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The electric field of the electrodes immersed into the rotating plasmas

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Abstract. The possibility of using an additional deflection electrodes for plasma separation of matter by mass in a reflex discharge is considered in the article. Two types of the additional electrodes configuration are used. The first type of electrodes is oriented transversely to the direction of plasma rotation; the second type is oriented along it. It is shown that the presence of additional electrodes of the first type leads to a decrease in the discharge current by 4 times. The electrodes prevent the rotation of the plasma, and as a consequence, there is no electric field between the electrodes. Electrodes of the second type do not prevent the plasma rotation and therefore an electric field can exist between them.

1. Introduction
The reprocessing of a spent nuclear fuel (SNF) is one of the key challenges facing the nuclear industry. Among other technologies the plasma based methods for reprocessing SNF are actively developed [1]. In the Smirnov’s method [2, 3] the plasma separation of matter by mass of ions is implemented in crossed electric E and magnetic H fields. The $E \times H$ fields should be immersed in plasma. This plasma can be created by an external rf field [4] and directly by end electrodes which preset distribution of the transverse electric field [5]. In [6] the possibility to separate particles by mass was investigated in the case if the injection of the particles occurs along the magnetic field. To enhance the separation effect, it is proposed to use “capacitor plates”—additional electrodes. These electrodes create an additional electric field perpendicular to magnetic field, which increases the transverse velocity component of particles, and therefore increases the force acting from the magnetic field on these particles.

Two configurations of electrodes were investigated in presence of the primary reflex discharge to ascertain the experimental possibility of creating the additional electric field.

2. Experimental setup and measuring methods
The setup of the additional electrodes system inside the chamber is shown in figure 1. The first electrode configuration consisted of two plane-parallel rectangular electrodes with a length of 40 cm and a height of 10 cm along the magnetic field lines and spaced from each other by 10 cm. One electrode is shifted relative to a vertical plane passing through the axis setup on 13 cm while another one is shifted on 23 cm. Virtue of this scheme with solid plates is the rigid equipotential distribution on their surfaces, which sets the boundary conditions for the electric field in the region between them. The main disadvantage is the fact that the plasma of the reflex
Figure 1. The scheme of the additional electrodes system location in plasma separator.

Figure 2. Experimental setup with the first electrode configuration.

discharge rotates, and the solid electrodes create a geometric “shadow”, causing plasma density reduction in the region between the electrodes.

The second electrode configuration consist of two pairs of rectangular electrodes $5 \times 10 \text{ cm}^2$, each of which based on its own set of magnetic field lines. The electrodes of every pair are spaced from each other by 25 cm and are biased at the same voltage. Thus a small reflex discharge is formed inside the main one. A plasma column of the small reflex discharge acts as deflecting electrode. In this scheme, the shading effect of the plasma rotation is obviously missing. However, the shape and the size of the electrodes can influence the reproduction of the potential along magnetic field lines from the respective pairs of electrodes. It caused by their small size in comparison with the electrodes of main reflex discharge.

The experiments are carried out in the separator chamber. The working gas is argon. The residual air pressure in the chamber is 0.02 mTorr and argon is of 0.5–1.3 mTorr at leakage rate of 3 cm$^3$/min at a standard temperature $T = 273$ K and pressure $P = 760$ Torr. At this pressure, the neutral particles free path is of 5–15 cm, and the electron free path is of 20–50 cm. Taking into account the drift of ions in crossed fields, the Larmor radius for ions is of 0.5–1.2 cm,
and for electrons of 0.005–0.007 cm. An important parameter for the analysis of the behavior of the plasma in the magnetic field is the Hall parameter $\omega \tau$, where $\omega$ is a cyclotron frequency and $\tau$ is a time between collisions. For ions it is of 700–1400, and for electrons of 1.4–2.7. Thus, the electrons in this system are strongly magnetized and extremely rarely experience collisions, in turn ions on the average experience 1 collision during 1–3 Larmor circle.

At the chamber ends there is an electrode system, consisting of seven concentric rings with an outer diameter of the assembly 78 cm. Six inner rings are electrically connected to each other and are biased the same voltage, external (seventh) ring is under a floating potential.

We use two methods of probe diagnostics. Electron temperature and plasma density were estimated by double probe method. Plasma potential was assessed with the help of floating probe. The probe potential is

$$U_{\text{meas}} = U_{\text{pl}} + U_{\text{fl}},$$

where $U_{\text{pl}}$ is plasma potential, $U_{\text{fl}}$ floating potential. Floating potential in argon is equal to $6.3T_e$. Since the electron temperature $T_e$ in these experiments was at the level of 5–12 eV, the error of the method amounted to 30–70 V or 5–10%.

3. Results and discussions

Presence of additional electrodes in the first configuration (figure 2) has led to discharge current decrease by 3–25 times in comparison with the same experiment, but without any additional electrodes. The degree of additional electrodes influence on the main reflex discharge depends on which of the concentric end electrodes of the main reflex discharge are biased.

At a pressure of 1.3 and 0.66 mTorr, the voltage on the end electrodes was of $-1.1$ kV, magnetic field of 1.3 and 2 kG in the center of the apparatus, the discharge current was of 32 and 15 mA respectively. The potential distribution of the floating probe was obtained in radial and chordal direction, figure 3(a). Here we use the chord measurements axis shown in figure 1. The presence of plasma in the interelectrode gap could not be established visually. Measurements of the plasma density with a double probe are ambiguous, but it is clear that in these experiments it did not exceed a value of $10^8$ cm$^{-3}$. The electron temperature was about 7 eV. It means that the ionization degree of such a plasma is of $10^{-6}$, and the Debye radius is greater than 3 mm.

The results of study of potential distribution between the additional electrodes is presented in figure 3(b). The probe swept in the interelectrode gap along the $x$-axis indicated in figure 1. Studies show that if the additional electrodes is under floating potential then the region of existence of the electric field near electrode 2 is 4 cm. If electrodes 1 and 2 are biased at $-900$ V and $-800$ V respectively, then this area is reduced almost 2 times.

We also studied the potential distribution along the $x$-axis at different $y$ coordinates (figure 4). Coordinate $y = 0$ is the middle of the additional electrode, and $y = 5$ cm is the upper edge of the electrode.

Figure 4(a) shows the potential distribution between the electrodes at different probe position along $y$-axis. The figure illustrates that the deeper the probe is inserted into the interelectrode gap, the greater the region of electric field existence. However, in the middle of the interelectrode gap, the electric field is absent at any $y$. Figure 4(b) shows the distribution of the potential behind electrode 1. It can be seen the dependence of nonzero electric field region on $y$ coordinate. This area increases with decreasing of $y$ coordinate as in figure 4(a). This dependence is due to the fact that plasma rotating around the axis runs into the additional electrode. Further, the plasma “flow around” the electrodes. The plasma ability to “flow around” is determined by the magnetic field. In any case, the electrode forms a “shadow” where plasma is absent. Part of the plasma penetrates into the interelectrode gap. Since the electrons are strongly magnetized, they cannot reach the area of the geometrical shadow. Ions are magnetized lesser, and some of them penetrate into the region of the geometrical shadow. Thus, a space charge is formed,
which leads to the existence of an electric field. The more the sweeping axis distant from the edge of the electrode the greater part of the axis is immersed in the geometric shadow.

In order to remove obstacles for the plasma rotation around the axis the second electrode configuration was investigated. In this configuration the electrodes are oriented along the plane of this rotation (figure 5).

Figure 6 shows three modes of voltage connection to the additional electrodes:

- both electrodes are floating (floating potential is about $-350$ V);
- the first electrode is biased at $-900$ V and the second one at $-400$ V;
- the first electrode is biased at $-900$ V and the second one at $-800$ V.

In all modes, the electric field in the interelectrode gap exists throughout the volume, and when the voltage on the additional electrodes are $-900$ and $-400$ V field strength in the center of the interelectrode gap reaches values of $4.6$ V/cm, while if the electrodes are under floating potential the field strength in this area is about $3.6$ V/cm. In the modes with applied voltage...
Figure 5. Experimental setup with second electrode configuration: (a) end view, (b) top view.

Figure 6. Potential distribution along the direction of the $x$-axis for the second configuration of the additional electrodes.

to the additional electrodes the current on each amounts about 10 mA when the main reflex discharge current is 120–160 mA.

4. Conclusion
The use of such additional deflecting electrodes together with the reflex discharge, apparently, is meaningless due to the low plasma density. However, it may be promising in combination with rf discharge. In this connection it is necessary to give preference to the second configuration with “transparent” electrodes, since they do not block the space for the plasma rotation in $\mathbf{E} \times \mathbf{H}$ direction and ensure the existence of the electric field in the interelectrode gap.
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