PROBE MEASUREMENTS IN DISCHARGE CHAMBER OF LOW-POWER ION THRUSTER

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Abstract

Low-power (from tens of Watts to several hundreds Watts) ion thrusters (IT) can be efficiently applied on board the small spacecraft (SC) (with mass less than 1000 kg) to solve the tasks of operation of remote sensing and communication SC in near-Earth space (atmospheric drag compensation of low Earth orbit SC, transfer into operating orbit, orbit adjustment, etc.).

Up to the present time KeRC in cooperation with MAI carry out the development and tests of laboratory models of xenon IT with 5- and 10-cm discharge chamber typical diameters[1, 2].

In this paper obtained experimental distributions of plasma local parameters (electron temperatures and densities, potentials of electrical field) in discharge chamber of 5-cm laboratory model of low power IT at nominal mode are presented.

Introduction

The heritage of development and study of different IT dimension types make it evident that the decrease of thruster power consumption level and, accordingly, its overall dimensions lead to the decrease of thruster efficiency because of ion production cost growth at comparable values of propellant utilization efficiency. In this case ionization losses also grow due to significant worsening of propellant ionization probability by electrons in discharge plasma and increase of probability of ion recombination on discharge chamber walls when reducing its geometrical size.

Up to date there are no efficiently operated ion thrusters with nominal power less than 300 W. Therefore, the task to develop small-size discharge chambers with low ion production cost together with high propellant utilization efficiency remains topical.

For 5-cm ion thruster with two-pole magnetic system it is necessary to find the values of parameters, which strongly affect the operation of discharge chamber[3, 4] (fig. 1): the length of cathode pole piece, the diameter of cathode pole piece, baffle diameter, its position relative to cathode pole piece, the position of the cathode in the pole piece. All these parameters form the geometry and the volume of so-called near-cathode area, which is responsible for input of primary electrons from the cathode to the main volume of discharge chamber and their following distribution. Besides, the length of cathode pole piece defines the length of ion production area, and together with cathode pole piece diameter – the configuration of magnetic field lines in discharge chamber. Magnetic induction can be varied by current change in electric magnet coils.

Preliminary experiments

Tests of laboratory model of ion thruster were carried out in "Kedr" facility at KeRC. Total volume of vacuum chamber was 1 m^3. Pumping system provided residual pressure of $(1\text{-}2)\cdot10^{-5}$ Torr and $(3\text{-}5)\cdot10^{-5}$ Torr during thruster operation (by xenon).

Dimensions of cathode pole piece were varied within wide range during experiments: external diameter – from 24 to 30 mm, length – from 14 to 26 mm. The set of perforated plates of molybdenum was used as accelerating system. The transparency of screen grid was 0.69, accelerator – 0.3. The potentials on the grids were constant (900 V on screen grid).

In experiments the distance between cathode pole piece edge and screen grid was kept constant. At that the depth of near-cathode area was 16-28 mm that has been considered as optimal[3]. Combined hollow cathode[5] was used during the study. Propellant flow rates to the cathode and discharge chamber were 30 and 60 eq.mA, correspondingly. For this type of cathode such value of flow rate was optimal.

Obtained dependencies of ion production cost from propellant utilization efficiency – $C_i(\beta_u)$ – indicated that the best thruster performance could be realized when using 18 mm and 22 mm "narrow" (24-mm external diameter) and 22 mm "wide" (30-mm external diameter) cathode pole pieces. It should be noted that the thruster with these cathode pole pieces provides not only high output parameters but also the most steady operation modes. Special experiment, conducted with one of selected cathode pole pieces – 18-mm "narrow" – showed that the best output parameters could be achieved at the current 4…5 A in electric magnet coils.

The study of thruster operation with baffle was carried out using 22-mm "wide" cathode pole piece. Baffle diameters were 9 and 12 mm. Baffles were put in three positions relative to cathode pole piece edge: -3 mm, 0 mm and 3 mm. Values of flow rate and electric potentials in accelerating system were the same. Based on analysis of obtained $C_i(\beta_u)$ functions it was concluded that for all studied options use of the baffle leads to decrease of output parameters, discharge voltage growth and in some cases – to intensive degradation of cathode surface and impossibility to get the discharge.

As a result of this experimental series the range of rational parameters of discharge chamber was obtained. This rational geometry provides high thruster output parameters: thrust – 3.8 mN, specific impulse – 3100 s, efficiency – 57% at power of ~100 W (losses of flow rate and power in neutralizer were not taken into account).

Probe measurements in discharge chamber

Automatized system of probe measurements was developed to get distributions of plasma parameters in discharge chamber. This system includes five units: probe unit, power supply system, signal transformation unit, synchronizer unit and recording system.

The system provides four recording channels: probe current, probe potential relative to the cathode, probe position and beam current. The rate of recording corresponded to 1 mm of probe path across discharge chamber. Each record included 256 points, which went in one period of experimental sinusoid. The rates of probe motion and measuring were selected in such way that it could be considered that each voltage-current curve is obtained at motionless probe position; all four channels are interrogated simultaneously; transition processes in plasma, connected with probe motion, do not affect voltage-current characteristic.

Planar Langmuir probes were picked out for measurements. The diameter of their working surface was 0.35 mm, their length – 100 mm. Probes positioning is shown in fig. 2. One probe was placed in near-cathode area, two – in the main volume of discharge chamber, one – near accelerating system. Probes were supplied alternately to avoid changes of discharge parameters.

Results of measuring of IT-5 output parameters during probe experiment are shown in fig.3. Initially, probes were at floating potential and maximally moved out of discharge chamber. For mentioned options of discharge chamber configuration ion production cost as a function of propellant utilization efficiency was obtained. Based on these functions the operating point, at which probe measurements were carried out, has been selected. Approximate maximum of ion thruster efficiency was taken as criterion to choose such operating point. In reference to this experimental series it means that ion beam current was about 72…75 mA.

The processing of experimentally obtained voltage-current curves was carried out using Strickfaden-Geiler-Medicus method[6-8]. To verify the values of plasma potential first and second derivatives of voltage-current characteristic were defined.

The range of plasma potential in experiments was 38.4…45.4 V; typical temperature of Maxwellian electrons was 12…14 eV; the density of Maxwellian electrons at discharge chamber axis was $(2.6…4.35)\cdot 10^{17}$ $1/m^3$; typical ratio of primary electron density to Maxwellian electron density was 10…15 %; average energy of primary electrons was 28…33 eV. The example of distributions of plasma potential, plasma density and electron temperature for the best case is shown in fig. 4.

The adequacy of probe-measured results was estimated in two ways. First, beam current beyond accelerating system was compared with ion current, calculated by Bohm equation, inside the discharge chamber near accelerating system. Since all probe measurements were conducted at specified value of beam current, then corresponding values of Bohm current should be not only close to beam current but also be approximately equal to each other.

Calculated results show that values of Bohm ion current are similar to each other (maximal difference does not exceed 6.2 %) and are close to the value of beam current with accuracy not worse than 18.7 %. The processing by Student criterion allows getting confidence interval of 63.2±3.5 mA at P_g=0.9 for mentioned values of Bohm current. Therefore, it can be concluded that obtained data concerning local plasma parameters are correct for concrete section (10 mm from screen grid) for all conducted experiments. Since the conditions and the order of conduction of all experiments and also the processing technology of obtained data were identical, then it can be stated that local plasma parameters in other sections are correct too and have the same values of absolute and relative errors.

The processing of ion part of voltage-current characteristic for several randomly chosen points of probe experiment allows obtaining the density of charged particles, which in 3-4 times exceed corresponding values, obtained from electron part of voltage-current characteristic. This fact can be also considered as satisfactory result.

Mathematical simulation on the base of probe-measured results

Obtained experimental data were used to draw two-dimensional functions, which define the distributions of plasma potential, plasma density and other discharge parameters in discharge chamber volume. All experimental curves were processed by similar procedure using multiple smoothing with B-spline. Curves of potential distribution were supplemented with anode potentials at the end points (r=26 mm). Based on densities of Maxwellian electrons n_{eT}, their temperatures, densities of primary electrons n_{ef} and their velocities v_{ef} ionization frequency of neutral atoms was calculated:

$$\nu_n = n_{es}\left\langle v_{eT}\sigma_i\left(v_{eT}\right)\right\rangle + n_{ef}v_{ef}\sigma_i\left(v_{ef}\right), \qquad (1)$$

where $\sigma_i\left(v_e\right)$ - ionization cross-section of xenon.

Besides, motion paths for ions, generated in discharge chamber, were calculated for each option. In accordance with these results, assuming homogeneous distribution of neutral atoms density in discharge chamber volume, the parameter γ was defined. γ - the ratio of ion current, reaching the surface of screen grid, to total ion current, coming to all electrodes (charged surfaces). Assuming that neutral density n_n is homogeneous all over the discharge chamber, ion beam current can be calculated by the equation:

$$I_b = n_n e\gamma\alpha_{si}\iiint\limits_V \nu_n dV \qquad (2)$$

where α_{si} - transparency of accelerating system for ions, e - electron charge, the integration is carried out by all volume of discharge chamber. The density of neutral atoms can be estimated using propellant utilization efficiency η_u:

$$n_n = \frac{1-\eta_u}{\eta_u}\,\frac{4I_b}{\alpha_{sn}\,e\,S_s\left\langle V_n\right\rangle}, \qquad (3)$$

where α_{sn} - transparency of accelerating system for neutral atoms, $\left\langle V_n\right\rangle$ - average velocity of thermal motion of neutral atoms, S_s - screen grid area. Putting (3) to (2), we get the condition

$$\frac{1-\eta_u}{\eta_u}\cdot\frac{4\gamma\,\alpha_{si}}{\left\langle V_n\right\rangle\alpha_{sn}\,S_s}\iiint\limits_V \nu_n dV = 1, \qquad (4)$$

which fulfillment can be considered as the criterion of validity for measured results.

The example of numerical simulation for configuration with 18-mm “narrow” cathode pole piece at electric magnet current of 5 A is shown in fig.5. In described option values of parameters, which form the left part of equation (4), were: S_s=1.67·10^{-3} m, η_u=0.83, γ= 0.46, $\left\langle V_n\right\rangle$=283 m/s (at neutral atoms temperature of 500°K), the integral of ionization frequency of neutral atoms by discharge chamber volume – 0.162 m^3/s. The ratio of ion current, reaching the surface of screen grid, to total ion current, coming to all electrodes, was 0.46. Effective transparencies of screen grid α_{si} and α_{sn} were numerically calculated using 2D-software of simulation of charged and neutral particle fluxes[9]. These values were α_{si} = 0.72, α_{sn} = 0.15. Their substitution to the left part of equation (4) gave 0.62.

Such result can be considered as satisfactory because it was obtained at rather crude assumption of neutral density distribution homogeneity by discharge chamber volume. To meet this requirement average free path of neutral atoms till ionization should be noticeably larger than typical size of discharge chamber. In described example calculated ionization frequency of neutral atoms near thruster symmetry axis was about 6000 s^{-1}. At average thermal motion velocity of neutral atoms of 283 m/s and temperature of 500°K, their free path till ionization is about 5 cm, i.e. it is equal to typical size of discharge chamber. Therefore, the distribution of neutral density close to the area of intensive ionization can be strongly inhomogeneous.

Conclusions

Based on the study of working parameters of 5-cm ion thruster laboratory model, operating at power of 50…150 W the range of rational parameters of magnetic system of discharge chamber is obtained.

The search for the range of rational parameters of magnetic system in IT-5 provides ion production cost between 305 and 395 W/A at propellant utilization efficiency of 0.75…0.85. Besides, these rational parameters together with perfected design parameters of other main units of IT-5 (cathode unit and accelerating system) make it possible to obtain the following thruster output parameters: thrust – 2.2…5.4 mN, specific impulse - 2700…4000 c, efficiency 47…65 % at power of 60…150 W (losses of flow rate and power in neutralized are not taken into account).

Automatized system for probe measurements was developed. This system allows obtaining local plasma parameters in discharge chamber of low-power ion thruster at real operating modes. Using this system distributions of local plasma parameters in discharge chamber of IT-5 were obtained at nominal mode: at beam current of 72…75 mA and at ion energy of 600…900 eV.

These distributions can be efficiently used in analysis and mathematical simulation of physical processes in discharge chamber of low-power ion thrusters.

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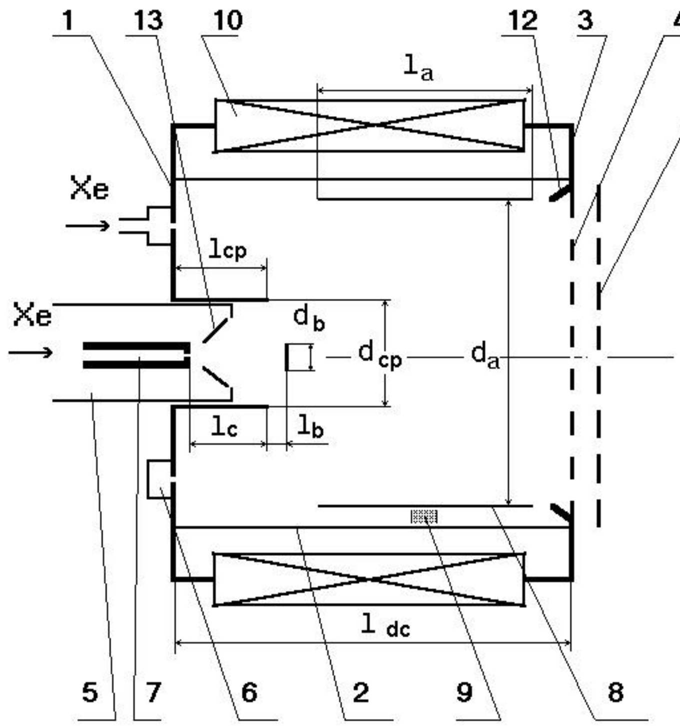


Fig. 1. 5-cm ion thruster principal schematic

1 – back plate, 2 – cylindrical shell, 3 – electrode holder, 4 – screen grid, 5 – cathode unit, 6 – collector-gas distributor, 7 – cathode, 8 – anode, 9 – anode insulator, 10 – coils of magnetic system, 11 – cathode pole piece, 12 – anode pole piece, 13 – keeper, 14 – accelerator grid.

l_a – anode length; l_{dc} – discharge chamber length; l_{cp} – length of cathode pole piece; l_C – distance between cathode edge and cathode pole piece edge; l_b – distance between cathode pole piece edge and baffle; d_a – anode diameter; d_{cp} – cathode pole piece diameter; d_b – baffle diameter.

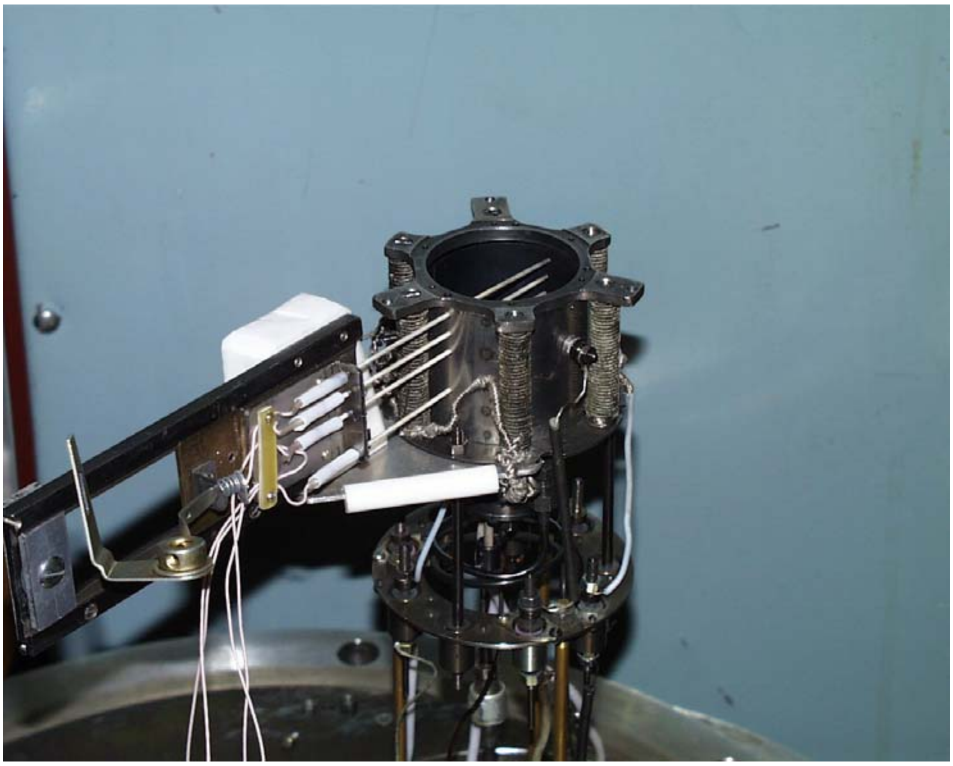


Fig. 2. General view of discharge chamber with probes.

Probes are placed at 17 mm, 32 mm, 39 mm and 46 mm from the back plate of discharge chamber

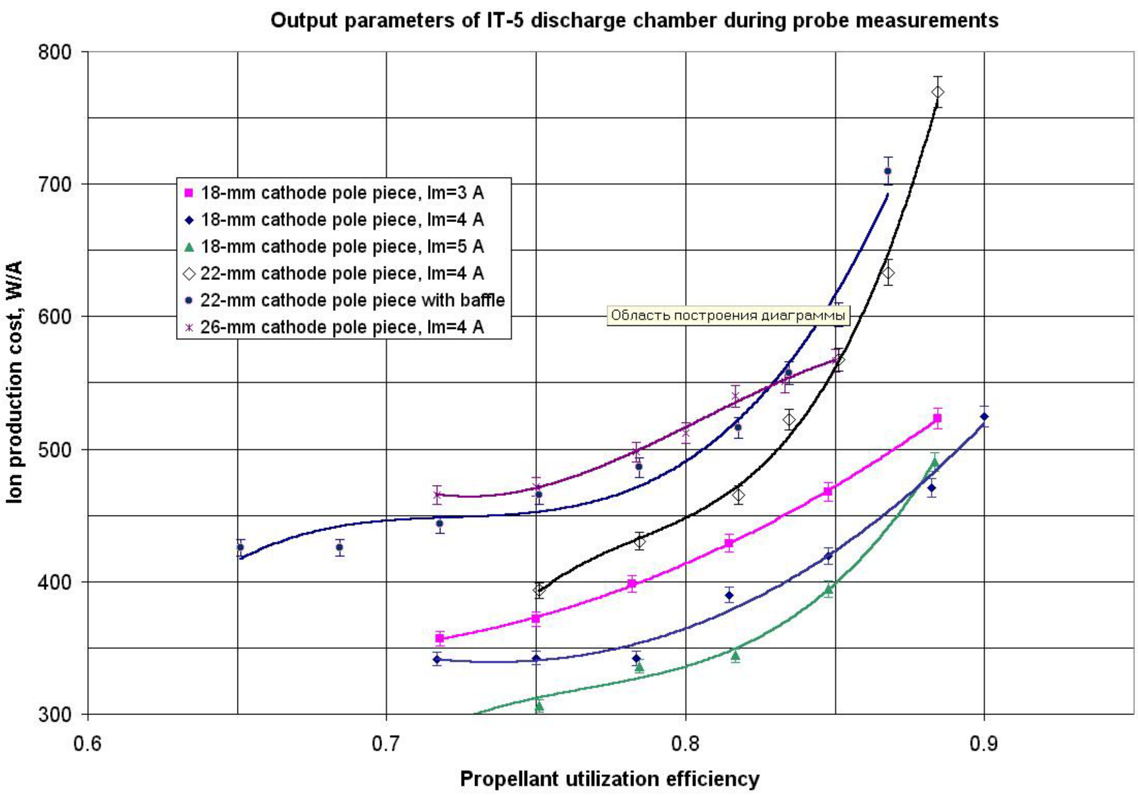
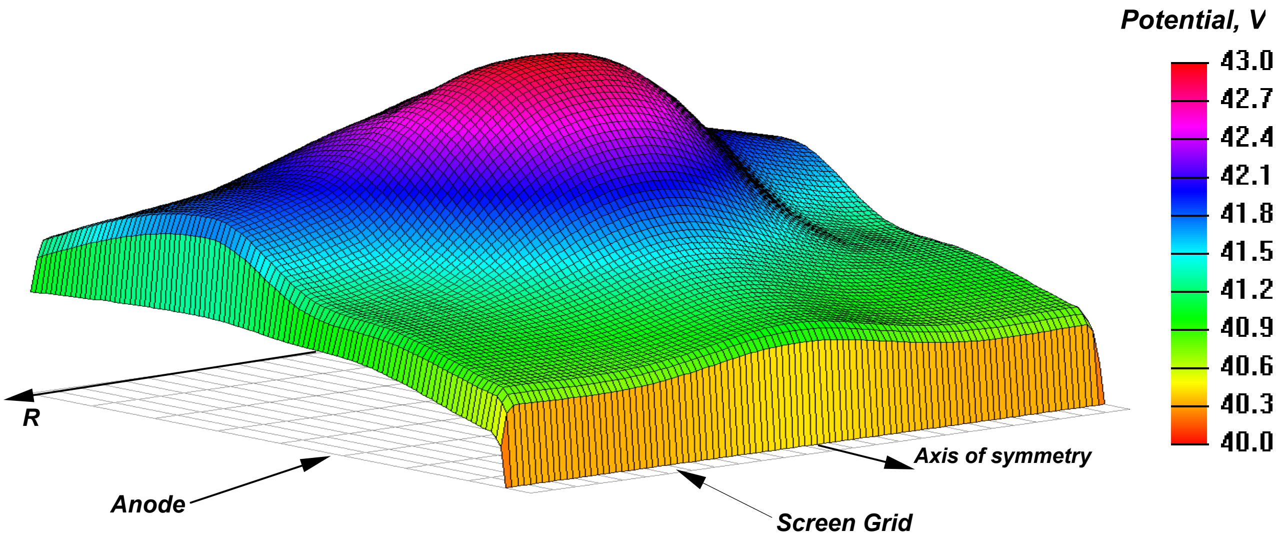
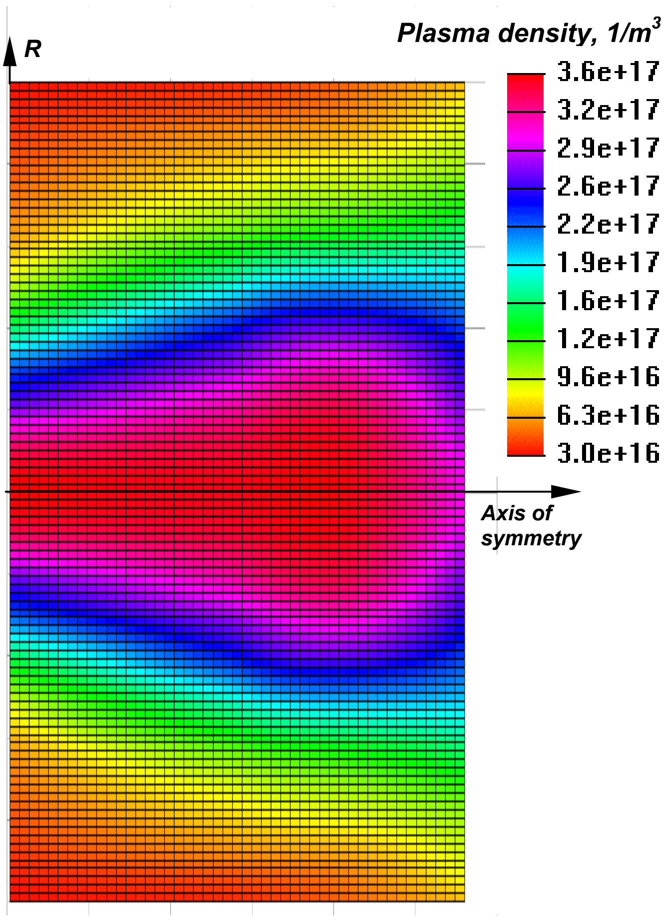


Fig. 3.



a)



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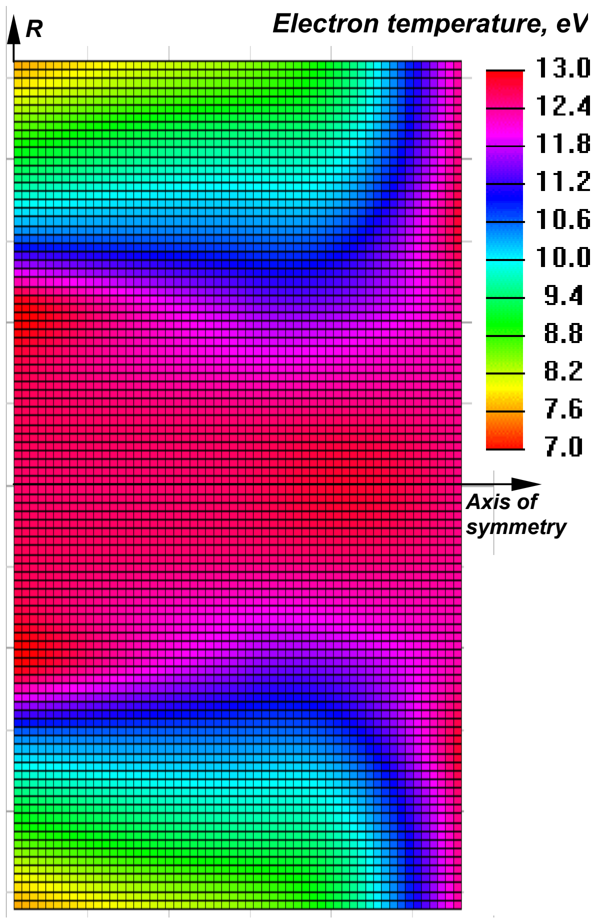

c)

Fig. 4. Example of local plasma parameters distributions:
a) plasma potential; b) plasma density; c) temperature of Maxwellian electrons

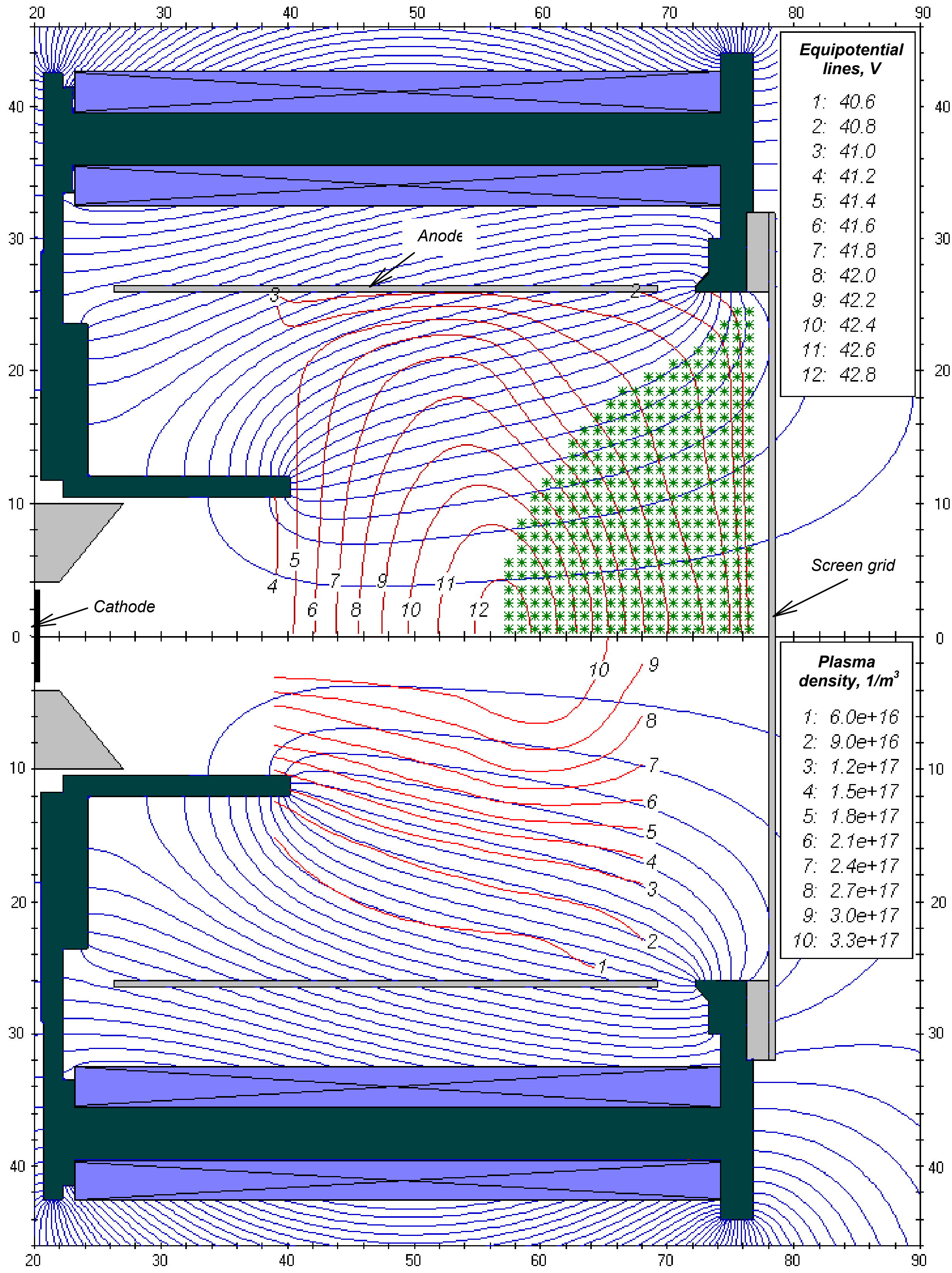

Fig. 5. Example of mathematical processing of probe-measured results.
Magnetic field lines, equipotential lines and lines of equal plasma densities are plotted. Discharge chamber area, generating ions that reach screen grid, is marked by "*".