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INVESTIGATION OF THE NOISE OF A TURBULENT PLASMA WITH THE AID OF A MAGNETIC SPECTRUM ANALYZER

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The electromagnetic self-radiation of a turbulent plasma in the wavelength range between 2 and 4.6 cm is measured for the first time by means of a magnetic spectrum analyzer. The time during which the spectrum was investigated was 1 microsecond. Radiation was detected in the region of the plasma frequency as well as near the double plasma frequency. The microwave radiation in the indicated range is emitted from the plasma with considerable delay relative to the beginning of the discharge. A possible theoretical explanation of the results is presented.

EXTENSIVE experimental material connected with turbulent heating of a plasma by a straight discharge current was obtained in[1-4]. It can now be regarded as firmly established that plasma heating is due to the development of ion-acoustic current instability in the plasma.

In the present communication we present results of an investigation of processes occurring in the turbulent plasma after prolonged flow of current; these processes are responsible for the loss of energy of the heated plasma at the ends of the apparatus. As was established earlier[5], one such process is the current-convective instability. After the development of such an instability, noticeable beams of electrons and intense electromagnetic radiation appear in the plasma[4].

Particular attention is paid in the present paper to investigation of the electromagnetic self-radiation of the plasma at frequencies close to the plasma frequency ω_{pe} and double its value $2\omega_{pe}$. A magnetic spectrum analyzer (MSA) has made it possible to obtain for the first time a time scan of the plasma radiation in the indicated frequency range.

1. GENERAL CHARACTERISTICS OF DISCHARGE

Just as in[1-5], the experiments were performed with the NPR-2 setup[2]. In the experiments described below, the plasma parameters were as follows: initial concentration $n_0 \sim 10^{12}$ cm^{-3}, confining magnetic field $H_0 = 2.5$ kOe, initial voltage on the straight-discharge capacitor V = 30 kV. The plasma diamagnetism was measured with the aid of a single-turn coil with an integration constant 10^{-4} sec. The current in the plasma was monitored with a Rogowski loop. The microwave radiation of the plasma was received by an open end of a waveguide (23 × 10 mm) and detected with a broad-band detector head. Figure 1 shows oscillograms of the diamagnetic signal (a), of the integral electromagnetic radiation from the plasma (b), and the current through the discharge gap (c). As follows from these oscillograms, the diamagnetic signal increases from the instant of appearance of current in the plasma, and after 1.7×10^{-6} sec the plasma energy density reaches a maximum value 2×10^{15} eV/cm^3. No microwave radiation is observed during that time interval. One can state with assurance that if heating during this interval of time were to be realized by a beam of electrons, then the growth of the diamagnetism would be accompanied by intense microwave radiation at a frequency $\sim 2\omega_{pe}$.

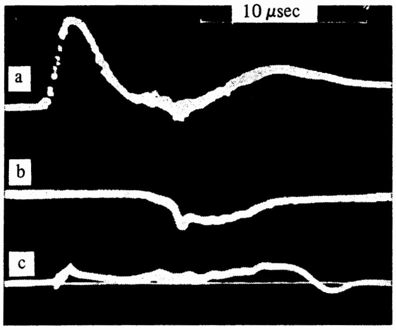

FIG. 1. General characteristics of discharge: a—diamagnetic signal, b—integral electromagnetic radiation of plasma, c—current through the discharge gap.

After the maximum value is reached, the energy content of the plasma begins to drop rapidly. After a time $\sim 3.3 \times 10^{-6}$ sec the value of nT decreases from 2×10^{15} eV/cm^3 to 2×10^{14} eV/cm^3. Such a drop of nT can be attributed to the start of the development of current-convective instability in the plasma[5], leading to a growth of the energy loss from the ends of the apparatus. According to the results of[4], the occurrence of current-convective instability is accompanied by the appearance of particle beams in the plasma. Still, however, no radiation is observed in a time 3.3×10^{-6} sec from the start of the decrease of nT. Then microwave radiation and periodic oscillations of the current appear almost simultaneously. We note that the period of the latter increases linearly with increasing confining field H_0. The time of growth of the microwave power from zero to maximum is $t \sim 8 \times 10^{-7}$ sec, and the duration of the radiation is 5×10^{-6} sec.

A study of the spectral composition of the radiation from the plasma would yield very useful information concerning the oscillation modes that develop in the plasma and the distribution of the oscillatory energy density among these modes.

2. ANALYSIS OF MICROWAVE RADIATION SPECTRUM

An analyzer for the spectrum of the microwave radiation, based on paramagnetic resonance, was proposed for the first time in[5]. In the present paper we propose a waveguide MSA scheme which is much more immune to interference, a fact of great importance for plasma experiments. A diagram of the MSA is shown in Fig. 2. Microwave radiation from the turbulent plasma passes through receiving antenna 1, ferrite valve 2, and waveguide switch 3 into the H arm of the double waveguide tee. In the side arms of the bridge are connected segments of waveguides filled with paramagnetic material ($CrCl_3$). Both side arms are short circuited on the ends by short-circuiting plungers 4. In the E arm of the tee is connected a broadband detector head 5. If identical loads are connected to the side arms of the bridge, then there should be no detector signal in a rather wide range of frequencies.

An external alternating magnetic field $\mathbf{H}_\sim$ is applied to one of the segments of the waveguide filled with the paramagnet ($\mathbf{H}_\sim$ is parallel to the waveguide axis). When the frequency of the microwave signal ω coincides with the Larmor frequency ω_1 in the medium, intense absorption of the signal power takes place in the given arm of the tee, and an unbalance signal appears in the detector. Thus, by varying periodically the value of $\mathbf{H}_\sim$ (and consequently also ω_1) it is possible to plot the frequency spectrum of the radiation as a function of the time, provided, of course, that the characteristic time of the evolution of the spectrum is much larger than the period $\mathbf{H}_\sim$.

It is obvious that the length of the waveguide filled with the paramagnet should be chosen such as to make the unbalance signal at the detector appreciable. In our case this length was 30 cm, but since the microwave signal experienced resonant absorption twice (on the path from the tee to the plunger and from the plunger to the tee), the effective length L was 60 cm.

As is well known, the resonant absorption power is $P_0(1 - e^{-\alpha L})$. The absorption coefficient α at the chosen orientation of the external field $\mathbf{H}_\sim$ for the TE mode is given by the formula

$$\alpha = \frac{\pi^3 g^2 \beta^2 N f(\nu)\delta}{kTAC}\,\nu\sqrt{\nu^2\varepsilon - \nu_{cr}^2},$$

where g is the spectroscopic splitting factor, β the Bohr magneton, N the number of paramagnetic particles per mole of substance, $f(\nu)$ the shape function of the paramagnetic resonance curve, k Boltzmann's constant, T the temperature, A the molecular weight, ν the frequency, ν_{cr} the critical frequency of the waveguide, δ the density of the medium, and ϵ the dielectric constant of the paramagnet.

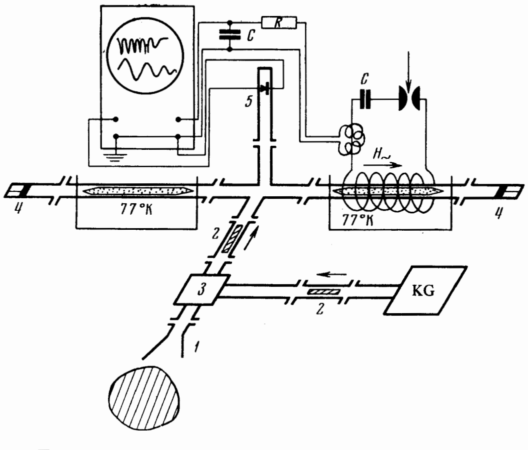

FIG. 2. Diagram of magnetic spectrum analyzer.

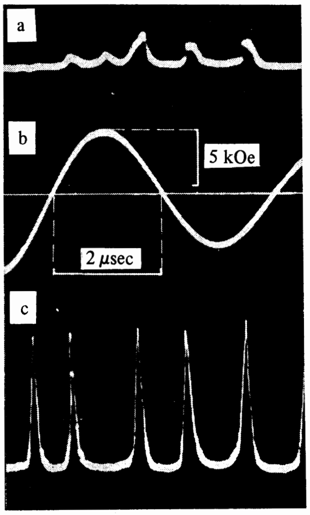

FIG. 3. Oscillograms illustrating the operation of the magnetic spectrum analyzer: a—plasma radiation spectrum; b—magnetic field of the instrument $H_\sim$; c—radiation spectrum of reference klystron generator.

At other orientations of the vector $H_\sim$ (perpendicular to the waveguide axis), the expression for α changes somewhat, but when $\nu^2\epsilon \gg \nu_{cr}^2$ the damping coefficient turns out to be the same for any orientation of the external magnetic field. Since α increases with decreasing temperature, both sections of the waveguide filled with the paramagnet were cooled with liquid nitrogen.

The operation of the magnetic spectrum analyzer was verified first at several monochromatic frequencies from klystron generators. Tests have shown that the instrument operates reliably in the wavelength band from 2 to 4.6 cm.

The MSA described above was used to obtain the spectrum of the self-radiation of a turbulent plasma with current. Figure 3 shows oscillograms of the plasma radiation spectrum (a), of the magnetic field $\mathbf{H}_\sim$ (b), and of the radiation spectrum of the reference klystron generator (λ = 3.4 cm) (c). On the first half-cycle of $\mathbf{H}_\sim$ one can see clearly the peaks of the radiation with wavelengths 4 and 2 cm, corresponding to radiation at the plasma and double the plasma frequency.

It is known that nonlinear interactions of Langmuir waves lead to emission of transverse waves at a frequency $\sim 2\omega_{pe}$, and the interaction of Langmuir waves with long-wave ion-acoustic waves produces radiation with frequency close to ω_{pe}.

From the results of our measurements it is possible to estimate the energy density of the ion-acoustic and plasma waves. The radiation power per unit volume of an unbounded plasma at the plasma and double the plasma frequencies, respectively, is given by the formulas[1]

$$\mathcal{P}_{\omega_{pe}} \sim 10\omega_{pe}\left(\frac{\omega_{pe}}{ck_0}\right)W_i\frac{W_e}{mnc^2},$$

$$\mathcal{P}_{2\omega_{pe}} \sim 30\omega_{pe}\left(\frac{\omega_{pe}}{ck_0}\right)^3 W_e\frac{W_e}{mnc^2},$$

where k_0 is the characteristic wave number, $W_{e,i}$ is the energy density of the plasma and acoustic waves, respectively, and the other symbols are standard.

The radiation power $\mathcal{P}$ was determined in the same manner as in[1]. The value of k_0 was estimated to equal $(1/4)r_{De}^{-1}$ [1], where r_{De} is the Debye radius. It turns out as a result that $W_e \approx 1.7 \times 10^{12}$ eV/cm^3 and $W_i \approx 1.3 \times 10^{12}$ eV/cm^3, i.e., just as in[1], $W_i \approx W_e$. We note also that the degree of turbulence $(W_i + W_e)/nT$ in these experiments it is equal to 0.015.

3. DISCUSSION OF RESULTS

The results of the experiments allow us to conclude that during the time of effective heating there are no electron beams. The two-stream instability sets in only during the second stage, after the development of the current-convective instability. These conclusions are in accord with the results of[4], where investigations of the bremsstrahlung x-radiation from the anode have demonstrated that the electron beams appear only during the second stage of the discharge. Indeed, during the first 1.5 microseconds the plasma is effectively heated, so that its energy content reaches 2×10^{15} eV/cm^3. In spite of the fact that the heating of the plasma is appreciable, there is no intense electromagnetic radiation during this stage, meaning that in the plasma at that time there are no electron beams of sufficient intensity, capable of generating oscillations and influencing the plasma heating. The ratio of the current velocity to the velocity of the ion sound c_s is of the order of 3–4. The level of the ion-acoustic oscillations during the time of the effective heating, as established earlier[3], is quite appreciable. It is therefore natural to assume that the ion-acoustic instability is responsible for the heating of the plasma.

After 1.7×10^{-6} sec from the start of the process, current-convective instability develops in the turbulent plasma, and leads to a drift of the particles to the end surfaces of the apparatus; it is accompanied by the appearance of electron beams which were identified in[4] by the x-radiation from the anode of the apparatus.

An analysis of the results makes it possible to obtain, on the basis of the theory, estimates of the electron beam velocity during the second stage of the discharge. We call attention (see Fig. 3) to the fact that the microwave radiation lags the start of the current-convective instability by 3.3 μsec, and then reaches power saturation within 0.8 μsec. These experimental facts admit of the following explanation.

When a certain density n_b and velocity v_b are reached by the plasma of the electron beam, buildup of Langmuir oscillations is possible with a characteristic increment $\gamma_l \sim \omega_{pe} n_b v_b^2 / n(\Delta v)^2$. At the same time, in view of the rather high level of the ion-acoustic noise, the following nonlinear processes are possible in the plasma and may lead to a drift of the waves from the region of the unstable k (see, for example,[7]):

a) three-plasmon scattering of Langmuir waves by long-wave sound, with a characteristic damping decrement[7]

$$\gamma_s \sim -\omega_{pe} \frac{m}{M} \left(\frac{v_b}{v_{Te}} \right)^2 \frac{W_{i(s)}}{nT},$$

b) stimulated scattering of Langmuir waves by the plasma electrons with reradiation into ionic plasma waves; the corresponding damping decrement can be estimated in the following manner:

$$\gamma_{pi} \sim -\omega_{pe} W_{i(pi)} / nT.$$

Here $W_{i(s)}$ and $W_{i(pi)}$ are the energy densities of the ion-acoustic waves in the long-wave (acoustic) and short-wave (ion-plasma) parts of the spectrum, respectively.

In the case when

$$\gamma_l - \gamma_s - \gamma_{pi} \sim \omega_{pe} \left[\frac{n_b}{n} \frac{v_b^2}{(\Delta v)^2} - \frac{m}{M} \left(\frac{v_b}{v_{Te}} \right)^2 \frac{W_{i(s)}}{nT} - \frac{W_{i(pi)}}{nT} \right] < 0, \quad (1)$$

i.e., when the relative density of the beam is smaller than a certain limiting value $(n_b/n)_0$, even if runaway electrons are present in the beam plasma, the latter cannot excite Langmuir oscillations (and consequently cannot take part in the plasma heating).

With increasing number of runaway electrons[1)] the inequality sign may become reversed and the level of the Langmuir waves begins to increase with an increment $\delta\gamma_l$: $\delta\gamma_l = \gamma_l - \gamma_0$. However, with increasing noise level one more nonlinear process comes into play, namely the scattering of plasma waves by the plasma electrons; this process has a characteristic frequency

$$\gamma_e \sim -\omega_{pe} \left(\frac{v_{Te}}{v_b} \right)^3 \frac{W_e}{nT}.$$

As soon as the noise energy density reaches a value

$$\frac{W_e}{nT} \sim \left(\frac{v_b}{v_{Te}} \right)^3 \delta\gamma_l \, \omega_{pe}^{-1},$$

its further growth stops.

These qualitative considerations are in good agreement with our experimental data. As was already mentioned, the electromagnetic radiation from the plasma appears only 3.3 μsec after the start of the development of the current-convective instability, and it appears simultaneously near the double plasma frequency and the plasma frequency. By estimating the value of $\delta\gamma_l$ from the rate of growth of the noise and the value of W_e/nT from the radiation power $\mathcal{P}_{2\omega_{pe}}$, we can determine the ratio v_b/v_{Te}. In our case $\delta\gamma_l \approx 1.25 \times 10^6$ sec^{-1} and $W_e/nT \approx 8.5 \times 10^{-3}$. Thus,

$$\frac{v_b}{v_{Te}} \sim \left(\frac{W_e}{nT} \frac{\omega_{pe}}{\delta\gamma_l} \right)^{1/3} \sim 7$$

The hardness of the electron beam, obtained from the foregoing estimates, agrees sufficiently well with that measured in the experiment[4]. Indeed, at $nT \approx 2 \times 10^{14}$ eV-cm^{-3} and $n_0 \sim 8 \times 10^{11}$ cm^{-3} we have $v_{Te} = 9 \times 10^8$ cm/sec, which yields a beam velocity $v_b \sim 6 \times 10^9$ cm/sec and accordingly an electron energy ~ 10 keV.

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[1)] According to the theory of Rudakov and Korablev [8], ion-acoustic instability cannot prevent runaway completely. The rate of runaway is proportional to the electric field, which can increase strongly in individual sections of the plasma column owing to the development of current-convective instability [5].

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144