RF plasma probe diagnostics: a method for eliminating measurement errors for Langmuir probes with bare protective shields

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Abstract. The new DC arc T-plasmatron of long service life [1] is studied. The well known method of the electric field strength measurements in a stabilized arc channel [2] was applied in a modified form as a consequence of the specific form of the presumably diffuse anode spot attached to a gas vortex on the external surface of the anode unit. The electrical field strength was determined assuming that the potential drop across the diffuse anode spot in the new plasmatron was small. This gave the mean argon plasma conductivity: \( \sigma \leq 118 \text{ Ohm}^{-1}\text{cm}^{-1} \) for arc currents \( I \leq 180 \text{ A} \) which agreed with the independent experiment [2] affirming the correctness of the above assumption. Analysis of the known experimental and theoretic data on atmospheric argon plasma conductivity resulted in the selection of R.S.Devoto’s theoretic dependence \( \sigma(T) \) [3] as the most reliable one for \( T=8000...20000 \text{ K} \) at \( P=1 \text{ atm} \) that allowed the evaluation of the mean argon plasma temperature at the exit of the plasmatron: \( T \leq 19500 \text{ K} \).

1. Introduction

The aim of the present work was to identify the reason for the discrepancies in plasma-probe measurements that were obtained by two cylindrical probes in one common cross-section. One probe was straight and radially movable, and the other was L-shaped and shifted from its center so that it could revolve around its own longitudinal axis to register the same radial plasma-parameter distributions as the straight probe. Plasma-parameter measurements were conducted in the inductive gas-discharge chamber (GDC) of a radio-frequency (RF) ion-thruster model using a planar antenna coil with a ferrite core and operating at the driving frequency \( f=2 \text{ MHz} \). The thruster’s ion-extracting grate (IEG) was replaced by a meshwork in the GDC pumping sleeve to provide xenon plasma pressure \( p=2 \text{ mTorr} \) at the flow rate of \( q=2 \text{ sccm} \). Plasma properties were measured using both probes in the middle cross-section of the thruster’s discharge space at a distance of 33 mm from the quartz window separating the antenna coil from the plasma. This research is necessary for effective thruster’s IEG development. Both measuring probes comprised reference probes with large collecting surfaces to protect the probe’s volt-ampere characteristics (VACs) against RF distortions. The probe leads were shielded by bare metal tubes to eliminate RF interferences in the probe circuits as has been done in previous research [1] dealing with microwave plasma. In the present work, the results of the
two probe measurements differed quite noticeably, especially in two common points, $r = 0$ (plasma space axis) and $r = 60$ mm (radial position), located 13 mm from the vacuum-chamber wall. The present work aimed to find the reason for this situation, a way to eliminate the measurement errors and to analyze its physical nature.

2. Experimental facility and plasma diagnostics arrangement

The schematic diagram of the ion thruster model was presented in work [2] where plasma parameters were measured using both types of probes, although that work was dedicated to the results obtained using only the straight probe. Figure 1 shows the draft of the thruster model.

![Figure 1. Drawing of the ion thruster model. 1. Vacuum chamber. 2. To the VGPS-12 probe station. 3. Movable UltraTorr vacuum seal. 4. Straight cylindrical probe. 5. Temperature-sensitive gauge. 6. Quartz window. 7. Planar antenna coil. 8. Ferrite core. 9. Cooling-air output. 10. To the matching network. 11. L-probe. 12. Reference probes. 13. One of eight xenon feeding holes, 0.4 mm in diameter. 14. “One-touch” sleeve for cooling-air input. 15. Xenon feeding KF16 fitting. 16. Xenon feeding circular collector. 17. IEG-mounting shoulder. 18. Lowest position of the L-probe. 19. Meshwork. 20. Metal sleeve connecting two parts of the L-probe shield. 21. Tungsten filament of an opened halogen lamp. 22. To the electronic transformer of the halogen lamp.](image)
The general view of this draft was presented in previous research [3] that studied a by-wall plane probe simulator. Following engineering traditions, this draft shows the details of two different cylindrical probe designs, including expanded dimensional data, which is very important for evaluations of the discharge plasma perturbations caused by both types of probes.

In the present work, the probe diagnostics were arranged as follows. The radially movable, straight cylindrical probe 4 could be moved in the radial position range \( r = 0 – 60 \text{ mm} \), and at \( r = 60 \text{ mm} \) (special point A), the probe shield was deepened by 4 mm into the body of the vacuum fitting 3. Therefore, the range of its shield lengths was \( l_{sh} = 0 – 56 \text{ mm} \). The L-probe 11 was inserted into the GDC through the port located at the bottom of the vessel, 30 mm from the axis of the discharge space, and could move in the range of longitudinal positions \( z = 33 – 69 \text{ mm} \), during which its vertical shield length varied in the range of \( l_{sh} = 71 – 107 \text{ mm} \) with 13 mm of the shield length of its shoulder, providing a range of full shield length equal to \( l_{sh} = 84 – 120 \text{ mm} \). These measurements will be used below to analyze the probe measurement results.

Probe diagnostics of the xenon plasma were conducted using the automated probe station VGPS-12, which is described on the Plasma Sensors Company’s web site [4] and briefly characterized in a review [5]. In this probe system, the objectivity of measurements was assured by using the most advanced experimental physics achievements, enhanced by the VGPS-12 creators’ multiple years of experience. Analysis of the quality and objectivity of the VGPS measurements showed that it registered electron temperature \( T_e \) and electron concentration \( n_e \) within an error margin of approximately ± 10% due to a wide dynamic range of EEPF registration (approximately 60 dB and more), resulting in highly precise EEDF determination [6]. The plasma potentials, floating \( V_f \) and plasma space \( V_s \), determining electron saturation current densities \( j_{es} \), were measured with much less errors.

The cylindrical probes used in the present work were made of tungsten filament 0.15 mm in diameter. Their length was 10 mm, which ensured negligible local plasma perturbations caused by charged particle recombination on the probe holder, which was 1.6 mm in diameter [7]. Figure 2 shows a draft of the straight cylindrical probe.

![Figure 2. Straight cylindrical probe. 1. Reference probe. 2. Protective shield. 3. To the VGPS-12 probe station. 4. Termination unit for probe leads.](image)

The tip of the L-shaped probe and its body, including the reference probe and the protective shield, were made similarly, with a rectangular bend that had a shoulder with a radial size of 30 mm from the vertical axis of its probe holder to the middle of the probe tip, as shown in figure 1.

3. Results of probe measurements

Probe measurements were conducted at \( z = 33 \text{ mm} \) in the middle cross-section of the gas-discharge space, where the straight cylindrical probe moved radially in the range \( r = 0 – 60 \text{ mm} \), and the L-probe revolved, passing three radial points: \( r = 0 \), 30, and 60 mm. The two probes had two common measurement points: \( r = 0 \) and \( r = 60 \text{ mm} \). In the axial position, both probe shields interacted with surrounding plasma, while at the point \( r = 60 \text{ mm} \), the straight probe’s shield was absent (\( l_{sh1} = 0 \)), and the L-probe’s shield had a maximal length of \( l_{sh2} = 120 \text{ mm} \). Figures 3–6 show the results of the \( T_e \), \( n_e \),...
$V_s$ and $j_{in}$ radial-distribution measurements obtained by both probes for the incident RF generator (RFG) powers $P_{in} = 50–200$ W. The straight probe’s data are represented by solid lines and the L-probe’s data by dashed lines.

Figure 3. Radial distributions of $T_e$ for two probe types at $P_{in} = 50–200$ W. Str = straight probe; L = L-probe.

Figure 4. Radial distributions of $n_e$ for two probe types at $P_{in} = 50–200$ W.
Figure 5. Radial distributions of $V_s$ for two probe types at $P_{in} = 50–200 \text{ W}$. Str = straight probe; L = L-probe.

Figure 6. Radial distributions of $j_{es}$ for two probe types at $P_{in} = 50–200 \text{ W}$.

The readouts of the two probes differed quite noticeably, although they registered plasma parameters in the same cross-section, and they had two coincident points at which their readouts differed quite noticeably, especially in the second position, $r = 60 \text{ mm}$, which was beside the GDC wall. Their general deviations were more substantial for plasma-space potentials $V_s$ (figure 5) and for electron temperatures $T_e$ (figure 3). As mentioned previously, due to the negligibility of local plasma distortions caused by the tips of both probes [7] and the use of protective reference probes and shields, we suspected that the probe-measurement discrepancies obtained in the present work were caused by some disturbances of the gas-discharge space structure. Possible explanations for these discrepancies include different probe designs, different ranges in shield-length variations, and their different locations. However, the question remained, what is the main reason for these measurement peculiarities?
4. The reason for measurement data discrepancies

In search of the answer to this question, we tried to analyze measured plasma EEDFs and their deviations from the ideal Maxwellian functions. This task was natural because the control program of the VGPS-12 probe station was based on the Druyvesteyn method, according to which, as the first step of the probe diagnostics, plasma EEDFs were registered very accurately and without any limitations of the EEDF forms. To reach a clear solution, we used the quantitative method for EEDF evaluation proposed in our previous work [8], because a qualitative comparison of EEDF appearances could not yield definitive conclusions. According to this method, the measured electron saturation current densities \( j_{es} \) are compared with theoretical Maxwellian ones using the ratios \( j_{es}/j_{esM} \), where \( j_{esM} \) is the electron saturation’s current density for the ideal isotropic Maxwellian plasmas calculated by the following formula:

\[
j_{esM} = \frac{1}{4} e n_e (8 e T_e / \pi m_e)^{1/2}
\]

using the measured plasma parameters \( n_e \) and \( T_e \), where \( e \) is the elementary electron charge, \( T_e \) is expressed in V, and \( m_e \) is the electron mass.

To simplify the forms of the symbols, we assumed that the ratio \( j_{es}/j_{esM} \) was denoted by \( R_M \), the straight probe by 1, and the L-probe by 2. The radial distributions \( R_M(r) \) were determined for both probes. Figure 7 shows the results of these calculations for the straight probe at \( P_{in} = 50–200 \) W.

![Figure 7](image)

**Figure 7.** Radial \( R_{M1} \) distributions for the straight probe at \( P_{in} = 50–200 \) W.

These results were interesting and unexpected, showing that for the straight probe, EEDFs and their deviations from the ideal Maxwellian functions varied linearly with the length of the shield \( l_{sh1} \) from the maximal spread \( R_{M1} = 0.7–0.82 \) at \( r = 0 \) and \( l_{sh1} = 56 \) mm. This spread linearly converged and its mean level also linearly rose with \( l_{sh1} \) to the single point \( R_{M1} \approx 0.87 \) at \( r = 60 \) mm that remained approximately constant for all levels of incident RFG power \( P_{in} \) at the point where the shield was absent, \( l_{sh1} = 0 \). Therefore, possible plasma perturbations around the straight probe were proportional to the length \( l_{sh1} \) of its shield, achieving minimal perturbation level at the special point A \( (l_{sh1} = 0, r = 60 \) mm – see figure 1), which can be considered as the point at which the probes of both types having determined the full set of plasma parameters enabled quantitative comparison of their values. Figure 8 shows the analogous data for the L-probe.
The radial distributions $R_{M2}(r)$ for the L-probe showed that its $R_{M2}$ ratios varied in lower ranges: 0.45–0.65 at $r = 0$, 0.6–0.72 at $r = 30$ mm, and 0.57–0.65 at $r = 60$ mm. In addition, their linear approximations demonstrated that the general EEDF perturbations for the L-probe weakly decreased toward the vacuum chamber wall that corresponded to a slight rise of $R_{M2}(r)$ approximating lines. At the special point A ($l_{sh1} = 0$, $r = 60$ mm), the EEDFs for the plasma around the L-probe deviated from the Maxwell function much more than the 13% deviations for the plasma around the straight probe corresponding to $R_{M1} \approx 0.87$. This fact means that at this point, the plasma-shield interactions for the straight probe were rather weak, but for the L-probe, they were much more active.

Therefore, measurement data for the L-probe 2 at this special point A ($l_{sh1} = 0$, $r = 60$ mm) can be quantitatively compared with the practically distortion-less data for the straight probe 1 to determine the actual plasma perturbations caused by the L-probe’s long shield. This was done by determination of the ratios $T_{cl}/T_{cl1}$, $n_{cl}/n_{cl1}$, $V_{cl}/V_{cl1}$, and $j_{es2}/j_{es1}$ using the special point’s data for both probes from figures 3–8. Figure 9 presents thus obtained experimental results in the form of $(x_2/x_1)(R_{M2})$ dependences for the L-probe at various levels of RFG incident power $P_{in}$ united with $R_{M1} \approx 0.87$ corresponding to $(x_2/x_1) = 1$ for the straight probe.
These \((x_2/x_1)(R_M)\) dependences together with the point \([(x_2/x_1) = 1, R_M \approx 0.87]\) were linearly approximated to the minimal level of \(R_M \sim 0.45\) that is shown in figure 8. This is a very important universal dependence that quantitatively characterizes the influence of EEDF perturbations on the measured probe parameters and allows transforming the \(R_M(r)\) functions from figures 7 and 8 into \((x_2/x_1)(r)\) dependences for definite plasma properties that can be denoted as \((x_{2D}/x_{1UD})(r)\), where \(x_2\) is a disturbed plasma parameter and \(x_{1UD}\) is an undisturbed one. These ratios can be used to reform the disturbed measurement results \(x_2(r)\) into the corrected functions \(x_{1UD}(r) = x_{Corr}(r)\).

By comparing measurement results for the L-probe with the data for the straight probe at the special point A \(L_{sh} = 0, r = 60 \text{ mm}\), we quantitatively evaluated the L-probe measurement errors that were caused by the EEDF distortions for the plasma around its probe tip. Analysis of figure 9 showed that at the special point A, the L-shaped probe lowered \(T_e\) by up to 13\%, \(n_e\) by \(\leq 28\%\), \(V_s\) by \(\leq 33\%\), and \(j_{es}\) by \(\leq 40\%\). These data resulted from parallel use of cylindrical probes of two different designs inserted into the vacuum chamber in two different locations with realization of the aforementioned special point A, which allowed us to determine the L-probe measurement errors caused by the bare shields contacting the RF plasma. These peculiarities in probe diagnostics presented quite unexpected data never before published and discussed in physics literature.

5. A method of RF plasma diagnostics error elimination for probes having bare protective shields

The abovementioned measurement errors for Langmuir probes having bare protective shields in contact with RF plasmas should be impossible when the probe shields are covered by dielectric coatings for in this case above considered phenomenon causing plasma distortions cannot arise. But when probe shields remain externally uninsulated because of technological difficulties, two unprotected probes should be used to refine the local diagnostics of RF plasmas using the method proposed in the present work. This technique can be accomplished using the two stages described below.

I. Preparing probe measurement corrections.

a) One probe, which we denote as probe No. 1, should be moved in the RF discharge space, varying the length of its shield in the range of \(L_{sh1} = 0 – L_{sh1m}\), where \(L_{sh1}\) is the maximal shield length for probe No. 1. Another probe, called probe No. 2, should have the possibility of reaching the special position A of probe No. 1 at \(L_{sh2} = 0\) when \(L_{sh2} \neq 0\). From the physical standpoint, it is better to use both probes in the common plasma space cross-section, with \(L_{sh2m}\) being not far from \(L_{sh1m}\).

b) After probe measurements of the plasma parameters in the form of disturbed functions \(x_{1D}(L_{sh})\) and \(x_{2D}(L_{sh})\) for \(x = T_e, n_e, V_s\), and \(j_{es}\) and EEDFs determinations, quantitative evaluations of the EEDF deviations from the Maxwell function can be made as \(j_{es}/j_{esM}\) = \(R_M\), using the measured values of \(j_{es}\) and those calculated with Eq. (1). In the case of probe No. 1, when \(L_{sh1} = 0\), the maximal \(R_{M1}\) value, \(R_{M1m}\), should represent a single upper \(R_M\) parameter for all levels of the RFG incident powers \(P_{in}\). These actions should yield the \(R_M(L_{sh})\) dependences [or \(R_M(r)\) in the case of a circular discharge space] for various \(P_{in}\) values.

c) The ratios of the measured disturbed/undisturbed probe parameters \((x_{2D}/x_{1UD})\) for \(x = T_e, n_e, V_s\), and \(j_{es}\) and for various \(P_{in}\) should be determined as functions of \(R_{M2}\) at the special point A at which \(L_{sh1} = 0\) with \(x_{2D}\) representing the disturbed parameters for probe No. 2 and \(x_{1UD}\) representing the undisturbed parameters for probe No. 1.

d) Dependences \((x_{2D}/x_{1UD})(R_{M2})\) should be united with \((x_2/x_1) = 1\) at \(R_{M1m}\), for which the shield influence on probe No. 1 is absent, and their combination should be linearly approximated to obtain the general function \((x_2/x_1)(R_M)\) similar to that in figure 9.
II. Correcting probe measurement results.

a) For a necessary plasma parameter \( x \), the RFG power \( P_{in} \) and the probe No. corresponding function \( R_{M}(l_{ab}) \) should be transformed into the dependence \( (x_{D}/x_{UD})(l_{ab}) \), using the general function \( (x_{2}/x_{1})(R_{M}) \) to exclude the intermediate variable \( R_{M} \).

b) The initial measurement points \( x_{D}(l_{ab}) \) reflecting the plasma disturbances should be divided by corresponding \( (x_{D}/x_{UD})(l_{ab}) \) corrective points to obtain the corrected measurement data \( (x_{UD})(l_{ab}) = (x_{Corr})(l_{ab}) \).

As an example, we are showing the correction of the straight probe’s measurement data on \( T_{e1}(r) \) and \( V_{s1}(r) \), from figures 3 and 5, respectively, for the practically useful RFG incident powers \( P_{in} = 100–200 \text{ W} \). Using dependences \( R_{M1}(r) \) from figure 7 for the straight probe and universal functions \( (x_{2}/x_{1})(R_{M}) \) from figure 9, we transform the initial diagnostics results into the correcting functions \( (T_{e2}/T_{e1})(r) \) and \( (V_{s2}/V_{s1})(r) \), where \( T_{e2} \) and \( V_{s2} \) were exposed to plasma distortions, and \( T_{e1} \) and \( V_{s1} \) represented undisturbed parameters. Then, we divide the \( T_{e1}(r) = T_{eD}(r) \) and the \( V_{s1}(r) = V_{sD}(r) \) points by the \( (T_{e2}/T_{e1})(r) = (T_{eD}/T_{eUD})(r) \) and \( (V_{s2}/V_{s1})(r) = (V_{sD}/V_{sUD})(r) \) points, respectively, to obtain the functions \( T_{eUD}(r) = T_{eCorr}(r) \) and \( V_{sUD}(r) = V_{sCorr}(r) \), which are represented in figures 10 and 11 by solid lines, respectively. In these same figures, the initial data on \( T_{e1}(r) \) and \( V_{s1}(r) \) are shown by dashed curves.

![Figure 10](image-url)

**Figure 10.** Radial distributions of \( T_{e} \) for the straight probe at \( P_{in} = 100–200 \text{ W} \). Dashed lines = distorted data; solid lines = corrected curves.
Figure 11. Radial distributions of $V_s$ for the straight probe at $P_{in} = 100$–$200$ W. Dashed lines = distorted data; solid lines = corrected curves.

Such corrections can be made for all measured probe parameters. They represent objective plasma properties with some small errors caused by the fact that at the special point ($l_{sh1} = 0$, $r = 60$ mm), the reference probe of the straight measuring probe might have excited some residual plasma distortions.

6. Physical nature of the disclosed plasma distortions
The identification of the linear relationships between the EEDF distortions and the length of the straight probe’s bare shield indicated that this effect may be related to some particular physics of plasma-shield interactions. To understand their physical nature, we turned to the authors’ previous works [9-20] on the behavior of large-scale conducting bodies in contact with plasmas. Some of these works [9-17] found that such bodies, represented by silicon wafers, were exposed to a short-circuited double-probe phenomenon, according to the authors’ physics common sense. The correctness of this idea was proved by successful arrangement of the silicon-wafer processings in the RF oxygen plasmas. Direct experimental confirmation of this phenomenon was presented in a report [18] that demonstrated its physical essence and displayed the classical double-probe VAC for a metal body consisting of two parts connected by an ammeter and a variable DC voltage source.

Two more works [19, 20] were dedicated to probe measurements in RF plasmas using bare metal protective shields underneath the floating potential. They showed qualitatively that the short-circuited double-probe phenomenon in such probe shields could lower the plasma-ionization balance, thus decreasing the plasma parameters along with the electrical power loss in the shield. Given this, it was of interest to compare the physical nature of the plasma-shield interactions for the shields underneath the floating potential [19, 20] and for those underneath the ground potential used in the present work.

We analyzed such interactions using the experimentally measured radial distribution of plasma floating potential, $V_f(r)$, which is presented as graph 1 in figure 12.
Figure 12. Radial $V_f(r)$ distribution in xenon plasma interacting with two versions of the bare probe shields. 1. Measured radial distribution of plasma floating potential $V_f(r)$. 2. Straight cylindrical probe with protective shield underneath the floating potential. 3. Straight cylindrical probe with grounded protective shield. 4. Measuring probe tips. 5. Reference probes. 6. Protective probe shields. 7. Sheaths of space charge beside probe shields and GDC wall. 8. Short-circuited double-probe currents, $I_{SC}$. 9. Steady-state lines dividing the collecting surfaces of bare probe shields. 10. Grounded GDC wall. A. Point of $V_f(r)$-probe axis intersection.

The five points on this graph for $r = 0–60$ mm represent the results of the straight probe measurements: $V_f = 4.39$ V = Const. for all levels of $P_{in}$. The point $V_f = 2.35$ V, at the boundary of the by-wall sheath, was determined using the plane-wall probe simulator and remained constant for the same $P_{in}$ range [3], while $V_f = 0$ corresponded to $r = 73$ mm, the internal surface of the grounded vacuum chamber wall.

The straight cylindrical probe 2 shown in figure 12 comprises probe tip 4, reference probe 5, and bare protective shield 6, which is insulated from the GDC wall to operate underneath the floating potential. Previous works [9-20] considered similar conducting bodies, including silicon wafers and large-scale metal bodies immersed in plasma. Experimental results [18] showed that, in this situation, large conducting bodies functioned as asymmetric short-circuited double-probes. This meant that the floating potential $V_f$ (figure 12), which exhibited negligible longitudinal potential variance in the metal shield because of its high conductivity, was established self-consistently on a level determined by the intersection of the shield’s axis with curve 1 in point A. This point belongs to line 9, which divides the shield’s collecting surface into two unequal parts. According to figure 12, the shield’s long, left part (more negative than the plasma) collected positively charged ions, while its short, right part (more positive than the plasma) collected negative electrons, forming a short-circuited current $I_{SC}$, which flowed along closed path 8 in the metal shield and in the plasma. The collecting surface of such self-established “double-probe” is proportional to the different mobilities of the ions and electrons, making this “probe” asymmetric. The authors’ previous works [9-20] showed that, if such a large-scale metal body was oriented along the plasma or discharge current, the plasma branch 8 of the $I_{SC}$ current would flow against this current, thereby reducing it and decreasing the plasma-ionization balance around this body, thereby lowering all plasma parameters. In addition to this effect, the flow $I_{SC}$ in the shield would heat it, increasing the loss of electrical power. These peculiarities represent the
physical nature of the plasma distortions caused by large-scale conducting bodies under floating potential in contact with plasmas.

In figure 12, the straight cylindrical probe 3 is shown to comprise the bare probe shield underneath the constant ground potential that was used in the present work. It is evident that the longitudinal variation of the plasma potential in contact with this metal body underneath the zero potential enables positively charged ions to be collected by the probe shield, which is more negative than the plasma. In the present experiment, the abovementioned phenomenon was realized a little bit differently. As did the previous version of the probe, the long, left shield surface collected positively charged ions that entered the shield and dragged the negatively charged electrons to the opposite end. As a result, a voltage decrease across the space-charge sheath that was beside the shield termination in the wall directed electrons into the right part of the probe shield. Due to high electron mobility, this part of the shield was rather small. Therefore, separation line 9 of the collecting surface of this macro-probe was self-consistently fixed to form a short-circuited double-probe current $I_{SC}$. This current resulted from deformation of the space-charge sheath around the short, right part of probe 3, and it also caused plasma perturbations analogous to those described above.

7. Discussion
In the abovementioned example [1] the probe measurements consisted of two stages. First were measurements with an unshielded ceramic probe that resulted in highly disturbed probe VACs caused by microwave interferences in the probe circuit that did not allow for determination of reasonable plasma parameters. Second were measurements by a probe having a copper protective shield, which resulted in classical probe VACs without microwave interference distortions that allowed determining more-or-less reasonable plasma parameters. The present work proposed a third stage for such an experiment—a refinement of the second stage results—in which all measured probe parameters are uplifted to eliminate the influence of the above considered phenomenon.

The present work showed that it disturbed plasma parameters proportionally to the shield’s length. To understand the reality of this situation, we must evaluate the $I_{SC}$ current in the probe shield and in the plasma around it and compare it with the mean current of the inductive discharge $I_p \approx 2–3$ A [8]. Consideration of the experimental probe VACs of the straight probe with a shield 1.6 mm in diameter and up to 56 mm long resulted in evaluating $I_{SC} \approx 28–56$ mA (in the beginning of the probe VAC’s ion branches, which should correspond to the shield’s short-circuited, double-probe VACs, ion-current densities were about $1 \times 10^{-3}$ A/mm$^2$, with the probe shield’s collecting surface $\sim 282$ mm$^2$). This probe was located $z = 33$ mm from the internal surface of quartz window 6 (figure 1). The discharge current in this location should be approximately one order of magnitude lower than the mean discharge current (i.e., about 0.2–0.3 A). Therefore, the $I_{SC}$ around the shield of the straight probe was only one order of magnitude lower than the local discharge current $I_p$. That is why discharge plasma EEDFs could be rather sensitive to $I_{SC}$, which was definitely reflected by the results of the present experiment. As for the L-probe, the collecting surface of its protective shield was twice as large, while its distance from the quartz window was much greater. That is why its EEDF distortions were much deeper compared to those of the straight probe.

When discussing the results of the present work, our chief consultant, Prof. V. Godyak, supposed that one of the reasons for the discrepancies in probe diagnostics could be some noticeable RF component of the plasma floating potential $V_{RF}$, which, in this experiment, was not measured due to organizational reasons. It is well known that this parameter can cause serious distortions of the probe VACs, resulting in probe measurement errors [5]. While preparing the present experiment, we followed the main features of the V. Godyak’s facility [21], using planar antenna coils enhanced by ferrite cores. In this work $V_{RF}$ was measured in the wide driving frequency range, including our $f = 2$ MHz, for RF power absorbed by plasma $P_p = 100$ W (which, in our facility, corresponded to $P_{in} \approx 120$ W) and for the plasma pressure range $p = (1–1000)$ mTorr. According to [21] for $p = 2$ mTorr, this parameter was approximately $V_{RF} \approx 0.4$ V, which was many times lower than the mean electron temperature $T_e \sim 3.5$ eV measured in the present work (see figure 4). In such situation distortions of
probe VACs should be negligible [21]. In general, the $V_{RF}$ depends on the $P_{in}$ level (in our experiments, it reached 200 W) and on the material properties of the ferrite. Therefore, it would be useful to measure the $V_{RF}$ in subsequent experiments. However, the present work showed that EEDF distortions from $V_{RF}$ can hardly depend on the length of the bare probe shield.

The present work will be very useful for all physicists engaged in plasma studies, especially those dealing with RF plasmas, because Langmuir probe diagnostics is a very important technique in plasma-parameter measurement. The present results clarify that the best way to make objective probe measurements of FR plasma parameters is to use protective shields coated with dielectric layers to eliminate the short-circuited double-probe phenomenon addressed in this work. In the case of probes having bare protective shields, it is beneficial to follow the method proposed in the present work.

8. Conclusions

1. Probe studies of the RF plasma were carried out using two cylindrical probes having bare protective shields. They moved in a common cross-section in such a way that in the single special point $A$ probe No.1 reached zero shield length with non-zero shield length here for probe No. 2.

2. Measurement results for both probes differed quite noticeably with maximal differences in the special point $A$.

3. The reason for this situation was found using the authors’ quantitative method of EEDF evaluations, which demonstrated linear dependence of EEDF deviations from the Maxwell function on the shield length for the probe No. 1.

4. Application of this action to the results of probe measurements in the special point $A$ helped to find the relationship between probe diagnostics errors and EEDF distortions and to correct measurement data for all plasma parameters in all probe positions.

5. Following previous conclusion points, a method of measurement error elimination has been proposed in the present work for probes immersed in the RF plasmas and having bare protective shields.

6. Physical nature of plasma distortions disclosed in the present work was the short-circuited double-probe phenomenon in the metal shields.

7. This phenomenon and its influence on the probe measurement results in RF plasmas would be absent if probe protective shields were covered externally by dielectric layers.

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