

# Spatio-temporal Dynamics of Fast Electrons and Plasma Turbulence in an Inhomogeneous Flare Plasma

P. V. Vatagin<sup>a</sup>, \* and I. V. Kudryavtsev<sup>a</sup>, \*\*

<sup>a</sup> *Ioffe Institute, St. Petersburg, 194021 Russia*

\**e-mail: pavelvat@gmail.com*

\*\**e-mail: Igor.Kudryavtsev@mail.ioffe.ru*

Received February 28, 2021; revised April 27, 2021; accepted June 10, 2021

**Abstract**—The spatio-temporal dynamics of the propagation of fast electrons in solar plasma is examined with consideration of their interaction with Langmuir waves, which are generated during the development of beam instability. As a result of numerical simulation, the electron-distribution function and the spectral energy density of Langmuir waves are obtained for different times and at different distances from the place of acceleration in the flare loop. It is shown that the maximum of the distribution function of fast electrons changes little at a distance of  $\sim 10^6$  cm. At large distances, the distribution function decreases; some of the electrons propagate in the flare loop, at least over a distance of  $\sim 10^8$  cm. The length of the region with an increased level of energy density of Langmuir waves is  $\sim 10^7$ – $10^8$  cm, and the maximum value of the energy density of Langmuir waves reaches  $10^{-2}$  erg/cm<sup>3</sup>.

DOI: 10.1134/S001679322108020X

## 1. INTRODUCTION

The main focus in research on the propagation of high-energy electrons appearing in solar plasma during solar flares is traditionally their Coulomb interaction with solar plasma particles (e.g., Nocera et al., 1985; Diakonov and Somov, 1988; Reznikova et al., 2009; Zharkova et al., 2010; Melnikov et al., 2013). In this case, both changes in the plasma concentration and changes in the magnetic field along the flare loop can be taken into account. This approach is explained primarily by the need to describe the parameters of hard X-ray emission of solar flares: the energy spectra, polarization, and directivity (Zharkova et al., 1995; Kudryavtsev and Charikov, 2012). Less attention is paid to the interaction of fast electrons with plasma waves in a flare plasma. It is known that fast electrons can excite Langmuir waves and that they quickly relax when interacting with them. In turn, these waves generate radio emission from the solar plasma (Zheleznyakov and Zaitsev, 1970; Kaplan and Tsytovich, 1972; Ratcliffe et al., 2014; Kudryavtsev and Kaltman, 2020, 2021), which carries information about physical processes on the Sun and is recorded during observations. This radio emission can be generated via the scattering of Langmuir waves by plasma particles and the coalescence of Langmuir waves (e.g., Tsytovich, 1971). Therefore, the study of the dynamics of fast electrons and Langmuir waves in a flare loop is of interest for the description of both the generation of hard X-ray radiation and the process of the generation

of radio emission by Langmuir waves. However, the study of the evolution of the distribution function of fast electrons and the spectra of Langmuir waves in a flare plasma is limited either by time dynamics in a homogeneous plasma without allowance for the spatial change (Ivanov and Rudakov, 1967; Tsytovich, 1971; Grogard, 1975; Melrose, 1986; Kontar et al., 2012) or spatial evolution in the stationary approximation (Kudryavtsev et al., 2019). In addition to the interaction of fast electrons with Langmuir waves, the evolution of the electron distribution function can be influenced by their interaction with ion-acoustic waves (Kudryavtsev and Charikov, 1991; Charikov and Shabalin, 2016) and whistlers (Stepanov and Tsap, 2002; Melnikov and Filatov, 2020).

In this work, since the acceleration process in flares can have an impulse (millisecond) structure (Dmitriev et al., 2006), we will consider the evolution of the electron distribution function  $f$  and the spectral energy density of Langmuir turbulence  $W_k$  with a pulsed injection of electrons.

## 2. SPATIO-TEMPORAL DYNAMICS OF FAST ELECTRONS AND LANGMUIR WAVES UPON PULSE ACCELERATION IN FLARE PLASMA

Let us consider the problem of the evolution of the electron-distribution function  $f$  in plasma and the spectral energy density of Langmuir waves  $W_k$  in the pulse mode of acceleration. In this work, we will focus

on the case of quasilinear relaxation, which will further allow us to analyze the role of nonlinear processes. This problem is described by the following equations (e.g., Zheleznyakov and Zaitsev, 1970; Tsytoich, 1971; Kontar et al., 2012)

$$\frac{\partial f}{\partial t} + v \frac{\partial f}{\partial x} = \frac{\partial}{\partial v} \left( D \frac{\partial f}{\partial v} + v_e \left( v f + v_{Te}^2 \frac{\partial f}{\partial v} \right) \right), \quad (1)$$

$$\frac{\partial W_k}{\partial t} + v_g \frac{\partial W_k}{\partial x} = (\gamma_k - v_{\text{eff}}) W_k + Q_k, \quad (2)$$

$$D = \frac{\pi \omega_e^2}{m_e n_e v} (W_k)_{k=\omega_e/v}, \quad \gamma_k = \left( \frac{\pi \omega_e}{n_e} v^2 \frac{\partial f}{\partial v} \right)_{v=\omega_e/k}, \quad (3)$$

where  $t$  and  $x$  are the time and coordinate;  $v$  is the speed of electrons,  $k$  is the wave number of Langmuir waves;  $v_e$  is the frequency of collisions of electrons with plasma particles;  $\omega_e$  is the electron plasma frequency;  $v_{Te}$  is thermal speed of electrons;  $v_g$  is the group velocity of Langmuir waves;  $\gamma_k$  is the increment of beam instability;  $v_{\text{eff}}$  is the effective frequency of the damping of Langmuir waves due to collisions of plasma particles;  $n_e$  is the concentration of plasma electrons; and  $Q_k$  is the power of spontaneous emission of Langmuir waves.

In this work, like Kontar et al. (2012), we will use the following expression for the function  $Q_k$

$$Q_k(t, x) = \frac{\omega_e^3 m_e}{4\pi n_e} \left( v \ln \left( \frac{v}{v_{Te}} \right) f \right)_{v=\omega_e/k}. \quad (4)$$

In the absence of fast electrons,  $Q_k$  describes the spontaneous emission of Langmuir waves by thermal plasma electrons.

When simulating the process of electron propagation in a flare plasma, like Kudryavtsev et al. (2019), we will assume that electrons propagate downward from the top of the flare loop, and the change in the plasma concentration is described by the expression

$$n_e = n_0(1 + x/L). \quad (5)$$

Let us supplement the system of equations (1)–(3) with the initial condition. Let accelerated electrons with a beam distribution function appear at the

boundary of the equilibrium plasma  $x = 0$  at the initial time instant  $t = 0$ . In this case, we will assume that the distribution function of fast electrons at the initial moment of time rapidly decreases into the plasma depth. Then, at time  $t = 0$ , the electron-distribution function  $f$  is the sum of the Maxwellian distribution of thermal plasma electrons  $f_M$  and the “beam” distribution of fast electrons  $f_b$ :

$$f(t = 0, x, v) = f_M + f_b \exp(-x/x_0),$$

$$f_M = \frac{n_e}{\sqrt{2\pi} v_{Te}} \exp\left(-\frac{v^2}{2v_{Te}^2}\right), \quad (6)$$

$$f_b = \frac{n_b}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(v - v_0)^2}{2\sigma^2}\right),$$

where  $n_b$  is the concentration of fast electrons at  $x = 0$ ;  $x_0$  is the characteristic scale of the decrease in the concentration of fast electrons deep into the plasma; and  $\sigma$  is the root-mean-square deviation of the velocity distribution of fast electrons.

As a boundary condition on  $x$ , we take a condition that describes the time decay of the distribution function of fast electrons entering the plasma at the boundary  $x = 0$ , i.e.,

$$f(t, x = 0, v) = f_M + f_b \exp(-t/t_0). \quad (7)$$

The parameter  $t_0$  sets the time decay of electrons injected into the plasma.

To agree with the previous conditions, we choose the following as the boundary conditions for the velocity  $v$ :

$$f(t, x, v = 0) = f_M(v = 0) + f_b(v = 0) \exp(-x/x_0) \exp(-t/t_0),$$

$$f(t, x, v = v_{\text{max}}) = f_M(v = v_{\text{max}}) + f_b(v = v_{\text{max}}) \exp(-x/x_0) \exp(-t/t_0). \quad (8)$$

As an initial condition for  $W_k$ , like Kontar et al. (2012), we will use the stationary spectrum of Langmuir waves in the absence of fast electrons, i.e., when the left side of equation (2) is zero:

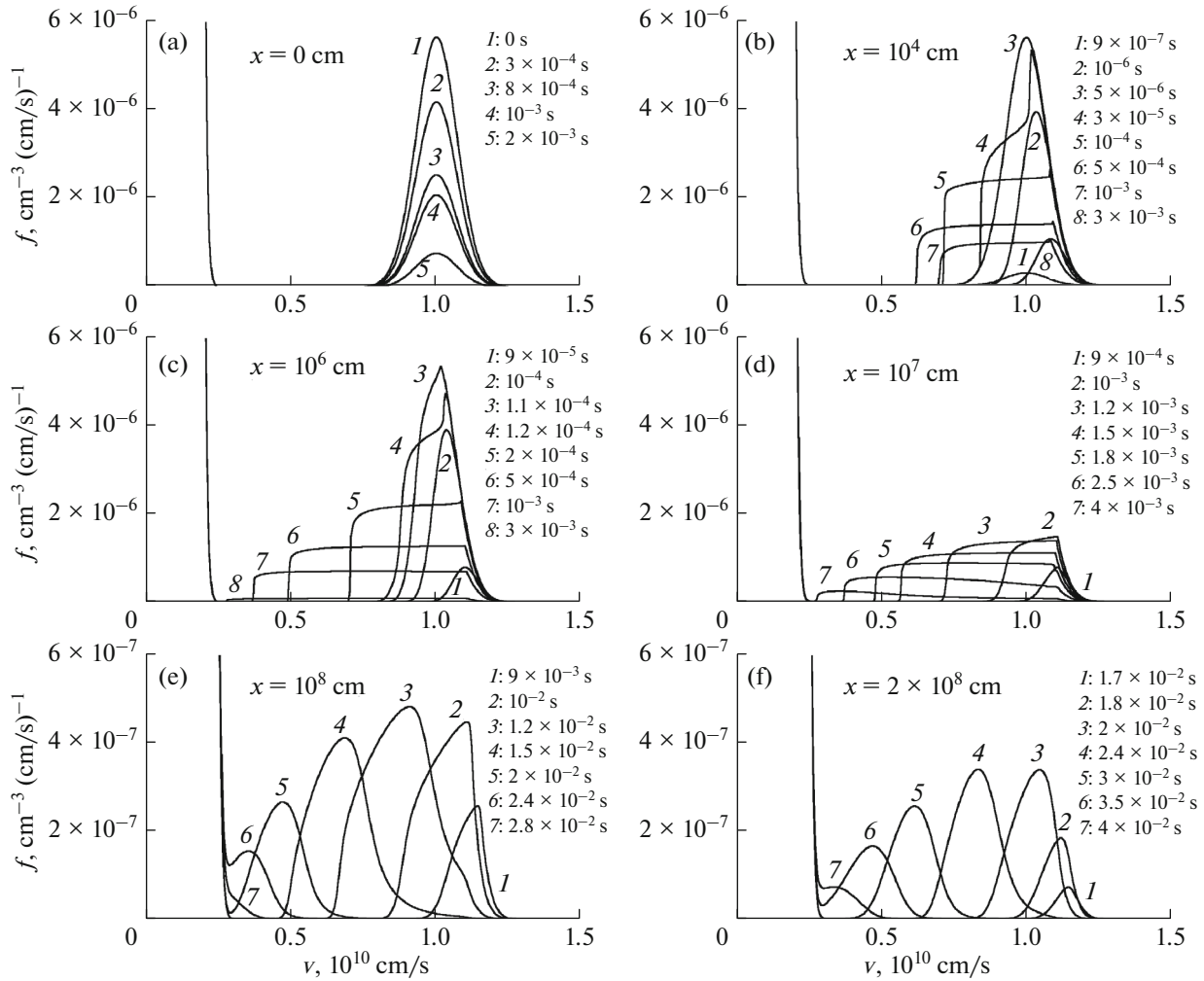
$$W_k(t = 0, x) = \frac{Q_k}{(v_{\text{eff}} - \gamma_k)} = \frac{\omega_e^3 m_e}{4\pi n_e} \left( v \ln \left( \frac{v}{v_{Te}} \right) f_M \right)_{v=\omega_e/k} / \left( v_{\text{eff}} - \left( \frac{\pi \omega_e}{n_e} v^2 \frac{\partial f_M}{\partial v} \right)_{v=\omega_e/k} \right). \quad (9)$$

In this formula,  $n_e$ ,  $\omega_e$ ,  $v_{\text{eff}}$  and  $f_M$  are functions of  $x$ .

This expression describes the thermal background level of Langmuir oscillations in the plasma. As a

boundary condition at the boundary  $x = 0$ , we also take the background level of oscillations:

$$W_k(t, x = 0) = \frac{Q_k}{(v_{\text{eff}} - \gamma_k)} = \frac{\omega_e^3 m_e}{4\pi n_e} \left( v \ln \left( \frac{v}{v_{Te}} \right) f_M \right)_{v=\omega_e/k} / \left( v_{\text{eff}} - \left( \frac{\pi \omega_e}{n_e} v^2 \frac{\partial f_M}{\partial v} \right)_{v=\omega_e/k} \right). \quad (10)$$



**Fig. 1.** Electron distribution function  $f$  at different distances  $x$  from the place of acceleration at different times  $t$ .

This choice of the initial and boundary conditions ensures their agreement at  $t = 0$  and  $x = 0$ . Moreover, like Hamilton and Petrosian (1987), we will assume that  $W_k = 0$  for  $k > \omega_e/v_{Te}$  as a result of Landau damping.

The system of equations (1)–(3) was solved with use of the method of summarized approximation (Samarskii, 1989).

Before proceeding to the description of the calculation results, it should be noted that expression (4) describes the spontaneous excitation of waves not only by thermal electrons, but also by fast electrons. Therefore, in the region of high phase velocities, the main contribution to the spontaneous generation of Langmuir waves is made by fast electrons.

The results of the calculation of the electron-distribution function  $f$  and the spectral energy density of Langmuir waves  $W_k$  for different instants of time and at different distances from the place of acceleration of electrons in the flare plasma are presented in Figs. 1 and 2 at  $n_0 = 10^{10} \text{ cm}^{-3}$ ,  $n_b = 10^4 \text{ cm}^{-3}$ ,  $T_e = 10^6 \text{ K}$ ,  $v_0 =$

$10^{10} \text{ cm/s}$ ,  $\sigma = 0.07v_0$ ,  $v_{\text{max}} = 1.5v_0$ ,  $x_0 = 10^2 \text{ cm}$ ,  $t_0 = 10^{-3} \text{ s}$ ,  $L = 10^7 \text{ cm}$ . In Figs. 1a–1c, it can be seen that the maximum  $f$  value remained practically unchanged up to  $x \sim 10^6 \text{ cm}$ , and its relaxation at these distances occurs upon interaction with Langmuir waves. In this case, there is an increase in Langmuir waves (Figs. 2a–2c). As the electron-distribution function decreases with time, the spectral energy density of Langmuir waves also decreases (curves 6, 7 in Figs. 2b, 2c). With the propagation of electrons over long distances, there is a decrease  $f$  (Figs. 1d–1f) and the spectral energy density of the waves (Figs. 2d–2f). In this case, a faster penetration of high-energy electrons into the plasma is clearly seen (curves 1, 2 in Fig. 1d–1f). This separation of fast electrons from slower ones leads to the formation of a region with a positive derivative of the function  $f$  (Figs. 1d–1f) and the continued excitation of Langmuir waves (Figs. 2d–2f).

Figure 3 shows the energy density of Langmuir waves  $W$  at different distances from the place of elec-

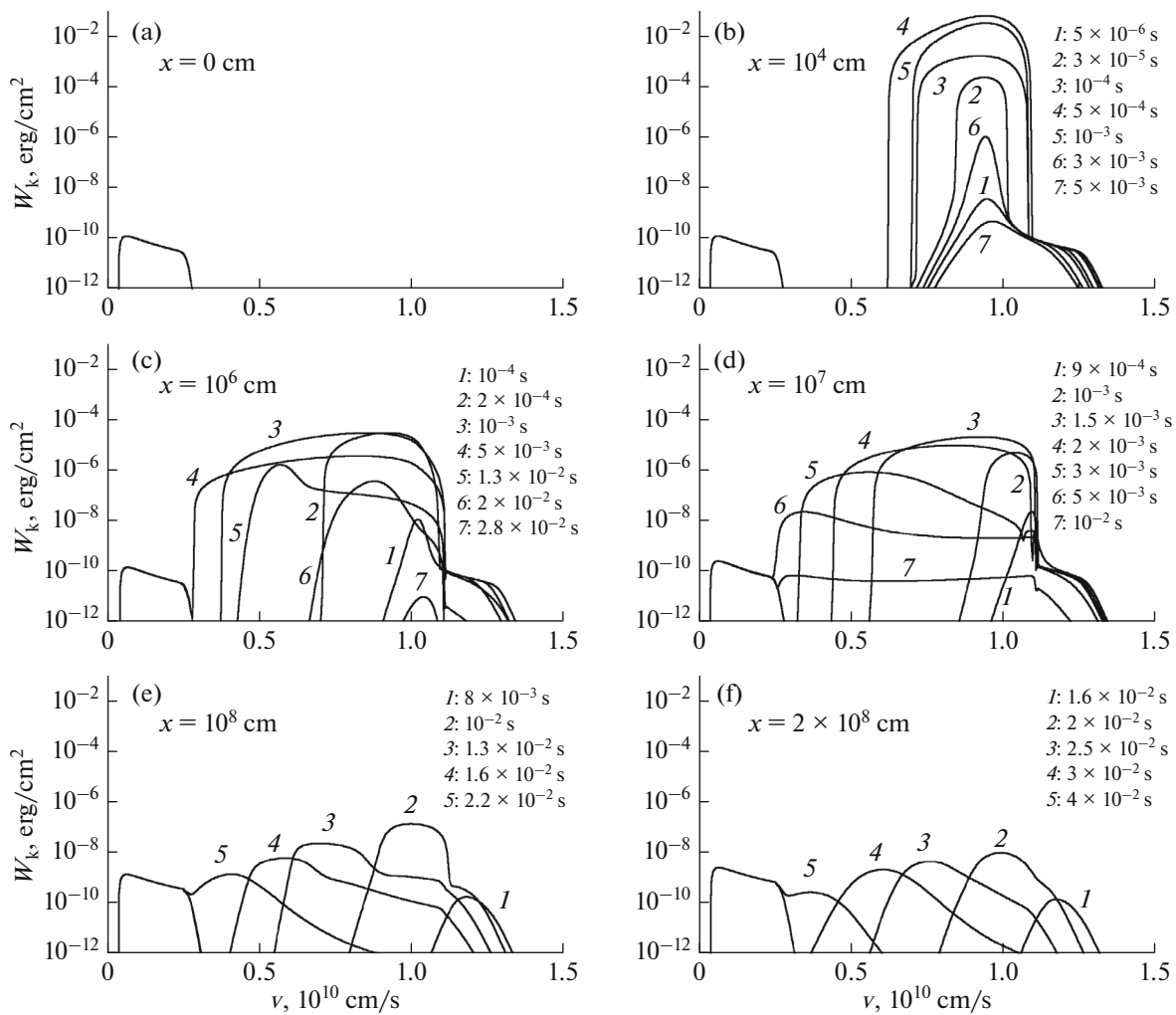


Fig. 2. Spectral energy density of Langmuir waves  $W_k$  at different distances  $x$  from the place of acceleration at different times  $t$ .

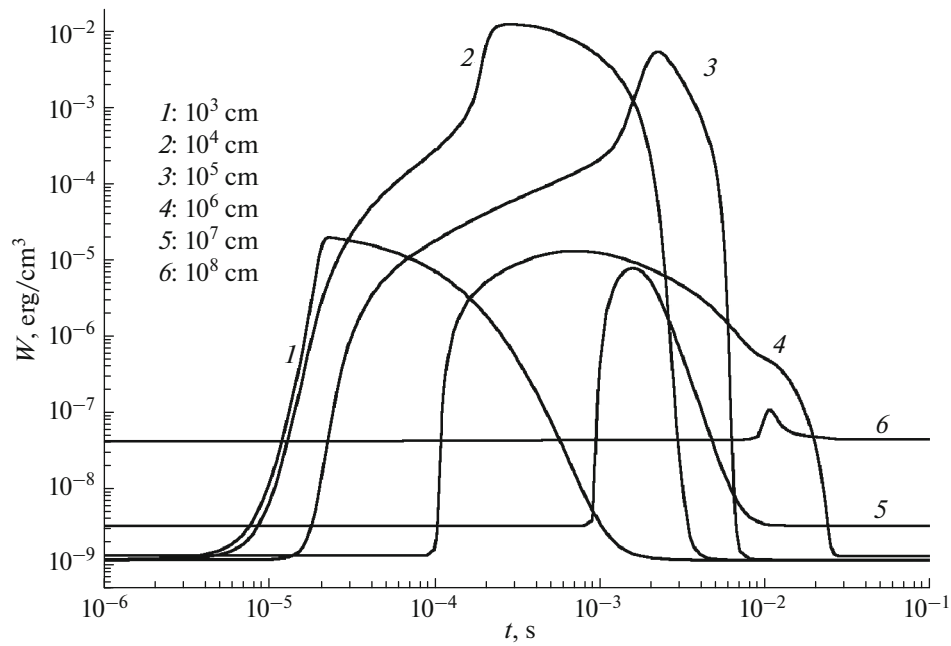
tron injection into the flare plasma as a function of time. As can be seen in the figure, for the used parameters of the plasma and fast electrons, the duration of the existence of Langmuir turbulence in the flare plasma is  $\sim 10^{-2}$  s. Figure 4 shows the distribution of the energy density of Langmuir waves along the plasma.

As follows from Fig. 4, two spatial regions can be distinguished in the flare plasma. For  $x < 10^6$  cm, Langmuir waves are generated as a result of the development of beam instability of fast electrons with an initial beam-type distribution function. This stage passes rather quickly, in a time  $t \sim 10^{-3}$  s (Fig. 1c). At distances exceeding  $x = 10^7$  cm (Fig. 1d), faster electrons begin to penetrate the plasma. This leads to the formation of a portion of the distribution function with a positive derivative with respect to the velocity and the continuation of the excitation of plasma waves (Fig. 2d). As the electron velocity decreases and the plasma concentration increases (at  $x = 10^8$  cm, the

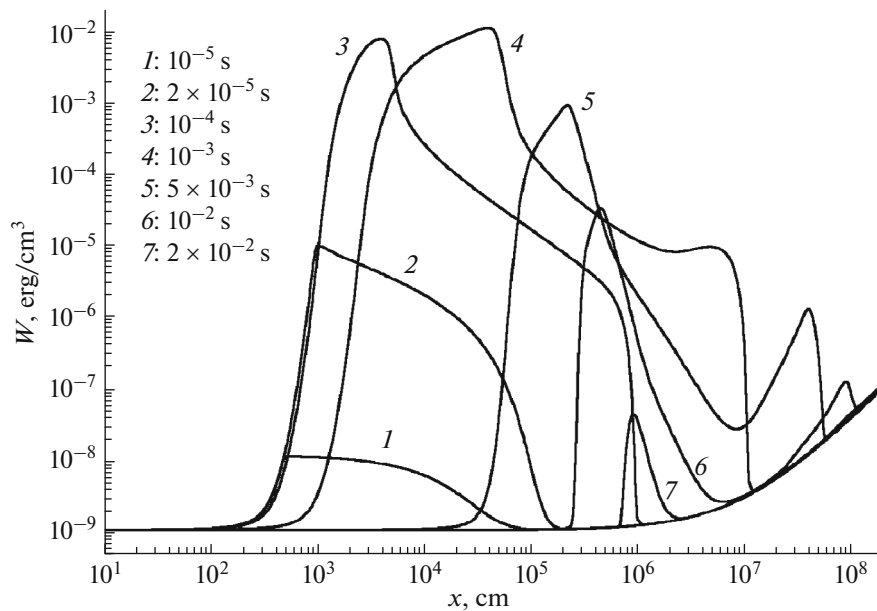
plasma concentration is  $n_e = 1.1 \times 10^{11}$  cm $^{-3}$ , and at  $x = 2 \times 10^8$  cm,  $n_e = 2.1 \times 10^{11}$  cm $^{-3}$ ), Coulomb collisions begin to play their role. Figures 1f–1e clearly show the Maxwellization of electrons of lower energies (curves 5–7) at  $t > 2 \times 10^{-2}$  s. In this case, the energy density of Langmuir waves approaches the background values (Fig. 4). The length of the region with an increased energy level of Langmuir waves is  $10^7$ – $10^8$  cm. A similar size of the turbulent region was obtained by Kudryavtsev et al. (2019) when they considered the stationary problem. This region of the loop with Langmuir turbulence will generate radio emission (e.g., Zaitsev and Stepanov, 1983).

### 3. CONCLUSIONS

The spatio-temporal dynamics of fast electrons and Langmuir waves in a flare plasma under pulsed acceleration of fast electrons was considered. It was shown that the faster penetration of fast electrons and the



**Fig. 3.** Time dependence of the energy density of Langmuir waves at various distances from the place of acceleration of electrons in a flare plasma.



**Fig. 4.** Energy density distribution of Langmuir waves in flare plasma for different moments of time.

effective deceleration of slow electrons lead to the continuation of the generation of Langmuir waves in the flare plasma outside the region of quasilinear relaxation of the distribution function. In this case, at a distance of  $\sim 10^6$  cm from the place of fast-electron acceleration, the maximum of the distribution function changes little. The maximum energy density of Langmuir waves reaches  $10^{-2}$  erg/cm<sup>3</sup> at the selected

parameters of plasma and fast electrons. The length of the region with an increased energy level of Langmuir waves is  $10^7$ – $10^8$  cm, and the lifetime of a layer with Langmuir turbulence is about  $\sim 10^{-2}$  s.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

## REFERENCES

- Charikov, Yu.E. and Shabalin, A.N., Hard X-ray generation in the turbulent plasma of solar flares, *Geomagn. Aeron. (Engl. Transl.)*, 2016, vol. 56, no. 8, pp. 1068–1074.
- Diakonov, S.V. and Somov, B.V., Thermal electrons run-away from a hot plasma during a flare in the reverse-current model and their X-ray bremsstrahlung, *Sol. Phys.*, 1988, vol. 116, pp. 119–139.
- Dmitriev, P.B., Kudryavtsev, I.V., Lazutkov, V.P., et al., Solar flares registered by the IRIS spectrometer onboard the CORONAS-F satellite: Peculiarities of the X-ray emission, *Sol. Syst. Res.*, 2006, vol. 40, no. 2, pp. 142–152.
- Grognard, R.J.-M., Deficiencies of the asymptotic solutions commonly found in the quasilinear relaxation theory, *Aust. J. Phys.*, 1975, vol. 28, pp. 731–753.
- Hamilton, R.J. and Petrosian, V., Generation of plasma waves by thick-target electron beams and the expected radiation signature, *Astrophys. J.*, 1987, vol. 321, pp. 721–734.
- Ivanov, A.A. and Rudakov, L.I., Quasilinear relaxations dynamics of a collisionless plasma, *Sov. Phys. JETP*, 1967, vol. 24, no. 5, pp. 1027–1034.
- Kaplan, S.A. and Tsytovich, V.N., *Plazmennaya astrofizika* (Plasma Astrophysics), Moscow: Nauka, 1972.
- Kontar, E.P., Ratcliffe, H., and Bian, N.H., Wave-particle interactions in non-uniform plasma and the interpretation of hard X-ray spectra in solar flares, *Astron. Astrophys.*, 2012, vol. 539, p. A43.
- Kudryavtsev, I.V. and Charikov, Yu.E., Kinetics of fast electrons in ion-acoustic waves in the turbulent plasma of solar flares, *Sov. Astron.*, 1991, vol. 35, no. 4, pp. 409–414.
- Kudryavtsev, I.V. and Charikov, Yu.E., Bremsstrahlung of relativistic electrons accelerated in solar flares: The intensity and degree of polarization, *Tech. Phys.*, 2012, vol. 57, no. 10, pp. 1372–1379.
- Kudryavtsev, I.V. and Kaltman, T.I., Influence of the angular distribution of Langmuir waves on the directivity of radio emission at double plasma frequency, *Geomagn. Aeron. (Engl. Transl.)*, 2020, vol. 60, no. 8, pp. 1122–1125.
- Kudryavtsev, I.V. and Kaltman, T.I., On the influence of Langmuir wave spectra on the spectra of electromagnetic waves generated in solar plasma with double plasma frequency, *Monthly Notices of the Royal Astronomical Society*, 2021, vol. 503, pp. 5740–5745.
- Kudryavtsev, I.V., Kaltman, T.I., Vatagin, P.V., and Charikov, Yu.E., Dynamics of fast electrons in an inhomogeneous plasma with plasma beam instability, *Geomagn. Aeron. (Engl. Transl.)*, 2019, vol. 59, no. 7, pp. 838–842.
- Melnikov, V.F. and Filatov, L.V., Conditions for whistler generation by nonthermal electrons in flare loop, *Geomagn. Aeron. (Engl. Transl.)*, 2020, vol. 60, no. 8, pp. 1126–1131.
- Melnikov, V.F., Charikov, Yu.E., and Kudryavtsev, I.V., Spatial brightness distribution of hard X-ray emission along flare loops, *Geomagn. Aeron. (Engl. Transl.)*, 2013, vol. 53, no. 7, pp. 863–866.
- Melrose, D.B., *Instabilities in Space and Laboratory Plasmas*, Cambridge: Cambridge Univ. Press, 1986.
- Nocera, L., Skrynnikov, Yu.I., and Somov, B.V., Hard X-ray bremsstrahlung produced by electrons escaping a high-temperature thermal source in solar flare, *Sol. Phys.*, 1985, vol. 97, pp. 81–105.
- Ratcliffe, H., Kontar, E.P., and Reid, A.S., Large-scale simulations of type III radio bursts: Flux density, drift rate, duration, and bandwidth, *Astron. Astrophys.*, 2014, vol. 572, p. A111.
- Reznikova, V.E., Melnikov, V.F., Shibasaki, K., et al., 2002 August 24 limb flare loop: Dynamics of microwave brightness distribution, *Astrophys. J.*, 2009, vol. 697, pp. 735–749.
- Samarskii, A.A., *Teoriya raznostnykh skhem* (Theory of Difference Schemes), Moscow: Nauka, 1989.
- Stepanov, A.V. and Tsap, Y.T., Electron-whistler interaction in coronal loops and radiation signatures, *Sol. Phys.*, 2002, vol. 211, pp. 135–154.
- Tsytovich, V.N., *Teoriya turbulentnoi plazmy* (Theory of Turbulent Plasma), Moscow: Atomizdat, 1971.
- Zaitsev, V.V. and Stepanov, A.S., The plasma radiation of flare kernels, *Sol. Phys.*, 1983, vol. 88, pp. 297–313.
- Zharkova, V.V., Brown, J.C., and Syniavskii, D.V., Electron beam dynamics and hard X-ray bremsstrahlung polarization in a flaring loop with return current and converging magnetic field, *Astron. Astrophys.*, 1995, vol. 304, pp. 284–295.
- Zharkova, V.V., Kuznetsov, A.A., and Siversky, T.V., Diagnostics of energetic electrons with anisotropic distributions in solar flares, *Astron. Astrophys.*, 2010, vol. 512, p. A8.
- Zheleznyakov, V.V. and Zaitsev, V.V., On the theory of type III solar radio bursts, *Astron. Zh.*, 1970, vol. 47, no. 1, pp. 60–75.