Features of Turbulence Excited by Pulsed High-Frequency Pump in a Magnetoplasma

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Turbulence developed in a magnetoplasma modified by a high-power high-frequency pulse fed to a loop antenna is discovered and studied on the large-scale KROT plasma device. Turbulence is manifested in the excitation of the electron density and magnetic field pulsations, deep self-modulation of the pump wave, and modulation of probe waves passing through the modified plasma region. The space–time characteristics of turbulence are determined using correlated plasma density measurements by a pair of miniature microwave resonator probes and a magnetic probe. It is established that turbulence is excited only in the transparency band of the dense magnetoplasma to electromagnetic radiation: turbulent perturbations of the density and magnetic field exist during pumping at frequencies lower than the electron cyclotron frequency and are absent at pumping frequencies exceeding the electron cyclotron frequency.

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Turbulent phenomena that are developed in plasma in intense high-frequency (HF) fields have been studied for more than 60 years in connection with the need to solve the problems of plasma heating in nuclear fusion devices and to explain the features of the propagation of intense radio waves in near-Earth space [1]. In particular, the effects of the generation of artificial ionospheric turbulence by radiation from terrestrial and satellite radio transmitters are of great interest [2–5]. Artificial ionospheric turbulence is manifested in the excitation of multiscale perturbations of plasma parameters and the generation of intense electromagnetic noise. The generation mechanisms of artificial ionospheric turbulence and its properties are still incompletely clear because the external parameters are variable, initial conditions are diverse, and experimental data obtained either remotely (e.g., by radio transmission methods [6] and radio wave scattering [7]) or in rare satellite [8] or rocket [9] measurements are limited.

The simulation of space plasma phenomena in laboratory facilities, which is based on similarity transformations, is considered as an efficient approach to study these phenomena [10]. The main advantages of the laboratory simulation of artificial ionospheric turbulence are, first, the possibility of repeated reproduction of effects with a necessary variation of the conditions for their occurrence in the controlled environment and, second, the possibility of direct (in situ) measurements of turbulence parameters in the region of its generation using a wide set of laboratory diagnostic tools. Examples of the laboratory simulation of the magnetoplasma turbulence in intense HF fields can be found in [11–13]. In [14], turbulence excited by an HF pulse in a laboratory plasma was described, which resembles that observed in active ionospheric experiments. This work presents the results of detailed experimental studies of the properties of this turbulence.

The experiments were carried out on a large-scale KROT plasma device (Fig. 1). The magnetoplasma was created by a pulsed HF inductive discharge (5 MHz, τ = 1 ms) in argon at a pressure of \( p = 3 \times 10^{-4} \text{ Torr} \) and decayed with a characteristic time of several milliseconds. The ambient magnetic field was \( B_0 = 45–180 \text{ G} \). The length and diameter of the plasma column were 4 and 1 m, respectively. The maximum plasma density at the time of the discharge was \( N_e \approx 10^{12} \text{ cm}^{-3} \), and the unperturbed electron and ion temperatures were \( T_e = 0.5–2 \text{ eV} \) and \( T_i \leq 0.5 \text{ eV} \), respectively. The KROT plasma device operated in a repetitively pulsed mode, and the discharge was ignited once every 20 s. The experiments were carried out in the decaying plasma after turning off the HF generators, when its density decreased to \( N_e = (3–6) \times 10^{11} \text{ cm}^{-3} \). The electron plasma and electron cyclotron frequencies in the experiment under unperturbed conditions were \( f_{pe} \sim 6 \text{ GHz} \) and \( f_{ce} = 0.13–0.5 \text{ GHz} \), respectively. Thus, their ratio \( f_{pe}/f_{ce} \approx 10–40 \) qualitatively corresponded to the conditions in the region of
the F-layer maximum of the mid-latitude ionosphere (where $f_{pe}/f_{ce} \approx 2–8$). The electron–ion collision frequency $v_{ei} \approx 3 \times 10^6$ s$^{-1}$ exceeded the electron–neutral collision frequency $v_{en} \approx 6 \times 10^5$ s$^{-1}$. The mean free path of strongly magnetized ($v_{ei}/(2\pi f_{ce}) \leq 4 \times 10^{-3}$) electrons under typical conditions was $\lambda_{ei} \approx 35$ cm and significantly exceeded their gyroradius $\rho_e = 0.3–1$ mm. The ions in the experiment can be considered as weakly magnetized: their mean free path $\lambda_{in} \approx 10$ cm was about the ion gyroradius $\rho_i = 5–15$ cm.

The HF pump pulse with a duration of $\tau_{pump} = 1$ ms and a frequency of $f_{pump} = 158$ MHz was fed to a circular loop antenna with a diameter of $D = 70$ mm, the plane of which was perpendicular to the magnetic field. The center of the antenna is taken in this work as the origin of the Cartesian coordinate system where the $x$ axis is directed along the external magnetic field, the $y$ axis is horizontal, and the $z$ axis is vertical (see Fig. 1a). A power amplifier with several transistor cascades and a terminal tube cascade was used as a source of HF pumping. The pump antenna circuit included a set of filters that suppressed out-of-band spectral components, a matching stub, and a ferrite valve that protected the amplifier output circuits from the reflected wave. The level of the HF power supplied to the antenna (taking into account the losses on all elements of the path) could change in a controlled manner in the range of $P = 25–300$ W. Depending on the $B_0$ value, the pump signal corresponded to either the whistler frequency range ($f_{pump} < f_{ce} < f_{pe}$) or the plasma evanescence band for electromagnetic radiation ($f_{ce} < f_{pump} < f_{pe}$). In the experiment, a weakly collisional regime of interaction of the HF field with the plasma was implemented: $v_{ei}/(2\pi f_{pump}) \leq 3 \times 10^{-2}$.

Plasma density measurements, including background values and turbulence-induced perturbations, were carried out with a pair of probes with miniature microwave cavities [15] with resonant frequencies of $f_{01} = 8.304$ and 7.595 GHz, moving along the $x$ and $y$ coordinates in the $z = 3$ and 7 cm cross sections (see Fig. 1a). The probe signal processing procedure proposed in [16] makes it possible to reconstruct the dynamics of the density together with its perturbations in one “shot” of the experimental setup for the known parameters of the microwave probe. The principle of the operation of hairpin microwave resonator probes allows one, first, to separate perturbations of the plasma density from perturbations of other parameters, primarily the electron temperature $T_e$ and the ambient magnetic field $B_0$, and, second, to confidently detect variations $\delta N_e(t)$ with a relative level on the order of and less than 1% from the average. A pair of microwave probes, providing a correlation analysis of density perturbations at different points in space, was used for the first time.

To detect low-frequency fluctuations of the magnetic field, a six-turn magnetic probe with a diameter of 20 mm was used in an electrostatic shield, which was covered with a dielectric layer to prevent possible nonlinear effects on the space charge layer near its surface [17]. Test waves with a frequency of $f_{test}$ 

![Fig. 1.](image-url)
49 MHz, which always corresponded to the whistler band under experimental conditions \(f_{\text{test}} < f_{\text{ce}}\), were emitted and received by single-turn loop antennas with diameters of 20, 30, and 70 mm mounted on one side of the pump antenna and on opposite sides of it. The power supplied to the antenna to emit the test wave did not exceed 20 mW. The electron temperature was measured using a Langmuir probe.

Experiments showed that the pump pulse heats electrons, and the corresponding thermal diffusion plasma redistribution results in the formation of an irregularity, i.e., a depleted electron density duct extended along the magnetic field [14]. The plasma redistribution dynamics under the action of a 50 W pump pulse is shown in Figs. 1b and 1c. A slightly asymmetric density distribution \(N_e\) along the transverse coordinate with respect to the axis \(x = 0\) is due to the configuration of the plasma generating system and insignificantly affects the results obtained. At the power used, the plasma density in the heated magnetic flux tube during the exposure to the HF pulse decreases by more than an order of magnitude with respect to the background value. Turbulence studied in this work is developed in the duct. This turbulence is manifested in low-frequency pulsations of the electron density and magnetic field in the heated region of the plasma, self-modulation of the pump pulse, and modulation of test waves passing through the modified region.

The dynamics of the development of the electron density duct and turbulence in it is well illustrated by the envelope of the pump signal received in the plasma (Fig. 2). A smooth increase in the amplitude of the HF field at 100–150 μs from the beginning of the pulse corresponds to the heating of the plasma and the establishment of the ducted propagation regime of the pump wave in the beginning of the formation of the duct (see Fig. 1c). After some time, depending on the HF power level, the pump self-modulation occurs because of plasma turbulence developed in the duct. Turbulent perturbations are developed in a well heated \((T_e > 3 \text{ eV})\) plasma with the electron density of \(N_e < 10^{11} \text{ cm}^{-3}\). The higher the pump power, the faster the plasma is displaced from the heated flux tube and, accordingly, the earlier turbulence is developed. The amplitude modulation is quite deep (up to 100%), is irregular in time, and is not reproduced from one “shot” of the setup to another, which is consistent with the concept of plasma perturbations as turbulence.

Figure 3 shows a typical signal from a microwave resonator probe along with the envelopes of the HF pump and test waves passing through the turbulent region of the plasma near the trailing edge of the pump pulse. We recall the principle of measuring time-varying perturbations of the plasma density by a microwave resonator probe. According to [15], if a microwave resonator probe is excited by a cw signal at a frequency \(f\) exceeding the resonant frequency of the probe in the absence of the plasma \(f_0\), then slow changes in the plasma density, which are due to its decay or diffusion redistribution under heating, lead to a probe response in the form of a resonance curve \(A_{\text{VHF}}(t)\), the maxima of which correspond to the time of the onset of resonance \(f^2 = f_0^2 + f_{\text{osc}}^2(t)\). In Fig. 3a, the signal from the microwave probe has two resonant peaks. The first peak corresponds to the stage of a heating-induced monotonic decrease in the plasma density in the duct, and the second corresponds to a monotonic increase in the plasma density during the relaxation of the duct (Fig. 3b). If, against the background of “slow” density changes, there are “fast” time-varying fluctuations, as, e.g., during the development of turbulence, then the resonance curve is modulated in time. In Fig. 3a, the turbulence-induced modulation of the probe signal is clearly visible at the first resonant peak during the pump pulse and is absent at the second peak after the end of pumping.

Pulsations caused by turbulence with the same characteristic periods of about 1 μs and higher are observed in envelopes of HF signals, and the pump and test waves are modulated in a similar way. After the end of the pump pulse, the modulation of the test wave disappears in a time of about 50 μs (Fig. 3d). For comparison, the characteristic cooling times of electrons in the modified plasma region and relaxation of a large-scale irregularity of the electron density (duct)
are 500 μs and 1 ms, respectively, i.e., significantly longer.

A specially performed calibration allows us to relate the instantaneous amplitudes of signals from microwave probes to the absolute values of the electron density at the same time on the slopes of the resonance curve [16]. Examples of waveforms of turbulent density perturbations, reconstructed in particular realizations during synchronous measurements by microwave probes at two points in space, are shown in Fig. 4a. In the cases where microwave probes spaced along the longitudinal coordinate are located on the same magnetic field line, the density perturbations recorded by them correlate well, especially in slow variations with periods larger than 10 μs. Across the magnetic field, the correlation scale of turbulent density perturbations is Δx ≈ 1 cm; the magnetic probe is mounted at a distance of Δz = 3 cm from the pump antenna; the microwave probe at a distance of Δz = 7 cm from the antenna; B_0 = 135 G and P = 150 W.

Figure 4b shows the waveforms of low-frequency perturbations of the magnetic field. Turbulent variations of the magnetic field are also distributed quite uniformly over the duct cross section and, together with electron density perturbations, decrease toward the edge of the duct (y ≈ 5 cm).
caused by transverse currents and plasma pressure variations.

The waveforms of the transverse component of the magnetic field perturbations ($\delta B_z$) associated with parallel electric currents correlate with turbulent density perturbations. The waveforms $\delta N_e(t)$ and $\delta B_z(t)$ are close to each other up to peak-to-peak coincidence for variations with characteristic periods $\delta t \geq 10 \mu s$ when magnetic and microwave probes on close field lines with the transverse spacing of $\Delta x, \Delta y \leq 1$ cm are installed. Thus, density perturbations and excited field-aligned electric currents are closely related to each other.

All diagnostics give similar data on the predominant periods of turbulent plasma perturbations. The turbulence spectrum is continuous, and it is limited from above by the frequency $f_{\text{LH}}$. For typical experimental parameters, the frequency band in which the turbulence is developed lies below the frequency of the lower hybrid resonance $f_{\text{LH}}$ and ion plasma frequency $f_{\text{pi}}$: $F_{\text{max}} < f_{\text{LH}} \sim 1$ MHz $< f_{\text{pi}} \sim 10$ MHz.

Another important property of the turbulence is that it is developed only if the magnetoplasma is transparent to radiation at a frequency of $f_{\text{pe}}$. We recall that a magnetoplasma with an electron density $N_e$, corresponding to the fulfillment of the condition $f_{\text{pe}} \ll f_{\text{ce}}$, is transparent to electromagnetic waves with frequencies $f < f_{\text{ce}}$; for the waves with frequencies $f_{\text{ce}} < f < f_{\text{pe}}$, the plasma is nontransparent. At the given frequency $f_{\text{pump}}$, both modes of interaction of the HF field with plasma can be implemented by varying the magnetic field $B_0$. The measured parameters of plasma turbulence at the given frequency $f_{\text{pump}}$ and various electron cyclotron frequencies $f_{\text{ce}}$ are shown in Fig. 6. In the evanescence band, the entire energy of the HF pulse supplied to the antenna is concentrated in its near-field region. In this case, plasma electrons are heated in a flux tube resting on the antenna, a depleted density duct is formed, and the effect of waveguide propagation of the test whistler wave in the duct is observed, for which the plasma remains transparent. However, although the electrons are sufficiently heated and the plasma density profile is modified owing to thermal diffusion in the same way as under pumping in the transparency band, turbulence is not developed.

Fig. 5. (a) Transverse profiles of the average value and amplitude of turbulent density perturbations $800 \mu s$ after the start of the pump pulse in the $z = 3$ cm cross section; $B_0 = 135$ G, $P = 50$ W. (b) Transverse profiles of turbulent perturbations of the magnetic field ($B_z$ and $B_y$ components) in the $z = 29$ cm cross section with respect to the plane of the pump antenna; $B_0 = 135$ G, $P = 150$ W.

Fig. 6. Cyclotron frequency dependences of the rms amplitudes of turbulent perturbations of (1) the magnetic field $2\delta B$ (in milligauss) and (3) the density $\delta N_e$ (in units of $10^8$ cm$^{-3}$), as well as (2) the mean-square amplitude of the pump signal recorded in plasma ($A_{\text{pump}}^2$) (in arbitrary units), measured $800 \mu s$ after the beginning of the pump pulse at distances of $z = (1) 29$, (2) 7, and (3) 22 cm from the plane of the pump antenna at $P = 150$ W.
duction of an additional mechanism for the loss of the HF energy due to the buildup of turbulence. All the above properties suggest that the source of turbulence is not the perturbation of the plasma parameters as a whole or the appearance of density gradients or fluxes of charged particles, but the HF wave field itself. The specific mechanism of turbulence generation will be determined in further studies.

At this stage, some conclusions regarding the structure of turbulence can be drawn from the comparison of the probe measurements of density fluctuations and magnetic field perturbations. As mentioned above, the density irregularities are field-aligned and have transverse scales of about 1 cm. It is reasonable to assume that the characteristic scale of modulation in the direction transverse to the magnetic field is the same for parallel currents. Using Ampère’s law, the drift velocity of the electrons that form the current can be estimated from magnetic measurements. The estimate looks like \( \delta_x = eN_c v_e \sim c \delta B_y / 4\pi \delta x \), where \( e \) is the elementary charge, \( v_e \) is the longitudinal electron velocity, and \( c \) is the speed of light in vacuum. For typical parameters of plasma perturbations in a duct \( (N_e = 3 \times 10^{10} \text{ cm}^{-3}, T_e = 3 \text{ eV}, \delta B_y \sim 5 \text{ mG}, \Delta x \sim 1 \text{ cm}) \), the drift velocity of electrons forming current is \( v_e \sim 10^5 \text{ cm/s} \). This velocity is several times higher than the speed of ion sound \( (V_s = 2.7 \times 10^4 \text{ cm}^{-3}) \), but is much less than the thermal velocity of electrons \( V_{te} = 10^8 \text{ cm/s} \).

It is known that the development and relaxation of narrow irregularities of a magnetoplasma strongly elongated along the magnetic field can occur in the regime of the so-called “unipolar” transfer with the excitation of eddy electric currents [16]. For example, magnetized electrons leave regions with the increased plasma density along the external magnetic field, weakly magnetized ions move across the magnetic field, and the resulting current circuit is closed through the surrounding (or background) plasma. Owing to the geometric factor (the cross-sectional area of a separate irregularity is significantly less than the area of its side surface), the density of field-aligned currents in the unipolar mode of the development and relaxation of irregularities can significantly exceed the current density across the magnetic field, which is consistent with the measurement results (see Fig. 5b). In addition, the plasma parameters, characteristic transverse scales of irregularities, and the estimated longitudinal electron velocity in this work are close to the results obtained earlier in experiments, where the unipolar plasma redistribution regime was observed explicitly [16]. If we assume that the characteristic longitudinal scale of irregularities is \( \delta z \sim 20 \text{ cm} \), and the transverse one is \( \delta x \sim \delta y \sim 1 \text{ cm} \), then the electrons leave the regions with an increased density along the magnetic field in a time of about 20 \( \mu \)s. Assuming, according to [16], that weakly magnetized ions leave the regions of the increased plasma density across the magnetic field at a speed several times lower than the speed of ion sound, we can estimate the time of ion escape as 10–20 \( \mu \)s, which is close to the electron escape time along the field. The lifetime of irregularities in the plasma density estimated in this way agrees in order of magnitude with the relaxation time of irregularities after the end of the pump pulse (50 \( \mu \)s) obtained from the analysis of the probe wave envelope (see Fig. 3d).

Turbulence, similar to that described in this work, can be developed in active ionospheric experiments conducted with beams of high-power radio waves and with spacecraft onboard radio transmitters. We note that, although turbulent perturbations of the magnetoplasma density under typical experimental parameters is saturated at a level not exceeding 3% of the background in terms of the rms value, self-modulation of the pump wave caused by the development of turbulence is very deep, up to 100%. Thus, the effects of turbulence can significantly reduce the quality of the signal emitted by space-born transmitters. Possible effects of turbulence should be taken into account when planning active space experiments, e.g., those on the impact on the magnetospheric plasma using whistler waves emitted from ionospheric spacecraft [18], including the introduction of restrictions on the duration of radio pulses and their power.

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**CONFLICT OF INTEREST**

The authors declare that they have no conflicts of interest.

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