Integral Diagnostics Method Characterizing Gas Discharge Unit of an RF Inductive Ion Thruster

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Valentin A. Riaby[1], Vladimir A. Obukhov[2], Pavel E. Masherov[3], Andrey I. Mogulkin[4], Viktor V. Balashov[5]
Research Institute of Applied Mechanics and Electrodynamics of the Moscow Aviation Institute (National Research University), 5 Leningrad Rd., Moscow 125080, Russia

Abstract: Integral diagnostics method for an RF inductively coupled plasma gas discharge unit of a plasma/ion apparatus has been proposed. This includes a priori measurements of antenna coil electrical parameters, experimental determination of the antenna coil currents with and without discharge using two Rogovsky belts encircling grounded lead of the coil and output line of an RF generator and additional Ohm's law calculations of system parameters. A methodical set of 25 design, operational, and combined system indicators was formed to characterize an RF inductive discharge unit. Two examples of practical use of the proposed method are given for a model of an ion source based on the known RF inductive plasma device with a planar antenna coil enhanced by a ferrite core and for an RF technologic ion source with a cylindrical antenna coil. Application of the proposed diagnostics method resulted in determination of the ways to elevate energy effectiveness of both devices.

Nomenclature of indexes

e = electrons
i = incident (power)
r = reflected (power)
tr = transferred (power)
d = discharge
gd = «RFG-discharge» (efficiency)
gc = «RFG-coil» (efficiency)
cd = «coil-discharge» (efficiency)
0 = without discharge (assembled unit)
eq = equivalent (resistance)
l = line (transferring RF power)
c = coil
f = driving frequency
$2f$ = doubled driving frequency
fr = in free space
в = eddy (current, inductance)
cedeq = coil, eddy, equivalent (resistance)

[1] Senior scientist, riaby2001@yahoo.com
[2] Deputy director, deutscher@mail.ru.
[3] Junior scientist, p.masherov@yandex.ru.
[4] Leading engineer designer, amagu@land.ru
[5] Production manager, bonfeu@mail.ru

1 = main position of current monitor (on a grounded coil lead)
2 = control position of current monitor (on an RFG output line)
lk = leak (current)
ld = load

I. Introduction

Inductively coupled plasma (ICP) discharge has been applied on a wide scale as an RF plasma source in space orbital RF ion thrusters as well as in technological ion/plasma apparatus. This form of gas discharge is convenient because of the absence of electrodes in the discharge space, which usually limits the technical lifetime of plasma systems and contaminate plasma with products of electrode material sputtering. Integral diagnostics of an ICP gas discharge unit carried out along with the studies of its operation process peculiarities makes it possible to tie up its technical state with working process physics that depends on space distributions of fundamental plasma properties like electron energy distribution function $f(\varepsilon)$, electron concentration n_e, electron temperature T_e, and plasma electrical potential. These parameters result from plasma absorption of RF power transferred from RF generator (RFG) to an antenna coil through RF feeding line comprising cables, connectors, and a matching device (MD). An idea for correct analysis of ICP operational process that demands knowledge of discharge power to compare it with integral plasma diagnostics data was expressed in[1].

Discharge power measurement presents the essence of a wide-spread ICP discharge integral diagnostics showing general energy effectiveness of a system. If the necessity to connect two kinds of ICP diagnostics was formulated in [1] only verbally, then in [2] simple equations based on Ohm's law were given where incident RF power P_i, reflected from the load RF power P_r, and their difference $P_{tr}=P_i-P_r$ representing RF power transferred to the load were used. One of them represents the effectiveness of RF power transfer from RFG to discharge plasma P_d, or energy effectiveness "RFG-discharge plasma" η_{gd} that is expressed as the ratio P_d/P_{tr} written as

$$P_d/P_{tr}=\eta_{gd}=1-(I/I_0)^2 \qquad (1)$$

Here I and I_0 are antenna coil currents measured with and without discharge respectively. These values are determined through active components R_{pe}, R_l, and R_c of the complex impedances Z_{pe}- plasma equivalent impedance included in-series into an antenna coil circuit according to the transformer model of an ICP discharge [3]; Z_l- impedance of an RF power feeding line (containing cables, connectors, MD), and Z_c- impedance of an antenna coil.

In the present work it is proposed to measure antenna coil currents at the zero reflected power P_r=0 when RFG is exactly matched with its load. It is well known that fulfillment of this condition in the experiment is not easy, it demands definite efforts. But its achievement results in the largest RF energy transfer into the load, i.e. maximal energy effectiveness of an ICP system which is economically preferable for any practical application of an ICP system. Besides it guarantees effective protection of an RFG that can be damaged with elevated level of reflected power P_r continuously affecting RFG during some time.

Exact matching of RFG with its load means that voltages for all reactive elements of an RF power feeding line are mutually compensated making its circuit purely active for which simple expressions based on Ohm's law can be used to determine circuit parameters. Equation (1) serves an example of such a possibility.

The most comprehensive, classical method of ICP discharge integral diagnostics has been proposed in a theoretical/experimental work [3]. Here the transformer model of a coil with the RF circular current flowing in ICP gas discharge plasmas and the system integral diagnostics for the general case of partial RFG-load matching are described. In this work antenna coil's electrical parameters, Q-factor, inductance, and active resistance, and also plasma properties, including electron collision frequency, were considered to be known *a priori*. First, the analytical expressions for the integral parameters averaged in the ICP discharge area were derived. In the experimental part of [3] the antenna coil current, its voltage, and phase shift between them were measured with and without discharge burning. As a result, the active and reactive components of the full coil impedance, mean values of the discharge current and impedance, electric field strength, discharge geometric dimensions, RF power loss in the antenna coil, and the RFG-discharge power transfer efficiency η_{gd} were obtained.

In the present work an extended method of integral ICP discharge unit diagnostics is proposed for *a priori* unknown local plasma parameters. The discharge parameters to be determined are antenna coil currents I and I_0 with discharge and without it, respectively, measured by two current monitors encircling the antenna coil's grounded lead and the RFG output line when RFG is exactly matched with its load. The proposed method includes determination of energy effectiveness of the system and allows disclosing physical-technical shape of an ICP gas discharge unit to be studied. Its peculiarities depend on uncontrollable RF power leak, quality of RF power transferring line and design of ICP discharge unit. The method comprises formation of a set of 25 control indicators beginning like in [3] from preliminary found antenna coil's electrical parameters that are measured unlike [3] when a coil is placed in free space (far from electrically conducting parts) and inside the assembled ICP unit. Besides, the proposed set of control indicators includes data on total RF power leak and some calculated parameters of the discharge circuit characterizing technical state of a system from different standpoints.

A. Preliminary measurements of the antenna coil's parameters

As it was noted above *a priori* determined antenna coil's parameters include Q-factor $Q=\omega L_c/R_c$, inductance L_c, and its active resistance R_c measured at the driving frequency f.

They are measured with Q-meter when an antenna coil is connected to the instrument forming a series oscillatory measurement circuit together with the inboard calibrated variable capacitor C. Adjusting the last, measurement circuit is tuned to resonance showing Q-factor Q_f and corresponding capacitance value of the panel capacitor C_f. Besides, the coil has its own turn capacitance C_c that should be added to C_f. For its determination the coil is usually tuned up to resonance at double $2f$ frequency with corresponding C_{2f} panel capacitance that allows to calculate C_c according to equation

$$C_c=(C_f-4C_{2f})/3. \qquad (2)$$

Inductance of the coil is calculated using Thompson formula $\omega=2\pi f=(LC)^{1/2}$:

$$L_и=[4\pi^2 f^2(C_f+C_c)]^{-1} \qquad (3)$$

and its active resistance is found using the Q-factor formula $Q=\omega L/R$:

$$R_c=\omega L_c/Q_f \qquad (4)$$

Measuring these parameters in free space one obtains maximal values of Q-factor Q_{fr} and inductance L_{cfr} together with minimal coil's own active resistance R_{cfr}. In an assembled system beside an antenna coil there always are electrically conducting (metal) parts in which RF magnetic field of the coil excites eddy currents. Their influence can be found by repeated measurement of the same parameters for an antenna coil installed inside the assembled ICP system. Let these values be denoted by index "0", Q_0, L_{c0}, and R_{c0}, that specifies initial state of the system prior to excitation of ICP discharge. Results of these measurements show the degree of system design influence upon electrical parameters of a coil: its Q-factor decreases due to eddy currents in metal parts because according to a transformer model of ICP discharge [3] electrical resistance of these currents is added to R_{cfr} in the form of equivalent resistance R_{ceq}, i.e. $R_{c0}=R_{cfr}+ R_{ceq}$, and magnetic field of eddy currents with inductance L_{ed} compensates part of coil's field decreasing L_{cfr}, i.e. $L_{c0}=L_{cfr}-L_{ed}$. Values of the said parameters depend on the system design and so they can start formation of the control indicator set as initial nine design indicators including 6 direct parameter values and 3 relative changes of Q-factor, inductance and active resistance: Q_{fr}=D1, L_{cfr}=D2, R_{cfr}=D3, Q_0=D4, $\Delta Q_{fr}=100\%(Q_{fr}-Q_0)/Q_{fr}$=D5, L_{c0}=D6, $\Delta L_{cfr}=100\%(L_{cfr}-L_{c0})/L_{cfr}$=D7, R_{c0}=D8, $\Delta R_{cfr}=100\%(R_{c0}-R_{cfr})/R_{cfr}$=D9.

Note that increased values of Q-factor and corresponding relatively low active resistances if they are discovered experimentally mean rather low loss of RF power in a coil and therefore increased level of system energy effectiveness η_{gd} [3].

B. Measurement of antenna coil current without discharge

This measurement is carried out without supplying working gas into the discharge space leaving it at vacuum not worse than $\sim 10^{-5}$ Torr or at atmospheric pressure, so that discharge ignition becomes impossible corresponding to distant left or right branches of the Paschen curve for a residual gas of the system. RF power is supplied to the antenna coil through MD, it is adjusted to reduce reflected power P_r to zero and then coil current without discharge I_0 is measured. For this purpose current transformer, usually Valter Rogovsky belt encircling a wire with RF current is used.

The proposed method of ICP system integral diagnostics comprises measurement of "pure" coil current I_{10} sustaining the discharge and the same current mixed with all currents of uncontrollable leaks I_{20} that can flow along all the RF power feeding line. For this purpose two current monitors installed on a grounded coil lead and on an RFG output line should be used. The first instrument to be called a main current monitor provides measurement of I_{10} coil current and the second one to be called a control current monitor measures the same current mixed with all leak currents I_{20} that flow passing antenna coil, in parallel to it.

The said leaks can appear in any element of the RF power feeding line. To begin with let us consider schematic of a typical ICP system with direct grounding of its antenna coil (Figure 1).

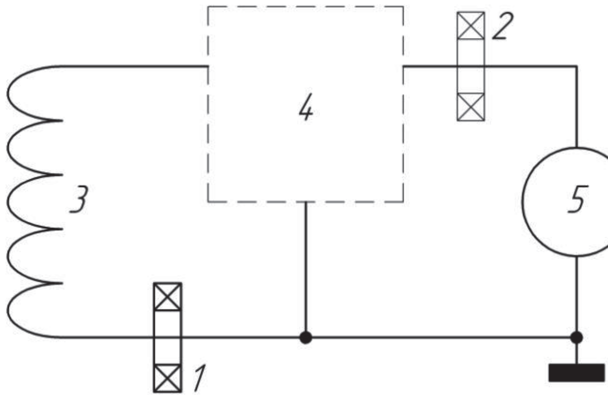


Figure 1. Schematic diagram of a typical ICP system *(1&2. main and control coil current monitors, respectively, 3. antenna coil, 4. MD, 5. RFG)*

It can be seen here that leak current in MD (in cables, connectors, in grounded parts) always flow in parallel to an antenna coil. It can play the main part when antenna coil is used at atmospheric pressure[1-3] with an MD using low quality cables, connectors, and component parts which is practically very unlikely. If all parts of an ICP system[7] or only its water-cooled antenna coil surrounding discharge chamber with an ion extraction system at its exit are installed in vacuum [6] then possibilities for different kinds of leaks become quite real and various. As an example in Figure 2 schematic diagram of the system [6] is presented (here initial five position numbers are the same as in Figure 1).

In this ion source current losses can arise in the capacitive MD 4, in the insulator of vacuum feed-through 7 for the high voltage lead of the coil 3 in the form of a surface discharge, in the capacitive discharge between antenna coil 3 and grounded system parts, and in the cooling water flow to the coil input 10. Channels of these losses are shown schematically in the Figure 3 (with the same initial five position numbers of Figure 1).

Note that gas discharge leak channels 7 and/or 8 can come alive only when working gas is supplied into vacuum chamber. If ICP discharge is excited inside the antenna coil then in channel 3 in series with the initial active coil resistance R_{c0} equivalent active plasma resistance R_{deq} appears.

Simultaneous measurement of coil current in both positions 1 and 2 gives functions $I_{10}(P)$ and $I_{20}(P)$ and in the presence of uncontrollable RF current leak $I_{20}(P)$ surpasses the first function $I_{10}(P)$ providing possibility to determine their relative difference $\Delta I_{leak0}(P)$=100%[$I_{20}(P)$-$I_{10}(P)$]/$I_{10}(P)$ giving leak current in percent of "pure" coil current. All three functions depend on the design and circuit engineering of the system. Therefore they are to be considered as design indicators D10, D11, and D12, respectively.

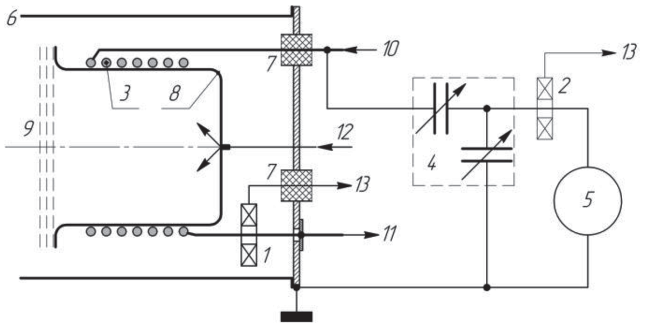


Figure 2. Schematic of the RIM-20 system[6]
(1&2. main and control coil current monitors, respectively, 3. antenna coil, 4. MD, 5. RFG, 6. vacuum chamber, 7. vacuum feed-though, 8. quartz gas discharge chamber, 9. ion extraction system, 10&11. input and output of coil cooling water, res

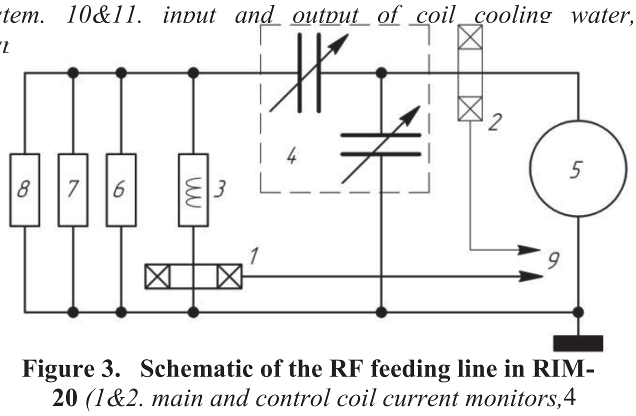


Figure 3. Schematic of the RF feeding line in RIM-20 *(1&2. main and control coil current monitors, respectively, 3. antenna coil, 4. MD, 5. RFG, 6. cooling water flow, 7. surface discharge in the vacuum feed-through of the coil's high voltage lead, 8. CCP RF discharge between the coil and grounded parts of the system, 9. to an RF voltmeter*

In the absence of discharge, circuit engineering and realization of the electrical feeding line together with system design determine minimal line resistance and therefore upper limit of the coil's RF currents $I_{10}(P)$ and $I_{20}(P)$. Ohm's law calculations give three more design indicators: minimal RFG output voltage $V_{g0}=P/I_{20}$=D13; load resistance $R_{ld0}=V_{g0}/I_{20}$=D14 equal to the RFG output resistance, and "generator-coil" efficiency $\eta_{gc}=P_{c0}/P=R_{c0}/R_{ld0}$=D15. So the number of system design indicators characterizing its design and electrical engineering turned out to reach fifteen.

With a transformer MD antenna coil can be grounded through an output wind of the matching transformer grounded in its middle point to make discharge voltage symmetric[2]. In this case main coil current monitor 1 should be installed on a grounding lead as in the previous variant and a control current monitor 2 – on the RFG output lead – see Figure 4 (with the same initial five position numbers of Figure 1).

This schematic diagram is interesting because in experiments [2] it not only provided convenient conditions for Langmuir probe measurements but allowed to obtain high system efficiency η_{gd}=0.8-0.95 at plasma pressure p=1-100 mTorr and discharge power $P\leq400$ W. In this work antenna coil was installed at atmospheric pressure conditions that is why uncontrollable current leaks were improbable in such a system and here coil current monitor location was not important. But if such an MD is used in a system with antenna coil installed in vacuum, then above problems can appear without any doubt.

C. Measurement of antenna coil current at the burning of ICP discharge

While ICP discharge burns at the given working gas flow rate, coil currents are measured using both current monitors at the exact matching of RFG with its load. As a result two dependences $I_1(P)$ and $I_2(P)$ are measured on the grounded coil's lead and on the output RFG line, respectively. Both functions depend on operational discharge parameters that is why they are to be considered as operational control indicators Nos 1 and 2, O1 and O2 though such a classification of these dependencies is partly conditional because they are functionally connected with limiting functions $I_{10}(P)$ and $I_{20}(P)$. The same is true for a possible leak current $I_{lk}(P)=I_2(P)-I_1(P)$ that is denoted as operational control indicator in the form of O3=$\Delta I_{lk}(P)=100\%[I_2(P)-I_1(P)]/I_1(P)$.

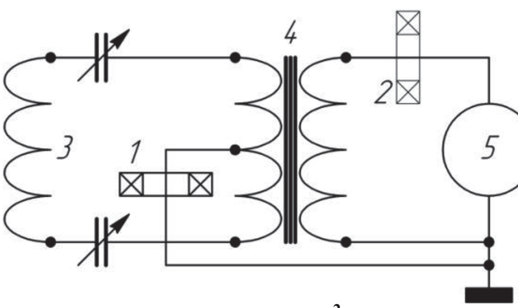


Figure 4. Transformer MD[2] *(1&2. main and control coil current monitors, respectively, 3. antenna coil, 4. MD, 5. RFG)*

Then using Ohm's law several additional system parameters can be found that we denote as operational indicators with subsequent numbers: RFG output voltage, or load voltage $V_{ld}(P)=P/I_2(P)$= O4, RFG load resistance $R_{ld}(P)=V_g(P)/I_2(P)$=O5, equivalent resistance of discharge plasma $R_{deq}(P)=R_{ld}(P)-R_{ld0}(P)$=O6, coil Q-factor at the burning of discharge $Q_d=\omega L_{c0}/(R_{c0}+R_{deq})$=O7 and efficiency "generator-coil" $\eta_{gc}(P)=[R_{c0}+R_{deq}(P)]/R_{ld}(P)$=O8.

"Pure" coil currents measured at the absence and burning of discharge can be used to calculate efficiency of RF power transfer into discharge $\eta_{gd}(P)$ using formula (1) and absolute RF power absorbed by discharge plasma $P_d(P)=\eta_{gd}(P)\cdot P$. These values depend on both design and operational system parameters, so we denote them as combined, design-operational system indicators DO1 and DO2, respectively. So general number of system control indicators in thus formed set reached twenty five:

a. Design Ds: D1=Q_{fr}; D2=L_{cfr}; D3=R_{cfr}; D4=Q_0;
D5=$\Delta Q_{fr}=100\%(Q_{fr}-Q_0)/Q_{fr}$; D6=$L_{c0}$;
D7=$\Delta L_{ed}=100\%(L_{cfr}-L_{c0})/L_{cfr}$; D8=$R_{c0}$;
D9=$\Delta R_{cfr}=100\%(R_{c0}-R_{cfr})/R_{cfr}$; D10=$I_{10}(P)$; D11=$I_{20}(P)$;
D12=$\Delta I_{lk0}(P)=100\%[I_{20}(P)-I_{10}(P)]/I_{10}(P)$;
D13=$V_{ld0}(P)$; D14=$R_{ld0}(P)$; D15=$\eta_{gc0}(P)=R_{c0}(P)/R_{g0}(P)$.

b. Operational Os: O1=$I_1(P)$; O2=$I_2(P)$;
O3=$\Delta I_{lk}(P)=100\%[I_2(P)-I_1(P)]/I_1(P)$; O4=$V_{ld}(P)$; O5=$R_{ld}(P)$; O6=$R_{deq}(P)=R_{ld}(P)-R_{c0}$; O7=$Q_d(P)$; O8=$\eta_{gc}(P)=[R_{c0}+R_{deq}(P)]/R_{ld}(P)$.

c. Design-operational DOs: DO1=$\eta_{gd}(P)$; DO2=$P_d(P)$.

This set of control indicators characterizes the system from diverse sides and for different devices it probably reflects their peculiarities in different ways.

Below are given two examples of practical application of the proposed method for an ICP unit integral diagnostics.

D. Examples of the proposed method realization

D1. Model of the RF ion thruster based on the facility[2]

Schematic diagram of the RF ion thruster model named as RIT-10F (RF ion thruster: ion beam diameter is about 10 cm, antenna coil has ferrite core) is presented in Figure 5 (with the same initial five position numbers of Figure 1).

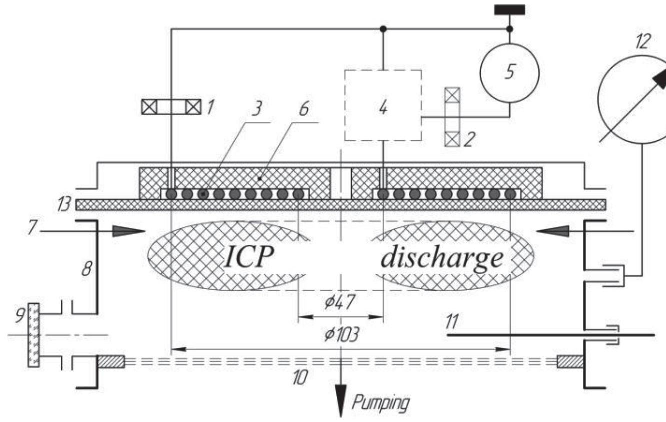


Figure 5. Schematic of the RF ion thruster based on the system[2]
(1&2. main and control coil current monitors, respectively, 3. antenna coil, 4. MD, 5. RFG, 6. ferrite core, 7. gas feeding, 8. vacuum chamber, 9. peephole, 10. ion extraction system, 11. Langmuir probe, 12. vacuum gauge, 13. dielectric window)

This model was designed following prototype of the article [2] dedicated to creation and study of an ICP technologic plasma source with a planar antenna coil enhanced by a ferrite core. Its elevated energy efficiency (up to 0.95) was recognized as the main advantage achieved due to magnetic field concentration within the ferrite core that suppressed magnetic field in its back area and increased coil's Q-factor and due to coil form that reduced depth of gas discharge area and the size of its side surface. As a result charged particle losses on a side wall of the prototype [2] were reduced that led to the growth of system efficiency and gave satisfactory uniformity of plasma distribution in the area of its practical use.

By now only preliminary studies of the model RIT-10F have been carried out but their results are presented here as an example of the proposed method realization due to entirety of measurements of the initial control indicator group including coil parameters in free space and inside the assembled system.

It can be seen in Figure 5 that planar coil 3 of the model is installed outside of vacuum space lowering danger of uncontrollable current losses in the electrical feeding line of the discharge. Gas discharge chamber of this device is formed by dielectric window 13 and close to it part of the metal vacuum chamber 8. This variant of an ICP unit helps to easily arrange plasma probe diagnostics and registration of its pressure.

Antenna coil of the RIT-10F model is made as flat spiral with turn number N=13, winded by a multiple-conductor copper, silver plated wire OD~1.5 mm covered with teflon insulation OD~2.1 mm. Its main dimensions are shown in Figure 5. The coil's ferrite core is made of nickel and manganese oxides, has relative magnetic constant up to 150 and Curie point up to 400 ^{o}C (produced in USA).

Q-factor of the antenna coil was measured using TESLA BM-560 Q-meter at the driving frequency f=1.86 and at the double frequency 2f=3.72 MHz to determine coil turn own capacitance C_c. Measurements in free space gave the following results: D1=Q_f=Q_{fr}=253, C_f=251 pF, Q_{2f}=143, C_{2f}=51 pF, C_c=15.8 pF, D2=L_{cfr}=27.4 μHn, D3=R_{cfr}=1.27 Ohm.

For the assembled model similar measurements resulted in the following: D4=Q_0=157, C_f=257 pF, D5=ΔQ_{fr}=100%(Q_{fr}-Q_0)/Q_{fr}=37.9%, Q_{2f}=41, C_{2f}=43.6 pF, C_c=27.4 pF, D6=L_{c0}=25.7 μHn, D7=ΔL_{cfr}=100%(L_{cfr}-L_{c0})/L_{cfr}=6.2%, D8=R_{cfr}=1.92 Ohm,
D9=ΔR_{cfr}=100%(R_{c0}-R_{cfr})/R_{cfr}≈51.2%.

So full initial stage of the integral diagnostics of an ICP unit provided obtaining more than half of the design control indicator group (9 of 15). It was found out that for this model at the transition from free space to an assembled apparatus L_{cfr} decreased by ~6% while R_{cfr} raised by ~51%. This effect corresponds to a model where ferrite core nearly eliminated eddy currents in the area behind a coil (in the metal cover schematically shown in Figure 5), therefore it is due to eddy currents only in the part of vacuum chamber close to the coil.

The said conclusion prompts that further raise of the model's energy effectiveness is possible if vacuum chamber or its part near the coil are made of dielectric material. The same can be achieved cutting thickness of the dielectric window 13 (Figure 5). For example it can be made of stronger and thinner corundum instead of 10 mm thick quartz used in the present experiments. In this case efficiency "coil-discharge" should increase due to raise of mutual induction of the coil and discharge plasma turn[5] with some limitation of this effect in the case of metal vacuum chamber due to deeper penetration of eddy currents into chamber wall.

Experimental study of the RIT-10F model can be used to check correctness of the coil inductance calculations for inductors of relatively simple forms using empirical data of the handbook[5]. For this purpose inductance of the planar antenna coil without its ferrite core was measured in free space with the result L_{cfr}=14.51 µHn and calculated according to [4], page 253: L_{ccalc}≈15.15 µHn. Relative difference of these results (~4.4%) lies well within the error field of our Q-meter (about ± 6%) which proves correctness of theoretical predictions using handbook [4].

D2. Technologic RF ion source RIM-20

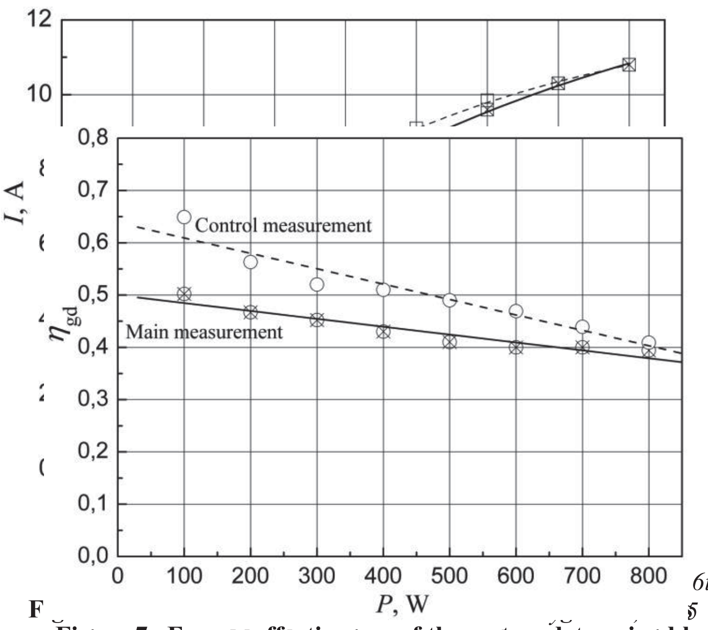
This ion source whose schematic diagram is given in Figure 2 represents an ICP system with disposed in vacuum cylindrical quartz OD~210 mm vessel surrounded with water-cooled antenna coil of 9 turns made of copper tube 6x1 mm (OD~6 mm, wall thickness 1 mm)[6]. The coil's ID is 210 mm, height is 120 mm. In the closed end of the vessel working gas feeding is arranged and at its opposite end three-electrode ion extraction system is installed. Electrical feeding of the gas discharge unit is provided with RFG operating at driving frequencies f=1.7-2.1 MHz and power up to 1 kW. RFG is connected to the antenna coil through an incident/reflected power meter and automatic MD.

At the present moment RIM-20's antenna coil parameters are measured only for the assembled ion source. The study at the driving frequency f=2 MHz showed: D4=Q_f=Q_0=37.5; C_f=428 pF, C_{2f}=45 pF; C_c=82,7 pF; D6=L_{c0}=12.4 µHn, D8=R_{c0}=4,15 Ohm. Relatively low level of Q_0 and enough large resistance R_{c0} demonstrate noticeable role of eddy currents in this system.

In the free space antenna coil parameters were not measured so far. This drawback can be partially filled by calculations of the coil inductance using handbook [5], page 247: for above RIM-20's cylindrical coil dimensions L_{cfr}= D2$_{calc}$=17.9 µHn which corresponds to a relative change of coil inductance ΔL_{cfr}=100%(L_{cfr}-L_{c0})/L_{cfr}= D7$_{calc}$≈30%. The found out effect of eddy currents in metal parts of the ion source exceeds similar result of the previous example by nearly 5 times. So the role of eddy currents in the RIM-20 design turned out to be really quite noticeable that confirmed given above evaluation of the Q-factor and active resistance of its antenna coil.

Partially completed initial stage of the ion source test was compensated by measurements of its antenna coil currents without discharge and during its burning. According to the proposed method they were carried out using two Rogovsky belts: the main instrument was installed on the coil grounded lead (position 1 in Figure 2) while the control one – on the RFG output line (position 2 in Figure 2). As the main Rogovsky belt current monitor Pearson 411C was used (a clamp-on instrument ready for vacuum use, the output voltage error ±1.0 %) and the control instrument was represented by the current monitor Pearson 2878 (one-piece instrument, ready for vacuum use, the output voltage error ±0.5 %). RFG operated at the driving frequency f=2 MHz and its incident power was set in the range 100-800 W. ICP discharge in this ion source was excited in the atmosphere of Xenon at flow rate q=16sccm≈1.46 mg/s. The results of these measurements are shown in Figure 6.

It turned out that without discharge $I_{20}(P)$ systematically exceeded $I_{10}(P)$ with



F… operation measured by the main and control current monitors vs. RFG incident power

Figure 7. Energy effectiveness of the system determined by data from the main and control current monitors vs. RFG incident power

the difference $I_{20}(P)$-$I_{10}(P)$=$I_{lk0}(P)$ up to 0.5 A. In particular in the middle of the incident RFG power range at P=400 W it was obtained: $I_{10}(P)$=D10~7.7 A, $I_{20}(P)$=D11~8.2 A, I_{lk0}=0.5 A and $\Delta I_{lk0}(P)$=D12≈6.5%. At the burning of the discharge $I_1(P)$ and $I_2(P)$ curves practically coincided, i.e. at the working mode of the ion source uncontrollable current leak disappeared. So current leak channels 6, 7, and 8 shown in Figure 3 were absent – this is one of the ion source RIM-20's peculiarities.

Efficiency "RFG-coil" D15=η_{gc0}=R_{c0}/R_{ld0} seems rather interesting: according to the main current monitor data it turned out to be nearly constant η_{gc0}=0.62, i.e. power losses in the discharge electrical feeding line were about 1\3 of the incident RFG power. Knowledge of this indicator is useful for the construction of the balance of the ion source power. Energy effectiveness of the system is characterized by the combined indicator DO1=$\eta_{gd}(P)$. Result of its measurement presented in Figure 7 by a solid line.

Lowering character of this function counteracts analytical data of [3] and known experimental information[2,3]. It seems that the main role in this peculiarity was played by high eddy currents in metal parts and RF power leak at the absence of discharge.

Dashed line in Figure 7 indicates analogous dependence obtained with the control current monitor. It is an artificial one in its essence being elevated with leak current flowing in parallel to antenna coil. But it can be noted that comparison of functions $\eta_{gd}(P)$ showed more sensitivity to coil leak current in contrast to comparison of curves $I_{20}(P)$ and $I_{10}(P)$.

Note that at burning of discharge design indicator, efficiency "RFG-coil" D15=η_{gc} that was measured in the absence of discharge, transforms into similar efficiency, operational indicator O8=η_{gc}=$(R_c+R_{deq})/\ R_{ld}$ and in the present experiment it was equal to nearly 0.8. Herefrom a particular efficiency "coil-discharge" can be determined as η_{cd}=η_{gd}/η_{gc}: when general efficiency η_{gd} varies in the range 0.5-0.4 then particular efficiency η_{cd} changes in the range 0.6-0.5. Thus for fullness of information about the device being studied one can separately evaluate efficiency of electrical feeding line stages "RFG-coil" and "coil-discharge".

In experiments [6] were also obtained other control indicators showing sensitivity to leak current. Their array determined technical shape of the RIM-20 ion source and indicated the following three ways to elevate its efficiency: a) to decrease bulk of metal parts in the vicinity of the antenna coil; b) to optimize geometry and fulfillment of the coil; c) to optimize matching device's schematic.

E. Final remarks

Proposed method of integral diagnostics of an ICP unit is based on obtaining 25 control indicators by way of measurements and calculations. Quite numerous indicators can differently react on different peculiarities of an ICP device under studies determining its technical shape. Summing up the contents of the present work it can be noted that realization of the proposed method of integral diagnostics creates opportunity to, firstly, find out the way to increase its energy efficiency in the presence of such a necessity and, secondly, to prepare with enough entirety physical-technical base to understand results of local plasma diagnostics of an ICP discharge.

II. Conclusion

1. A modified method of ICP discharge integral diagnostics is proposed.
2. It consists of measurements and calculations of 25 control indicators of an ICP system characterizing its general physical-technical shape.
3. Two examples of the proposed method realization are described that showed ways to elevate energy efficiency of both devices.

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