Research Article

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Elevating the Precision of Plasma Probe Diagnostics by Elimination of Bare Probe Protective Shields' Influence

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Abstract
Probe diagnostics of the low pressure inductive xenon plasma were conducted using classic cylindrical Langmuir probes with conventional protection of their circuits against radio frequency interferences by bare metal shields. The dimensions of their probetips were determined in the special experiment that provided negligible local plasma distortions. Accurate probe measurements were used to determine the spatial plasma parameter distributions in a gas discharge unit of an ion thruster model which helped to develop its ion-extracting grate. The subsequent analysis of probe measurements showed that in these experiments, the plasma electron energy distribution function (EEDF) was quite noticeably deviated from the Maxwell function depending on the main probe shield length that varied from maximum to zero. Use of an additional probe in the special position where its shield was rather long with zero shield length of the main probe showed that the additional shield lowered all plasma parameters. Comparison of both probes' data identified the principled relationship between measurement errors and EEDF distortions caused by bare probe shield and this dependence was used to correct the initial probe measurements. Therefore plasma probe diagnostics became more precise due to the lowered influence of the bare probe protective shields. Its physical analysis based on previous authors' works showed that this effect was caused by a short-circuited double-probe phenomenon in the bare metal shields.

Keywords: Inductive Plasma, Langmuir Probe, Reference Probe, Short-Circuited Doubleprobe Phenomenon

Introduction
In the authors' previous works dedicated to the behavior of large-scale conducting bodies in contact with plasmas it was found that in such bodies, represented by silicon wafers, a short-circuited double-probe phenomenon was initiated [1]. It was evaluated qualitatively following physical common sense. The correctness of this idea was proved by successful arrangement of the silicon-wafer processing in the RF oxygen containing plasmas [2]. Direct experimental qualitative confirmation of this phenomenon was presented in a report that demonstrated its physical essence and displayed the classical double-probe Volt-Ampere characteristic for a metal body consisting of two parts connected by an ammeter and a variable DC voltage source [3]. It was shown that this phenomenon was present in the bare metal protective shields protecting Langmuir probes against RF interferences [4]. Physical picture of this phenomenon showed initiation of short-circuited current in the shield and in plasma where its direction was oppositional to plasma current, including discharge one, which lowered the plasma-ionization balance and decreased all plasma parameters.

Usually real scale of this phenomenon was considered to be rather low when metal shields shortcircuited rather small plasma potential differences and collected currents that were much less than the discharge currents which could hardly influence plasma state. That is why probe leads are usually protected by bare metal shields against RF interferences [5, 6].

In such a way we have arranged probe diagnostics of the low pressure (2 mTorr) inductive xenon plasma generated in the gas discharge unit of the radio frequency (RF) ion thruster model at the driving frequency $f = 2$ MHz. These measurements were necessary for the effective thruster development. They were conducted using classic cylindrical Langmuir probes with tungsten measuring tips 0.15 mm in diameter and 10 mm long and with 1.6 mm diameter of the probe holder. Such probe dimensions were determined in the special experiment to provide negligible local plasma distortions [7]. To arrange the highest possible accurateness of plasma parameter measurements we used the advanced VGPS-12 probe station (Plasma Sensors Co., USA) where the most effective achievements of experimental physics were applied [8].

The results of plasma parameter measurements are presented in works containing their radial distributions in the middle cross-section of gas discharge space obtained by the straight radially movable probe that we call the main probe-1 [9,10]. Its measurements were carried out several times in every probe position at the exact RF generator's (RFG) matching with its discharge load. That is why data were considered to be rather precise and objective [9,10]. The additional L-shaped probe-2 was immersed in plasma to repeat probe-1's measurements in the middle cross-section of gas discharge space and to move down in order to evaluate longitudinal plasma parameter distributions reaching the location of the thruster's ion-extracting grate. In the present work plasma electron energy distribution function (EEDF) distortions were discovered that lowered plasma parameters measured by probes having bare protective shields. Besides, combination of two different probes helped to quantitatively evaluate influence of such shields on probe diagnostics and to correct previously published data obtained by the main probe-1 [9,10].

Quantitative evaluations of EEDF distortions by the main probe-1

The said method proposed in is based on the comparison of the measured electron saturation current densities, j_{es}, and theoretical Maxwellian ones in the form of ratios j_{es}/j_{esM}, where j_{esM} is the electron saturation current density for the ideal isotropic collisionless Maxwellian plasmas calculated using the measured plasma parameters, electron concentration n_e and electron temperature T_e:

$$j_{esM} = (1/4)en_e(8kT_e/\pi m_e)^{1/2} \quad (1)$$

Here, e is the elementary electron charge, k is the Boltzmann constant, and m_e is the electron mass. Denoting these ratios as $R_M = (j_{es}/j_{esM})$ we have determined their radial distributions $R_M(r)$ for the straight probe-1 that moved in the middle cross section of the gas discharge space at radial positions, r = 0-60 mm, corresponding to its shield length variation from the maximal length, l_{sh} = 56 mm at r = 0 (axial position) to l_{sh} = 0 at r = 60 mm. The last point was located at the distance of 13 mm to the vacuum chamber wall. In this probe position, only 8 mm piece of the reference probe remained in contact with plasma and the rest probe elements were hidden in the movable vacuum fitting. The results of this action for the incident RFG power P_{in} = 50-200 W are presented in figure 1.

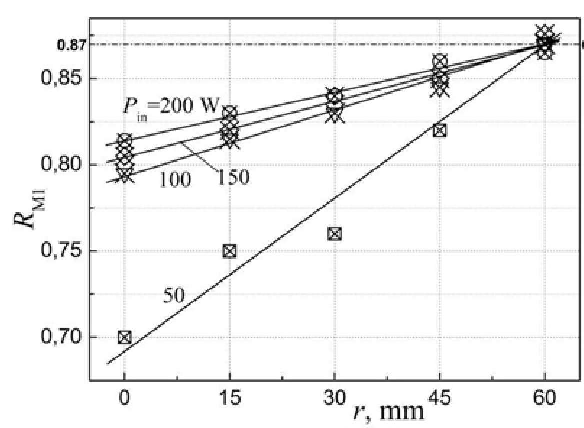

Figure 1: Radial R_{M1} distributions for the straight probe at different incident RFG powers P_{in}

This information turned out to be quite unexpected. At r = 0 ratio R_M varied in the range 0.7-0.82, representing rather noticeable EEDF distortions, which linearly converged along the radius r with a linear rise of R_M nominal values up to the single peripheral point, $R_M \approx 0.87$ at r = 60 mm for all levels of P_{in}. This fact showed that, in the case of the straight probe, the ratio R_M, which characterizes EEDF deviations from the Maxwell function and, therefore, their distortions, turned out to linearly depend on the length of the bare probe protective shield.

It can be seen in figure 1 that maximal EEDF perturbations reached about 30%, though usually experimentalists did not expect such situation. Our discussions showed that in their opinion, bare probe shields short-circuited rather small plasma potential differences and collected currents that were much less than the discharge currents. Therefore, in this situation, plasma state could hardly feel the presence of a probe in plasma. That is why probe leads were usually surrounded by bare metal shields to protect them against RF interferences [5,6]. According to our previous works, where the behavior of large conducting bodies immersed in plasma was analyzed qualitatively, it was found that such bodies self consistently acquired single plasma floating potential at the point close to the minimal floating potential beside the body. This point divided its collecting surface quite unequally: negative part of the body relative to plasma was large and collected positive ions, while its positive part relative to plasma was small, collecting negative electrons with high mobility. These two currents formed short-circuited double-probe current that flowed in the metal body and in plasma. This current flowing in plasma was directed against the general plasma space current and therefore, lowered ionization degree of plasma and all its parameters. Such bodies in the form of bare probe protective shields were qualitatively analyzed in [1]. In the present work, metal probe shields operated under constant ground potential, being in contact with grounded vacuum chamber.

That is why they were always more negative than plasma and collected positively charged ions. At the same time they dragged negative electrons at the shield spot, corresponding to minimal plasma potential that was located beside shield termination in the wall where thickness of its space-charge sheath self-consistently decreased to collect electron current and form the above mentioned short circuited double-probe current I_{sc}. So formed "double-probes" were very asymmetric due to large differences in ion and electron mobilities and their short-circuited currents could be evaluated as ion saturation currents to these "probes". They could be calculated using ion saturation current density to a Langmuir probe that could be related to nearly all shield's collecting surface (~200 mm^2 for the straight probe-1 shield in the present work). Here, ion saturation current density to the probe at maximal RFG power reached about 10^{-4} A/mm^2, resulting in a short-circuited shield current ~0.02A.

The main probe-1 was moved at a distance of 33 mm from the quartz window that separated the antenna coil from plasma. At this distance, a small piece, 13 mm long, of the additional shield-2 was present, with its rest part located far away from the antenna coil. Therefore, for both probes, the local discharge current was far less than its mean value. At discharge current about 2 A [10], its local value beside a probe could not exceed ~0.2 A. Therefore in the present experiment at maximal RFG power, the difference between discharge and shield currents reached about one order of magnitude, which seems to be a reasonable explanation for noticeable EEDF perturbations. As for the point $r = 60$ mm, here the straight probe-1 operated without the influence of its bare shield. That is why its plasma parameters reached maximal levels. Very fruitful situation in the present work is connected with the possibility to position in this special point similar classic Langmuir probe-2 exposed to influence of its non-zero protective shield. In such a way, we had created the opportunity to register its quantitative influence on the probe measurement results.

Comparative plasma diagnostics using both probes at the special point $r = 60$ mm

The additional probe-2 had the same dimensions of its probe tip as the main probe-1. So they both could not generate local plasma distortions. Therefore, measurement results for the probe-2 could reflect its bare shield influences. In the present experiment, its total shield length was about two times longer than the probe-1's shield. Only its small part and the reference probe were located in the same cross-section with the straight probe-1, while the rest part of its shield was positioned along the downstream plasma flow. Both probes were used in different experiments because they could not operate simultaneously at the same position. At the special point r = 60 mm plasma parameters measured by both probes were quite identical because RFG power was set with the precision of 1 W, the reflected power was zero, and xenon flow rate, $q = 2$ sccm was set with the error of about 1%.

Accurate measurements with the probe-2 at the special point $r = 60$ mm showed that all its results turned out to be lower than the data of the straight probe-1. Their comparison in the form of ratios (x_2/x_1) for $x = T_e$, n_e, V_s, and j_{es} are presented in figure 2.

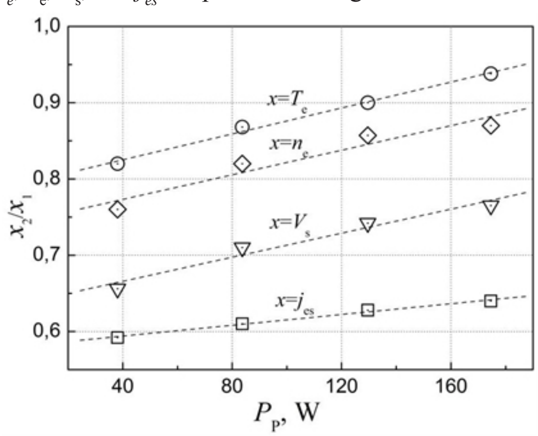

Figure 2: Comparison of measurement results obtained by probes No. 1 and 2 in the special point vs. RF power absorbed by plasma

Note that the increase of the RF power absorbed by discharge plasma lowered the differences between measurement results for both probes. Evaluation of EEDF deviations from the Maxwell function as it was done above for the straight probe-1 showed that the long bare shield of the probe-2 caused deeper plasma distortions than the shorter shield of the straight probe-1 which can be seen in figure 1. Results of these calculations are presented in figure 3 in the form of (x_2/x_1) (R_{M2}) dependencies for different plasma parameters, together with the point $(x_2/x_1) = 1$ at $R_{M1} = 0.87$ obtained by the straight probe-1 for all plasma parameters.

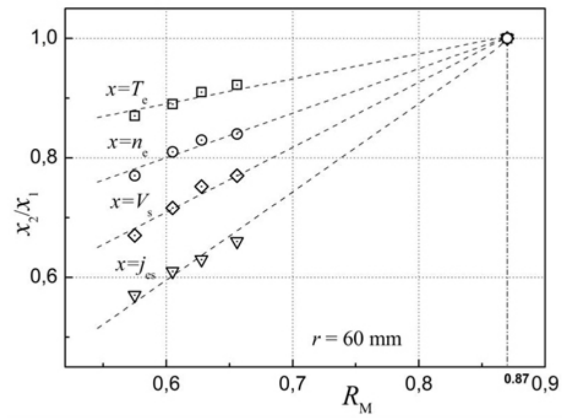

Figure 3: Dependencies of plasma parameter lowerings vs. R_{M2} for the additional probe-2 and for the main probe-1 that has obtained the point $[R_{M1} = 0.87, (x2/x1) = 1]$ with minimal EEDF distortions

Unification of these data and their linear approximations resulted in the universal physical dependencies of probe measurement errors that characterized plasma interaction with the bare protective shield of the probe-2 that generated the above mentioned short-circuited double-probe phenomenon with local probe current in plasma directed against the general plasma space current, which lowered plasma ionization equilibrium and all its parameters. Thus obtained physical dependencies will help to relate bare shield influence on the plasma parameters beside the main probe-1 and to determine its measurement errors.

Correction of measurement results obtained by the main probe-1

To solve this problem, we have to consider figures 1 and 3 in order to exclude intermediate variable R_M that reflects influence of bare probe shield on plasma state. It can be done rather easily using analytical expressions for the straight lines in both figures. In figure 1, we have

$$P_{in}=50\text{ W: } R_{M1}(r)=3.10^{-3}r + 0.69; \quad (2)$$
$$P_{in}=100\text{ W: } R_{M1}(r)=1.283.10^{-3}r + 0.793; \quad (3)$$
$$P_{in}=150\text{ W: } R_{M1}(r)=1.1.10^{-3}r + 0.804; \quad (4)$$
$$P_{in}=200\text{ W: } R_{M1}(r)=0.933.10^{-3}r + 0.814 \quad (5)$$

In figure 3:

$$(T_{e2}/T_{e1}) = 0.3919R_M + 0.659 \quad (6)$$
$$(n_{e2}/n_{e1}) = 0.7838R_M + 0.3181 \quad (7)$$
$$(V_{s2}/V_{s1}) = 1.0811R_M + 0.0594 \quad (8)$$
$$(j_{es2}/j_{es1}) = 1.5405R_M - 0.3402 \quad (9)$$

To determine radial distributions for T_e measurement corrections, we inserted equations (2)-(5) into the equation (6), which resulted in the following expressions:

$$P_{in}=50\text{ W: } (T_{e2}/T_{e1}) = 1.1757.10^{-3}r+0.9294 \quad (10)$$
$$P_{in}=100\text{ W: } (T_{e2}/T_{e1}) = 0.5028.10^{-3}r+0.9698 \quad (11)$$
$$P_{in}=150\text{ W: } (T_{e2}/T_{e1}) = 0.4311.10^{-3}r+0.9741 \quad (12)$$
$$P_{in}=200\text{ W: } (T_{e2}/T_{e1}) = 0.3658.10^{-3}r+0.978 \quad (13)$$

In the form of linear graphs these equations are presented in figure 4.

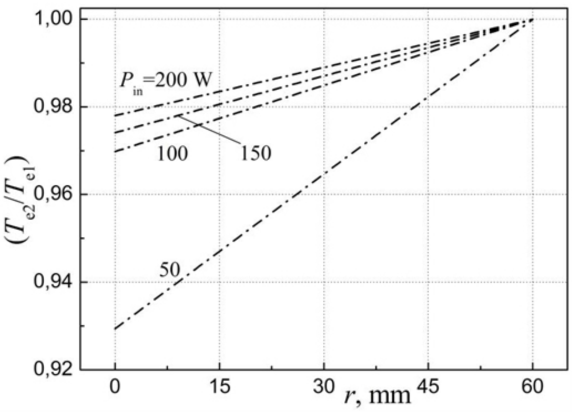

Figure 4: Radial distributions of the T_e correction ratios for P_{in} = 50-200 W

Inserting equations (2)-(5) into linear expressions (7), (8) and (9), we obtained similar measurement correction dependencies for the remaining three plasma parameters, n_e, V_s, and j_{es} as graphically shown in figures 5-7.

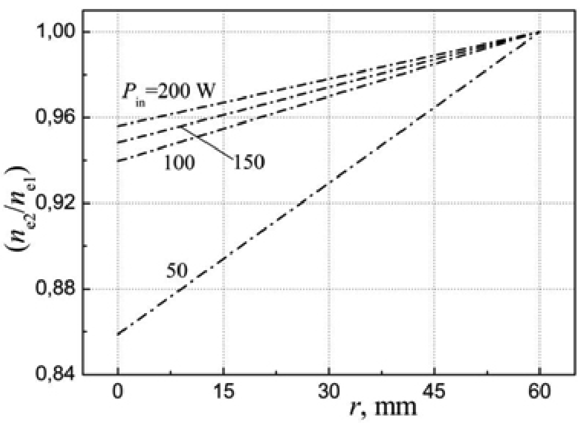

Figure 5: Radial distributions of the n_e correction ratios for P_{in} = 50-200 W

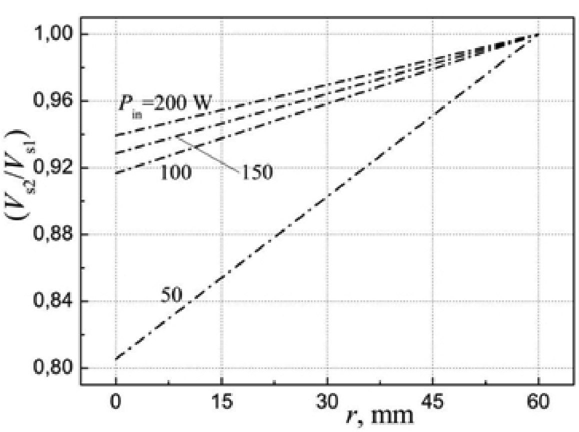

Figure 6: Radial distributions of the V_s correction ratios for P_{in} = 50-200 W

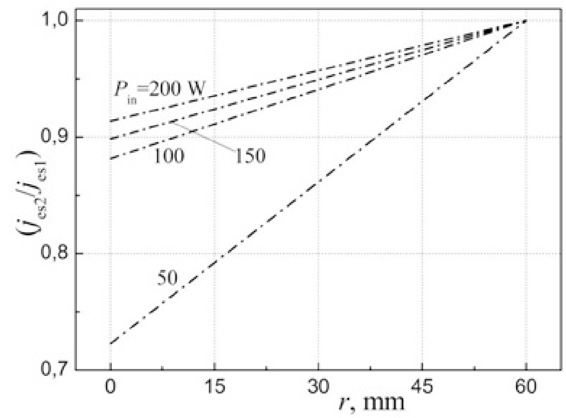

Figure 7: Radial distributions of the j_{es} correction ratios for P_{in} = 50-200 W

According to these dependencies, errors in T_e measurements reached about 7%, for n_e - up to 14%, for V_s - up to 20%, and for j_{es} - up to 28 %. Sometimes, such errors can be considered as unimportant, especially for T_e and n_e, but in some situations like the proposed expansion of probe diagnostic possibilities [11, 12] they can presumably result in rather weighty changes. At last, all measurement points of radial distributions $T_e(r)$, $n_e(r)$, $V_s(r)$, and $j_{es}(r)$ [9, 10] were divided by the corresponding correction ratios taken from figures 4-7 which resulted in the corrections of these distributions, where influences of the bare protective shield of the straight probe-1 were nearly excluded. Corrected radial distributions $T_e(r)$, $n_e(r)$, $V_s(r)$, and $j_{es}(r)$ shown by solid lines in comparison with distorted measurement results in the form of dashed lines are presented in figures 8-11.

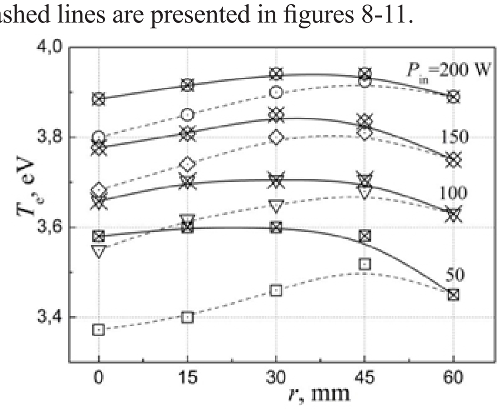

Figure 8: Corrected and distorted radial distributions of plasma electron temperatures $T_e(r)$ for different P_{in} levels

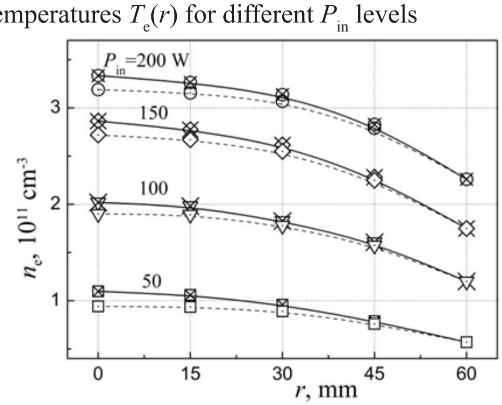

Figure 9: Corrected and distorted radial distributions of plasma electron concentrations $n_e(r)$ for different P_{in} levels

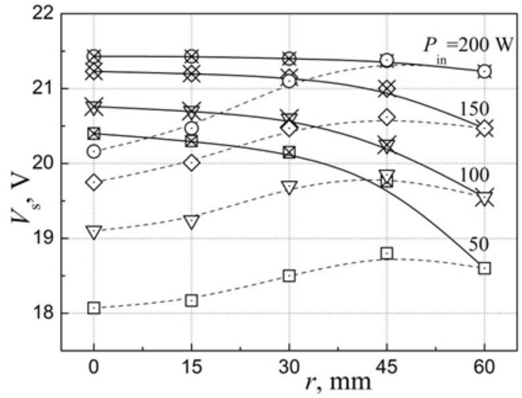

Figure 10: Corrected and distorted radial distributions of plasma space potentials $V_s(r)$ for different P_{in} levels

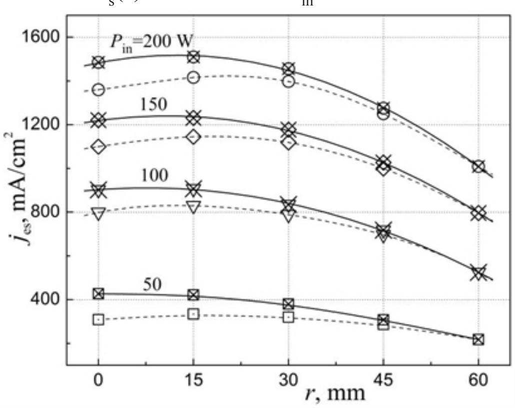

Figure 11: Corrected and distorted radial distributions of electron saturation current densities $j_{es}(r)$ for different P_{in} levels

Note that EEDF distortions and measurement errors caused by the additional probe-2 were presented here at the special point r = 60 mm to register measurement errors for the probe-1. In principle we could determine such errors for both probes because in the present work the probe-2 had possibility to determine radial distributions of plasma parameters in the same cross-section as the probe-1. But measurements by the probe-1 were carried out more accurately because they were our initial diagnostic actions repeated several times in the same points and then they were prepared to be published in works and were used to find the possibilities of probe measurement expansion [9-12].

Discussion

The results of the present work cannot be considered as full elimination of measurement errors caused by bare protective shield of the main probe-1 because in the special point its reference probe remained in contact with plasma that could generate plasma distortions similar to the bare probe protective shield. That is why $R_M \approx 0.87$ in the special point r = 60 mm could be slightly raised in the absence of this probe element that could result in less EEDF distortion and in a little uplifted values of corrected parameters. But it was not possible here because the reference probe was responsible for objective probe diagnostics, which had always been a very important experimental feature.

Besides, universal dependencies in figure 3 were based on short-circuited double-probe phenomenon in the additional probe shield-2 for which only its rather short shield near the probe tip was positioned in the middle cross-section of plasma space together with the probe-1 influencing its readouts actively, while the rest long part of its shield was immersed in the plasma down flow interacting with it in a different way. Therefore it would be better to position all parts of the additional probe-2 in the common cross-section with the main probe-1. Such possibility can be realized in future because in the present experiment the L-formed probe-2 was necessary for the ion thruster development.

Conclusions

1. A method of probe measurement error reduction has been proposed for Langmuir probes having bare protective shields.
2. Probe measurements and their physical analysis showed that previously discovered qualitative short-circuited double-probe phenomenon in conducting bodies immersed in plasmas was quantitatively confirmed in the present work.
3. The proposed corrections were realized in inductive xenon plasma of low pressure (2 mTorr) for the radially movable straight cylindrical probe.

Acknowledgments

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