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Optimization analysis of a plasma separator with a vacuum arc based plasma source configuration

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Abstract. In the work, the comprehensive analysis of a plasma separator with a vacuum arc based plasma source is performed. The main purpose is to identify the interdependencies of the initial parameters set and separation rate to be able to optimize the configuration with the possible experimental limitations. The \( X-Y-Z \) modeling is performed with KARAT code in a single-particle approximation. Injected particles are single-charged ions with energies from 0 to 20 eV with atomic masses \( A = 150 \) and 240 and spreading angle in the range of \( 0^\circ - 30^\circ \). Magnetic field is produced by 2 coils of wire, the characteristic field strength in an uniform area is 1–2 kG. Electric field is produced by several electrodes with electric potential up to 1000 V. As a result the correlations were identified, and experimental configuration guidance was developed.

1. Introduction
The plasma separation is a very perspective direction and still has not a general resolution [1–3]. According to the results obtained in the work [4] a promising way to achieve efficient plasma separation is to supplement a plasma separator and a vacuum arc based plasma source that in turn means placing the plasma source inside the separator with the main injection direction along magnetic lines. However the experimental limitations like construction aspects, potential reconstruction in the plasma volume may prevent realizing the calculated configuration. Thus a one calculated configuration is not sufficient and a clear guidance how the configuration parameters may be changed without separation rate decline should be developed. The current work provides a comprehensive analysis of the configuration parameters change influence on the separation effect and gives clear recommendations about the reasonable parameters change with corresponding interdependencies.

2. Simulation
The modeling have been made with the use of the KARAT code [5] in Cartesian \( X-Y-Z \) geometry. The detailed description of the calculation techniques, physical equations to solve and the basic configuration geometry is described in the work [4]. A short description follows. KARAT code uses PIC (particle-in-cell) method. For calculation of the electric field Laplace equation is solving. Magnetic field is calculated as fields of coils with given geometry and currents. The ion dynamic is simulating by solving of Lorentz equations. The basic geometry consists of the cylindrical chamber (anode) with radius \( R = 45 \) cm and length \( L = 200 \) cm. The chamber center
coordinates are $\left(0, 0, 0\right)$. The magnetic field is creating by 2 coils of wire to produce the uniform magnetic field in a center of the chamber and a modeling area. Atomic masses of the injected single-charged positive ions are $A_1 = 150$ and $A_2 = 240$. The ions of both sorts are launched randomly from the injection region in a given time interval of 0.1 ns and with a random energy in 0 to 20 eV range and a random moving direction in a solid angle of $60^\circ$ around the main injection direction. The injection region position is represented in figure 1—position 3. The injection launches from the anode plate with a potential 10 V. The dimensions of the injection region are $\Delta X = 4$ cm, $\Delta Y = 2$ cm. The region center coordinates are $(4, -26, -25)$. For separation achievement 2 cylindrical electrodes are used. The electrodes diameter is 4 cm, the position is along $Z$ axis with the full chamber length. The first electrode is a focusing one with the center coordinates $(0, 0)$ in $X$–$Y$ cross-section and the potential $U_1 = -500$ V. The second electrode is a deflecting one with the center coordinates $(0, 12)$ in $X$–$Y$ cross-section and the potential $U_2 = -500$ V. To provide the drift effect of the particles in the direction of the focusing electrode two capacity plates are set. The plates are perpendicular to $X$ axis and have the potentials $U_a = 0$ and $U_b = 15$ V. The injecting particle source is located among the plates. Magnetic field strength in an uniform area is 1.4 kG. Let us denote the described configuration as a base one.

2.1. Influence of capacity plates that ensure ions drift

The capacity plates $a$ and $b$ ensure ions drift in the direction of focusing electrode. In case of eliminating of these plates or setting the potential of 0 the separation effect disappears. The particles continue their movement along $Z$ axis with the rotation radius nearly several centimeters. The best separation result is achieved with the following parameters $U_a = 0$ and $U_b = 5$–20 V. The separation picture is not presented on the additional figure as the result is

Figure 1. Magnetic lines in the central cross-section $x = 0$ near the injection region. Numbers in frames designate the injection region position cases. The arrows show the main injection direction.
Figure 2. Characteristic trajectories of ions in the base configuration. Blue lines correspond to the ions with atomic masses 150, green lines—240. 1 and 2 are focusing and deflection electrodes correspondingly, $a$ and $b$ are capacity plates.

Figure 3. Characteristic trajectories of ions in the configuration with one changed parameter $U_b = 50$ V compared to the base configuration.

close to the base configuration (see figure 2). Under $U_b > 50$ V appears relatively large impact to $Y$-component of ion velocity that results in separation rate decline (figure 3).

To sum up we can make definite conclusion about the capacity plates that ensure ions drift. The plates are an essential part of the configuration. The optimal potentials value are $U_a = 0$ and $U_b = 5$–20 V.

2.2. Influence of magnetic field strength
In the context of the present paper, magnetic field strength means the value in a uniform area. The change of magnetic field strength influences the ion trajectories as follows: the trajectories
Figure 4. Characteristic trajectories of ions in the configuration with one changed parameter compared to the base configuration: $B = 1000$ (I) and 2000 Gs (II).

Figure 5. Characteristic trajectories of ions injected from the position 4 and with corresponding parallel shift of the electrodes and plates without potential values change compared to the base configuration.

“uncoil” to $Y$-axis at the magnetic field strength equal to 1000 Gs and “coil” at the magnetic field strength equal to 2000 Gs (figure 4). The range above 2000 Gs is not considered because it is more complicated from the experimental point of view.

Based on the trajectories change tendency one can suppose that the change of the potentials at the focusing and deflecting electrodes may lead to the proper separation rate. The additional calculations were performed. The calculations showed that the proper separation rate is definitely achieved under the certain potential values. The characteristic potential value for 1000 Gs equals to $-200$ and $-1000$ V for 2000 Gs. Herewith the best division distance in case of
1000 Gs equals to 10 cm. Thus the range below 1000 Gs we exclude from the further analysis as it this range implies more “uncoiled” trajectories that in turn makes the separation impractical. To sum up, in case of experimental limitations related to the spatial potential reconstitution in plasma such limitations could be handled by reducing the magnetic field strength down to 1000 Gs.

2.3. Influence of focusing and deflecting electrodes
The focusing electrode ensures the flattening of the particles initial angle and energy dispersion that is very important to achieve a proper separation rate. The deflecting electrode ensures a necessary for separation effect shift of the trajectories of the ions with different masses and different rotation radius consequently. It is obvious that none of these electrodes could be eliminated as the elimination will result in disappearance of the separation effect. There are numerous of configurations with potentials of each electrodes, their respective position and position against the injection area. In view of numerous calculations we do not present the results of each scenario but we bring the final conclusions:

- To achieve a proper level of separation the appropriate potential range at the focusing electrode is much tighter than the corresponding range at the deflecting electrode. In case of the base configuration a change of potential at the focusing electrode from the value of $-500 \text{ V}$ to the values of $-300$ or $-700 \text{ V}$ significantly decline the separation rate as in the first case the focusing potential is not sufficient to flatten the particles initial angle and energy dispersion and in the second case the particles come too close to the electrode that the following division becomes more difficult. However, a potential at the deflecting electrode could be varied in the range of $-200$ to $-1000 \text{ V}$ with a minimal influence on the separation rate.

- The distance between the electrodes could be varied. The distance could be compensated by the potential of the deflecting electrode: more distance—more potential.

- The distance from the injection area to the focusing electrode can not be compensated by the potential of the focusing electrode as the distance–time that ions move in the fields matters. That is why it is not possible to give a the clear recommendation for this parameter. It is a matter of modeling.

- Taking into account the analysis of the magnetic field strength influence we can derive the characteristic values of the potentials in the context of magnetic field strength: $-200 \text{ V}$ for 1000 Gs, $-500 \text{ V}$ for 1400 Gs, $-1000 \text{ V}$ for 2000 Gs.

2.4. Influence of injection area position
The positions of the injection area out of the chamber, at the bottom of the chamber with the main injection direction perpendicular to the magnetic lines were considered in the work [6] and do not fit the requirements if the vacuum arc based plasma source [7]. As the chamber and modeling area are mainly located in the area of uniform magnetic field so for the general conclusions about the influence of the change of the injection area position compared to the base configuration it is enough to model the ion trajectories from the injection area located in the chamber center—position 4 in figure 1. In a constrained geometry the available place for separation is of importance. Under the injection from the position 4 and with corresponding parallel shift of the electrodes and plates without potential values change compared to the base configuration the separation takes place but with minimal acceptable division distance of 10 cm (figure 5).

Thus, in the given geometry, we can place the ion source between the positions 3 and 4. The position closer to the position 3 will give a better separation rate.
3. Conclusion
The main conclusion is that for the experimental realization of the plasma separator with a vacuum arc based plasma source one can use the base configuration with necessary modifications made in accordance with clear recommendations provided in the current work.

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