Ion mass separation modeling inside a plasma separator

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Abstract. The results have been obtained in a continuation of the work for ion trajectories calculation in crossed electric and magnetic fields and also in a close alignment with the plasma separation study development. The main task was to calculate trajectories of ions of the substance imitating spent nuclear fuel in order to find a feasible plasma separator configuration. The three-dimensional modeling has been made with KARAT code in a single-particle approximation. The calculations have been performed under the following conditions. Magnetic field is produced by 2 coils of wire, the characteristic field strength in a uniform area is 1.4 kG. Electric field is produced by several electrodes (axial ones, anode shell and capacitor sheets) with electric potential up to 500 V. The characteristic linear size of the cylindrical separator area is $\sim 100$ cm. The characteristic size of injection region is $\sim 1$ cm. Spatial position of the injection region is inside the separator. The injection direction is along magnetic lines. Injected particles are single-charged ions with energies from 0 to 20 eV with atomic masses $A = 150$ and 240. Wide spreading angle range was investigated. As a result of simulation a feasible separator configuration was found. This configuration allows to achieve more than 10 cm spatial division distance for the separated ions and is fully compliant with and supplementary to the vacuum arc-based ion source research.

1. Introduction

One of important tasks in developing the concept of spent nuclear fuel (SNF) plasma separation [1] is to solve the integration question of plasma separator and injection plasma source. In the investigation of the question one will encounter the 2 types of the problems: sensibility of the plasma separation method for the spatial position and dimensions of the plasma source and the influence of electric and magnetic fields on the source functioning. The first type of the problems is due to non-uniform electric fields that is required for the separation [2]. The other type is associated with an existence of the requirements from the source for the necessary field’s intensity and lines direction. Current study is dedicated to the investigation of the mentioned above integration question of plasma separator and plasma source. The means is ion mass separation modeling inside a plasma separator. The modeling is based on three-dimensional simulation of the ion dynamics in crossed electric and magnetic fields that is performed by KARAT code [3] in a single-particle approximation that allows to gain the quick outcomes with the preservation of the phenomenon picture. Buffer gas and plasma are not taken into consideration. The goal of the current study is to find the best configuration of the plasma separator and plasma source.
2. Simulation
The search of the proper plasma separation configuration should take into account a large number of the parameters: geometry, electric and magnetic fields picture, ion source spatial position and dimensions, the range of the initial values of the injected particles energy and injection direction, the stability of the separation under the parameters change. Moreover, one should analyze the practical feasibility to reproduce the obtained results that means taking into consideration the special aspects of the reconstruction of the potential in plasma as well as limitations and requirements from the plasma source.

The simulation have been made by KARAT code in Cartesian $X$–$Y$–$Z$ geometry. For calculation of the electric field the KARAT code solves Laplace equation using boundary value of potential. Magnetic field is calculated as fields of coils with given geometry and currents. Then in these fields the code simulates the ion dynamic by solving of Lorentz equations under the frame of PiC (particle-in-cell) method. Since mass-to-charge ratio of the real particles is the same as for respective PiC particles the dynamics simulation results are the same as well. That’s why we omit the reference to PiC particles in further discussion. The computational grid consists of 100 cells along each axis. Now no buffer gas or plasma is loaded to the calculation volume. We model the separation of two substances imitating SNF with atomic masses $A_1 = 150$ 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. Each new particle is a single-charged positive ion with a random energy in 0.2 to 3 eV or 0 to 20 eV range (depending on the calculation series) and a random moving direction in a solid angle of 60 degrees around the main injection direction. The basic configuration for the simulation is taken from the article [4] as a promising one and is depicted on figure 1.

As a result of modelling there were found 3 configurations that result in plasma separation. On the figure 2 one can find the difference between the configurations that is source spatial
Figure 2. Magnetic lines in the central cross-section \( x = 0 \) near the injection region. The numbers designate the configuration source spatial position. The arrows show the main injection direction.

Figure 3. Values of \( Z \) and \( Y \)-components of magnetic field in the central cross-sections \( x = 0 \) and \( z = 0 \) respectively.

Below one can find the general configurations descriptions. Configuration 1—the ion source position is beneath the chamber in the central cross-section. The main injection direction is along \( Y \) axis and is perpendicular to magnetic lines. The advantage is a simple geometry. The disadvantage is a strong perpendicular magnetic field that imposes significant limitations for the plasma source.
Figure 4. Magnetic field near the injection area.

Configuration 2—the ion source position is under the chamber in the central cross-section. The main injection direction is along $Y$ axis. The advantage is a low magnetic field ($< 20$ Gs) near the injection area that allows to decrease the requirements for the plasma source. The disadvantage is a presence of a zero magnetic field area on the ions track that results in significant difficulties for the electric fields in plasma reproduction.

Configuration 3—the ion source position is inside the chamber in a uniform magnetic field area. The main injection direction is along $Z$ axis, that is along magnetic lines. The advantage is a relatively simple experimental reproduction of the whole configuration including plasma source.

Configuration 1 and 2 are described in detail the work [5]. So now we will closely look at configuration 3 as the most promising one. Configuration 3 fits the requirements of the vacuum-arc based plasma source [6]. So for the simulation the initial range of the injected ions energies should be 0 to 20 eV and the injection should be carried out from the anode (that is a front part of the vacuum-arc based plasma source) with the potential of 10 V.

To find a proper separation effect under the parameters above a number of options was considered. On the figure you could find the configuration parameters that lead to the best separation effect. There used 2 electrodes: focusing and deflecting ones. Along the main injection directions 2 capacity sheets are set. These sheets result in drift effect in a focusing electrode direction. On figure 4 one can find the electric field picture near the injecting anode area.

Configuration 3 under the initial parameters above (large initial energy range especially) is sensible for the source dimensions. So the good separation rate (figure 5) is achieved when the injection area is located in $Z = -25$ plane with the center coordinates $(0, -26, -25)$ and the dimensions $dX_3 = 4$ cm; $dY_3 = 1$ cm.

Moving the source on the right—the center coordinates $(-4, -26, -25)$ allows to achieve even better separation (figure 6) as it flattens the initial injection angle range by means of the focusing electrode.

The one important thing about configuration 3 should be noted. As distinct from configurations 1 and 2 the separation in configuration 3 takes place in the space, not in the plane. That is in configuration 3 the separation takes place both in $X$–$Y$ and $Y$–$Z$ planes. This characteristic allows to achieve a better level of separation.
Figure 5. Bordering trajectories (all ion trajectories are inside the depicted pattern) of ions with atomic masses 150 (blue lines) and 240 (green lines), energy range 0–20 eV, spreading solid angle 60 degrees, magnetic field in the center of chamber is 4 kG, 1 and 2 are electrodes with the voltage $U_1 = -500 \text{ V}$ and $U_2 = -500 \text{ V}$, the diameter 4 cm, the electrodes centers area (0,0) and (0,12), electrodes are located along Z axis, $a$ and $b$ are capacity sheets with angle the opposite angles coordinates $(-12,-32,-25)$–$(-12,-22,25)$ and $(12,-32,-25)$–$(12,-22,25)$, the injection area center is $(0,-26,-25)$.

Figure 6. Bordering trajectories (all ion trajectories are inside the depicted pattern) of ions with atomic masses 150 (blue lines) and 240 (green lines), energy range 0–20 eV, spreading solid angle 60 degrees, magnetic field in the center of chamber is 4 kG, 1 and 2 are electrodes with the voltage $U_1 = -500 \text{ V}$ and $U_2 = -500 \text{ V}$, the diameter 4 cm, the electrodes centers area (0,0) and (0,12), electrodes are located along Z axis, $a$ and $b$ are capacity sheets with angle the opposite angles coordinates $(-12,-32,-25)$–$(-12,-22,25)$ and $(12,-32,-25)$–$(12,-22,25)$, the injection area center is $(-4,-26,-25)$.

3. Conclusion

Experiment-fit configuration for separation of single-charged ions with the energies in the range from 0 to 20 eV with atomic masses $A = 150$ and 240 and spreading solid angle of 60 degrees is identified. The configuration solves the question of integration of the plasma separator and the vacuum arc-bases plasma source. This is an important step for the next stage of the plasma separation concept development.
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References
[1] Zhil’tsov V A, Kulygin V M, Semashko N N, Skovoroda A A, Smirnov V P, Timofeev A V and Kudryavtsev
E G 2006 At. Energ. 101 755–9
[2] Smirnov V P, Samokhin A A, Vorona N A and Gavrikov A V 2013 Plasma Phys. Rep. 39 456–66
[3] Tarakanov V P 1992 Users Manual for Code KARAT (Springfield: VA: Berkley Research)
[4] Vorona N A, Gavrikov A V, Samokhin A A, Smirnov V P and Khomyakov Yu S 2015 Phys. At. Nucl. 78
1624–30
[5] Gavrikov A V, Sidorov V S, Smirnov V P and Tarakanov V P 2016 J. Phys.: Conf. Ser. 774 012197
[6] Amirov R Kh, Vorona N A, Gavrikov A V, Lizyakin G D, Polishchuk V P, Samoilov I S, Smirnov V P,
Usmanov R A and Yartsev I M 2015 Plasma Phys. Rep. 41 808–13