Generation of a controlled potential profile in the plasma to develop plasma separation method

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Generation of a controlled potential profile in the plasma to develop plasma separation method

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Abstract. Questions of generation buffer magnetized plasma and creation of given profile of the electrostatic potential in the working volume of the separators chamber were investigated for the purposes of plasma separation spent nuclear fuel method. Experimental researches with reflective discharge in helium were carried out. Pressures were 1 and 35 mTorr, the magnetic field was up to 2.1 kG and voltages were up to 1.2 kV. Volt-current characteristics of the discharge and the potential distribution profile, obtained using the isolated probe, were measured. Helicon discharge was chosen as a source of buffer plasma. For a discharge antenna characteristics required for generating buffer plasma in a volume of 2 m³ were calculated.

1. Introduction
One of the key problems in developing the plasma separation spent nuclear fuel (SNF) method is the creation of controlled electric potential profile in magnetized plasma [1]. Creation of an electrostatic field in the plasma can be effected using electrodes immersed into it. Whereas the potential is reproduced in the plasma volume along the magnetic field lines based on the electrodes [2–4]. Thus, the practical implementation of this approach involves the following tasks: research of discharge on a given electrodes in the absence of buffer plasma, the generation of buffer plasma and, finally, the study of the spatial distribution of potential in the plasma. In the present study the first two of these problems are discussed taking into account the conditions that necessary for plasma separation [1].

2. Experimental data and discussion
Reflex discharge was investigated to testing generation mechanisms of nonuniform electric field in helium plasma at pressures of 1 and 35 mTorr, magnetic field and voltage up to 2.1 kG and 1.2 kV correspondingly. The length and diameter of the discharge chamber was \( L \sim 1.8 \) and \( D \sim 0.9 \) m.

Volt-current characteristics (VCC) of the discharge and the potential distribution profile, obtained using the isolated probe, were measured.

Inhomogeneous electric potential was created using reflective discharge. Its features are the following factors that distinguish this study from the work conducted in this area: first, the size of the discharge chamber (\( V \sim 2 \) m³) significantly exceeds the typical size of a cell of this type (\( V \leq 10^{-3} \) m³), secondly, the cathodes are placed on the dielectric plate, shielding end flanges
Figure 1. Schematic diagram of the experiment. 1—anode, 2—dielectric plate, 3—cathodes, 4—magnetic field coils.

The experimental setup is illustrated in figure 1. The anode of discharge is the cylinder course of the camera. The cathode and anode is made of non-magnetic stainless steel, chamber grounded, and the magnetic field created coaxial coils.

Figure 2. Volt-current characteristics of the discharge at a pressure of a) 1 mTorr, b) 35 mTorr.

Volt-current characteristics (VCC) of the discharge in a magnetic field were obtained in the following way: initially it was set a fixed value of the magnetic field in the range 0–2100 gauss. Then interelectrode voltage was increased and discharge current was register. figure 2a presents VCC of the discharge at a pressure of 1 mTorr, it is easy to see that the discharge current in the whole investigated values range of the magnetic field monotonically increases with increasing voltage on the cathode. At the same time in a magnetic field since 600 V current increases by two orders of magnitude compared to the current in the discharge without the magnetic field, under the same voltage. This current increase can be explained by the increase of the electrons trajectory length in a vacuum chamber volume. Reflected from a cathode, an electron oscillates along the magnetic line, producing a large number of ionization, as long as it will not reach the anode in the result of diffusion. A VCCs is changed dramatically if pressure of helium in the
chamber is increased to values 35 mTorr, (figure 2b). In contrast to figure 2a there is a range of values of the magnetic field, for which the dependence is non-monotonic. At magnetic fields up to 280 gauss VCCs lie to the right of the curve corresponding to the discharge without the magnetic field, it is also as in the case of figure 2a is due to the increased electron trajectory length in a vacuum chamber volume. However, for magnetic fields above 560 gauss VCCs lie to the left of the curve obtained in the discharge without magnetic field. Apparently, it is connected with the starting mechanism of the breakdown between the anode and cathode in a magnetic field. This conclusion follows from the fact that changing the order of turning on of the electric and magnetic field the discharge current with the same parameters will be significantly higher. Thus, a magnetic field does not prevent the operation of the discharge with a large current, but reduces the equilibrium current if at the time of the breakdown it was enabled. In the range of magnetic fields between 280 and 560 gauss realize the optimal conditions for operating discharge and starting from 800 V VCC of discharge becomes descended.

Radial potential distribution profiles at pressures of 1 mTorr and 35 mTorr are presented in figure 3a and figure 3b, respectively. Figure 3a it is seen that near the axis there is a significant potential gradient and consequently high strength of radial electric field. While in figure 3b profiles are rather diffused near the axis. The profile of the potential, which will allow us to effectively separate particles described in [3]. In accordance with [3] the profile must contain an area of about 10 cm with a field of 20 V/cm (localization of the potential trap). On this basis, we can conclude that despite the fundamentally different character of figure 3a and figure 3b both cases are suitable for plasma separation tasks. When the helium pressure 1 mTorr region of strong field is in the range \( r = 1–10 \text{ cm} \) and at a pressure of 35 mTorr \( r = 15–25 \text{ cm} \) (\( r=0 \) chamber axis).

Consider the second problem associated with the generation of buffer plasma. As mentioned previously, magnetic field lines must be based on the electrodes in order to provide necessary potentials in the plasma. This fact imposes significant restrictions on the choice of ways to generate plasma buffer and makes necessary supplying energy for plasma generation perpendicular magnetic field lines. It should be noted that for separating plasma SNF method it is necessary to generate a plasma density of \( 10^{13} \text{ cm}^{-3} \) in the working chamber volume of 2 m\(^3\) [1,5]. In view of stated it can be argued that one of the most promising ways to generate buffer plasma for the plasma separation method is helicon discharge [5–7]. In the vast majority studies on the helicon plasma sources generation was carried out in volumes with typical diameters of
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{helicon_antennas.png}
\caption{Helicon antennas coil(left) and saddle(right) types; a) antenna, the arrows indicate the direction of the current; b) the direction of the magnetic field lines; c) a metal vacuum chamber.}
\end{figure}

\ (~ 10 cm, limited dielectric walls [8, 9]. Thus, helicon plasma generation issue in the amount of about 2 m$^3$ bounded by conducting walls is actual and requires further study.

For further experimental studies were performed: type selection of helicon antenna, estimation of their diameter and length. It was made based on the works of Chen [6, 10]. In the estimation were used chamber geometry (85.6 x 192 cm) and the required parameters of the buffer plasma: the working gas is helium, the generation frequency ($\omega = 5.1 \pm 0.2$ MHz), the plasma density ($n \sim 10^{12}$ cm$^{-3}$) and magnetic induction ($B = 1.5 \pm 0.1$ kG). As a result, two different antenna configurations were selected: coil type for waves with $m = 0$, saddle-type for waves with $m \leq 1$ (figure 4), where $m$—the azimuthal wave number of helicon waves [7]. The diameter of the coil antenna is 30 cm, diameter of the saddle antenna is 23 cm, its length is 127 cm.

Preliminary experiments for obtaining high-frequency plasma were produced. For determining plasma parameters, the method of double electric probe was used. In the experiments coil type antenna was used, which in these researches allowed reaching the concentration of the order of $2 \times 10^9$ cm$^{-3}$ and outlined steps to increase it.

\section{Conclusion}
As a conclusion, we will briefly formulate the main results. It is ascertain that by pressure of the gas (helium) 1 mTorr in the investigated voltage range current-voltage characteristics are increased monotone, and at pressure of 35 mTorr there is a range of values of magnetic fields, in which starting from 800 V VCCs becomes descended. It is shown that the plasma column potential of reflective discharge in this geometry is significantly different from the potential of the anode. In addition, the profile of the electric field potential is such that it is possible to implement effective separation. For plasma separation, SNF method two types of helicon antennas were selected: coil with diameter of 30 cm, saddle with diameter of 23 cm and 127 cm in length.

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