Dynamics of Plasma-Wave Channels in Magnetized Plasmas

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The article concerns a quasi-nonstationary model of the plasma-wave channel dynamics. Such channels are excited in magnetized plasmas in the so-called resonant conditions when a wave-vector surface is open — for example, in the lower hybrid frequency range.

The plasma-wave channel is a plasma density duct that is elongated along the external magnetic field. It is formed due to ionization of a background plasma or gas in the region of antenna's strong field. The growth of channel is supported by the waves that are radiated by the antenna and propagated inside the channel. Therefore, the plasma-wave channel is a self-consistent and self-sustaining discharge structure. The waves that support the channel are quasi-electrostatic ones under the resonant conditions.

Such plasma-wave channels have been studied for many years both theoretically and experimentally in laboratories and the Earth's ionosphere [1–3]. However, a very important non-stationary problem that concerns the channel growth along the magnetic field has not been studied yet because of the complexity of the self-consistent non-linear system of equations for the radiation field and plasma density.

We use the quasi-electrostatic approximation: $\mathbf{E} = -\nabla\Phi$ ($\mathbf{E}$ and Φ are the complex amplitudes of the electric field $\mathrm{Re}\left(\mathbf{E}\exp(-i\omega t)\right)$ and potential $\mathrm{Re}\left(\Phi\exp(-i\omega t)\right)$, respectively; $\omega = 2\pi f$, f is the radiation frequency). This approximation is correct if a characteristic length of the antenna L is much less than the length of whistler mode λ ($L \ll \lambda$), that is propagated along the magnetic field.

We assume that ionization in the channel is caused by collisions and is impeded by electron attachments. In accordance with stated above, one should write down a self-consistent non-linear system of equations for the electron density N and potential as follows:

$$\frac{\partial N}{\partial t} = D_{\|}\frac{\partial^2 N}{\partial z^2} + D_{\perp}\Delta_{\perp}N + \left(p\,|\nabla\Phi|^2 - \nu_a\right)N + q_{ext}, \qquad (1)$$

$$\mathrm{div}\left(\hat{\varepsilon}(N)\nabla\Phi\right) = -4\pi\kappa_{ext}, \qquad (2)$$

where $D_{\|}$ and $D_{\perp}$ are the coefficients of diffusion along and across the magnetic field, respectively, ν_a is the electron attachment frequency, $p = \nu_a/E_c^2$, E_c is the ionization threshold, q_{ext} is the power of external source of ionization that supports an equilibrium background plasma density ($q_{ext} = 0$ in neutral background gases), κ_{ext} is the volume density of external charge that is turned on at $t = 0$: $\kappa_{ext} = \kappa(\mathbf{r})\theta(t)$ ($\theta(t)$ is the Heaviside step function), $\hat{\varepsilon}(N)$ is an operator of plasma dielectric permittivity.

Obviously, it is impossible to obtain a solution of (1)–(2) so it is essential to make some simplifications.

Firstly, we assume that the channel consists of a stationary, non-stationary, and diffusion regions (Fig. 1). The stationary region originates from a channel formation region and grows along the magnetic field at a group speed of quasi-electrostatic waves $\mathbf{v}_{gr}$. The steady state conditions are satisfied here, i. e. the field amplitude doesn't depend on time in this region. The non-stationary region is actually an ionization front, and one must not neglect time dependence in this region. It is important to notice that its length along the magnetic field is much less than the radius of channel a which is determined by $D_\perp$. The field in the diffusion region is exponentially small, the ionization processes don't take place here. The presence of charged particles here is caused by longitudinal diffusion from the discharge region.

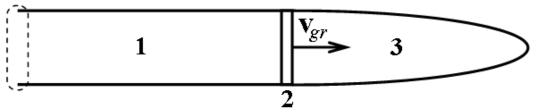

Figure 1: *The stationary (1), non-stationary (2), and diffusion (3) regions of the channel. The formation region is dotted.*

Secondly, we assume that the electron density is approximately constant in space and time in the stationary region. In particular, it follows from the experiments. The corresponding value may be estimated from energy consideration [4].

The electric field in the stationary region has a mode structure (see (2)) and decreases with z because the energy that is transferred by the wave goes for ionization. It is essential to notice that, according to (1), the plasma density is non-uniform in the stationary region. However, the calculations show that the corresponding term is quite small so it doesn't affect the field structure.

The electric field spatial distribution in the stationary region near the ionization front is shown on Fig. 2. The plots correspond to the different moments of time. As one may see, the field is concentrated in the vicinity of characteristics of the hyperbolic operator in (2) that originate from the antenna and reflect from the channel borders into contiguous ones.

Such plasma-wave channels may be used with the purpose of active antenna diagnostics of the near-Earth plasma parameters because they can efficiently excite the electromagnetic waves on a frequency of amplitude modulation of the initial signal that produces a periodic longitudinal current [5]. This allows to consider the plasma-wave channels as LF plasma antennas. Therefore, an analysis of their dynamics and development of the corresponding mathematical

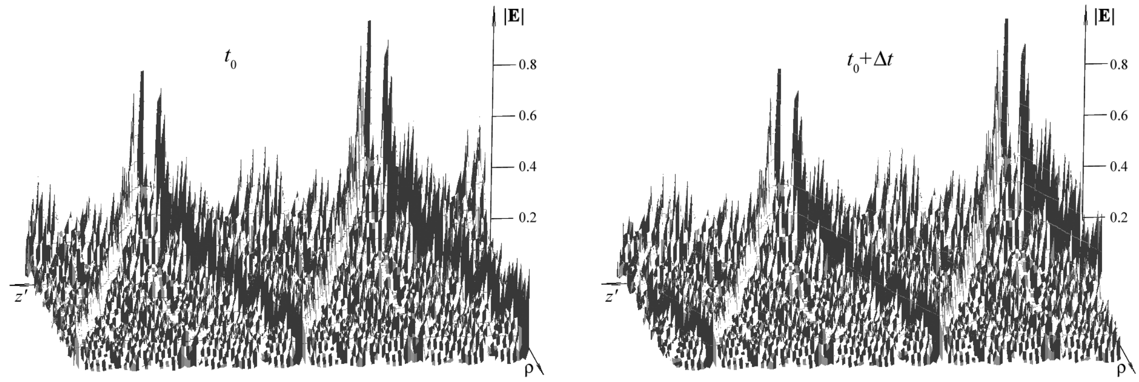

Figure 2: *The field distribution* $|\boldsymbol{E}|/|\boldsymbol{E}_{max}|$ *in the stationary region. The ionization front is not moving in this coordinate system:* z' *is a longitudinal coordinate* ($z'_f - 4a/\mu \leq z' \leq z'_f$, $z' = z'_f$ *is the ionization front position,* $\mu = \sqrt{|\varepsilon/\eta|}$, ε *and* η *are the transversal and longitudinal components of permittivity tensor, respectively),* ρ *is a transversal coordinate* ($0 \leq \rho \leq a$)*. The time difference between the pictures is* $\Delta t = 0.4a/(\mu v_{gr})$.

models are important both for abstract science and such fields as space exploration, telecommunications and navigation systems.

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References

[1] G.A. Markov, V.A. Mironov, A.M. Sergeev, JETP Letters, **29**, 10, p. 617–620 (1979)

[2] I.G. Kondratiev, A.V. Kudrin, T.M. Zaboronkova. Electrodynamics of Density Ducts in Magnetized Plasmas. CRC Press, 288 p. (1999)

[3] P.V. Bakharev, T.M. Zaboronkova, A.V. Kudrin, C.Krafft, PLASMA PHYS REP, **36**, 11, p. 919–930 (2010)

[4] G.A. Markov, L.L. Popova, Yu.V. Chugunov, Technical Physics Letters, **11**, 23, p. 605–607 (1985)

[5] Yu.V. Chugunov, G.A. Markov, JASTP, **63**, 17, p. 1775–1787 (2001)