ExB Workshop - Princeton - Nov. 1st/2nd 2018

Rotating Plasmas

ExB Configurations for Plasma Mass Separation

Renaud Gueroult

Laboratoire Plasma et Conversion d'Energie (LAPLACE), CNRS, Toulouse, France

in collaboration with

J.-M. Rax

Université de Paris XI - Ecole Polytechnique, LOA-ENSTA-CNRS, Palaiseau, France

N. J. Fisch, S. J. Zweben, I. E. Ochs, F. Levinton

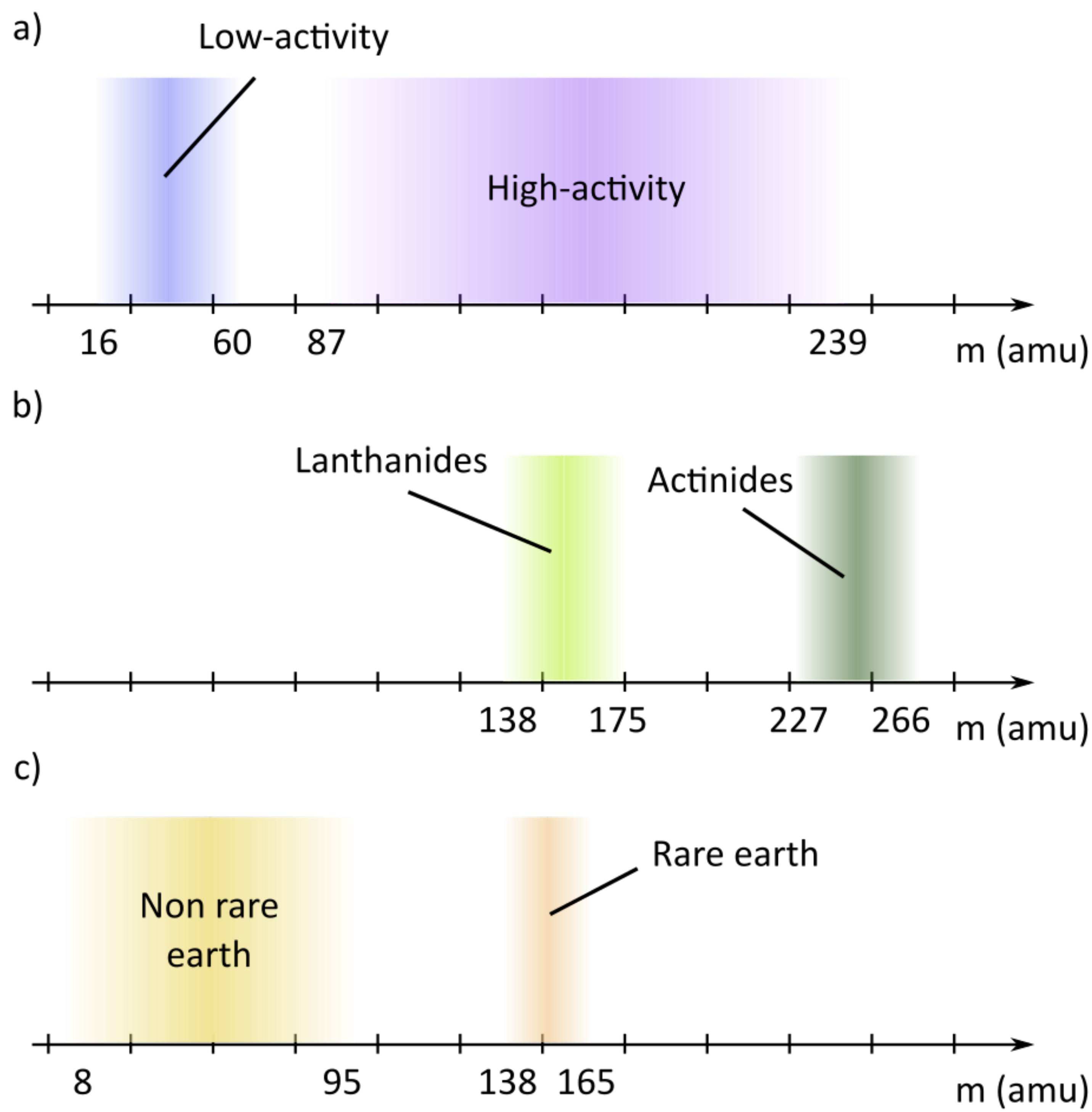
Princeton Plasma Physics Laboratory, Princeton NJ, USA

NEW NEEDS FOR MASS SEPARATION AT ELEMENTAL LEVEL

Nuclear waste cleanup

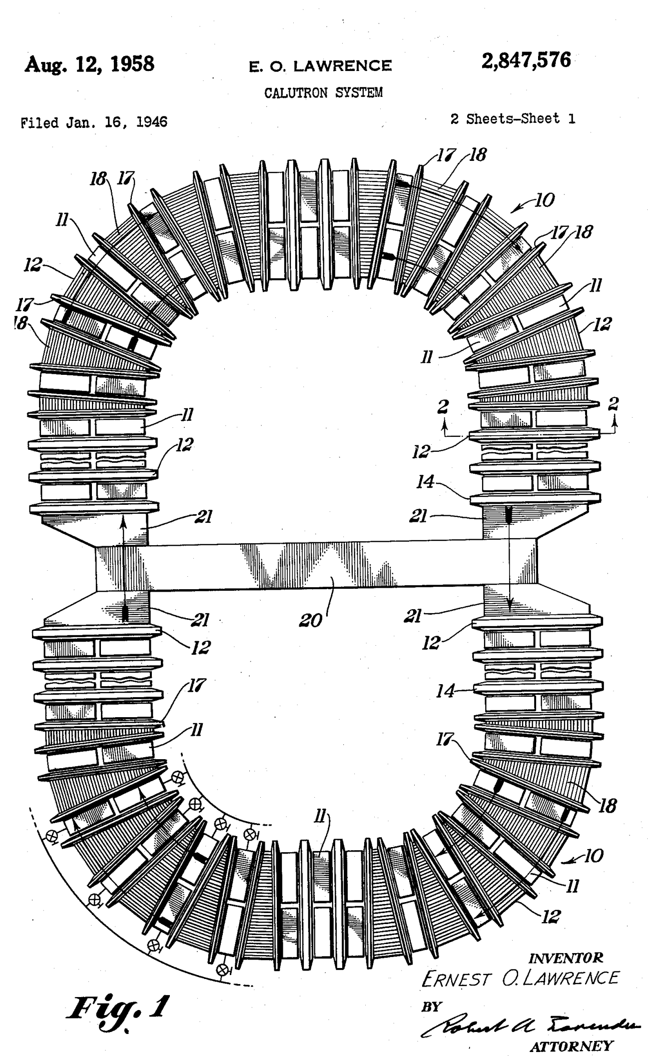
Spent nuclear fuel reprocessing

NdFeB magnets recycling.



Mass Separation at the Elemental Level

Mass separation at the elemental level was initially driven by isotope separation. Plasma separation was developed in this context.



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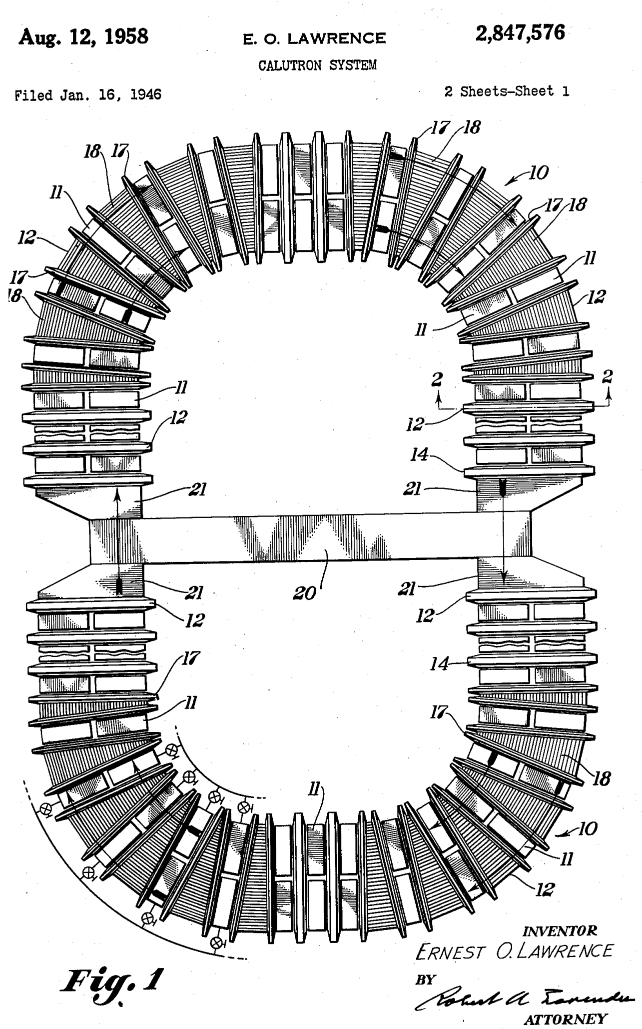
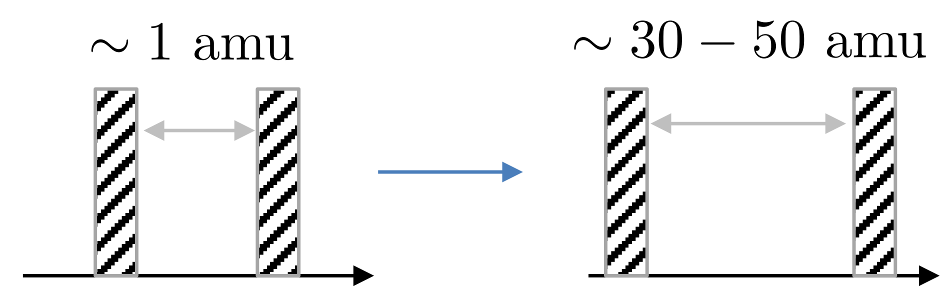
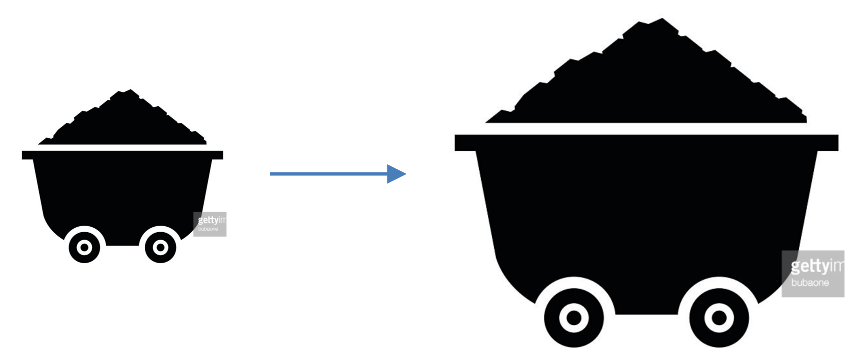


New needs require new solutions for at least two reasons:

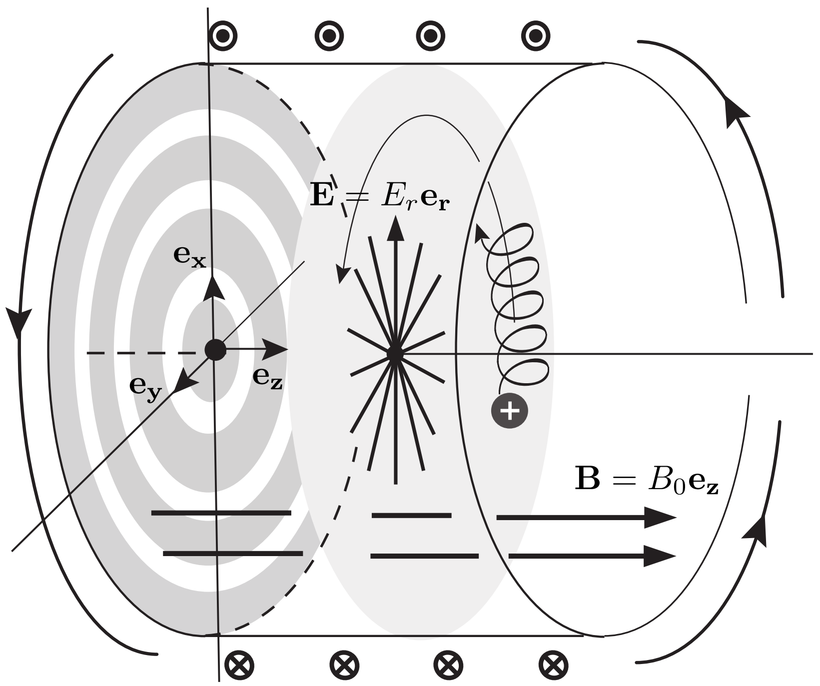


Large mass differences



$10\ \mathrm{kg/year}$ $10\ \mathrm{T/year}$

High throughput

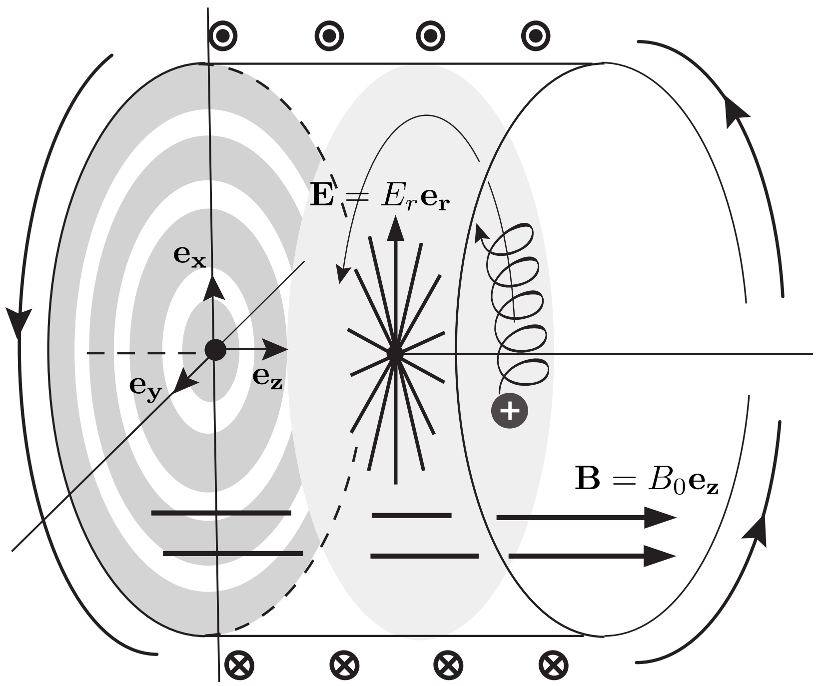


In a crossed field configuration with axial B_z field and radial E_r field, centrifugal forces create an additional drift. The angular frequency is not $E_r/(B_z r)$.

$$\omega_B{}^{-} = -\text{sgn}(q)\frac{\Omega}{2}\left[1 - \sqrt{1 + 4\text{sgn}(q)\frac{\Omega_E}{\Omega}}\right]$$

$$\underset{|\Omega_E| \ll \Omega}{\longrightarrow} \Omega_E$$

with $\Omega = |q|B_0/m$ and $\Omega_E = -E_r/(rB_0)$.



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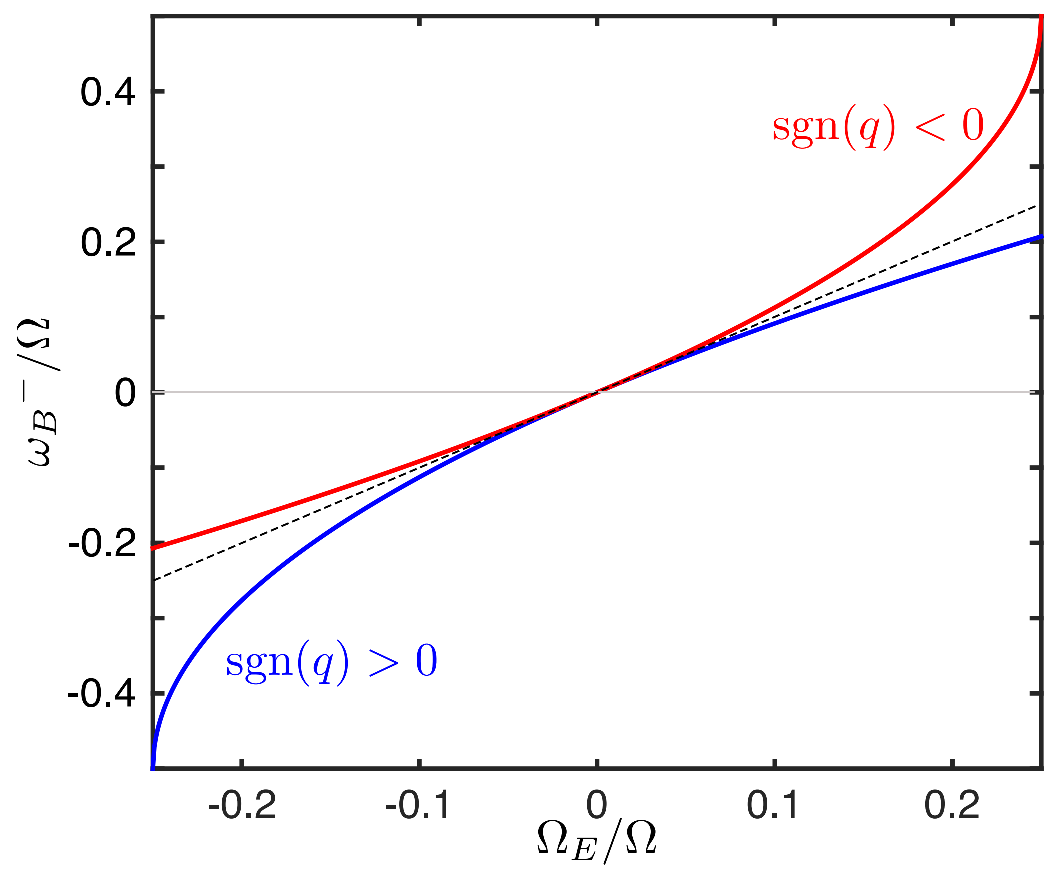

Centrifugal forces accelerate rotation for $\mathrm{sgn}(q)\Omega_E < 0$, and slow down rotation for $\mathrm{sgn}(q)\Omega_E > 0$.

If $\mathrm{sgn}(q)\frac{\Omega_E}{\Omega} \geq -1/4$, there is no radial confinement.

Laplace

Another way to look at this is through the effective potential in the rotating frame where the magnetic field cancels,

$$\phi^{\star}(\tilde{r}) = \phi(r) + \frac{q{B_0}^2}{8m}\tilde{r}^2 \longleftarrow \text{Centrifugal + Coriolis}$$

with $\phi(r)$ the electric potential applied in the lab frame.

ExB Flow in Uniform Magnetic Field (2)

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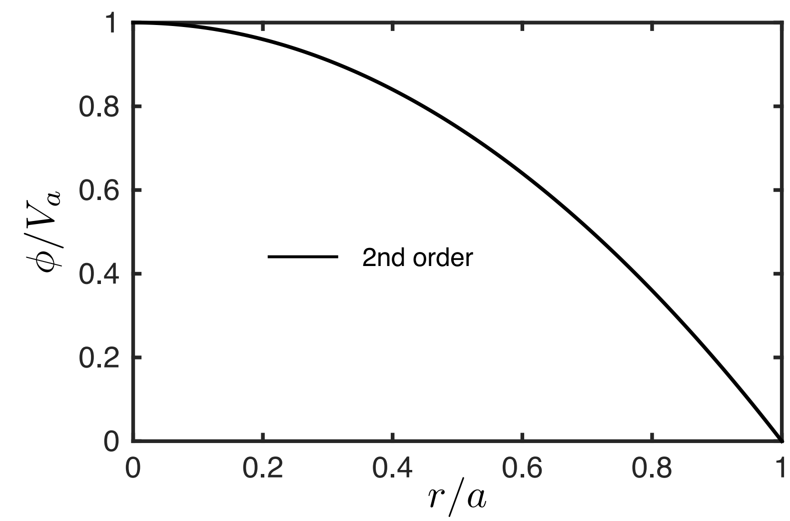
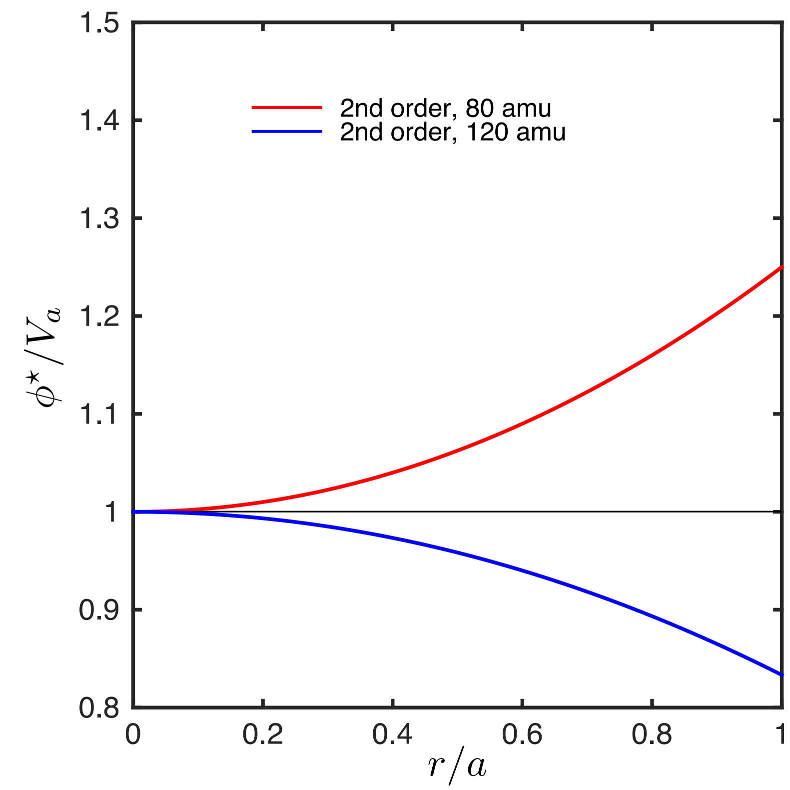
Take a parabolic profile $\phi(r) = \alpha(1 - r^2)$ (solid body rotation), and write $\alpha = q{B_0}^2/(8m^\diamond)$. Then

$$\phi^\star = \frac{q{B_0}^2}{8mm^\diamond}(m^\diamond - m)r^2 \quad \hookrightarrow \quad \text{Light ions confined, heavy ions unconfined}$$



(a) Laboratory potential $\phi(r)$



(b) Effective potential $\phi^\star(r)$

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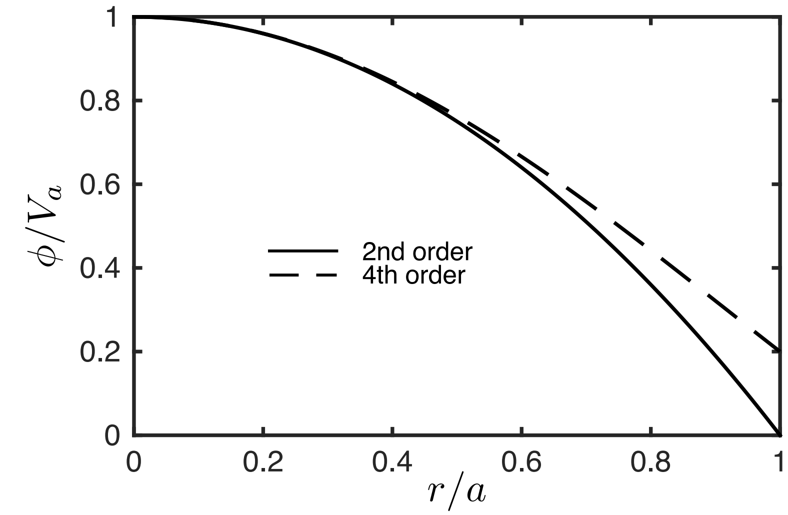

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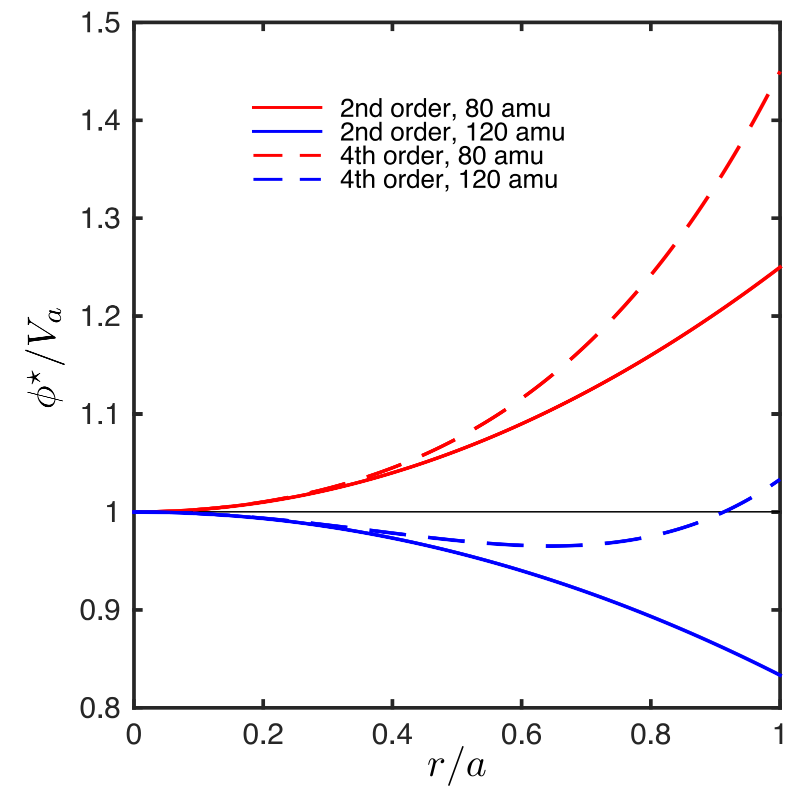
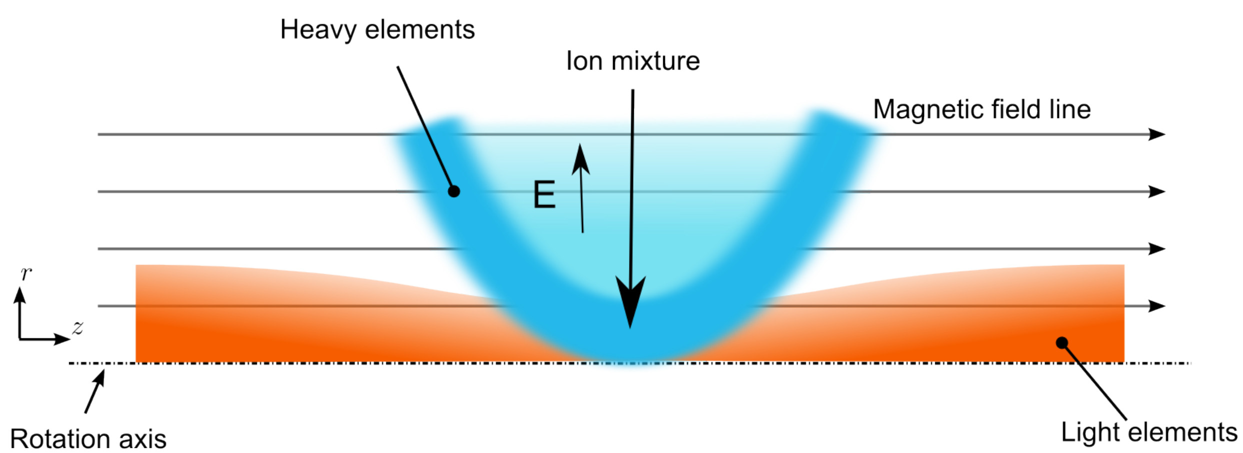


(b) Effective potential $\phi^{\star}(r)$

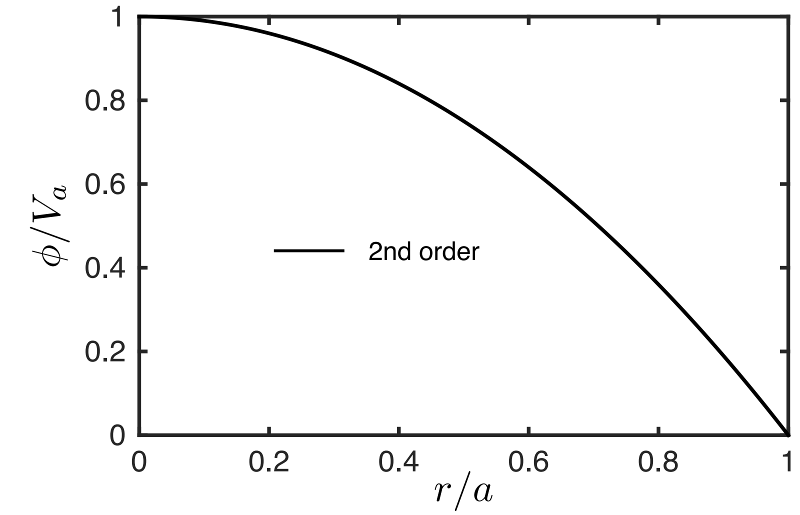
Higher order potential profile in the lab frame can be used to create wells in effective potential. The well radial position depends on the ion mass.

Laplace

Axial - radial separation in parabolic profile
Solid body rotation



Ohkawa and Miller (2002), Phys. Plasmas, **9**, 5116



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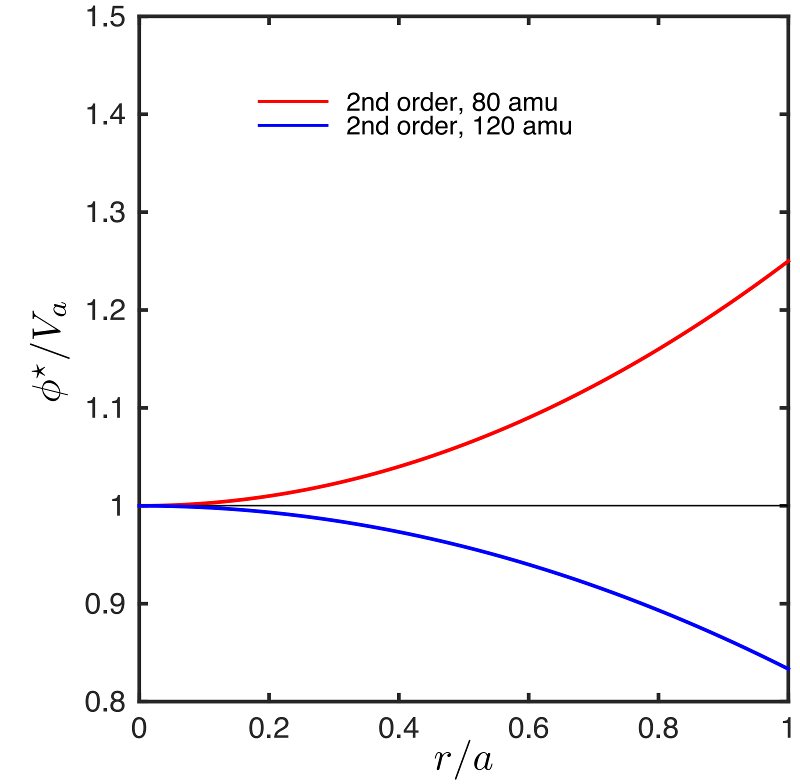
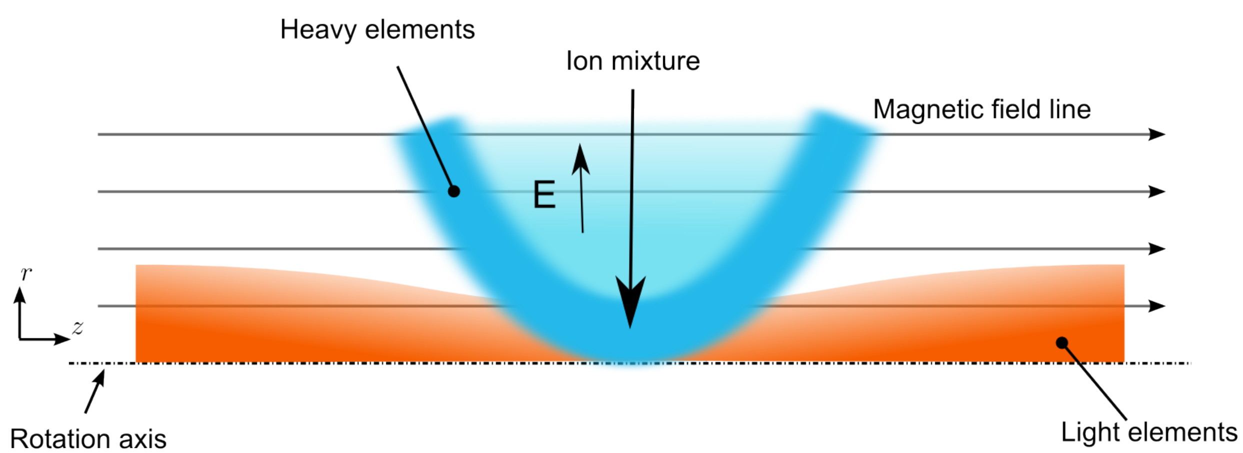


(b) Effective potential $\phi^\star(r)$

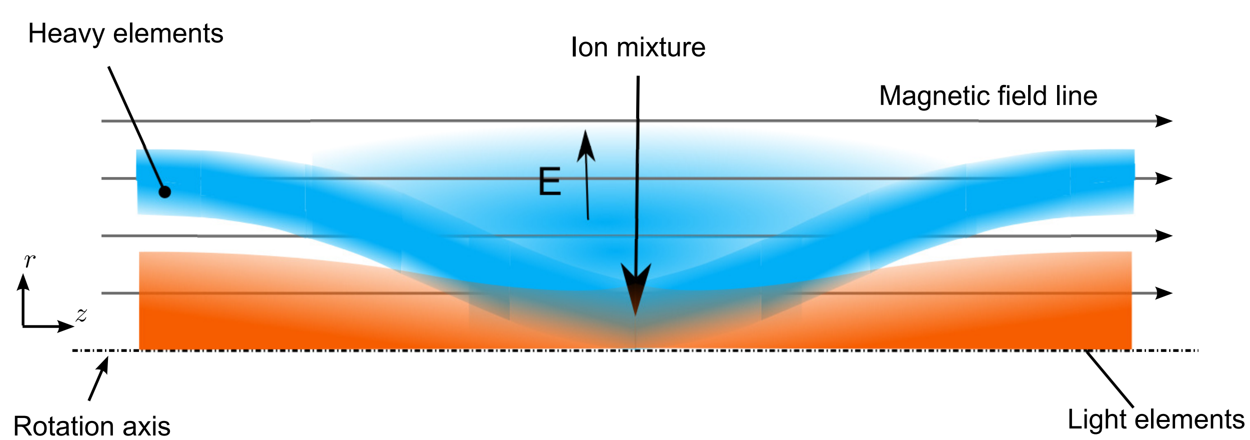
ExB Separators in Uniform Axial Magnetic Field

Axial - radial separation in parabolic profile
Solid body rotation

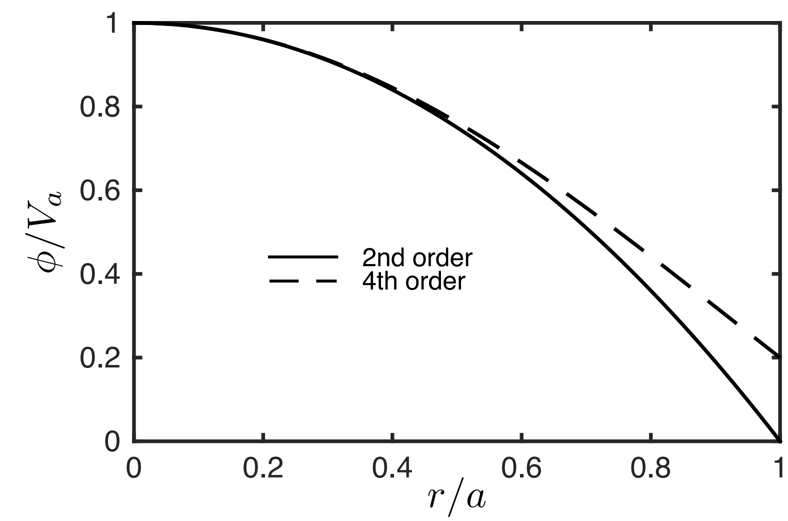


Ohkawa and Miller (2002), Phys. Plasmas, **9**, 5116

Axial - Axial separation with a 4th order potential
Sheared rotation



Gueroult *et al.* (2014), Phys. Plasmas, **21**, 02070



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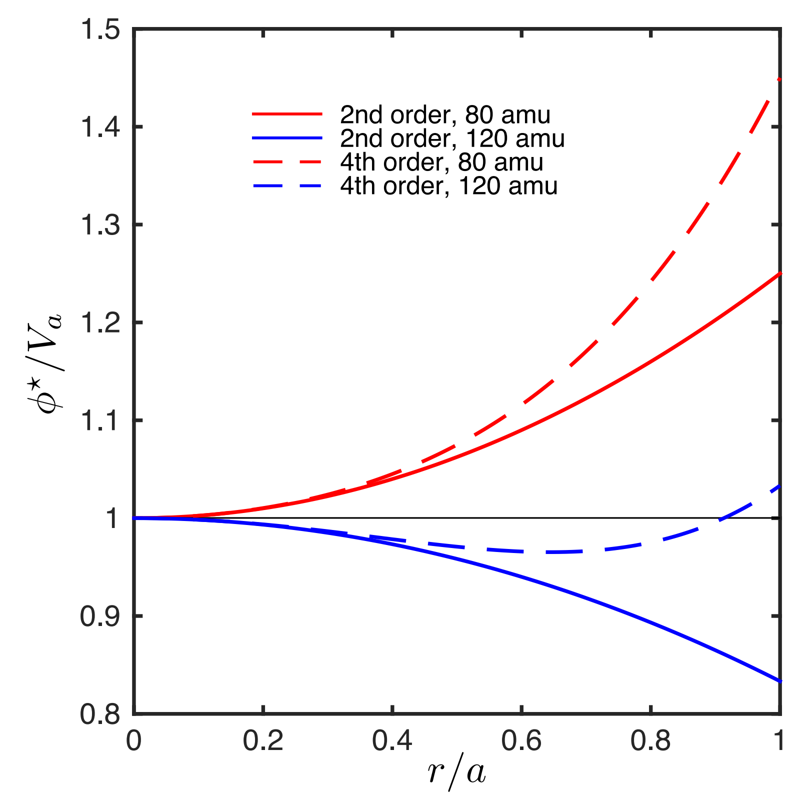

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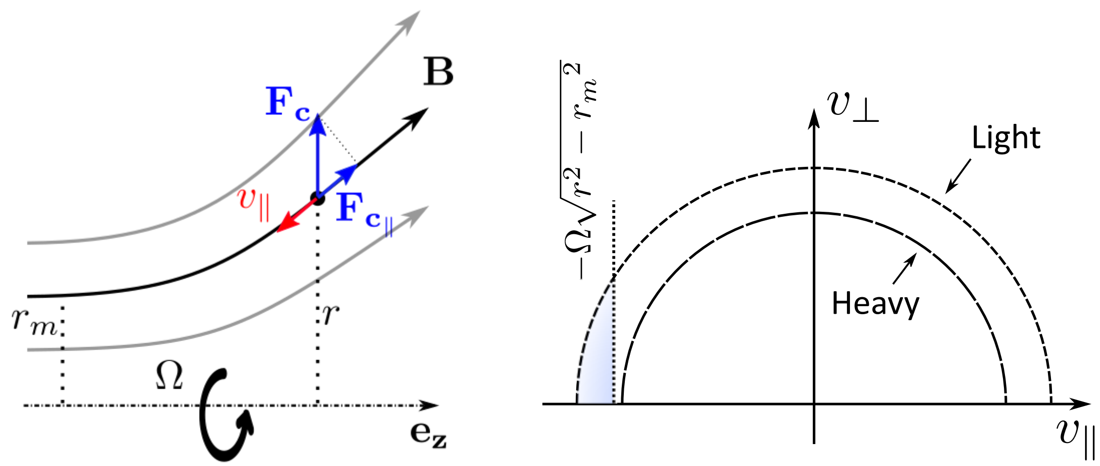
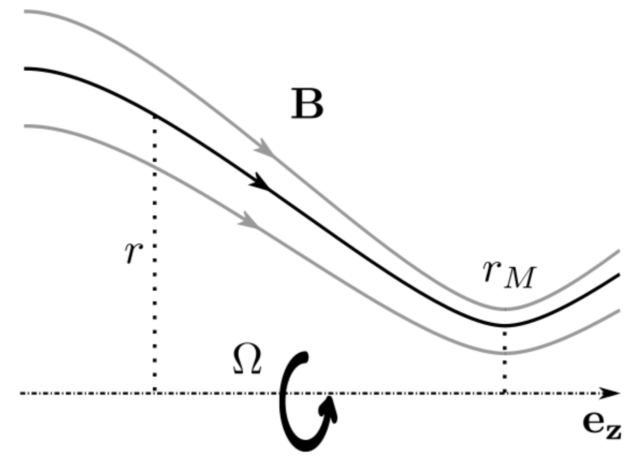


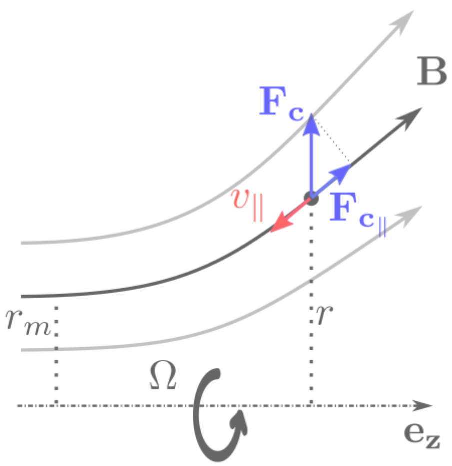
Iso-rotation states $\Omega = cst$ along a field line.

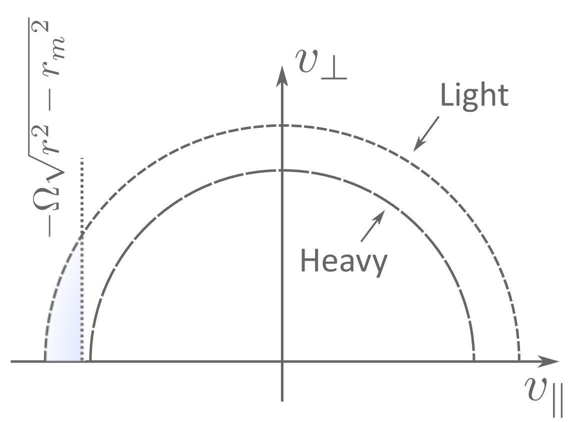
$\hookrightarrow$ there is a centrifugal potential barrier $m\Omega^2(r^2 - {r_m}^2)/2$.

Gueroult *et al.* (2018), Plasma Phys. Controlled Fusion, **60**, 014018

What Happens in a More General Field $B_r\mathbf{e_r} + B_z\mathbf{e_z}$







Iso-rotation states $\Omega = cst$ along a field line.

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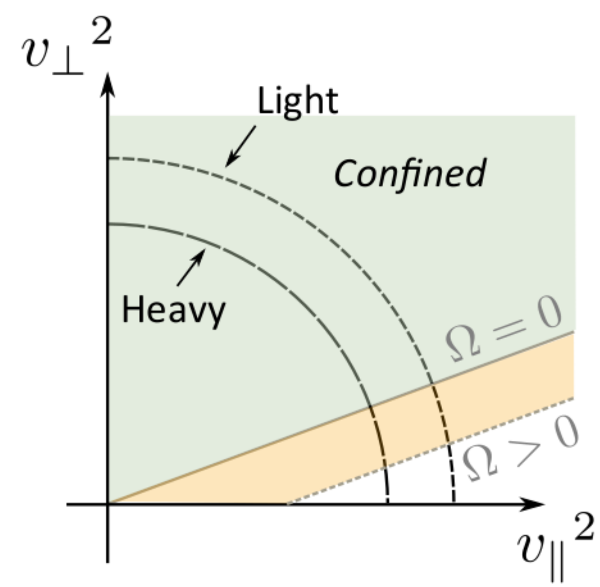
$${v_\parallel}^2 \leq (r\Omega)^2\left(1 - \frac{{r_M}^2}{r^2}\right) + {v_\perp}^2\left(\frac{B_M}{B} - 1\right)$$

Rotation

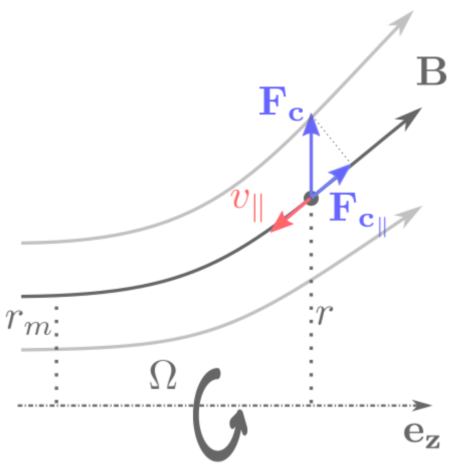
$r_M/r < 1$

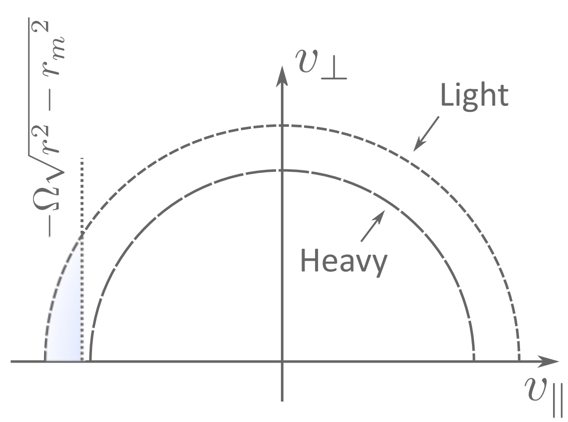


Rotating mirror:
enhanced confinement
loss "cone" ↘ m

Gueroult *et al.* (2018), Plasma Phys. Controlled Fusion, **60**, 014018

What Happens in a More General Field $B_r\mathbf{e_r} + B_z\mathbf{e_z}$





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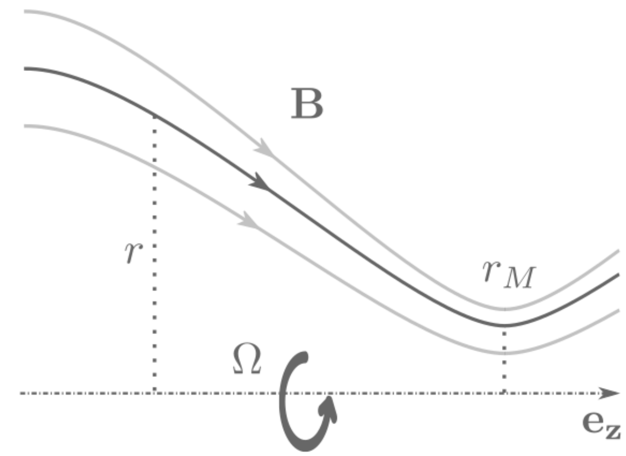

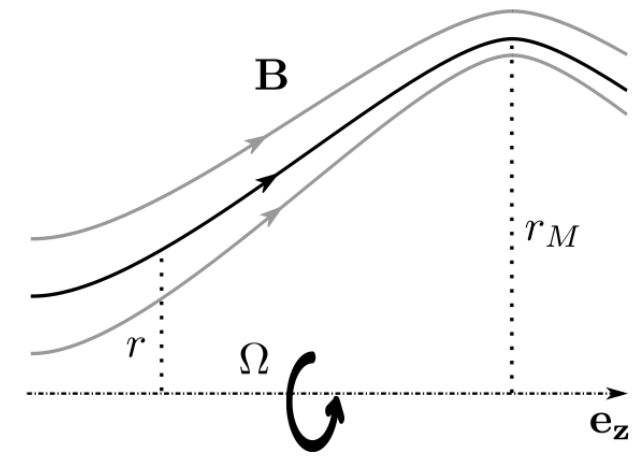

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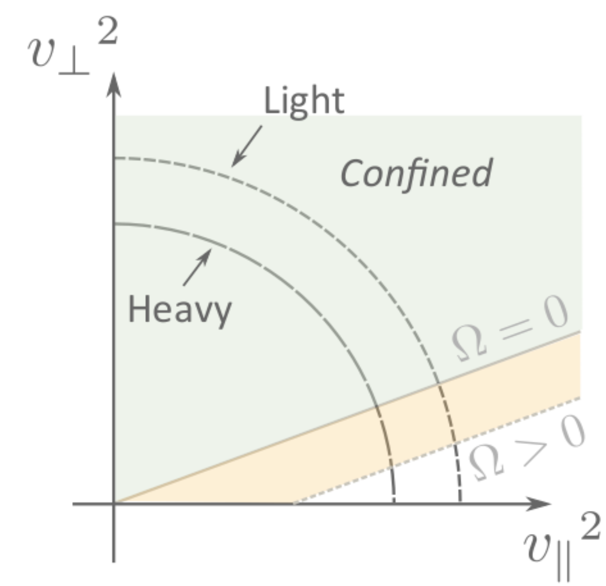
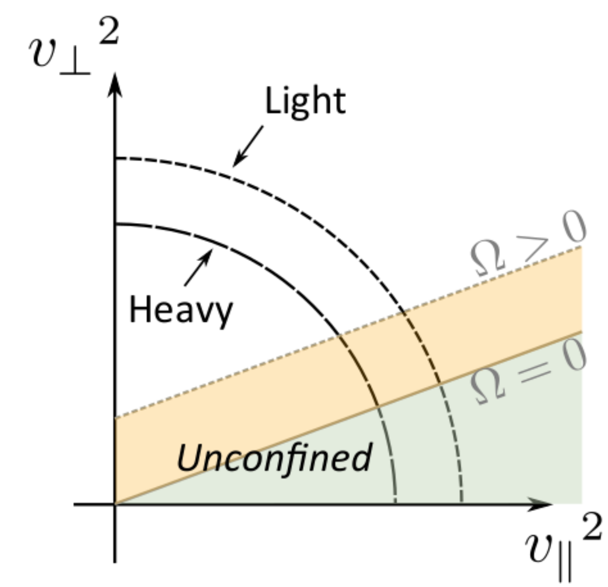


Rotating mirror:
enhanced confinement
loss "cone" ↘ m

$r_M/r > 1$

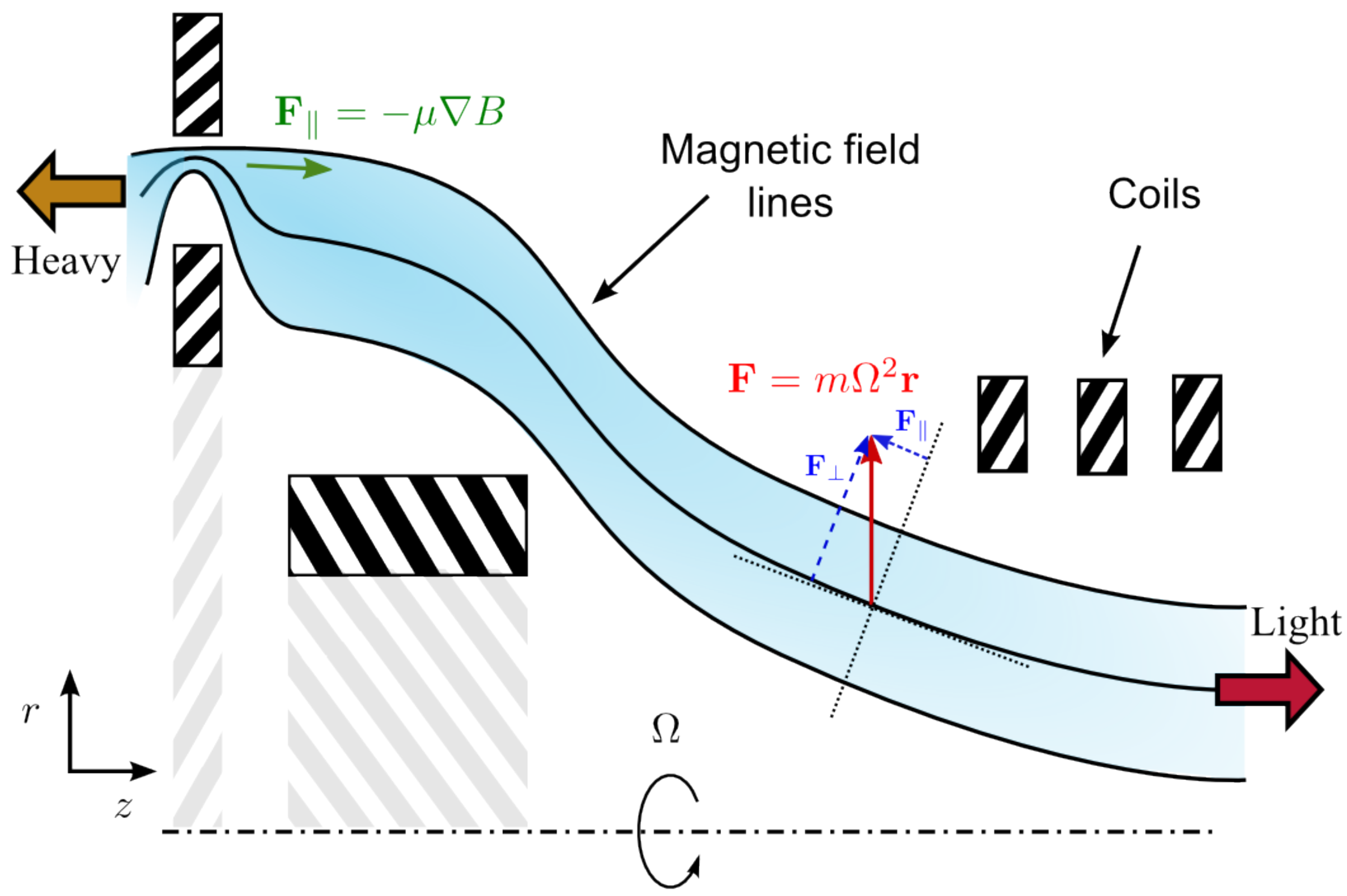


Separation:
degraded confinement
loss "cone" ↗ m

Gueroult *et al.* (2018), Plasma Phys. Controlled Fusion, **60**, 014018

Axial - Axial separation in an symmetric rotating plasma

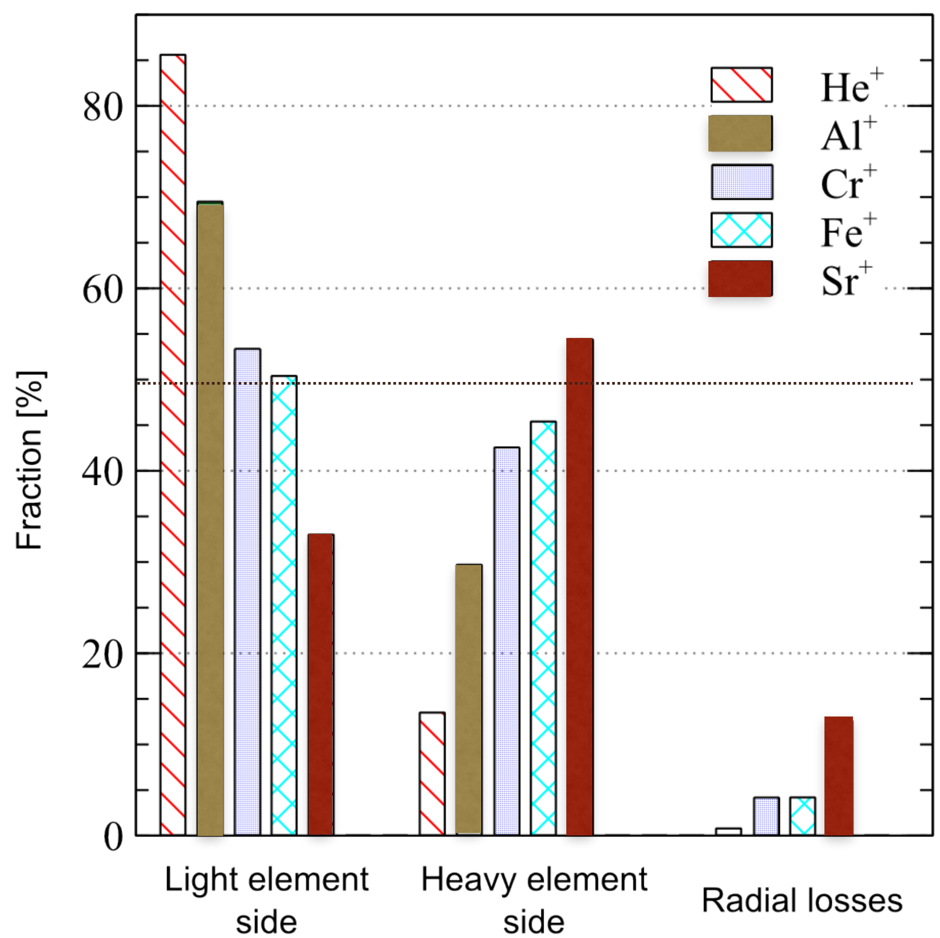
The Magnetic Centrifugal Mass Filter



Fetterman and Fisch (2011), Phys. Plasmas, **18**, 094503

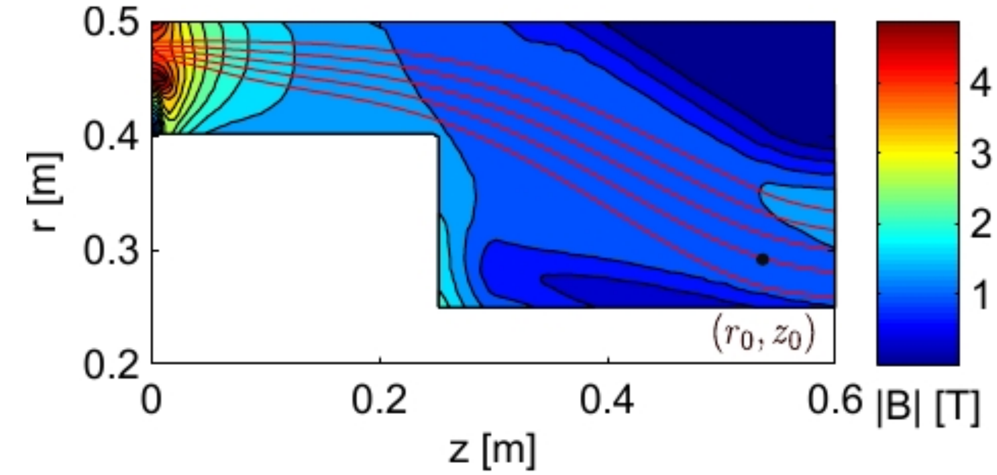
Gueroult and Fisch (2012), Phys. Plasmas, **19**, 122503

Preliminary estimates for separation efficiencies in the MCMF device

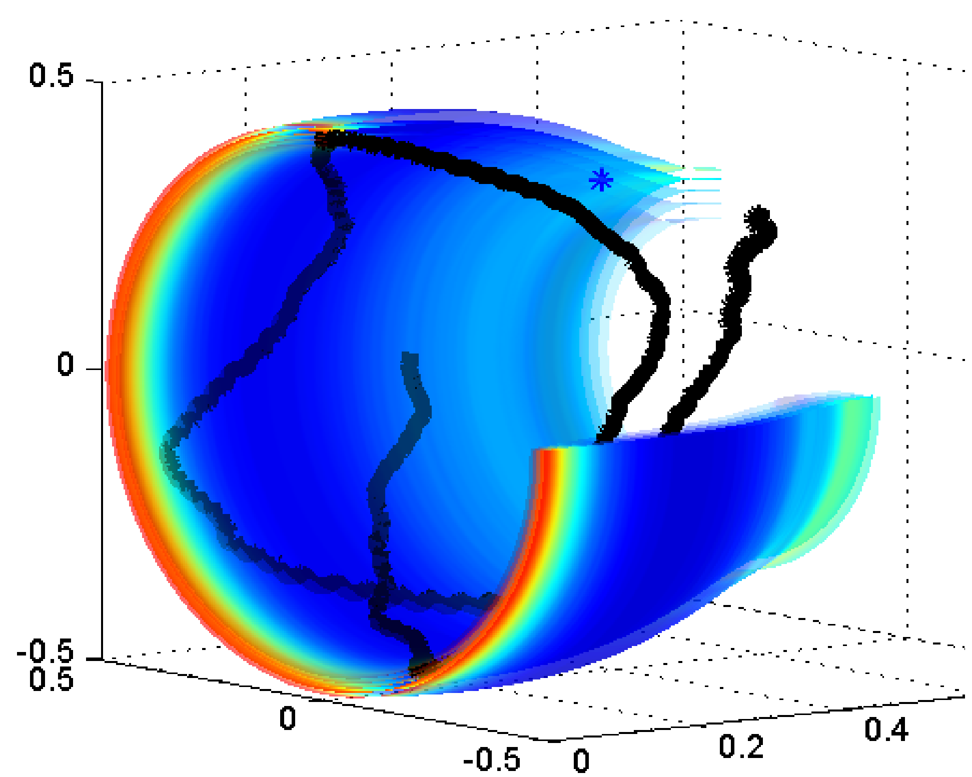


$$n_e = n_i = 1.5\ 10^{12}\ \text{cm}^{-3}$$

$$T_i = 20\ \text{eV}, T_e = 2\ \text{eV}, v_{\mathbf{E}\times\mathbf{B}} = \ 8.5\text{km. s}^{-1}$$



Magnetic field map used as a simulation input, and ion (144 amu) trajectory in the 3D field with collisions (^{241}Am).



Rotating, and more generally crossed-field, plasma configurations are only a subset of the many options plasmas offer for mass separation. Yet, these concepts already reveal a common set of scientific and technological challenges. To name a few:

Zweben, Gueroult and Fisch (2018), Phys. Plasmas, **25**, 090901

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- Separation is generally based on the ion charge to mass ratio *Ze/m*

  → *Need to get as close as possible to uniform charge state, which is challenging in mixtures.*

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- For each filter concept, separation is conditioned upon a suitable collisionality regime

  → *Need to control plasma parameters, in particular neutral and plasma densities and* T_i.

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- Separation is generally based on the ion charge to mass ratio *Ze/m*

  → *Need to get as close as possible to uniform charge state, which is challenging in mixtures.*

- For each filter concept, separation is conditioned upon a suitable collisionality regime

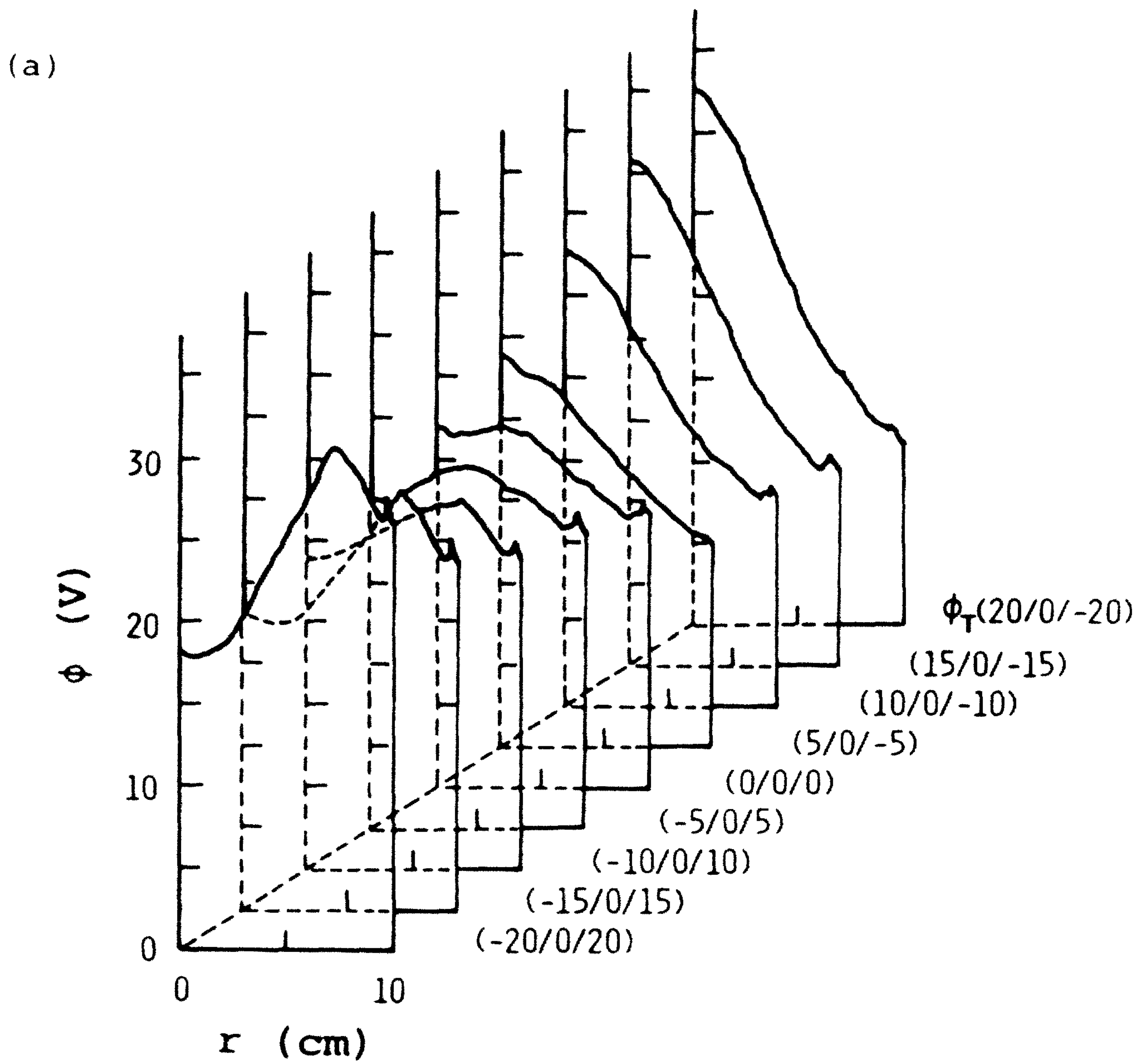
  → *Need to control plasma parameters, in particular neutral and plasma densities and* T_i.

- Each ExB filter concept requires a particular perpendicular electric field

  → *Need to control the perpendicular electric field for plasma parameters derived from other constraints.*

n	T_i	T_e	E
10^{13} cm^{-3}	10-100 eV	1-5 eV	20 V/cm

Tsushima *et al.* (1986), Phys. Rev. Lett., **56**, 1815



Successful in creating positive and negative electric field using three ring electrodes in an ECR plasma in mirror geometry.

n	T_i	T_e	E
~1/50	~1/100	~1	~1/10

Relative to values targeted for separation