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Mechanism of radiation absorption by condensed targets irradiated by subpicosecond highly contrast laser pulses with an intensity of up to 3×10^{16} W cm^{-2}

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Abstract. The mechanism of absorption of laser radiation by metal targets exposed to 0.8-ps laser pulses with the contrast ratio above 10^{12} and the intensity of up to 3×10^{16} W cm^{-2} is studied. The reflectivity and the energy of plasma electrons are measured for gold and aluminium targets. The reflectivity measurement data are consistent with calculations by the Drude model for the absorption of a light wave in a plasma of solid-state density in the regime of normal skin effect. An anomalous dependence of the energy of plasma electrons on the polarisation of laser radiation was observed.

1. Introduction

Recently extensive investigations of the interaction of superstrong light fields with solids have been performed. These experiments are stimulated by the possibility of studying the properties of a matter under extreme conditions (a plasma with a solid-state density and a temperature of 1 – 10 keV [1 – 3]). The applied aspect of the problem involves the development of a subpicosecond X-ray radiation source [4, 5].

The key parameter that determines the regime of interaction of a high-power subpicosecond laser pulse with a condensed target is the pulse contrast ratio — the peak-to-prepulse intensity ratio. For instance, for a pulse with a peak intensity of 10^{17} W cm^{-2}, the nanosecond prepulse intensity should not exceed the ablation threshold for the target material ($\sim 10^8$ W cm^{-2}), i. e., the contrast should be higher than 10^9. Otherwise the main pulse would interact with the low-density vapour of the target material, which screens the target surface. The contrast ratio of the existing subpicosecond laser systems (with $\lambda \sim 1$ μm) does not exceed 10^8 [6] and, in fact, the only known way to substantially improve the contrast ratio is the generation of the second harmonic of laser radiation in crystals [4, 5]. In this case, however, the IR pulses cannot be studied.

We used in our experiments a radically new laser system with an extremely high contrast ratio of above 10^{12} [7]. Our previous investigations of the generation of harmonics in a laser-produced plasma [8] showed indirectly that laser pulses with an intensity of 10^{16} W cm^{-2} and a high contrast ratio interact with a condensed target in the skin-effect regime, and the density of the resultant plasma approaches that of solids. The regime of radiation absorption and the plasma parameters can be more reliably established from the measurements of the radiation absorption coefficient and the energy spectrum of the electrons emitted from the plasma.

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2. Experimental setup and measuring techniques

The 0.8-ps radiation pulses at 1056 nm were produced by a laser system comprising neodymium phosphate glass amplifiers and an SRS master oscillator. This system was described in detail in Ref. [7]. An extremely high contrast ratio was attained owing to a two-stage nonlinear conversion of a 30-ps, 693-nm pulse of a ruby laser (SRS compres sion in liquid SF_6 and forward SRS in hydrogen). This yielded a high-power ~ 0.8-ps radiation pulse at 1055 nm with an energy of 0.1 – 0.15 mJ and a steep leading edge (the calculated intensity build up was 12 orders of magnitude in 1 ps). The pulse energy was subsequently amplified up to 30 mJ in neodymium glass amplifiers. The brightness of amplified spontaneous emission was experimentally measured at the output of the laser system. In accordance with calculations, it was found to be 12 orders of magnitude lower that the brightness of the amplified subpicosecond pulse [7].

The laser radiation was injected into a vacuum chamber evacuated to 10^{-4} Torr and was focused with an objective on the target surface. The convergence angle of the focused beam was 0.4 rad. The intensity distribution in the focal plane was close to a Gaussian with a diameter of 6 μm. The peak intensity was as high as 5×10^{16} W cm^{-2}.

Aluminium and gold films ~ 1 μm thick evaporated onto an optically polished plane glass plate were employed as targets. The angle of radiation incidence onto the target was 45°. After every laser pulse, the target was shifted to expose an unperturbed area to the next laser pulse.

In the reflectivity measurements, the laser radiation reflected from the target within an angle of 0.46 rad was collected by a lens and directed to a calorimeter. It is known [9] that upon irradiation of a condensed target by subpicosecond pulses with an intensity of below 10^{17} W cm^{-2} and a high contrast ratio, the plasma surface is plane and the fraction of diffusely scattered radiation does not exceed several percent. This permits a reasonably precise determination of the radiation absorption coefficient from the measurements of the specular reflectivity.

The spectrum of electrons emitted from the plasma was studied by the method of time-of-flight spectroscopy. Unlike the K_{α}-spectroscopy [10, 11] and the time-of-flight ion spectroscopy [11], this method allows one to obtain the electron emission spectrum directly and draw a conclusion regarding the energy distribution of plasma electrons.

After flying a distance of 55 cm, the electrons emitted within an angle of 10^{-2} sr in the direction of specular reflection of the laser beam were collected by a detector (a Faraday cup). The amplified signal from the detector was fed to an oscilloscope with an amplification bandwidth of 5 GHz.

Fig. 1 shows typical time dependences of the electron current to the detector for different gas pressures in the chamber. For a pressure of 0.1 Torr, the mean free path of electrons with an energy of 0.1 – 1 keV does not exceed 1 cm [12] and the plasma electrons do not reach the detector. In this case, one can observe only the electron current from the detector surface arising from the photoemission under the UV plasma irradiation.

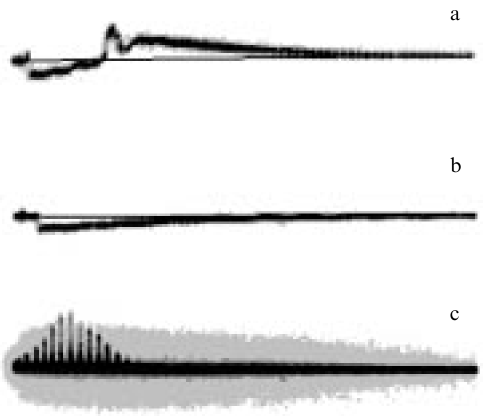

Figure 1. Time dependences of the electron current to the detector (Au target, p-polarised radiation with an intensity of 3×10^{16} W cm^{-2}) obtained when the gas pressure in the chamber was 10^{-4} (a) and 10^{-1} Torr (b), and the shape of the output pulse of the mode-locked ruby laser (for time-base calibration; the pulses of the train are spaced at 7.72 ns) (c).

Upon lowering the residual gas pressure to 10^{-4} Torr, the mean free electron path (5×10^{3} cm) becomes far longer than the flight distance, which permits recording the electrons emitted by the plasma. In this case, the photoelectron current from the detector surface changes only slightly. This allowed us to obtain the time dependence of the electron current by subtracting the signal recorded at a pressure of 10^{-1} Torr from that at a pressure of 10^{-4} Torr. Note that the signals vanished completely when a 1-mm-thick glass plate was placed in front of the detector.

Straightforward estimates show that, owing to its expansion alone, the plasma cools down adiabatically by a factor of 100 in one nanosecond, which is far less than the flight time ($\sim$ 10 ns) of sub-10-keV electrons. Therefore, we can assume that the electron emission from the plasma occurs instantaneously, and we record the energy spectrum of the emitted electrons.

Also note that the flight time of even the thermal electrons with an energy of $\sim$ 200 eV is more than 20 times shorter than that of aluminium ions with energies up to 20 keV. In other words, the peak of the ion current appears much later than the electron current peak, and therefore the ion emission does not affect the shape of the electron current pulse. For a heavy (gold) target, the situation is all the more favourable.

3. Experimental results and discussion

Fig. 2 shows the typical energy distribution of electrons emitted from the plasma obtained by processing the oscilloscope traces. A similar energy distribution with two maxima and a similar dependence of their amplitudes on the radiation intensity and polarisation was also observed in Ref. [10] for the ions emitted from the plasma produced by laser pulses with a high contrast ratio and an intensity of $\sim 10^{16}$ W cm^{-2}. The authors [10] did not discuss the observed distribution; they only noted that it was observed only for a high contrast ratio of laser pulses.

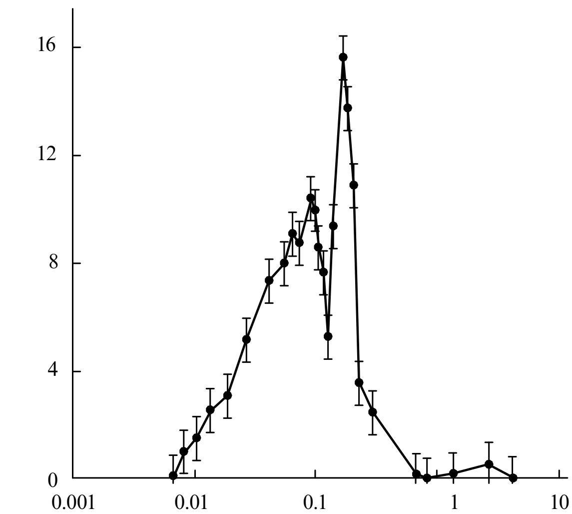

Figure 2. Spectrum of the electrons emitted from a gold target (p polarised radiation with an intensity of 3×10^{16} W cm^{-2}).

In our opinion, the first peak in the distribution is related to the emission from the plasma during the laser pulse when the electron energy achieves its maximum. The subsequent emission from the thermalised expanding plasma forms the second broad peak of the distribution in the lower energy region.

Taking into account the similarity of the spectra observed for p- and s-polarised laser radiation and the absence (to within the sensitivity of the recording system) of fast electrons with energies above 10 keV, we can conclude that the laser radiation is absorbed in the skin layer of the supercritical-density plasma. This statement is also based on the fact that the plasma has a sharp boundary with a density gradient scale length of the order of a hundredth of one wavelength of the laser radiation and fast electrons are absent [13], which was determined in our studies of high-order harmonic generation in a laser-produced plasma [8].

Table 1. Average energy of emitted electrons (in electronvolts).

Target	p polarisation	s polarisation
Au	169 ± 9	191 ± 11
Al	192 ± 10	213 ± 12

The average electron energies corresponding to the highest narrow peak in the distribution are given in Table 1. These energy values were obtained for aluminium and gold targets in the $(1-3)\times10^{16}$ W cm^{-2} range of laser radiation intensity. (The lower intensity bound was determined by the sensitivity of the recording system.) To within the experimental error (~ 6 %), we observed no variation in the average electron energy in response to the variation in the laser radiation intensity.

A substantially weaker dependence of the electron temperature T_e (which was in the $200-300$ eV range) on the laser radiation intensity I than that obtained theoretically for a fully ionised plasma [14, 15] ($T_e \sim I^{0.33}$ for the normal skin effect and $T_e \sim I^{0.75}$ for the anomalous skin effect) was also observed in Refs [16, 17]. This discrepancy is unlikely to be attributable to the inclusion of energy expenditures on ionisation in calculations.

Table 2 presents the measured and calculated reflectivities for the aluminium and gold targets. (The reflectivity of the aluminium target for the p-polarised light wave coincides, within the limits of experimental error, with that obtained in Ref. [6] who employed a femtosecond laser with a high contrast ratio.) The reflectivities were calculated using the Drude model [1]. Classical formulas were invoked to calculate the electron–ion collision frequency [12].

Table 2. Measured and calculated reflectivities.

Target	p polarisation		s polarisation	
	Experiment	Calculation	Experiment	Calculation
Au	30 ± 2	44	50 ± 3	66
Al	58 ± 3	58	67 ± 3	75

The electron temperature in electronvolts was assumed equal to the average measured electron emission energy (Table 1). The plasma density was assumed equal to the density of metal targets. The average ion ionisation degree Z in the plasma as a function of the temperature (measured in kiloelectronvolts) was determined by the formula $Z = 76T^{5/6}$ for the gold target and the formula $Z = 16T^{1/3}$ for the aluminium target [15]. For a plasma temperature of 200 eV, we obtain $Z = 21$ for gold and $Z = 10$ for aluminium. With these plasma parameters, the electron – ion collision frequency is several times higher than the laser radiation frequency and the skin depth turns out to be longer than the mean free electron path. The laser radiation should therefore be absorbed in the regime of normal skin effect.

One can see from Table 2 that the experimental and calculated reflectivities agree well in the case of a light (aluminium target). For a heavy target, the measured reflectivity for both p- and s-polarised radiation was found to be lower than the calculated one by approximately 15 %. We attribute this discrepancy to inaccuracy of the ionisation degree estimate arising from neglect of the lowering of the ionisation potential in the plasma due to the Coulomb screening [18]. In a dense plasma, the decreasing of the ionisation potential ΔE caused by this effect can be quite significant:

$$\Delta E = \frac{(Z+1)e^2}{4\pi\varepsilon_0\lambda_D},$$

where λ_D is the Debye screening radius. For instance, for a plasma where $\lambda_D \approx 0.1$ nm (a temperature of 200 eV and an electron density of 10^{24} cm^{-3}), the decreasing of the ionisation potential (in electronvolts) is $\Delta E = 13(Z+1)$. As a result, the above effect can have a stronger influence in the plasma of higher density at the same temperature, and the real electron density and ionisation degree can significantly exceed the calculated values. This reduces the reflectivity of the heavy target compared to the calculated one.

Our experimental data and calculations suggest that collisional absorption in the skin layer of a solid-density plasma in the regime of the normal skin effect dominates when metal targets are irradiated by subpicosecond laser pulses with the contrast ratio above 10^{12} and the intensity up to 3×10^{16} W cm^{-2}.

Other kinds of absorption, such as resonance absorption and 'vacuum' heating, prove to be inefficient under our experimental conditions. Their influence could manifest itself in a strong dependence of the electron temperature and the absorption coefficient on the radiation polarisation, because these heating mechanisms require the p polarisation of the light wave. However, this dependence was not observed in our work. Its absence cannot be attributed to the bending of the plasma surface, which occurs, for instance, when a target is irradiated by long (nanosecond) radiation pulses or for a low contrast ratio of a picosecond pulse [1]. Our previous study of high-order harmonic generation at the target surface showed [8] that the plasma surface remains plane during the action of an intense subpicosecond laser pulse.

Note also that we did not observe, unlike the findings of Ref [19], a reduction in the reflectivity of the p-polarised light wave compared to that calculated using the Drude model. The authors [19] explained the reduction in the reflectivity to the onset of the 'vacuum' heating mechanism at intensities above 10^{15} W cm^{-2}.

The unexpected experimental result is that the average electron energy for s polarised radiation exceeds that for p polarised radiation both for aluminium and gold targets by about 10 %, i. e., we observe an anomalous dependence of the electron energy on the polarisation of the light wave.

Both the absorption coefficient and the electron plasma temperature for p-polarised radiation are normally higher than those for s-polarised radiation. At present, we cannot suggest a clear interpretation of this effect. It is possible that this anomalous dependence is caused by an anisotropic electron velocity distribution in the plasma. In this case, the velocity component normal to the target surface in the case of p polarised radiation may be higher than that for s polarised radiation. The heat flux inside the target, which is determined by the normal component of the electron velocity, would in turn be higher for p polarisation. This may result in a faster plasma cooling in the region of laser radiation absorption (in the skin layer) and in a decreasing of the electron temperature. Another possible cause of the above anomalous dependence might be the excitation of ion Langmuir waves in the plasma of solid-state density in the case of p- polarised light wave.

Therefore, the investigations outlined above suggest that the radiation of a subpicosecond laser at 1.06 μm with a contrast ratio above 10^{12} at intensities at the metal target surface up to 3×10^{16} W cm^{-2} is absorbed in the plasma of solid-state density with a temperature of ~ 200 eV in the regime of normal skin effect.

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