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Spatial Anisotropy of the Long Wavelength Branch of Ion Sound in a Current-Carrying Turbulent Plasma

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The low-frequency region of the spectrum of the ion-acoustic oscillations ($\Omega \ll \omega_{pi}$) of a plasma under conditions of turbulent heating by a current in a closed system is investigated. A technique for observing incoherent scattering of electromagnetic waves of $\lambda_0 = 8.4$ and 2 mm by the plasma oscillations is described. It is found that the spectrum of the observed frequencies Ω is considerably narrower than the transmission band of the receiver. It is suggested that this is due to the anisotropy of the angular distribution of the long-wavelength ion-acoustic oscillations. An expression has been obtained for the apex angle θ_{s0} of the anisotropy cone, which, under the conditions of our experiment, was $\sim 20°$. As in [1], a time lag is observed between the time of application of the electric field, producing the turbulent heating, and the moment of appearance of the low-frequency ion-acoustic oscillations. A general law for the development of the spectrum $\Omega(t)$ is established. It is suggested that this time lag is connected with energy transfer across the spectrum into the low-frequency region due to induced scattering of the ion-acoustic oscillations ω_{pi} by ions.

IT has been shown in investigations of a number of authors[1,2] that in the dissipation of energy during turbulent plasma heating by a current an important role is played by the ion-acoustic instability, which has been theoretically investigated in[3,4]. As is well known[5], a broad spectrum of oscillations may be excited under these conditions.

The present work was undertaken with the object of investigating the low-frequency region of the spectrum of turbulent plasma pulsations ($\Omega \ll \omega_{pi}$) under conditions of turbulent heating by a current in a closed system. For the observation of the plasma pulsations we used the noncoherent electromagnetic-wave scattering technique which has been theoretically investigated in[6,7] and which has been used to study the Langmuir oscillations in a turbulent plasma[8-11], as well as the magnetohydrodynamic turbulence of the plasma of a heavy-current quasi-stationary discharge[12].

1. PROCEDURE FOR OBSERVING THE SCATTERING SIGNALS

The experiments were conducted on the toroidal installation "Vikhr'-2"[13,14]. Noncoherent scattering in a plasma of electromagnetic waves with $\lambda_0 = 8.4$ and 2 mm was studied. The frequency of the incident electromagnetic wave was high in all the experiments ($\omega_0 \gg \omega_{pe} \gg \omega_{He}$), and the wavelength was $\lambda_0 < d_{pl}$. The experimental conditions precluded the effect of multiple scattering of the UHF signal along the propagation path in the plasma, since the condition[1]

$$\frac{\pi d_{pl}}{\lambda_0} \frac{n}{n_{cr}} \frac{\Delta n}{n} \ll 1.$$

is always fulfilled.

The noncoherent scattering of UHF waves was, in the main, observed at small angles (within the limits of the ±20° aperture angle of the directivity pattern of the UHF antennas). To perform these measurements on the "Vikhr'-2" installation, we had to use highly sensitive broadband equipment, since the relative broadening of the spectrum of the UHF electromagnetic wave caused by the scattering is extremely small, while the lifetime of the turbulent state of the plasma is extremely short. To separate the signal at the plasma-oscillation frequency Ω at which the scattering takes place, we employed the method of homodyne conversion of the entire UHF signal received by the crystal detector. The useful signal at the frequency Ω was subsequently amplified by a broadband amplifier (the band extended from 0.8 to 150 MHz) and was observed with an S-1-11 oscilloscope. The frequency spectrum of this signal was analyzed by varying the lower edge of the transmission band of the video amplifier (from 0.8 to 50 MHz). The sensitivity of the receiver for $\lambda_0 = 8$ and 4 mm was not worse than 10^{-6} W. Such a sensitivity in the indicated wave bands turned out to be quite sufficient for the detection of the effect. However, to observe the noncoherent scattering in the plasma of a signal by a 2-mm wave, it became necessary to construct a more sensitive, broader-band receiver. This problem was solved with the aid of a homodyne UHF receiver with a second frequency conversion by means of a superheterodyne receiver, the block diagram of which is shown in Fig. 1.

The UHF generator 1 generates an electromagnetic wave of frequency ω_0, which irradiates the plasma filament 16 through the horn antenna 15. Owing to the scattering of the electromagnetic wave ω_0 by the low-frequency of the plasma oscillations Ω, satellites of

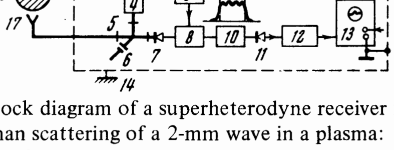

FIG. 1. Block diagram of a superheterodyne receiver for the observation of Raman scattering of a 2-mm wave in a plasma: 1) 2-mm waveband generator; 2), 3) attenuators; 4) phase shifter; 5) double T-junction; 6) plunger; 7) UHF detector; 8) mixer; 9) HF heterodyne; 10—intermediate-frequency amplifier (IFA); 11) video detector; 12) video amplifier; 13) S-1-11 oscilloscope; 14) electrostatic screen; 15), 17) transmitting and receiving antennas; 16) plasma.

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[1] Here n is the plasma density, n_{cr} is the critical density and d_{pl} is the diameter of the plasma filament.

frequency $\omega_0 \pm \Omega$ appear in the frequency spectrum of the UHF signal received by the antenna 17. This signal is mixed in the crystal detector 7 with a signal of frequency ω_0 coming in through the reference channel, and a signal of frequency Ω appears as a result of the homodyne conversion. A HF signal of frequency ω_H from the tunable HF heterodyne 9 is received by the same detector 7 through the mixing unit 8. The intermediate-frequency amplifier 10 is tuned to the frequency $\Omega + \omega_h = 970$ MHz. On the basis of the time characteristics of the investigated plasma process, a 60-MHz band was chosen for the amplifier 10. To obtain this band, HF pass-band filters were used (the coupled cavity resonators had a total $Q \sim 10$). The intermediate-frequency signal was then detected and the envelope of the oscillations of frequency Ω was observed on the screen of the S-1-11 oscilloscope. Tuning the HF heterodyne made it possible to investigate the oscillations in the plasma in the frequency range from 200 to 800 MHz. The sensitivity of the receiver was in this case $\sim 10^{-7}$ W.

2. EXPERIMENTAL RESULTS

All the results cited below pertain to turbulent heating of a plasma in the toroidal "Vikhr'-2" installation by a single current pulse (duration ~0.25 μsec) under conditions of anomalous resistance. Typical oscillograms of scattering signals are shown in Fig. 2.

The oscillograms of the plasma oscillations of frequencies Ω, obtained during the noncoherent scattering of UHF electromagnetic waves by the methods described above, were used to determine, first, the frequency spectrum of the turbulent pulsations; second, their lifetimes; and third, the relative efficiency of the noncoherent scattering (P_{sc}/P_0).

1. The oscillograms 4 and 5 (Fig. 2) of the plasma oscillations at frequencies Ω much lower than ω_{pi} are the clearest. They were obtained with the aid of the first of the receivers described above during the scattering of waves of $\lambda_0 = 4$ and 8 mm. We can make some judgement about the spectrum of the frequencies Ω directly from the shape of the oscillograms. It is noteworthy that the spectrum of the observed frequencies is considerably narrower than the band of the video receiver. For example, oscillations in the frequency range $\Delta\nu = 60 \pm 5$ MHz are observed on the oscillogram 5 with a video-channel transmission bandwidth of 30–150 MHz.

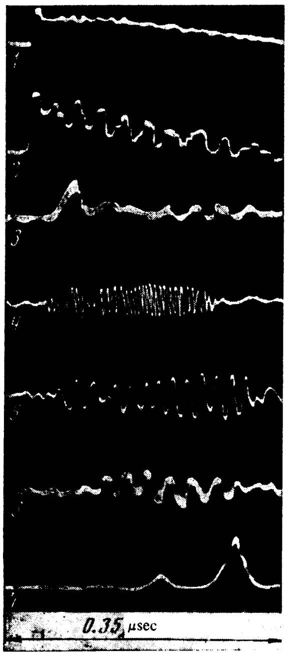

FIG. 2. Typical oscillograms observed when waves in the 2–30-mm band are scattered by the turbulent pulsations of a plasma. 1) Electric field E_θ; 2) current; 3) envelope of signal of frequency $\Delta\nu = 240$ MHz when a 2-mm wave is scattered ($\omega_h = 730$ MHz, band of the video channel, 0.8–60 MHz); 4), 5) fluctuation signals when 4- and 8-mm waves are respectively scattered; 6), 7) fluctuation signals due to the reflection of a 30-mm signal from the boundary of the plasma at the level of 10^{-3} P_{ref} and 10^{-2} P_{ref} respectively ($n \sim 2 \times 10^{12}$ cm^{-3}, H = 2 kOe, $E_\theta = 150$ V/cm); the oscillograms 4, 5 and 6 were obtained with an amplifier band of 30–150 MHz, and 7 was obtained with a band 0.8–100 MHz.

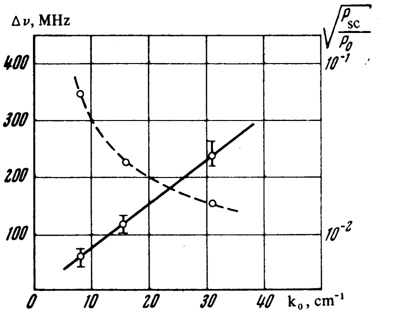

FIG. 3. Dependence of the frequency shift occuring in the Raman scattering of UHF waves (continuous line) and of the scattering factor (dashed curve) on the length of the wave vector of the sounding wave.

The oscillogram 3 in Fig. 2 is the envelope of the plasma oscillations observed during the scattering of a $\lambda_0 = 2$ mm wave, in the case when the superheterodyne receiver was tuned to the frequency range $\Delta\nu = 240 \pm 30$ MHz. At other frequencies Ω between 200 and 800 MHz, with the same sensitivity of the receiver, no scattering signals were detected.

To verify that the oscillations Ω registered on oscillograms 3–5 (Fig. 2) do in fact represent plasma-density pulsations and not oscillations of the plasma filament as a whole, we set up a check experiment on the reflection of a $\lambda_0 = 30$ mm wave from the boundary of the plasma filament[2)]. Typical oscillograms of the fluctuations of the phase and amplitude of the reflected signals (6–7 in Fig. 2) clearly show that the frequencies of the oscillations of the boundary of the filament are considerably lower than the frequencies Ω of the signals observed during the scattering of $\lambda_0 = 2.4$ and 8 mm UHF waves that had penetrated into the turbulent plasma.

The experimental dependence of the averaged frequency shift $\Delta\nu$, which occurs in Raman scattering, on the length of the wave vector $\mathbf{k}_0$ of the scattered electromagnetic signal was found from the data of the oscillograms in Fig. 2. As shown by the continuous line in Fig. 3, this dependence is linear.

2. It can be seen from the oscillograms of Fig. 2 that all the Raman-scattering signals appear and exist only during the time when the current flows in the plasma. In accord with previously published results obtained on the "Vikhr'-2" installation[1], the frequency and moment of appearance of the low-frequency oscillations, $\Omega < \omega_{pi}$, observed by means of the Raman-scattering method, are related to each other: the higher the

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[2)] The maximum density of the plasma in the filament was n_{max} 2×10^{12} cm^{-3}. It was established by UHF-interferometry at the wavelengths 2, 4, 8 and 30 mm, with a time resolution $\sim 10^{-8}$ sec, that the mean plasma density and diameter of the plasma sheath remained constant to within 10% during the heating by the current.

frequency of the plasma oscillations, the sooner they will appear after the current is switched on.

3. Knowing the absolute sensitivity of the receivers, we could, using the oscillograms of the scattered signals—of the type shown in Fig. 2—determine, for each section of the Ω-frequency spectrum, the dissipated power P_{sc} received by the UHF horn antenna and, consequently, the scattering factor P_{sc}/P_0, where P_0 is the power of the unscattered signal. The power of the wave incident on the plasma was about 10^{-2} W in all the experiments. The dependence of the scattering factor on k_0 is shown in Fig. 3 by the dashed curve and can be approximately described by the relation $P_{sc}/P_0 \sim \lambda_0^2$.

The growth of the scattering factor with increase in the solenoidal electric field E_θ in the circuit of the plasma filament (and with a corresponding increase of the plasma temperature, see[1,14]) was clearly observed in the experiments. It is interesting to note that a quadratic growth of the scattering factor for UHF waves scattered by low-frequency pulsations of the turbulent plasma was observed when the electric field strength E_θ was less than 200 V/cm. At $E_\theta > 200$ V/cm, some limitation on the growth of the energy of the turbulent plasma pulsations is observed. An entirely similar dependence of the energy of the fluctuations on E_θ was obtained in the same experiment with an electric double probe introduced into the turbulent plasma.

3. DISCUSSION OF THE RESULTS AND CONCLUSIONS

1. The effect of noncoherent scattering of electromagnetic waves in a plasma, observed in this work, can be described as scattering by long wavelength ($k_s \ll k_0$) ion sound.

Indeed, the frequency shift occurring in such scattering is determined by the Brillouin-Mandel'shtam formula:

$$\Delta\nu = 2\nu_0 \frac{c_s}{c} \sin\frac{\theta_0}{2}, \tag{1}$$

where ν_0 is the frequency of the incident wave, c_s is the velocity of the ion sound, and θ_0 is the observation angle (angle between the wave vectors of the incident and scattered waves).

In the experiment on the "Vikhr'-2" installation, with $T_e \sim 2$ kV, $n = 2 \times 10^{12}$ cm^{-3}, and $\lambda_0 = 2.4$ and 8 mm, the observed frequency shifts $\Delta\nu$ correspond to Eq. (1) when the aperture angle of the directivity pattern of the receiving antenna is $\theta_0 \sim 40 \pm 5°$. For given T_e and θ_0, the frequency shift $\Delta\nu$ depends linearly on k_0 (see Fig. 3), while at fixed λ_0 and θ_0, as reported in[1], $\Delta\nu \sim \sqrt{T_e} \sim c_s$.

2. The experimental data indicate that after excitation of high-frequency ion-acoustic oscillations with $k_s \sim k_0$ in the plasma by the current, there occurs a redistribution of energy over the spectrum of the turbulent oscillations with the result that a low-frequency ion sound appears. As in[1], a delay was observed in this experiment between the moment of application of the electric field effecting the turbulent heating and the moment of appearance of the low-frequency ion-acoustic oscillations. This time lag, which was revealed by the appearance of the corresponding Raman-scattering signal, turned out to be in good correspondence with the $\tau_d(\nu)$ plot in[1]. It is interesting to note that it agrees with a general law of spectrum evolution of the form

$$\Omega(t) \sim \omega_{pi} \exp\left[\frac{\tau_{pi} - t}{\tau_{pi}}\right] \quad \text{for } t \geqslant \tau_{pi}.$$

The redistribution of energy into the low-frequency region of the spectrum is indicated[1] by the fact that the peak of the frequency spectrum in the region ω_{pi} was observed to fall at the same time as the intensity of the low-frequencies increased. This is also attested to by the experimental dependence of the scattering factor on the wavelength of the sounding wave, shown in Fig. 3: $P_{sc}/P_0 \sim \lambda_0^2$.

The transfer of energy to the low-frequency region of the spectrum can, apparently, be attributed to induced scattering of the ion-acoustic oscillations ω_{pi} by ions[15]. The experimentally observed delays in the appearances of the low-frequency oscillations ($\tau \sim 10^{-8}$—10^{-7} sec) are sufficiently well described by the formula for the characteristic time of energy redistribution over the spectrum[15]:

$$\frac{1}{\tau} = \Omega_s \frac{W}{nm_e v_{Te}^2} \frac{k}{\Delta k} \frac{T_i}{T_e} 8\pi^2 \theta_{s0}^2,$$

for the parameters of the plasma in the "Vikhr'-2" installation, under the assumption that $kT_i/T_e\Delta k \sim 1$.

3. The foregoing model of the appearance of low-frequency ion-acoustic oscillations of a current-carrying turbulent plasma in the "Vikhr'-2" installation would seemingly lead us to expect to observe a continuous spectrum of frequency shifts $\Delta\nu$, corresponding to the aperture angle of the directivity pattern of the antenna, in the entire transmission band of the receiver. In reality, however, the experimentally observed broadening of the spectrum of $\Delta\nu$ (see the oscillograms of Fig. 2) is considerably narrower than the transmission band of the receiver. Such selectivity in the scattering of electromagnetic waves can, apparently, be explained if we assume that the angular distribution of the recorded ion-acoustic oscillations is anisotropic, i.e., that the waves are propagated only in a comparatively narrow cone defined by the directions $\mathbf{k}_s$.

Another cause of the narrowness of the observed spectrum of the scattering could be the nonstationarity in time of the isotropic spectrum of $\mathbf{k}_s$. Under this assumption the range of the observed values of k in the scattered signal is bounded from above by the condition that the vector $\mathbf{k}_0 + \mathbf{k}_s$ fall in the antenna aperture angle, and from below by the exponential decrease of the spectrum according to the relation[15]

$$W_k = W_0 \exp\{(k_s - k_{s0})t/\tau\},$$

where $\tau \sim 4 \times 10^{-8}$ sec under the conditions of our experiment[1]. However, the first supposition seems sounder.

It is not difficult to show from the laws of energy and momentum conservation that the apex angle of the anisotropy cone is determined by the expression

$$\delta\theta_s = \frac{c_s\Omega_0}{c\Delta\Omega \sin\theta_s}\left\{\left(1 + \frac{\Delta\Omega}{\Omega_0}\right)\sin\theta_0\delta\theta_0 - (1 - \cos\theta_0)\frac{\delta(\Delta\Omega)}{\Delta\Omega}\right\}, \tag{2}$$

where the scattering angle θ_s (angle between $\mathbf{k}_0$ and $\mathbf{k}_s$) has, under the conditions of our experiment, the value $\pi/2 + \pi/12$. Substituting in Eq. (2) the experimental data for $\Delta\Omega = 2\pi\Delta\nu$ and the other quantities, we find that the wave vectors of the ion sound, from which the Raman scattering of the UHF waves took place, lie inside a cone with an apex angle $\theta_{S0} = 2\delta\theta_S \sim 20°$. Such a strong anisotropy of the long-wavelength branch of the ion sound is easily explained if we recognize that according to the theory of anomalous resistance[3] the short-wavelength ion sound is highly anisotropic and that the long-wavelength ion sound observed by us is the product of the conversion of the former.

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