INVESTIGATION OF THE SPECTRUM OF THE INTRINSIC ELECTROMAGNETIC RADIATION IN A "PLASMA-BEAM" SYSTEM

L. P. ZAKATOV, A. S. KINGSEP, A. G. PLAKHOV, and V. D. RYUTOV

Submitted April 5, 1971

Zh. Eksp. Teor. Fiz. 61, 1009–1015 (September, 1971)

The frequency spectrum of the electromagnetic radiation from a plasma interacting with an electron beam is analyzed. A novel spectral analyzer is proposed, based on transmission of the electromagnetic signal through a layer of plasma from a solid. A broad spectrum of the radiation from the plasma is observed in the characteristic frequency range $\omega_{pe} - 2\omega_{pe}$. The energy density of the Langmuir noise in a plasma is estimated on the basis of the radiation of frequency $2\omega_{pe}$. The presence of radiation of frequency ω_{pe} indicates that low-frequency oscillations are produced in the plasma in addition to Langmuir oscillations.

At the present time there is a considerable number of reports (see, for example,[1-3]) of research on collective interaction of plasma with charged-particle beams. The latter, as is well known, can excite in the plasma a spectrum of electromagnetic oscillations and then relax by being scattered from these oscillations. At the same time, the attenuation of the noise by the plasma particles causes the plasma to be heated. To investigate the interaction of particle beams with a plasma, and especially for a detailed understanding of the mechanism of such an interaction, it is important to know the energy density and the spectral distribution of the noise in the plasma during the heating process. Since direct observation of the noise is frequently quite difficult, various methods that yield indirect information are used, particularly measurement of the intrinsic plasma radiation. Thus, the energy density of Langmuir waves can be deduced from radiation at double the plasma frequency, $2\omega_{pe}$, the energy density of ion-acoustic waves from the radiation at the frequency ω_{pe}, etc.

The purpose of the present investigation was to measure the frequency spectrum of electromagnetic radiation from a plasma interacting with a high-power electron beam. The measurements were performed in the frequency range including the characteristic plasma frequencies ω_{pe} and $2\omega_{pe}$.

1. EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

The setup used for the experiment (described in detail in[4]) was a magnetic trap of mirror configuration (Fig. 1). The magnetic field intensity was 1 kOe at the center of the chamber and 5.25 kOe in the mirrors. The electron beam and the hydrogen plasma were injected into the trap along the symmetry axis in opposition to each other. The plasma was prepared with a titanium injector[4], and its concentration was varied in the range 10^{12}–10^{13} cm^{-3}; the plasma electron temperature was $T_e \sim 5$ eV. The beam parameters were: energy $\mathcal{E} \approx 30$ keV, current 10 A, pulse duration $\tau = 250\ \mu$sec, and particle concentration in the beam $n_b \sim 2 \times 10^9$ cm^{-3}.

We note that under our conditions the following inequalities were satisfied:

$$\omega_{pe} n_b / n \ll \omega_{He} \ll \omega_{pe}. \tag{1.1}$$

It follows from (1.1) that the plasma oscillations could be regarded as nonmagnetized, and the beam exciting the oscillations as magnetized.

To investigate the intrinsic electromagnetic radiation of the plasma we have proposed a new type of spectrum analyzer, the operating principle of which is based on the existence in a solid-state plasma of weakly-damped electromagnetic waves—helicons—the dispersion of which is given by

$$\varepsilon_0 - \frac{\omega_{pe}^2}{\omega\omega_{He}}\left(i\frac{\nu}{\omega_{He}} \pm 1\right) = \frac{c^2k^2}{\omega^2}\cos \widehat{\mathbf{kH}}, \tag{1.2}$$

where ϵ_0 is the dielectric constant of the lattice, ω_{He} the cyclotron frequency, ν the collision frequency, and H the external magnetic field.

In our experiments we used a single crystal of n-InSb with a carrier density 5×10^{13} cm^{-3} and a mobility 6×10^5 cm^2/V-sec at liquid-nitrogen temperature. The crystal with dimensions $11 \times 6 \times 0.4$ mm was placed in a waveguide of 11×5.5 mm, and completely covered its cross section. For the wave under consideration, the plasma layer of thickness L constitutes a Fabry-Perot interferometer, whose transmission coefficient was an oscillating but not periodic function of the magnetic field. The transmission extrema corresponded to the conditions $\sin^2 kL = 0$ and 1. In addition, and most importantly for our purposes, there exists a rather sharp transmission threshold on the side of weaker magnetic fields. The location of this threshold depends on the helicon frequency. The latter circumstance makes it possible to use such a system as a spectrum analyzer. The transmission-coefficient oscillations, which are undesirable for our purpose, can be eliminated by choosing a sufficiently small thickness of the plasma layer L. In our case L = 0.4 mm, and for waves with frequency below f_{max} = 36 800 mHz no spatial resonances were observed.

The instrumental setup was as follows (Fig. 1): the investigated signal entered the receiving end of the waveguide from a horn antenna and passed further through the crystal (in the form of a helicon wave), was detected, and registered with an oscilloscope.

The oscillograms of Fig. 2 show: a) the signal from the detector head of the instrument after a monochro-

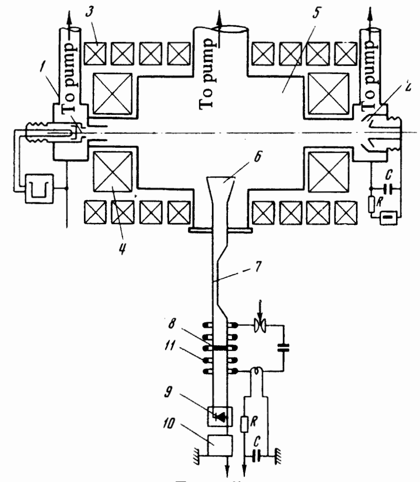

FIG. 1. Diagram of experimental setup and of the spectral analyzer for the microwave radiation: 1—electron gun, 2—plasma injector, 3—coil of main magnetic field, 4—mirror coils, 5—vacuum chamber, 6—horn antenna, 7—waveguide operating beyond cutoff, 8—InSb crystal, 9—detector head, 10—preamplifier, 11—solenoid producing a longitudinal magnetic field H~ in the crystal.

matic frequency f = 26,200 MHz was applied to the input from a klystron oscillator and b) the time dependence of the external longitudinal magnetic field $H_{\sim}$.

It is seen from the oscillograms that the transmission coefficient of the system increases linearly starting with a certain magnetic field H_1 and reaches a maximum value at a certain field H_2, after which it no longer depends on the magnetic field. The $H_1(f)$ and $H_2(f)$ dependences measured by us were reduced by least squares; the results can be represented with sufficient accuracy by the expressions

$$H_1(f)=4540(f/f_1)^{-2,84},\quad H_2(f)=6560(f/f_1)^{-2}, \tag{1.3}$$

where $H_{1,2}$ are in Oe and f in MHz (f_1 = 18,800 MHz).

The character of the transmission of the microwave signal by the system allows us to regard our spectrum analyzer as a waveguide that operates beyond cutoff and can be rapidly tuned in frequency. In the present investigation, the spectrum was analyzed within a time equal to one quarter of the period of the field $H_{\sim}$, i.e., within t = 3 μsec. During this time interval we were able to plot the spectrum of microwave radiation in the range from 18 800 to 36 800 MHz.

Let us establish the dependence of the signal I(H) passing through the critical on the spectral radiation density P_f. It is clear from the foregoing that at frequencies below the threshold $f_1(H)$ the signal does not pass through the crystal. The threshold frequency is determined by the condition $H \equiv H_1(f_1(H))$. We can determine in similar fashion the second characteristic frequency $f_2(H)$, above which the transmission coefficient does not depend on the magnetic field $H \equiv H_2(f_2(H))$. The $f_1(H)$ and $f_2(H)$ curves are described by formulas (1.3). When $f_2(H) > f > f_1(H)$ the transmission coefficient depends linearly on H.

Thus, we obtain the equation

$$I(H)=\int_{f_1(H)}^{f_2(H)} df\,k_f\frac{H-H_1(f)}{H_2(f)-H_1(f)}P_f+\int_{f_2(H)}^{\infty} df\,k_fP_f, \tag{1.4}$$

where k_f is the system transmission coefficient at $H > H_2(f)$. It follows from (1.4), in particular, that

$$\frac{d^2I}{dH^2}=\frac{Hf_1'(H)}{H_2[f_1(H)]-H}k_{f_1}P_{f_1}+\left(1-\frac{H}{H-H_1[f_2(H)]}\right)f_2'(H)k_{f_2}P_{f_2}. \tag{1.5}$$

The expression (1.5) makes it possible to construct the dependence of P_f from the experimental I(H) dependence. In our case, however, the high noise levels did not make it possible to differentiate I(H) twice, so that the data were reduced by a different method.

We subdivide the investigated frequency interval (f_{min}, f_{max}) by means of points f_k such that $f_{k+1} > f_k$; $f_0 = f_{min}$; $f_n = f_{max}$. We separate the values of the alternating magnetic field $H_k = H_1(f_k)$. Equation (1.4) can now be rewritten in the form

$$I(H_i)=\sum_{k=1}^{n}a_{ik}\langle k_fP_f\rangle_k,$$

$$a_{ik}=\begin{cases}0, & k<i\\ f_{k+1}-f_k, & f_k>f_2(H_i).\\ \displaystyle\int_{f_k}^{f_{k+1}} df\frac{H-H_1(f)}{H_2(f)-H_1(f)}, & f_k\leqslant f_2(H_i),\\ & k\geqslant i\end{cases} \tag{1.6}$$

If the segments $f_{k+1} - f_k$ are made sufficiently small, the intervals to which the points $f_2(H)$ belong make a negligible contribution to the sum (1.6), so that the error in the determination of the coefficients a_{ik} becomes negligible.

The solution of the system (1.6) entails no difficulty even at large n, since the matrix a_{ik} is diagonal. Substituting in the left-hand side the measured values of $I(H_i)$ and taking into account the dependence of k_f on f (Fig. 3), we determine $\langle P_f\rangle_i$.

2. MEASUREMENT RESULTS

As already indicated, in our experiments we investigated the intrinsic electromagnetic radiation pro-

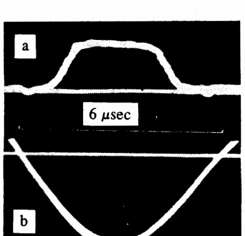

FIG. 2. Characteristics of spectral analyzer: a—signal from detector head of the instrument when a monochromatic frequency f = 26 200 MHz is applied to the input; b—time dependence of the external longitudinal magnetic field H~.

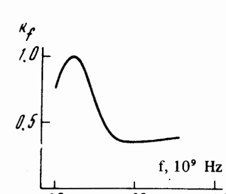

FIG. 3. Frequency dependence of the transmission coefficient of the system.

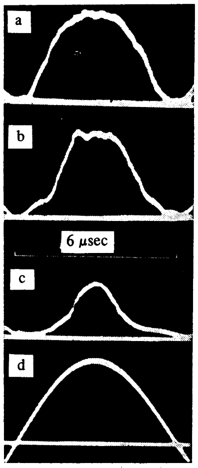

FIG. 4. Oscillograms obtained with the aid of the spectrum analyzer at different plasma concentrations: a–n ~ 7 × 10^{12} cm^{-3}, b–n ~ 4 × 10^{12} cm^{-3}; c–n ~ 10^{12} cm^{-3}; d–longitudinal magnetic field $H_\sim$.

duced in the "plasma-beam" system. The integral electromagnetic radiation from the plasma in the investigated frequency band (18,000 MHz < f < 36,800 MHz) was observed during the entire lifetime of the beam (τ ~ 250 μsec). The emission spectrum was analyzed 50 μsec after the electron beam was turned on. Since we used a pulsed spectral analyzer for the measurements, the characteristic evolution time of the spectrum must be much larger than the analysis time if an undistorted spectrum is to be obtained.

Figure 4 shows the oscillograms obtained with the aid of the spectrum analyzer at different plasma concentrations. It is clearly seen from this figure that the spectrum remains unchanged during the analysis time under the given conditions—the signal from the analyzer output is symmetrical with respect to the maximum of the field $H_\sim$. We note that at higher concentrations, in individual experiments, the opposite picture was observed, and the spectrum varied more rapidly than the analysis time.

Figure 5 shows the results of the reduction of the oscillograms of Fig. 4a–c by the method described above. The ordinates Q represent the powers radiated by 1 cm^3 of plasma in a specified frequency interval (f_k, f_{k+1}). In the data reduction we took into account the variation of the directivity pattern of the antenna with changing frequency.

Figure 5a clearly shows an intensity peak near the plasma frequency ω_{pe}. The radiation power per cm^3 of plasma amounts in this range to $\mathscr{P}_{\omega_{pe}} \sim 2 \times 10^{-2}$ cm^{-3}. With decreasing concentration, the spectrum

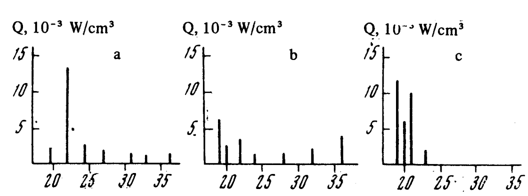

FIG. 5. Power radiated by 1 cm^3 of plasma in a specified frequency interval (f_k, f_{k+1}) at different plasma concentrations: a–n ~ 7 × 10^{12} cm^{-3}, b–n ~ 4 × 10^{12} cm^{-3}, c–n ~ 10^{12} cm^{-3}.

begins to shift towards lower frequencies. It is seen from Fig. 5b that the spectrum contains frequencies corresponding to radiation at double the plasma frequency $2\omega_{pe}$, and that further decrease of the concentration causes only radiation at $2\omega_{pe}$ to fall in the investigated frequency range (Fig. 5c). As can be seen from Fig. 5c, no radiation at frequencies above $2\omega_{pe}$ is observed at a given sensitivity level of the instrument--the spectrum has a sharp limit on the high-frequency side.

From the known power radiated by the frequency at double the plasma frequency ($\mathscr{P}_{2\omega_{pe}} \sim 5 \times 10^{-3}$ W-cm^{-3} at n ~ 4 × 10^{12} cm^{-3}) we can estimate the energy density of the Langmuir noise in the plasma. As is well known, radiation at the frequency $2\omega_{pe}$ is attributed to the nonlinear process of Langmuir-wave coalescence. The power radiated by 1 cm^3 of the plasma is connected with W by the expression[5,6]

$$\mathscr{P}_{2\omega_{pe}} \sim 30\omega_{pe}\left(\frac{\omega_{pe}}{ck_0}\right)^3 \frac{W^2}{mnc^2}, \tag{2.1}$$

where k_0 is the characteristic wave number and the remaining notation is standard.

The quantity ω_{pe}/ck_0, under the condition of the beam experiment can be estimated at $(2\mathscr{E}/mc^2)^{1/2}$, where $\mathscr{E}$ is the beam energy. Calculations yield

$$W \approx 1.4 \text{ erg/cm}^3 \sim 2\cdot 10^{12} \text{ eV/cm}^3 \tag{2.2}$$

at $n \approx 4 \times 10^{12}$ cm^{-3}.

3. DISCUSSION OF RESULTS

The presence of radiation at the frequency $2\omega_{pe}$ is evidence that intense Langmuir noise builds up in the plasma as a result of two-stream instability. An estimate of the total noise intensity is in good agreement with the oscillator fields in the plasma as measured by the Stark broadening of the spectral lines of hydrogen[7]. The energy density (2.2) calculated in accord with formula (2.1) is actually higher by a factor 2–3, this being due to accumulation of the radiation in the metal chamber. By introducing the appropriate correction, we obtain $W \approx 10^{12}$ eV-cm^{-3}, which agrees with the result of[7]. This effect, naturally does not in any way influence the energy distribution over the spectrum (Fig. 4).

From the foregoing data on the spectral distribution of the radiation it follows that the radiation near the frequency $2\omega_{pe}$ is a rather broad line: $\delta\omega \sim \omega/4$. Such a line width cannot be attributed either to quasi-linear relaxation of the beam (which yields $\delta\omega \sim \omega T_e/\mathscr{E}$), or to the buildup of oblique waves, which should lead to a broadening $\delta\omega \sim \omega(\omega_{He}/\omega_{pe})^2 \sin^2 \widehat{\mathbf{kH}}$. Finally the beam radius is so small compared with the plasma radius that one should exclude also the influence of the radial variation of the concentration (the wave frequency is an integral of the motion), so that the broadening of the radiation spectrum can be attributed only to the longitudinal inhomogeneity of the concentration within the volume of the plasma

The radiation at a frequency close to ω_{pe} can be attributed to nonlinear interaction of Langmuir waves with some low-frequency branch of the oscillations. The latter can build up in the plasma as a result of the development of two-stream instability, but nonlinear transformation of Langmuir into low-frequency waves via scattering by the plasma electrons is also possible.

The authors thank E. K. Zavoĭskiĭ for constant interest in the work and E. Z. Meĭlikhov for valuable discussions.

[1] Ya. B. Faĭnberg, Atomnaya ênergiya 11, 313 (1961).

[2] L. D. Smullin and W. D. Getty, Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Culham, CN-21/122, 1965.

[3] A. G. Plakhov, V. D. Ryutov, and V. V. Shapkin, Third International Conference on Controlled Nuclear Fusion, CN-24/L-3, Novosibirsk, 1968.

[4] L. P. Zakatov and A. G. Plakhov, Zh. Eksp. Teor. Fiz. 60, 588 (1971) [Sov. Phys.-JETP 33, 320 (1971)].

[5] R. E. Aamodt and W. E. Drummond, J. Nucl. Energy, C6, 147 (1964).

[6] Yu. G. Kalinin, D. N. Lin, V. D. Ryutov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. 55, 115 (1968) [Sov. Phys.-JETP 28, 61 (1969)].

[7] L. P. Zakatov, A. G. Plakhov, V. V. Shapkin, and G. V. Sholin, Dokl. Akad. Nauk SSSR 198, 1306 (1971) [Sov. Phys.-Doklady 16, 451 (1971)].

Translated by J. G. Adashko
102