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Apparatus and Method for Separation of Ions According to Mass

Abraham J Fetterman, Nathaniel J Fisch

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Apparatus and method for separation of ions according to mass

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September 11, 2008

This is a device that uses rotating plasma and radiofrequency waves in order to separate ions within the plasma according to their mass. The device fundamentally consists of a mirror configuration (a primarily axial field) with a radial electric field, producing rotation. Radiofrequency waves are injected to produce diffusion paths allowing select species to exit through the loss cone. The use of these waves within the trap maintains the radial electric field, and allows species to be removed at low energy and with precise control over the location of exit.

1 Introduction

This concept is superficially similar to many devices designed to separate species by their mass using plasmas. Many devices use waves in a plasma to energize one species, and then make use of the resulting energy difference between species to assist separation [1, 3]. Other devices use the centrifugal force generated in a rotating plasma to separate charged particles by their mass. The device and method presented here is in some sense a fusion of the two: waves near the cyclotron frequency of one species are injected into a rotating plasma. Unlike most devices using waves to heat ions, a combination of waves is used to remove ions from the trap at low energy.

Rotating plasma solutions to the problem of mass separation include plasma centrifuges and the Ohkawa filter [2, 3, 4]. Plasma centrifuges take advantage of the differential rotation of ions in rotating plasmas. Collisional drag between the species drives the lighter species inward and the heavier species outward [5]. The Ohkawa filter is a collisionless device in which ions below a threshold mass are trapped, while ions above the threshold are untrapped and lost radially. An advantage of the Archimedes Filter is that the timescale for separation is faster than the collision timescale; however, the density must remain low enough for the plasma to be collisionless.

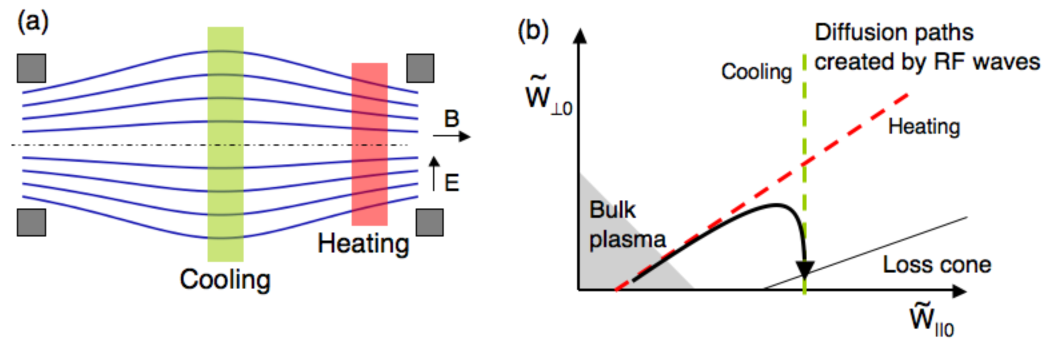

Figure 1: A simple example of phase space manipulation in a centrifugal mirror trap. (a) shows the position of the RF regions in the device. (b) shows the corresponding paths in phase space as dashed lines. The overall diffusion path of the particles is given by the solid black line.

2 General Description

Here, we describe a device similar to both the plasma centrifuge and the Ohkawa filter, in that it uses a rotating plasma to perform the separation of heavy materials from light ones. The device has a magnetic mirror configuration and a radial electric field. The magnetic mirrors trap both heavy and light particles, with a trapping lifetime much greater than an ions bounce time.

Within the device are regions with radio frequency (RF) waves, satisfying a resonance condition with at least one ion species. These waves will interact with a particle of interest to diffuse its position in phase space along a constrained path. Particularly, it will connect the region of phase space populated by the species to a region of phase space near the loss cone, simultaneously changing the radial position. The change in radial position is essentially a radial current; this current supports the radial potential that produces plasma rotation. The method for describing these diffusion paths is given in the Appendix.

When a particle enters the loss cone, it will exit the mirror axially. By overcoming the centrifugal potential and being removed at the throat, the particle transfers rotation energy and parallel energy to the radial potential. This improves the energy efficiency of the device. The RF waves also allow control of the location where expelled material may be collected. This may improve the safety or convenience of the device.

3 Example implementation

Figure 1 shows an example of how this phase space manipulation might be implemented. Ions of one species in the bulk plasma interact with a wave, which provides perpendicular heating (labeled "Heating"). This wave is at mirror ratio R_H. In rotating-frame midplane coordinates $\tilde{W}_{\perp 0}$ and $\tilde{W}_{\parallel 0}$, this diffusion path has a slope $(R_H - 1)^{-1}$, as shown by the red dashed line. This heating is necessary to provide the particle with energy to overcome the centrifugal potential.

The other wave is labeled “Cooling,” and the purpose is to connect the phase space region containing hot ions to the phase space loss cone. This wave has rotating-frame frequency $\tilde{\omega}$, parallel wavenumber $k_\parallel$, resonant velocity $v_\parallel$, and toroidal mode number n_θ; these properties must satisfy the resonance relationship $\tilde{\omega} - k_\parallel v_\parallel = \tilde{\Omega}_c$. (Here we have used conventions introduced in the Appendix for denoting rotating-frame terms with a tilde). In order to remove the perpendicular energy of the particle so that it may exit the device through the loss cone, we place this wave at the midplane. It is important that this wave have a high resonant parallel velocity $v_\parallel$, so that it will only interact with particles that have enough energy to leave the device.

3.1 Single species removal

The simplest implementation of this method involves interaction with only one species. When the particles exit the loss cone, they leave the device axially. The material collected at the endplates is then the product containing the enriched species. The effluent then remains in the device, and its removal may take place by radial diffusion, or by operating the device in batches.

3.2 Wave energy exchanges

Because the cooling wave reduces the kinetic energy of the particle, there is an energy surplus for this wave. Usually, this would simply amplify the interacting RF wave. However, in a rotating plasma there are additional energy sources and sinks: the particle potential energy and rotation energy. In our previous paper (whose relevant section is reproduced in the Appendix), we defined the *branching ratio* as the fraction of the kinetic energy change converted to potential energy. For perpendicular waves ($k_\parallel v_\parallel \ll \tilde{\Omega}_c$):

$$f_E \approx \frac{-n_\theta \Omega_E \Omega_c}{\omega \tilde{\Omega}_c - n_\theta \Omega_E \Omega_c} = \frac{-n_\theta \chi}{1 + 4\chi + 2\left(2 + n_\theta\right)\chi^2}$$

where we have used the resonance condition $\tilde{\omega} \approx \tilde{\Omega}_c$ and defined $\chi = \Omega_E / \Omega_c$. We can thus choose the amount of energy converted to potential energy by appropriately choosing n_θ. In selecting the optimum value for f_E, we consider the amount of power required to maintain the cooling wave at sufficient amplitude (the diffusion coefficient is proportional to the wave amplitude, and the diffusion time must be faster than the collision time for the channeling to be effective). The remainder of the energy is most effectively converted to potential energy, requiring $0 < f_E < 1$. This potential energy will then support the rotation of the plasma, maintaining it against collisional decay.

The potential energy can also be used to supplement wave energy in the heating wave; or, alternatively, the heating wave may also provide rotation energy. If the cooling wave provides more power than is necessary to maintain rotation, the heating wave can transfer some potential energy to particle kinetic energy. This may be done by choosing $0 < f_E$ for the heating wave (the kinetic energy increases but the potential energy decreases). Alternatively, if the cooling wave does not provide enough power to maintain the rotation, wave energy from the heating wave can be converted into potential energy. This is accomplished by choosing $f_E < 0$ for the heating wave.

By converting wave energy or particle energy to potential energy, the rotation of the plasma may be maintained. With sufficient power provided this way, it would not be necessary to have end electrodes provide a radial potential. This would significantly reduce the engineering complexity of the device. It is especially useful since the end region will be used for the removal of the separated plasma components. By removing the requirement for end electrodes, one would not have to worry about combining systems for applying voltage and collecting separated materials.

4 Alternative separation methods

It may be desirable to eject two or more species into separate areas on the endplates. This would make the collection of both species more efficient. Two novel methods for separation may be implemented using these wave interaction techniques.

4.1 Radial separation

As the perpendicular energy of the particles change, so will the distance from the device center. We consider moving the heavy species outward. Both the heating and cooling waves may provide radial transport. First consider the change in radius due to the heating wave. The maximum energy the particle will reach is $W_{max} = W_{\| resC} \left(R_H - 1\right)^{-1}$, where $W_{\| resC}$ is the resonance parallel energy of the cooling wave. Using Eq. (9), the wavenumber $k_\theta = n_\theta / r$, and assuming the ion begins at temperature T,

$$\Delta r_H = \frac{R_H k_{\theta H}}{m \tilde{\Omega}_c^2} \left[\frac{W_{\| resC}}{R_H - 1} - T \right].$$

For a mirror with magnetic ratio $R_m = \tilde{B}_m^2 / \tilde{B}_0^2$, the loss cone begins at energy $W_E \left(1 - R_m^{-1}\right)$, and has slope $\left(R_m - 1\right)^{-1}$. This means the particle will exit at energy $W_{\| resC} \left(R_m - 1\right)^{-1} - W_E / R_m$. Thus:

$$\Delta r_C = \frac{k_{\theta C}}{m \tilde{\Omega}_c^2} \left[\frac{W_{\| resC}}{R_m - 1} - \frac{W_E}{R_m} - \frac{W_{\| resC}}{R_H - 1} \right].$$

So the total change in radius is:

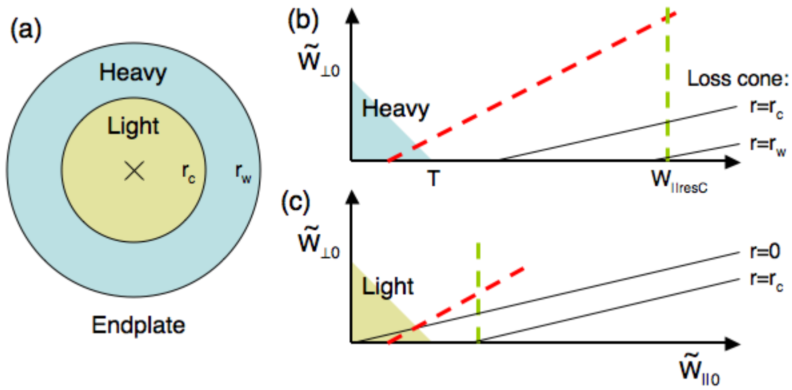

Figure 2: Diagrams for extraction of species with radial separation. "Light" and "Heavy" refer to the light and heavy species, respectively. (a) shows an end-on view of the collection areas at the endplate. (b) and (c) show possible diffusion paths (dashed lines) to achieve this separation in rotating midplane energy coordinates, with the loss cone drawn for particles of different radii (solid lines).

$$\Delta r = \frac{W_{\|resC}}{m\tilde{\Omega}_c^2}\left[\frac{R_H k_{\theta H} - k_{\theta C}}{R_H - 1} + \frac{k_{\theta C}}{R_m - 1}\right] - \frac{k_{\theta C} W_E}{R_m m \tilde{\Omega}_c^2} - \frac{R_H k_{\theta H} T}{m\tilde{\Omega}_c^2}$$

To maximize this, choose $k_{\theta H} > 0$ and $k_{\theta C} < 0$. Because they must move outward Δr in order to exit through the loss cone, all heavy ions exiting the trap axially will have midplane radius $r_0 > \Delta r$, or at the endplate $r > r_c$, where $r_c = \Delta r / R_m$ is the cutoff radius (Fig. 2a).

The lighter species has a lower centrifugal confinement potential due to its lighter mass, and there is also a reduced confinement potential at small radii due to the lower rotation energy (the resulting phase space diagram is shown in Fig. 2c). These effects combined mean that the lighter species will scatter into the loss cone at a much greater rate than the heavy species.

Waves may also be used that interact with the light species, enhancing the rate of diffusion out of the device and channeling more energy into rotation. A single wave with $v_\|$ less than the species thermal speed would be able to diffuse ions at the very center of the device out through the loss cone (for example, the red diffusion path in Fig. 2c). One may also consider a pair of diffusion paths, one for heating and one for extraction (the red and green diffusion paths in the same diagram). The resonant parallel velocity of the CE wave may be chosen to be sufficient to overcome the centrifugal potential for $r < r_c$, but not for $r > r_c$. In this case, $W'_{\|resC} = \frac{1}{2} m' \Omega_E^2 r_c^2 (R_m - 1)$.

It is also possible to accomplish radial separation by limiting the region for waves interacting with light particles to $r < r_c$, and for waves interacting with

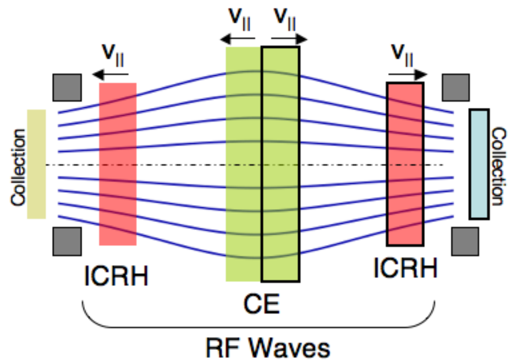

Figure 3: Diagram for asymmetric removal of species. Boxed RF waves are resonant with the heavy species (removed at the right), while unboxed waves are resonant with the light species (removed at the left).

heavy particles to $r > r_c$.

4.2 Axial separation

One may instead wish to remove the light species from one side of the device, and the heavy species from the other side. This may be accomplished by using two pairs of waves, interacting with the heavy and light species, as shown in Fig. 3. In this diagram, the boxed RF waves are resonant with the heavy species, and have resonant velocities directed to the right. This means that after the heavy ions get their last "kick" by the waves, they exit the device on the right side. The unboxed waves are resonant with the light species travelling to the left. The light species may then be collected on the left side.

5 Advantages

This method has several advantages over alternative rotating plasma or RF methods. Compared to other rotating plasma schemes, this device has the advantage that no end electrodes are needed to support the rotation. The rotation is supported through the wave interaction.

A secondary benefit is that ions are removed cold (at low energy) at the endplates. They will only reach the endplates after overcoming the centrifugal potential; in doing so, ions transfer most of their rotational and parallel energy back into the radial potential. Ion cyclotron resonance devices must increase the particle energy to many times the thermal energy in order to get reasonable separation; this energy is lost when the particle is collected [1]. In the case of the Ohkawa filter and some centrifugal filter designs, ions are removed radially in the middle of the device, where they have a maximal rotation energy. In devices with positive E_r, ions extract additional energy from the potential by being removed radially (the outer wall is acting as a cathode drawing a current).

Lastly, another advantage of this method is that separated materials are collected over a small surface area (the endplates). This will reduce the contamination of other areas, improving the safety of devices in which hazardous or radioactive elements are being separated.

6 Conclusion

A device and method are described here for separating ions of different mass, using a rotating plasma. The key improvement to existing technologies is the use of radiofrequency waves to drive the rotation of the device. The waves also improve the energy efficiency of the device, as well as reduce the area used for collection of separated materials. Further research will determine the effect of collisions on the separation efficiency, and will compare throughput to other mass separation devices. While only two species are considered here, the system may be generalized to an arbitrary number of species.

7 Appendix

To derive the new effects, define the angular rotation frequency $\mathbf{\Omega_E} = \Omega_E \hat{z}$, so that the $\mathbf{E} \times \mathbf{B}$ drift velocity can be written as $\mathbf{\Omega}_E \times \mathbf{r} = \mathbf{E} \times \mathbf{B}/B^2$. For simplicity, consider constant Ω_E (solid-body rotation). Although some aspects may vary with the rotation profile, the concept should be applicable to arbitrary profiles $\Omega(r)$. The electric and magnetic field in the rotating frame are [6],

$$\tilde{\mathbf{E}} = \mathbf{E} + \frac{m}{q}\Omega^2 \mathbf{r} + (\mathbf{\Omega} \times \mathbf{r}) \times \mathbf{B}, \tag{1}$$

$$\tilde{\mathbf{B}} = \mathbf{B} + 2\frac{m}{q}\mathbf{\Omega}. \tag{2}$$

The second term in Eq. (1) produces the centrifugal force, and the second term in Eq. (2) is due to the Coriolis effect. For $\mathbf{\Omega} = \mathbf{\Omega}_E$, the first and third terms in Eq. (1) will cancel. However, there will still be drifts due to the centrifugal force. We define as $\Omega_E^\star$ the unique frame of reference in which $\hat{\theta} \cdot \tilde{\mathbf{E}} \times \tilde{\mathbf{B}} = 0$ for the species of interest. Note that the magnetic moment is seen as invariant only in the frame rotating with frequency $\Omega_E^\star$. Our notational convention is to denote terms in this frame with a tilde.

Note that by flux conservation, $r^2/r_0^2 \propto \tilde{B}/\tilde{B}_0$. Thus for magnetic mirror ratio $R_m = \tilde{B}_m/\tilde{B}_0$, there is an effective confinement potential $\Phi_c = \frac{1}{2}m\Omega_E^{\star 2} r_0^2 \left(1 - R_m^{-1}\right)$, which varies with the midplane particle radius r_0. The loss-cone diagram is depicted in Fig. 4. The maximum confinement potential is $W_{E0w}\left(1 - R_m^{-1}\right)$, where $W_{E0w} = \frac{1}{2}m\Omega_E^{\star 2} r_w^2$, and r_w is the midplane radius of the last field line not intersecting a wall.

Now consider a wave with frequency ω, parallel wave number $k_\parallel$ and azimuthal mode number $n_\theta = k_\theta r$. Due to the rotation, the wave frequency in the rotating frame will be $\tilde{\omega} = \omega - n_\theta \Omega_E^\star$. The wave-particle resonance condition is then $\tilde{\omega} - k_\| v_\| = n\tilde{\Omega}_c$, where the resonance is at the n^{th} harmonic of the rotating-frame cyclotron frequency $\tilde{\Omega}_c = q\tilde{B}/m$ (q is the ion charge and m is its mass). The parallel velocity $v_\|$ is independent of the rotating frame, and corresponds to energy $W_{\|res} = mv_\|^2/2$. Unlike in the stationary case, the related midplane parallel energy, $W_{\|0res}$, will not be constant across the radius of the device. For an RF region at mirror ratio $R_{rf} = \tilde{B}_{rf}/\tilde{B}_0$, the resonant parallel energy in rotating midplane coordinates is

$$W_{\|0res} = W_{\|res} + W_{E0}\left(1 - R_{rf}^{-1}\right), \tag{3}$$

where $W_{E0} = m\Omega_E^{\star 2} r_0^2/2$. These resonant regions appear as the shaded region in Fig. 5.

Since the mirror system is axisymmetric, the diffusion paths will be the same as those for tokamaks [7],

$$dP_\theta/d\tilde{W} = n_\theta/\tilde{\omega}, \tag{4}$$

$$d\tilde{\mu}/d\tilde{W} = qn/m\tilde{\omega}, \tag{5}$$

where $\tilde{\mu} = m\tilde{v}_\perp^2/2\tilde{B}$ is the ion magnetic moment in the rotating frame; $\tilde{W} = \tilde{\mu}\tilde{B} + mv_\|^2/2$ is the kinetic energy in the rotating frame; and P_θ is the azimuthal canonical angular momentum (which is frame-independent).

The significant difference in the rotating frame is that the interaction of the particle with a wave at axial position z_{rf} changes the particle's perpendicular, parallel, and rotational kinetic energy, as well as its potential energy. The change in perpendicular energy may be written $\tilde{W}_\perp(z_{rf}) \to \tilde{W}_\perp(z_{rf}) + \Delta\tilde{W}_\perp$; the change in parallel energy, $\tilde{W}_\|(z_{rf}) \to \tilde{W}_\|(z_{rf}) + \Delta\tilde{W}_\|$; and the change in rotational energy, $W_E(z_{rf}) \to W_E(z_{rf}) + \Delta W_E$. Thus the wave interaction, breaking the adiabatic invariance of $\tilde{\mu}$, gives stochastic kicks in $\Delta\tilde{W}_\perp$, $\Delta W_\|$, and ΔW_E.

The energy kicks are correlated through the properties of the wave. The relation between $\Delta\tilde{W}_\perp$ and $\Delta\tilde{W}_\|$ is found, by Eq. (5), to be $\Delta\tilde{W}_\| = \Delta\tilde{W}_\perp k_\| v_\|/(n\tilde{\Omega}_c)$. The radial excursion is determined in terms of the perpendicular energy change by Eq. (4), yielding $r\Delta r = \Delta\tilde{W}_\perp n_\theta/(m\tilde{\omega}\tilde{\Omega}_c)$. This then gives the rotational energy change, $\Delta W_E = m\Omega_E^{\star 2} r\Delta r = \Delta\tilde{W}_\perp n_\theta \Omega_E^{\star 2}/(\tilde{\omega}\tilde{\Omega}_c)$, and the potential energy change, $q\Delta\Phi = -qE\Delta r = n_\theta\Omega_E\Omega_c/(\tilde{\omega}\tilde{\Omega}_c)\Delta\tilde{W}_\perp$.

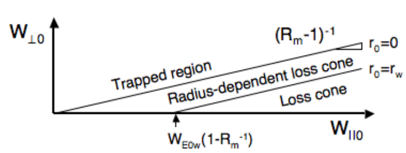

Figure 4: The loss cone in (rotating) midplane energy coordinates for a rotating plasma, including centrifugal confinement.

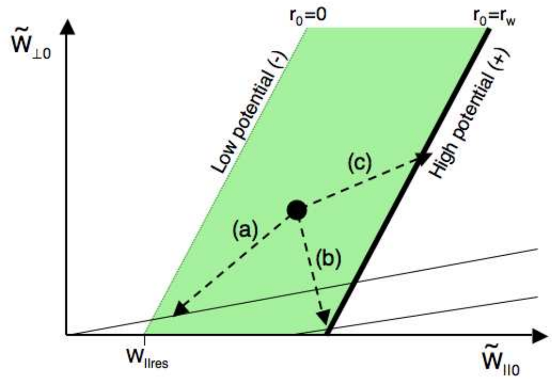

Figure 5: The shaded region is the region of wave resonance, dependent on radius, for interaction with an RF wave at mirror ratio R_{rf}. The hatched lines depict three diffusion paths that would eject particles, using only perpendicular diffusion. Path (a) reduces both the kinetic and potential energy of the particle, path (b) increases potential energy but decreases kinetic energy, and path (c) increases both kinetic and potential energy. The energy balance is assumed by the wave.

Using the adiabatic invariance of $\tilde{\mu}$, flux conservation ($r^2/r_0^2 \propto \tilde{B}/\tilde{B}_0$), and conservation of energy, we require

$$\Delta\tilde{W}_\perp + \Delta\tilde{W}_\| - \Delta W_E = R_{rf}^{-1}\Delta\tilde{W}_\perp + \Delta\tilde{W}_{\|0} - R_{rf}\Delta W_E, \tag{6}$$

so that the changes in rotating midplane coordinates can be written as,

$$\Delta\tilde{W}_{\perp 0} = \Delta\tilde{W}_\perp / R_{rf}, \tag{7}$$

$$\Delta\tilde{W}_{\|0} = \left[\frac{k_\| v_\|}{n\tilde{\Omega}_c} + (R_{rf}-1)\frac{n_\theta \Omega_E^{\star 2}}{\tilde{\omega}\tilde{\Omega}_c} + \left(1 - R_{rf}^{-1}\right)\right]\Delta\tilde{W}_\perp, \tag{8}$$

$$\Delta r_0 = \frac{R_{rf} n_\theta}{m r_0 \tilde{\omega}\tilde{\Omega}_c}\Delta\tilde{W}_\perp. \tag{9}$$

As the particle diffuses in radius it also changes its rotation energy W_E. This will lead to a change in midplane parallel energy for $R_{rf} > 1$, as can be seen in Eq. (3). This is the source of the second term in brackets in Eq. (8). Note that the particle remains in resonance with the wave on its entire path in the limit $n_\| \to 0$.

With reference now to Fig. 5, note three ways particles might be extracted from a rotating mirror, with perpendicular diffusion only ($\Delta\tilde{W}_\| = 0$). The particle begins midway between the axis and wall of the device. Suppose the particle may be removed through the loss cone by path (a) at a low potential energy and a low kinetic energy. This requires the wave phase velocity in the rotating frame to be positive ($\tilde{v}_p = k_\theta/\tilde{\omega} > 0$). The same wave may be used to remove particles through the last flux surface at high kinetic and potential energy (shown by path (c)). The energy balance in each case is carried by the interacting wave. Path (b) describes a diffusion path where the particle is removed with less kinetic energy than at its birth but at a higher potential energy. The particle may be removed either through the loss cone or the last flux surface. This is the useful case for maintaining the radial electric field.

To calculate the *branching ratio* f_E, the ratio of energy going into the radial potential to the total energy change, consider that the change in rest-frame kinetic energy is

$$\Delta W = \left(\frac{\omega}{\tilde{\omega}} + \frac{k_\parallel v_\parallel}{n \tilde{\Omega}_c} \right) \Delta \tilde{W}_\perp, \tag{10}$$

giving the branching ratio

$$f_E = \frac{-n_\theta \Omega_E \Omega_c}{\omega \tilde{\Omega}_c + \tilde{\omega} k_\parallel v_\parallel / n - n_\theta \Omega_E \Omega_c}, \tag{11}$$

$$\approx \frac{-n_\theta \Omega_E}{\Omega_c + 2 k_\parallel v_\parallel + 4 \Omega_E}, \tag{12}$$

where the approximation in Eq. (12) uses the resonance condition $\tilde{\omega} = \tilde{\Omega}_c + k_\parallel v_\parallel$, with $\Omega_E, k_\parallel v_\parallel \ll \Omega_c$. If these conditions are sufficiently strong, the fraction of the total energy change provided to the radial electric field is $f_E \approx -n_\theta \Omega_E / \Omega_c$. In the case $f_E > 1$, the particle reduces its kinetic energy and simultaneously absorbs wave energy, which can be expected because the direction of the RF wave phase velocity in the rotating frame, $\tilde{v}_p = \tilde{\omega}/k_\theta$ is opposite that in the laboratory frame, $v_p = \omega / k_\theta$. Path (b) in Fig. 5 describes a diffusion path in which the wave will be amplified if $f_E < 1$ (not all kinetic energy is converted to potential), or damped if $f_E > 1$ (wave energy transferred to potential energy).

Related patents

1. Isotope/mass separation by radiofrequency waves

   (a) J. M. Dawson, "Separation of isotopes by time of flight." US Patent # 4,059,761 (1977)

   (b) J. M. Dawson, "Isotope separation by ion waves." US Patent # 4,066,893 (1978)

   (c) J. M. Dawson, "Isotope separation by magnetic fields ." US Patent # 4,081,677 (1978)

   (d) R. L. Stenzel, "Method of and apparatus for the electrostatic excitation of ions." US Patent # 4,093,856 (1978)

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   (f) J. M. Dawson, "Method for flowing a large volume of plasma through an excitation region." US Patent # 4,213,043 (1980)

2. Isotope/mass separation by rotating plasmas

    (a) J. L. Hirschfield and M. Krishnan, "Method and apparatus for separating substances of different atomic weights using a plasma centrifuge." US Patent # 4,458,148 (1984)

    (b) T. Ohkawa, "Plasma mass filter." US Patent # 6,096,220 (2000).

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[2] B. Bonniver, "Experimental evidence of element and isotope separation in a rotating plasma." Plasma Physics **13,** 763 (1971).

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[4] T. Ohkawa, "Plasma mass filter." US Patent 6,248,240 (2001).

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[7] N. J. Fisch and J. M. Rax, "Interaction of energetic alpha particles with intense lower hybrid waves." Phys. Rev. Lett. **69** 612 (1992).

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Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
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