THE NEW HIGH FREQUENCY ION THRUSTER (HFIT) DEVELOPMENT

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Abstract

The possibility to develop effective enough high frequency thruster (HFT) of capacitive type is investigated by RIAME MAI and PROEL. The main idea was to organise electron cyclotron resonance (ECR) under low value of magnetic induction in the discharge chamber. On the basis of made theoretical analysis the coaxial scheme of the discharge chamber with longitudinal magnetic field was chosen and studied under the frequency f=100MHz, corresponding to the value of ∼3.8 mT. The results of investigations show that it's possible to obtain high enough efficiency of gas ionization in the discharge chamber of the studied type, namely: under Xe mass flow rates corresponding to the level of the mass efficiency higher than 0.7 was received with energetical ion cost C_i∼600 eV/ion.

This data allows to obtain total thruster efficiency η ≥0.5 under specific impulse I_sp ≥3000 s and total thruster power N ≤100 W. Such thruster could be interesting for small satellites orbit control mission.

INTRODUCTION

As it is known [1,2] the development of the ion thrusters (IT) reaches the significantly high level. In particular, the high thrust efficiency and life time is obtained. It permits to begin its practical using. So the preparation for such application have already started: flight tests of the propulsion systems, based at the artificial satellites "Eureca" (Europe) and ETS-V1 (Japan) are

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carried out. Flight tests according to the program “Artemis” is under preparation. So it is interesting to develop the new IT schemes, with wider range of their integral parameters which will permit to improve the thruster performance. For our mind the development of high effective IT with small power level is very important. Such thrusters could be successfully used at the small artificial satellites, the interest for which have increased last years. So RIAME MAI and PROEL TECHNOLOGIE have began the development of the thrusters with small power level, which would successfully operate under small power levels.

We choose the high frequency thruster with electron-cyclotron resonance (ECR). In principle, such type of thrusters permit to obtain the high ionization efficiency under small power in discharge. The significant limit of existing thrusters defining the main peculiarities of their design, is the necessity to use the electromagnetic fields with magnetic induction \( B \approx (0.1...10)T \). So the problem of developing thrusters, which permit to obtain ECR under small magnetic fields [3] was formulated.

Taking into account all mentioned above, we have investigated if it is possible to create the electron-cyclotron high frequency ion thruster (HFIT) with small power level.

1. The HFIT discharge chamber scheme choice

Choosing the discharge chamber scheme, we took into account, that it had been able to realize the ECR with significantly high ionization efficiency in the ion source chamber with longitudinal magnetic field, in which SHF electromagnetic field with circular polarization is supplied from one of the discharge camber ends [4]. It is possible to analyse it theoretically and because of it, its very interesting. Because it is necessary to decrease the magnetic induction inside the discharge chamber, and respectively to decrease the cyclotron frequency \( \Omega = eB/m \) where \( e \) and \( m \) - electron charge and mass, \( B \) - magnetic induction, the operating frequency \( f = \omega / 2\pi \) of the high frequency generator is decreased too. For the first stage of the investigation, the operating frequency \( f = 100 \text{ MHz} \) was chosen. Such frequency decreasing required to revise the method of the electromagnetic energy supplying into the discharge chamber: in particular, we decided to perform the energy input with the help of the co-axial cable and to develop exciter of the electromagnetic field in the discharge chamber volume do with the help of the coaxial electrodes.
The theoretical analyses of the possible waves in the limited magneto-active plasma showed, that it is possible to excite either azimuth-symmetrical waves, travelling along the magnetic field, either waves with rotating vector of the electromagnetic field (around the chamber axis). The estimations showed, that under the resonance conditions, i.e. under the round frequency \( \omega = \Omega \) it is possible to expect the electromagnetic wave (EMV) energy adsorption by plasma in another case it's possible to imagine. The energy adsorption by plasma under the regime of the pure capacitor discharge, when the field, created by electrodes, penetrates into plasma at the great depth. It is clear, that it was difficult to obtain accurate estimations because of the complicated picture of the process. So the main conclusions have been tested with experiments, in particular, the models of the discharge chambers with longitudinal magnetic field and ion sources with such discharge chambers (Fig. 1) were developed.

The high frequency source of ions consisting of the discharge chamber 1 with diameter 100mm and controlling length up to 100mm, manufactured from stainless steel and limited from one side by quartz insert 2 and from the other side - by the ion-optical system 3. Working gas is feeding under the pressure into the discharge chamber through the system of uniformly located around the circle gas feeding holes. The magnetic field is created by the electromagnet. The central electrode 4 was manufactured from stainless steel and it was replaceable in order to investigate its form and sizes influence to the source efficiency.

HF electric energy is supplied to the exciter 4 with the help of the co-axial cable 7 from the HF generator with operating frequency 100 mHz, the output power of which can be varied from 20 up to 500 W. Adjustment of the input plasma source impedance with HF generator is performed in the feeder channel by two parallel tails.

Ion-optical system consists of the accelerating and emission electrodes, manufactured from Mo, each of them have 400 holes with diameter 2mm and 4 mm respectively. The ion-optical system transparency is about 0.64 relatively emission electrode. The ion-optical system parameters permit to obtain normal performance in the working flow rate range up to \( \sim 2 \) sccm under accelerating potentials from 0.9 up to 2.5 kV.

The operation performance of the electrostatic thrusters is usually calculated using the ion current density \( j_i \) following from plasma to the IOS wall. As it is well known, \( j_i \) is determined by the following dependence:
\[ I_i = 0.4en \left( \frac{T_e}{M} \right)^{1/2} \]

where: \( e \) - electron charge, \( n \) - plasma concentration, \( T_e \) - electrons temperature in the electrical units, \( M \) - ions mass. So in the experiments the dependence for total ion current dependence \( I_i = j_iS \) (\( S \) - IOS cross section area) on the solenoid current value (magnetic field induction), power of the HF generator, the working medium flow rate and the discharge chamber geometry is used.

The examine of the typical dependencies \( I_i \) on the current in the electromagnet \( I_m \) (Fig.2) show that there are at least two \( I_i \) maximums, for which the ratio between currents in the solenoid coil \( I_{m1}/I_{m2} = 2 \), i.e the corresponding ratio of the cyclotron frequencies is equal to 2. The first maximum is narrow, and the second one - longer. Their analyse shows, that the obtained results can be explained as the result of the ECR.

Then we will assume that under steady state operation mode inside the discharge chamber there is the uniform plasma with concentration \( n_e \) and electron temperature \( T_e \). Near the metallic surface of the chamber (see dashed lines in the scheme), the areas \( (R_1 < r \leq R_1' \) and \( R_2' \leq r \leq R_2) \) of positive space charge is realized which is appeared as a cause of the chamber wall negative potential relatively plasma (floating potential). In the scheme the radiuses of the chamber and uniform plasma are denoted as \( R_B \) and \( R_B' \) (\( S=1,2 \)) respectively. The high frequency energy inputting is described by the Maxwellion equations with boundary conditions:

\[
\begin{align*}
\text{rot} \bar{E} &= -\frac{1}{c} \frac{\partial \bar{B}}{\partial t}, \\
\text{rot} \bar{B} &= \frac{1}{c} \frac{\partial \bar{E}}{\partial t}, \\
D_1 &= \varepsilon_{ij}E_j, \\
B_1 &= B_{(\varphi,z)}(R_B') = B_{(\varphi,z)}(R_B),
\end{align*}
\]

where the cylindrical system of coordinate \((r, \varphi, z)\) with \( Z \) axis along the axis of symmetry is used;

\( S=1,2: \) \( E_{\varphi,z}, B_{\varphi,z} \) - components of the electric and magnetic fields in the plasma volume \( (R_1' \leq r \leq R_2') \); \( E_{\varphi,z}^e, B_{\varphi,z}^e \) - analogous components outside of the plasma volume (for HF fields - vacuum); \( \varepsilon_{ij} = \varepsilon_{ij}(\omega, k, \Omega, n) \) - tensor of the of the dielectric permeability of the magneto-active
plasma for $R_1 \leq r \leq R_2$ and for $R_1 \leq r \leq R_1'$ and $R_2' \leq r \leq R_2$, $\varepsilon_{ij} = 1$ - vacuum dielectric permeability.

As a tensor $\varepsilon_{ij}(\omega,k,\Omega,q)$ the well known in physics of plasma tensor $\varepsilon_{ij}(\omega,k,\Omega)$ without collision considering $v$ is used. For flow rates $\sim 1$ sccm ($P-1 \cdot 10^{-4}$) Torr, $n_a=3 \cdot 10^{-10}$ cm$^{-3}$ the gas atom concentration under $t=20^\circ C$ the collision frequency $v_{ea}=(1-2,5) \cdot 10^6$ s$^{-1}$ and $v_{es}=(2-0,1) \cdot 10^6$ s$^{-1}$ for the electron energies $(1-10)$ eV. So the electromagnetic waves collisional attenuation, proportional to $v/\omega = (1-4) \cdot 10^{-3}$ for $\omega=2\pi \cdot 10^8$ [s$^{-1}$] is significantly small. This fact forces to use another waves absorption mechanisms, which is characterized by the following parameters:

$$\beta_0 = \left| \frac{\omega}{k_z V_e} \right| = \left| \frac{\omega \pm m\Omega}{k_z V_e} \right| = \beta_0|l \pm m|X|, \quad X = \Omega / \omega \geq 1, \ m = 1,2,...,$$

where $v_e$ - electrons heat velocity; $k_z$ - wave number. The components of tensor $\varepsilon_{ij}(\omega,k,\Omega)$ is not reasonable to write, because they are known. Taking into account the values $k_z$, $v_e$ and dependencies $\Omega=\Omega(z)$ in the different zones ($\Omega(z)=\omega; 2\omega; 3\omega$) tensor permits to make different simplifications and it permits to determine the absorption performances in the different zones. Lets examine these zones sequentially.

1. The cold plasma approximation (i.e. $\beta_0 >> 1$, $x \geq 3$), which is correct for $3\omega < \Omega(z)$ zone.

Solution of the Maxwellian equations with the boundary conditions leads to the following characteristics of the azimuthal-symmetrical waves ($\frac{\partial}{\partial \phi} = 0$):

transversal $k_1$ and longitudinal $k_z$ wave numbers are:

$$k_{1s} = \frac{\mu_s}{R_1}, \quad \text{and} \quad k_{zs} = \frac{k_{1s}}{(x^2-1)^{1/2}} \sqrt{1 + 2N_s^2},$$

where $N_s^2 = 3.55 \cdot 10^{-12} n/k_{1s}^2$, and $\mu_s$ - S-th root ($S=1,2,...$) of the dispersion equation

$J_1(\lambda y)Y_1(\varphi) - J_2(\varphi)Y_1(\lambda y) = 0, \ y = k_{1s} R_1^1, \ \lambda = R_2^1/R_1^1, \ J_1, Y_1$ - Bessel function of the first and the second kind of the first order. As an information, we give the table of the roots $\mu_s < \mu_{s+1}$.
For mentioned flow rates (~1sccm) the plasma concentration $n < n_a \approx 10^{12} \text{cm}^{-3}$, so, taking into account the chamber geometrical sizes $R_1, R_2$ ($R_1', R_2'$ are differ from $R_1, R_2$ on some Debye radiuses $r_D << R_1, R_2$) it is easy to realize the value $N_s^2 << 1$. Under this $N_s$ value, the field structure of the electromagnetic field is the following:

**E-wave**

$$
\begin{align*}
E_{s\tau} &= iA_s (x^2 - 1)^{1/2} \\
B_{\psi\psi} &= iA_s \frac{\omega - \omega_s}{\omega} N_s \\
E_z &= A_s f_i^2(k_5 r),
\end{align*}
$$

where $f_i^2(x_s) = J_i(x_s) + Q_s Y_i(x_s)$, $i=0,1$, $\omega - e$ - electron plasma frequency, $A_s$ - is defined by the wave, following from the generator; $S=1,2,3...$

**H-wave** has the negligible small components relatively to E-wave, so they are not given.

In order to excite the mentioned E-wave, it is necessary to secure the agreement between chamber length $L$ and $k_z$, i.e. $L = \pi / k_z$. In this case the wave with the greatest length, corresponding to $k_z$ is excited the most effective.

If we take into account the electrons collisions $v$ in the tensor $\varepsilon_{ij}$, the wave number $k_z$ will take a complex value:

$$
k_z^B = \frac{k_{1s}}{(x^2 - 1)^{1/2}} \left(1 + 2N_B^2 \right)^{1/2} \left(1 - \frac{v}{2\omega} \right),
$$

the real and imaginary parts of which define the refraction ($N$) and absorption ($c$) indexes of field:
So, the wave relative HF absorption index considering the estimation \( v/\omega \), mentioned above, negligibly small:

\[
\delta = \frac{|\chi|}{N} = \frac{v}{2\omega} = 10^{-3}
\]

2. Lets examine the zone for \( \Omega(z)=2 \), for which \( \beta_0=3, \chi = 2 \).

In this case the solution of Maxwellian equations leads to the dispersion equation:

\[
k_z^2 - k_{1s}^2 \left( \frac{1 + 2N_s^2}{x^2 - 1} \right) \left[ 1 + i \sqrt{\pi / 2} \left( 1 / 2 + N_s^2 \right)^2 \left( x^2 - 1 \right) \beta e^{-\left( \beta_0^2 \left( 1 - x \right)^2 / 2 \right)} + \beta_0^3 e^{\left( \beta_0 \left( 1 - x \right)^2 / 2 \right)} \right] = 0,
\]

\[
k_{1s} = \mu_s / R_1, \quad N_s^2 = 3.55 \cdot 10^{-12} n / k_{1s}^2 << 1,
\]

from which the complex value of the longitudinal wave number is obtained:

\[
k_z^s = k_{1s} \left( \frac{(1 + 2N_s^2)}{x^2 - 1} \right)^{1/2} \left[ 1 + i \sqrt{\pi / 8} \left( 1 / 2 + N_s^2 \right) \left( x^2 - 1 \right) \beta_0 e^{-\left( \beta_0^2 \left( 1 - x \right)^2 / 2 \right)} + \beta_0^3 e^{\left( \beta_0 \left( 1 - x \right)^2 / 2 \right)} \right],
\]

For this area the relative absorption index is equal:

\[
\delta_2 = \frac{|\chi|}{N} = \frac{Im k_z^s}{Re k_z^s} = \left( \pi / 8 \right)^{1/2} \left( 1 / 2 + N_s^2 \right) \left( x^2 - 1 \right) \beta_0 e^{-\left( \beta_0^2 \left( 1 - x \right)^2 / 2 \right)} + \beta_0^3 e^{\left( \beta_0 \left( 1 - x \right)^2 / 2 \right)}
\]

and for \( \beta_0=3, c=2 \) and compose value \( d=c/N=0.2 \), which by two order of magnitude more than in the previous case.

3. At last, lets examine the ECR area \( \Omega/\omega \), where \( \beta_0=3 \) and \( \beta_0 \left( 1 - \chi \right) << 1 \).

For ECR area the dispersion equation has the following form:
\[ k_z^3 = i\left(\frac{\pi}{2}\right)^{1/2} \frac{\omega^2 e}{c^2 v_e} \left(1 + \frac{1}{2N_s^2}\right), \]

from which we will obtain the complex value for the longitudinal wave number.

\[ k_z^2 = \left(\frac{\pi}{2}\right)^{1/6} \left[ \frac{\omega(1 + 2N_s^2)}{2V_e} k_{1s}^2 \right]^{1/3} \left(\frac{3}{2} + \frac{i}{2}\right), \]

where \( k_{1s} = \mu_s/R_1 \) and \( N_s^2 = 3.55 \times 10^{-12} n/k_{1s}^2 \)

In this case the relative absorption index is equal \( S_3 = \sqrt{3} = 0.58 \). Moreover the value \( d_3 = \text{const} = 0.58 \) in the very narrow changing range \( 0.9 < \omega/\Omega < 1.1 \), i.e. in the narrow changing range of the external magnetic field \( B \) or current in the solenoid coil at the ECR.

Now let's analyze the HFIT characteristics \( I_1 = \text{f}(I_m) = \text{f}(B) = \text{f}(\Omega) = \text{f}(\lambda) \), obtained during the experiment (see fig. 2). Under \( \Omega = 2\omega \) the relative absorption coefficient is characterized by the value

\[ \delta_2 = \left(\frac{\pi}{8}\right)^{1/2} \left[ \beta_0^3 - \frac{\beta_0}{2} + \left(0.5 + N_s^2\right)(\chi^2 - 1)\beta_0 e^{-\frac{\beta_0(1-\chi)^2}{2}} \right], \quad \chi = \frac{\Omega}{\omega}, \]

where the first component is responsible for the absorption in the Cherenkov resonance conditions (Landay damping), and the second - corresponds to the cyclotron absorption under \( \Omega = 2\omega \). It is easy to see, that under \( \Omega >> 2\omega \) (in the real conditions \( \beta_0 = 3 \) already under \( \Omega = 2.5\omega \)), the share of the second component is negligible small.

So the mentioned source operation regimes can not be explained as the realization of the ECR only. So, the real picture of the processes in the discharge chamber is significantly more complicated, than we have assumed in the beginning.
From the application point of view, regimes with \( \omega = 2\Omega \) are the more acceptable, because they are more stable. The performance, presented in the Table 1, have been obtained at these regimes.

<table>
<thead>
<tr>
<th>Q (sccm)</th>
<th>Pd (W)</th>
<th>Li (mA)</th>
<th>( \eta_m )</th>
<th>Ci (W/A)</th>
<th>Isp (m/s)</th>
<th>T (mN)</th>
<th>Ct (W/mN)</th>
<th>( \eta_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>18.0</td>
<td>35.7</td>
<td>0.71</td>
<td>505</td>
<td>33439</td>
<td>2.29</td>
<td>31.3</td>
<td>0.53</td>
</tr>
<tr>
<td>0.70</td>
<td>25.0</td>
<td>43.6</td>
<td>0.87</td>
<td>573</td>
<td>40911</td>
<td>2.80</td>
<td>32.3</td>
<td>0.63</td>
</tr>
<tr>
<td>0.70</td>
<td>34.0</td>
<td>49.6</td>
<td>0.99</td>
<td>655</td>
<td>46498</td>
<td>3.18</td>
<td>34.1</td>
<td>0.68</td>
</tr>
<tr>
<td>1.00</td>
<td>28.0</td>
<td>51.5</td>
<td>0.72</td>
<td>544</td>
<td>33763</td>
<td>3.30</td>
<td>31.9</td>
<td>0.53</td>
</tr>
<tr>
<td>1.00</td>
<td>39.0</td>
<td>63.4</td>
<td>0.89</td>
<td>615</td>
<td>41591</td>
<td>4.06</td>
<td>33.0</td>
<td>0.63</td>
</tr>
<tr>
<td>1.00</td>
<td>50.0</td>
<td>69.1</td>
<td>0.97</td>
<td>723</td>
<td>45365</td>
<td>4.43</td>
<td>34.7</td>
<td>0.65</td>
</tr>
<tr>
<td>1.50</td>
<td>52.0</td>
<td>73.0</td>
<td>0.68</td>
<td>712</td>
<td>31936</td>
<td>4.68</td>
<td>34.5</td>
<td>0.46</td>
</tr>
<tr>
<td>1.50</td>
<td>61.0</td>
<td>80.0</td>
<td>0.75</td>
<td>763</td>
<td>34999</td>
<td>5.13</td>
<td>35.3</td>
<td>0.50</td>
</tr>
<tr>
<td>1.50</td>
<td>72.0</td>
<td>82.5</td>
<td>0.77</td>
<td>873</td>
<td>36092</td>
<td>5.29</td>
<td>37.0</td>
<td>0.49</td>
</tr>
</tbody>
</table>

From these data one can see, that under even very small flow rates, corresponding to the equivalent currents \( \text{Li} < 70 \text{ mA} \), it is possible to receive the significantly high ionization efficiency (the mass efficiency \( \eta_m > 0.7 \) under ion energetic cost in the charge \( \text{Ci} \approx 500\text{eV} \)). It confirms that it is possible to create the HF IT, which has significant efficiency at the power level \( \text{N} \leq 100\text{W} \).

**CONCLUSIONS**

Our investigations confirm that it is possible to create the effective high frequency ion thruster with power \( \sim 100\text{W} \) under operation frequency in the discharge chamber \( f < 100\text{MHz} \).
REFERENCES


Fig. 1. The HP17 diagram.

Fig. 2. Ion current $I_1$ in the beam versus $\rho$.