ION SEPARATION IN A PLASMA MASS FILTER BASED ON THE BAND GAP FILTER PRINCIPLE

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The mass separation in a multicomponent collisionless plasma rotating in an axial homogeneous magnetic field and a radial electric field with dc and ac components at the parametric resonance conditions is considered. For given conditions, it is shown that when the variable component of a radial electric field with $\omega = 0.57\Omega$ is superposed on the dc component, the resonant uranium dioxide ions are ejected into the wall of the plasma mass filter, which is currently being developed for the separation of nuclear fuel and fission products. The correlation between the oscillation frequency of ac voltage component with the modified (vortex) ion-cyclotron frequency is shown.

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Plasma methods for SNF (spent nuclear fuel) reprocessing are a promising alternative to radiochemical technologies. However, there is a number of problems with plasma separation of fission products (FPs) and nuclear fuel (NF). The difficulties are connected with SNF multicomponent composition, the proximity of masses in case of isotopes and the presence of the multicharged ions. Thus, many problems appear and many variants of their solution are considered [1, 2]. In the light of this so-called ion band gap filter is of interest, which provides various modes of ion separation in a plasma by mass [3].

This paper considers the plasma mass filter for separating NF and FPs [4] based on the band gap filter principle. Below the conditions for the separation of ions by mass (mass/charge) in a multicomponent collisionless plasma rotating in an axial homogeneous magnetic field, B_z, and a radial electric field, E_r, with dc and ac components are studied. The radial electric field E_r is generated by coaxial electrodes – 6. The oscillation frequency, ω, for the ac component of E_r is set by a tuner – 7.

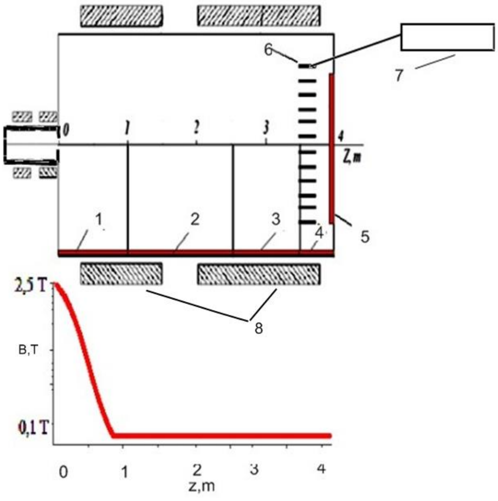

Fig. 1. Schematic view of the plasma mass filter:
1 – 4 – of the longitudinal collector; 5 – end collector;
6 – coaxial system of electrodes; 7 – tuner;
8 – system of solenoids

If E_r periodically changes in time, its value can be represented as a superposition of the ac and dc components. In frequency terms this corresponds to [3]:

$$\omega_E = \omega_{Edc} + \omega_{Eac}\cos(\omega t), \tag{1}$$

where ω_E – angular frequency which includes; ω_{Edc} – constant and ω_{Eac} – variable components.

At a sinusoidal change of ω_E, the Mathieu equation for parametric resonance to determine the frequency of orbit oscillations in a plasma can be used:

$$\frac{1}{4}\frac{d^2 s}{d\tau} + [\alpha - 4\beta\cos(2\tau)]s = 0. \tag{2}$$

The solution of the Mathieu equation is connected with determination of the coefficients α and β.

$$\tau = \omega t/2, \alpha = (\frac{\Omega^2}{4} - \omega_{Edc}\Omega)/\omega^2, \beta = \frac{\omega_{Eac}\Omega}{4\omega^2}. \tag{3}$$

Frequency intervals in which the ions have localized and non-localized orbits are shown in Fig. 2.

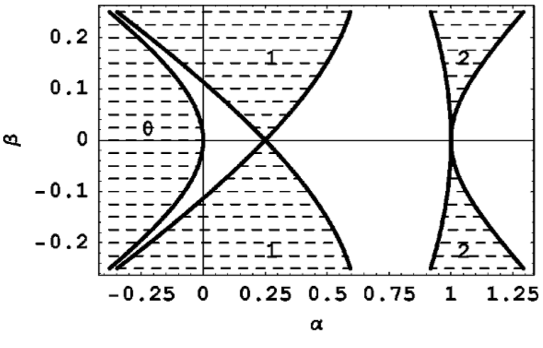

Fig. 2. A graph of the first few confined and unconfined regions of the solution for s in α-β space: $4\alpha_0>-32\beta^2$ for the interval (0); $1-8\beta<4\alpha_{1\pm}<1+8\beta$ for the interval (1); $4-16/3\beta^2<4\alpha_{2\pm}(\beta)<4+80/3\beta^2$ for the interval (2). The dashed regions are the unconfined regions [3]

The combinations of the coefficients α and β, which correspond to dc and ac components of the radial electric field E_r, determine the penetration to the zones of magnetized / unmagnetized ions. To determine the conditions for the separation of ions in the plasma mass filter [4], let's consider the frequency characteristics at

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the boundaries of the instability intervals, that is, at the threshold of the transition from a stable state, where the ions are magnetized, to the unstable one, where the ions are not magnetized. This correlates with the equation of the forces balance in the plasma mass filter with positive radial electric field, that is discussed below.

There are three forces acting on a charged particle (ion) in a collisionless plasma rotating in E⊥H fields [5]: centrifugal – $F_c = m_i r\omega_i^2$, electric – $F_E = eE_r$, and magnetic – $F_B = er\omega_i B_z$, where m$_i$ – mass of i-kind ion, ω_i is the angular rotation frequency for i-kind ion, r is the particle's distance to the axis of rotation, E_r is radial electric field strength proportional to r (E_r / r=const), B_z is a value of magnetic field on the axis, and e – the charge of the electron. Rotation of a plasma is obtained by its interaction with radial electric field, E_r and axial magnetic field, B_z.

In the plasma mass filters with a positive potential, the electric and centrifugal forces are directed outward, and Lorenz force is directed inward. An equilibrium conditions in a radial direction can be expressed:

$$\sum F_r = 0, \tag{4}$$

or

$$m_i r\omega_i^2 + eE_r - er\omega_i B_z = 0. \tag{5}$$

The ion cyclotron freduency for the i-kind ion is written:

$$\Omega = zeB_z / m_i. \tag{6}$$

Thus, the solution of equation becomes:

$$\omega_i = \Omega/2(1 \pm \sqrt{1 - 4E_r/(rB_z\Omega)}), \tag{7}$$

where ω_i is an angular freguency of the i-kind ion.

The critical options of plasma rotation can be determined from the discriminant of the equation equal to zero, that is, at $4E_r/(rB_z\Omega) = 1$, which corresponds to $E_r = E_r^{cr}, B_z = B_z^{cr}, r = R$. In turn, from the solution of the Mathieu equation this state corresponds to the point ($\alpha = 0, \beta = 0$) (Fig. 2) at the boundary of the instability interval (0) [3]:

$$4\alpha_0 = -2^5\beta^2. \tag{8}$$

At $\beta = 0$, separation of ions into heavy and light ions occurs in the mode of operation of the Ohkawa (Archimedes) plasma mass filter [5]. Separation mass of M_{cr} is determined by critical value of electric field E_r^{cr} r and magnetic field B_z^{cr}:

$$M_{cr} = zeR(B_z^{cr})^2/(4E_r^{cr}), \tag{9}$$

or

$$M_{cr} = zeR^2(B_z^{cr})^2/(8U_{dc}), \tag{10}$$

where $U_{dc} > 0$ is the positive potential of electric field along the longitudinal axis, R is the radius of the cylindrical chamber.

In this case, the light ions with $m_i/z < M_{cr}$ have localized orbits, and the heavy ions $m_i/z > M_{cr}$ have non-localized orbits. The parameters E_r^{cr}, B_z^{cr}, R determine the conditions of separation process in the plasma mass filter. For $4E_r/(rB_z\Omega) < 1$, that is, for $0 < E_r < E_r^{cr}$, equation (5) has a real solution (7), and ions with mass $m_i/z < M_{cr}$ have localized orbits.

To set the parameters for ion separation in a multi-component collisionless plasma rotating in E⊥H fields, it is necessary to consider the modified (vortex) cyclotron frequency Ω_i, that determines the phase of deceleration and acceleration for i-kind singly charged ion [6]:

$$\Omega_i = \Omega\sqrt{1 - \frac{m_i}{M_{cr}}}. \tag{11}$$

At $\Omega_i = 0$ the value of ω_i is equal to the subharmonic of the cyclotron frequency ($\omega_i = \Omega/2$) [6]. In this case, a system with rotating plasma appears on the boundary of the instability interval (0) at the point $\alpha = 0, \beta = 0$ (see Fig. 2).

At $4E_r/(rB_z\Omega) > 1$, expression (7) has imaginary roots. In this case, the ions with $m_i/z > M_{cr}$ have non-localized orbits in the instability interval (0), and the forces in (5) are not balanced (see Fig. 2).

The instabilities in a plasma are associated with the presence of oscillations. In particular, a harmonic analysis of plasma oscillations in a rotating plasma at cyclotron resonance instability conditions showed that there was a number of harmonics of the fundamental ion cyclotron frequency Ω in the spectrum [7]. In addition, the instability in a plasma due to the relative motion of plasma components and nonlinear effects in the movement of charged particles in the electric field under oscillations can lead to the appearence of a parametric resonance, that may influence on an ion separation process [8, 9].

The growth of the ac component of a radial electric field (at growth β) for the critical parameters of plasma rotation in the plasma mass filter (at $\alpha = 0$, see Fig. 2) leads to the transition to the instability interval (1) corresponding to the main parametric resonance.

The resonant conditions for the instability interval (1) in the frequency terms are given by [3]:

$$\omega^2 = \Omega^2 - 8\frac{zeU_{dc}}{mR^2}, \tag{12}$$

where ω is the frequency of ac voltage component.

If $U_{dc} = 0$ the oscillation frequency ω in the gap of frequency interval (1) is equal to the ion cyclotron frequency, $\omega = \Omega$. In this case, the acceleration of the resonant ions occurs at the fundamental harmonic Ω. These conditions determine the separation regime for isotope separation, similar to the ICR (ion cyclotron resonance) method [3].

In the case of $U_{dc} \neq 0$, under the conditions of parametric resonance, another separation mode can be realized, when in a plasma mass filter, together with ions of $m_i/z > M_{cr}$, it is possible to allocate the target ions of $m_i/z < M_{cr}$ [3].

This separation mode is considered for ejection of uranium dioxide ions to the longitudinal collector of the plasma mass filter (Fig. 1).

Let's determine the radius R for the separation of the molecular ions of the multicomponent oxides with $m_i / z > M_{cr}$ at initial conditions $B_z = 0.1\,\mathrm{T}$, E_0=400 V/m and $M_{cr} = 400$. In accordance with expression (9) $R = 1.3\,\mathrm{m}$.

The oscillation frequency ω for the resonant conditions (12) in mass terms [3] becomes:

$$\omega = \Omega\sqrt{1 - \frac{m_i}{zM_{cr}}}\ . \tag{13}$$

Thus, at paramatric resonance conditions the frequency ω is equal to the modified ion cyclotron frequency Ω_i (11). So, there is correlation between equations (2) and (5) in respect to Ω_i, that is, at parametric resonance conditions, the oscillation frequency ω of the resonant (i-kind) ion orbit is connected with the self-oscillations of i-kind ion determined at critical plasma rotation options.

Thus, for $M_{cr} = 400$ and $m_i / z = 270$, which corresponds to to the molecular ions UO_2^+, from (13) we obtain ω = 0.57 Ω. It follows, that at superposition of ac voltage component with ω = 0.57 Ω and dc component the uranium dioxide ions are filtered out to the collector of the plasma mass filter (see Fig. 1). This is confirmed in the calculation of the trajectories for the resonant uranium dioxide ions at their ejection into the chamber wall of R = 1.3 m (Fig. 3,a).

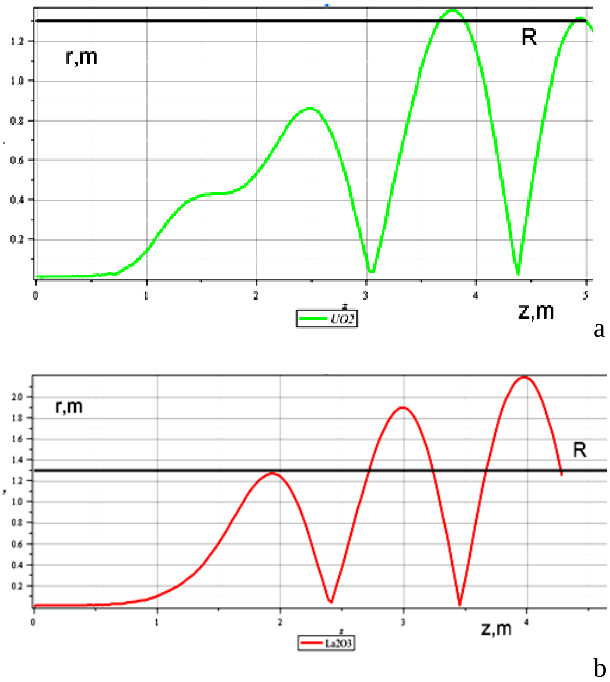

Fig. 3. Trajectories of ions in the plasma mass filter [4] at oscillation frequency ω = 0.57 Ω (UO_2^+) of ac voltage component: UO_2^+ (a); $La_2O_3^+$ for initial conditions described in [10] (b)

From expression (6) the value of Ω for B_Z=0.1 T and $m_i / z = 270$ is defined: Ω(UO_2^+) = $3.56 \cdot 10^4$ rad/s, and, correspondingly, f = 5.6 kHz (f=Ω/2π).

The width of the parametric resonance is determined according [3]:

$$\frac{\Delta m}{m} = \frac{4(2\beta\omega)\omega}{\omega^2 + \Omega^2}, \tag{14}$$

where $(2\beta\omega)$ – is the growth of the amplitude of oscillations.

The transition to the interval of instability (1) at $E_r = E_r^{cr}$ is carried out at the boundary $(\alpha = 0, \beta = \pm 1/8)$ (see Fig. 2).

The value of β was obtained from the boundary equation:

$$4\alpha_{1\pm}(\beta) = 1 \pm 8\beta \tag{15}$$

Substituting the value of β in (14), $m \pm \Delta m$ may be written as:

$$\frac{\Delta m}{m} = \pm\frac{\omega^2}{\omega^2 + \Omega^2}\,. \tag{16}$$

At ω=0.57 Ω the resonance width becomes $\frac{\Delta m}{m} \cong \pm 0{,}25$.

Thus, in the resonant conditions, the ions with mass numbers of 270±68, that is, the total spectrum of single-charged actinide ions and their oxides can reach to the longitudinal collector.

As can be seen (Fig. 3,b), in these conditions, the mass corresponding to single-charged molecular ions of lanthanide oxides are also filtered out to $R = 1.3\,\mathrm{m}$. In order to exclude these ions from the resonant conditions, the operating frequency for the tuner should be ω < 0.57 Ω (UO_2^+). The results of calculations [10] showed that this problem can be solved at exact value of ω = 0.5 Ω (UO_2^+), that is, a.c. voltage component must be tuned to a radio frequency of 2.8 kHz at given initial conditions.

CONCLUSIONS

1. The correlation between the ion orbit oscillation frequency and the modified (vortex) ion-cyclotron frequency in parametric cyclotron mass filter is shown.
2. For given conditions, it is shown that when ac voltage component with oscillation frequency ω = 0.57 Ω (UO_2^+) is superposed on the dc component, the resonant uranium dioxide ions are ejected into the wall of the plasma mass filter [4].
3. For given conditions, the resonance width has been determined: $m \pm \Delta m$ =270±68. Thus, to the longitudinal collector, in addition to the uranium dioxide ions it is possible to filter out the ions of actinides and their oxides.
4. An analysis of the results showed that for the separation of the molecular ions of actinides and lanthanides oxides in the mass filter under consideration, a.c.voltage component must be tuned to ω = 0.5 Ω (UO_2^+)

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СЕПАРАЦИЯ ИОНОВ В ПЛАЗМЕННОМ ФИЛЬТРЕ МАСС С ПРИНЦИПОМ ДЕЙСТВИЯ ПОЛОСОВОГО ФИЛЬТРА

В.О. Ильичева

Рассмотрено разделение ионов по массам в многокомпонентной бесстолкновительной плазме, вращающейся в осевом однородном магнитном поле и радиальном электрическом поле с постоянной и переменной компонентами в условиях параметрического резонанса. Для заданных условий показано, что при суперпозиции переменной компоненты радиального электрического поля с частотой колебаний $\omega=0{,}57\ \Omega$ и постоянной компоненты, резонансные ионы диоксида урана выходят на боковую стенку плазменного фильтра масс, который в настоящее время разрабатывается для разделения ядерного топлива и продуктов деления. Показана корреляция частоты колебаний с модифицированной ионно-циклотронной частотой.

СЕПАРАЦІЯ ІОНІВ У ПЛАЗМОВОМУ ФІЛЬТРІ МАС З ПРИНЦИПОМ ДІЇ ПОЛОСОВОГО ФІЛЬТРА

В.О. Ільічова

Розглянуто розподіл іонів за масами в багатокомпонентній беззіткненій плазмі, що обертається в осьовому однорідному магнітному полі та радіальному електричному полі з компонентами постійного та змінного струму в умовах параметричного резонансу. Для заданих умов показано, що при суперпозиції змінної компоненти радіального електричного поля з частотою коливань $\omega = 0{,}57\ \Omega$ та постійної компоненти, резонансні іони двоокису урану виходять на бічну стінку плазмового фільтра мас, який в даний час розробляється для розділення ядерного палива та продуктів поділу. Показана кореляція частоти коливань з модифікованою іонно-циклотронною частотою.