Gradient-drift instability applied to Hall thrusters

N A Marusov\textsuperscript{1,2,3} , E A Sorokina\textsuperscript{2,3} , V P Lakhin\textsuperscript{2,3} , V I Ilgisonis\textsuperscript{3,4} and A I Smolyakov\textsuperscript{2,3,5}

\textsuperscript{1} Moscow Institute of Physics and Technology, Institutsky lane 9, Dolgoprudny, Moscow, 141700, Russia
\textsuperscript{2} NRC ‘Kurchatov Institute’, 1 Kurchatov Sq., Moscow, 123182, Russia
\textsuperscript{3} Peoples’ Friendship University of Russia (RUDN University), 3 Ordzhonikidze St., Moscow, 117198, Russia
\textsuperscript{4} State Atomic Energy Corporation ROSATOM, 24 Bolshaya Ordynka St., Moscow, 119017, Russia
\textsuperscript{5} University of Saskatchewan, 116 Science Place, Saskatoon, SK S7N 5E2, Canada

E-mail: marusov.na@phystech.edu

Received 12 July 2018, revised 13 September 2018
Accepted for publication 18 September 2018
Published 11 January 2019

Abstract
The stability of gradient-drift waves in a Hall-type plasma thruster is investigated within the framework of two-fluid ideal magnetohydrodynamics. The analysis is based on the dispersion relation, which includes the effects of equilibrium electron current, finite ion flow velocity, electron inertia, electron temperature, magnetic field and plasma density gradients, and also the Debye length effects. The features of unstable modes are calculated along the thruster channel. Three spatially separated areas of instability are revealed: (i) the near-anode region with long-wavelength azimuthal oscillations, (ii) the main part of the acceleration channel with short-wavelength axial modes destabilized by macroscopic ion flow, and (iii) the plume region characterized by short-wavelength oblique waves.

Keywords: drift waves, instabilities, Hall thrusters, electric propulsion, two-fluid MHD, [ExB]-flow, gradient-drift modes

1. Introduction
The operation of a Hall-type plasma thruster exhibits a wide range of oscillations [1]. There are usually three typical frequency bands: \textasciitilde 1–10 kHz, \textasciitilde 100 kHz, and \textasciitilde 1–10 MHz. The low frequency band is traditionally associated with the axial breathing modes [2, 3] and azimuthal rotating spokes [4]. The middle frequency band corresponds to the transient-time oscillations [5]. The high frequency band includes different types of plasma waves and is related both to the high-frequency branch of transient-time oscillations and Rayleigh-type instabilities [1, 6, 7]. The observed fluctuations may be responsible for turbulence and anomalous electron transport across the external magnetic field [8, 9].

The gradient-drift instability is inherent in partially magnetized plasmas immersed in crossed external electric and magnetic fields [10]. In this paper, we study the stability of gradient-drift modes along the thruster channel of classical plasma thruster SPT-100. Our approach is based on the solution of the dispersion relation obtained recently in [11] within the framework of the advanced ideal two-fluid model. It includes the effects of the equilibrium $\mathbf{E} \times \mathbf{B}$ electron current, finite ions velocity, electron inertia, magnetic field and plasma density gradients, and the Debye length effects.

The paper is organized as follows. In section 2 the dispersion law for the gradient drift modes under consideration is introduced. In section 3 the distribution of the employed plasma parameters along the thruster channel is presented. Section 4 is devoted to the numerical solution of the considered dispersion relation. Studies of finite electron temperature effects and the effects of equilibrium ion flow are performed consistently. A comparison of the obtained features of instability with simple analytical expressions from
channel: \((\kappa_n, \kappa_B) = d \ln(n_e, B)/dx\). The perturbations are characterized by the frequency \(\omega\), and by the transverse (with respect to equilibrium magnetic field) wave-vector \(k_z = \sqrt{k_x^2 + k_y^2}\). Due to the geometry used, we call the perturbations with \(k_z \gg k_y\) axial perturbations and perturbations with \(k_z \gg k_x\) azimuthal ones. Below a right-handed coordinate system is used, so that \(V_E = -V_B/B, V_D = -(2cT_e/eB)\kappa_B\), and \(u_e = V_E + V_B\).

Dispersion relation (1) describes electrostatic plasma perturbations in the frequency range between the ion and electron cyclotron frequencies, \(\omega_{Bi} \ll \omega \ll \omega_{Be}\), propagating strictly perpendicularly to the external magnetic field. The first two terms in equation (1) are related to electron inertia and the Debye length effects. The third term corresponds to the response of ions and includes the ion flow velocity, \(v_i\). The last term is due to the electron response. It incorporates the equilibrium electron flow, \(u_e\), and the gradients of plasma density and magnetic field magnitude. In the equation (1) the effects of temperature perturbations and of equilibrium temperature gradient are not included and the cold ion approximation, \(\omega \gg k_z v_{Ti}\) (\(v_{Ti}\) is the ion thermal velocity), is used.

3. Axial profiles of equilibrium plasma parameters

In the classical coaxial Hall thruster the magnetic field increases from the anode region and reaches its maximum at the channel exit. Then it decreases in the plume region. To approximate this behavior, we use the expression from [13]:

\[
B(x) = B_m \exp\left[-\nu_1\left(\frac{x}{d} - 1\right)^2\right].
\]

(2)

Here \(B_m\) is a maximal value of the magnetic field at position \(x = d\) corresponding to the exit plane; \(x = 0\) indicates the position of the anode; \(\nu_1\) is a coefficient characterizing the rate of change of function \(B(x)\).

According to the data from different thrusters studies (see, e.g., [13–15]) the plasma density profile often has the same shape as the magnetic field. It reaches its maximum inside the acceleration channel and rapidly decreases towards the channel exit. Thus, for the plasma density profile we can use the following approximation:

\[
n(x) = n_m \exp\left[-\nu_2\left(\frac{x}{l_i} - 1\right)^2\right].
\]

(3)

where \(n_m\) is a maximal value of the plasma density at some point \(l_i < d\); \(\nu_2\) is a coefficient characterizing the rate of change of function \(n(x)\). Then the parameters \(\kappa_B\) and \(\kappa_n\) linearly depend on \(x\):

\[
\kappa_B(x) = -\frac{2\nu_1}{d}\left(\frac{x}{d} - 1\right), \quad \kappa_n(x) = -\frac{2\nu_2}{l_i}\left(\frac{x}{l_i} - 1\right).
\]

(4)

2. Dispersion relation for gradient-drift waves

For the description of a Hall-type plasma thruster geometry we consider a simplified slab model in Cartesian coordinates \([x, y, z]\)—see figure 1. The \(z\)-coordinate corresponds to the radial direction of the predominant magnetic field \(B = Be_z\). The \(x\)-coordinate corresponds to the axial direction along the thruster channel, i.e., it is the direction of the external electric field \(E = Ec\), and of the accelerated ions velocity \(v_i = v_i e_i\); in general all equilibrium plasma parameters depend on \(x\). The \(y\) coordinate is in the azimuthal direction coinciding with the direction of stationary electron flow \(u_e = u_e e_y\), which is a superposition of \([E \times B]\)-drift velocity in crossed electric and magnetic fields, \(V_E = (c/B^2)(E \times B)\), and gradient drift velocity in inhomogeneous magnetic field, \(V_D = (2cT_e/eB^3)(B \times \nabla B)\). Hereafter, the CGS units are used; \(e\) is the speed of light, \(c\) is the elementary charge, \(T_e\) is the temperature of electrons.

To study the stability of gradient-drift waves we use the dispersion relation, which follows from the more general one\(^6\) derived in [11]:

\[
1 + \frac{\omega_{pe}^2}{\omega_{Be}^2} = \frac{\omega_{pi}^2}{(\omega - k_z v_i)^2} - \frac{\omega_{pe}^2}{\omega_{Be}^2 (\omega - k_z u_e)} = 0.
\]

(1)

Here \(\omega_{pe(e,i)} = \sqrt{4\pi n e^2/m_{pe(e,i)}}\) are the electron and ion plasma frequencies; \(\omega_{Be} = eB/m_e c\) is the electron cyclotron frequency; \(m_{pe(i)}\) are the masses of electron and ion, respectively; parameters \(\kappa_e\) and \(\kappa_i\) describe the gradients of plasma density, \(n\), and of magnetic field magnitude along the thruster.

\(^6\) The dispersion relation of [11] also includes the finite electron Larmor radius (FLR) effects. The negligibility of FLR effects for typical parameters of the Hall plasma thruster is shown in [12].

Figure 1. Geometry of a Hall-type thruster. Here \(d\) is the length of the acceleration channel.

[12] is given. In section 5 we briefly summarize and discuss the results of the paper.
For further analysis we set $\nu_1 = 2.5$, $\nu_2 = 4$ and $l_2 = 0.62d$. For these values the profiles (2) and (3) are in good qualitative agreement with the smoothed profiles in the SPT-100 thruster presented in [14]. The considered profiles of $B(x)$, $n(x)$, $\kappa_B(x)$ and $\kappa_n(x)$ are shown in figure 2.

To describe the equilibrium electric field we introduce the electrostatic potential $\Phi$ in the form:

$$\Phi(x) = \Phi_m a_1 \left( \arccot \left[ \frac{x}{l_2} \right] - a_2 \right),$$  \hspace{1cm} (5)

where $\Phi_m$ is the potential on the anode; $l_2$ corresponds to some point inside the acceleration channel ($l_2 < d$), where the electric field reaches its maximal value; $a_1 = 1/(\arccot[-\nu_1] - a_2)$ is a normalizing factor; $\nu_1$ is a coefficient characterizing the rate of change of function $\Phi(x)$ and $a_2$ is a parameter which allows us to set a minimal value of the potential behind the channel exit. Then the profile of axial electric field ($E = -\partial \Phi / \partial x$) is

$$E(x) = E_m \sqrt{\left\{ 1 + \nu_1^2 \left( \frac{x}{l_2} - 1 \right)^2 \right\}},$$  \hspace{1cm} (6)

In a uniform magnetic field ($\kappa_B = 0$) and neglecting equilibrium ion flow ($v_i = 0$) condition (7) reduces to the well-known instability criterion by Simon and Hoh [16, 17]:

$$E \cdot \nabla n > 0.$$  \hspace{1cm} (7)

In the general case the gradient-drift instability is due to a combination of electron $E \times B$ and magnetic drift flows and the ion flow parallel to the electric field (the instability drive) and the inhomogeneity of plasma density.
and magnetic field magnitude in the direction perpendicular to the magnetic field (the instability trigger).

Typical operational regimes of Hall plasma thrusters are characterized by high values of electron current \(u_e\) up to \(10^8\ \text{cm}\ s^{-1}\). In [12] it is shown that when equilibrium ion flow is neglected the most unstable modes are purely azimuthal ones and in the limit of strong instability drive \((k_\perp u_e \gg \omega_{lb})\), \(\omega_{lb} = (\omega_{Be}\omega_{Bi})^{1/2}\) is the lower-hybrid frequency) their main features can be described by the following expressions:

\[
\begin{align*}
    k_x^* &= \frac{\omega_{lb}}{\sqrt{\omega_{Bi}}} \sqrt{\frac{(\kappa_n - 2\kappa_{eh})}{u_e}}, \\
    \omega^* &= \frac{\omega_{lb}}{2} \left( -\frac{u_e(k_n - 2\kappa_{eh})}{\omega_{Bi}} \right)^{1/6}, \\
    \gamma^* &= \frac{\sqrt{3}}{2} \frac{\omega_{lb}}{\omega_{Bi}} \left( -\frac{u_e(k_n - 2\kappa_{eh})}{\omega_{Bi}} \right)^{1/6}.
\end{align*}
\]

(8)

Here \(k_x^*\), \(\omega^*\) and \(\gamma^*\) are the wave number, frequency and growth rate of the most unstable mode in the spectrum, correspondingly. The sign of wave phase velocity in the azimuthal direction coincides with the sign of equilibrium electron rotation velocity, \(u_e\). For further analysis we fix the sign of \(k_x^*\) assuming that \(k_x^* > 0\). Below, expressions (8) are compared with the results of the direct numerical calculation.

4.1. Plasma with cold electrons

Under the assumption of cold electrons \(T_e \rightarrow 0\) the instability drive is only due to electron \(\mathbf{E} \times \mathbf{B}\)-drift, \(u_e = V_\parallel\), which, for the profiles considered, does not change the sign along the axis. The necessary instability condition (7) in this case takes the simplest form

\[
\kappa_n - 2\kappa_{eh} > 0. \tag{9}
\]

Thus, the region of instability is determined only by the gradients of plasma density and magnetic field. The axial profile of \(\kappa_n = 2\kappa_{eh}\), calculated using (4), is shown in figure 4. The value \(\kappa_n = 2\kappa_{eh}\) decreases with the growth of \(x\) (hereafter \(x\) implies the dimensionless value \(x/d\)) and becomes equal to zero at some axial position \(x_{lb}^* \approx 0.27\)—see the red circle in figure 4. According to (9) the instability occurs only in the region \(x < x_{lb}^*\), i.e., in the near-anode region.

The features of the revealed instability—frequencies \(f^* = \omega^*/2\pi\), growth rates \(\gamma^*/2\pi\), and wave numbers \(k_x^*\)—calculated by solving equation (1) are shown in figure 5. The instability is characterized by the long wavelength; its frequency and growth rate are of the order of \(\omega_{lb}\). The most unstable mode in the channel is localized at \(x \approx 0.21\); its growth rate is \(\gamma^*/2\pi \approx 730\ kHz\), its frequency is \(f^* \approx -450\ kHz\), and the wave number is \(k_x^* \approx 2.6\ \text{rad cm}^{-1}\). The negative sign of frequency means that the wave propagates in the direction of \(\mathbf{E} \times \mathbf{B}\)-drift. The obtained features of instability are in good agreement with analytical approximations (8)—see the analytical curves in figure 5.

![Figure 4](image)

Dependence of \(\kappa_n - 2\kappa_{eh}\) on \(x/d\). Green color indicates the stability region in the model with cold electrons, red color indicates the unstable near-anode region.

![Figure 5](image)

Dependencies of the instability features on \(x/d\) in the near-anode region in the model with cold electrons: (a) frequencies \(f^*\) (dashed lines) and growth rates \(\gamma^*/2\pi\) (solid lines); (b) wave numbers \(k_x^*\). Analytical curves are calculated using equation (8).
4.2. Plasma with hot electrons

Taking into account the finite electron temperature effects, the instability drive also includes the magnetic drift term, \( u_e = V_E + V_D \), and the necessary instability condition takes the form:

\[
(V_E + V_D)(\kappa_a - 2\kappa_b) < 0.
\] (10)

To study the instability behavior we use the temperature profile obtained numerically in [14] and approximate it by a simple analytical expression:

\[
T_e(x) = T_{e}^{\text{max}} \exp \left[ -u_e \left( \frac{x}{l_b^*} - 1 \right)^2 \right] + T_{e}^{\text{min}}. \quad (11)
\]

For \( \nu_e = 8 \), \( l_b = 0.92d \), \( T_{e}^{\text{max}} = 21 \text{ eV} \) and \( T_{e}^{\text{min}} = 4 \text{ eV} \) dependence \( T_e(x) \) is in good qualitative agreement with the original profile from [14]—see figure 6.

The profiles of velocities \( V_E, V_D \) and \( V_E + V_D \) for the assumed electron temperature profile are shown in figure 7(a); figure 7(b) represents the instability regions in accordance with necessary instability condition (10). At \( x < 1 \) \( V_E \) and \( V_D \) are of the same sign, at \( x > 1 \) \( V_D \) changes the direction due to the change of the direction of magnetic field gradient. The electron magnetic drift results in the appearance of the second instability region—in the plume region at \( x > x_b^{\text{out}} \approx 1.43 \). The axial position \( x_b^{\text{out}} \) is defined by the condition \( V_E + V_D = 0 \). At this position the stationary electron velocity \( u_e \) changes its sign because at \( x > x_b^{\text{out}} \) \( V_D \) exceeds \( V_E \). In the near-anode region the finite electron temperature effect results in the significant increase of instability drive—see the difference between \( V_E \) and \( V_E + V_D \)-curves in figure 7(a). The boundary of the near-anode instability, \( x_b^{\text{in}} \), remains the same as in the model with cold electrons: it is determined only by the function \( \kappa_a - 2\kappa_b \) and does not depend on the value of \( V_D \).

A comparison of the instability features in the near-anode region for models with cold and hot electrons is shown in figure 8. The differences between the instability features are as follows: the finite electron temperature effects result in the increase of both the growth rate and frequency—on average by \( \sim 10^9 \text{ kHz} \) and \( \sim 48 \text{ kHz} \), correspondingly. The most unstable mode is located at \( x \approx 0.21 \) and has the growth rate \( \gamma^* / 2\pi \approx 830 \text{ kHz} \) and the frequency \( f^* \approx -505 \text{ kHz} \). The wavelength of unstable modes changes the most. On average the wavenumber decreases by \( \sim 1.4 \text{ rad cm}^{-1} \) and for the most unstable mode it equals \( k_y^* \approx 1.78 \text{ rad cm}^{-1} \). The decrease in the wavenumber with the increase in instability drive is predicted by analytical formula (8).

The features of instability in the plume region at \( x > x_b^{\text{out}} \) are presented in figure 9. The most unstable mode is characterized by the following features: \( x = 1.47 \), \( \gamma^* / 2\pi \approx 605 \text{ kHz} \), \( f^* \approx 396 \text{ kHz} \), and \( k_y^* \approx 46 \text{ rad cm}^{-1} \). The instability in the plume region is characterized by the shorter wavelengths compared to the near-anode instability. The shorter wavelengths of the most unstable modes in the plume region are due to the weaker instability drive (\( u_e = 0 \) at \( x_b^{\text{out}} \)) leading to the increase of \( k_y^* \).
4.3. Influence of the equilibrium ion flow

To study the influence of finite ion flow velocity we use an assumption of the ballistic ion acceleration. Then the dependence of \( v_i \) on the \( x \)-coordinate is given by the relation:

\[
v_i(x) = \sqrt{\frac{2e}{m_i}(\Phi_m - \Phi(x))}.
\]  

The obtained profile of \( v_i \) is shown in figure 3.

The numerical solution of equation (1) shows that in the near-anode region \((x < x_b^{in})\) the finite ion flow velocity does not affect the instability behavior due to the smallness of \( v_i \) in this area—see figure 10. The most unstable modes in this region remain the purely azimuthal ones (see figure 10(c), which shows the growth rate of instability in the \( k_x-k_y \)-plane at \( x = 0.21 \)) and their features are the same as described in section 4.2.

It has been shown above that the main part of the acceleration channel \((x_b^{in} \leq x \leq x_b^{out})\) is stable when the ion flow effects are neglected. However, even the small ion flow velocity \(|v_i| \ll |u_e|\) leads to the destabilization of this area. The features of instability in the main part of the acceleration channel are shown in figures 11(a)–(b). The growth rate and the frequency increase when \( x \) increases from \( x = x_b^{in} \) towards the channel exit \( x = 1 \) and take a wide range of values: \( \gamma^*/2\pi \approx 0.01 - 0.92 \text{ MHz} \) and \( f^* \approx -(0.31 - 3.39) \text{ MHz} \) respectively. The typical range of axial wave numbers is \( k_x^* \approx -9.36 - 15.1 \text{ rad cm}^{-1} \) and \( k_y^* \approx 0 \).

The instability in this part of the channel occurs for the purely axial modes. Its qualitative description can be obtained from the necessary instability condition (7). Taking into account that in the main part of the channel \( \kappa_n - 2\kappa_B < 0 \) and \( u_e < 0 \), we reduce condition (7) to the following form

\[
-k_x^* \geq \frac{|u_e|}{v_i}.
\]  

Since the ion velocity in the considered region is still small, the unstable modes are almost axial ones, \(|k_x| \gg |k_y|\), and their axial \( k_x \) and azimuthal \( k_y \) wave vectors have different
signs. This is demonstrated in figure 11(c), showing the contour plots of the growth rate in the \(k_x-k_y\) plane at \(x = 0.5\). At this position the most unstable mode is characterized by \(k_x^* \approx -15.1 \text{ rad cm}^{-1}\) and \(k_y^* \approx 0.08 \text{ rad cm}^{-1}\).

In the plume region \((x > d)\) the velocities of ions and electrons become comparable \(|v_i| \sim |u_e|\). Thus, in accordance with condition (7), the axial and azimuthal wave numbers become comparable too, \(|k_x| \sim |k_y|\), i.e., the oblique
waves are excited. A direct numerical solution of equation (1) for this region demonstrates a significant impact of the ion flow effects—see figure 12. The most unstable mode in this region is located at \( x \approx 1.22 \) and is characterized by \( \gamma^* / 2\pi \approx 1.28 \text{ MHz}, \ f^* \approx -10.21 \text{ MHz}, \ k^*_{r} \approx -38.6 \text{ rad cm}^{-1}, \) and \( k^*_{\theta} \approx 5.3 \text{ rad cm}^{-1}. \) The contour plots of the growth rates in the \( k_r-k_\theta \) plane at this position are shown in figure 12(c).

5. Summary and discussion

The full picture of gradient-drift instability in the Hall plasma thruster is summarized in figure 13. The acceleration channel can be divided into three spatially-separated areas characterized by different types of unstable oscillations: (i) the near-anode region \( (x < x^0) \) with purely azimuthal long-wavelength oscillations, (ii) the main part of the acceleration channel \( (x^0 < x < d) \) with axial short-wavelength modes, (iii) the plume region \( (x > d) \) with oblique propagating waves.

In the near-anode region the long-wavelength perturbations \( \kappa_r^* \approx 0.01 - 2.1 \text{ rad cm}^{-1} \) with frequencies in the range \( f^* \approx -(295-505) \text{ kHz} \) propagating in \( \mathbf{E} \times \mathbf{B} \)-direction are excited. The mechanism of instability of these oscillations is related to classical azimuthal gradient-drift instability [18], which occurs from the inhomogeneity of plasma density and magnetic field in accordance with the criterion \( d(n/B^2)/dx > 0. \) The features of instability in the near-anode region are well described by analytical expressions (8).

Unstable modes in the main part of the acceleration channel are in the high-frequency range \( f^* \approx -(0.31 - 3.39) \text{ MHz} \). They propagate from anode to cathode and have short wavelengths, \( \kappa_r^* \approx -(9.36 - 15.1) \text{ rad cm}^{-1} \). Axial modes are destabilized by the equilibrium ion flow, however, the mechanism of their excitation distinctly differs from the axial current flow instability [19] existing even at \( k_r = 0. \)

In the plume region \( (x > d) \) unstable waves propagate both in \( \mathbf{x} \) and \( \mathbf{y} \) directions. The wave rotates in the \( \mathbf{E} \times \mathbf{B} \) direction and moves away from the thruster. The unstable modes are characterized by the wide ranges of frequencies \( f^* \approx -(0.01 - 12.16) \text{ MHz} \) and wavelengths, \( \kappa_r^* \approx -(0.2 - 44.3) \text{ rad cm}^{-1} \) and \( \kappa^*_{\theta} \approx 0.7 - 26.1 \text{ rad cm}^{-1}. \) They are also strongly affected by the equilibrium ion flow.

The effects of finite electron temperature and ion flow velocity considered in the paper appear to be crucial for the description of plasma stability in the Hall thruster. It is shown that the commonly used approximation of cold electrons and stationary ions [1, 6, 18, 20, 21] works well only in the near-anode region of the plasma thruster. The electromagnetic effects considered in [18, 20, 21] become important for sufficiently long-wavelength perturbations with \( \kappa^2 \rho^2_e \lesssim \omega^2_e / (1 + \omega^2_{Be}/\omega^2_{pe}) [18] \). For the considered profiles the electromagnetic effects are important only for the perturbations with \( \kappa_r^2 \lesssim 0.2 - 1.8 \text{ rad}^2 \text{ cm}^{-2}. \) Such unstable modes exist only in the very narrow region near \( x^0 \)—see figure 10(b)—therefore, the electromagnetic effects are not of significant interest for the presented study. The results of calculations performed taking into account the finite electron Larmor radius effects [11, 22] differ by less than 10% from the presented results. This small difference is explained by the large
value of electron current (instability drive) in typical operational regimes of the Hall plasma thrusters. The non-ideal effects such as the collisions between electrons and neutral atoms and ionization processes can also be important in Hall thrusters. Such effects are outside of the scope of this paper. The analysis of their influence on fluid-like plasma instabilities can be found, e.g., in [23–27].

Acknowledgments

This work was supported in part by the Russian Science Foundation (Project No 17-12-01470), and was also prepared with support from ‘RUDN University Program 5-100’. VII appreciates the financial support of the Russian Foundation for Basic Research (Grant No 16-02-00640), which provided the results described in section 4.3.

ORCID iDs

N A Marusov https://orcid.org/0000-0002-0763-1505
E A Sorokina https://orcid.org/0000-0002-2735-6918
V I Ilgisonis https://orcid.org/bp0000-0002-4874-3503
A I Smolyakov https://orcid.org/0000-0002-4975-2743

References

[1] Choueiri E Y 2001 Phys. Plasmas 8 1411
[2] Morozov A and Saveljev V 2000 Fundamentals of stationary plasma thruster theory Reviews of Plasma Physics ed B Kadomtsev and V Shafranov vol 21 (New York: Kluver) p 203
[3] Barral S and Peradatzynski Z 2009 Proceedings of the XXXI International Electric Propulsion Conference (Michigan, USA) IEPC-2009-070
[4] Ellison C L, Raiteses Y and Fisch N J 2012 Phys. Plasmas 19 013503
[5] Esipchuck Y, Morozov A, Timlin G and Trofimov A 1974 Sov. Phys. Tech. Phys. 18 928
[6] Litvak A A and Fisch N J 2004 Phys. Plasmas 11 1379
[7] Litvak A A, Raiteses Y and Fisch N J 2004 Phys. Plasmas 11 1701
[8] Keidar M and Beilis I 2006 IEEE Trans. Plasma Sci. 34 804
[9] Lazurenko A, Coduti G, Mazouf hre S and Bonhomme G 2008 Phys. Plasmas 15 034502
[10] Mikhailovskii A B 1974 Theory of plasma instabilities. Volume 2: Instabilities of an Inhomogeneous Plasma (New York: Consultants Bureau)
[11] Lakhin V P, Ilgisonis V I, Smolyakov A I, Sorokina E A and Marusov N A 2018 Phys. Plasmas 25 012106
[12] Lakhin V P, Ilgisonis V I, Smolyakov A I, Sorokina E A and Marusov N A 2018 Phys. Plasmas 25 012107
[13] Boeuf J and Garrigues I 1998 J. Appl. Phys. 84 3541
[14] Heter R, Mikkelides I, Katz I and Goebel D 2007 XLIII AIAA/ASME/SAE/ASEE Joint Propulsion Conference (Cincinnati, OH) 2007–5267
[15] Kronhause I, Kapulkin A, Balabanov V, Rubanovich M, Guelman M and Natan B 2012 J. Phys. D: Appl. Phys. 45 175203
[16] Simon A 1963 Phys. Fluids 6 382
[17] Hoh F C 1963 Phys. Fluids 6 1184
[18] Esipchuck Y V and Timlin G N 1976 Sov. Phys. Tech. Phys. 21 417
[19] Koshkarov O, Smolyakov A I, Romadanov I V, Chapurin O, Umansky M V, Raiteses Y and Kaganovich I D 2018 Phys. Plasmas 25 011604
[20] Tomilin D 2013 Phys. Plasmas 20 042103
[21] Nikitin V D, Tomilin D, Lovtsov A and Tarasov A 2017 Europhys. Lett. 117 45001
[22] Smolyakov A I, Chapurin O, Frias W, Koshkarov O, Romadanov I, Tang T, Umansky M, Raiteses Y, Kaganovich I D and Lakhin V P 2017 Plasma Phys. Control. Fusion 20 014041
[23] Escobar D and Atho E 2015 XXXIV International Electric Propulsion Conference (Kobe, Japan) IEPC-2015-371
[24] Litvak A A and Fisch N J 2001 Phys. Plasmas 8 648
[25] Singh S, Malik H K and Nishida Y 2013 Phys. Plasmas 20 102109
[26] Malik H K and Singh S 2013 Phys. Plasmas 20 052115
[27] Singh S and Malik H K 2012 J. Appl. Phys. 112 013307

Figure 13. The features of unstable modes along the channel of the plasma thruster.