Theoretical Models of Suppression of Instabilities in Hall Thruster by Shear of Magnetic Field

IEPC-2019-A-470
Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

A. Kapulkin[1]
Asher Space Research Institute of Technion, Haifa,32000, Israel

Abstract: In the paper, influences of the magnetic field shear on the instability in the near-anode region of the conventional Hall thruster (HT) and on the instability in the near-anode cavity of the CAMILA HT are theoretically studied These instabilities can lead to the unfavorable potential distribution in areas of their localization. It is shown that the acceptable changes of the magnetic field lines direction should result in significant reducing the growth rate of the instabilities.

I.Introduction

ONE of the major problems faced by the developers of Hall thrusters is the optimization of the distribution of the electric field in the acceleration channel in order to ensure the maximal efficiency and required lifetime of the thruster. Taking into account the fact that the distribution of the electric field in the acceleration channel is largely determined by the amplitudes of some plasma perturbations in the thruster, the problem of controlling the instabilities that excite these perturbations is of considerable interest. Among the instabilities which affect strongly the distribution of the electric field, the next two occupy an important place: 1) relatively low-frequency instability in the near anode region of conventional Hall thrusters, where the drift velocity due to a finite temperature of electrons and a non-uniformity of the magnetic field can exceed the electrical drift velocity[1,2], 2) relatively low-frequency instability in the anode cavity of the CAMILA Hall thruster[3-7].

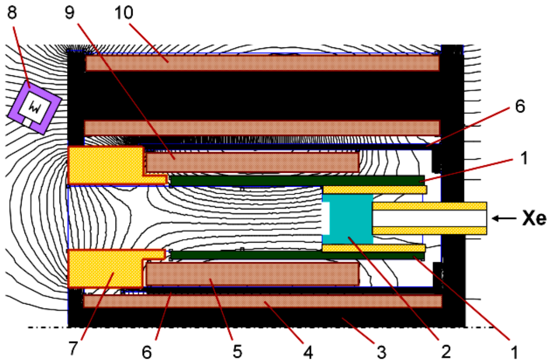
The near-anode region of the conventional Hall thruster, defined as the area of the acceleration channel between the anode and the zone of intense ionization, occupies a significant fraction of the channel – up to half of its length. Even for this reason alone, the near-anode region needs caring attitude towards it. More specifically, the near-anode area performs a function of great importance: it provides transfer of electrons, born in the zone of ionization, to the anode. In the near-anode region, the electrons should move to the anode without exiting oscillations which can influence on stability of the discharge firing in the whole acceleration channel.

In the anode cavity of the CAMILA Hall thruster (Fig.2), the radial electrical field should prevent ion colliding the walls of the anode cavity. It is possible at the large enough resistance of plasma with magnetized electrons. However, the real conductivity across the magnetic field is Bohm's one[6,7] that significantly reduces barrier's electrical field for ions. The reason of this is a strong instability due mainly to the positive density gradient along the electrical field.

Thus, we need suppression of noted above instabilities. The application of a well-established method to suppress these instabilities, namely, using the positive gradient of the magnetic field[8] is unacceptable since the positive gradient of the magnetic field along the acceleration channel is itself the reason of the instability in the first case[1] and it is difficult to create it in the anode cavity in the second case.

.

[1] Adviser on Scientific Research, email: kapulkin@technion.ac.il.



1 – Anode, 2 – Gas-distributor, 3 – Magnetic circuit,
4 – Central magnetic coil, 5 – Inner anode coil,
6 – Magnetic screens, 7 – Acceleration channel wall,
8 – Cathode-neutralizer, 9 – Outer anode coil,
10 – Outer magnetic coils.

Figure1. Schematic of CAMILA Hall thruster

In works on thermonuclear synthesis (tokamak, stellarator), the method of suppressing instabilities of perturbations propagating across a magnetic field by the variation of the magnetic field lines direction (the so-called "magnetic shear") is widely used[9]. The paper is for the first time devoted to the theoretical estimations of a possibility of applying the magnetic shear to reduce the growth rate of the low-frequency instability in the near-anode region of the conventional Hall thruster and in the anode cavity of the CAMILA Hall thruster. But before studying influence of the shear on the instabilities, we should consider a consequence of real three-dimensionality of the perturbations.

II.Theoretical Model of Low-Frequency Instability in Near-Anode Region with Taking into Account Motion of Perturbed Electrons Along Magnetic Field

A. Basic Assumptions and Governing Equations

Usually at a study of hydrodynamic instabilities due to convection of charged particles the perturbation wave length is explicitly or implicitly assumed to be equal to infinity along the magnetic field, that is, $k_z = 0$. Now, we discard this assumption.

We use the assumptions which were applied in Ref. 1, namely: 1) Cartesian frame with X and Z axes directed parallel to the thruster axis and the applied magnetic field, respectively, as shown in Fig.2; 2) the perturbations are assumed to be potential, quasi-neutral and non-dissipative; 3) the ionization processes are not taken into consideration; 4) the analysis of the stability of the plasma is carried out under the approximation of two-fluid magneto-hydrodynamics with cold non-magnetized ions and hot magnetized electrons; 5) the temperature of the electrons is assumed to be constant (the finite temperature of the electrons is to be taken into account because in the near-anode region, as distinguished from the acceleration area, the velocity of the drift motion of the electrons, due to the temperature of the electrons, is comparable in magnitude with the velocity of the electrical drift).

The finite temperature of the electrons brings about two drifts: 1) Larmor drift due to the gradient of electron pressure; 2) drift due to the gradient of the magnetic field. The latter deserves special attention. If a magnetized charge particle moves in a curvilinear magnetic field (any non-uniform magnetic field in the absence of the electrical current is a curvilinear one), it experiences a force. This force is directed to the convexity of the magnetic field lines and transverse to the magnetic field. (See, for example, Ref. 10) For electrons, the expression for the force is as follows:

$$\left|F_B\right| \cong \frac{mv_T^2}{R} = \frac{2T_e}{R} = 2T_e\left|\nabla_\perp \ln B_0\right| \qquad (1)$$

where R – the radius of curvature of the magnetic field line, B_0 – the module of induction of the magnetic field.

(We assume that the pressure of the plasma is much less than the pressure of the applied magnetic field.)

Under the effect of the force, the electron drifts transverse to both the magnetic field and the force.

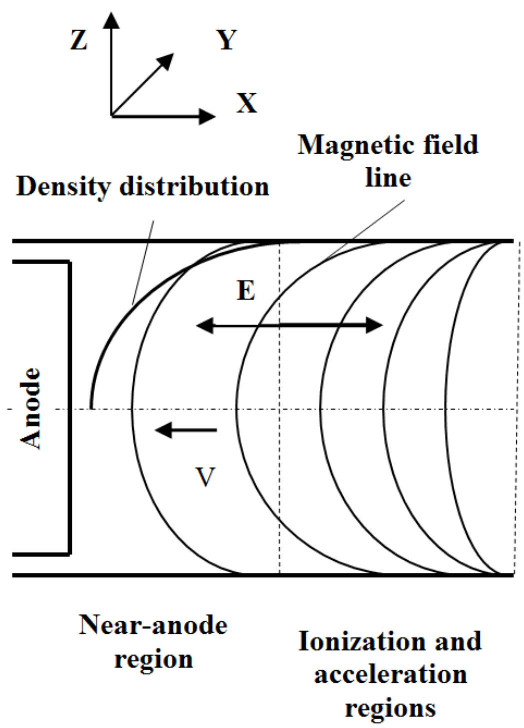


Figure2. A sketch of near-anode region in conventional Hall thruster

As a distinction from Ref. 1, we take into consideration moving the perturbed electrons along the magnetic field. In doing so, we assume that $\omega/k_z > v_{Te}$ (2), where v_{Te} is the thermic velocity of electrons.

Under the above assumptions, the linearized set of equations of the two-fluid magneto-hydrodynamic model in the small-scale approximation for the perturbations takes the following form:

Equations for the ion component

$$\frac{\partial V_x}{\partial t}+V_{x0}\frac{\partial V_x}{\partial x}=-\frac{e}{M}\frac{\partial \Phi}{\partial x} \tag{3}$$

$$\frac{\partial V_y}{\partial t}+V_{x0}\frac{\partial V_y}{\partial x}=-\frac{e}{M}\frac{\partial \Phi}{\partial y} \tag{4}$$

$$\frac{\partial n}{\partial t}+n_0\frac{\partial V_x}{\partial x}+V_{x0}\frac{\partial n}{\partial x}+n_0\frac{\partial V_y}{\partial y}=0 \quad . \tag{5}$$

Equations for the electron component

$$e\frac{\partial\Phi}{\partial x}+\frac{T_{e0}}{n_0^2}\frac{\partial n_0}{\partial x}n-\frac{T_{e0}}{n_0}\frac{\partial n}{\partial x}-eu_yB_0=0 \qquad (6)$$

$$e\frac{\partial\Phi}{\partial y}-\frac{T_{e0}}{n_0}\frac{\partial n}{\partial y}+eu_xB_0=0 \qquad (7)$$

$$\frac{\partial u_z}{\partial t}+u_{y0}\frac{\partial u_z}{\partial y}=\frac{e}{m}\frac{\partial\Phi}{\partial z} \qquad (8)$$

$$\frac{\partial n}{\partial t}+n_0\frac{\partial u_x}{\partial x}+u_x\frac{\partial n_0}{\partial x}+n_0\frac{\partial u_y}{\partial y}+u_{y0}\frac{\partial n}{\partial y}+n_0\frac{\partial u_z}{\partial z}=0 \qquad (9)$$

where V_x , V_y – the projections of perturbed velocity of the ions on the *X* and *Y* axis, respectively, u_x, u_y, u_z - the projections of perturbed velocity of the electrons on the *X*, *Y* and *Z* axis, respectively, *M* – the ion mass, *m* – the electron mass, Φ – the plasma potential perturbation.

The quantities with index "0" are non-perturbed.

The non-perturbed electrical field E_{x0} is directed towards the anode that due to the large gradient of the electron pressure in the near-anode region of the conventional Hall thruster. The non-perturbed velocity of the electrons u_{y0} is directed along the *Y* axis. To find it, we use the projection of the equation of non-perturbed motion of electrons on the *X* axis:

$$-en_0E_{x0}-\frac{2T_{e0}n_0}{R}-T_{e0}\frac{\partial n_o}{\partial x}-eu_{y0}B_0n_0=0 \qquad (10)$$

From Eq. (9), it follows:

$$u_{y0}=-\frac{E_{x0}}{B_0}-\frac{2T_{e0}}{eB_0R}-\frac{T_{e0}}{eB_0n_0}\frac{\partial n_0}{\partial x}. \qquad (11)$$

. Below, the approximate equality $\frac{1}{R}\cong\frac{1}{B_0}\frac{\partial B_0}{\partial x}$ is used.

B. Dispersion Equation

We seek the solution of the set of equations (3) – (9) and Eq. (10) in the form:

$$\mathbf{F}(x,y;t)=\mathbf{F}_k\exp(-i(\omega t-k_xx-k_yy-k_zz))$$

where $\mathbf{F}$ and $\mathbf{F}_k$ are consequently the vector of perturbed parameters and vector of their Fourier components, k_x, k_y and k_z– the projections of the wave vector on the axes *X*, *Y* and *Z*, respectively.
In doing so, we restrict ourselves for simplicity by the case $k_xV_{x0} << \omega << k_yu_{y0}$ (12)

As a result, we obtain the following local dispersion equation,

$$\omega^2 - \frac{e(k_x^2 + k_y^2)\left(E_{x0} + \dfrac{2T_{e0}}{el_B}\right)}{M\left(\dfrac{1}{l_B} - \dfrac{1}{l_N}\right)\left[1 - \dfrac{k_z^2 e B_0^2}{k_y^2\left(E_{x0} + \dfrac{T_{e0}}{e}\left(\dfrac{2}{l_B} + \dfrac{1}{l_N}\right)\right)\left(\dfrac{1}{l_B} - \dfrac{1}{l_N}\right)m}\right]} = 0 \qquad (13)$$

Where $l_N = 1 \Big/ \dfrac{d}{dx}\ln n_0$, $l_B = 1 \Big/ \dfrac{d}{dx}\ln B_0$.

From the dispersion equation (13), it follows that at 0 < l_N < l_N and $\left|E_{x0}\right| < 2T_{e0}/el_B$, we have aperiodic instability with the growth rate of

$$\gamma = \sqrt{\frac{e(k_x^2 + k_y^2)\left(\dfrac{2T_{e0}}{el_B} - \left|E_{x0}\right|\right)}{M\left(\dfrac{1}{l_N} - \dfrac{1}{l_B}\right)\left[1 + \dfrac{k_z^2 e B_0^2}{k_y^2 m\left(\dfrac{T_{e0}}{e}\left(\dfrac{2}{l_B} + \dfrac{1}{l_N}\right) - \left|E_{x0}\right|\right)\left(\dfrac{1}{l_N} - \dfrac{1}{l_B}\right)}\right]}} \qquad (14)$$

One can see that taking into account $k_z \neq 0$ leads to reducing the growth rate of the instability. At first glance, at the width of the acceleration channel of $h = 1.5\cdot 10^{-2}$m, a minimal value of $k_z = \dfrac{\pi}{h}$ should be equal to 3.14·10^{2} m^{-1}. Then, at B_0 = 10^{-2} T, T_{e0} = 10 eV, l_N = 9·10^{-3} m, l_B = 10^{-2} m, E_{x0} = - 1.8·10^{3} V/m, $k_y \approx k_x$ = 2·10^{2} m^{-1}, the growth rate of the instability should be reduced by a factor of 23.4, that is, should be negligible small. However, this is not the case. The fact is that at frequencies well below than electron Langmuir one, the potential of plasma in Hall thruster does not almost change along a length of the magnetic field line (a phase shift is almost absent), excepting an abrupt change near the wall of the thruster. This justifies application of k_z =0 approximation in theoretical models of low-frequency perturbations in the conventional magnetic field (without shear!).

III.Estimation of Influence of Magnetic Field Shear on Low-Frequency Instability in Near-Anode Region

Now let the magnetic induction vector $\mathbf{B_0}$ have two components B_{z0} and B_{y0}, which depend on x. The latter simulates the azimuthal component of the magnetic field, which should be applied to create the sheared magnetic field (Fig. 3).

$$\mathbf{B_0} = B_{0z}(x)\mathbf{e_z} + B_{0y}(x)\mathbf{e_y} \qquad (15)$$

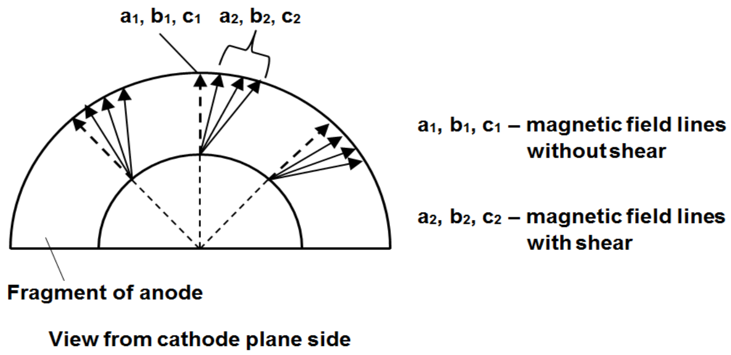


Figure3. Schematic of magnetic field shear in Hall thruster

(For simplicity, the magnetic field lines are assumed to be straight ones.) Divided both left and right parts of Eq.(15) into B_0, we obtain:

$$\mathbf{e_0} = h_z(x)\mathbf{e_z} + h_y(x)\mathbf{e_y} \tag{16}$$

Where $\mathbf{e_0}$ is the unit vector in the direction of the magnetic field line,

$$h_z = \frac{B_{z0}}{B_0}\;,\quad h_y = \frac{B_{y0}}{B_0} \tag{17}$$

We write the equations for the electron component (6) – (9) with a new magnetic field in old Cartesian coordinates, after that convert them to new Cartesian coordinates:

$$x = x',\quad y = h_z y' + h_y z',\quad z = -h_y y' + h_z z' \tag{18}$$

The new Cartesian coordinates correspond to the rotation of the Y' and Z' axes around X axis until Z' coincides with the direction of the new magnetic field line. Performed Fourier-transformation of all perturbed variables and substituted the expressions for the perturbed velocities into the continuity equation, we obtain, with taking into account Eq. (12), the following equation for the electron density:

$$n = -\frac{B_0\Phi}{E_{x0} + \frac{2T_{e0}}{eB_0}\frac{\partial B_0}{\partial x}}\left[\frac{1}{k_b}\frac{\partial}{\partial x}\left(\frac{k_b n_0}{B_0}\right) + \frac{e k_{\parallel}^2 n_0 B_0}{m k_b^2\left(E_{x0} + \frac{T_{e0}}{e}\left(\frac{2}{B_0}\frac{\partial B_0}{\partial x} + \frac{1}{n_0}\frac{\partial n_0}{\partial x}\right)\right)}\right] \tag{19}$$

Where
$$\begin{aligned} k_b &= k_y h_z - k_z h_y \\ k_{\parallel} &= k_z h_z + k_y h_y \end{aligned} \tag{20}$$

Indexes b and $\|$ denote along binormal to the magnetic field and along the magnetic field, respectively.

We assume that $\omega / k_{\parallel} > v_{Te}$ (21)

In the equation (19) under the sign denoting the derivative there is k_b. Though according to Eqs (20), k_b depends on x, however at the small deviation of B_0 from the initial direction (i.e. at $h_z \approx 1$), the change of k_b is only slight since at all interesting for suppression of instabilities values of k_z, $k_z << k_y$. Therefore, one can take out k_b from under the sign of the derivative. Then, we have:

$$n=\frac{n_0}{E_{x0}+{}^{2T_{e0}}\!/_{el_B}}\left[\left(\frac{1}{l_B}-\frac{1}{l_N}\right)-\frac{eB_0^2k_{\|}^2}{mk_b^2\left(E_{x0}+{}^{T_{e0}}\!/_{e}\left({}^{2}\!/_{l_B}+{}^{1}\!/_{l_N}\right)\right)}\right]\Phi \tag{22}$$

(It is necessary to note that because of large term k_yh_y in the second equation of Eqs (20), the small deviation of B_0 from initial direction can lead to the large change of $k_{\|}$.)

After performing the same procedure with the equations (3) – (5), with taking into account Eq. (12), we obtain the equation for the ion density:

$$n=\frac{e\left(k_x^2+k_b^2\right)n_0\Phi}{M\omega^2} \tag{23}$$

Equating the right sides of equations (19) and (20) gives the following dispersion equation:

$$\omega^2-\frac{e(k_x^2+k_b^2)\left(E_{x0}+\dfrac{2T_{e0}}{el_B}\right)}{M\left(\dfrac{1}{l_B}-\dfrac{1}{l_N}\right)\left[1-\dfrac{k_{\|}^2eB_0^2}{k_b^2\left(E_{x0}+\dfrac{T_{e0}}{e}\left(\dfrac{2}{l_B}+\dfrac{1}{l_N}\right)\right)\left(\dfrac{1}{l_B}-\dfrac{1}{l_N}\right)m}\right]}=0 \tag{24}$$

From the dispersion equation, we obtain the growth rate of the instability:

$$\gamma=\sqrt{\frac{e(k_x^2+k_b^2)\left(\dfrac{2T_{e0}}{el_B}-|E_{x0}|\right)}{M\left(\dfrac{1}{l_N}-\dfrac{1}{l_B}\right)\left[1+\dfrac{k_{\|}^2eB_0^2}{k_b^2m\left(\dfrac{T_{e0}}{e}\left(\dfrac{2}{l_B}+\dfrac{1}{l_N}\right)-|E_{x0}|\right)\left(\dfrac{1}{l_N}-\dfrac{1}{l_B}\right)}\right]}} \tag{25}$$

If at any point x_0 $k_{\|}(x_0)=k_zh_z(x_0)+k_yh_y(x_0)=0$, then near x_0

$$k_{\|}(x)=\left[h_z^2k_b\frac{\partial}{\partial x}\left(\frac{B_{y0}}{B_{z0}}\right)\right]_{x=x_0}(x-x_0) \tag{26}$$

(See, for example, Ref. 10)

From Eq. (26) and Eq. (20), it follows that if at some $k_{z\max}$, the growth rate of the instability attains zero in the magnetic field without shear, then the shear provides a suppression of the instability at

$$\Theta>\frac{k_{\|\max}k_xL}{k_b} \tag{27}$$

Where $\Theta\cong Lh_z^2\frac{\partial}{\partial x}\left(\frac{B_{0y}}{B_{0z}}\right)$ has meaning of the angle of the magnetic field line rotation on the distance L, i.e. it is the measure of the rate of the magnetic field line direction change,
L can be considered as the length of the instability localization area.

In our case, at any k_z and, correspondently, at any $k_{\|}$, the growth rate does not attain zero. Therefore, we should replace inequality (27) by the following equality

$$\Theta \cong \frac{k_{\|r.es} k_x L}{k_b} \tag{28}$$

It connects $k_{\|r.es}$, at which the growth rate reduces essentially (for example, by a factor of 2), with the angle of the rotation of the magnetic field lines.

Let us consider the sample from section II. From (22), it follows:

$$\frac{\gamma_\Theta}{\gamma_0} = \left(1 + \frac{k_{\|r.es}^2 e B_0^2}{k_b^2 m \left({2T_{e0}}/{l_B} - |E_{x0}| \right) \left({1}/{l_N} - {1}/{l_B} \right)} \right)^{-1/2} \tag{29}$$

Where γ_Θ and γ_0 -the growth rate with shear and without shear, respectively.

From Eq. (29), we obtain that at parameters of the near-anode region and plasma in it, presented in section II, ${\gamma_\Theta}/{\gamma_0} = 1/2$ at $\left| {k_{\|r.es}}/{k_b} \right| = 4.96 \cdot 10^{-2}$. Substituting the obtained ratio of the wave numbers into Eq. (26), we have $\Theta \cong 0.156$.

IV.Estimation of Influence of Magnetic Field Shear on Convective instability in Anode Cavity of CAMILA Hall Thruster

In the anode cavity of the CAMILA Hall thruster $T_{e0}/eU_a < 1$, where U_a is the needed drop of the potential between the anode and centerline of the cavity providing ionization of Xe-atoms predominantly in the cavity[4]. Therefore, as first approximation, we neglect by the thermic effects. For the rest, we use the same assumptions, differential equations, procedures as under consideration of the influence of the magnetic field shear on the low-frequency instability near-anode region. As a result, we obtain the following dispersion equation:

$$\omega^2 - \frac{e(k_x^2 + k_b^2) E_{x0}}{M \left(\frac{1}{l_B} - \frac{1}{l_N} \right) \left[1 - \frac{k_{\|}^2 e B_0^2}{k_b^2 E_{x0} \left(\frac{1}{l_B} - \frac{1}{l_N} \right) m} \right]} = 0 \tag{30}$$

As a distinction from the near-anode region of the conventional Hall thruster, in the anode cavity of the CAMILA Hall thruster $E_{x0} > 0$ and $l_B < 0$. In this case, we have the aperiodic instability with the growth rate

$$\gamma = \sqrt{\frac{e(k_x^2 + k_b^2) E_{x0}}{M \left(\frac{1}{l_N} + \frac{1}{|l_B|} \right) \left[1 + \frac{k_{\|}^2 e B_0^2}{k_b^2 m E_{x0} \left(\frac{1}{l_N} + \frac{1}{|l_B|} \right)} \right]}} \tag{31}$$

As in the case of the near-anode region of the conventional Hall thruster, in the anode cavity of the CAMILA Hall thruster, the magnetic field shear does not eliminated the instability, but reduces its growth rate.

Let us consider the following sample.

At the distance between co-axial anode and centerline of $6 \cdot 10^{-3}$ m and the needed drop of the potential of 40 V, we have $E_{x0} = 6.67 \cdot 10^3$ V/m. Other parameters: $l_N = 6 \cdot 10^{-3}$ m $l_N = 2.4 \cdot 10^{-3}$ m, $k_x = 5.23 \cdot 10^2$ m^{-1}, $B_0 = 1.4 \cdot 10^{-2}$ T. In this case, using Eq. (31) and Eq.(28), we obtain that reducing the growth rate of the convective instability by a factor of 2 can be attained at $\Theta \cong 1$

V.Concluding Remarks

As a result of the conducted investigations, the following it was shown:

1. The shear of the magnetic field influences strongly on the instability growth rates as in the near-anode region of the conventional Hall thruster so in the anode cavity of the CAMILA Hall thruster.
2. In both cases, the shear of the magnetic field does not eliminate instability. It only reduces the growth rate.
3. For reducing the growth of the instability by a factor of 2, it is sufficient to change the direction of the magnetic field line by $\Theta \cong 0.156$ in the near-anode region of the conventional Hall thruster and by $\Theta \cong 1$ in the anode cavity of the CAMILA Hall thruster.

It should be noted the following. Strongly speaking, in the case of the low-frequency instability in the near-anode region of the conventional Hall thruster, inequality (21) is valid at small values of Θ, only. At the large values of the Θ, the kinetic consideration of the problem should be applied.

It is necessary also to note that, as is shown in Ref. 11, imposing the azimuthal magnetic field as an addition to radial magnetic field should not interrupt a drift of electrons in the devices with closed electron drift. In Ref. 11, such the configuration of the magnetic field was suggested to apply for the mass separation of the high density ion flux.

The possible way to create the shear of the magnetic field with in the Hall thruster is using along with the solenoidal winding, the helical winding with opposite directions of a current in neighboring turns.

References

[1]Kapulkin A. and Guelman M. Low-Frequency Instability in Near-Anode Region of Hall Thruster // IEEE Transaction on Plasma Science, Vol.36, No. 5, pp. 2082 – 2087, 2008.

[2]Frias, W., Smolyakov, A., Kaganovich, I., and Raitses Ye. "Long wavelength gradient drift instability in Hall plasma devices. I. Fluid theory," *Phys. Plasmas* **19**. 072112 (2012).

[3]Kapulkin Alexander, Guelman Mauricio Moshe, Balabanov Vladimir, and Rubin Binyamin, "Low-Power Hall Thruster," Patent No.: US 9,447,779 B2, Date of Patent: Sep. 20, 2016. Priority US/09.11.06/USP 865033.

[4]Kapulkin A., Guelman M., "Theoretical modeling of Ionization Processes in Anode Cavity of CAMILA Hall Thruster," *The 31st International Electric Propulsion Conference, University of Michigan,* Ann Arbor, Michigan, USA, Sep 20 – 24, 2009, IEPC-2009-068.

[5]Kronhaus I., Kapulkin A., Balabanov V., Rubanovich M., Guelman M., and Natan B., "Investigation of physical processes in CAMILA Hall thruster using electrical probes," *Journal of Physics D: Applied Physics*, Vol.45, p. 175203, 2012.

[6]Kronhaus, I., Kapulkin, A., Balabanov, V., Rubanovich, M., Guelman, M., and Natan, B. Discharge Characterization of the Coaxial Magneto-Isolated Longitudinal Anode Hall Thruster, Journal of Propulsion and Power, Vol. 29, No. 4, 2013, pp.938-949.

[7]Rubanovich, M., Kapulkin, A., Balabanov, V., Behar, E., Gurfil, P., Experimental Investigations and Optimization of CAMILA Hall Thruster with Strong Longitudinal Magnetic Field,66th International Astronautical Congress, Jerusalem, Israel, Oct 12-16, 2015, IAC-15-C 4.4.3.

[8] Morozov, A. I., Esipchuk,Yu. V., Kapulkin, A. M., Nevrovskii, V. A., and Smirnov, V. A.,"Effect of the Magnetic Field Configuration on Operation Mode of a Closed Electron Drift Accelerator," *Sov. Phys. Tech. Phys*., Vol. 17, 1972, pp. 482-487

[9]Mikhailovskii, A. B., *Instabilities in a Confined Plasma*, Institute of Physics Publishing, Bristol (UK) and Philadelphia (USA), 1998.

[10]Mikhailovskii, A. B., *Theory of Plasma Instabilities*, Vol. 2, Atomizdat, Moscow, (in Russian), 1970.

[11]Morozov, A., I., Lebedev, S., V., "Plasmaoptics," in book: Problems of Plasma Theory, Moscow, Atomizdat, (in Russian), pp. 247-384, 1974