Radio frequency source of weakly expanding wedge-shaped xenon ion beam for contactless removal of large-sized space debris objects

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Abstract

Theoretical-experimental research has been carried out to obtain characteristics of a radio frequency (RF) source generating weakly expanding wedge-shaped xenon ion beam. Such ion beam geometry is interesting as a prototype of service spacecraft's on-board ion injector realizing contactless "Ion Shepherd" method of large-sized space debris object removal from geostationary orbit. Wedge shape of the ion beam provides longer "range" as compared with conical ion beam. This source comprises a gas discharge chamber (GDC) with a flat antenna coil enhanced by ferrite core and three electrode ion extraction grid (IEG) unit of the slit type. The profiled accelerating cells of the ion extracting electrode provide formation of ion beam 100 mm in diameter. Calculation results for IEG accelerating cells and ion trajectories allowed for determination of beam expansion half-angle dependence on reduced perveance. These calculations were based on the measurements of xenon plasma parameter spatial distributions in the GDC space for different levels of incident RF power supplied by RF generator (RFG) at frequency f=2 MHz and pressures p=2-4 mTorr. Tests of the source showed that at RFG power 100-250 W and xenon flow rate q=2-4 sccm≈0.2-0.4 mg/s ion beam current was 90-250 mA. The form of the ion beam was determined by spatial distributions of target erosion depths caused by ion bombardment. The optimal value of the reduced perveance for minimal ion beam expansion was $1.9 \cdot 10^{-4}$ A/(m^{2}V$^{3/2}$) that agreed well with calculations. At this parameter half-angle of beam expansion across IEG slits was about 2-3° and along them – close to 0°. These studies showed possibility to create an on-board ion injector that can be used in spacecrafts of new generation for debris object removal and for orbit servicing.

Introduction

The interest to weakly expanding ion beam is caused by the idea of large-sized space debris objects' (SDO's) removal from circumterrestrial geostationary orbit (GSO) affecting them with high-intensity ion beam injected from aboard a service spacecraft (SSC) [1, 2]. The distance between SSC and SDO in the process of SDO transportation to a burial orbit should exceed the sizes of both objects. According to evaluations it can reach 30-60 m that is the necessary "range" of ion beam [3, 4]. The problem of weakly expanding beam generation can be solved using radio frequency (RF) gas discharge ion source. Motivation of this possibility resulted from theoretical-experimental research carried out in the present work that is included into the framework of the R&D Contract with the "Roscosmos" State Space Corporation – its principal consumer.

The design of the ion source

The design of the RF ion source model developed in the present work is presented in Fig. 1.

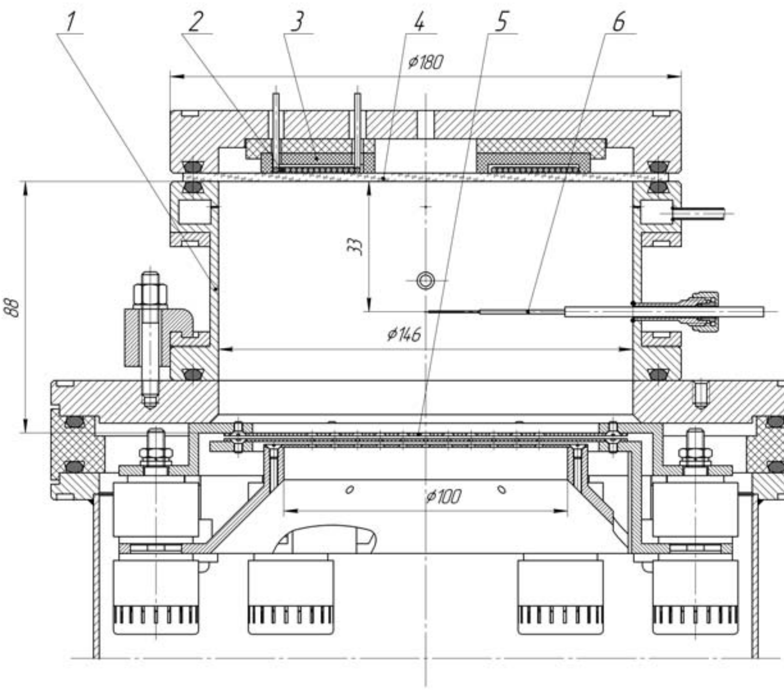

Fig. 1 The design of the ion source model based on an ICP gas discharge unit

It contains a metal gas discharge chamber 1 (GDC) as an inductive xenon plasma source with 146 mm internal diameter. It is supplied with frontal flat antenna coil 2 enhanced with ferrite core 3. The antenna unit is separated from gas discharge space with 5 mm thick quartz window 4. An ion extracting grid (IEG) of the model contains three perforated flat electrodes with slotted holes: an extracting (emission) electrode (EE), contacting GDC plasma, an accelerating electrode (AE) and a delaying electrode (DE).

The design of gas discharge unit of this source was developed following its prototype [5, 6] that features design simplicity, enhanced energy effectiveness, and acceptable uniformity of plasma parameter spatial distribution. The geometry of IEG accelerating cells corresponding to a classical scheme "acceleration-delay" was determined by calculations based on GDC plasma parameter measurements in preliminary experiments using Langmuir probes 6 that radially moved at 33 mm distance from internal surface of the quartz window 4.

Studies of integral GDC characteristics and local plasma parameters in autonomous experiments

Integral GDC diagnostics was carried out to measure RF power absorbed by the discharge plasma at the exact matching of RF generator (RFG) with its load in the form of inductively coupled plasma (ICP) discharge. This procedure served as the base for subsequent analysis of local GDC plasma diagnostics results. Besides it allowed for determination of RF power loss in all elements of the discharge electrical feeding line beginning from the antenna coil and metal parts beside it. The method of this diagnostics that determined physical-technical shape of the studied ion source including its design and circuit engineering of the electrical feeding line, has been published as patent application [7] for which positive decision has been taken, and described in detail in [8]. Integral diagnostics of GDC showed that at RFG incident RF power P_g=100-250 W the power absorbed by plasma varied in the range P_p=84-220 W that corresponded to the RF energy transfer effectiveness from RFG to discharge η_{gp}=0.84-0.88 for plasma pressure p=2 mTorr. As an additional result of this diagnostics the ionization degree of xenon plasma was evaluated being not more than 1.5 % at pressures p=2 and 4 mTorr corresponding to xenon flow rate q= 2 and 4 sccm ≈ 0.2 and 0.4 mg/s. In general, these measurements confirmed that a GDC with flat antenna coil and ferrite core featured enhanced energy effectiveness with simplified design as compared to previously known RF ion thrusters (RITs) with cylindrical, conical and domelike GDC.

Local properties of ICP xenon plasma were studied at pressure p=2 mTorr using classical cylindrical Langmuir probes. They were made of tungsten filament 0.15 mm in diameter with probe tip length in the range l_p=3-10 mm. Measurements showed that at l_p=10 mm charged particle recombination on the probe holder 1.6 mm in diameter practically did not influence plasma parameters [9]. Local diagnostics of this plasma showed that spatial distributions of its parameters feature were more uniform than in previously known RIT models.

Ion current density to the IEG EE being a wall under floating potential was studied using radially movable plane wall probe simulator fixed flush with the ceramic rod's butt where dielectric surface exceeded probe collecting surface by about 10 times [12]. Measurements of electron energy distribution function (EEDF) for plasma beside this plane probe showed that it differed noticeably from Maxwell function. Therefore in these conditions Boltzmann law could not be used to determine sought-for ion current density using measured values of electron saturation current densities to the plane probe. So this problem could be solved only by linear extrapolation of probe volt-ampere characteristics' (VACs') ion branches to the floating potential of the plane probe that in the present experiment was constant V_f=2.35 V. To make this procedure be closer to reality, the recommendations of work [13] were followed using ion branch linear extrapolations of semi-logarithmic or double-logarithmic VACs' having some definite theoretical bases. Mathematically this technique means some power law of ion current dependence on probe potential. Both ways of these extrapolations in the present work gave the same results that are shown in Fig. 2.

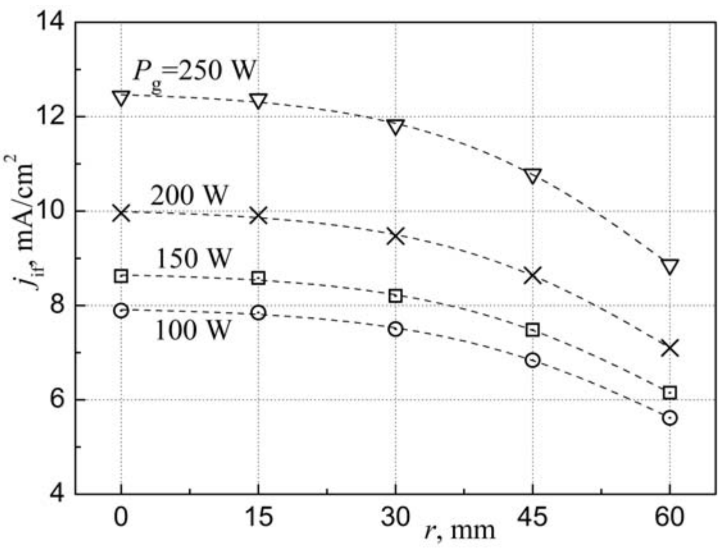

Fig. 2. Radial distributions of ion current densities to IES EE at different values of P_g

Processing of plane probe VACs by Druyvesteyn method resulted in radial distributions of electron temperature T_e and concentration n_e for xenon plasma that are presented in Figs 3 and 4.

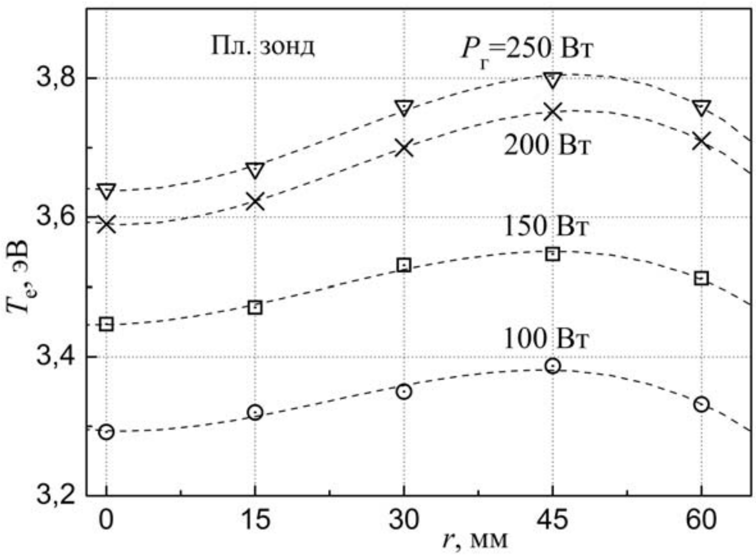

Fig. 3. Radial T_e distributions for different P_g

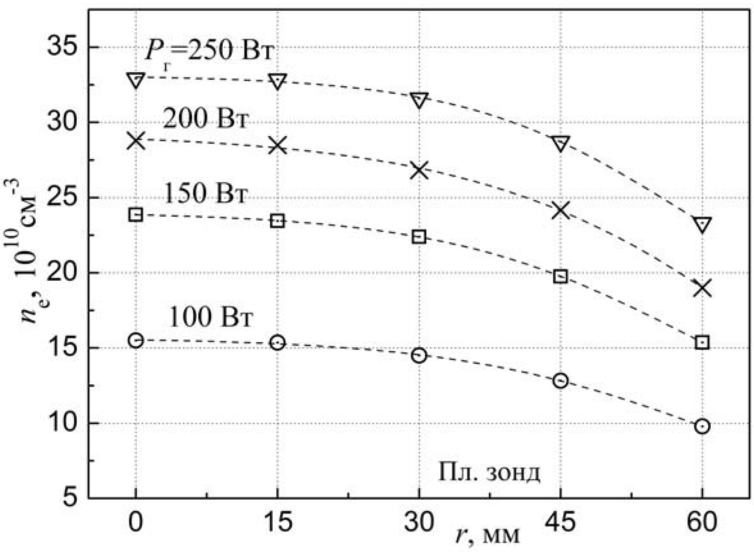

Fig. 4. Radial n_e distributions for different P_g

Note that these data were obtained at the distance of 33 mm from quartz window 4 (Fig. 1) while the IEG of the source was located 88 mm off the same window. Measurements of longitudinal distributions of plasma parameters in GDC made with longitudinally and rotary movable L-probe [11] showed rather high uniformity of plasma in this range of distances. So the data of Figs 2-4 with good precision correspond to xenon plasma parameters just beside the IEG EE.

In [14, 15] it has been shown that local diagnostics of undisturbed plasma, close to a Maxwellian substance, gives not only standard probe parameters but also two additional plasma characteristics. One of them is thickness of probe sheath confirming correctness of Langmuir-Druyvesteyn probe theory used for probe measurement interpretation. The other one is the mean ion mass showing the degree of plasma purity.

IEG calculation

It is well known the creation experience for hydrogen ion sources generating fast atom beams for used to achieve weak ion beam expansion. Similar IEG cell geometry was used in the calculation studies of the present work. The peculiarity of ion beam formation in slit IEG consists in its wedge shape. In this case ion beam expansion along the slit is limited because it should correspond only to transverse ion thermal velocity. In the ICP discharge of the present work the temperature of heavy particles is rather low (about 500 K) that is why thermal expansion of ion beam is rather weak. Even if ion velocity scatter about $e\Delta U=\pm 25$ eV [17] is considered as evaluation of the upper limit of the transverse ion movement at the IEG inlet, it does not result in substantial beam expansion along the slit. As the matter of fact, $\mathrm{tg}\alpha=\Delta U/U_{EE}$ where U_{EE} is the EE potential determining beam ion energy and α is half-angle of beam expansion. According to the said evaluation this angle can reach 0.4-0.8° for U_{EE}=4500-2000 V respectively. As for beam expansion across the slit, it depends on focusing IEG properties that were studied numerically. Calculations of ion trajectories in elementary IEG cells were carried out using IGUN program [18]. In [3, 4] the ion beam configuration in an IEG cell and the dependence of α on the cell reduced perveance $\Pi=j_i/U^{3/2}$ are given as an example (j_i is ion current density to EE and $U=U_{EE}+|U_{AE}|$ is potential difference between EE and AE) – see Figs 5 and 6.

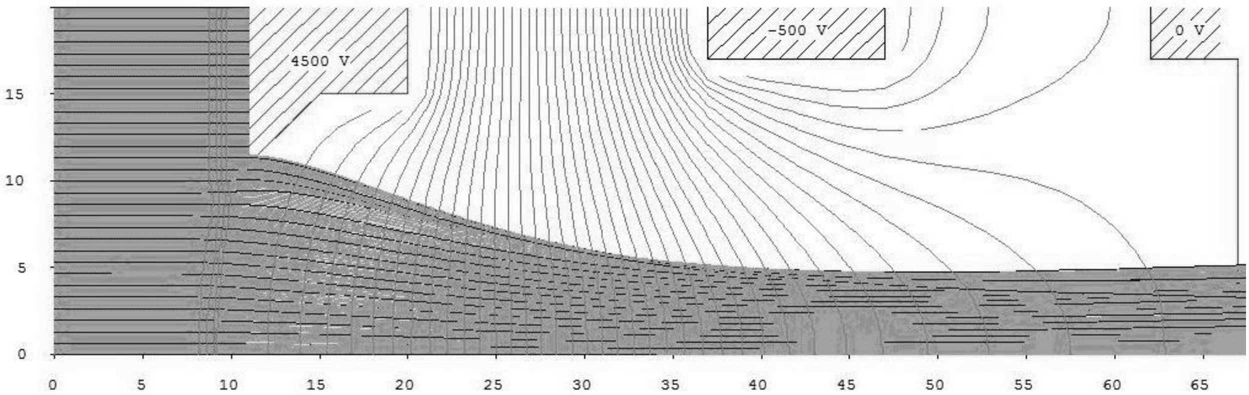

Fig. 5. An example of calculated beam configuration for U=5 kV

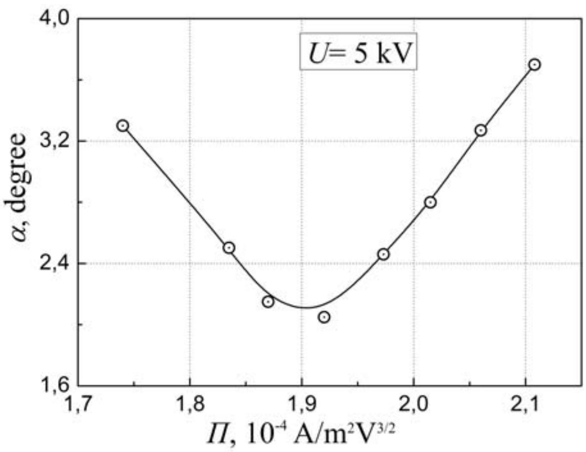

Fig. 6. Dependence of beam half-angle expansion on reduced perveance

In this version of the cell geometry for U=5 kV (U_{EE}=4.5 kV) EE and AE thicknesses are equal to 1 mm, slit width is 2 mm and the inter-electrode gap is 1.7 mm. The cell geometry and electrode potentials shown in Fig. 5 were considered in [3, 4] as the most acceptable features of an on-board SSC ion injector. The calculated reduced perveance value $\Pi=1.9\cdot 10^{-4}$ A/m^{2}V$^{3/2}$ for the minimal half-angle of ion beam expansion that was about 3º, may serve as a checkpoint for selection of discharge parameters for on-board ion injector.

The ion source studied in the present work is a lab model of such injector. The main task of this research is to confirm the possibility to achieve acceptable ion beam focusing and reliability of computational IEG study using program complex IGUN [18]. For this source the EE was manufactured according to current technological possibilities with the cell geometry shown in Fig. 5. Calculation results shown in Fig. 6 mean that deviation from quazi-Pierce geometry can result in increase of expansion half-angle from 3º to 5º for the optimal reduced perveance close to both (??) IEG cell geometries. Therefore the reduced perveance Π=1.9·10^{-4} A/m^{2}V$^{3/2}$ served as IEG similarity criterion for the present task. Following this peculiarity ion current density was recalculated for varied values of U and operational parameters of the source. Thus at U=2500 V (Figs 7 and 8) ion current density for minimal ion beam expansion was about 24 A/m^2.

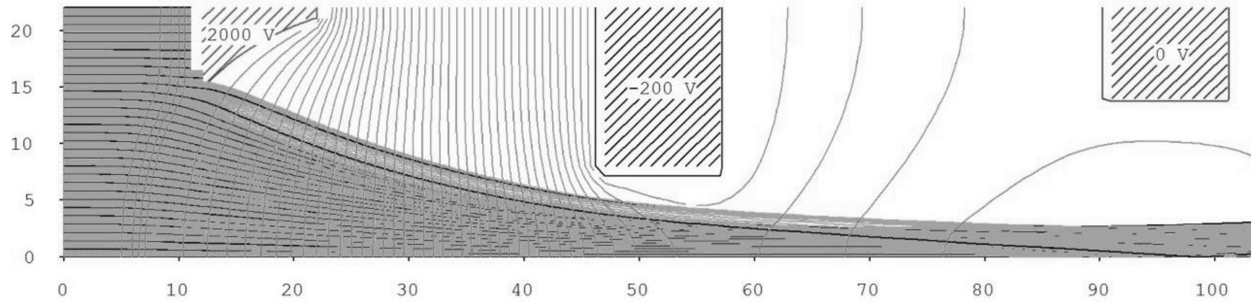

Fig. 7 Calculated beam configuration for U=2.5 kV

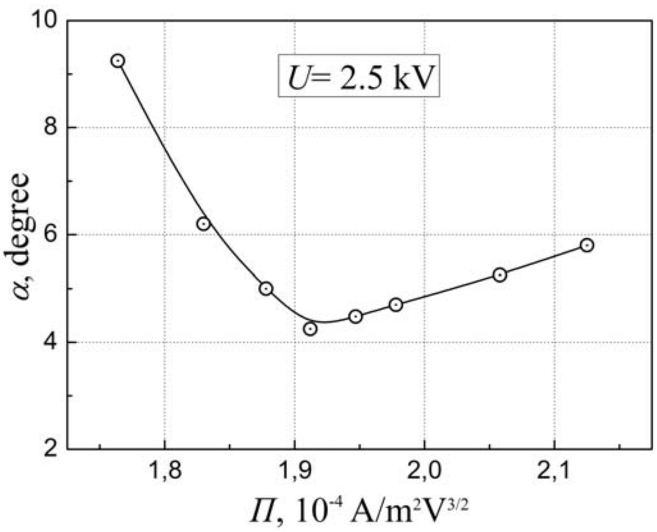

Fig. 8 Dependence of beam half-angle expansion on reduced perveance

It is evident that calculation gives approximate evaluation of expansion half-angle and it needs to be checked experimentally. In Fig. 9 photo is presented of EE, AE, and DE (from the left to the right) made of graphite with cell geometry corresponding to Fig. 7.

Fig. 9 IEG electrodes made of graphite

Experimental study of ion beam properties

Experiments were carried out in a big vacuum chamber provided with turbo-molecular and cryogenic pumps. Its volume was about 20 m^3 that allowed for ion beam generation in vacuum space. The design of the ion source connection with this vacuum chamber is presented in Fig. 10.

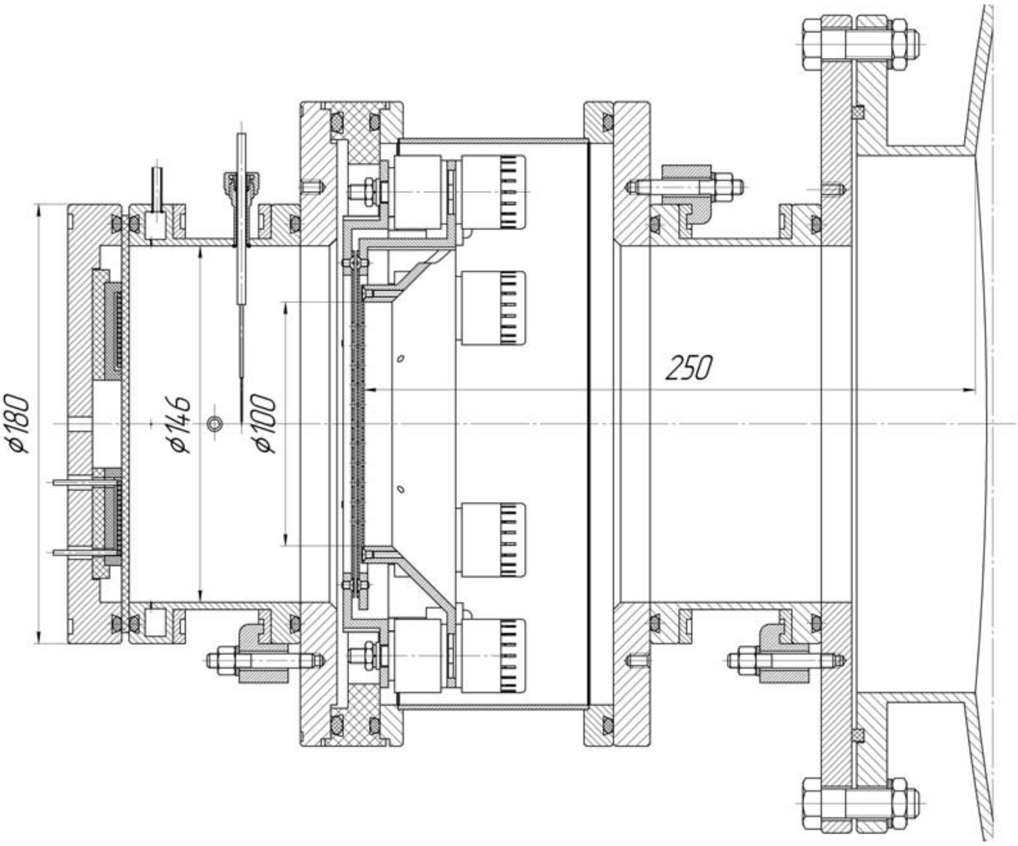

Fig. 10 The ion source model connected with the big vacuum chamber

The GDC of the source is located at the external flange of the vacuum chamber being surrounded by atmospheric air. Its appearance is shown in Fig. 11.

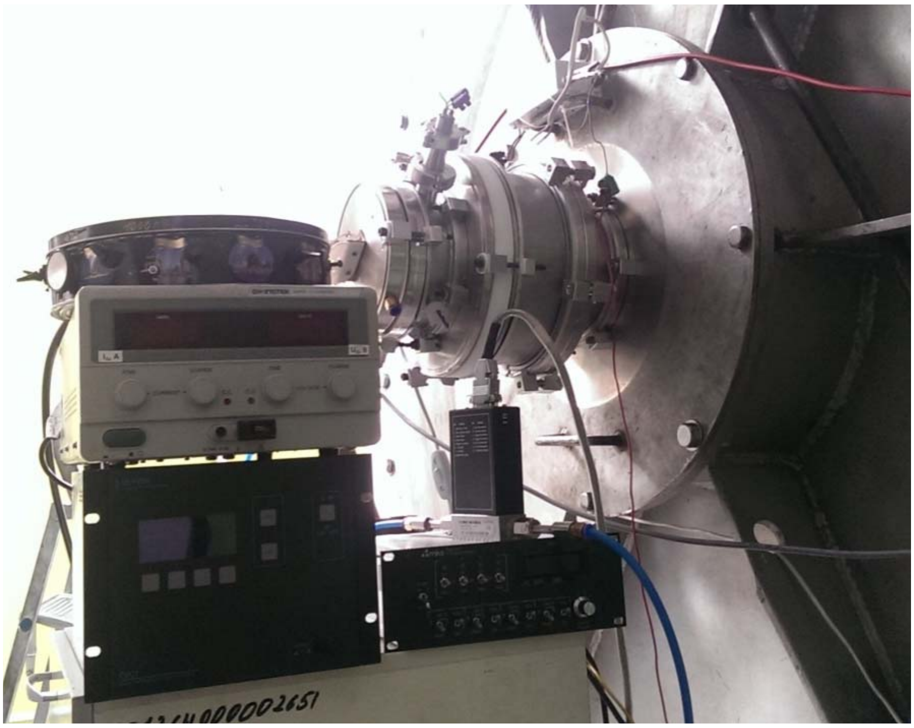
Fig. 11. RF ion source mounted on the big vacuum chamber

In similar way the source's GDC with the antenna coil at atmospheric pressure conditions was tested in autonomous experiments mentioned above. Such arrangement of GDC tests allowed for probe measurements of plasma parameters and for plasma pressure registration by pressure gauge in autonomous tests with IEG gas-dynamic model and in tests on the big vacuum chamber with real IEG electrodes. Measurements showed that in autonomous experiments using small vacuum chamber plasma pressure was equal to 2 mTorr at xenon flow rate 2 sccm ≈ 0.2 mg/s. In the big vacuum chamber at this flow rate plasma pressure was about 1.2 mTorr. Therefore pressure of previous local plasma diagnostics can be achieved at higher xenon flow rate.

So far the preliminary experiments were carried out at xenon flow rate 0.2 mg/s and plasma pressure 1.2 mTorr. Their results are presented in the Table being compared with calculation data. In general they seem interesting with quite acceptable agreement of theory with experiment.

Table. Comparison of calculated and measured parameters of the source model

Parameter	Calculation	Measurement
Beam current, mA	90	90
Xenon flow rate, mg/s	0,2	0,2
Ion current density, A/m^2	2,4	2,06
RF power, W	-	90
EE potential, V	2000	2000
AE potential, V	-500	-200
Plasma pressure, mTorr	2	1,2
Electron consentration, m^{-3}	$0{,}75\times10^{17}$	Not measured
Electron temperature, eV	5	Not measured
Half-angle of across slit expansion	$3\text{-}4^0$	$2\text{-}3^0$
Half-angle of longitudinal expansion	$<1^0$	$<1^0$

Ion beam expansion was measured using targets installed in the vacuum chamber at the distance of 580 mm from the IES exit on which ion beam left its traces. Initially for expansion angle qualitative evaluation titanium sheet was used. The photo of ion beam erosion traces on this target is shown in Fig. 12.

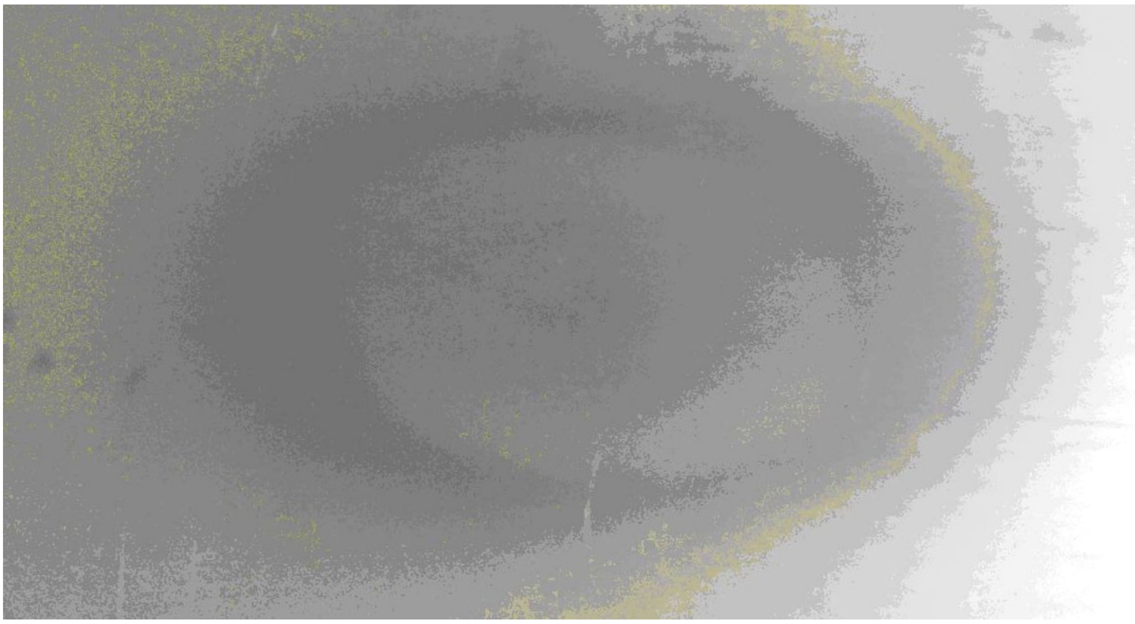

Fig. 12 Erosion trace on titanium target

They show that ion beam expansion along IEG slits is much less than across them with the last half-angle not more than several degrees. Based on these data operational parameters of the source were made closer to optimal situation presented in the Table. More strict quantitative evaluation of the beam configuration was obtained using glass target shown in Fig. 13.

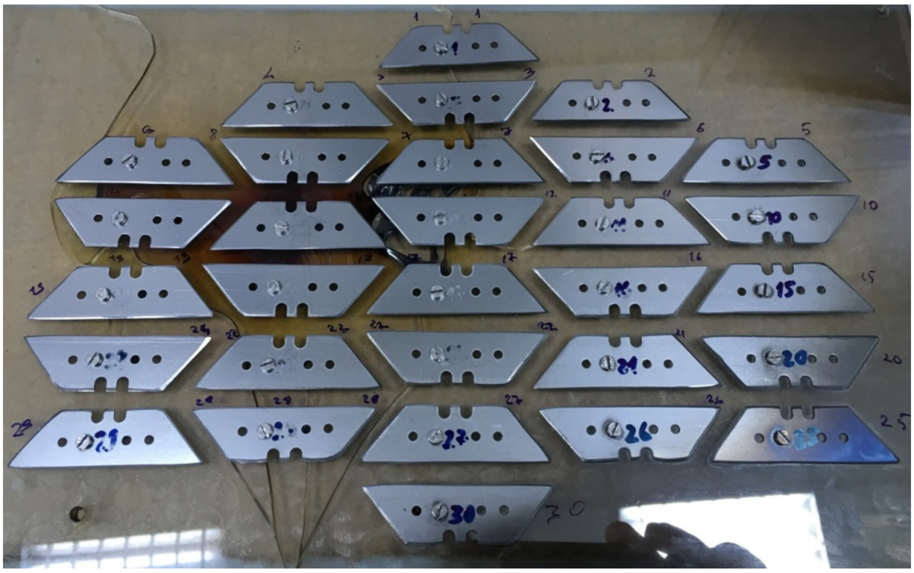

Fig. 13 Glass target covered by metal masks with holes open for ion bombardment

Glass target reinforced with protective film on the reverse side against cracking, was covered by a group of metal strip masks with holes open for local ion etching of glass. Thus obtained etch pits were studied using the contact profile meter KLA D-600 with the error of ±5 nm for the step method. Lines of equal glass erosion depths are shown in 2D Fig. 13 and their spatial distribution – in 3D Fig. 14.

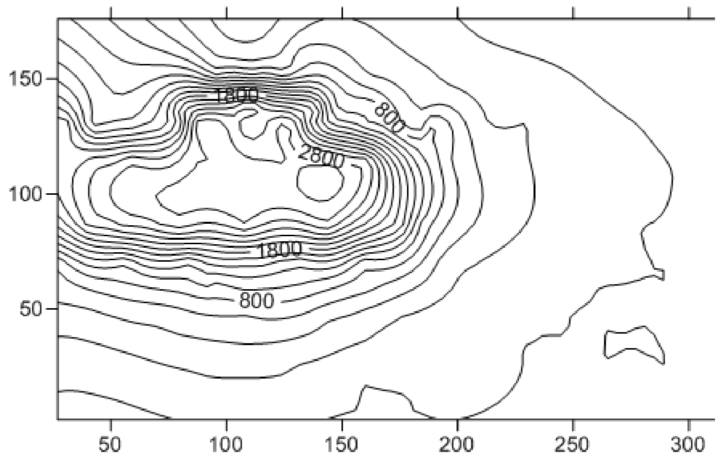

Fig. 13 Lines of equal erosion depths in the glass target

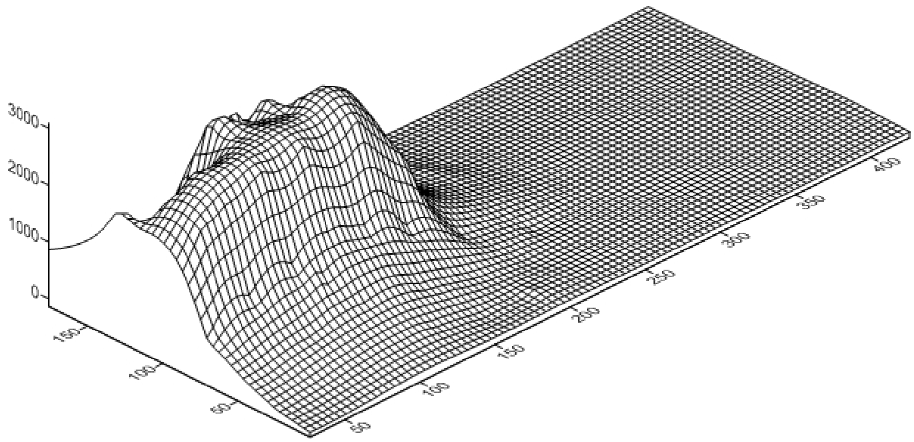

Fig. 14 Spatial distribution of erosion depths in the glass target

Conclusion

The model of the RF ion source having gas discharge chamber with flat antenna coil and ferrite core and slit IEG has been created and studied experimentally. It features simplified design and acceptable uniformity of ion current density to EE at enhanced energy transfer effectiveness from RFG to plasma. Operational parameters of the source providing minimal expansion of ion beam were found in these experiments. It was shown that at RFG incident power P_g=100-250 W and xenon weight flow rate g=0.2-0.4 mg/s ion beam current varied in the range I=90-250 mA. Geometry of ion beam was determined by erosion traces on targets. Minimal ion beam expansion corresponded to reduced perveance equal to $1.9\cdot10^{-4}$ A/m^{2}V$^{3/2}$ that agreed well with calculations. At ion beam current I=90 mA, EE potential 2000 V, and AE potential -200 V half-angle of ion beam expansion was 2-3° across IES slits and about 0° along them.

The present ion beam source can be used at SSC to remove large-sized SDOs from protected area of GSO. Preliminary evaluating calculations showed that one such SSC can remove more than ten SDOs.

Acknowledgment

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