Propagation of the end-face electrodes potential in the plasma volume of rf discharge

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Abstract. The problems of the creating a stationary electric field in a magnetized plasma of rf discharge are investigated. Helmholtz coils create a magnetic field in a cylindrical vacuum chamber with a diameter of 85.6 cm and a length of 220 cm. Radio-frequency discharge is generated at a frequency of about 5 MHz. Radio-frequency power absorbed by the plasma is in the range of 0.5–1.5 kW. Negatively charged electrodes are placed on the end-face of the chamber. We study three cathode configurations with diameters from 55 to 295 mm. Argon is used as the working gas. Radial profiles of plasma potential, electron density and electron temperature are obtained. The dependence of plasma potential in the discharge center on the voltage of end-face electrodes is studied.

1. Introduction
One of the crucial issues of spent nuclear fuel (SNF) reprocessing is a problem of fission products separation from actinides. SNF plasma separation method [1–3] can overcome this problem. The most significant feature of the plasma-based method distinguishing it from the commonly adopted electromagnetic methods of ions separation [4] is that ions of the separated elements are moving in the conditions of the compensated space charge, whereas the restriction on the ionic current value is lifted and the productivity rate required for its practical application in the nuclear industry can be achieved. Development of plasma separation method [3,5] implies a number of challenges, among them: creating a high-performance plasma source [6–8] and the separation of ions by mass in two groups $m > 235$ u, $m < 160$ u [9,10]. To separate the plasma stream, one have to create a configuration of crossed $\mathbf{E} \times \mathbf{H}$ fields immersed in plasma. Given electric field configuration should be created in a cylindrical chamber, which is filled with plasma and is placed in a magnetic field parallel to its axis. For this purpose, the electrodes are located at the ends of the cylindrical chamber and under equal potential. The ability of this approach has been described in [11, 12]. Plasma is created by the end-face electrodes and by an external source (rf generator). It abut on the electrodes, and according to [12], electrodes potential have to penetrate into the plasma volume along the magnetic field lines. Despite the theoretical prediction of the effect, the experimental studies in this direction practically are absent.

It is important to note that the end electrodes are at a negative potential, and in conjunction with the cylindrical surface of the grounded chambers form geometry of reflex discharge [13]. Discharge studies and effect of different parameters such as gas pressure, magnetic field, discharge...
voltage and electrode geometry on the spatial distribution of the electrostatic potential carried out in [14, 15].

2. Experimental setup and measuring method

Figure 1 shows the experimental setup. The cylindrical vacuum chamber of the separator 1 is grounded. Helmholtz coils 2 generate the magnetic field. A negative relative to the ground voltage through the ballast resistor applied to the electrodes 3. At the opposite ends of the chamber, the electrodes are positioned in the same way. Also at the ends-face of the chamber dielectric plates 4 are located with 80 cm in diameter (the distance between them 200 cm). The plates screen the discharge gap from the grounded end-face flanges of the vacuum chamber. The working gas is argon. Movable probe 5 scans along discharge radius. The rf generator antenna is located in the section 6 and operates at a frequency of 5 MHz.

The probe can operates both in dual probe mode for detecting the temperature of electrons and ion concentration and in floating probe mode for detecting the plasma potential. The probe is made of a tungsten wire of 0.35 mm diameter, jutting out by 9 mm from the ceramic tube of 20 cm length, which is fixed on the metal pipe. The measuring probe head is moved in the radial direction in the plane perpendicular to the axis of the chamber and situated at a distance of 800 mm from one of its ends. The probe is equipped with a cascade of resonant filter plugs to compensate rf distortion of the probe characteristic.

Due to the fact that the chamber dimensions are comparable with the dimensions of the magnetic coils, hence magnetic field distribution is nonuniform in considered volume. In the text of the article referring to the magnitude of the magnetic field, we mean a field at the point O (figure 2). A current of 0.5 kA corresponds to a magnetic field of 65 mTorr at O. In figure 2, one can see a photo of the end-face electrodes.
Figure 2. Photography of end-face electrodes.

When rf voltage is applied to the antenna and DC voltage is applied to the end-face electrodes two discharges operate simultaneously: rf and reflex. Experimentally it has been found that the combination of these two discharges causes changes in the electrical parameters of the load, which is antenna and plasma for rf generator. This in turn leads to the fact that the parameters of the matching device differ for the case when only rf discharge operates and when rf and reflex discharge operates. By varying the experimental parameters the plasma characteristics may undergo abrupt changes leading to mismatching of generator and load. The experiments are carried out by the following procedure:

- the chamber is filled with argon gas up to a pressure $P = 10$ mTorr and rf discharge is ignited;
• the chamber is pumped up to a pressure of $P = 5$ mTorr, and a magnetic field is switched on $B = 13$ mTorr;
• voltage is applied on the end-face electrodes;
• the parameters of the matching device is changed;
• the magnetic field was increased up to 65 mTorr.

We studied three electrode configurations: 1—flat circle shaped electrode with a diameter of 55 mm located on the axis of the discharge, 2—flat circle electrode with a diameter of 55 mm and a ring shaped electrode with inner diameter of 235 mm and an external of 295 mm located concentric to the axis of the discharge (figure 2), 3—a solid circle shaped electrode with a diameter of 300 mm.

3. Results of experiments and discussions
In electrode configuration 1 with a magnetic field of 65 mTorr and with voltage on the electrodes of $-300$ V, the distributions of the plasma concentration, the plasma potential (figure 3) and the electron temperature (figure 4) along the radius were obtained. In the same configuration and with the same magnetic field, the dependence of the plasma potential on the voltage at the electrodes was investigated (figure 5). In figure 5, one can see that the plasma potential on the chamber axis in the investigated range is practically independent of the voltage at the electrodes.

The electric field creation in plasma is possible because of the limited mobility of electrons across the magnetic field. At creating of negative potential in the plasma, i.e. the creation of an excess of negative charges two processes compete. The first is the death of ions on the electrode and the second is the escape of electrons across the magnetic field. The escape of electrons across the magnetic field can occur both in the plasma volume due to collisions and along the surface of the end-face dielectric due to near-wall conductivity [9]. Thus, the more the first process dominates on the second one, the greater stationary electric field can be obtained in the plasma. The electron lifetime in a column of a negative potential in plasma is determined by
three factors: the magnitude of the magnetic field, the gas pressure and column cross-section. This time can be increased by decreasing of gas pressure and increasing of electrode surface. It should be noted that an increasing of the area of the electrodes also affects the number of uncompensated ions leaving discharge, which leads to an increase in the absolute value of the potential. These hypotheses were experimentally verified in the electrode configurations 2 and 3.

Figure 6 shows the dependence of the plasma potential on the discharge axis on the gas pressure in electrode configuration 2. In this experiment, to the inward electrode was applied
Figure 6. Plasma potential dependence on the discharge axis upon the gas pressure.

Table 1. Plasma potential dependence on voltage applied to end-face electrodes.

| Voltage on end-face electrodes (V) | Plasma potential (V) |
|-----------------------------------|----------------------|
| −55                               | −1                   |
| −120                              | −2                   |
| −158                              | −31                  |

a voltage of −350 V, and −150 V at external ring-shaped electrode. The magnetic field in the center of the chamber was 52 mTorr. It can be seen that with a decrease of pressure, the plasma potential shifts to a region of negative values and reaches −25 V at 0.6 mTorr.

In electrode configuration 3 the surface of the electrodes is almost 30 times larger than in configuration 1. Therefore, at decreasing of the voltage across the electrodes the effect of lowering the plasma potential on the discharge axis should be expressed more clearly. The dependence is shown in table 1.

4. Conclusions

Thus, it can be concluded that in plasma of helicon discharge with electrodes immersed in it, a stationary electric field across the magnetic field can be created. The plasma potential on the discharge axis (i.e., increasing the potential difference between a grounded cylindrical chamber and plasma on its axis) can be lowered by increasing of the electron lifetime in the region of the plasma column perching on the cathode and also by increasing the number of discharge leaving ion. These recommendations can be realized by increasing the cathode area, and also by reducing the working gas pressure, when the role of collisions of magnetized electrons decreases and, as a consequence, the diffusion of electrons across the magnetic field decreases. The following facts prove this assumption:
• The dependencies obtained in the experiment demonstrate that when the argon pressure in the chamber decreases (to 0.6 mTorr), the potential at the center of the plasma column varies from $-5$ to $-25$ V.

• In the case of small diameter end-face electrodes (55 mm), the electrical potential generated in the plasma is practically independent on the voltage applied to the electrodes. In the case of larger diameter electrodes (configurations 2 and 3), such dependence is observed, and the value reaches $-30$ V.

• It should be noted that the work revealed that when the end electrode surface is enlarged, the currents flowing to this electrode begin to exert a noticeable effect on the matching of the rf generator with the plasma load, and at voltages in the order of $-300$ V abrupt mismatch occurs.

• This study confirms the possibility of creating an electric field in the plasma volume, and also allows us to outline the steps necessary to create the spatial distribution of the potential required to realize the method of SNF plasma separation.

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