IN MEMORIAM

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Research areas Grigory Pereverzev

- …….

- Current drive in magnetized plasmas

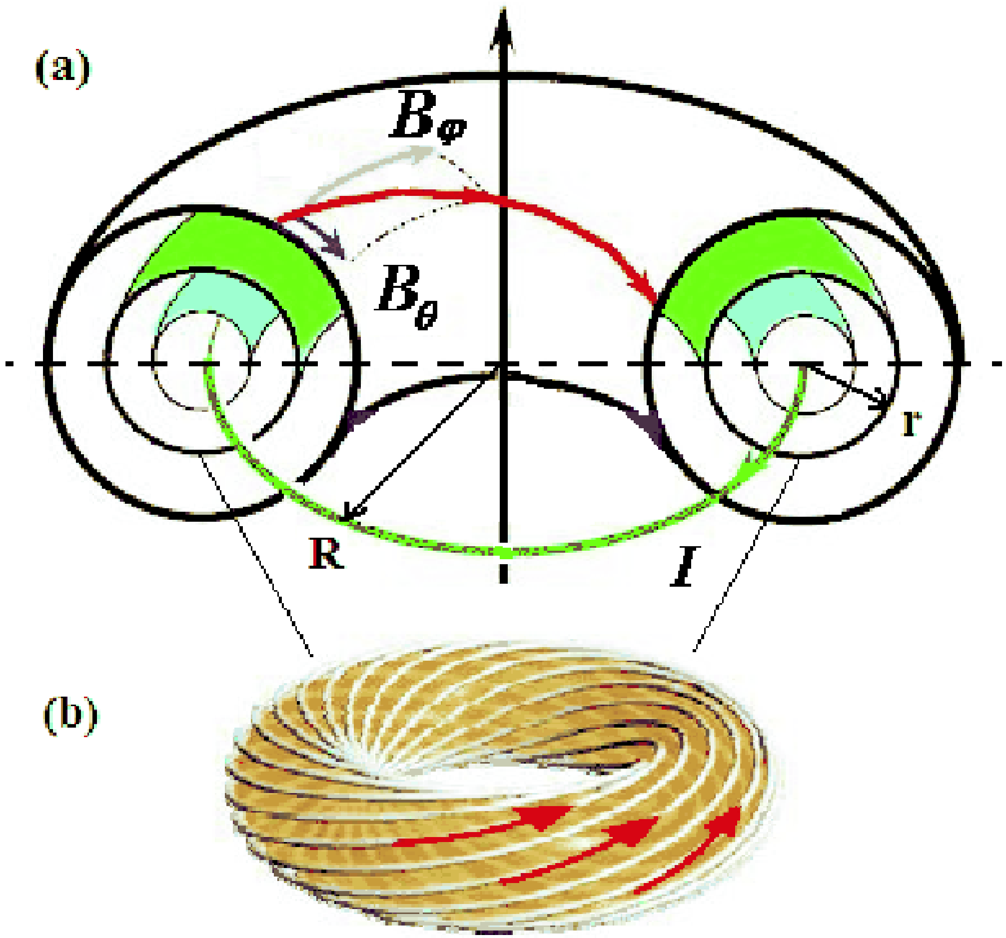
- Transport (ASTRA transport code)

- Wave propagation in inhomogeneous anisotropic media including refraction and diffraction

Some definitions

Toroidal direction: the long way around the donut

Poloidal direction: the short way around the donut



Current drive efficiency

- A photon carries momentum and energy E= $\hbar\omega \quad p = \hbar\, k$
- Absorption (wave vector along the magnetic field) generates an electron energy and momentum
  $\mathrm{E_k} = m v_{||} \Delta v_{||} \qquad p_k = m \Delta v_{||}$
- This momentum source generates a current that is reduced by the electron ion collisions

$$mn\frac{dv}{dt} = \frac{dN}{dt} p_k - mn\nu_{ei}(u_e - u_i)$$

- Current drive efficiency

$$J_{||} = \frac{e p_k}{m \nu_{ei}} \frac{dN}{dt} = \frac{e}{m v_{||} \nu_{ei}} P$$

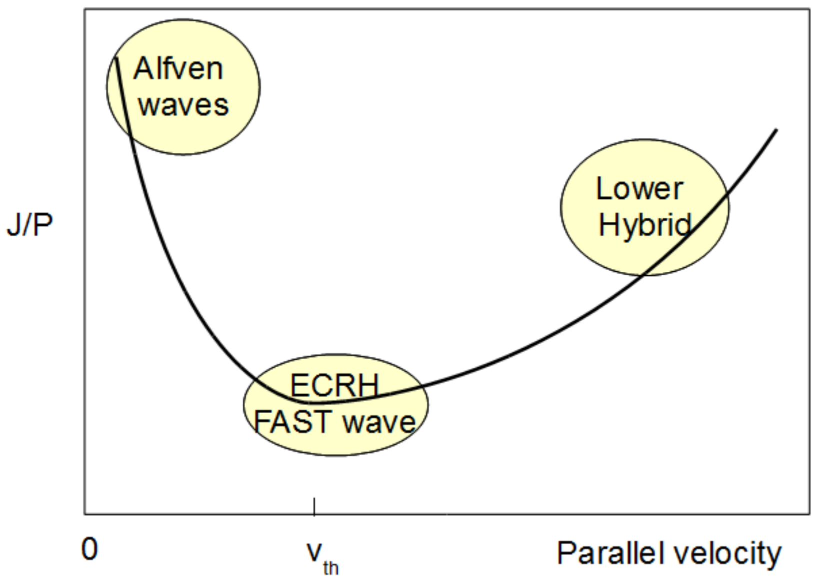


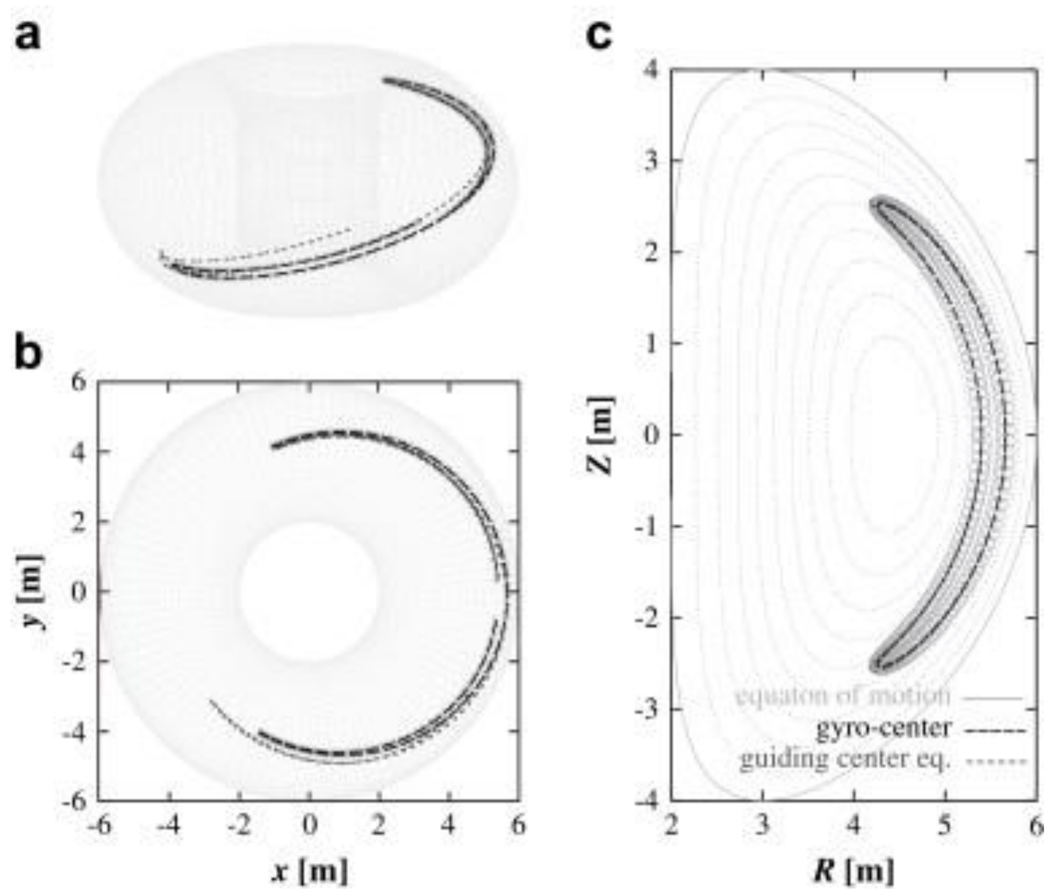
Figure: Schematic picture of the dependence of the current drive efficiency J/P as a function of the parallel velocity. Both low as well as high resonant velocities can lead to high efficiencies.

The problem: trapped particles

- Magnetic moment and kinetic energy are conserved

$$\mu = \frac{m\, v_\perp^2}{2B} \qquad E = \frac{1}{2} m v_{||}^2 + \frac{1}{2} m v_\perp^2$$

- In a tokamak the magnetic field strength increases towards the inside of the torus
- Some particles are trapped and bounce back and forth in the magnetic well → They do not carry any net averaged momentum



Most resonant particles are trapped

- Trapped particles occupy a region in velocity space for which the parallel velocity is small compared to the perpendicular velocity
- Because the phase velocity of the Alfven wave is small compared to the thermal velocity, most of the resonant particles are trapped.
- These particles can not carry the parallel current the wave is supposed to generate.

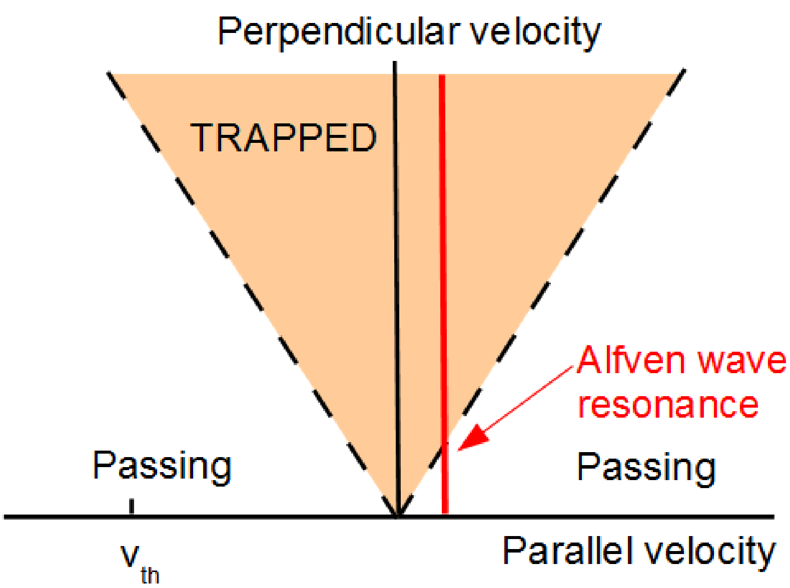


Figure: Trapped particle domain in velocity space. In red is indicated the Alfven wave resonance. Most of the particles that absorb energy from the wave are trapped.

Current drive efficiency reduced

- Assuming the trapped particles can not carry any current one finds a strong reduction in the current drive efficiency → Alfven wave current drive is not an acceptable scheme

- Is this correct? What about the transferred momentum. Is it simply lost?

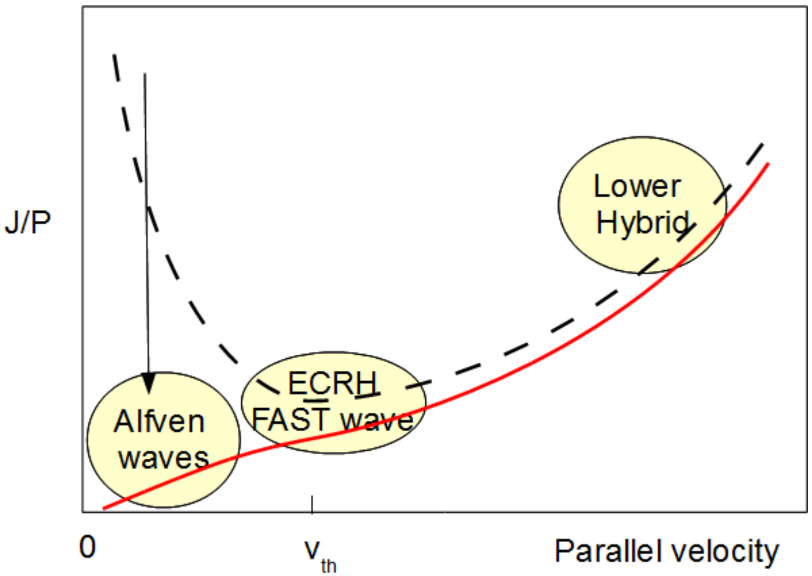


Figure: Schematic picture of the dependence of the current drive efficiency J/P as a function of the parallel velocity including the effect of trapped particles. The efficiency at low resonant velocities is strongly reduced.

Radial excursion of the orbit

- Besides the motion along the magnetic field there is a small drift perpendicular to the field generated by a perpendicular force
- The mirror force leads to the grad B drift

$$\boldsymbol{F} = -\mu \nabla B$$

$$\boldsymbol{v}_d = \frac{\boldsymbol{F} \times \boldsymbol{B}}{ZeB^2} = \frac{\mu}{Ze} \frac{\boldsymbol{B} \times \nabla B}{B^2}$$

- The drift leads to a small excursion from the surface

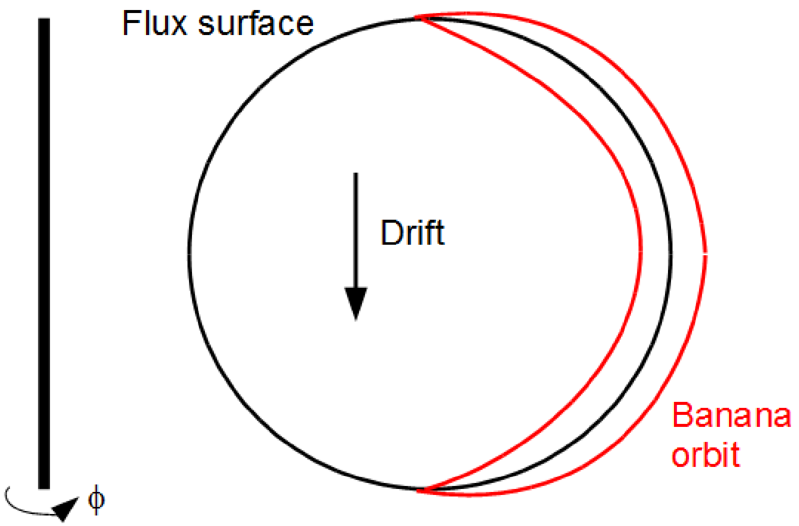


Figure: Schematic picture of a trapped particle orbit. Shown is the poloidal projection of the orbit.

Width of the orbit

- Width of the orbit can most easily be estimated using the conservation of canonical toroidal angular momentum

$$p_\phi = m v_{||} R - e\,\psi$$

- It follows that if you change the parallel velocity of the particle it shifts radially.

$$\Delta\psi = \frac{mR}{e}\Delta v_{||} = R B_p \Delta r$$

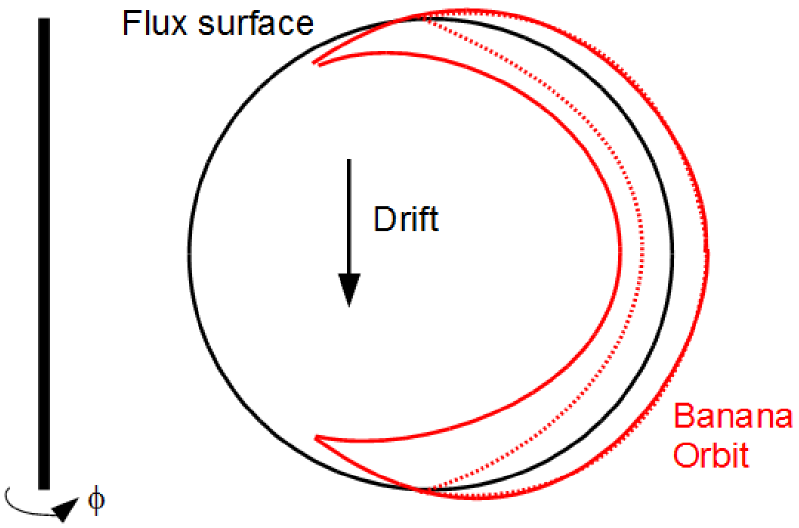


Figure: Schematic picture of the trapped particle orbit. When the parallel velocity is increased on the outboard side the orbit drifts inward.

The plasma is quasi-neutral

- If electrons are moved inward a second flow of charge is necessary to maintain quasi-neutrality
- This is provided by the polarization of the ions

$$\boldsymbol{F} = q\,\boldsymbol{E} \quad v_E = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

$$\boldsymbol{F} = -\frac{m\boldsymbol{B}}{B^2} \times \frac{\partial \boldsymbol{E}}{\partial t} \quad \boldsymbol{v}_{pol} = \frac{m}{eB^2}\frac{\partial \boldsymbol{E}_\perp}{\partial t}$$

- Demanding neutrality one can solve for the radial electric field

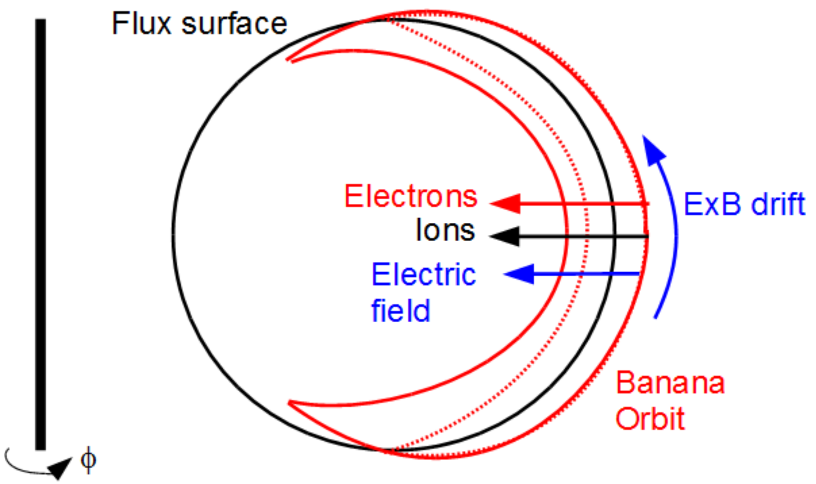


Figure: Inward motion of electrons must be balanced by an inward motion of ions to preserve quasi-neutrality

Toroidal rotation trapped orbit

- The ExB velocity is (mostly) in the poloidal direction
- For a trapped particle this however leads to toroidal rotation
- Simple derivation from force balance

$$q\boldsymbol{E} + q\,\boldsymbol{v} \times \boldsymbol{B} = 0$$

- Demand that the velocity is in the toroidal direction

$$E_r = v_\phi B_p \qquad v_\phi = \frac{E_r}{B_p}$$

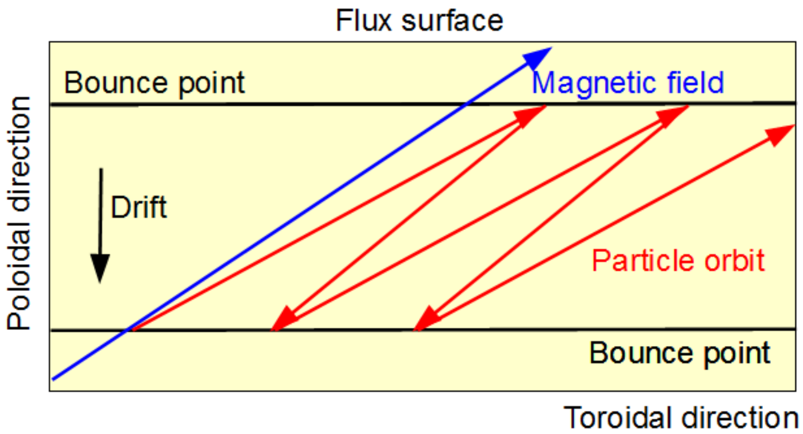
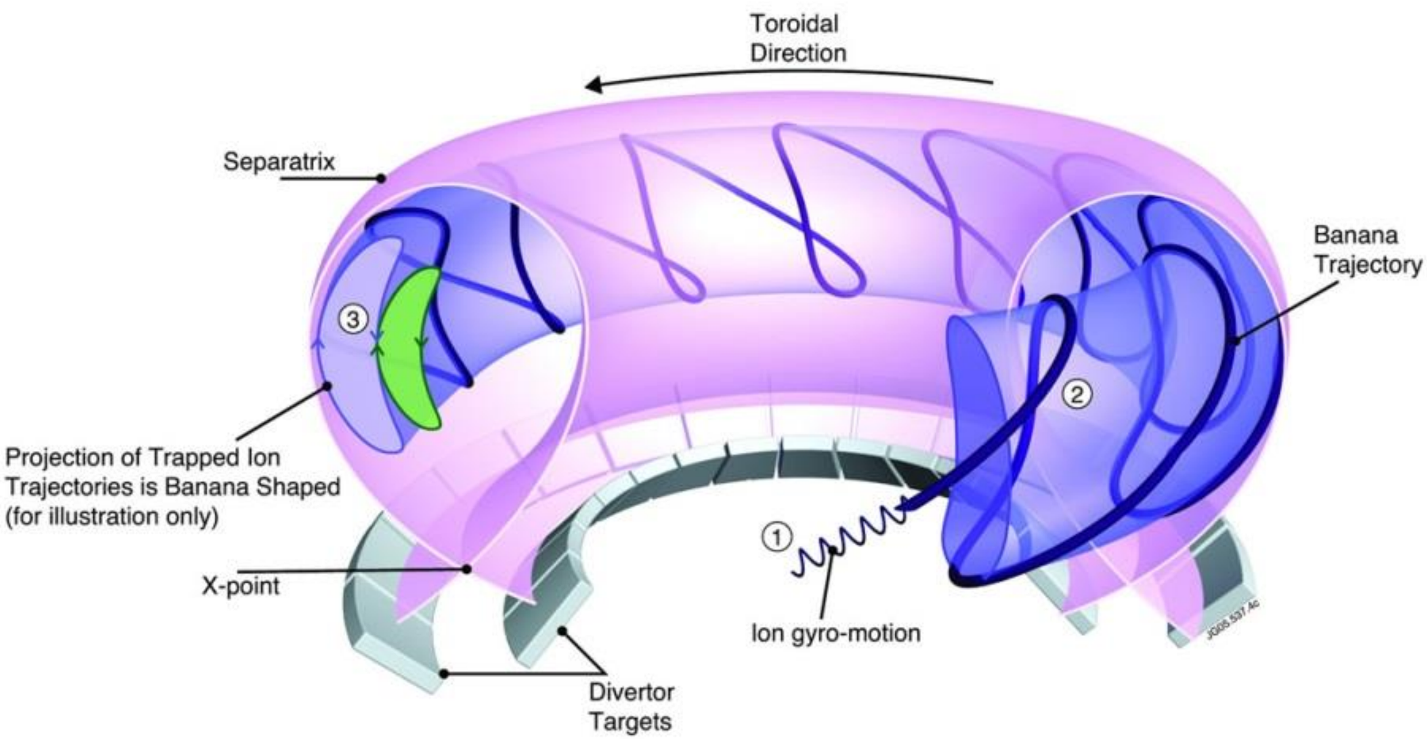


Figure: A poloidal ExB drift for trapped particles leads to a toroidal rotation (that is in fact larger than the ExB velocity itself)

Parallel momentum to trapped electrons

- Is transferred to a global motion of trapped ions and electrons around the torus



Momentum conservation?

- Using the above no momentum conservation is obtained. The polarization must be modified
- The averaged parallel velocity of trapped particles is nonzero

$$\langle v_\phi \rangle = \frac{E_r}{B_p} \gg v_E$$

- Averaging the canonical momentum over the orbit

$$\frac{mR}{B_p}\frac{\partial E_r}{\partial t} = e\frac{\partial \psi}{\partial t} = eRB_p v_{pol}^{Nc}$$

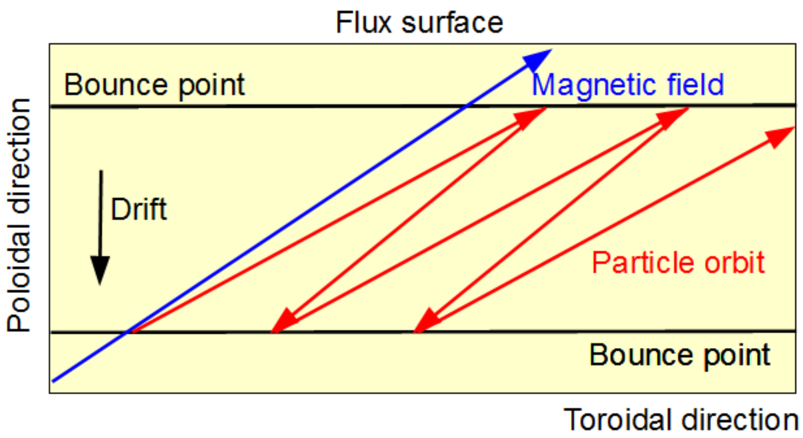


Figure: A poloidal ExB drift for trapped particles leads to a toroidal rotation (that is in fact larger than the ExB velocity itself)

Momentum conservation

- Transfer momentum to a trapped electron leads to a radial shift of the orbit

$$m_e \Delta v_{||} \quad \rightarrow \quad \Delta r = \frac{m_e \Delta v_{||}}{e B_p}$$

- An electric field builds up that moves trapped ions in the same direction

$$\sqrt{\epsilon} m_i n_i \int v_{pol}^{NC} \, dt = \frac{\sqrt{\epsilon} m_i n_i E_r}{e B_p^2} = \frac{m_e \Delta v_{||}}{e \, B_p}$$

- The electric field that follows from the neutrality equation above corresponds to a total toroidal momentum in the trapped ion population of

$$P_i = \sqrt{\epsilon} m_i n_i \frac{E_r}{B_p} = m_e \Delta v_{||}$$

Conclusions

- Trapped particles reduce the current drive efficiency
  - Parallel momentum given to trapped particles lead to a shift of the orbit in the radial direction
  - An electric field builds up which can be calculated from the polarization if one demands neutrality
  - The electric field rotates the trapped ions (an electrons) in the toroidal direction
- The momentum intended for current drive goes into an toroidal rotation of trapped ions
- On longer timescales collisional exchange between trapped and passing particles must be considered.
- To obtain exact momentum conservation one has to consider neo-classical effects in the polarization drift.