Ion mass separation in crossed electric and magnetic fields as a part of the concept of spent nuclear fuel plasma separation

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Abstract. Presented results have been obtained to develop the concept of spent nuclear fuel plasma separation. The main task is to calculate trajectories of ions of the substance imitating spent nuclear fuel in crossed electric and magnetic fields. The 3D calculations have been made by the KARAT code in a single-particle approximation. The calculations have been performed for a number of combinations of azimuthal and axial magnetic fields and different electric fields configurations. Magnetic field is produced by 2 main coils with the characteristic field strength up to 1.4 kG and in several series with additional coil with the characteristic field strength up to 1.6 kG. Electric field is produced by 2 electrodes with electric potential up to 1 kV. The characteristic linear size of the calculation area is 100 cm. The characteristic size of injection region is 1 cm (up to 10 cm along main axis). Spatial position of the injection region and axis of the injection direction are varied. Injected particles are single-charged ions with energies from 0.2 to 3 eV with atomic masses \( A = 150 \) and \( 240 \), spreading angle is 60°. Calculations have revealed several options to realize a spatial separation of spent nuclear fuel ions.

1. Introduction
One of key tasks in developing the concept of spent nuclear fuel (SNF) plasma separation [1] is to determine a proper geometry and specific electromagnetic fields configuration for spatial ion mass separation. In the recent study [2] a principal possibility of ion mass separation in axial magnetic field configuration was shown. Current study continues that work by providing a detailed analysis of possible experiment-fit configurations. The analysis is based on 3D simulation of the ion dynamics in crossed electric and magnetic fields that is performed by KARAT code [3] in a single-particle approximation. Buffer gas and plasma are not taken into consideration. This simplification is based on the understanding of the main purposes of buffer plasma use (space charge compensation, base for controlled spatial potential profile under lack of significant impact on the injected beam) that result in similar conditions as used in the chosen model. The outcomes of the current study are the specific field configurations as well as geometries for efficient stable experiment-fit ion separation.

Several items that are used in the current article need to be clarified for the reader:

- **Stable separation** means that under different combinations of initial parameters within the given range the separated substances are not mixed inside the separation area.
• Efficient separation means that a spatial division of separated substances exceeds 10% of characteristic geometric size that is 9 cm in our case.

2. Simulation results and analysis

The simulation has 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. The basic configuration for simulation is represented on figure 1. The configuration is close to the experimental one [4].

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 (the geometry is depicted on figure 1) 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 range and a random moving direction in a solid angle of 60° around the main injection direction along \( Y \)-axis. The trajectories of the injected particles have been calculated and analyzed for the different electric and magnetic fields configurations and injection volume spatial positions. In the sections below one can find the detailed simulation results and analysis.

2.1. Option 1

In the calculation series related to the option 1 the injection region is located in the bottom of chamber in the central cross-section (\( z = 0 \)) as it is shown on figure 1. This option in turn have been divided into two sub-options: with and without additional electrodes.

Option 1.1 implies no electrodes inside the chamber. In this case Larmor radius does not exceed 3 cm. This means that efficient ion mass separation is impossible for this option. Moreover the scatter in energies and angles leads to full mix of particles on the chamber walls. Thus from the authors’ point of view to realize an efficient spatial separation in the given geometry one needs to meet further requirements: 1. Focus ions to solve angle and energy scattering issue; 2. Add an electric field gradient that influences heavy particles and does not effect the light ones.

Option 1.2 meets the requirements listed above by means of addition of two electrodes along \( Z \)-axis: focusing one that will accelerate ions in a given direction, decreasing angle and energy scattering impact; deflecting one, that will allow to address the electric field gradient question.

Based on the conclusions above two principal electrode configurations have been found. The first one (1.2a option) realizes unstable separation, i.e. small change of initial parameters leads to breaking the separation. On figure 2 one can see that under given conditions the trajectories of ions with atomic masses 150 (blue lines) and 240 (green lines) are well divided. Figure 3 shows that a change of spreading angle leads to the trajectories mix up.

The second configuration (1.2b option) ensures a stable efficient separation. Figures 4 and 5 show that under different conditions the spatial division of ion trajectories near anode is more than 10 cm. Change of the electrode position (plus-minus 5 cm), electrode potential (plus-minus 500 V) and injected particles initial parameters (increasing angle range up to 120° and energy range up to 10 eV) does not stop the separation effect—just slightly decreases spatial division. Moreover the described configuration allows to create relatively simple traps in spatially divided regions where the separated particles have a low kinetic energy (turn points).
Figure 1. The basic configuration for simulation: cylindrical chamber (anode) with radius $R = 45$ cm and length $L = 200$ cm; main coils of wire with internal radius $R_c = 50$ cm, $dR = 21.5$ cm, $dZ = 22$ cm, internal distance $b_c = 50$ cm, number of coils $N_c = 100$, current strength up to $I_c = 1$ kA, that results in characteristic magnetic field strength up to $1.4$ kG along $Z$ axis ($x = 0, y = 0$); additional coils of wire (for a number of calculation series) with internal distance (radius) $b_{c2} = 10$ cm, $dR_{c2} = 3$ cm, $dZ_{c2} = 3$ cm, $d_{c2} = 10$ cm, number of coils $N_{c2} = 100$, current strength is varied in different calculation series; injection regions with size $dX_{i1;2} = 1$ cm, $dY_{i1;2} = 1$ cm, $dZ_{i1;2} = 10$ cm and spatial position of the center $(0, -44.5, 0)$ for option 1 and $(0, -81.5, 0)$ for option 2. Electrodes (except for anode) are not depicted on the scheme.

The 1.2b configuration is a reliable solution of the given separation task. However a wider look at the plasma separation study uncovers the related injection plasma source questions. One of possible mechanisms for the plasma source is vacuum arc [5]. The presented option implies that the injection region is located in the area with strong magnetic field. It makes the plasma creation process more complicated. This means that other options with injection region in the low magnetic field should be analyzed to find a proper configuration with less limitations for the plasma source.

2.2. **Option 2**

In the calculation series related to the option 2 the injection region is located in $d_{c2} = 10$ cm under the main coil of wire (that is depicted on figure 1), where the strength of magnetic field from the main coils is low (the magnitude is less than 20 Gs). The magnetic field picture without
Figure 2. Option 1.2a: ionic trajectories for atomic masses 150 (blue lines) and 240 (green lines). Energy range 0.2–3 eV, Spreading angle $0^\circ$, magnetic field in the center of chamber is 215 Gs, the diameter of electrodes is 1 cm, the length along $Z$ axis equals 200 cm, potentials of the electrodes $U_1 = -110$ V, $U_2 = -200$ V, the electrodes center coordinates in $X$–$Y$ cross-section are $(-10, -30)$ and $(0, 0)$ respectively.

Figure 3. Option 1.2a: ionic trajectories for atomic masses 150 (blue lines) and 240 (green lines). Energy range 0.2–3 eV, Spreading angle $60^\circ$, magnetic field in the center of chamber is 215 Gs, the diameter of electrodes is 1 cm, the length along $Z$ axis equals 200 cm, potentials of the electrodes $U_1 = -110$ V, $U_2 = -200$ V, the electrodes center coordinates in $X$–$Y$ cross-section are $(-10, -30)$ and $(0, 0)$ respectively.

Figure 4. Option 1.2b: ionic trajectories for atomic masses 150 (blue lines) and 240 (green lines). Energy range 0.2–3 eV, Spreading angle $60^\circ$, magnetic field in the center of chamber is 1400 Gs, the diameter of electrodes is 1 cm, the length along $Z$ axis equals 200 cm, potentials of the electrodes $U_1 = -1000$ V, $U_2 = -1000$ V, the electrodes center coordinates in $X$–$Y$ cross-section are $(0, -25)$ and $(0, 0)$ respectively.

Figure 5. Option 1.2b: ionic trajectories for atomic masses 150 (blue lines) and 240 (green lines). Energy range 0.2–10 eV, Spreading angle $120^\circ$, magnetic field in the center of chamber is 1400 Gs, the diameter of electrodes is 1 cm, the length along $Z$ axis equals 200 cm, potentials of the electrodes $U_1 = -1000$ V, $U_2 = -1000$ V, the electrodes center coordinates in $X$–$Y$ cross-section are $(0, -25)$ and $(0, 0)$ respectively.

additional coils is represented on figures 6–8. Figure 6 shows the magnetic lines in the central cross-section ($x = 0$). On figure 8 the values of $Z$ and $Y$-components of magnetic field in the central cross-sections are depicted. One can see that the magnetic field around point $(0, -80, 0)$
(i.e. around the injection region) is low and non-uniform. The relative uniformity begins in the chamber area. This means that it is reasonable to try to deliver the injected particles to the bottom of chamber without significant scattering and then realize a separation inside the chamber area. Figure 7 shows that in the region around point \((0, -80, 0)\) the sign change of \(z\)-component of magnetic field takes place. This in turn means a presence of zero magnetic field area that should be taken into consideration for the experiment preparation.

To meet the ion source position requirements the magnetic field configuration should be extended by additional coils. Usage of additional coils around the injection region (as depicted on figure 1) results in changing direction of the magnetic lines near injection region to the direction along \(Y\) axis. This field configuration is interesting because it allows simplifying a possible use of vacuum arc based source of ions or plasma as in this case injection of the particles occurs along the magnetic lines.

Use of the similar electrodes configuration as in 1.2b option allows achieving a separation effect. The simulation results with different magnetic field strength from additional coils of wire are represented on figures 9, 10, 11. Figure 11 shows the change of \(y\)-component of magnetic field in the central cross-section \(z = 0\). The use of additional coils resulted in the appearance of the predominant direction of the magnetic field along \(Y\)-axis near injection region that was required by ion source position. Figure 9 represents that when the field from additional coils
**Figure 9.** Option 2.a: ionic trajectories for atomic masses 150 (blue lines) and 240 (green lines). Energy range 0.2–3 eV, Spreading angle 60°, magnetic field in the center of chamber is 1400 Gs, the diameter of electrodes is 1 cm, the length along $Z$ axis equals 200 cm, potentials of the electrodes $U_1 = -1000$ V, $U_2 = -1000$ V, the electrodes center coordinates in $X$–$Y$ cross-section are (0, −40) and (0, −15) respectively, $Y$-component of magnetic field from additional coil near injection region is approximately 350 Gs.

**Figure 10.** Option 2.b: ionic trajectories for atomic masses 150 (blue lines) and 240 (green lines). Energy range 0.2–3 eV, Spreading angle 60°, magnetic field in the center of chamber is 1400 Gs, the diameter of electrodes is 1 cm, the length along $Z$ axis equals 200 cm, potentials of the electrodes $U_1 = -1000$ V, $U_2 = -1000$ V, the electrodes center coordinates in $X$–$Y$ cross-section are (0, −40) and (0, −15) respectively, $Y$-component of magnetic field from additional coil near injection region is approximately 1600 Gs.

**Figure 11.** Values of $Y$-components of magnetic field from the superposition of main and additional coils for option 2.a.
equals 350 Gs (option 2.a) the ion trajectories are well divided. However, larger magnetic field from additional coils (1600 Gs) leads to the trajectories mix up (option 2.b). Thus the option 2.a configuration may be used to separate the particles.

3. Conclusion
Experiment-fit configurations for separation of single-charged ions with the energies in the range from 0.2 to 3 eV with atomic masses $A = 150$ and 240 and spreading angle of 60° are identified. These configurations (options 1.2b and 2.a) are stable ones with a characteristic spatial separation division more than 10 cm. The important thing that one (option 2.a) of identified configurations allows to place the injection region to the area with a magnetic field strength less than 20 Gs that in turn leads to a significant reduction of limitations for a proper ion or plasma source creation.

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