Investigation of the generation of high-energy electrons in a laser plasma

V. V. Ivanov, A. K. Knyazev, A. V. Kutsenko, A. A. Matsveĭko, Yu. A. Mikhaĭlov, V. P. Osetrov, A. I. Popov, G. V. Sklizkov, and A. N. Starodub

P. N. Lebedev Physics Institute, Russian Academy of Sciences, 117924 Moscow, Russia
(Submitted 26 July 1995)
Zh. Éksp. Teor. Fiz. **109**, 1257–1266 (April 1996)

Anomalous emission of electrons from a laser plasma has been discovered. The results are described from studies of the macroscopic currents and potentials generated in a high-temperature laser plasma in the range of intensities 10^{13}–$5\cdot 10^{14}$ W/cm^2. A method of direct measurement of the electron emission from a laser plasma was developed and used to investigate the generation of fast electrons in the case of plasma heating by laser pulses of duration 3 ns and 5 ps. A maximum energy of fast electrons up to 380 keV was observed with a very high total current of electrons from the target up to 8 kA. The results of measurements of the emission of high-energy electrons versus the flux density of the laser radiation are given. A comparison is made with theoretical estimates, and possible applications are discussed.
 [S1063-7761(96)01404-7]

1. INTRODUCTION

The formation in a laser plasma of electrons with an energy many times greater than that of the thermalized electrons is an extremely interesting and important physical phenomenon, both from the point of view of fundamental study of the interaction of laser radiation with matter and from the practical point of view for a variety of laser plasma applications.

From the stand point of fundamental research, study of the generation and acceleration of fast electrons in a laser plasma makes it possible to understand and investigate some complicated physical processes that can accelerate electrons to very high energies. Examples of such processes are the resonant absorption of laser radiation in a plasma and parametric instabilities near the critical density,[1–3] two-plasmon decay in the region of the quarter-critical density,[4,5] and stimulated Raman scattering in plasma coronas.[6–8]

From the practical point of view, it is very promising to use a laser plasma that generates fast electrons as the cathode of an injector of high-current pulsed accelerators,[9] since such laser-plasma cathodes can, compared with traditional types of cathodes, ensure a high initial energy of the electrons ($>10^2$ keV), a short duration of the injection pulse ($<10^{-9}$ s), and huge current densities ($>10^6$ A/cm^2).

The generation of fast electrons in a laser plasma can play a very important role for the purposes of laser thermonuclear fusion,[10,11] both negative and positive.

For example, in schemes of hydrodynamic acceleration and compression of thermonuclear targets, even a small number of high-energy electrons, carrying less than 1% of the absorbed laser energy penetrating into the central region of the target can, cause it to be preheated and thereby catastrophically lower the compression by more than an order of magnitude and prevent the attainment of the necessary value of the confinement parameter ρR (ρ and R are the density and radius of the compressed core of the target, respectively).[11–13]

On the other hand, in the currently widely discussed promising scheme of laser thermonuclear fusion known as "fast ignition,"[14,15] one of the decisive factors in achieving success is the possibility of generating in the coronal region of the thermonuclear target high-energy electrons under the influence of an ultrashort pulse of laser radiation in order to ensure effective transport of energy via these electrons into the ignition region. Losses during energy transport can significantly reduce the proximity of the region of generation of fast electrons to the ignition region. This can be achieved by increasing the parameter $q\lambda^2$ (where q and λ are the flux density and wavelength of the laser radiation) and by correspondingly increasing the critical plasma density n_c near which the laser radiation is absorbed and fast electrons generated. An important role is here played by relativistic effects[16] that arise at high flux densities of the laser radiation ($q \geqslant 10^{18}$ W/cm^2) and lead to an increase of the critical density:

$$n_c = n_{c0}\sqrt{1+10^{-18} q\lambda^2}, \tag{1}$$

where n_{c0} is the critical density at small q and λ ($[q]=1$ GW/cm^2, $[\lambda]=1$ μm). All these above considerations indicate the importance of investigating the processes of generation of fast electrons in the corona of a laser plasma.

So far there have been several theoretical studies (see, for example, Refs. 13 and 17–21) of the possibility of obtaining in a laser plasma superthermal electrons with energies from tens of kilo-electron-volts to a few mega-electron-volts depending on the flux density. There have also been several experimental studies of the generation of fast electrons in laser plasmas when radiation of a CO_2 laser ($\lambda = 10.6$ μm, Refs. 22 and 23), Nd laser ($\lambda = 1.053$ μm, Refs. 24–27), and the harmonics of this laser ($\lambda = 0.263$ μm and $\lambda = 0.526$ μm, Ref. 28) act on the material. The energy of the electrons observed in some experiments was more than 10^2 keV. The studies of Refs. 23 and 27, in which the energies of individual electrons exceeded 10^3 keV, should be especially mentioned.

In all these experiments, the electron detectors (silicon diodes of photoemulsions) were placed at different distances

 1063-7761/96/040677-06$10.00

from the laser target, and the measurements of the emission were made in small solid angles. In such an experimental arrangement, even if several detectors are pointed in different directions in order to measure the angular distribution of the emission of the fast electrons (see, for example, Refs. 22, 23, and 28), it is difficult to obtain reliable experimental data on the total currents produced by the fast electrons. The same can be said of another group of experiments, in which the superthermal electrons were not investigated directly but on the basis of an analysis of the spectrum of x rays from the plasmas.[27,29,30]

2. DESCRIPTION OF THE EXPERIMENT

In the work reported here, we investigated electron emission from a laser plasma by means of a special technique that made it possible on the basis of direct measurements to obtain the maximum energy of the fast electrons and measure the integrated values of the macroscopic currents generated by them.[31,32] A minimum estimate of the electron energy was found from direct measurement of the macroscopic potential generated by the laser plasma while the laser pulse was acting.

The experiments were performed in the Laser Plasma Laboratory of the P. N. Lebedev Physics Institute using the PIKO facility. Aluminum was the material of the irradiated target. The effect of laser radiation on the target was investigated in the range of flux densities q from 10^{13} to $5\cdot 10^{14}$ W/cm^2 for two laser pulse lengths in the nanosecond and the picosecond ranges. Radiation from Nd lasers ($\lambda = 1.06\ \mu$m) was focused on the flat surface of a cylindrical target, which was simultaneously the inner plate of a coaxial capacitor. The pressure p of the residual gas in the target chamber was varied from 10^{-2} to $6\cdot 10^{-6}$ torr.

The width at half maximum of the laser pulse was $\tau = 2$ ns or 5 ps. The laser energy E in the nanosecond regime of target irradiation was varied from 2 to 20 J, corresponding to a variation of q from 10^{13} to 10^{14} W/cm^2. In the picosecond regime of target irradiation, the energy of an individual pulse was varied from 40 mJ to 240 mJ, and the corresponding values of the flux density q were varied in the range 10^{14}–$5\cdot 10^{14}$ W/cm^2. The divergence of the radiation, estimated from the focusing spot, was $2\alpha = 5\cdot 10^{-4}$–$8\cdot 10^{-4}$ rad depending on the regime of laser operation. The energy contrast of the radiation focused on the target, K_E, varied from shot to shot in the range $\sim 10^3$–10^5. The half-width $\Delta\lambda$ of the radiation spectrum of the nanosecond laser was 30 Å, while that of the picosecond laser was 5–8 Å.

To determine the size of the region of the high-temperature plasma responsible for the generation of the fast electrons and to measure the electron temperature in it by the method of absorbers, we used a multichannel x-ray pinhole camera with Be filters of thickness from 50 μm to 800 μm and the x-ray photoemulsion UF-VR-2 as a radiation detector.[33–35]

3. DETECTION SCHEME

We consider briefly the characteristic features of the method of the measurements that made it possible to detect the anomalously high energies of the electrons and electron current generated by fairly moderate flux densities on the target.

The basic scheme for detecting the electron emission for the present series of experiments is described in Ref. 31. The construction of the target unit consisted of the target itself in the form of a cylindrical rod of diameter 5 mm and length 25 mm placed inside a cylindrical shell with the gap between them filled by an insulating film made of mylar or Teflon. The combination consisting of the target, screen, and insulator constituted a coaxial capacitor. The signal from the central plate through a coaxial high-voltage resistance reached a cable transmission line. The system consisting of the resistance and the coaxial cable acted as a high-voltage divider, the signal from which passed through a system of coaxial attenuators and synchronized dividers to the plates of a fast oscillograph. Unfortunately, the irradiation geometry did not allow strict matching of the parameters of the coaxial capacitor to the coaxial transmission line; however, this did not affect the detected oscillogram, since the "electric length" of the capacitor was less than the duration of the laser pulse and the resolution of the oscillograph. The characteristic time of the natural oscillations of the coaxial capacitor was approximately 0.04 ns.

The detection circuit was calibrated by passing through it a specially shaped high-voltage pulse shorter than the laser pulse. We note that the characteristic time for generation of anomalously high-energy electrons for the given fluxes cannot in principle exceed the duration of the laser pulse. Direct calibration of the measurement circuit in this manner was not possible for the case of the picosecond pulse since in this case the laser pulse was significantly shorter than the time resolution of the measuring circuit.

The triggering of the oscillograph was synchronized with the nanosecond and picosecond lasers by means of a coaxial photocell and a corresponding delay line. The synchronization system ensured an accuracy of detection of the time of onset of the emission of the high-energy electrons relative to the onset of the heating of the target by the laser pulse of ± 0.1 ns.

Typical oscilloscope traces of the laser pulse and the current pulse of the high-energy electrons from the plasmas heated in the nanosecond and picosecond regimes are shown in Fig. 1. The maximum energy of the electrons was determined from the potential that arose on the target relative to the capacitor surrounding it. In its turn, the maximum value of the potential was calculated from the amplitude of the first pulse on the oscillograph screen with allowance for the parameters of the attenuators in the long transmission line and the experimentally measured transmission coefficient of the detection circuit.

4. RESULTS OF THE MEASUREMENTS

The largest peak energy of the high-energy electrons measured in the work described here was $E_{\max 1} \approx 380 \pm^{20}_{80}$ keV in the case of heating by the nanosecond laser pulse and $E_{\max 2} \approx 30 \pm 5$ keV in the case of the picosecond pulse. The scheme used for the detection of the electron emission, considered in detail above and in Ref. 31, enables us to assert

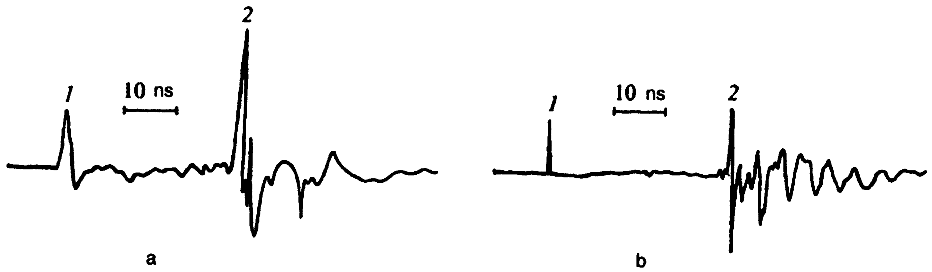

FIG. 1. Typical oscillograms of the laser pulse (1) and the current pulse of the high-energy electrons from the plasma (2): a) heating of the plasma by a nanosecond laser pulse; b) heating of the plasma by a picosecond laser pulse. The amplitudes of the positive pulses 2 correspond to 320 keV (a) and 30 keV (b).

that the current from the target through the capacitor greatly exceeded the current through the high-voltage resistance of the measuring circuit. Therefore, using the oscillograms to calculate an upper limit of the characteristic rise time τ of the current pulse of the high-energy electrons (Fig. 1), we can estimate the maximum value of the current using only the current through the target–capacitor circuit:

$$J_c \sim \frac{\pi E_{\max} C}{e\tau},$$

where C is the capacitance of the target–capacitor circuit, which has the value $6 \cdot 10^{-11}$ F, and e is the electron charge. It is readily seen that when a nanosecond pulse acts the target the characteristic duration of the current pulse is about $3 \cdot 10^{-9}$ s. Then the measured value of the electron current averaged over the pulse reaches about 8 kA. The current corresponding to the high-energy electrons with $E \geqslant E_{\max}$ was determined by the current through the high-voltage divider and was approximately equal to 12 A. The corresponding density of the average current with allowance for the size of the focusing spot of about 150 μm was of order 1 MA/cm^2. The charge carried away by this current during the time τ can be estimated at $\sim 10^{-5}$ C.

With regard to the maximum values of the current and potential in the case of a picosecond pulse, the resolution of the detection scheme permit measurement of the actual values, which may exceed by several orders of magnitude the value corresponding to a nanosecond pulse. An estimate from the oscillogram obtained with resolution ± 0.1 ns gives ~ 1 kA. If, however, we note that the high-energy electrons must be generated during the laser pulse, then the estimated macroscopic electric current for a characteristic time of measurement of the current equal to the laser-pulse duration of 5 ps reaches a value of about 0.5 MA, and the corresponding current density is $\sim 10^9$ A/cm^2. This last value is only a surmise and requires further experimental verification. For this, it is necessary to develop a new method of measurement permitting significant improvement of the time resolution.

The electron temperature measured in the nanosecond case by the method of absorbers varied, depending on the flux density of the laser radiation on the target, from $T_{\min} = 80 \pm 20$ eV to $T_{\max} = 300 \pm 55$ eV. The results of the x-ray photography of the plasma were also used to verify the calculated flux density of the laser radiation on the target.

The dependence of the emission of high-energy electrons from the plasma on the flux density was investigated by varying the energy of the laser radiation focused on the target while keeping unchanged the remaining parameters of the laser and the conditions of focusing. Figures 2 and 3 give the results of measuring the maximum energy of the electrons as a function of the radiation intensity for heating of the plasma by nanosecond (Fig. 2) and picosecond (Fig. 3) laser pulses for different pressures of the residual gas in the target–diagnostics chamber: $p_1 = 10^{-2}$ torr and $p_2 = 10^{-5}$ torr. Note the strong dependence of the maximum electron energy on

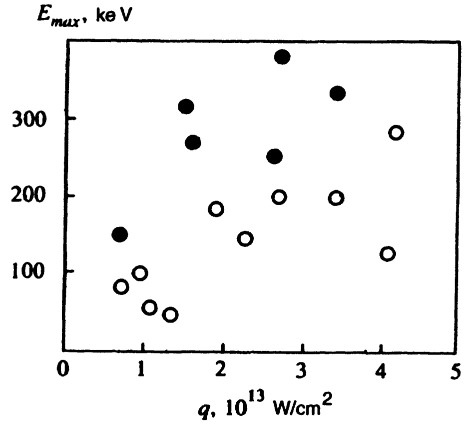

FIG. 2. Dependence of the maximum energy of the high-energy electrons on the flux density of the laser radiation on the target for an aluminum plasma heated by a nanosecond laser pulse; the open circles and black circles are for $p_1 = 10^{-2}$ torr and $p_2 = 10^{-5}$ torr, respectively.

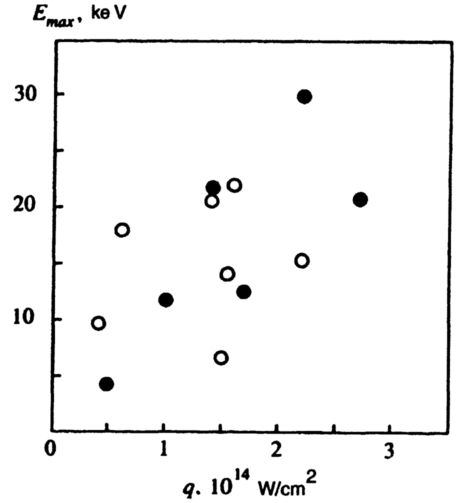

FIG. 3. Dependence of the maximum energy of the high-energy electrons on the flux density of the laser radiation on the target for an aluminum plasma heated by a picosecond laser pulse; the open circles and black circles are for $p_1 = 10^{-2}$ torr and $p_2 = 10^{-5}$ torr, respectively.

the intensity of the heating radiation for both the nanosecond and the picosecond pulses of the heating radiation and also the significant effect of the residual gas surrounding the target on the generation of high-energy electrons in the case of a nanosecond pulse and the absence of such an influence in the case of a picosecond pulse. The maximum energies of the high-energy electrons measured in the case of heating by the picosecond laser radiation were found to be approximately an order of magnitude less than in the case of heating by the nanosecond pulse. However, we must mention the lower (by approximately a factor of 10) value of the energy contrast of the picosecond laser pulses and the integrated nature of the oscillograms detected in this case. It is also necessary to take into account the fact that the mechanisms for which the high energy electrons are generated in the nanosecond and picosecond cases are, to judge by all the appearances, essentially different. For example, longitudinal plasma oscillations cannot develop during a time $\sim 10^{-12}$ s, to say nothing of the time required for the establishment of a thermodynamic state of the electrons and ions of the plasma and radiative equilibrium of it.

5. DISCUSSION OF RESULTS

It is interesting to compare the results with theoretical estimates. Generally speaking, modeling the interaction of electrons with plasma waves and electromagnetic radiation in a laser plasma in the relativistic case is a very complicated problem. Thus, the plasma waves capable of ensuring electron acceleration, like the nonlinear mechanisms, lead to a very complicated form of the dispersion relation $\omega(\mathbf{k})$, where ω is the frequency and $\mathbf{k}$ is the wave vector. Besides these complications, an electron in the plasma can, undergo multiple interactions with one or several waves before it escapes. In our case, the situation is aggravated by the fact that the measured currents have huge values. This leads to macroscopic violation of the electrical neutrality of the high-temperature region of the laser plasma. It is therefore difficult to separate one simple mechanism of acceleration of electrons in the laser plasma.

In Ref. 19 there is a theoretical estimate of the maximum energy of the electron oscillations, which determines the maximum energy of the high-energy electrons, for resonant absorption with linear density profile:

$$E_{\max}\approx 4eE_0L\sqrt{fc/\pi\omega L}\approx 2\cdot 10^{-6}\sqrt{fq\lambda L}, \tag{2}$$

where e is the electron charge, E_0 is the field strength of the laser radiation, f is the fraction of the energy of the electromagnetic wave transformed into an electrostatic field, L is the characteristic length scale of the plasma, and q is the flux density of the laser radiation ($[q]=1$ W/cm^2, $[\lambda]=1$ μm, $[L]=1$ μm). Taking $f\approx 1$, $q\approx 5\cdot 10^{13}$ W/cm^2, $L\approx 50$ μm, we obtain for the fundamental radiation frequency of the Nd laser the estimate $E_{\max}=10^2$ keV.

A similar estimate is obtained by considering a model of the formation of the high-energy electrons in a localized field that was studied in detail in Ref. 13. In accordance with this model, the presence in a laser plasma of localized fields—cavitons—gives rise to a superthermal component of the electron energy distribution function that is characterized by a "hot temperature" T_h, which can be approximated by the expression

$$T_h\approx 9.6\,\frac{R_0^{0.2}}{A_b^{0.26}}\left(\frac{z+4}{14}\right)^{0.26}(q\lambda)^{0.4}, \tag{3}$$

where R_0 is the radius of the evaporation wave, A_b is the coefficient of absorption of the laser energy in the plasma, $[q\lambda]=10^{14}$ W$\cdot\mu$m/cm^2, and $[T_h]=1$ keV. For the characteristic parameters of the experiment we obtain $T_h\approx 10$ keV, in good agreement with the measurements based on the spectrum of the continuum x-ray radiation. In Ref. 13, the following estimate was obtained for the cutoff energy (maximum energy) of the spectrum of fast electrons on the basis of T_h:

$$E_{\max}\approx 0.125D^2T_h, \tag{4}$$

where $D=d/\lambda_D$ is the half-width of the field (caviton) expressed in Debye radii λ_D in the neighborhood of the critical density. For the typical value $D\simeq 7$ we obtain $E_{\max}\approx 60$ keV.

The estimates of the maximum energy of the electrons obtained on the basis of these models give values of $E_{\max}$ appreciably lower than those measured experimentally in the present study, at least in the case of the plasma heating by the nanosecond pulses. A possible reason for the increase in the electron energy could be, for example, acceleration of the electrons in local regions of the plasma, in which the high degree of coherence of the laser radiation could give rise to small-scale bursts of the flux density with peak values exceeding the mean flux density on the target by orders of magnitude.[36,37]

6. CONCLUSIONS

In conclusion, we also mention some interesting aspects of the generation of high-energy electrons and ultrahard x rays in a plasma heated by ultrashort laser pulses (duration $\tau\approx 1-10$ ps) with flux density $q\geqslant 10^{18}$ W/cm^2. At such fluxes, the electrons can be accelerated in the field of the laser electromagnetic wave with field strength $\mathscr{E}$ to relativistic energies $E_{\max}\sim e\mathscr{E}\lambda$ greatly exceeding the electron rest energy. As we have already mentioned above, in some experiments individual high-energy electrons have been observed,[23,27] with energy up to 0.2–1 MeV even in the case of long pulse durations.

The density of the separated electric charge Q in the plasma can reach values greater than ~ 10 C/cm^3, while the derivatives of the charge and current reach fantastic values: $dQ/dt\sim 10^{10}-10^{13}$ C$\cdot$cm$^3\cdot$s^{-1} and $dJ/dt\sim 10^{12}-10^{15}$ A/s. The maximum value of the current due to the charge separation at the energy $E_{\max}$ of the generated electrons for a focal spot of radius R_f and pulse of duration τ can be estimated at

$$J\approx 2R_fE_{\max}/e\tau\geqslant 10^3\ \text{A}. \tag{5}$$

This estimate applies to an isolated spherical target. For a massive nonisolated target, the experiment showed that if a charge sink exists the current from the laser plasma can be appreciably greater than the estimate obtained above. At the same time, the amplitude of the macroscopic magnetic field reaches values $H \sim 10^7 - 10^8$ G. The radiated flux of electromagnetic energy, actually determined by the derivative of the current and estimated from the Poynting vector, then has a value ($S \sim 10^{17}$ W/cm^2) only an order of magnitude less than the flux of the laser radiation. However, the brightness of this radiation is much less than that of the laser radiation, since it is emitted into the complete solid angle 4π.

The presence in the laser plasma of fluxes of high-energy electrons makes it possible to observe ultrahard x rays due to Compton scattering of some of the laser radiation by these electrons.[38] Indeed, for relativistic electrons satisfying $1-\beta \ll 1$ the energy $\hbar\omega'$ of a photon scattered through angle ϑ relative to the direction of motion of an electron is determined by the well-known relation

$$\hbar\omega' \approx \frac{4\hbar\omega}{(1-\beta)^2 + 4\hbar\omega/E_{\max} + \vartheta^2}, \tag{6}$$

where β is the electron velocity, and $\hbar\omega$ is the energy of a laser photon; alternatively, in the ultrarelativistic case

$$\hbar\omega' \approx 4E_{\max}^2 \hbar\omega/(mc^2)^2,$$

where mc^2 is the electron rest energy. Such photons propagate in the opposite direction to the laser beam in the narrow solid angle $\vartheta \sim (mc^2)^2/E_{\max}^2$. Using the expression (6) for an estimate under the conditions of our experiment ($E_{\max} \approx 3 \cdot 10^5$ eV at $q \sim 3 \cdot 10^{13}$ W/cm^2) and the dependence of the energy of the accelerated electrons on the flux $E_{\max} \sim \sqrt{q}$, we obtain for $q \sim 10^{20}$ W/cm^2 the result $\hbar\omega' \sim 2 \cdot 10^6 \hbar\omega$ eV, where for the Nd laser with $\hbar\omega \approx 1$ eV the scattered photons are in the megavolt energy range. The predominant direction of the beam of scattered photons is determined by the direction of the current of the emitted accelerated electrons and is in opposite that of the laser beam. The characteristic divergence may reach $\alpha \sim 10^{-3}$ rad.

We should also note the remarkable fact that the energy expended on separating the charges in our experiments was a significant fraction of the energy of the laser pulse. Thus, in a number of firings the energy of the charge on the target capacitor reached 30% of the absorbed laser energy. This means that the energy of the macroscopic electromagnetic field in the laser plasma may be comparable with the gas-kinetic energy and the energy of the thermal radiation (see, for example, Ref. 39). This last fact can have a strong influence on calculations relating to the energy balance of laser plasmas, which is important in the theory of the compression of spherical thermonuclear targets, especially in the "fast compression" regime, in which the original laser radiation varies greatly on the target surface. Thus, in gas-dynamic calculations of laser plasmas, at least for fluxes greater than 10^{14} W/cm^2, one must approach with care the inclusion in the equation of state of the terms associated with the macroscopic currents during while the laser radiation acts and during their ponderomotive interaction.[40] With regard to the connection between these results and the problem of laser thermonuclear fusion, we must, in addition to what we have said above, take into account in the calculations of models of plasma compression and the construction of thermonuclear targets the generation of high-energy electrons in the plasma. In addition, it is necessary to design special experiments to investigate the generation of high-energy electrons for laser heating of special targets that model thermonuclear targets, both for the regime of "hydrodynamic compression" and for the "fast ignition" regime. Such investigations will make it possible not only to construct an adequate model of the generation of high-energy electrons but also to optimize the conditions for their generation in accordance with the requirements of the chosen regime for heating and compression of thermonuclear laser targets.

This work was done with the support of the International Science Foundation (Grants MN5000 and MN5300) and the Russian Fund for Fundamental Research (Grant No. 94-02-05794).

[1] E. J. Valeo and W. L. Kruer, Phys. Rev. Lett. **33**, 750 (1974).
[2] K. Estabrook, E. J. Valeo, and W. L. Kruer, Phys. Fluids **18**, 1151 (1975).
[3] D. W. Forslund, J. M. Kindel, and K. Lee, Phys. Rev. Lett. **39**, 284 (1977).
[4] C. S. Liu and M. N. Rosenbluth, Phys. Fluids **19**, 967 (1976).
[5] A. Simon, R. W. Short, E. A. Williams, and T. Dewandre, Phys. Fluids **26**, 3107 (1983).
[6] C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids **17**, 1211 (1974).
[7] J. F. Drake, P. K. Kaw, Y. C. Lee *et al.*, Phys. Fluids **17**, 778 (1974).
[8] D. M. Forslund, J. M. Kindel, and E. L. Lindman, Phys. Fluids **18**, 1002 (1975).
[9] V. K. Lugovskoĭ, F. A. Nikolaev, and G. V. Sklizkov, Kvantovaya Elektron. (Moscow) **3**, 614 (1976) [Sov. J. Quantum Electron. **6**, 331 (1976)].
[10] V. V. Ivanov, A. K. Knyazev, A. V. Koutsenko *et al.*, in *Proceedings of the 12th International Conference on Laser Interaction and Related Plasma Phenomena* (Osaka, Japan, 1995).
[11] J. Nuckolls, L. Wood, R. Thiessen, and G. Zimmermann, Nature, **239**, 139 (1972).
[12] N. G. Basov, S. Yu. Gus'kov, and V. B. Rosanov, Tr. Fiz. Inst. Akad. Nauk SSSR **170**, 3 (1986).
[13] V. B. Rozanov and S. A. Shumskiĭ, Tr. Fiz. Inst. Akad. Nauk SSSR **170**, 8 (1986).
[14] N. G. Basov, S. Yu. Gus'kov, and L. P. Feoktistov, J. Sov. Laser Research **13**, (5), 396 (1992).
[15] M. D. Perry and G. Morou, Science **264**, 917 (1994).
[16] P. Kaw and J. Dawson, Phys. Fluids **13**, 472 (1970).
[17] K. Estabrook, W. L. Kruer, and B. F. Lasinski, Phys. Rev. Lett. **45**, 1399 (1980).
[18] P. Mora and F. Amiranoff, J. Appl. Phys. **66**, 3476 (1989).
[19] J. Albritton and P. Koch, Phys. Fluids **18**, 1136 (1975).
[20] L. M. Kovrizhnykh and A. S. Sakharov, Fiz. Plazmy **2**, 97 (1976) [Sov. J. Plasma Phys. **2**, 54 (1976)].
[21] L. M. Kovrishnykh and A. S. Sakharov, Fiz. Plazmy **5**, 840 (1979) [Sov. J. Plasma Phys. **5**, 470 (1979)].
[22] N. A. Ebrahim, H. A. Baldis, C. Joshi, and R. Benesch, Phys. Rev. Lett. **45**, 1179 (1980).
[23] N. A. Ebrahim, H. A. Baldis, and C. Joschi, Phys. Rev. Lett. A **84**, 253 (1981).
[24] D. W. Phillion, E. M. Campbell, K. Estabrook, and G. E. Phillips, Phys. Rev. Lett. **49**, 1405 (1982).
[25] M. P. Kalashnikov, Yu. A. Mikhaĭlov, and V. K. Lyapidevskiĭ, *et al.*, Kratk. Soobshch. Fiz. **8**, 41 (1983).
[26] A. E. Danilov, Yu. A. Mikhaĭlov, F. A. Nikolaev *et al.*, JETP Lett. **37**, (11), 622 (1983).
[27] N. G. Basov, V. V. Kushin, V. K. Lyapidevskiĭ *et al.*, Tr. Fiz. Inst. Akad. Nauk SSSR **203**, 69 (1990).
[28] C. Rousseaux, F. Amiranoff, C. Labaune, and G. Matthieussent, Phys. Fluids B **4**, 2589 (1992).
[29] R. L. Keck, L. M. Goldman, M. C. Richardson *et al.*, Phys. Fluids **27**, 2762 (1984).
[30] J. Meger and L. E. Legault, Phys. Fluids B **2**, 1224 (1990).
[31] V. V. Ivanov, A. K. Knyazev, N. E. Korneev *et al.*, Prib. Tekh. Eksp. (4), 77 (1995).
[32] N. R. Isenor, J. Appl. Phys. **36**, (1), 316 (1965).

[33] A. A. Kologrivov, Yu. A. Mikhaĭlov, G. V. Sklizkov *et al.*, Kvantovaya Elektron. (Moscow) **2**, 2223 (1975) [Sov. J. Quantum Electron. **5**, 1210 (1975)].
[34] N. G. Basov, Yu. A. Mikhaĭlov, G. V. Sklizkov, and S. I. Fedotov, *Reviews of Science and Technology, Series Radiophysics,* Vol. 25, Part [in Russian] (VINITI, Moscow, 1983).
[35] N. G. Basov, M. P. Kalashnikov, Yu. A. Mikhaĭlov *et al.*, Tr. Fiz. Inst. Akad. Nauk **203**, 3 (1990).
[36] N. G. Basov, A. E. Danilov, V. V. Orlov *et al.*, Tr. Fiz. Inst. Akad. Nauk SSSR **178**, 120 (1987).
[37] N. G. Basov, A. E. Danilov, Yu. A. Mikhaĭlov *et al.*, Tr. Fiz. Inst. Akad. Nauk SSSR **178**, 89 (1987).
[38] P. G. Kryukov, A. I. Nikishov, V. I. Ritus, and V. I. Sergienko, *Preprint* FIAN, No. 11, Moscow (1993).
[39] A. V. Gurevich, L. V. Pariĭskaya, and L. P. Pitaevskiĭ, Zh. Éksp. Teor. Fiz. **49**, 647 (1965) [Sov. Phys. JETP **22**, 449 (1966)].
[40] H. Hora, *Physics of Laser Driven Plasmas,* (John Wiley and Sons, New York, 1981).

Translated by Julian B. Barbour