple scintillator based detector (3 cm thick plastic scintillator coupled to PMT), absolutely calibrated by Sr90 beta-source, with a linear response in the range 100-4000 keV and energy resolution of 10%. However due to ADC limitations (the signal was digitized by 8-bit digital oscilloscope with 500MHz bandwidth) the maximal detectable energy in our case was $\sim600$ keV. The device was installed outside the chamber at a distance of 30 cm from the beam waist. For measurements four angles of observation were available in the plane of beam polarization: along $k$-vector, at 22.5 and 45 degrees and almost in the polarization direction (≈85 degrees). The entrance aperture of the detector was 11 mm in diameter. Between the interaction region and the sensitive area of the detector there was a set of filters: a 20 μm mylar as vacuum chamber window, $\sim3$ cm of air at atmospheric pressure and 12 μm Al foil to protect the scintillator against visible light. Altogether it gives a 100 keV low energy cut off and high attenuation of electrons within this energy range. By Monte-Carlo simulation of electrons transport through matte using CASINO code [18] we processed the accumulated data to take into account the spectral distortions.

![Figure 1](image_url)

**Figure 1.** (a) Experimental setup: 1 – laser pulse, 2 – vacuum chamber, 3 – off-axis parabolic mirror (OAP), 4 – scintillation electron detector, 5 – PC with digital oscilloscope. (b) Transvers profile of the beam in the focus of the OAP. The red dashed line shows the Gaussian fit of the experimental curve.
We also made the “null” experiment. The placement of a 1 cm thick piece of plastic in front of the detector (stopping all the electrons below 2 MeV and transparent for X-ray above 10 keV) lead to the decrease of signal down to the zero pedestal level. Hence we were convinced that the signal on the detector without the shielding is caused by the electrons and not by the X-rays, which may be generated via attenuation of electrons on the chamber walls etc.

The Figure 2 illustrates the Monte-Carlo processed electron spectra, measured at different angles, and also the integrated over all angles spectrum (dashed curve). One may notice the exponentially decreasing behavior of each curve with energy growth. At the same time two peculiarities are observed. At first, a greater number of low energy electrons (below 200 keV) is detected along the polarization direction (~85 degrees). The particle, trapped by the laser pulse at its periphery, oscillates dominantly by the action of the electric field of the pulse and leaves the caustic with a finite residual energy due to permanent drift from high to low intensity region. Second, the particles with maximal energy (above 500 keV), are measured at 45 degrees from the laser k-vector. The quantity of high energy electrons (above 200 keV) is also higher in this specific direction, compared to the others. Because of the limited angular resolution in our experimental setup, we cannot state definitely, that electrons with higher energy are not lying in some intermediate angle. However such a behavior may be roughly described by the model of isolated electron movement in a planar electromagnetic wave, which gives the escape angle $\varphi = \arctg \left( \frac{2}{\alpha} \right)$, where $\alpha$ is the classical normalized momentum of the electron quivering in the electric field [16]. For intensity $I=10^{19}$ W/cm$^2$ the angle $\varphi$ is around $\pi/4$. The rather unexpected result is the relatively high flux of particles along the beam axis. According to the simulations with test particle the electrons are expelled along the k-vector at much higher peak intensities [19]. It is worth mention, that all the measurements were carried out in the polarization plane of the radiation. The studies in the perpendicular plane may reveal other features.

![Figure 2. Electron energy spectra, registered at different angles of observation in the polarization plane. The dashed curve depicts the integrated over all angles spectrum.](image)

3. **Numerical simulations and discussion**

To make an insight on the experimental data we carried out the numerical PIC simulations using the fully relativistic code MANDOR [20]. Here 2D3V simulation was made with box size 30x60 microns, grid resolution 0.01 microns and temporal resolution 0.003 fs. The Gaussian pulse with a duration of 50 fs (FWHM) was focused into a 2.5 μm (FWHM as well) spot. The polarization was in the plane of the simulation box. We varied the peak intensity from $2.5 \times 10^{18}$ W/cm$^2$ to $25 \times 10^{18}$ W/cm$^2$. To make the effects of interaction and collision between the charged particles negligible the initial electron density was taken $10^{14}$ cm$^3$, which corresponds to the gas pressure $10^{-2}$ Torr, similar to the experimental value. In order to follow the particles in the region with the maximal intensity we were also able to take into account
the ionization on the basis of Ammosov, Delone, Krainov ADK model [21]. Otherwise, the ponderomotive force already at the front of the pulse will expels the particles from the caustic area. The ionization potentials for Argon were introduced.

The ionization process was exhaustively regarded, for instance, by N. Ekanayake et al. [10], so here we pay attention on the particles distribution. Figure 3 illustrates angular-energy diagrams of particles for different laser intensities. Basically, we observe the similar tendency of the appearance of the dominant direction of high energy electrons as it was in the experiment and as it follows from the theory: the angle of maximal emission coincides well with the theoretical angle $\phi$, mentioned above. This angle decreases (if measured from the $k$-vector) with the intensity growth. Similar angular-energy diagrams were observed in [10]. The maximal ionization state of Argon in the simulation was $+16$.

However, the direct comparison of the numerical and experimental data (Fig.2 and Fig.3(b)), reveals some discrepancy, which is manifested the most in the high energy part of spectrum. It may be partially explained by the fact, that the experimental spectra are averaged over a few thousands shots. Since the energy of the pulse is distributed around the mean value with an error of 10-15% the measured spectra are slightly blurred in comparison to the calculated. The experimentally observed acceleration of electrons along the beam axis also cannot be explained by the model to the moment. It should be noted, that the non-uniformities in the transvers energy distribution over the focal spot may be responsible for the divergence. However, some rings or hot spots play a role at much higher peak intensity (above $10^{20}$ W/cm$^2$). Whereas for the discussed intensity range (~$10^{19}$ W/cm$^2$) only the central focal spot must be considered, in our opinion.

![Figure 3](image)

**Figure 3.** (a) Angular energy diagrams of electrons in the plane of beam polarization accelerated by the field of laser pulse with varied peak intensity. (b) Calculated spectra of electrons at different angles for intensity $I=10^{19}$ W/cm$^2$.

As for the intensity determination, two techniques in principle may be proposed. The first, more simple but requiring a sufficient number of laser shots, is based on the measurement of electron energy spectra in a specific direction: ~45 degrees from the laser wavevector for intensity ~$10^{19}$ W/cm$^2$ and closer to the beam axis (~15-25 degrees) at ~$10^{20}$ W/cm$^2$ and higher. For this a single scintillator coupled PMT may be utilized. The main problem is that the total number of electrons, encountered in the caustic region, must be low enough to avoid collective effects. Hence, the single shot methods, such as magnetic separation of particles by energy and registration on an imaging plate, are complicated as requiring high dose to trig the detector. Afterwards, the peak intensity may be calculated through the comparison with the numerical modeling. The second method is based on the measurement of the angular position of high energy peak, which is strictly connected with the intensity, see Fig.3(a). A position-sensitive detector (sensitive to single particles though) could afford such task. The main advantage is the ability to evaluate the intensity in each laser shot.

4. Conclusions
In summary, the acceleration of electrons directly in the field of tightly focused femtosecond laser pulse with peak intensity around $10^{18}$ W/cm$^2$ was studied experimentally. The electrons were born via field ionization or noble gas (Argon) with a pressure around $10^{-2}$-10$^{-1}$ Torr in the focal region. It is shown that the electron may gain residual energy exceeding 500 keV with an exponential decaying spectrum. At the same time the angular distribution of accelerated particles reveals the dominant direction of escape for low energy particles along the polarization direction of the radiation, whereas the high energy electrons are expelled mainly at an angle of 45 degrees from the laser $k$-vector in the polarization plane, which is in a reasonable agreement with the theory of single electron motion in a plane electromagnetic wave. Numerical simulations of laser interaction with low density plasma have shown, that electrons may gain energy up to a few MeV in a specific direction, also in accordance with the theoretical model, under the influence of a laser pulse with intensity around $10^{19}$ W/cm$^2$. At the same time the angular-energy distribution of electrons is very sensitive to the peak laser intensity, which gives the opportunity to build a simple model of peak laser intensity evaluation, based on detection and spectral measurements of the outgoing from the beam waist particles.

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