ON THE POSSIBILITIES OF RF ION THRUSTERS OPTIMIZATION

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Abstract: The possibilities of RF power thruster optimization are considered on the basis of plasma power absorption efficiency study and conditions of effective plasma generation analysis. RF inductive thrusters without external magnetic field as well as ion thrusters enhanced by magnetic field are considered.

Nomenclature

R_{ant}	=	antenna resistance
R_{pl}	=	plasma resistance
L_{ant}	=	antenna inductance
P_{Gen}	=	power of RF oscillator
P_{ant}	=	power allocated in antenna
P_{pl}	=	power allocated in plasma
I	=	current through antenna
L	=	length of ion thruster gas discharge chamber (GDC)
R	=	radius of ion thruster gas discharge chamber (GDC)
ω	=	working frequency of RF ion thruster
E_r	=	radial electric field
E_φ	=	azimuth electric field
E_z	=	longitudinal electric field

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$\varepsilon_\perp$, $\varepsilon_\parallel$, g = components of dielectric susceptibility tensor
g = diagonal permittivity
ω_{res} = resonance frequency
ω_{Le} = plasma frequency
Ω_e = Larmour frequency
k = wave number
c = light speed
n_e = electron density
γ = gas efficiency
C_i = ion beam production cost

I. Introduction.

Several kinds of RF and HF ion thrusters are known nowadays, i.e. ion thrusters based on inductive RF discharge, ECR ion thrusters and ion thrusters based on helicon and Trivelpiece-Gould waves excitation[1-3]. Analysis of the typical ion beam production cost shows that RF and HF ion thrusters require more power than DC thrusters for generation of the same ion beam. This fact stimulates interest to the problems of power expenditures reduction for RF inductive discharge maintenance and possibilities of RF thrusters optimization.

Development of the effective RF ion thruster requires the solution of several interconnected problems, i.e. 1) organization of the effective power input to plasma, 2) generation of plasma with maximal electron density at given power input and 3) providing homogeneous plasma density distribution over gas discharge chamber radius, 4) providing ion thruster longterm reproducible operation.

The present paper is devoted to the study of each of above mentioned problems as well as to the revealing of the conditions when fruitful solutions of all problems can be matched. First the results of numerical simulation are represented. They are accompanied by results of experimental study of ion thruster parameters working at the frequency 13.56MHz.

II. How we can organize effective power input to plasma.

A. The equivalent scheme of the discharge. Concept of equivalent resistance.

Well-known[4], that equivalent scheme of inductive RF discharge without magnetic field can be presented as transformer, shown on Fig. 1. RF oscillator is loaded on the transformer which primary winding consists of the antenna having resistance R_{ant} and inductance L_{ant}, while secondary winding represents a current induced in plasma. The transformer scheme can be reduced easily to the scheme[5] representing connected in series resistance and inductance of the antenna, equivalent resistance and inductance of plasma (see Fig.1 (b)). So RF power of oscillator P_{Gen} appears to be connected with the power allocated in antenna P_{ant} and plasma P_{pl} by expressions:

$$P_{Gen} = P_{Ant} + P_{Pl} \tag{1}$$

$$P_{Gen} = I^2 \left(R_{Ant} + R_{Pl}\right) \tag{2}$$

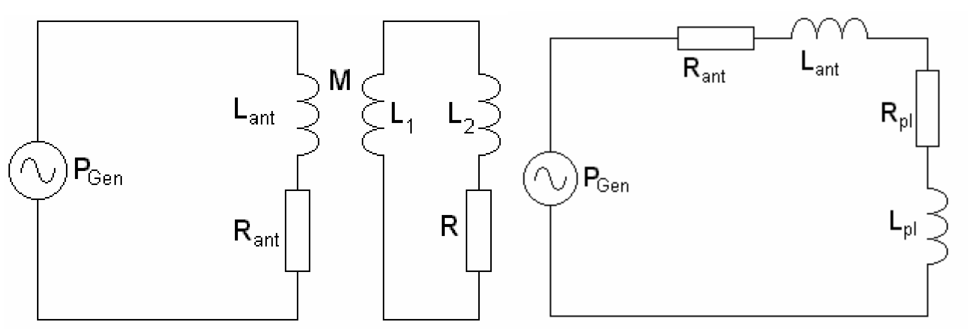


Figure. 1. The equivalent scheme of inductive RF discharge.

At the presence of magnetic field the azimuthal antenna current can induce in plasma not only azimuthal, but also radial and longitudinal currents[6-10]. In this case presentation of inductive RF discharge as the transformer becomes less evident. It is more reasonable to take advantage of expression for P_{pl} [11]:

$$P_{pl} = \frac{L\omega}{4}\int_0^R r \cdot dr \cdot \left\{ \varepsilon''_{\perp} \left|E_r\right|^2 + \varepsilon''_{\perp} \left|E_{\varphi}\right|^2 + ig''\left(E_{\varphi}E_r^* - E_r \cdot E_{\varphi}^*\right) + \varepsilon''_{\parallel}\left|E_z\right|^2 \right\} \quad (3)$$

determining relationship between power absorbed by plasma and RF electric fields. All RF electric fields generated in plasma of inductive discharge (independently on the presence of magnetic field) are proportional to antenna current. Thus power P_{pl} absorbed in plasma, is defined by a square of the current through antenna I, and multiplier R_{pl}, having dimensionality of resistance:

$$P_{pl} = R_{pl}\, I^2, \quad (4)$$

Multiplier R_{pl} is named[6] as equivalent plasma resistance.

Thus formula (2) is valid in case of plasma enhanced by magnetic field too.

B. Power balance in RF oscillator load.

Equation (1) shows that power of RF oscillator is redistributed between two channels: plasma and elements of an external circuit possessing resistance. In order to increase efficiency of ion thruster operation it is necessary to reduce power expenditures in the external load. The best result can be achieved when

$$P_{Gen} \approx P_{pl} >> P_{ant}, \quad (5)$$

That is equivalent to the requirement:

$$R_{pl} >> R_{ant.} \quad (6)$$

It is worth to underline that if inequality (6) is satisfied then operational regimes of RF thrusters will be stable and reproducible.

Let's note, that in real cases active resistance of the antenna is determined not only by resistance of the antenna, but also by losses in matching system , connecting wires, etc. The review of the experimental works [12-15] devoted to research of efficiency of RF power input to plasma shows that the effective resistance of external circuit R_{ant} measured in various experiments lies within the range 0.2-3 Ohm. Low values of R_{ant} are typical for experiments with glass discharge tubes without closely located metal elements of installations where parasitic RF currents can be induced. It is clear that in the majority of cases special efforts directed on reduction of RF power losses in an external circuit are necessary. Otherwise the basic part of power of RF oscillator will go on heating of elements of matching system, sockets, antenna, etc.

Other way of RF power losses reduction is organization of inductive discharge under conditions when equivalent plasma resistance is large and obviously surpasses possible resistance of the antenna.

The problem of RF power absorption by low pressure inductive plasma sources was considered theoretically in [6-10]. Formulae for plasma equivalent resistance obtained in [6-10] were used for numerical simulation of power absorption in RF ion thrusters without magnetic field and in magnetically enhanced RF ion thrusters.

C. Dependence of plasma equivalent resistance on plasma parameters (inductive discharge without external magnetic field).

Results of equivalent resistance calculations for Ar plasmas executed for flat disk-shaped sources without magnetic field are submitted on Fig. 2.

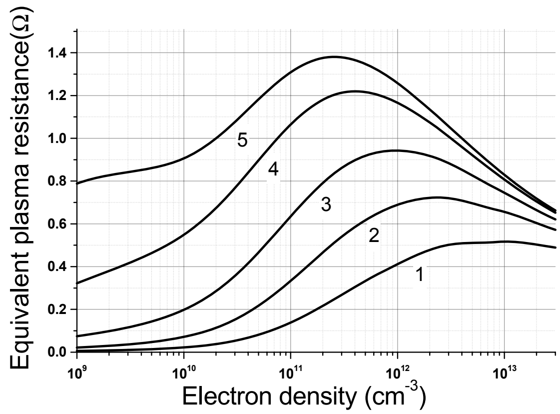


Figure. 2. Dependence of equivalent plasma resistance on plasma density. Calculation is executed for flat disk-shaped sources of radius 1 - 2.5, 2 - 5, 3 – 10, 4-15 and 5-25cм. Pressure of neutral gas - 10^{-4}Torr. Equivalent plasma resistance does not depend on thruster length.

Let us consider the range of plasma densities typical for ion thrusters, that is n_e~10^{11} - 10^{12}cм$^{-3}$. In this range equivalent plasma resistance first increases with plasma density, reaches its maximum and then starts to decrease. Absolute values of R_{pl} increase with radius of ion thruster. However, even maximal value of the equivalent resistance of 50cм in diameter ion thruster does not exceed 1.4 Ohm. As it was mentioned above, the effective resistance of external circuit R_{ant} measured in various experiments[12-15] typically belongs to the range of 0.2-3 Ohm. So it is easy to see that without special arrangements main part of RF oscillator power will be lost for heating of the antenna, elements of matching system, etc.

In order to find ways of equivalent plasma resistance increase values of R_{pl} were calculated at increased argon pressure and working frequencies 6, 27 and 81 MHz.

Results of calculations of equivalent plasma resistance at various argon pressures are shown on Fig.3. Increase in pressure leads to essential rise of R_{pl}. Unfortunately large values of R_{pl} can be obtained at pressures higher than that typical for ion thrusters.

Calculations of equivalent plasma resistance at various working frequencies (see Fig. 4) showed that optimal working RF frequency of small diameter ion thrusters lies in the range 13 – 41MHz. In case of large size ion thrusters it is close to 13.6MHz. Unfortunately even using optimal working frequency it is impossible to achieve substantial increase of equivalent plasma resistance.

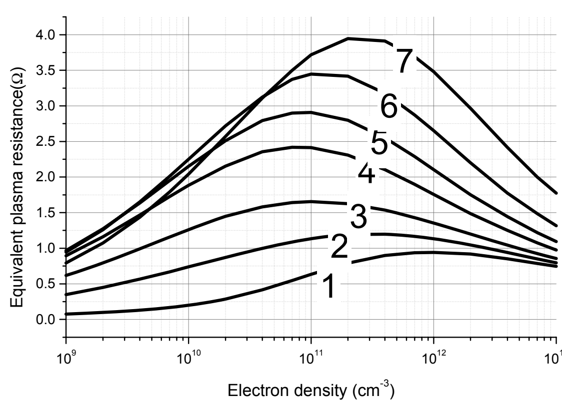


Figure. 3. Dependence of equivalent plasma resistance on density of plasma. Calculation is executed for flat disk-shaped sources at different pressure of neutral gas: 1 - 1mtorr, 2 - 5mtorr, 3 - 10mtorr, 4 - 20mtorr, 5 - 30mtorr, 6 - 50mtorr, 7 - 100mtorr.

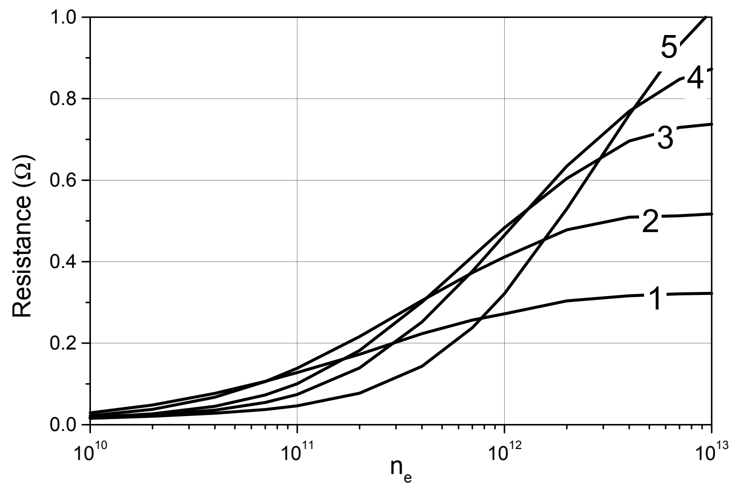


Figure 4a. Dependence of equivalent plasma resistance on plasma density at various RF working frequencies 1 - 6MHz, 2 - 13MHz, 3 - 27MHz, 4 - 41MHz, 5 - 81 MHz. Calculation is executed for flat disk-shaped sources of radius 2.5cm. Pressure of neutral gas is 10^{-3}Torr.

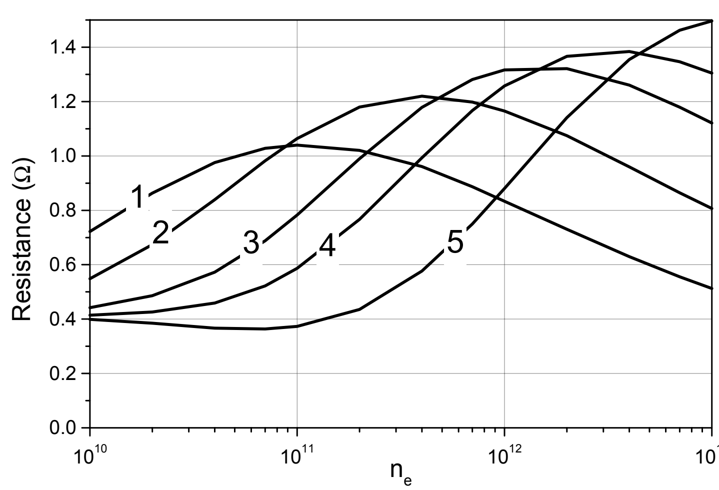


Figure 4b. Dependence of equivalent plasma resistance on plasma density at various RF working frequencies 1 - 6MHz, 2 - 13MHz, 3 - 27MHz, 4 - 41MHz, 5 - 81 MHz. Calculation is executed for flat disk-shaped sources of radius 25cm. Pressure of neutral gas is 10^{-3}Torr.

D. Dependence of plasma equivalent resistance on plasma parameters (inductive discharge with external magnetic field close to ECR conditions).

Mathematical simulation showed that significant increase of equivalent plasma resistance can be achieved in case if inductive discharge is enhanced by external magnetic field. Let us first consider RF ion thrusters operating under ECR conditions. Results of equivalent plasma resistance calculations at magnetic fields close to ECR conditions are shown on Fig. 5.

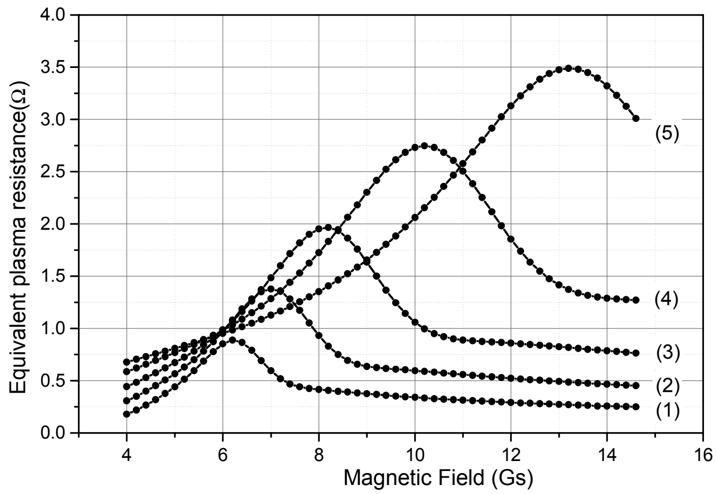


Figure 5. Dependence of equivalent plasma resistance on a magnetic field calculated for electron density 1-3.10^9, 2-1.10^{10}, 3-3.10^{10}, 4-1.10^{11} and 5-3.10^{11} cm^{-3}. Pressure of neutral gas is 10^{-3}Torr. R=2.5cм.

Fig.5 shows that dependence of plasma equivalent resistance on magnetic field value has wide maximum. Maximum position is shifted to larger B with increase of plasma density. It means that resonance occurs not under conditions

$$\omega=\Omega_e \tag{7}$$

that are usually referred as ECR but at magnetic fields[7] , corresponding to condition

$$\omega_{res}=\Omega_e-\frac{\omega_{Le}^2\Omega_e}{k^2c^2} \tag{8}$$

It follows from eq. (8), that resonant frequency is close to Larmour one, but is a little bit lower. Therefore resonance is reached only in area $\Omega_e > \omega$. At smaller fields the resonance is absent.

Fig. 5 shows that simultaneously with shift of resonant frequency maximal values of R_{pl} also grow. R_{pl} turns to be essentially higher, than values received for the inductive discharge without a magnetic field. Growth of radius of a thruster (see Fig. 6), as well as in the case without magnetic field, leads to increase of equivalent plasma resistance and improvement of RF power input to plasma. At resistance of an external circuit 1Ohm and magnetic fields, corresponding to ECR conditions it is possible to input to plasma 95 % of RF oscillator power if thruster radius is equal to 25cm.

It is necessary to note that rather high values of R_{pl} were received at low plasma density. It is argument in favor of development of low power plasma thruster based on ECR. For the benefit of practical use of ECR also speak low values of an external magnetic field necessary for achieving resonance conditions. Besides there are ways of the further increase of equivalent resistance. For example, it can be done, increasing frequency of the RF oscillator (see Fig. 7).

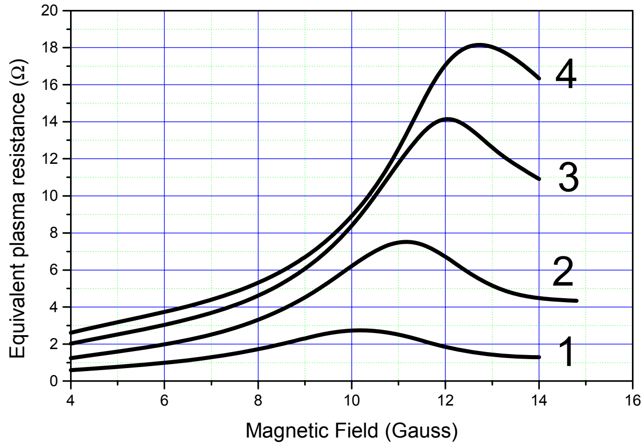


Figure 6. Dependence of equivalent plasma resistance on a magnetic field, for ion thrusters with radius 1-2.5, 2 -5, 3-10 and 4-25см. Electron density is equal to1.10^{11}cm^{-3}. Pressure of neutral gas is 10^{-3}Torr.

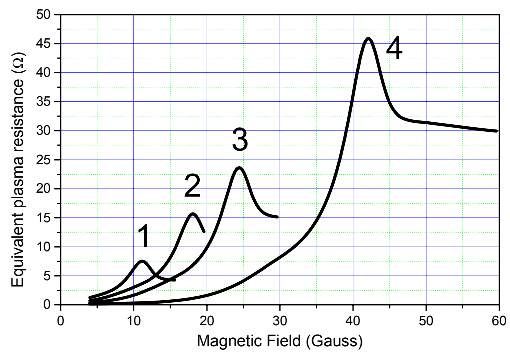


Fig. 7. Dependence of equivalent plasma resistance on a magnetic field at frequencies of the RF oscillator 1- 13, 2-27, 3-41 and 4-81 MHz. Electron density is equal to1.10^{11}cm^{-3}. Pressure of neutral gas is 1.10^{-3}Torr. R=5см.

Fig.5-7 correspond to low pressure of neutral gas. Increase of gas pressure leads to decrease of equivalent plasma resistance values. This result is opposite to that observed in case of the inductive discharge without a magnetic field.

Summarizing the results devoted to ECR RF ion thrusters, it is possible to draw a conclusion, that utilization of resonant absorption of RF power in ECR area allows to improve essentially RF power input. The effect is especially significant at frequencies higher, than 13MHz.

E. Dependence of plasma equivalent resistance on plasma parameters (inductive discharge with external magnetic field corresponding to conditions of helicon and Trievelpice-Gould waves excitation).

Results of calculation of equivalent resistance for Ar plasma (pressure -10^{-3}torr, working frequency - 13.56 MHz, concentration of electrons -10^{11}см$^{-3}$), executed for cylindrical sources with radius 2.5-25cm and lengths 10cm are represented on Fig. 8.

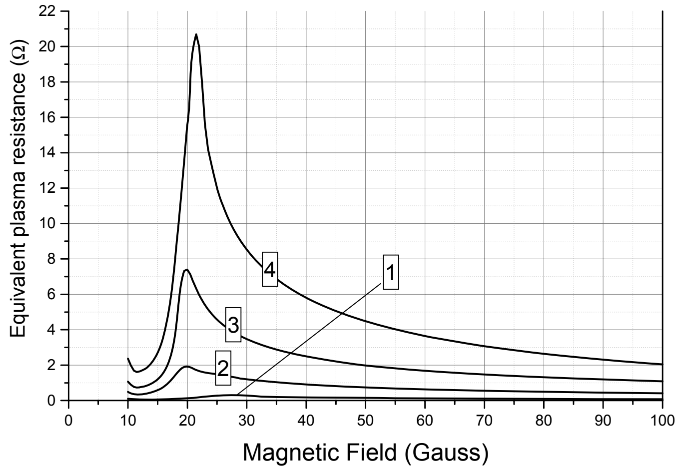


Figure 8. Dependence of equivalent plasma resistance on a magnetic field, for ion thrusters with radius 1-2.5, 2 -5, 3-10 and 4-25см. Electron density is equal to 10^{11}cm^{-3}. Pressure of neutral gas is 10^{-3}Torr.

Equivalent plasma resistance essentially depends on an induction of external magnetic field. As well as in case of the inductive RF discharge without a magnetic field, values of equivalent resistance rise with increase of radius of ion thruster. Practically full absorption of the power of RF oscillator is provided in ion thrusters with radius higher than 10cm.

In case of disk-shaped sources of plasma without a magnetic field equivalent resistance did not depend on the length of ion thruster. In case of magnetically enhanced ion thruster situation is opposite. It is possible to increase R_{pl} by increasing the ion thruster length (see Fig. 9). This can be useful for development of small radius ion thrusters.

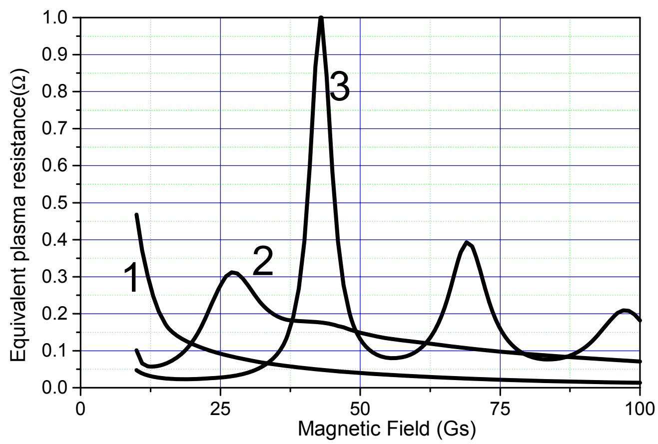


Figure. 9. Dependence of equivalent plasma resistance on a magnetic field. Radius of a source is 2.5см. Pressure of neutral gas is 10^{-3}Torr. 1 – L=5cm, 2 = L=10cm, 3 –L =15cm.

One more parameter, allowing to increase R_{pl} is working frequency of RF oscillator. Fig.10, shows that increase of ω leads to essential growth of R_{pl} and displacement of R_{pl} *(B)* maximum to the realm of higher magnetic fields. It is worth to add that R_{pl} oscillations are observed at the increased working frequency.

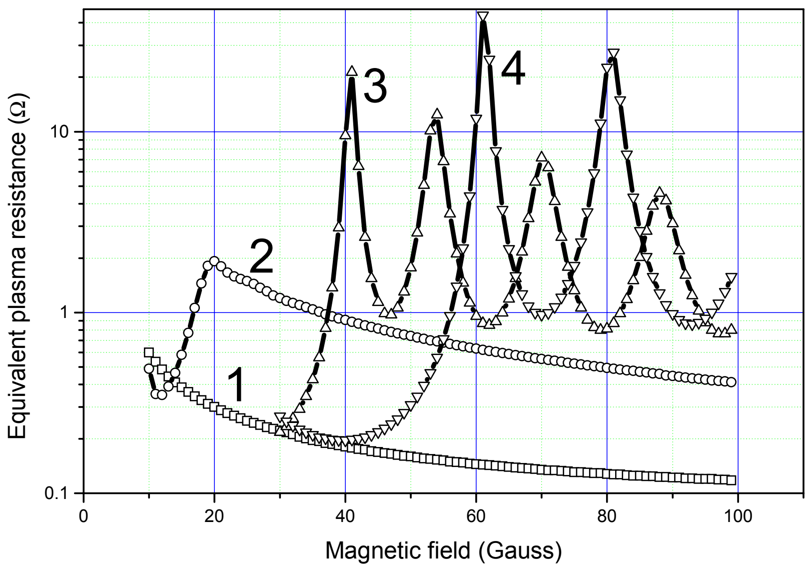


Figure 10. Dependence of equivalent plasma resistance on a magnetic field for various working frequencies 1 – 6, 2-13, 3-27 and 4 –41MHz. Radius of thruster is 5см, length 10см, plasma density is equal to 1.10^{11}см$^{-3}$. Pressure of neutral gas is 1.10^{-3}Torr.

In section II.C it was marked, that the increase of working gas pressure led to the increase of equivalent plasma resistance in case of RF inductive discharge without a magnetic field. In case of the magnetic fields corresponding to area of excitation of helicon and Trivelpiece-Gould waves, situation is opposite, i.e. peak values of R_{pl} decrease with growth of gas pressure. However decrease of R_{pl} takes place at pressures higher than that used in RF ion thrusters.

Above mentioned results have been received for electron density equal to 10^{11}см$^{-3}$. Fig. 11 shows that increase of n_e leads to growth of equivalent plasma resistance. However, R_{pl} growth is accompanied by displacement of effective plasma resistance maximum position to higher magnetic fields.

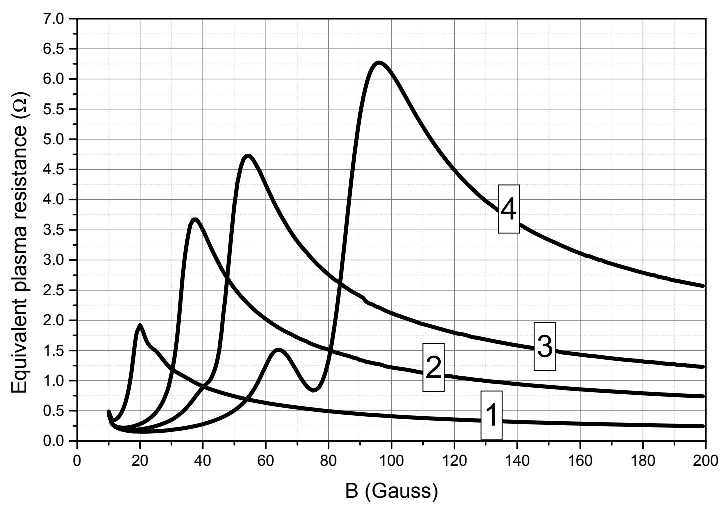


Figure 11. Dependence of equivalent plasma resistance on a magnetic field at different plasma density 1 - 10^{11}, 2- 3.10^{11}, 3 – 5.10^{11} and 4-1.10^{12} cm^{-3}. Radius of thruster is 5см, length 10см. Pressure of neutral gas is 10^{-3}Torr.

F. Comparison of absorption efficiency of RF power by the inductive discharge plasma at various values of external magnetic field inductance.

The values of equivalent resistance, received at various methods and conditions of plasma excitation, allow to formulate a number of conclusions concerning possible ways of efficient RF power input to plasma. Fig.12 summarizes the obtained results. It shows areas of plasma parameters corresponding to conditions of optimal RF power input at various methods of inductive discharge excitation for working frequency 13.6 MHz. At low pressures corresponding to RF ion thrusters operation it is worth to utilize ECR condition if low ion current is necessary. In case of high ion currents it is reasonable to utilize magnetic fields corresponding to excitation of helicon and Trivelpiece-Gould waves. In order to increase efficiency of RF power input to ion thrusters sources of small radius, it is worth to increase thruster length or working frequency.

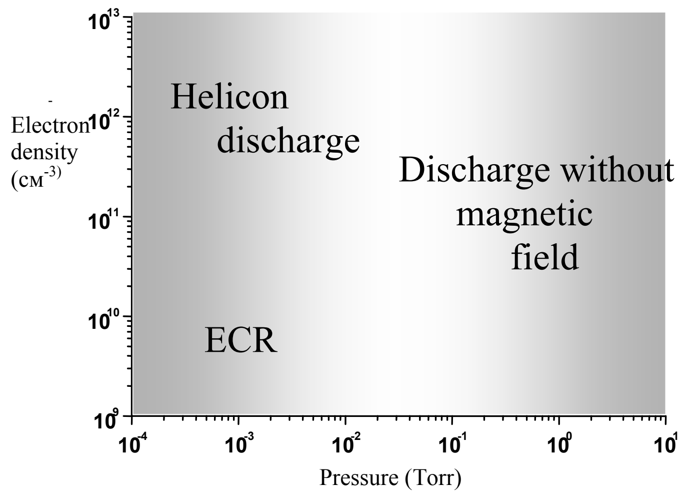


Figure 12. Areas of plasma parameters where it is possible to achieve effective power input to plasma at various methods of excitation of the inductive RF discharge. Frequency is 13.6MHz.

III. How we can generate plasma with maximal electron density at given RF power input.

A. Relation of the plasma parameters to the RF power deposit to plasma.

The relationship between the power deposited in the plasma and the plasma parameters can be determined from a simple physical model of a low pressure RF inductive discharge[6]. The model is based on the following assumptions:

(i) the electron energy distribution function is Maxwellian,

(ii) the density of multiply ionized atoms is negligibly low, and

(iii) the density of the ion current to the walls of an ion source is constant at any point.

The model equations are the balance equations for the numbers of ions, electrons, and heavy neutral particles, the power balance equation, and the equation fixing quasineutrality condition [4].

B. Parameters, that affect efficiency of ion thruster operation.

Increase of plasma density at the given RF power input can be achieved by the choice of 1) optimal ratio between ion thruster radius and length; 2) optimal transparency of ion extraction system for ions and neutrals, and 3) optimal magnetic field induction and configuration.

Three different magnetic systems are reasonable to be considered.

1. Magnetic field is absent. It means that electrons can reach any part of thruster gas discharge chamber (GDC) surface except the surface of the holes in ion extraction system.
2. Weak longitudinal magnetic field. It means that ions motion is not affected, electron mobility perpendicular to magnetic field is reduced.. For simplicity it is possible to assume that electrons can reach only end-walls of ion thruster except the surface of the holes in ion extraction system.
3. Weak longitudinal magnetic field and "magnetic wall" near top end-wall of ion thruster. In this case electron can reach only bottom end-wall of ion thruster except the surface of the holes in ion extraction system.
4. Strong longitudinal magnetic field. Both electrons and ions are confined.

Numerical simulation was carried out for 10cm in diameter ion thruster working on Xe

C. Results of numerical simulation.

Figure13 represents dependencies of RF power necessary for 300mA ion current generation on Xe flowrate calculated for different length L of ion thruster gas discharge chamber (GDC). It is possible to distinguish two different modes of ion thruster operation. In the first one the reduction of Xe flowrate results in the significant increase of necessary RF power input, in the second one necessary power practically does not depend on Xe flow rate. Figure 13 shows that the minimal power expenditures for ion current generation in the second mode can be obtained with the shortest GDC. However, the border between two modes in case of 2.5cm length GDC is shifted towards high Xe flow rates. This can reduce gas efficiency of RF ion thruster. In order to improve γ it is worth to utilize ion extraction system with reduced transparency for neutrals (see Fig.14).

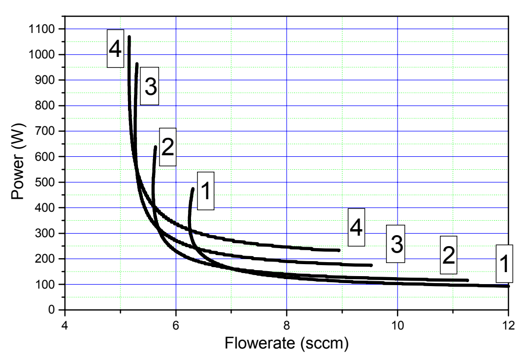


Figure13. Dependence of RF power necessary for 300mA ion current generation on Xe flowrate calculated for different length of ion thruster gas discharge chamber 1-2.5cm, 2-5cm, 3-10cm and 4 –15cm. Transparency of ion optic system for ions and neutrals is equal to 0.6.

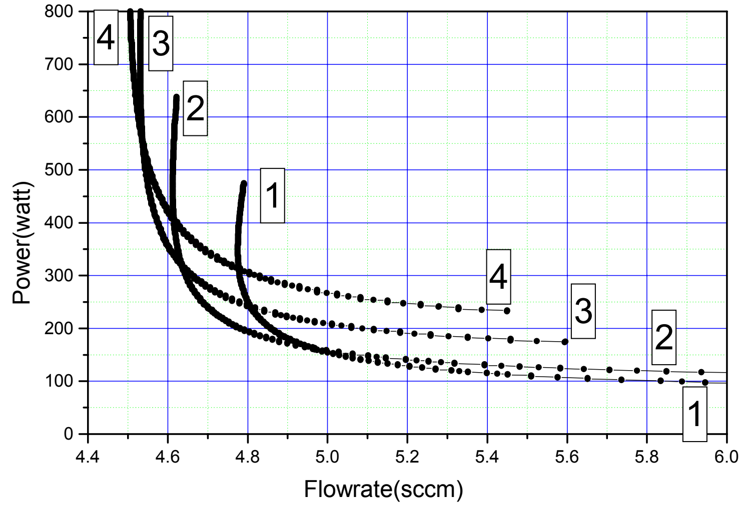


Figure 14. Dependence of RF power necessary for 300mA ion current generation on Xe flowrate calculated for different length of ion thruster gas discharge chamber 1-2.5, 2-5,3-10 and 4 –15cm. Transparency of ion optic system for ions and neutrals is equal to 0.6 and 0.15 correspondingly.

In order to make the comparison between ion thrusters with different dimensions and magnetic systems more visual let us consider the dependencies of ion beam production cost C_i on gas efficiency γ and choose C_i corresponding to γ=0.7. Fig.15 represents a set of C_i values specified in the above mentioned way. Fig.15 shows that decrease of GDC length first leads to the substantial decrease of ion beam production cost, then after reaching minimum at critical length L* C_i abruptly increases. The increase of the extracted ion current results in the reduction of L* and decrease of ion beam production cost values. Weak magnetic field gives the opportunity to reduce C_i but significant decrease of ion cost values can be achieved only at magnetic fields confining not only electrons but ions too.

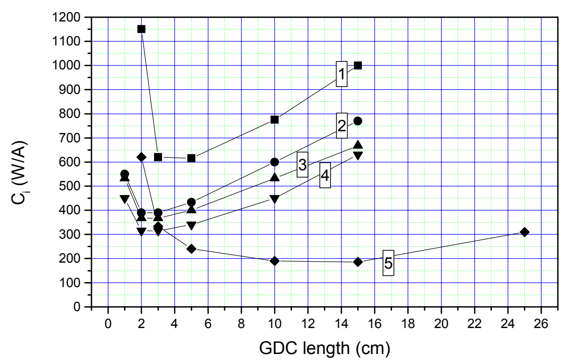


Figure 15. Dependence of C_i on gas discharge chamber length. 1 corresponds to the case when 100mA ion beam is generated, weak magnetic field; 2 –5 correspond to the cases when 300mA ion beam is generated, 2 – weak magnetic field, 3 – weak magnetic field with "magnetic wall", 4 –strong magnetic field.

Let us summarize the results. Mathematical simulation of RF ion thruster operations showed that power expenditures can be reduced by the presence of magnetic field, by the growth of extracted ion current, by decrease of ion optic system transparency for neutrals and by reduction of GDC length in the realm of L>L*.

IV. How to match conditions of good RF power absorption with conditions of efficient plasma generation.

In section II it was shown that RF power absorbed by plasma is not equal to the power of RF oscillator. Let us compare the conditions of good RF power absorption revealed in section II with conditions of efficient plasma generation revealed in Section III.

Simple physical model of inductive discharge gives the possibility to calculate a set of plasma parameters for given RF power input. Determined plasma parameters can be used for calculation of equivalent plasma resistance and estimation of the power input efficiency $\delta = P_{pl}/P_{Gen}$. The δ values are presented on Fig.16 for the case of antenna resistance equal to 1Ohm. Figure16 shows that utilization of short GDC provides low power efficiency of RF ion thruster. Increase of GDC length is accompanied by the growth of power input efficiency and 15cm in length GDC provide nearly 100% transfer of RF oscillator power to plasma. Thus consideration of the power losses in the external circuit changes conclusion about optimal length of the ion thruster. This can be also proved by Fig.17 where C_i values corrected by power efficiency factor are represented.

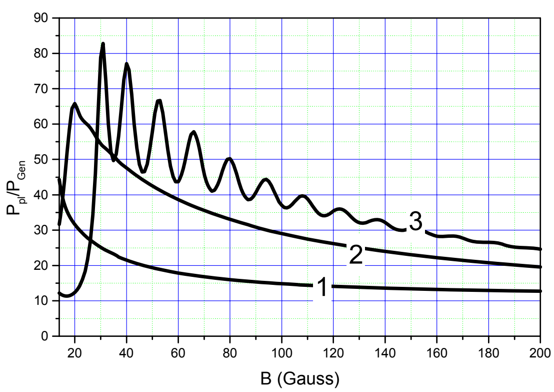
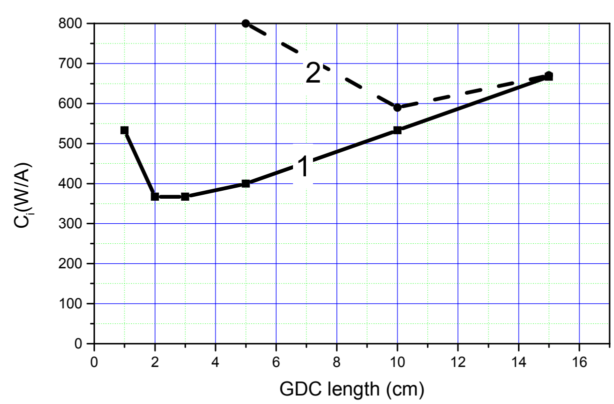


Figure16. Dependence of power input efficiency on magnetic field for electron density 1.10^{11}cm^{-3}. Radius of GDC is equal to 5cm, length is equal to 1-5,2-10 and 3-15cm.

It is worth to remind that the lowest C_i values where obtained in III for the case of strong magnetic field. It can be seen from Fig.11 that for plasma densities typical for ion thruster operation plasma equivalent resistance in the realm of high magnetic fields is very low. Thus operation of RF ion thruster enhanced by strong magnetic field will be ineffective.

Figure17. Dependence of C_i on gas discharge chamber length. 1- C_i are calculated on the basis of power absorbed by plasma values, 2 C_i are calculated on the basis of RF oscillator power.



Summarizing the results of this sections it is possible to point out that the most efficient 10cm RF ion thruster working at 13.6MHz must be based on the 10cm in length GDC located in the weak magnetic field with “magnetic wall” near upper end wall and ion extraction system with high transparency for ions and low transparency for neutrals.

Fig.17 shows that the resultant ion cost that can be obtained with the above mentioned RF ion thruster is rather high. The way out can be obtained by the increase of the ion thruster working frequency. Fig.18 shows that the increase of ω up to 41 MHz gives the opportunity to obtain 90% power input in the RF ion thruster with 5cm in length GDC.

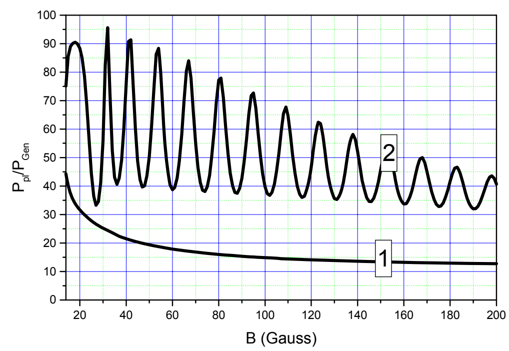


Figure 18. Dependence of power input efficiency on magnetic field for electron density $1.10^{11}cm^{-3}$. Radius of GDC is equal to 5cm, length is equal to 5cm. 1 – 13, 2 – 41MHz.

V. Optimization of the ion thruster parameters working at the frequency 13.56MHz (Experiment).

A. Experimental set-up and experimental methods.

Experimental set-up is described in details elsewhere[3]. The scheme of low power RF ion thruster is shown on Fig.19. RF ion thruster consists of glass GDC (1), gas distributor (2), magnetic system (3), based on electromagnets which produced magnetic field with induction 0...0.1 Tl on the axis of GDC; ion optical system (4), consisting of three electrodes. Several GDC with diameter equal to 10cm and length 5, 7, 10 and 15cm were tested. Spiral antennae located on external side surface or upper end-wall of GDC as well as Nagoya III type antenna were used. All antennae were cooled by the water flow.

In order to ignite discharge antenna ends located on the external side of ion thruster GDC were connected through the matching box to RF oscillator. RF oscillator power was determined as the difference between measured forward and reflected power. The reflected power did not exceed 3% of the forward power. Antenna current was measured with the help of Rogovskiy coil. In order to determine antenna resistance the dependence of I on P_{Gen} was measured without discharge. In order to determine equivalent plasma resistance first value of $R_{ant}+R_{pl}$ was determined by measuring P_{Gen} and I :

$$R_{ant}+R_{pl} = P_{Gen}/I^2; \qquad (9)$$

Then R_{pl} was determined using predetermined R_{ant}.

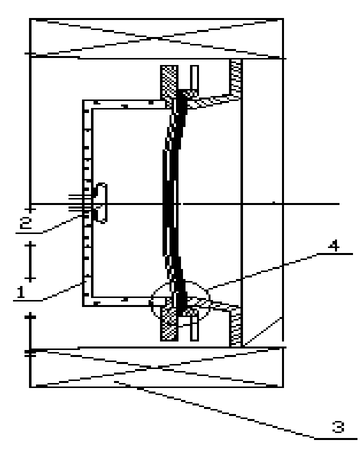


Fig.19. The scheme of RF thruster.

B. Results of equivalent plasma resistance measurements.

Figures 20-22 show the dependencies of R_{pl} on magnetic field value B measured with 10cm in diameter 13.6MHz ion thruster prototype. One can see that under condition $B=0$ equivalent plasma resistance is close to 1Ω. R_{pl} significantly increases its value under conditions of magnetic field increase and reach maximum at B corresponding to conditions of helicon and Trivelpiece-Gold waves excitation. Existence of several local maxima of $R_{pl}(B)$ dependence can be attributed to the resonance waves excitation. Figs.20-22 show that similar to simulated values experimental R_{pl} increases with increase of GDC length. GDC with length equal to 10cm and more provide efficient power input to plasma.

It is worth to note that under condition of 10cm in length gas discharge chamber the increase of power input to plasma leads to the decrease of R_{pl}. This can reduce efficiency of ion thruster in case of large thrust values.

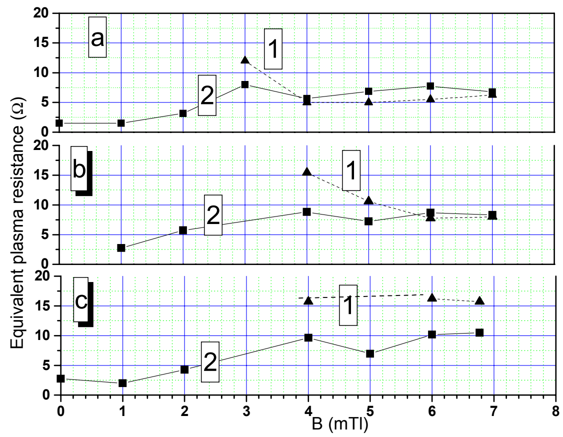


Figure 20. Dependence of equivalent plasma resistance on magnetic field for ion thruster with 15cm in length GDC. Xe flowrate is equal to a - 1.5, b - 3 and c – 5 cm^3/min. 1 - P_{pl}=100W, 2- P_{pl}=200W.

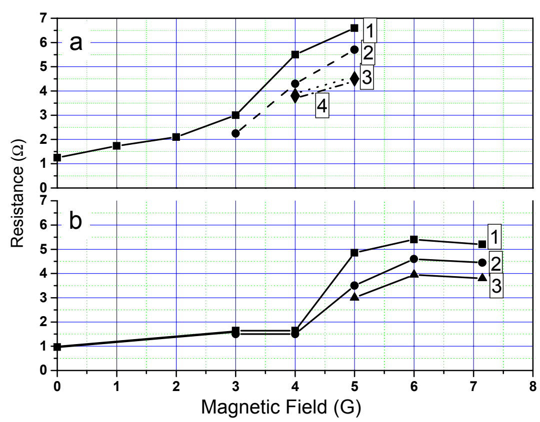


Figure 21. Dependence of equivalent plasma resistance on magnetic field for ion thruster with 10cm in length GDC. R=5cm. Xe flowrate is equal to a - 1.5 and b - 3cm^3/min. 1 - P_{pl}=100W, 2- P_{pl}=150W, 3 - P_{pl}=200W, 2- P_{pl}=250W.

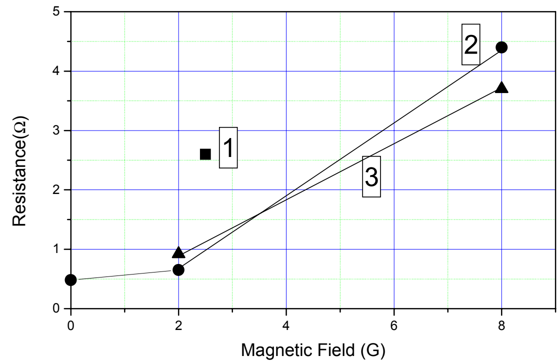
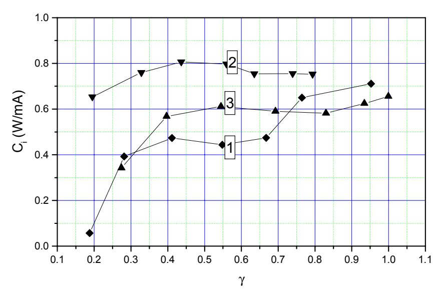


Figure 22. Dependence of equivalent plasma resistance on magnetic field for ion thruster with 5 (1 - P_{pl}=100W) and 7cm in length GDC (2- P_{pl}=100W, 3 - P_{pl}=200W).

C. Results of the ion cost measurements.

Basing on results of mathematical simulation it was supposed that existence of external magnetic field should decreases values of ion production cost. Unfortunately experiment showed opposite result.

Results of C_i and P_{pl}/P_{Gen} determination at different values of magnetic field are represented on Figs.23 and 24. Figure 23 shows that increase of external magnetic field results in significant increase of ion beam production cost. At the same time Figure24 indicates substantial improvement of RF power efficiency input in accordance with R_{pl} behavior (see section V.B). It means that under conditions of experiment conditions of good power absorption and efficient plasma generation could not be matched. The last conclusion gave rise to more detailed study of magnetic field influence on discharge parameters.



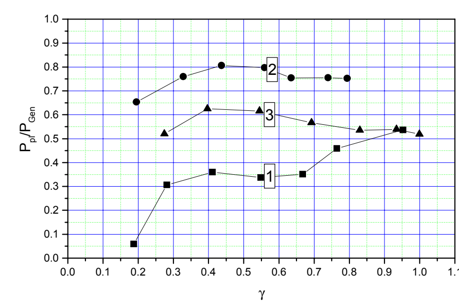


Figure 23. Dependence of C_i on γ. **Figure 24. Dependence of P_pl/P_{Gen} on γ.**
1 - RF discharge without magnetic field, 2 - RF discharge with uniform magnetic field, 3 - RF discharge with non-uniform magnetic field.

Figure 25 represents dependencies of equivalent plasma resistance, power absorbed by plasma and ion beam current on magnetic field measured at fixed power of RF oscillator. The most astonishing is the fact that ion current value is not proportional to RF power absorbed by plasma. Further experiments showed that the reason of this effect lies in the spatial redistribution of electron density due to the presence of magnetic field. Figure 26 shows radial distribution of ion beams current measured near the ion extraction system at different B. One can see that ion beam current reaches its maximum at magnetic field corresponding to uniform radial distribution of ion beam current density. At magnetic field corresponding to maximum of equivalent resistance ion beam current density peaks near thruster axis and at the periphery ion beam current density is low. Redistribution of plasma density along

GDC length also contributes to the increase of ion beam production cost.

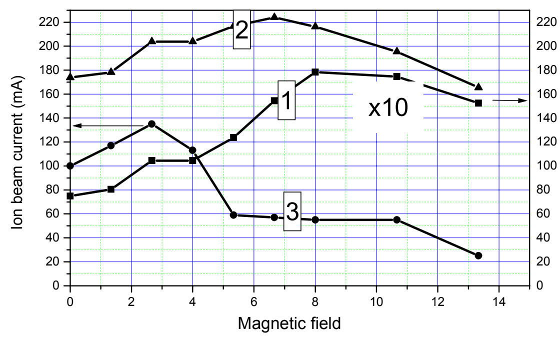


Figure 25. Dependence of equivalent plasma resistance (1), power absorbed by plasma (2) and ion beam current (3) on magnetic field.

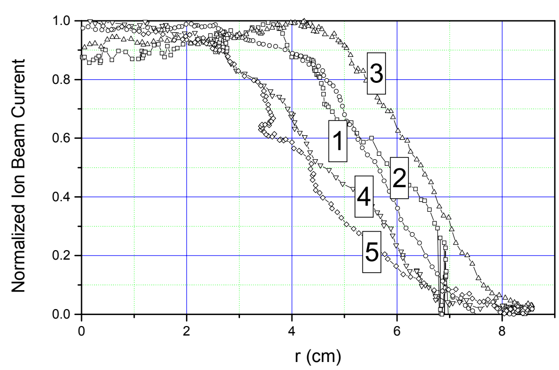


Figure 26. Ion beam profiles at different values of magnetic field. 1- B=0, 2-B=1.5, 3 – B=3, 4-B=6 and 5 – B=11.

Results obtained with the thruster model equipped by electromagnets providing uniform magnetic field were rather pessimistic. Nevertheless the way out was found by utilization of non-uniform magnetic field that caused positive changers in plasma parameters spatial distribution. The ion cost values obtained with non-uniform magnetic field gave the possibility to obtain satisfactory both ion production cost and power input efficiency.

The attempts to test ion thrusters with 5 and 7 cm in length GDC were negative due to poor RF power input efficiency resulted in non-stable operation of ion thrusters.

YI. Conclusions.

1. The power of RF oscillator is divided between two channels: antenna and plasma. The power absorbed by plasma is defined by equivalent plasma resistance.
2. The factors that lead to increase of equivalent plasma resistance are the growth of GDC radius and presence of external magnetic field. In case of ion thrusters enhanced by magnetic field equivalent plasma resistance can be

increased by the growth of GDC length and working frequency.

3. Power expenditures for discharge generation can be reduced by the presence of magnetic field, by the growth of extracted ion current, by decrease of ion optic system transparency for neutrals and by reduction of GDC length in the realm of L>L*.
4. Conditions of efficient plasma generation should be matched with conditions of efficient power input.
5. Non-uniform magnetic field should be used for reduction of ion beam production cost.

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