Experimental investigation of the interaction of an electromagnetic field with a plasma layer

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The effect of nonlinear transparency of a plasma layer in the field of an intense electromagnetic wave is investigated experimentally. It is observed that the plasma bleaching is accompanied by an anisotropic change of the distribution function, wherein the maximum number of fast particles is observed in a direction parallel to the projection of the wave field on the surface of the plasma layer. The bleaching process has a nonstationary character. The results are interpreted theoretically. It is shown that the main characteristics of the effect are well explained by assuming that a modulation instability develops in the plasma and leads to excitation of nonlinear Langmuir waves.

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Problems connected with plasma heating by powerful laser radiation to thermonuclear temperatures,[1] as well as the possibility of artificially modifying the ionosphere by intense radio emission,[2] have stimulated theoretical and experimental investigations of parametric processes in a dense plasma. The present paper is devoted to an exposition of the experimental results obtained in the investigation of collisionless nonlinear interaction of an electromagnetic field with an inhomogeneous plasma layer. Principal attention was paid to the study of the change of the electrodynamic characteristics of the plasma layer and the concomitant effects under the influence of intense radiation. The first theoretical papers dealt with the possibility of waveguide propagation in an opaque plasma, connected with the redistribution of the plasma density in the field of the electromagnetic wave and with formation of regions of decreased concentration with dimensions on the order of the radiation wavelength λ_0.[3] One-dimensional models for the increase of the transmission coefficients, which are connected with this effect for a tenuous plasma ($N<N_{cr}$, where N_{cr} is the critical concentration for the radiation field at the frequency ω_0) and for a dense plasma ($N>N_{cr}$) were presented in[4,5]. In an experimental investigation of this phenomenon,[6–8] an anomalously rapid establishment of nonlinear transparency of the plasma was observed (the bleaching time did not exceed the rise time $\tau_{fr}\approx 3\times 10^7$ sec of the electromagnetic pulse), and could not be explained within the framework of the aforementioned models, which call for the redistribution of the plasma in the entire interaction region, i.e., over a dimension on the order of the wavelength λ_0. This process should occur within a time $\tau\approx\lambda_0^2\nu_s^{-2}\nu_{im}\approx 10^{-5}$ (v_s is the ion-sound velocity and ν_{im} is the ion collision frequency). It was proposed as early as in[6,7] that the fast bleaching may be due to breakdown of the plasma, in the intense field, into layers with dimensions much smaller than the radiation wavelength and oriented perpendicular to the electric-field vector. This suggestion was confirmed by observation of the polarization anisotropy of the plasma in a strong field with the aid of a linearly polarized sounding wave.[6] It was shown in[9] that the bleaching of an opaque plasma results from modulation instability of the Langmuir oscillations, and estimating relations were obtained for the characteristic parameters of the effect. The value obtained for the threshold field amplitude was

$$\frac{E_m^2}{E_p^2}>\frac{1}{64}\left(\frac{2M}{m}\right)^{1/2}|\epsilon_m|^{3/2} \qquad (1)$$

(E_m is the maximum field of the incident wave in the plasma, $E_p^2=4(T_e+T_i)(m\omega^2/e^2)$ is the characteristic plasma field, and ϵ_m is the value of ϵ at the maximum of the layer); the estimate obtained for the stratification scale was

$$l_{opt}\approx 2\pi r_d\left[\frac{m}{3M}\left(\frac{E_m}{E_p}\right)^4\right]^{-1/8} \qquad (2)$$

(r_d is the Debye radius), and the estimate for the bleaching time

$$\tau_{bl}\approx 5\omega_{pe}^{-1}\left[\left(\frac{3M}{m}\right)^{1/2}\left(\frac{E_m}{E_p}\right)^{-1}\right] \qquad (3)$$

(ω_{pe} is the plasma frequency).

The proposed model explains well the main singularities of the onset of nonlinear transparency of a transcritical plasma. In connection with this representation of bleaching as a "macroscopic" manifestation of strong Langmuir turbulence, it is particularly important to investigate this effect further together with its concomitant processed. Notice must be taken first of the acceleration of the electrons by the Langmuir turbulence, and consequently of the change in the conditions under which the bleaching takes place. Some results pertaining to the investigation of these processes are treated in[6]. In this article we present new detailed experimental data on the processes that accompany the change of plasma transparency in an intense electromagnetic field. It is shown, in particular that a rapid change of the coefficient of passage through a plasma layer is observed also in a tenuous plasma at a concentration $N_e<N_{cr}$.

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EXPERIMENTAL CONDITIONS

The experiments were performed with a setup whose schematic diagram is shown in Fig. 1. The vacuum chamber 2, after evacuation to $p = 5\times10^{-5}$ Torr, was filled with hydrogen to a working pressure $p = 3\times10^{-4}$ Torr. The plasma layer was formed as the result of development of a high-frequency (at $f_g = 4.5$ MHz) pulsed ($\tau_{pl} = 2.5$ msec) inductive discharge inside a two-turn inductor *4* of 50 cm diameter. The maximum concentration was determined by the level of the supplied RF power. Using this property of the discharge under the experimental conditions, the necessary density, reaching $\Delta N/N \approx 2\cdot10^{-2}$, could be established with high accuracy. To this end, the RF power pulse was shaped such as to fall off from the start to the end by an amount such that the corresponding change of concentration did not exceed 10% during the last 1.5 milliseconds (Fig. 2). Thus, the concentration was determined by the delay relative to the start of the discharge. By way of illustration of the accuracy of the time resolution of the concentration, the same figure shows a series of oscillograms of the cutoffs of the probing signals at various frequencies; it is seen from the oscillograms that the maximum resolution was not worse than

$$\Delta N/N \approx 2\Delta f/f \approx 2\cdot10^{-2}.$$

Coarse adjustment of the density in the range $N_m = 8\cdot10^{10}$–$4\cdot10^{11}$ cm^{-3} (N_m is the concentration of the charged particles at the center of the layer) was effected by varying the average RF-generator power. It must be noted that at sufficiently high accuracy of the relative measurements of the concentration the accuracy of the absolute measurements did not exceed 10–15%.

The distribution of the plasma density in the layer in a longitudinal (relative to the inductor axis) direction was bell-shaped and measured ≈20 cm. In the transverse direction, in the plane of the inductor, the distribution was uniform inside the inductor, and dropped off towards the chamber walls. The transverse dimension of the layer was determined by the position of the absorbing screen (*3* in Fig. 1) and amounted to 70 cm.

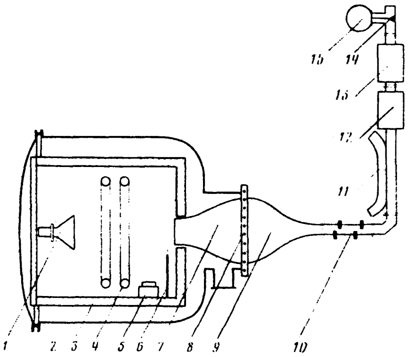

FIG. 1. Diagram of experimental setup: *1*—receiving horn; *2*—vacuum chamber; *3*—absorbing screen; *4*—inductor; *5*—electrostatic analyzer; *6*—moving probe; *7*, *9*—waveguide junctions; *8*—microwave vacuum port; *10*—matching elements; *11*—directional couplers; *12*—ferrite gate; *13*—ferrite attenuator; *14*—coax-to-wave transition; *15*—generator.

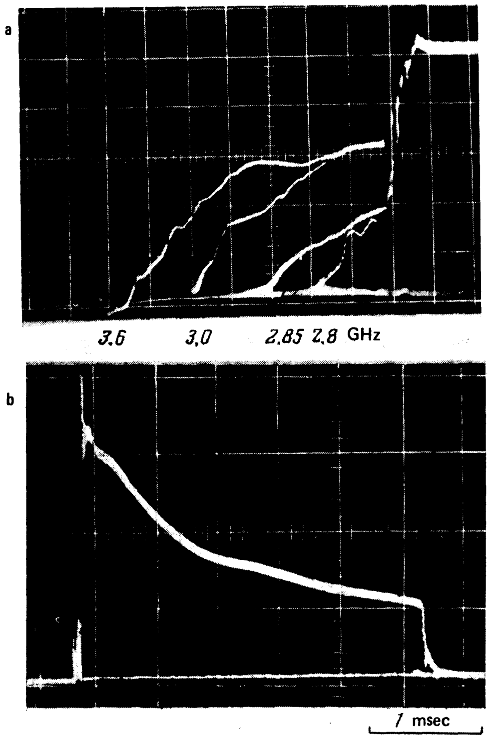

FIG. 2. Oscillograms of the cutoffs of the sounding signals at various frequencies (a) and of the ion current to the probe (b).

An important characteristic of the state of the plasma is the concentration-fluctuation level. The presence of the intense electromagnetic field of the inductor at the frequency $\omega_g \ll \omega_{pe}$ gave rise to ion-sound waves excited in the plasma skin layer near the inductor (the skin layer depth was $\delta = (c^2 v_{Te}/\omega_{pe}^2\omega_0)^{1/3} \approx 3$ cm). An estimate of the damping length of these oscillation shows that at $T_e/T_i \approx 20$

$$l \approx \frac{v_s}{\omega_g}\left(\frac{8M}{\pi m}\right)^{1/2} \approx 15 \text{ c.m.} \qquad (4)$$

Thus, the amplitude of the ion-sound waves decreased towards the center by not more than one order of magnitude, and, as shown by measurements with an RF probe[1], amounted to $\Delta N/N \approx 10^{-4}$ at the center.

A pulse of 10-cm-band electromagnetic radiation of duration $\tau_i = 12.5$ μsec was fed to a plasma through a waveguide channel comprising the following principal elements: (see Fig. 1): ferrite gate *12* and attenuator *13* with dynamic range 30 dB, directional couplers *11* with directivity 25 dB and intended to register the incident and reflected signals, a vacuum microwave port in the form of a quarter-wave plate *8*, and matching elements *10* that made it possible to raise the standing-wave ratio SWR of the radiator to 1.02. The radiator was the open end of a rectangular 15×15 cm waveguide placed on the inductor axis at a distance $2.5\lambda_0$ from its center (λ_0 is the radiation wavelength).

The field amplitude at the radiator end was calculated from the incident power, which was measured with a thermistor wattmeter connected to the channel through a directional coupler and calibrated calorimetrically. The power-measurement accuracy was 10%.

The signal passing through the plasma was registered with a horn antenna placed on the inductor axis. The reflection from the chamber walls and the bending of the plasma-layer by the electromagnetic wave were eliminated by the absorbing coating *3*.

The field distribution produced in the chamber by the open end of the waveguide in the absence of plasma was plotted with a high-frequency probe 1 cm long. The obtained curves can reflect only qualitatively the actual picture of the distribution, since this measurement method did not make it possible to separate the longitudinal and transverse components of the field. At the same time, if the dimension of the region occupied by the field in free space is commensurate with the wavelength, then the longitudinal and transverse components must be of the same order, and for the fundamental mode the transverse component is maximal at the center of the wave beam while the longitudinal is equal to zero at the center and is maximal on the periphery. The dimension of the field region (at the $0.5E_{max}$ level) in the cross section of the inductor was $\sim 2\lambda_0$.

The plasma concentration was measured by cutting off the microwave signals applied to the plasma simultaneously with the main pulse. The sounding signal was excited in the waveguide channel with the aid of a directional coupler and was registered with a horn antenna, which was used also to receive the high-power pulse.

ELECTRODYNAMIC PROPERTIES OF THE LAYER

The main purpose of the present work was to investigate the bleaching characteristics at different values of the plasma concentration and of the incident-wave intensity. It must be noted that under the experimental condition we spotted the onset of the linear transparency with the aid of the value of the transfer coefficient through the plasma layer: $T^2 = E^2_{trans}/E^2_{vac}$ (E_{vac} and E_{trans} are the amplitudes of the signals registered by the receiving horn in the absence and presence of plasma, respectively). Since the receiving waveguide intercepted only part of the transmitted electromagnetic-energy flux, the changes of T^2 could be due not only to the onset of the nonlinear transparency, but also with the nonlinear redistribution of the energy flux as a result of refraction effects. The transfer coefficient did not make it possible to distinguish between these two processes, but yielded, together with the reflected signal, enough information to construct simplified qualitative models of the interaction of the electromagnetic field with the plasma in both the linear and nonlinear regimes.

Since the main nonlinearity parameter in a collisionless plasma is the ratio of the oscillatory velocity of the electron $v_\sim \approx eE/m\omega$ to its thermal velocity $v_{T_e} = (3T_e/m)^{1/2}$, we shall use hereafter the parameter $v_\sim/v_{T_e}$ to describe the intensity of the electric field of the wave. Since $|\nabla N|\lambda_0/N \approx 1$ under our conditions and consequently the homotropic enhancement of the field at $N \approx N_{cr}$

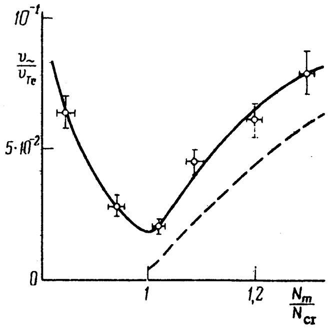

FIG. 3. Threshold values of the parameter $v_\sim/v_{T_e}$, at which the nonlinear transparency of the plasma is observed, vs. the charged-particle concentration. The dashed curve shows the same relation calculated in accord with the results of [9]

should be negligible, the field value for the calculation of $v_\sim$ was chosen for concreteness equal to its value on the open end of the radiator. This, naturally, underestimated the local values of $v_\sim/v_{T_e}$, but did not distort the qualitative dependence on this parameter.

A study of the dependence of the transmitted signal on the field intensity of the incident wave has shown that if the parameter $v_\sim/v_{T_e}$ exceeds a certain value (that depends on the plasma density, Fig. 3), an increase in the layer transparency was observed. This effect was accompanied by a decrease, at the center of the plasma layer, of the amplitude of the ion-sound waves propagating from the direction of the inductor.[10] The fast development rate of the bleaching (in the experiment the bleaching time did not exceed the rise time $\tau_{fr} = 0.3$ μsec of the incident pulse) did not make it possible to observe the transient processes.

When the field exceeded only slightly the threshold value, the transmitted signal duplicated the shape of the incident pulse. This might offer partial evidence that the bleaching process becomes stationary and that the produced structure (the state of the plasma) is stationary.

Figure 4a shows the dependence of the maximal (during the time of the pulse) value of T^2 on the parameter $v_\sim/v_{T_e}$. As seen from these diagrams, the transparency of the plasma layer first increased sharply when the

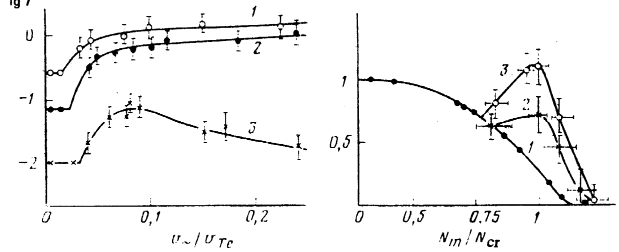

FIG. 4. a) Transfer coefficient vs. the parameter $v_\sim/v_{T_e}$: 1) $N_m \approx N_{cr}$. 2) $N_m \approx 1.1N_{cr}$, 3) $N_m \approx 1.2N_{cr}$; b) dependence of this coefficient on the plasma density: 1) $v_\sim = 0$, 2) $v_\sim = 0.04v_{T_e}$; 3) $v_\sim = 0.1v_{T_e}$.

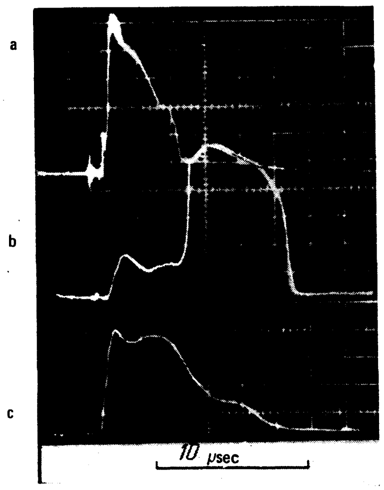

FIG. 5. Oscillograms of the transmitted (a) and reflected pulses (b) and of the current of hot electrons to a multigrid probe at $N_m \approx 1.2N_{cr}$ (c) (the scale corresponds to 10 μ sec).

field exceeded the threshold value, and then either saturated (curves 1 and 2) or started to decrease (curve 3).

An investigation of the dependence of the transmitted signal on the plasma concentration in the layer at different values of the incident-wave field (Fig. 4b) shows that the maximum change of transparency is observed at $N_m \approx N_{cr}$. In this case the transmitted signal could exceed the vacuum value.

With increasing incident-wave power the interaction ceased to be stationary: the transmitted signal started to decrease and the reflected signal to increase towards the end of the pulse (Figs. 5a and 5b). The characteristic time τ_n of this process decreased with increase of both the field intensity and the plasma density. From the logarithmic plots in Fig. 6 it is clearly seen that at small excesses above threhsold the dependence of τ_n on $v_\sim/v_{T_e}$ takes the form $\tau_n \sim (v_\sim/v_{T_e})^n$, where n ranges from $n=-2$ at a concentration $N_m \approx N_{cr}$ to $n=-3$ at $N_m \approx 1.4N_{cr}$.

At larger values of the parameters $v_\sim/v_{T_e}$ and N_m/N_{cr}, the nonstationarity time assumed a value on the order of the pulse rise time (1 on Fig. 6); this decreased the bleaching effectiveness.

ELECTRON ACCELERATION

To explain the character of the processes that occur in a plasma in the presence of an intense electromagnetic field we followed the variation of the energy distribution of the electron simultaneously with the measurement of the transfer coefficient.

The distribution function was investigated with a collimated electrostatic multigrid analyzer that made it possible to separate the electrons with velocities in a narrow solid angle ($\Omega \approx 0.04$ sr). This probe construction made it possible to investigate the degree of anisotropy of the distribution function and simplified the reduction of the probe characteristics, since the distribution function of the collimated electron beam can be obtained by a single differentiation of the probe curve.

In the course of the experiment we investigated the characteristics of electrons moving in three orthogonal directions: 1—along the inductor axis, $\mathbf{v}_e \parallel z_0$; 2—along the layer, parallel to the incident-wave field, $\mathbf{v}_e \parallel x_0$; 3—along the layer, perpendicular to the field, $\mathbf{v}_e \parallel y_0$. In the first case the velocity was parallel to the concentration gradient and to the longitudinal component of the field. In the second it was perpendicular to ∇N and parallel to the transverse field component. In the third it was perpendicular to both the density gradient and the wave field. In the first case the analyzer was placed behind the layer on the system axis, and in the second and third cases it was placed in the inductor plane.

High-energy electrons were observed in all three directions when the parameter $v_\sim/v_{T_e}$ exceeded a certain threshold value (Fig. 7). The electron-flux intensity and

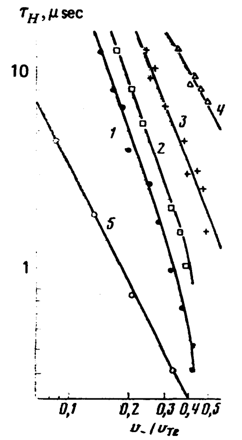

FIG. 6. Characteristic time of development of "nonstationarity" (1–4) and delay of the hot-electron current at $N_m \approx 0.8N_{cr}$ (5) vs. the parameter $v_\sim/v_{T_e}$. 1) $N_m=1.38N_{cr}$, 2) $N_m=1.3N_{cr}$, 3) $N_m=1.22N_{cr}$, 4) $N_m=1.15N_{cr}$; 5) $N_m=0.8N_{cr}$.

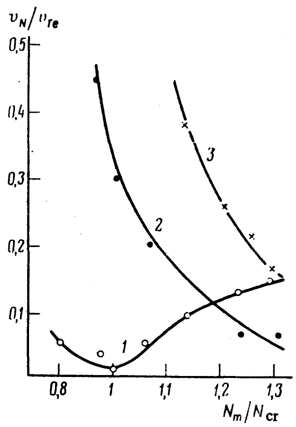

FIG. 7. Plots of the "threshold" values of the parameter $v_\sim/v_{T_e}$ at which electrons with energy $w_e > 300$ eV appear and their current is $I=10^{-2}I_0$ (I_0 is the current to the probe at $\varphi_a=0$): 1) $\mathbf{v} \parallel x_0$, 2) $\mathbf{v} \parallel z_0$, 3) $\mathbf{v} \parallel y_0$.

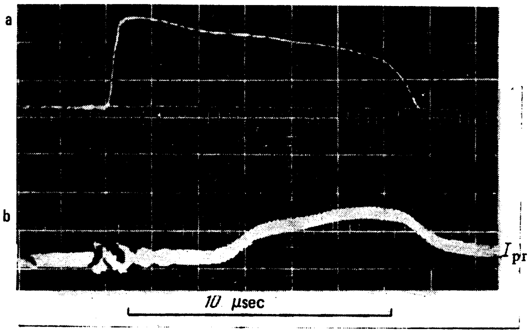

FIG. 8. Oscillograms of the incident pulse (*a*) and of the hot-electron current $I_{pr}(b)$ to the probe at $N_m = 0.8N_{cr}$.

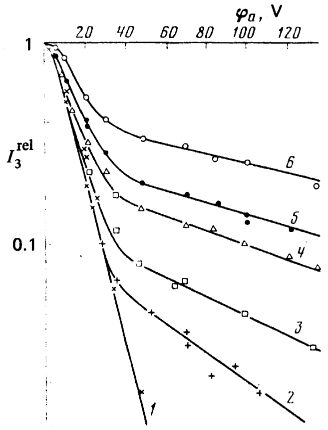

FIG. 9. Family of probe characteristics at different values of the incident-wave intensity: 1) $v_\sim = 0$, $T_e^c = 10$ eV; 2) $v_\sim/v_{Te} = 0.04$; $T_e^h = 45$ eV; 3) $v_\sim/v_{Te} = 0.055$; $T_e^h = 70$ eV; 4) $v_\sim/v_{Te} = 0.1$; $T_e^h = 80$ eV; 5) $v_\sim/v_{Te} = 0.17$; $T_e^h = 90$ eV; 6) $v_\sim/v_{Te} = 0.4$; $T_e^h = 95$ eV.

its time dependence were different for different directions. Along the plasma layer (in the x_0 direction) at $N_m \gtrsim N_{cr}$ the energetic electrons appeared simultaneously with the onset of bleaching. The threshold for the appearance of the accelerated electrons agreed approximately with the bleaching threshold. In the z_0 direction (parallel to ∇N) the appearance of the accelerated electrons was observed only at $N_m > N_{cr}$ and in a much higher threshold field that decreased with increasing concentration. In the $y_0 \perp E_0$, ∇N direction, a flux of accelerated electrons appeared only at the instant when the bleaching stopped and when the reflected signal increased strongly (Figs. 5a and 5b). At a concentration $N_m < N_{cr}$ we also observed electron acceleration in the x_0 direction, but their appearance was delayed somewhat relative to the start of the interaction (Fig. 8). This delay depended on the pump-field intensity and on the plasma concentration. Line 5 of Fig. 6 shows that the delay decreases with increase of the parameter $v_\sim/v_{T_e}$, namely $\tau_d \propto E^{-2}$. The delay decreased also with increasing plasma density and vanished completely at $N_m \approx N_{cr}$.

It was thus established that the bleaching of the plasma layer is accompanied by the appearance of hot electrons moving in the direction $x_0 \perp \nabla N$. Let us describe the results for this case in greater detail.

An investigation of the dependence of the current to the probe on the cutoff potential (Fig. 9) has shown that the energy distribution of the electrons is a superposition of two Maxwellian functions with different densities (N_e^c and N_e^h) and two temperatures (T_e^c and T_e^h). The exponential character of the hot-electron current to the probe as a function of the potential φ_a could be reliably traced up to values $\varphi_a \approx 600$ V. At larger values of φ_e either the instrument was not sensitive enough or the scatter of the results was too large.

Figure 10a shows the dependence of the hot-component temperature on $v_\sim/v_{T_e}$ and on N_m/N_{cr}. It is clearly seen that the energy of the accelerated electrons increases steeply with increasing wave field and then saturates,[2)] the largest effect being observed at $N_m \approx N_{cr}$. Simultaneously with the increase of T_e^h, a certain increase is observed in the cold component, reaching a value $T_e^h \approx 25$ eV at the maximal fields.

Whereas the determination of the electron temperature from the probe characteristics entailed no difficulty, an estimate of the relative number of hot particles generated in the interaction region was difficult and only qualitative for the following reasons. First, the analyzer was taken outside the interaction region and only electrons incident on the probe from the peripheral region were analyzed. In this case the number of cold electrons was determined by their concentration in the probe region and did not change in the course of the interaction. At the same time the flux of the accelerated particles was incident on the probe from the region occupied by the field and depended on the character of the heating. The results thus reflected only a tendency of the number of hot particles to change in the interaction region. Second, the plasma potential increased with increasing number of the hot electrons. This led to the cutoff of the cold electrons in the double layer and to a decrease in their flux to the analyzer. To decrease the

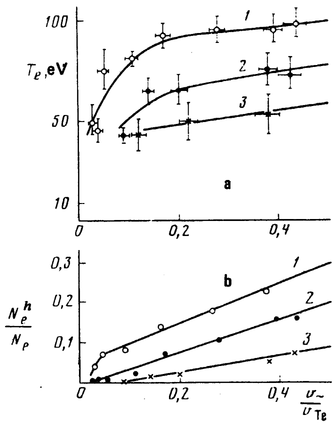

FIG. 10. Dependence of the temperature (*a*) and of the relative number of accelerated electrons (*b*) on $v_\sim/v_{Te}$: 1) $N_m \approx N_{cr}$; 2) $N_m \approx 0.95N_{cr}$; 3) $N_m \approx 1.1N_{cr}$.

effect, low energies must be investigated without ion cutoff at the entry into the analyzer. In this case the ions cancel out the plasma charge all the way to the collector.

If we assume for simplicity that the cold-electron density in the probe region remains unchanged, and the current increase is due only to the appearance of accelerated electrons:

$$\frac{I^h}{I^0}=\frac{N_e^c\sqrt{T_e^c}+N_e^h\sqrt{T_e^h}}{N_e\sqrt{T_e}} \tag{5}$$

(I^0 and I^h are respectively the current to the probe prior to the interaction and at the instant of interaction with the field), then we can obtain an estimate of the number of accelerated electrons by solving the expression with respect to N_e^h/N_e^c and assuming that $N_e^c+N_e^h=N_e$:

$$\eta=\frac{N_e^h}{N_e}=\frac{I^h/I^c-1}{I^h/I^c+(T_e^h/T_e^c)^{1/2}-1}. \tag{6}$$

Figure 10 shows plots of η against the parameter $v_\sim/v_{T_e}$, obtained in this manner for different values of the concentration. It is clearly seen that the number of hot electrons increases monotonically with increasing field intensity. By virtue of the foregoing causes, the presented dependence is only qualitative. It can be stated, however, that whereas the temperature of the hot particles reached saturation at $v_\sim/v_{T_e}\approx 0.1$, their number continued to increase monotonically with increasing field. The maximum change in the electron-gas energy density was observed at $N_m\approx N_{cr}$ and decreased steeply both with increasing and with decreasing charged-particle concentration.

The increase of the average electron-gas energy because of the heating of the cold component and of the appearance of the accelerated electrons has led to a change of the plasma potential and to acceleration of the ions emitted from the plasma. Measurements have shown that ions incident on the electrostatic analyzer had a directional energy that depended on the average electron energy and reached a maximum at $N_m\approx N_{cr}$. In fields corresponding to $v_\sim/v_{T_e}=0.4$, the energy of the ion directional motion reached ≈35 eV. Before we proceed to discuss the experimental data, let us list the main results of the experiment.

1. We investigated the nonlinear increase of plasma transparency with increasing pump field at different charged-particle concentrations. Saturation of the transfer coefficient was observed, wherein the transmitted signal could exceed the vacuum value by 1.5 times. The bleaching effect was observed in both subcritical and transcritical plasma, reaching a maximum at $N_m\approx N_{cr}$.

2. The nonlinear change of the electrodynamic properties of a plasma was accompanied by the appearance of accelerated electrons with an isotropic velocity distribution such that the maximum number of fast particle was observed in a direction parallel to the wave-field projection on the plasma-layer surface (Fig. 7). The energy distribution of the accelerated electrons was close to Maxwellian with a temperature substantially exceeding the energy of the thermal and oscillatory motions. Saturation of the hot-component temperature was observed when the pump field was increased, whereas the number of heated particles increased monotonically in the investigated range of field-intensity variation.

3. At concentrations lower than critical, a delay was observed between the instant when the field was turned on and the appearance of the accelerated electrons; the delay decreased with increasing pump field like $1/E^2$.

The plasma bleaching and heating process had a nonstationary character. The characteristic evolution time of the nonstationarity decreased both with increasing concentration and with increasing intensity of the high-frequency field.

DISCUSSION OF RESULTS

The experiments described above were performed with a plasma layer that is very thin compared with the wavelength. Under these conditions, the reflection from the permittivity gradient led to a noticeable decrease of the transmitted signal even at $N_m\approx 0.5N_{cr}$. In the nonlinear interaction regime, a change of transparency was observed in both a "transcritical" plasma ($N_m>N_{cr}$) and in a "transparent" plasma ($N_m<N_{cr}$) (Fig. 4). The aggregate of the results (short transient time, polarization selectivity, particle acceleration) suggests that in both cases the bleaching is due to development of parametric instability in the plasma. The resultant turbulent state leads, obviously, to a change of the electrodynamic properties of the plasma. This can cause both a decrease of the reflection coefficient and a change in the refraction characteristics. These two qualitatively different effects determine the transfer coefficient of the plasma layer. At a small excess of the field over threshold value, the increase of the transfer coefficient is due primarily to bleaching in the case of passage through a transcritical plasma, and to a decrease of the refractive beam divergence for passage through a transparent plasma. In a sufficiently strong field, such that the amplitude of the transmitted signal exceeds the vacuum value, the decisive factor is the change of the refraction characteristics, which leads to external self-focusing of the beam.

Since the final theoretical picture that describes the dynamics of the three-dimensional distributions of Langmuir oscillations in the case of parametric instability is not fully clear, we use for the interpretation a one-dimensional model, which preserves the main qualitative regularities of the processes and makes it possible to estimate the parameters of the plasma and of the field. The concrete form of the instability may be different at $N_m>N_{cr}$ and $N_m<N_{cr}$; we consider therefore the processes ineach of these regions separately. Since only one type of instability can be realized in a transcritical plasma, the modulation (aperiodic) instability,[11] we consider first the bleaching process at $N_m>N_{cr}$.

The mechanism proposed for the penetration of the field into a transcritical plasma is the following. When the field exceeds the threshold, modulation instability develops in the skin layer of the incident wave and leads to formation of soliton-like field "bunches" and to stratification of the plasma perpendicular to the wave field. The ensuing structure can be transparent to electromagnetic waves with $\omega < \omega_p$, so that the stratification process will continue in the succeeding skin layer and will lead either to bleaching or to a shift of the reflection point. The experimentally observed rapid establishment of the bleaching ($\tau \lesssim \tau_{fr} = 3\times10^{-7}$) and the results of the investigation of the penetration of the field into the plasma[7,8] agree with the theoretical estimates.[9] For a minimal threshold field ($v_\sim/v_{T_e} \approx 2\cdot10^{-2}$), in accord with (3), the bleaching time is $\tau_{bl} \approx 2\times10^{-7}$. The good qualitative agreement between the measured threshole fields and those calculated under the assumption that the bleaching is due to the modulation instability (1),

$$\frac{v_\sim}{v_{T_e}} \geqslant \frac{1}{8}\left(\frac{2M}{m}\right)^{1/4}\left|1-\frac{N_m}{N_{\text{кр}}}\right|^{3/4}, \tag{7}$$

is illustrated by Fig. 3 (dashed curve). The minimum threshold at $N_m/N_{cr} \approx 1$ is determined by the collision frequency ν:

$$v_\sim/v_{T_e}|_{min} = (\nu/\omega)^{1/2} \approx 5\cdot10^{-3}.$$

This value of the parameter $v_\sim/v_{T_e}$ is somewhat smaller than the one measured in the experiment ($\approx 2\times10^{-2}$). In our opinion it is difficult to expect exact quantitative agreement between the estimates and the measurement results, owing to the absence of a complete self-consistent theory of strong Langmuir turbulence and to the complexity of the real system. The effect of the inhomogeneity of the field and of the plasma on the threshold of the modulation instability is apparently inessential, since no electric-field energy emerges from the system in this case, and the saturation is determined by the redistribution of the nonlinear energy over the spatial spectrum.

In a plasma with concentration lower than critical the situation is somewhat more complicated. Theoretical (see, e.g.,[11]) and experimental investigations point to the existence at $N_m < N_{cr}$ of various types of instability and to their competition during the nonlinear stage. Even in this case, however, it is natural to expect the intensity of the turbulent pulsation to be a monotonically increasing function of the pump field E_0, and consequently the transfer coefficient should increase with increasing E_0. This process, just as in an opaque plasma, is characterized by a short transient time with a threshold field value that increases with increasing ϵ_0.

Another manifestation of the plasma turbulent state is the acceleration of the electrons predominantly in the direction of the incident-wave field. The main features of this process are that as the pump-wave field increases the temperature of the hot particles saturates while the current, i.e., the electron density, increases (Fig. 10). This effect is observed simultaneously with the bleaching and is most strongly pronounced at $N_m \approx N_{cr}$ ($\epsilon \approx 0$). This means essentially that a strong Langmuir instability is excited in the plasma, i.e., regularly or randomly disposed solitons. In either case, its spectrum is bounded. This makes it possible to interpret the main features of the particle-acceleration process in the following manner: It is obvious that the minimal accelerated-particle velocity corresponding to the maximal wave number of the plasma turbulence is determined by the electron pass through the field "bunch" in a nonadiabatic manner:

$$v_{min} = d\omega/2\pi, \tag{8}$$

where d is the characteristic dimension of the soliton. With increasing pump-wave intensity the region occupied by the field (d) decreases and consequently, increasingly colder particles become accelerated. This is experimentally confirmed by the shift of the boundary between the currents of the hot and cold components of the electron gas (Fig. 9) and by the monotonic increase of the hot-particle current (Fig. 10). Numerical estimates of the velocity v_{min} show that at the threshold field we have $v_{min} \approx 3v_{T_e}$, and v_{min} is of the order of the thermal velocity already at $v_\sim/v_{T_e} \approx 0.3$, i.e., almost all the particles are accelerated (curve 6 on Fig. 9).

The maximum possible velocity resulting from the particle acceleration and corresponding to the minimal wave number is determined from the condition that the time required for the electron to negotiate at this velocity the average distance L_s between solitons be equal to the period of the field

$$v_{max} = L_s\omega/2\pi. \tag{9}$$

The order of magnitude L_s is that of the optimal modulation-instability scale l^{opt} (2) and is a function of the pump field and of the electron-gas temperature. Calculating L_s with the aid of (2) and recognizing that the acceleration is hindered if the regions where the electrons are trapped by the spatial harmonics of the nonlinear field distribution of the Langmuir turbulence do not overlap, we can estimate the maximum possible effect of the acceleration:

$$v_{max}^2/v_{T_e}^2 \approx 6.$$

Bt determining the average electron from the energy of the ions emitted from the plasma we can estimate the maximum energy of the accelerated electrons. Since the ions were incident on the probe with a directional energy 35 eV, at $v_\sim/v_{T_e} \approx 0.4$ it is easy to obtain the maximum electron energy, ~200 eV, which is one-third the experimentally observed value. In the non-one-dimensional case one should expect a more intense acceleration and consequently better agreement. The saturation of the temperature of the hot particles under these conditions is probably due to the finite dimension of the region occupied by the field, although other causes (plasma inhomogeneity, additional ionization, etc.) are also possible.

The decrease of the fast-electron energy with increasing concentration may be due to the increase of the threshold of the development of modulation instability.

The maximum plasma-state perturbation, manifest in particular in the appearance of an accelerated-particle flux, was observed at $N_m \approx N_{cr}$. In this case the critical-concentration layer was a plane perpendicular to the propagation direction of the incident wave, and the interaction conditions were similar to those realized in the experiments described in[12]. Our results, however, differ from those of[12], and we still do not understand the cause of the discrepancy.

In a transparent plasma the compression of the Langmuir wave should become weaker as the particle concentration at the maximum of the layer decreases, so that the acceleration effectiveness should become lower, as in fact observed in experiment. The delay in the appearance of the hot electrons can be ascribed, within the framework of the considered model, to the increased time of establishment of the spatial harmonics of the principal scale of the modulation instability.

The experimentally observed nonstationary behavior of the bleaching is due to rapid changes in the macroscopic state of the plasma, and calls for further study.

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1)The details of the measurement of ion-sound oscillations with a resonant probe are considered in [10].

2)The experiments did not yield a convincing $T_e(v_\sim/v_{Te})$ dependence at small excesses above threshold. The minimum temperature of the accelerated electrons registered by the analyzer was $T_e \approx 45$ eV.

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Ionizing shock waves in a transverse magnetic field

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Criteria are obtained for the existence of stationary and nonstationary magnetic structures in the front of a transverse ionizing shock wave. An additional relation is obtained between the magnetic field and the velocity on either side of the front; this relation eliminates the indeterminacy in the formulation of the Rankine-Hugoniot conditions. It is shown that the discontinuity H_2/H_1 of the magnetic field in the shock wave depends substantially on whether there is enough time for a stationary front structure to be established. This time is determined by the electric field ahead of the front, which is proportional to v_1H_1. The results of the theory are compared with experiment.

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1. INTRODUCTION

When an attempt is made to develop a theory of stationary ionizing shock waves (the magnetic field lies in the plane of the wave front) a difficulty is encountered immediately when it comes to write down the Rankine-Hugoniot conditions. In fact, on the discontinuity we have only three equations for the four quantities that characterize the state of the gas—the temperature T, the density ρ, the velocity v, and the magnetic field H. These are the momentum and energy conservation equations and the continuity equation. In the analogous problem of a transverse shock wave in a plasma the additional equation is the condition that the induction electric field vanish (on both sides of the discontinuity) in the coordinate system connected with the gas stream; this condition takes the form $v_1H_1 = v_2H_2$. In the case of an ionizing shock wave in a neutral gas there can apparently exist, generally speaking, any electric field ahead of the wave front.

