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The magnetic centrifugal mass filter

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Mass filters using rotating plasmas have been considered for separating nuclear waste and spent nuclear fuel. We propose a new mass filter that utilizes centrifugal and magnetic confinement of ions in a way similar to the asymmetric centrifugal trap. This magnetic centrifugal mass filter is shown to be more proliferation resistant than present technology. This filter is collisional and produces well confined output streams, among other advantages. © *2011 American Institute of Physics*. [doi:10.1063/1.3631793]

Plasma techniques have long been used for isotope separation. Rotating magnetized plasmas are a convenient way to separate particles by mass because the equations of motion allow easy distinction of ions based on mass.[1] Various plasma techniques based on wave-particle resonances that similarly make fine discriminations in mass are also suitable for isotope separation.[2,3] However, recently plasmas have also been studied for separating the radioactive fission product from nuclear waste, which requires less precise mass discrimination.[4] Here, we propose a new type of rotating plasma mass filter based on magnetic and centrifugal confinement that is well suited for separating waste but poorly suited for separating isotopes. Because proliferation risk is often a concern for mass separation techniques, this is a notable advantage.

Two major methods of mass separation employing rotating plasmas have been explored in the past. One is the plasma centrifuge, which was mostly explored for separation of isotopes.[1,5,6] This uses collisional diffusion of particles to produce radial separation of ions within a plasma column. Although in the past rotation speeds have been limited to the Alfven critical ionization velocity, it may be possible to overcome this limit by driving rotation with radio frequency waves.[7]

The other method for mass separation that has been studied extensively is the Ohkawa filter. In this filter, particles are separated by a radial confinement condition which depends on the charge to mass ratio.[4] The heavy stream is not confined and is collected at the outer plasma radius (limiter surface), and the light stream is confined and collected along the field lines. In the Ohkawa filter, the biased electrodes are used both to create rotation and to collect an ion current. The Ohkawa filter requires a collisionless plasma, which may limit the throughput.

Here, we propose a magnetic centrifugal mass filter, what we call MCMF. The MCMF draws upon ideas proposed by Volosov for very different purposes, the confinement of aneutronic fusion fuels.[8,9] The asymmetric centrifugal trap (ACT) uses a rotating plasma with both centrifugal and magnetic confinement. Different confinement conditions at either end allow charged fusion product to exit at one end and fuel to exit at another end. This improves the efficiency of recovering energy from both types of ions.

The MCMF uses a similar magnetic field configuration to the ACT. Although the ACT is a collisionless confinement device that separates high energy particles from low energy particles,[8] the MCMF described here is a high throughput, low temperature filter to separate particles of different mass. Particles in the ACT exit separate ends because of different energies. Particles in the MCMF have the same energy because of collisions but exit at different ends because of different confinement means.

A key element of the asymmetric centrifugal trap is that in a rotating system, either an increase in the magnetic field or a decrease in radius will confine particles. The change in magnetic field is familiar as the confining force in magnetic mirrors. The confinement of particles depending on radius arises because, if particles move along a magnetic field line toward the axis of rotation, the particles must overcome the centrifugal force which has a component along the field line. This is an effective centrifugal potential barrier.

In a magnetic mirror, the radius of a field line is related to the magnetic field, $B/B_0 = r_0^2/r^2$. However, this need not be the case if there are magnetic coils near the axis of the mirror (as in Fig. 1). In a centrifugal trap, for example, the magnetic field decreases at the mirror throat but the radius also decreases. In the absence of rotation, the plasma would flow freely away from the midplane, but in this case, the plasma is confined by the centrifugal force and ambipolar potential. To describe these possibilities, we define both a magnetic mirror ratio, $R_m = B_m/B_0$, and radial mirror ratio, $R_r = r_0^2/r_m^2$. We also define the rotation frequency $\Omega_E = -E_r/rB_z$.

The confinement condition for a particle at the midplane with parallel energy $W_{\parallel 0}$, perpendicular energy $W_{\perp 0}$, and rotation energy $W_{E0} = m\Omega_E^2 r^2/2$ is then

$$W_{\parallel 0} < W_{\perp 0}(R_m - 1) + W_{E0}\left(1 - R_r^{-1}\right). \qquad (1)$$

For $R_m \ll 1$ and $R_r \gg 1$, the confinement condition becomes $W_{\perp 0} + W_{\parallel 0} < W_{E0}$. The confinement depends only on the midplane energy, not on pitch angle, and on W_{E0} which varies according to mass (not charge-to-mass ratio). If the plasma is collisional, both heavy and light ions will have the same average kinetic energy, but the barrier will be much higher for heavy particles. Therefore, more light particles will exit through the boundary.

We can create a boundary that lets through more heavy particles than light ones using $R_r < 1$. We then use an

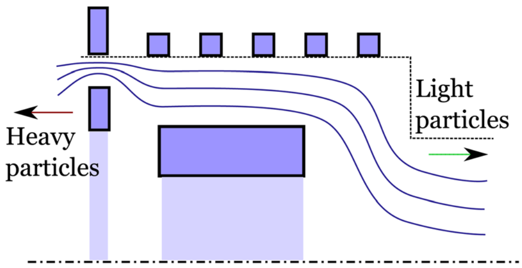

FIG. 1. (Color online) A magnetic centrifugal mass filter. The solid lines indicate magnetic field lines, shaded squares indicate magnetic field coils, the dashed line indicates the vacuum boundary, and the dashed-dotted line indicates the axis of symmetry.

increased magnetic field $R_m > 1$ for confinement. A line indicating the confinement region in phase space for particles with different mass is shown in Fig. 2.

Electrons in the MCMF are confined by an ambipolar potential on both the light and heavy sides, Φ_ℓ and Φ_h, respectively. This will produce a stronger deconfining effect for multiply charged ions than for singly charged ions. However, because $\Phi_\ell \sim \Phi_h \sim T_e$, this effect is much smaller than the centrifugal confinement as $T_e \lesssim T_i \ll W_{E0}$.[10]

The plasma ions may be created at any position along the device, but it may be advantageous to inject ions in the region beyond the light boundary. Because of the rotation, ions will be accelerated away from the source toward the midplane where they become trapped after undergoing a collision. By injecting plasma along field lines, the density profile can be controlled and neutral drag can be minimized.

One often cited reason to avoid nuclear fuel reprocessing is the risk of nuclear proliferation. The conventional separation process PUREX produces a separate plutonium waste stream. Many tons of plutonium would be produced by each plant each year, but only 8 kg plutonium is needed for a nuclear weapon. Protecting and controlling this stream is both challenging politically and costly.

Because plasma mass filters would separate all actinoids together, this issue could be mitigated. If plutonium remains mixed with depleted uranium, a much larger quantity of waste would need to be processed to isolate the plutonium. Constructing the facility for isolating plutonium from the actinoids may also be challenging.

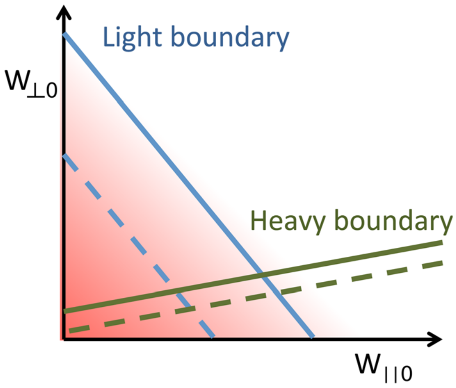

FIG. 2. (Color online) Phase space at the midplane in an asymmetric centrifugal trap. The solid line indicates the loss boundary for heavy particles and the dashed line indicates the loss boundary for lighter particles. Particles to the left of the line are confined. The shaded region indicates the thermal ion population. The "light boundary" allows more light particles to pass and the "heavy boundary" allows more heavy particles to pass.

However, another proliferation risk is introduced by some plasma mass filters. It may not be difficult to repurpose a different plasma mass filter to separate uranium isotopes. For the plasma centrifuge, only the rotation speed would need to be increased (or temperature decreased) to allow separation of ions with a smaller mass gap. The Ohkawa filter could be similarly modified.

The MCMF, though, could not be used for isotope separation because the throughput drops off exponentially for large separation factors. For example, for a light boundary with $R_m \ll 1$, only particles with energy above W_{E0} pass through. For a Maxwellian plasma, the throughput of a given species is like $1 - \mathrm{Erf}(\sqrt{W_{E0}/T}) \approx e^{-W_{E0}/T}\sqrt{T/W_{E0}}$. This throughput will be similar for both species, resulting in little separation, unless $\alpha = e^{(m_2-m_1)\Omega_{E0}/T} \gg 1$. However, the throughput of species 1 is like $\alpha^{-m_1/(m_2-m_1)}$. If $m_1 \gg m_2 - m_1$, which is the case for isotope separation, this throughput will be too small to be useful at all. On the other hand, for $m_1 \lesssim m_2 - m_1$, as in waste separation, this may be an acceptable reduction in throughput.

An advantage of the MCMF over other mass separation methods is that it acts on the true mass of the ions rather than the charge-to-mass ratio. Multiply charged ions can create an upper limit on separation power in the Ohkawa filter or plasma centrifuge unless an alternate system is in place to capture these particles.[4] The alternate methods, such as creating band gaps with radio frequency waves, still work based on charge-to-mass ratio, targeting specific multiply charged ion species.

Another benefit of the MCMF is that two well-confined and well separated output streams are produced. The Ohkawa filter spreads the heavy particles over the outer wall, so the entire plasma-facing surface is a collector for particles. Particles leave the MCMF only along field lines. They also leave at opposite ends, so that the decontaminated stream can be handled in a different way than the radioactive stream. The streams are collected over an area of a few square meters, rather than hundreds of square meters. This is particularly important when the heavy stream is radioactive, as the increased radiation can impede access and maintenance to the device.

Finally, the MCMF could require much less energy than the Ohkawa filter. In the Ohkawa filter, heavy particles must travel from the anode to the cathode to be removed from the device. For the proposed device, energy use is close to 500 eV per particle.[11] In the MCMF, however, particles remain on the field lines and most rotation energy can be recovered.

In summary, MCMF is a simple technique to separate nuclear waste and spent nuclear fuel. Compared to other mass filters, it appears to be relatively proliferation-resistant because the throughput diminishes exponentially in accommodating small mass differences. The separation function depends on the mass of particles rather than the charge-to-mass ratio. It has well-confined output streams to simplify collection of processed waste. The plasma is collisional, which may allow higher throughput than the Ohkawa filter, and injection of ions may be done along field lines to reduce neutral drag. Finally, the rotation may be produced by radio frequency waves, eliminating the complexity required for segmented electrodes.[12] While this research note suggests a new and interesting separation device, it certainly remains to examine practical issues such as radiation losses, ionization and heating mechanisms, and operating regimes in density and temperature. Indeed, the utility of this idea will hinge upon the resolution of many practical issues. Yet, on the basis of the fundamental underlying physical separation mechanisms, the MCMF does appear to be a very promising mass filter for nuclear waste separations, with minimum proliferation risk.

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