Improved Bulk Plasma Uniformity in a Discharge System with Electron Injection[1]

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Abstract – The paper presents the results of experimental study with the aim to improve the bulk plasma uniformity in a constricted-arc discharge system with electron injection. The discharge operated in argon in the dc mode. The operating voltage of the main discharge was varied between 20 and 100 V, and the emitter current between 3 and 15 A. The pressure in the vacuum chamber was 0.5 mTorr. The radial plasma distribution was measured with a plane movable Langmuir probe. It is shown that geometrical modifications of the intermediate electrode exit aperture and of the main discharge cathode add little to the uniformity of the produced plasma. Improved bulk plasma uniformity is observed where a special distributing grid electrode and a main discharge voltage lower than 20-30 V were used. The application of a weakly divergent magnetic field in the region of the intermediate electrode exit aperture made it possible to decrease the plasma nonuniformity from 20 to 14% over a distance of 30 cm. The bulk plasma uniformity was also improved through compensating the magnetic self-field of the injected electron beam by the reverse magnetic field produced with a special distributing electrode. It is shown that an increase in discharge current causes a proportional increase in back current in the distributing electrode. The approach allows a decrease in plasma nonuniformity from 20 to 13% over a distance of 30 cm.

1. Introduction

One of the main requirements imposed on gas-discharge plasma generators is uniformity of the plasma produced in the vacuum chamber. The production of uniform plasma in a large volume provides condition for uniform ion irradiation of the entire surface of large objects or a great quantity of objects with a large total area. The improvement of gas plasma uniformity is much addressed in the literature. The problem is solved by various methods, e.g., by changing the geometry of the extractor grid [1], by placing dielectric or metal distributing electrodes across the propagating electron beam [2, 3], or by superimposing a weak magnetic field [4].

The author of [5] show that the use of distributing grid electrodes in a discharge system with external electron injection allows a decrease in the uniformity of the produced plasma from 40 to 20% of the average value over a distance of 50 cm. However, despite the higher uniformity of the bulk plasma, the positioning of this electrode causes an undesirable decrease in the current of the main discharge and in the density of the produced plasma by, on average, 20% due to partial interception of the electron flow by the distributing electrode.

The above study also show that as the emitter discharge current is increased (to over 10 A), the spatial nonuniformity of the plasma distribution in the volume increases on account of focusing of the injected electrons along the system axis by their self-field.

The paper presents the results of experiments with the aim to improve the uniformity of the bulk gas-discharge plasma produced in a constricted-arc discharge system with electron injection. The problem under consideration is solved by changing the electrode geometry, superimposing a weak magnetic field, and compensating the magnetic self-field of the injected electron beam.

2. Experimental arrangement

Schematic of the experimental arrangement is shown in Fig. 1.

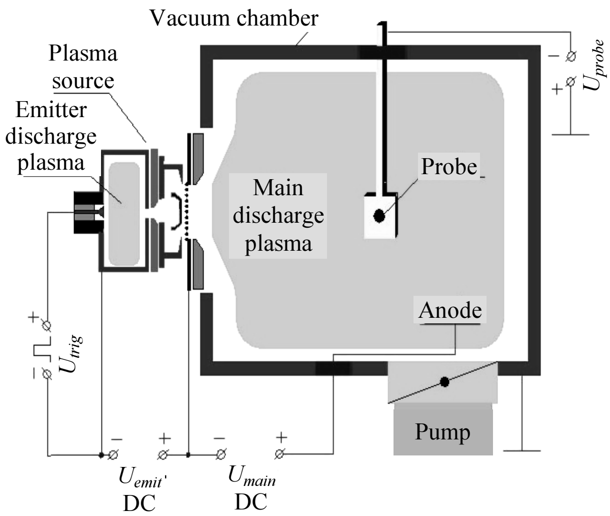

Fig. 1. Experimental arrangement: *1* – emitter discharge cathode; *2* – shield; *3* – intermediate electrode; *4* – emitter discharge grid anode (main discharge cathode)

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Plasma was produced in a two-stage discharge system in the continuous mode. A detailed description of the discharge system and the principle of its operation can be found elsewhere [6]. The operating voltage of the main discharge was varied between 20 and 100 V and the current of the emitter discharge between 3 and 15 A. The working gas (argon) was supplied to the cathode cavity of the emitter discharge. The operating pressure in the vacuum chamber was kept constant at about $5 \cdot 10^{-4}$ Torr. The vacuum chamber was made of stainless steel. The diameter and length of the vacuum chamber were 50 and 60 cm, respectively. Vacuum was produced by a cryogenic pump. The anode of the main discharge was a separate electrode with an area of 240 cm^2 insulated from the grounded walls of the vacuum chamber. The distribution of the ion current density was measured using a plane Langmuir probe with a guard ring. The areas of the probe and of the guard ring were 10 and 100 cm^2, respectively. The guard ring was a movable water-cooled holder. The probe was arranged 30 cm away from the plasma source. A negative bias of 250 V was applied to the probe and was sufficient for reflection of high-energy plasma electrons and for saturation of the ion branch of the current-voltage characteristic of the probe.

3. Results and discussion

The injected electrons are accelerated in the main in the cathode layer of the main discharge. Therefore, for the injected electrons to move in the required direction, namely from the axis to the periphery of the chamber, convex and concave grid electrodes with different curvature radii were made. For reducing the distortion of the radial distribution of the bulk plasma density, due to focusing of the injected electrons by their self-field, the current of the emitter discharge was kept at about 3 A.

The experiments show that with a main discharge voltage of 100 V, the modification of the grid cathode shape does little to the uniformity of the bulk plasma. Apparently, this is due to the insufficiency of the cathode layer thickness to change the trajectory of the injected electrons and, hence, of the energy of the injected electrons; as a result, the electrons loose their directed velocity over a distance much smaller than the vacuum chamber length.

The modification of the intermediate electrode exit aperture also does little to the uniformity of the produced bulk plasma. In the experiments, we used an electrode with one central emission hole. The other two electrodes had several holes with the same total area (with and with no narrow coupling slots between each other) at the electrode periphery. Conceivably, the fact that the geometry of the intermediate electrode exit aperture has little or no effect on the uniformity of the produced bulk plasma owes to overlapping and merging of electron flows from different holes into a single flow at a distance of 30 cm, as is the case with the electrode with one hole.

Improved uniformity of the produced plasma is observed where the voltage of the main discharge is decreased to 20–30 V. Since for these parameters, the cathode layer thickness was 1 mm and the grid mesh was 1–2 mm, this ensured the formation of a near-cathode layer with undulatory equipotential lines, thus assisting in more efficient electron scattering and in more uniform bulk plasma. However, decreasing the main discharge voltage decreases the energy of the injected electrons and, hence, the density of the produced plasma. For increasing the plasma density in this case, one should either increase the operating pressure with the corresponding increase in gas flow rate or increase the emitter current. However, the increase in pressure in the vacuum chamber is undesirable, because it leads to an increase in the flow of gas atoms to the treated surface and hence to a decrease in the efficiency of ion treatment. At the same time, increasing the current of the emitter discharge increases the plasma nonuniformity due to focusing of the injected electrons by their self-field.

The effect of a weak external magnetic field in the region of the intermediate electrode exit aperture on the uniformity of the produced plasma was studied at a main discharge voltage of 100 V and an emitter discharge current of 3 A. The magnetic field was produced by a solenoid located directly on the intermediate electrode inside the discharge system. The maximum magnetic field at the center of the coil was 1 mT at a current of 3 A. The coil was connected in series to the emitter discharge circuit. The intermediate electrode was an electrode with two groups of holes. The first group (8 holes of diameter 11 mm) was made on a radius of 17 mm, while the other (8 holes of diameter 4 mm) on a radius of 7 mm. The electrode of this configuration decreases the number of injected electrons on the field lines along the discharge system axis and increases their number at the periphery.

Figure 2 shows the results of computer computation of the configuration of the magnetic field lines in the region of the intermediate electrode exit aperture and of the cathode grid of the main discharge.

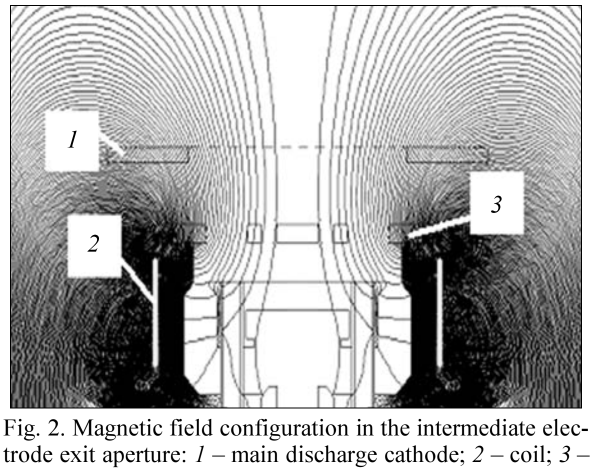

Fig. 2. Magnetic field configuration in the intermediate electrode exit aperture: *1* – main discharge cathode; *2* – coil; *3* – intermediate electrode

It is seen that with this position of the magnetic coil, the magnetic field lines in the acceleration region of the injected electrons are strongly divergent. Under these conditions, the Larmor radius for electrons is about 3 cm and the chamber diameter is 50 cm, and hence the magnetic force lines diverging from the axis to the periphery of the discharge system may be considered as being mainly responsible for the direction of the injected electrons.

The radial distribution of the ion current density for this case is shown in Fig. 3.

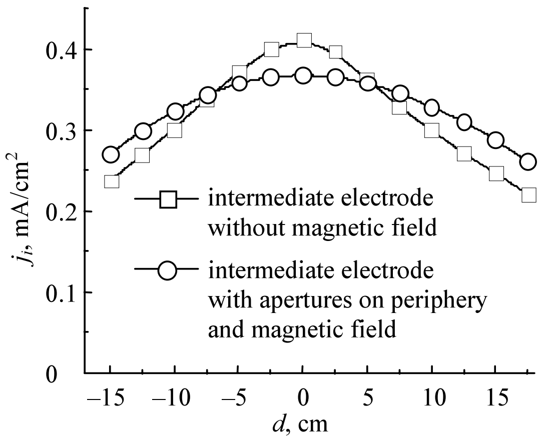

Fig. 3. Radial distribution of the ion current density: U_{main} = 100 V, $I_{emit.}$ = 3 A, $p = 5 \cdot 10^{-4}$ Torr

It is seen that the superimposition of the weak magnetic field diverging in the region of the main discharge cathode and the use of the intermediate electrode with holes at its periphery appreciably improves the uniformity of the produced plasma. Because the solenoid was connected in series to the emitter discharge circuits, the increase in discharge current causes a proportional increase in coil current and, hence, in magnetic field scattering the electron beam, resulting in improved uniformity of the produced bulk plasma.

Obviously, the further increase in magnetic field will have a beneficial effect on the uniformity of the produced bulk plasma. Unfortunately, these experiments were not conducted, because the thermal conditions of the magnetic coil located in the narrow gap limited the maximum current to about 3–5 A.

With an emitter discharge current higher than 5 A, an electrode-compensator with a back current was used to improve the plasma uniformity. The electrode-compensator was four conductors made of steel wire of diameter 1 mm and length 15 cm connected with each other. The compensator was mounted on the face of the plasma generator and was connected in series to the power supply circuit of the main discharge. The power supply circuit with the compensator is shown schematically in Fig. 4.

Figure 5 shows the radial distribution of the ion current density for different currents of the emitter discharge. With no compensator, as in [3], increasing the emitter discharge current increases the radial nonuniformity of the produced plasma due to focusing of the injected electrons along the discharge system axis.

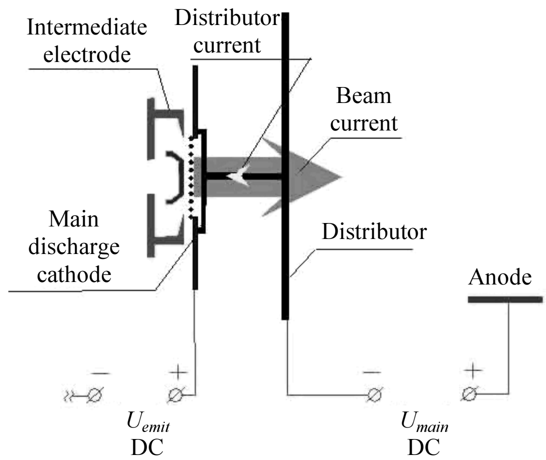

Fig. 4. Circuit of the electrode-compensator with back current

The use of the electrode-compensator with a back current allows a decrease in radial plasma nonuniformity from 20 to 13% of the average value over a distance of 30 cm at an emitter discharge current of 10 A. Since the compensator is powered through series connection to the main discharge circuit, the increase in the current of the injected electrons causes a proportional increase in compensator back current. Thus, the compensation of the magnetic self-field of the injected electrons using the magnetic field produced by the back current in the distributor circuit has a beneficial effect on the plasma uniformity even with increasing the emitter discharge current.

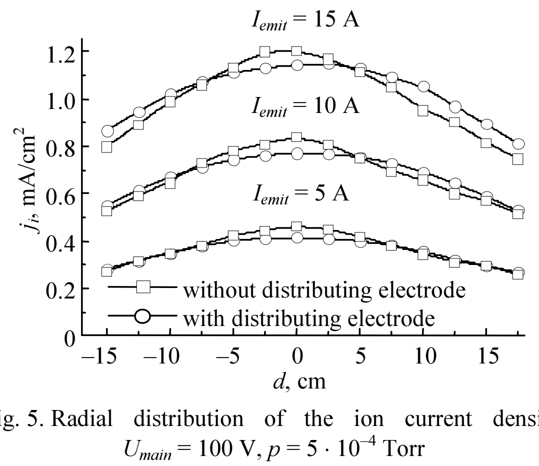

Fig. 5. Radial distribution of the ion current density: U_{main} = 100 V, $p = 5 \cdot 10^{-4}$ Torr

The experiments show that the uniformity of the plasma distribution is also affected by the length of the region in which the electron beam interacts with the reverse magnetic field produced by the electrode with back current. Increasing the compensator length improves the uniformity of the radial plasma distribution. At the same time, the dimensions of this electrode are limited by the requirements for the maximum dimensions of the plasma generator and for the absence of its parts in the treatment zone. For this reason, the maximum length of the electrode with back current in the experiments was no greater than 15 cm.

4. Conclusion

Thus, the experiments demonstrate the use of a weak scattering magnetic field in the region of the main discharge cathode in combination with a specially shaped exit aperture of the intermediate electrode, or with a back-current electrode, which compensates the magnetic self-field of the injected electron beam, makes it possible to increase the bulk plasma uniformity in the two-stage constricted-arc discharge system with electron injection.

The advantage of the proposed methods is the absence of interception of the electron flow by the distributing electrodes and, hence, the absences of decrease in main discharge current.

The scattering magnetic coil and the electrode-compensator connected to the power supply circuit of the discharges ensure a so-called negative feedback and, thus, compensation of the increase in plasma non-uniformity with increasing the discharge parameters.

References

[1] P.M. Stchanin, *Charged-partciles sources with a plasma emitter*, Ekaterinburg, Nauka, 1993.

[2] N.N. Koval, Candidate-degree thesis, IHCE SB RAS, Tomsk, 1984.

[3] N.V. Gavrilov, G.A. Mesyats, S.P. Nikulin, A.J. Perry, and J.R. Treglio, J. Vac. Sci. Technol. A. **14**(3), 1050–1055 (1996).

[4] S.P. Nikulin, D.F. Chichigin, and P.V. Tretnikov, Zh. Tekh. Fiz. **74**, No. 9, 39–42 (2004).

[5] M.V. Shandrikov, Candidate-degree thesis, IHCE SB RAS, Tomsk, 2005.

[6] A.V. Vizir, M.V. Shandrikov, G.Yu. Yushkov, and E.M. Oks. *in Proc. of 7^{th} Int. Conf. on Modification of Materials with Particle Beams and Plasma Flows*, 2004, pp. 81–84.