SEPARATION OF THE PRODUCTS OF PLASMA CHEMICAL REACTIONS IN MASSES IN PLASMA IMMERSED IN CROSSED E AND H FIELDS IN THE PRESENCE OF NEUTRAL GAS WITH HIGH IONIZATION POTENTIAL

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ABSTRACT

This paper deals with separation of the products of plasma chemical reactions and isotopes in plasma sustained by plasma beam interaction.To increase the separation velocity of isotopes it is proposed to add the substance with a very high ionization potential in fully ionized plasma.

The opportunity of reaction products quenching is the main problem in carrying out of dissociative reactions in plasma. One of the ways of products quenching is thier space separation.It can be realized in plasma immersed in crossed electric and magnetic fields.Let us consider the axial symmetrical system with the axial magnetic and the radial electric fields.In such a system one can study,for example, the reduction of the metals from chlorides,oxides and fluorides. An appropriate choice of electron temperature and density are suggested to provide the full dissociation of molecules and ionization ofthe metal atoms (the potential of ionization of metals is 4÷6 eV,i.e. significantly lower than that of electronegative gases),the atoms of electronegative gases - O,F,Cl being practicaly neutral.In crossed E and H fields the metal ions to the periphery of the system,neutral partticles of the electronegative gas being distributed uniformly along the radius.Radial velocity of ions is propotional to the mass of particle,so the effective separation of the elements by masses is possible.For example one can study the separation of Zr and Hf from the mixture $ZrCl_4$,$HfCl_4$. In this case Zr and Hf can be collected at the different radii of the system.Experiments with noble gases mixtures /1/ have demonstrated the coefficients of separation to be sufficient to separate not only the elements,but the isotopes as well /2/.To explain separation in fully ionized plasma sustained by plasma beam interaction /3/ the polarizational mechanism was proposed /4/.Separation due to this very mechanism occurs in the thin "near-the-end-plates" layer δ_{ion} (δ_{ion} - the ionization length). On the length δ_{ion} the particles travelling along the magnetic field lines are affected by the changing radial electric field. This causes the polarizational current to flow along the radius and results in separation of ions in masses. The change of the electric field in axial direction deals with the change of the ionization degree near the end plates. The penetration of the electric field into the volume of fully ionized plasma is difficult obviously. Thus, total current is bounded in the thin "near-the-end-plate" layer δ_{ion}. The ionization length at usual conditions ($n_e \sim 10^{13}$) is much smaller than the length of the system L ($\delta_{ion} \ll L$). Hence the entire volume of plasma is free of radial current. The value of ion current determins the velocity andthe separation coefficient, so the limitation of the radial current due to the small thickness of the conducting layer leads to the deterioration of the separation parameters mentioned above.The increase of the plasma density causes the raising of radial current as a result.It should be mentioned that the total radial velocity of the particles in polarizational mechanism is determined not only by the ionization time $(1/\nu_{ion})$ but by the time of flight over the whole system (L/C_s) as well. So at some values of the electron density the inequality $(L/C_s) > (1/\nu_{ion})$ begins to be fulfilled (C_s is the ion sound velocity).In the case of the low electron density the condition $(L/C_s) \ll (1/\nu_{ion})$ is suitable and the ion radial velocity is given by:

$$V_r = V_\varphi \frac{\nu_{ion}}{\omega_{Hi}} \qquad (1)$$

here V_φ - the rotating velocity of the plasma, ω_{Hi} - the ion cyclotron frequency.When the plasma density is high enough so that $(1/\nu_{ion}) < (L/C_s)$ the expression (1) should be modified to

$$V_r' = V_\varphi \frac{C_s/L}{\omega_{Hi}} \qquad (2)$$

The ion current in the radial direction is determined as follows:

$$J = en_i \cdot V_r \cdot S = e\, n_i \cdot V_r \cdot 2\pi R \cdot 2\,\delta_{ion} \qquad (3)$$

here R - the radius of plasma; S - the lateral current receiving surface.Substituting the expression for the radial velocity (2) to (3) one obtains formula for the current J, being independent on the plasma density:

$$J = 4\pi R\, V_\varphi \frac{U}{\langle\sigma v\rangle_{ion}} \cdot \frac{(C_s/L)}{\omega_{Hi}}$$

where $\delta_{ion} = \frac{U}{\langle\sigma v\rangle_{ion} \cdot n_e}$; U -the velocity of the neutral particles.For Ar ions and $L=10^2$cm; $T \sim 10$eV the condition $(1/\nu_{ion}) < (L/C_s)$ fails when $n_e \geq 10^{12}cm^{-3}$.Thus,to increase the radial current it is necessary to transform the "end-plate" regime of separation so that the separation occurs over the whole volume. For this purpose the substance with a very high ionization potential could be used analogicaly to the case of the metals discribed above. Let us consider a system containing neutral atoms of noble gas in addition to the ions to be separated /5/. The equation of motion for ions in the presence of neutral gas is

$$M_i \frac{d\vec{V_i}}{dt} = e\vec{E} + \frac{e}{c}[\vec{V_i}\vec{H}] - \nu_{in}\vec{v}_{OTH}\widetilde{M} \qquad (5)$$

here $\nu_{in} = \langle \sigma_{in}(v_i - v_n) \rangle n_N$; σ_{in} - the cross section of elastic collisions of ions with neutral particles; $M = M_n M_i/(M_n+M_i)$; M_n, v_n, n_n - are the mass, velocity and concentration of neutral atoms respectively. Supposing $\omega_{Hi} > \nu_{in}$ one obtains for the first approximation

$$v_r = v_\varphi \frac{\nu'_{in}}{\omega_{Hi}} \qquad (6)$$

here $\nu'_{in} = \nu_{in}\frac{M_n}{M_n + M_i}$, and the radial current

$$J = 2\pi R \cdot L \cdot v_\varphi \cdot \frac{\nu'_{in}}{\omega_{Hi}} \cdot n_e \cdot e \qquad (7)$$

When the velocity of the separation due to volume mechanism (3) is greater than that of polarizational mechanism (6), the first one is predominant, i.e.

$$\nu'_{in}/\nu_{ion} > 2\delta_{ion}/L \qquad (8)$$

or

$$\nu'_{in} > \frac{2u}{L} \qquad (9)$$

Thus, the necessary density of neutral particles for the volume mechanism to be predominant can be estimated as

$$n_N > \frac{2u}{\langle \sigma v \rangle_{in} L} \cdot \frac{(M_n + M_i)}{M_n} \qquad (10)$$

For Ar ions and He neutral particles; $L \sim 100$ cm, $u \sim 5\cdot 10^4$ cm s^{-1}; $\langle \sigma v \rangle_{in} \sim 10^{-10} cm^3 s^{-1}$ one obtains $n_{min} = 10^{14} cm^{-3}$. Optimal length of the system can be estimated from the condition that the ion flow along the magnetic field lines $(n_e \pi R^2 C_s \cdot \lambda/L)$ is equal to the radial flow through the lateralsurface $2\pi R L_{opt}$, i.e.

$$L^2_{opt} = \frac{R\lambda}{2} \cdot \frac{C_s}{v_\varphi} \cdot \frac{\omega_{Hi}}{\nu_{in}} \qquad (11)$$

For Ar ions and neutral He atoms, $T_e \sim T_i \sim 10$eV; $ER \sim 500$ V; $n_n \sim 10^{15}$ cm^{-3} one obtains $L \sim 10^2$ cm. The expression for the enrichment coeffitient in this case is analogical to that of the "near-the-end-plate" separation /4/:

$$\ln\alpha = \frac{v_\varphi}{v_{Ti}} \cdot \frac{\nu_{in}}{\nu_{ii}} \cdot \frac{\tilde{R}}{\rho_{Hi}} \cdot \frac{\Delta M}{M} \cdot \ln\frac{R}{r_0} \qquad (12)$$

here R -is averaged value of the radius of the system;

ρ_{Hi} -the Larmor radius of a heavy ion. The enrichment coefficient is the higher the greater is the concentration of the neutral gas. The system parameters can be chosen in such a way that the condition $\nu_{in} > \nu_{ion}$ is fulfilled and the enrichment coefficient does not become smaller but even increases as compared to the case when He-atoms are absent. But one should keep in mind that there exist the upper limit of the neutral particle concentrarion given by the condition $\nu_{in} < \omega_{Hi}$. Presence of the radial current in the system with plasma-beam interaction can play a definite role in the ionization processes. The radial current causes the increase of the electron density at the periphery of the system and the decrease of that at the center. The growth rate of the beam-plasma instability being given by $\gamma \sim (n_b/n_e)$ where n_b is the electron beam density, the energy transfer rate from the beam into plasma in the central region and it's ionization increase. On the other hand the radial current is caused by the radial ions motion so the radial field energy seems not to contibute to the ionization processes. Partially this energy is transformed into the energy of electrons increasing ionization of the gas. Actually if S_1 is the current via surface close to the axis, S_l is the lateral surface and mentionning that S_1 receives the electrons and S_l receives the ions one obtains

$$n_{eo} v_e S_1 = n_{ip} v_{ir} S_l$$

where n_{eo} is the electron density in the central region, v_e -longitudinal electron velocity, n_{ip} - ion density at the periphery of the system, v_{ir}-radial ion velocity. One has n_{ip} , $S_l \gg S_1$, so $v_e >> v_{ir}$ and when the radial current is high enough v_e can esceed the value of ion-sound instability. The latter causes the electron energy to be transformed from the directed form into thermal energy inducing additional ionization.

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