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Beams of Abnormally Accelerated Electrons Emitted by a Vacuum Discharge Plasma with Laser Ignition

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Abstract—It has been experimentally shown that a low-power vacuum pinch discharge with laser ignition can emit a beam of abnormally accelerated electrons with maximum energies per unit charge almost an order of magnitude higher than the voltage across the discharge gap. It has been found that the intensity of the X-ray radiation generated when the beam is applied to the target significantly decreases with an increase in the laser pulse energy. The maximum energy of X-ray quanta is inversely proportional to the mass of the cathode substance ablated by laser radiation during discharge ignition. Possible mechanisms of the electron-beam generation process have been discussed.

Keywords: vacuum discharge, laser ignition, X-ray radiation, electron beam, pinch.

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The fluxes of energetic electrons moving near the discharge axis in the direction of the anode were recorded in early experiments with high-voltage vacuum discharges at the moments of the discharge current failure [1, 2]. Later, beams of accelerated electrons with an energy per unit charge exceeding the voltage at the discharge gap ("abnormally" accelerated electrons) were repeatedly recorded in different types of pinch discharges: high-power *Z*- and *X*-pinches with wire loads [3, 4], as well as high-current vacuum-spark discharges [5]. A possible mechanism for the formation of fast electron beams was connected with the formation of micropinch structures in the plasma column and the acceleration of electrons in the electric field generated during the collapse of the micropinch or with the development of abnormal plasma resistance during the pinching of the discharge plasma [6, 7]. It should be emphasized that the effects of plasma column pinching and emission of abnormally accelerated electrons were observed in these discharges at currents of the order of hundreds of kiloamperes and higher.

Previously, the authors discovered the effects of the formation of micro-pinch structures, the generation of electron beams [8], as well as recording beams of abnormally accelerated ions [9] in a low-power vacuum discharge with laser ignition (current ~10 kA, and voltage up to 20 kV). In this Letter, measurements of the characteristics of electron beams emitted by a discharge in a wide range of laser pulse energies were carried out for the first time to clarify the possibility of implementing the mechanism of anomalous electron acceleration under these experimental conditions and identifying the features of this mechanism—in particular, the relationship of the characteristics of the beams with the conditions of initiation of the discharge.

The studies were carried out on a laboratory bench consisting of a vacuum diode with a residual pressure in the working volume of less than 10^{-4} Pa, a neodymium laser emitting at a wavelength of 1.06 μm, and X-ray diagnostics based on a VEU-7 electronic multiplier. The scheme of the experiment is shown in Fig. 1. The discharge was initiated on a flat Fe-cathode by a laser beam with a half-height duration of 6 ns and a focal spot size of ~80 μm incident at an angle of 45° relative to the normal to the surface. The peak radiation power densities on the cathode surface for the pulses with energies $J = 2$ and 300 mJ were 10^{10} and 10^{12} W/cm^2, respectively. The current in the discharge circuit with an inductance of 63 nH was maintained by a capacity of 0.22 μF and measured by a Rogowski coil installed in the cathode circuit. At the short-circuit mode, the half-period of current fluctuations was equal to 0.4 μs and the current amplitude value at the voltage on the storage device of −10 kV was ~17 kA. The distance between the cathode and the grounded steel anode was 7 mm. The electron beam emitted by the plasma passed through a hole in the anode with a diameter of 9 mm and fell on the Ta plate connected to

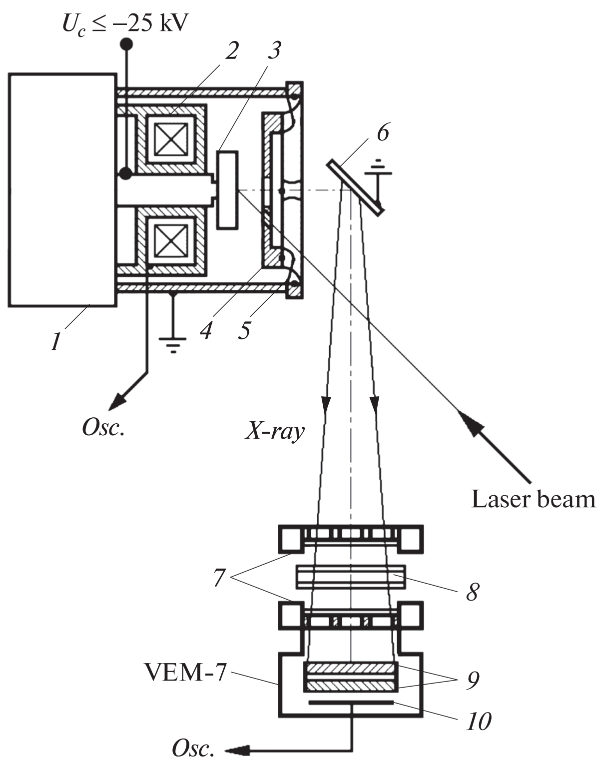

Fig. 1. Experiment scheme. (*1*) Capacitor, (*2*) Rogovsky coil, (*3*) cathode, (*4*) anode, (*5*) flexible conductive bus, (*6*) Ta plate, (*7*) Be-foil windows, (*8*) block of additional absorbers, (*9*) microchannel plates, and (*10*) electron collector.

the anode and oriented at an angle of 45° to the beam axis. Under the influence of the electron beam, the plate emitted X-ray radiation, which, through a window vacuum-tightly closed with a Be foil 400 μm thick and the air gap, fell into a vacuum volume closed with the identical foil, where the X-ray recorder was placed. The minimum energy of X-ray quanta recorded in the absence of additional absorbers was determined by the level of 0.1 of the transmission curve of Be filters with a total thickness of 800 μm and was 3 keV. The maximum energies of X-ray quanta were also estimated by the transmission curves of a set of additional absorbers, selected so that the signal at their transmission at the level of 0.1 did not exceed 50 mV with the maximum gain of VEU-7 corresponding to the value of 6.7×10^6, which was due to the optimal permissible signal-to-noise ratio. The sensor signals were recorded by a TDS 5054B oscilloscope with a 500-MHz bandwidth.

Figure 2 shows the waveforms of current derivatives and X-ray pulses with a quantum energy of more than 3 keV at different values of the laser pulse energy. From the figure it is seen that at the moment of reaching the maximum of the singularity on the derivative of the discharge current an X-ray pulse is observed, meaning that at this moment, the discharge plasma emits a beam of accelerated electrons. As laser energy J increases, the signals shift to the range of large discharge currents, while the current derivative singularity amplitude decreases. This effect is quantitatively illustrated in a wide range of laser pulse energies in Fig. 3. It follows from the figure that the discharge emits a relatively intense electron beam with a maximum energy E of about 90 keV at a small energy value J = 1.8 mJ. With an increase in J, the value of E decreases according to the scaling $E \propto J^{-0.4}$ and slightly exceeds 10 keV at J = 300 mJ. Since the mass/density of the target-cathode material ablated by laser radiation is related to the laser pulse energy by the dependence $M \propto J^{0.56}$ according to [10], it can be concluded that with an increase in M, the maximum energy of the electron beam decreases approximately in proportion to $1/M$. In addition, the X-ray pulse duration increases with the laser beam energy and the X-ray pulse amplitude decreases. Thus, the duration of the X-ray pulse increases from 6 to 24 ns with J increasing in the range of 1.8–4 mJ (Fig. 2).

Note that, at high energies of the laser pulse, in addition to the radiation caused by the emission of electron beams at the moments of occurrence of current derivative singularities (the corresponding signals are marked with the number II in the lower fragment in Fig. 2), an X-ray radiation pulse generated when the target is exposed to an electron beam emitted by a laser plasma (the signal is marked with the number I) at the spark stage of the discharge development is also recorded.

The previous experiments of the authors [11] showed that an increase in the plasma density in the discharge gap, e.g., because of an increase in J, leads to the formation of a "plasma coat" surrounding the cathode jet, an increase in the pinching current, and a slower development of the sausage instability with the formation of micropinch. Similar trends are observed for the time parameters of the current derivative signal singularity and of the X-ray detector signal (Fig. 2), which allows us to conclude that the pinching process which allows us to conclude on the relationship between the pinching of a jet and the emission of beams of anomalously accelerated electrons. At the same time, in the case of an increase in J, the value of the discharge current is probably insufficient to realize the final stage of the pinching process and the breakage of the current channel, while the plasma density in the neck increases [12], the amplitude of the singularities on the current signals decreases and the acceleration of electrons/ions decreases. At low energy J, there is practically no plasma coat and the discharge current magnitude is sufficient to form a micropinch, the subsequent collapse of which leads to a partial breakage of the current channel and a restriction of current transfer.

According to another approach developed in [13], when the discharge current increases, the substance

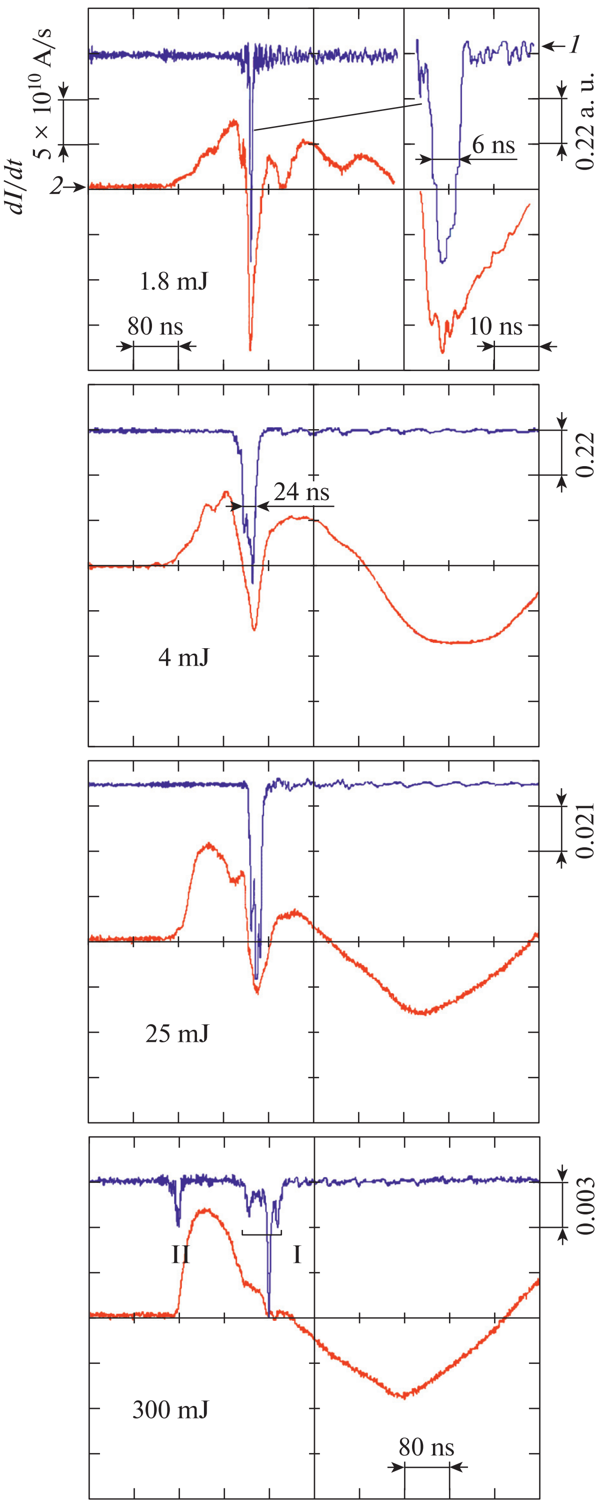

Fig. 2. Waveforms of X-ray pulses with a quanta energy of more than 3 keV (beam *1*) and current derivatives (beam *2*) at different values of laser pulse energy *J*.

for its transmission is not enough and a double electric layer is formed that leads to a partial breakdown of the current and the formation of a beam of accelerated electrons. This does not contradict the possibility of

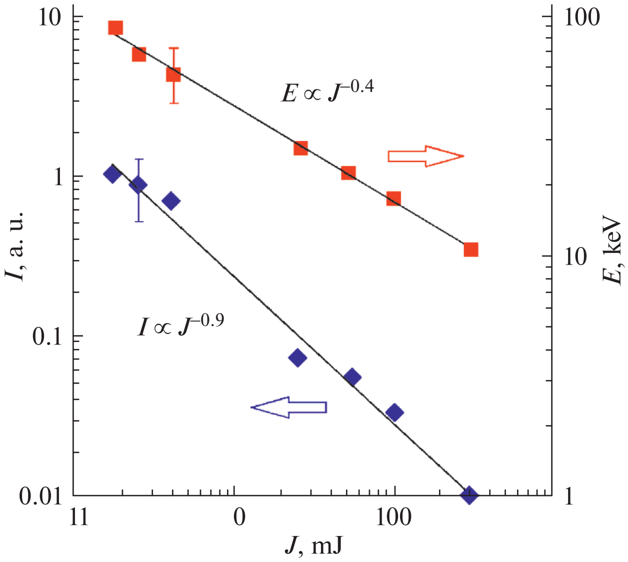

Fig. 3. Dependences of electron-beam maximum energy and intensity of the X-ray radiation of the target on laser-pulse energy.

forming a neck in the plasma jet. Plasma pinching in this case increases the degree of ionization, but it is not the main mechanism of acceleration.

Earlier studies performed under the same experimental conditions showed that the decrease in the laser-pulse energy corresponds to the mode of anomalous acceleration of the ions of the cathode material [9]. This suggests that the ions are captured and accelerated by the space charge field of an abnormally accelerated electron beam [14]. This conclusion is consistent with the fact that the emission of the beams of abnormally accelerated electrons/ions was observed earlier at the moments of current bursts in a high-voltage vacuum-spark [1, 2]. At the same time, the authors of [15] attributed these effects to the capture and acceleration of particles by the electric field of the density cavity formed at the nonlinear stage of the Buneman instability.

Thus, the experiment shows that a vacuum discharge with laser ignition and moderate energy in a wide range of laser pulse energies emits a beam of abnormally accelerated electrons, the maximum energy of which is almost an order of magnitude higher than the voltage at the discharge gap. Note that this energy is comparable to the energy of electron beams emitted by high-current pinch discharges [5].

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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