Measurement of microwave scattering by low frequency turbulent plasma oscillations

V. K. Zhivotov, G. I. Kalinnikov, A. S. Kingsep, M. F. Krotov, V. V. Rusanov, and Yu. V. Tarasov

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The Raman scattering spectrum has been measured in the millimeter range using interference filters and plasma oscillations with frequency of the order of twice the ion Langmuir frequency. The measurements are interpreted as the result of the interaction between the radiation and helicons. The helicon field strength is estimated.

One of the most effective methods of investigating turbulent plasmas is to use microwave scattering by plasma oscillations. In this research, we have investigated plasmas with a high level of ion-acoustic instability in a Tokomak installation, using turbulent dc heating. We studied the Raman spectrum in the millimeter range and determined the frequency shift of the red satellites, which is roughly equal to the ion Langmuir frequency of the plasma. Experimental difficulties involved in such measurements are usually concerned with information on the low-frequency plasma oscillations.[1-3]

METHOD

Microwave scattering as an experimental technique has continued to attract independent interest. However, the cross sections for scattering by low-frequency oscillations are largely unknown. The main difficulty in the case of scattering with a small frequency shift Ω is the suppression of the strong signal due to the primary radiation at frequency ν_0. The most common methods are superheterodyne reception and the use of cavity resonators.

In this paper we report the use of quasioptical interference filters (Fig. 1). These are open resonators which are essentially Fabry-Perot interferometers with mirrors in the form of metal grids. The primary radiation of frequency ν_0 is suppressed by introducing a rejector filter into the system. This filter must transmit radiation in the frequency band $\nu_0-\Omega$ and reject the adjacent frequency ν_0 (Fig. 2). To achieve this purpose we use the dependence of the reflection coefficient R of metal grids on frequency. The coefficient R for a grid with period p increases monotonically from zero to unity as the frequency is increased from zero to $\nu = c/p$. The period of the reflecting grids in the Fabry-Perot interferometer was chosen to be c/ν_0 and the Fabry-Perot itself was tuned to resonance at the frequency $\nu \approx \nu_0 - \Omega$. As the frequency approaches ν_0, the transmission of the mirrors S tends to zero, and when $\nu = \nu_0$ the radiation is diffracted by the grid and diffraction losses are observed. This results in a rapid fall in the transmission T of the interferometer. For ideal grids, the transmission T is proportional to $S^2/(S + \epsilon)^2$ and tends to zero at the point $\nu = \nu_0$ ($\epsilon = 1 - R - S$ represents losses on reflection from the mirrors).

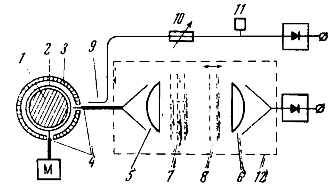

FIG. 1. Measurement of scattered radiation: 1—cross section of plasma, 2—chamber, 3—envelope; measuring system: 4—dielectric antennas, 5, 6—horn-lens antennas, 7—three-mirror interference filter, 8—two-mirror interference filter; monitoring system: 9—waveguide coupler, 10—attenuator, 11—wave meter, 12—screen made of damp gauze.

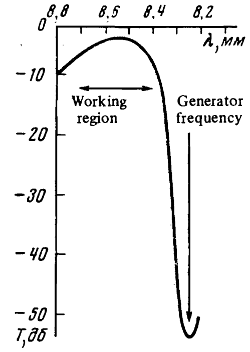

FIG. 2. Transmission of the three-mirror interferometer.

To achieve the most rapid variation in the transmission of the filter, the interferometer was constructed from three mirrors.[4] For the optimum choice of the reflection coefficients of the mirrors $[R_{int} = 4R_{ext}/(1 + R_{ext})^2]$, the resonance transmission curve falls as the fourth power of the frequency, i.e., more rapidly than the dispersion profile of the two-mirror Fabry-Perot. The three-mirror rejector filter attenuated the primary radiation of frequency ν_0 by 50 dB (Fig. 2). The working transmission band of the filter extends from 8.4 to 8.7 mm, and this corresponds to Raman shifts in the region Ω = 700–2000 MHz. The scattered spectrum was investigated in this band with a two-mirror tunable filter. The tuning was achieved by varying the mirror separation. The resolving power $\lambda/\Delta\lambda$ was varied between 100 and 250 at the extreme points in the spectrum. The mirrors of this filter also had the period $p = c/\nu_0$, and this ensured additional attenuation of the primary radiation by 30 dB. Thus the overall attenuation was 80 dB.

EXPERIMENT

The plasma system used in this work was similar to that described in[5]. The plasma was produced in a toroidal alundum chamber placed in a copper envelope. The longitudinal magnetic field was H = 8 kOe. The plasma density was $n_0 \sim 10^{14}$ cm^{-3}. Turbulent heating was achieved by applying to the plasma 1.5 μsec voltage pulses producing an electric field E_0 = 20 V/cm in the plasma. The electron temperature was up to 100 eV. The data were obtained as a result of measurements on the diamagnetism and laser scattering.

The geometry of the experiment will be clear from Fig. 1. Teflon rod antennas placed inside the alundum chamber were used to introduce the radiation into the plasma and to detect it. In this way, the level of radiation which was multiply reflected from the walls of the copper envelope was small because of absorption in the alundum (absorption coefficient ~0.75). The horn-lens antenna 5 produces a plane wave. A more detailed description of the filters can be found in[4,5]. The monitoring channel enables us to control the operation of the generator. The entire quasioptic part of the equipment is surrounded by a shield consisting of damp gauze. In the absence of this absorbing shield the radiation from the generator, which is diffracted by the filter mirrors, is reflected by various metal objects, fills the enclosure isotropically, and finally reaches the receiving antenna 6.

The 8-mm generator producing pulse lengths of 0.3 μsec gave a total radiation flux $P = 10^4$ W in the plasma. The generator was activated 0.3 μsec after the appearance of the voltage pulse. The scattered radiation was observed during strong plasma heating. The scattered spectrum is shown in Fig. 3. The integrated scattered power was $P_1 \sim 2 \times 10^{-4}$ W. Moreover, $P_1/P \approx 2 \times 10^{-8}$.

DISCUSSION

The observed scattered frequency shift is naturally associated with ion-acoustic oscillations. In fact, the ion plasma frequency $\Omega_{pi} = (ne^2/M\pi)^{1/2}$ determined from the maximum concentration $n_0 \sim 10^{14}$ cm^{-3} turns out to be of the order of 2000 MHz. However, the primary radiation (~36 000 MHz) is cut off by the plasma for $n_{crit} = 1.7 \times 10^{13}$ cm^{-3}. Moreover, the ion sound frequency is close to the ion plasma frequency only for high enough wave numbers $k_s \sim k_{De} = (4\pi ne^2/T_e)^{1/2}$. The characteristic wave numbers for both the incident and the scattered waves are much smaller. Therefore, the conservation law

$$\mathbf{k}_{t_1}=\mathbf{k}_t+\mathbf{k}_s \tag{1}$$

cannot be satisfied and we must exclude from our analysis the direct interaction between electromagnetic radiation and ion sound.

In addition to ion sound, the plasma may support nonpotential oscillations, i.e., helicons, when $\omega_{He} \gg 2\pi\Omega \gg \omega_{Hi}$. The dispersion relation for helicons

$$\Omega=kk_z c^2\omega_{He}/2\pi\omega_{pe}^2$$

shows that, in our case,

$$k \approx \frac{\omega_{pe}}{c}\left(\frac{\omega_{pi}}{\omega_{Hc}}\right)^{1/2}$$

and this is consistent with (1). It is shown in[6] that such oscillations can be formed as a result of the nonlinear interaction between ion acoustic waves for which the characteristic frequency is $\Omega \sim 2\Omega_{pi}$. The first experimental detection of such whistlers was reported in[6]. Their level in plasma with a high density of ion acoustic noise was found to be consistent with theoretical estimates. A more detailed theoretical study of the interaction between ion acoustic waves is given in[7].

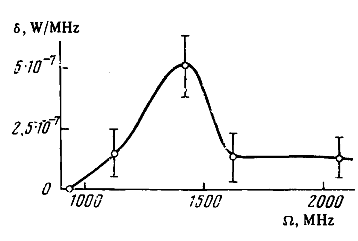

FIG. 3. Spectral density of scattered radiation as a function of the Raman frequency shift.

The characteristic scattered frequency shift in our experiments is in accordance with the frequency $2\Omega_{pi}$ and, therefore, it is natural to suppose that we are observing the scattering of electromagnetic radiation by helicons formed during ion-acoustic turbulence.

Nonlinear scattering by helicons is described by

$$W^t_{1\mathbf{k}}=\sum_{\mathbf{k}'} Q_{kk'}W^h_{\mathbf{k}'}W^t_{\mathbf{k}\pm\mathbf{k}'},$$

where W^t_k, W^t_{ik}, W^h_k are the spectral energy densities in the incident radiation, the scattered radiation, and the helicons in plasma. The probability of the process, Q_{qq}, can be calculated by the well known methods of the theory of weak turbulence (see[8], and for helicons in particular[7]). The actual calculation is rather complicated, and we therefore simply quote the final result:

$$W^t_{1\mathbf{k}}=\omega_{pe}^2\left(\frac{\omega_{pe}}{\omega_{He}}\right)^2\int d\mathbf{q}\,\frac{W_{\mathbf{q}}^h}{nmc^2}W^t_{\mathbf{k}\pm\mathbf{q}}\delta(\omega^t-\omega_1^t-\Omega^h).$$

For the integrated noise density we can obtain a simple estimate by assuming that the helicon distribution is isotropic. In this case the δ function is replaced by integration with respect to the angle between **q** and H_0. Integrating with respect to **k** as well, we obtain

$$W_1\sim\omega_{pe}\left(\frac{\omega_{pe}}{\omega_{He}}\right)^3\frac{H_\sim^2}{8\pi nmc^2}W, \tag{2}$$

where W_1 is the density of the scattered radiation, W is the density of the incident radiation, and $H_\sim$ is the magnetic field of the helicons.

The quantity W_1 can be estimated as follows: $W_1 = 6P_1/V$, where V is the volume of the plasma in the field of view of the antenna, P_1 is the received scattered power and the factor 6 represents the fact that the radiation is received from a single direction. Correspondingly, W = P/sc, where P is the generated power, and s is the cross section of the beam. The quantities P and P_1 are known. Using the characteristic parameters n and H_0, we can readily show from (2) that $H_\sim \sim 1$ Oe.

This result is in agreement with earlier direct measurements of the spectral density of helicons in a similar installation for $E_0 = 40$ V/cm. The measurements were carried out with an electric probe and a waveguide Fourier analyzer[9] for the decimeter wavelength range. The helicon spectrum had a well defined maximum at twice the ion Langmuir frequency. Calculations of the helicon intensity gave $H_\sim \sim 1.3$ Oe.

It is important to note that the observed helicon energy density is greater by an order of magnitude than the prediction of the theory of weak turbulence[6,7]:

$$H_\sim^2 \sim \frac{(W_s)^2}{nMc^2}\omega_{pi}t$$

when the ion acoustic noise density determined from the anomalous resistance is substituted into this expression. It may be that this discrepancy is due to the strong anisotropy in the spectrum of acoustic oscillations. Better agreement was obtained in[6] where the experimental result was $H_\sim \sim 0.5$ Oe. Of course, our estimate of the helicon level in the plasma is very approximate if only because we have not taken into account the concentration profile of the plasma.

We have thus observed, for the first time, the scattering of electromagnetic waves by helicons formed in plasma as a result of the nonlinear interaction between ion acoustic waves, which leads to the appearance of the satellite with the characteristic frequency shift $\sim 2\Omega_{pi}$. The results are in agreement with previous measurements of the helicon field using magnetic[6] and electric probes.

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