Local bursts of electromagnetic radiation in a plasma with strong Langmuir turbulence

D. M. Karfidov, A. M. Rubenchik, K. F. Sergeĭchev, and I. A. Sychev
Institute of General Physics, Academy of Sciences of the USSR

(Submitted 5 August 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 6, 315–318 (25 September 1988)

There is a correspondence between the dynamics of local bursts of electromagnetic radiation in a plasma in a state of strong Langmuir turbulence and the model of a collapse of plasma waves.

Strong Langmuir turbulence is known to be characterized by such phenomena as the collapse of plasma waves,[1] the excitation of short ion acoustic waves,[2] the acceleration of electrons,[3] and finally, bursts of electromagnetic radiation from collapsing density cavitons.[4,5] In the present letter we demonstrate that the electromagnetic radiation can serve as a satisfactory source of information on the dynamics of local processes of a strong Langmuir turbulence which occur in a real plasma, rather than in the specially organized plasma of model experiments, e.g., those of Ref. 6.

A strong Langmuir turbulence occurs during the injection of an electron beam into a plasma. The plasma itself is produced by a beam-plasma discharge in a static longitudinal magnetic field $H_0 \approx 100$ G in argon or xenon at a pressure $p_{\mathrm{Ar,Xe}} \approx 5 \times 10^{-4}$ torr. The beam is injected during the plasma decay stage after the end of the discharge pulse, while the plasma parameters at the axis of the (axisymmetric) column have the following values: a particle density $n_0 \lesssim 10^{12}$ cm^{-3}, an electron temperature $T_e \approx 2.5$ eV, a difference between the ion and electron temperatures described by $T_i/T_e \lesssim 0.1$, a space potential $\varphi_0 = 0$–5 V, and density fluctuations $\delta n/n_0 < 5 \times 10^{-3}$. The energy and current of the beam are varied over the ranges $U_b = 0$–300 V and $I_b = 0$–15 A; the length of the injection pulse is $\tau_b = 5$ μs. The beam moves through an essentially homogeneous plasma, since the typical size of the cross section of the plasma column, ~ 10 cm, is substantially larger than the beam diameter, ~ 3 cm.

The injection of the beam is accompanied by bursts of nonthermal electromagnetic radiation at a frequency near the plasma frequency $f_{pl} = (2\pi)^{-1}(n_0 e^2/\epsilon_0 m)^{1/2}$, where e and m are the charge and mass of an electron, and ϵ_0 is the permittivity of free space. The bursts are detected with thin insulated loop or dipole antennas immersed in the plasma (the wire diameter is 0.01 cm, and the loop diameter is 0.5 cm). The length scale of the radiation sources is determined by a method based on the correlation between the signals from two identical antennas which are moved with respect to each other. Figure 1 shows an example of this correlation between signals for the particular case in which the distance between antennas is $L \sim 0.1$ cm, with $U_b = 300$ V and $I_b = 6$ A. The arrows mark coincidences in the signals representing bursts of radiation. At $L > 0.2$ cm no coincidences of the signals are observed at all, or there is a likelihood that they could be random. We see from Fig. 1 that there is not an absolute correspondence in all the bursts received by the two antennas; nor should there be, since the dimensions of the radiation sources are $L_r < 0.1$ cm, while the coupling between the field of a radiating dipole of small dimensions $L_r \ll c/f_{pe}$ and the antenna

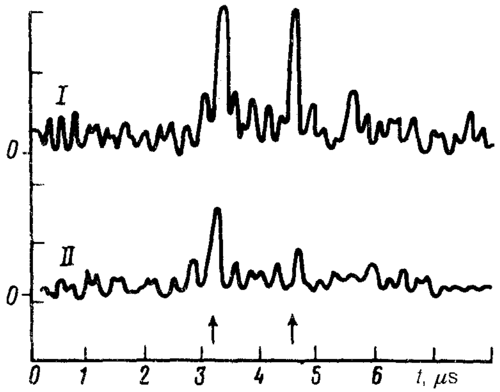

FIG. 1. Oscilloscope traces of bursts of electromagnetic radiation in a plasma at the frequency $f_{pe} = 4.8$ GHz from two identical loop antennas separated by ~ 0.1 cm.

falls off in proportion to r^{-3}, where r is the distance from the center of the dipole. This circumstance means that only if the antennas are close to the radiating dipole, and then only if they are positioned symmetrically, will identical signals appear. The most likely case is that in which there is no symmetry in the coupling between the antennas and the radiating dipoles. Confirmation that the antennas are receiving transverse electromagnetic radiation, rather than longitudinal plasma fields (directly through a capacitive coupling), would be the observation of completely identical signals, detected in a contactless manner by means of a horn-lens receiving antenna focused on the center of the column. In the latter case, admittedly, the total number of bursts detected would be significantly higher, because a short-focal-length antenna will effectively collect the radiation of the bursts over the entire focal volume, with a typical diameter ~ 5 cm.

We compared the durations of individual bursts of radiation for the plasmas of different gases, e.g., argon and xenon. The duration of the radiation burst in the argon plasma at half the amplitude value is $\tau_p \approx 0.08$ μs, while that in a xenon plasma is 0.17 μs, in satisfactory agreement with the inverse proportionality between the duration of the process and the square root of the mass of the ion. We can thus conclude that the duration of the burst of radio emission is determined by the velocity of the ions.

It was also found that the appearance of radiation bursts occurs only above a threshold value of the beam current at a fixed energy U_b. Working from the measured values of the threshold current $I_{b\,\mathrm{thr}} = F(T_e, U_b)$, we plotted the threshold value of the ratio of the beam and plasma densities, n_b/n_0, against the quantity T_e/mv_b^2, where $v_b = (2U_b/m)^{1/2}$ (Fig. 2). According to Galeev *et al.*,[7] this plot should characterize the transition of a plasma with a beam to a regime of strong Langmuir turbulence; the dependence found, however, with a proportionality $(n_b/n_0)_{\mathrm{thr}} \sim (T_e/mv_b^2)^2$, is not the dependence predicted theoretically by Galeev *et al.*,[7] according to which this density ratio would be proportional to $(T_e/mv_b^2)^3$. Furthermore, at small values of $T_e/$

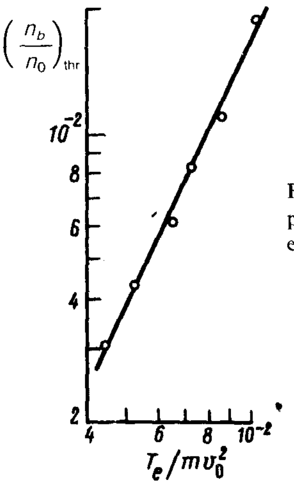

FIG. 2. Dependence of the ratio of the densities of the electron beam and the plasma, n_b/n_0, on the parameter T_e/mv_0^2 for the occurrence of bursts of electromagnetic radiation. A threshold is involved here.

mv_b^2 the experimental threshold is substantially higher than the theoretical threshold; a refinement of the theory seems to be necessary. Another fact worth noting is that the bursts of radio emission are sometimes observed even after the beam current ends, after a delay up to 0.5 μs. This effect can be explained on the basis that during the collapse stage the Langmuir field of a caviton ceases to depend on the pump field and continues to evolve even if the pump is turned off. The residual level of the current at the trailing edge of the pulse is below a threshold level. The delay found, Δt, corresponds in order of magnitude to the duration of the collapse of the Langmuir field in a caviton, $\tau_c \sim L_c/v_s \approx 2\times10^{-7}$ s. Here $L_c \sim k_{\max}^{-1}$ is the initial size of a caviton, which corresponds to a wave number $k_{\max}$ for the maximum growth rate at the threshold for the modulational instability,[8] and $v_{sd} = (\kappa T_e/M)^{1/2}$ is the ion sound velocity. One of the basic consequences of a strong Langmuir turbulence is the excitation of short-wave ion sound[2] with frequencies f_s close to the ion plasma frequency $f_{pi} = (2\pi)^{-1}(n_0e^2/\epsilon_0 M)^{1/2}$. We studied the spectrum of ion acoustic waves by measuring the oscillations in the ion current in the circuit of a Langmuir probe biased $-$ 50 V with respect to the plasma. The probe current was sent through a tunable resonant frequency filter to an amplifier. The signal showing the current drawn by the Langmuir probe at the selected frequency (Fig. 3a) is amplitude-modulated. The nature of the modulation appears to be quite similar to the nature of the bursts of electromagnetic radiation, but it is difficult to establish a temporal correlation between the two processes because of the delay in the response of the high-Q filter. The fact that the amplitude of the modulated ion acoustic signal decreases sharply and that the modulation itself disappears, along with the bursts of radio emission, as the ratio n_b/n_0 is reduced below the measured

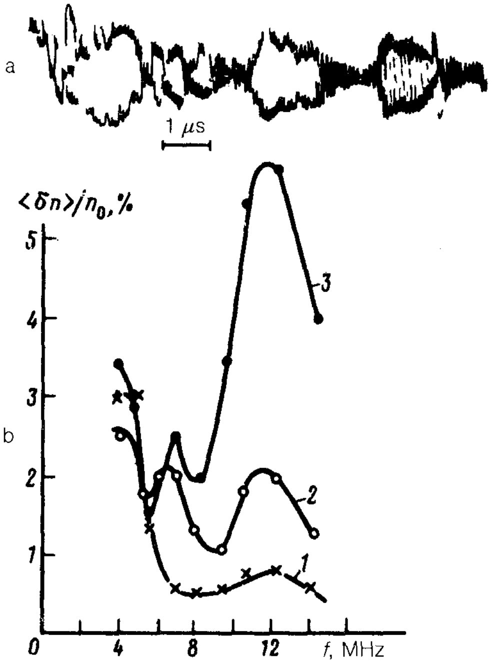

FIG. 3. Spectra of ion acoustic waves. a: Oscilloscope trace of the ion current drawn by a Langmuir probe and passed through a resonant filter tuned to 12 MHz. b: Spectra of waves measured at a fixed value of the beam energy, $U_b = 300$ V, and at three values of the parameter n_b/n_0: 1—$n_b/n_0 = (n_b/n_0)_{\rm thr} = 3.2\times10^{-3}$, 2—$n_b/n_0 = 2(n_b/n_0)_{\rm thr}$, 3—$n_b/n_0 = 12(n_b/n_0)_{\rm thr}$. The ion plasma frequency is $f_{pi} = 16$ MHz.

threshold is a convincing argument in favor of a relationship between the excitation of sound and strong-turbulence phenomena.

Figure 3b shows measured frequency spectra of the ion acoustic waves for three values of n_b/n_0 at a fixed $U_b = 300$ V. When n_b/n_0 is slightly above the threshold, a peak forms at the frequency $f_s = 11.5$ MHz; as n_b is increased further, the peak grows. It is thus a simple matter to estimate the size of the cavitons, L_c, under the assumption that they correspond to the length of the sound wave which is excited: $L_c \sim \lambda_s = v_s/f_s = 2.5\times 10^{-2}$ cm $\sim 10 r_{De}$, in agreement with theoretical predictions of the final size of a caviton.[9]

In summary, the nonthermal radio emission from a plasma during the injection into the plasma of a beam of electrons with a density above a certain level—which can be identified as the threshold for strong Langmuir turbulence—is of the nature of sporadic bursts at the plasma frequency. The sources of this radiation are of small size (no more than 100 Debye lengths), and they are random formations, scattered in an arbitrary way over the plasma volume. The dynamics of the individual bursts of radio emission corresponds to the time scales for the collapse of the cavitons, which are inversely proportional to the ion acoustic velocity. The bursts of radio emission appear at the same time as the excitation of short-wave ion sound, and they have the same excitation threshold in terms of the density of the injected beam. The measured threshold for strong Langmuir turbulence is proportional to $(T_e/mv_b^2)^2$.

[1] V. E. Zakharov, Zh. Eksp. Teor. Fiz. **62**, 1745 (1972) [Sov. Phys. JETP **35**, 908 (1972)].

[2] A. A. Galeev, R. Z. Sagdeev, V. D. Shapiro, and V. I. Shevchenko, Zh. Eksp. Teor. Fiz. **73**, 1352 (1977) [Sov. Phys. JETP **46**, 711 (1977)].

[3] V. E. Zakharov, in: Basic Plasma Physics, North-Holland, Amsterdam.

[4] V. V. Yan'kov, Fiz. Plazmy **8**, 86 (1982) [Sov. J. Plasma Phys. **8**, 48 (1982)].

[5] V. A. Mironov, A. M. Sergeev, and A. V. Khimich, Zh. Eksp. Teor. Fiz. **94**, 76 (1988) [Sov. Phys. JETP **67**, 476 (1988)].

[6] A. Y. Wong and P. Y. Cheung, Phys. Rev. Lett. **52**, 1744 (1984); P. Y. Cheung, and A. Y. Wong, Phys. Fluids **28**, 1538 (1985).

[7] A. A. Galeev, R. Z. Sagdeev, V. D. Shapiro, and V. I. Shevchenko, Interaction of Intense Electromagnetic Waves with Collisionless Plasmas, Gor'kii, 1980, 6.

[8] V. D. Shapiro and V. I. Shevchenko, in: Basic Plasma Physics, Vol. 2, North-Holland, Amsterdam, 1984.

[9] V. E. Zakharov, A. N. Pushkarev, A. M. Rubenchik *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 239 (1988) [JETP Lett. **47**, 287 (1988)].

Translated by Dave Parsons