On Current Drive and Wave Induced Bootstrap Current in Toroidal Plasmas

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Large bootstrap currents and non-inductive current drive are instrumental for steady state operation of tokamaks.

To use waves with low phase velocity resonating with particles with low parallel velocities to drive current was proposed by Wort [Plasma Phys. 1971]; however, a large fraction of the power is absorbed on trapped particles, and results in a low current drive efficiency [R.J. Bickerton, 1975].

Recent FWCD experiments at JET demonstrated a larger current drive than modelled [T. Hellsten et al., Nuclear Fusion 2005]. Can this discrepancy be explained by power absorbed on trapped particles? Or transport by wave-particle interaction?

New Monte Carlo operators consistent with neoclassical transport.

Two mechanisms for recovering momentum on trapped particles for current: change in the bootstrap current by the RF-induced transport and selective detrapping of trapped particle orbits.

Neoclassical collision operator

How do we model neoclassical transport with Monte Carlo codes, where the drift orbits of individual particles are followed?

Changing the weights of the markers for δf-methods such that momentum and energy is conserved [Z. Lin, W.M. Tang and W.W. Lee, Phys. Plasmas **2** 2975 (1995).].

For full *f* – Monte Carlo methods, binary collisions to conserve momentum and energy have been used in conjunction with including the **E**×**B**-drift caused by charge separation [J. Heikkinen, *et al.*, Journal of Computational Physics **173** 527 (2001)].

New approach, based on quasi-neutrality, suitable for orbit averaged Monte Carlo operators in the banana regime.

The effect of the E×B-drift is calculated along unperturbed orbits.

Outline of the talk

Collisions operator consistent with neoclassical particle transport in the banana regime.

"Radial electric fields" at strong gradients and losses.

Effects of transport arising from wave-particle interactions on radial electric fields and bootstrap currents.

Two new mechanisms for recovering momentum absorbed on trapped particles for current drive, important for mode conversion current drive and FWCD.

Trapped and passing orbits

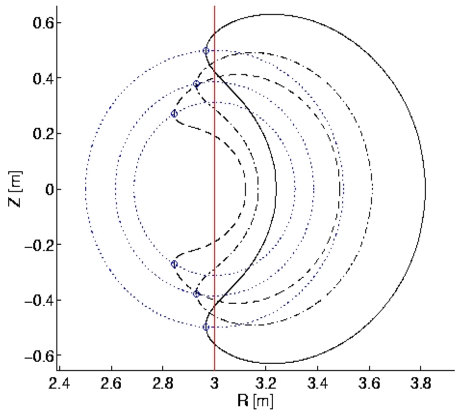
In an axisymmetric torus the canonical angular momentum, $P_\phi = mRv_\phi + Ze\psi$, is an invariant of motion.

The turning points of a trapped orbit are given by $v_\phi = 0$; located at the poloidal flux surface $\psi_T = P_\phi/Ze$.

Changes in the angular momentum by collisions or wave-particle interactions result in changes in the turning points by $\Delta\psi_T = \Delta P_\phi/Ze$; essentially due to changes in the parallel velocity.

Changes in the perpendicular velocity of a trapped particle change the width of the orbit, and to a less extent the turning points.

Passing orbits stay close to a flux surface.



Effects of Collisions (like particles)

Collisions between passing particles: Their parallel velocities changes such that the averaged toroidal velocity is conserved and they remain close to the same flux surface.

Collisions between trapped particles: Their turning points are displaced without changing the average position of the particles.

Collisions between trapped and passing particles: The trapped particle will change its averaged position in the plasma and the passing will remain at the same flux surface but change its parallel velocity.

Thus, like particle collisions can lead to a spatial transport of the trapped particles and a corresponding acceleration of the passing ones such that the total canonical momentum is conserved.

Radial electric field

For a peaked density profile ion-ion collisions lead to a net outward transport of trapped ions and a toroidal acceleration of the passing ions in the co-current direction.

The outward transport of the ions, without a corresponding fast transport of the electrons, result in an electric field directed inward.

The radial electric field results in a toroidal precession of the trapped ions (and electrons) with a velocity $v_\phi = E_r/B_\theta$ in the counter-current direction.

The passing ions will have a net averaged parallel velocity opposite to the precessing trapped particles.

Radial Electric Field and Precession of Trapped orbits

The difference in the averaged parallel velocities of the trapped and passing ions results in a friction between the two classes of particles.

The friction produce an inward displacement of the trapped ions and a reduction of the averaged parallel velocity of the passing ions.

$$\Delta\psi_{\mathrm{T}} = mR\Delta\upsilon_{\phi}/Ze$$

In steady state the radial electric field will grow up until the radial flux due to diffusion of the trapped ions from the collisions with the passing ions is balanced by the friction.

Neoclassical Electric Field

In the standard neoclassical theory the radial electric field is given by

$$V_{i\parallel}^{(0)} = -\frac{IT_i}{m_i\Omega_i}\left\{\frac{1}{p_i}\frac{\partial p_i}{\partial\psi} + \frac{Z_i e}{T_i}\frac{\partial\Phi}{\partial\psi} - 1.173\, f_c\left(\frac{B}{B_0}\right)^2 \frac{1}{T_i}\frac{\partial T_i}{\partial\psi}\right\}$$

To relate it to the previous formulation we rearrange the terms

$$V_{i\parallel}^{(0)} - \frac{B_\phi}{B}\frac{E_r}{B_\theta} = -\frac{T_i}{Z_i e}\frac{RB_\phi}{B}\left\{\frac{1}{n_i}\frac{\partial n_i}{\partial\psi} - \left(1.173\, f_c\left(\frac{B}{B_0}\right)^2 - 1\right)\frac{1}{T_i}\frac{\partial T_i}{\partial\psi}\right\}$$

Which is the difference between the averaged parallel velocity of the passing ions and the parallel component of the toroidal precession of the trapped ions.

Model the collisions by shifting $V_{if\parallel}^{(0)} = \frac{B_\phi}{B} R\Omega_{if}(\psi)$ the parallel velocity of the test particle.

$$u_{if}(\psi) = R_0\Omega_{if}(\psi) = \frac{E_r}{B_\theta} - \frac{B}{B_\phi}V_{if\parallel}^{(0)}$$

Proposed Monte Carlo Operators for Coulomb collisions consistent with neoclassical transport

Use the Coulomb collisions operators calculated for a local Maxwellian background, Eriksson and Helander, Phys. Plasmas 1994.

$$\Delta W = \left\langle \mu_W^{(if)} \right\rangle \Delta t + \zeta_1 A_{WW}^{(if)}$$

$$\Delta \Lambda = \left\langle \mu_\Lambda^{(if)} \right\rangle \Delta t + \zeta_2 A_{\Lambda\Lambda}^{(if)} \qquad \Lambda = \mu B_0/W$$

$$\Delta P_\phi = \left\langle \mu_{P_\phi}^{(if)} \right\rangle \Delta t + \zeta_1 A_{P_\phi W}^{(if)} + \zeta_2 A_{\Lambda W}^{(if)} + \zeta_3 A_{P_\phi P_\phi}^{(if)}$$

Shift the parallel velocity of the test particle for trapped particles with $\upsilon_\parallel$ and for passing particles colliding with trapped particles. No shift for passing colliding with trapped.

$$\upsilon_\parallel = \Omega(\psi) R B_\phi / B$$

$\Omega(\psi)$ is in lowest order calculated from quasi-neutrality in the next order or from the collisional electron flux.

The Flux of Trapped Orbits

The diffusive flux of trapped ions colliding against passing ions

$$\Gamma^{(if)}_{\psi:D} \approx -\int_{\substack{trapped\\ \psi_T=\psi}} \frac{\left\langle \dot{\sigma}^{(if)}_{P_\phi P_\phi} \right\rangle}{2\left(Ze\right)^2} \left(\frac{1}{n}\frac{\partial n}{\partial \psi} + \left(\frac{W}{kT} - \frac{3}{2} \right) \frac{1}{T}\frac{\partial T}{\partial \psi} \right) FRB_\theta \sqrt{g}\, dW d\Lambda$$

where $\dot{\sigma}^{(if)}_{P_\phi P_\phi} = m^2 R^2 \left(B_\phi / B\right)^2 \left(\xi^2 \beta^{(if)} + \frac{1}{2}\left(1-\xi^2\right)\gamma^{(if)} \right)$ and $F(W,\Lambda,P_\phi;\sigma)$

The flux due to the friction between trapped and passing ions due to their difference in averaged parallel velocity from the precession

$$\Gamma^{(if)}_{\psi:d} \approx \frac{1}{Z_i e} \int_{\substack{trapped\\ \psi_T=\psi}} \left\langle \dot{\mu}^{(if)}_{P_\phi} \right\rangle_\tau F_{0i} RB_\theta \sqrt{g}\, dW d\Lambda$$

where $\dot{\mu}^{(if)}_{P_\phi} = m_i R \xi \left(B_\phi / B\right)\left(\alpha^{(if)} - \gamma^{(if)}/2\upsilon\right)$

The background f is a shifted Maxwellian $V^{(0)}_{i\parallel} = \frac{B_\phi}{B} R\Omega_{if}\left(\psi\right)$

Quasi-neutrality

The total flux of ions and electrons has to satisfy quasi-neutrality

$$\sum_{i=ions} Z_i \left\{ \sum_{f=ions} \left(\Gamma^{(if)}_{\psi:D} + \Gamma^{(if)}_{\psi:d} \right) + \Gamma^{(i)}_{\psi:RF} + \Gamma^{(ie)}_{\psi:D} + \Gamma^{(ie)}_{\psi:d} \right\} =$$

$$\sum_{i=ions} \left\{ \Gamma^{(ei)}_{\psi:D} + \Gamma^{(ei)}_{\psi:d} \right\} + \Gamma^{(e)}_{\psi:RF} + \Gamma^{(ee)}_{\psi:D} + \Gamma^{(ee)}_{\psi:d}$$

Expanding the collision operator in mass ratio $(m_e/m_i)^{0.5}$; quasi-neutrality gives due to the higher collision frequency for ion-ion collisions

$$\sum_{i=ions} Z_i \left\{ \sum_{f=ions} \left(\Gamma^{(if)}_{\psi:D} + u^{(0)}_{if} L^{(if)}_t \right) + \Gamma^{(i)}_{\psi:RF} \right\} - \Gamma^{(e)}_{\psi:RF} = 0$$

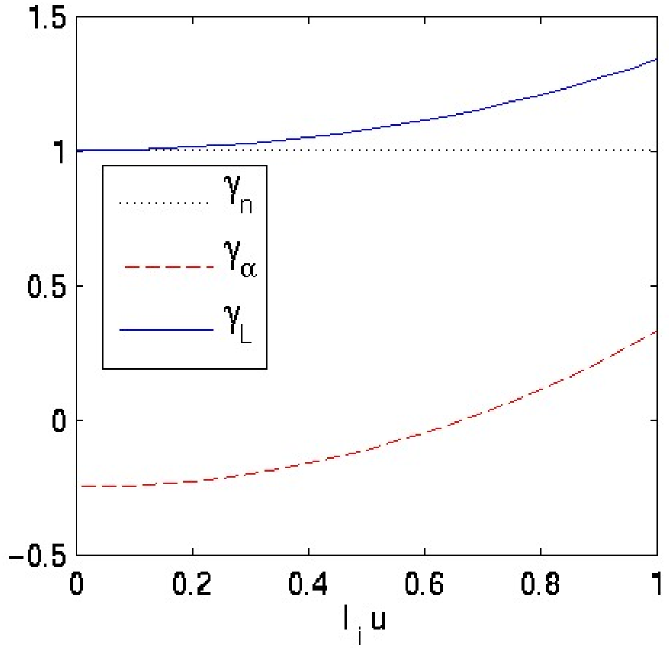
where $\Gamma^{(if)}_{\psi:d} \equiv u^{(0)}_{if} L^{(if)}_t$

$\upsilon_{\|\mathrm{if}} = R\Omega_{\mathrm{if}}(\psi)B_\phi/B$ and $u_{\mathrm{if}}^{(0)} = R_0\Omega_{\mathrm{if}}(\psi)$.

Radial Electric Field

$$u_i^{(0)} = u_{i_t i_p}^{(0)} = -\frac{\Gamma_{\psi:D}^{(ii)} + \Gamma_{\psi:RF}}{L_t^{(ii)}}$$

$$\Gamma_{\psi:RF} \equiv Z_i \Gamma_{\psi:RF}^{(i)} - \Gamma_{\psi:RF}^{(e)}$$



$$-u_i^{(0)} \equiv V_{i\parallel}^{(0)} - \frac{B_\phi}{B}\frac{E_r}{B_\theta} = -\gamma_n \frac{T_i R_0}{Z_i e n_i}\frac{\partial n_i}{\partial \psi} - \gamma_\alpha \frac{T_i R_0}{Z_i e T_i}\frac{\partial T_i}{\partial \psi} + \frac{\Gamma_{\psi:RF}}{Z_i e L_t^{(ii)}}$$

$$\gamma_L = L_t^{(ii)}(0) \big/ L_t^{(ii)}\left(l_i u_i^{(0)}\right)$$

We obtain $\gamma_n = 1$, $\gamma_\alpha(0) = -0.25$ standard neoclassical -0.17. γ_α and γ_L are non-linear function of $u_i^{(0)}$, radial electric field. γ_α changes sign for $l_i u_i = 0.67$ and can contribute to a stronger radial electric field. Bifurcated solutions.

Important for transport barriers

The Effect of Wave Induced Transport or Prompt Losses on the Radial Electric Field

$$-u_i^{(0)} \equiv V_{i\|}^{(0)} - \frac{B_\phi}{B}\frac{E_r}{B_\theta} = -\gamma_n \frac{T_i R_0}{Z_i e n_i}\frac{\partial n_i}{\partial \psi} - \gamma_\alpha \frac{T_i R_0}{Z_i e T_i}\frac{\partial T_i}{\partial \psi} + \frac{\Gamma_{\psi:RF}}{Z_i e L_t^{(ii)}}$$

Wave induced ion particle transport or prompt ion losses
or a reduction of the wave induced electron transport
increases $|u_i^{(0)}|$, radial electric field.

Wave induced electron transport reduces the radial electric field.

To be of significance the transport should be comparable to the neoclassical transport due to ion-ion collisions i.e. about 40 times the neoclassical particle transport.

Wave particle interactions

Wave-particle interaction both change the invariants of motion and displace the guiding centre. $\Delta \mathbf{x} = \left(\mathbf{k} \times \mathbf{B} / ZeB^2 \omega \right) \Delta W_{RF}$

Conservation of momentum $\Delta \left(m \upsilon_{||} \right) = \left(k_{||} / \omega \right) \Delta W_{RF}$

The changes in P_ϕ and Λ are related to the change in energy, ΔW_{RF}

$$\Delta P_\phi = \left(n_\phi / \omega \right) \Delta W_{RF}$$

$$\Delta \Lambda = \left(n \omega_{co} / \omega - \Lambda \right) \Delta W_{RF} / W$$

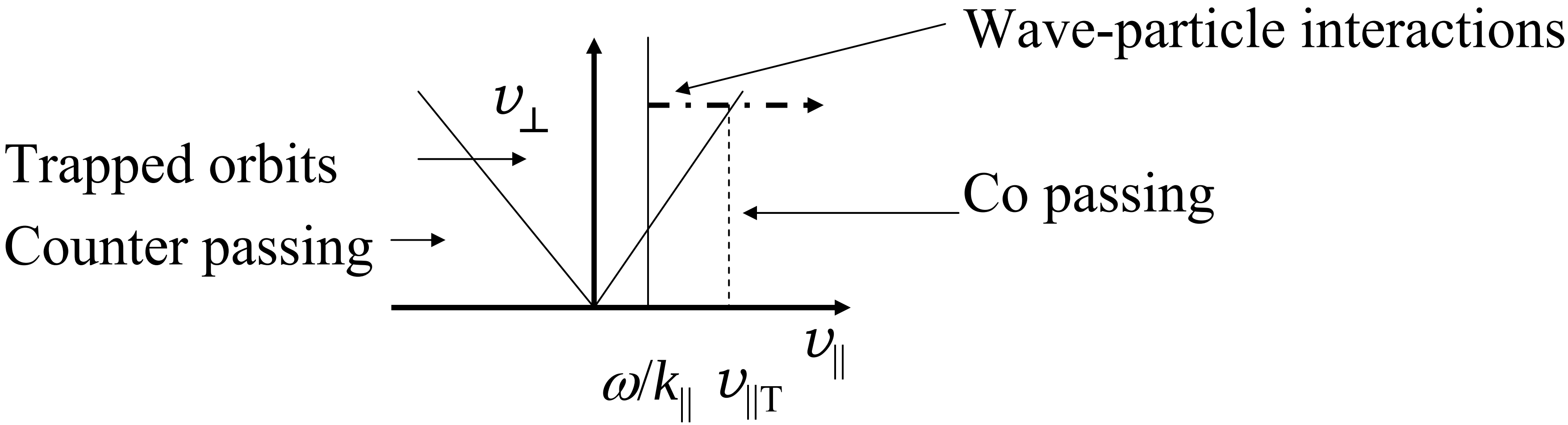
A change in P_ϕ results in displacements of of the turning points by:

$$\Delta \psi_T = \left(n_\phi / \omega Ze \right) \Delta W_{RF}$$

$$\Delta B_T / B_0 = - \Delta \Lambda_{RF} / \Lambda$$

For a circular cross-section: $\Delta \theta_T / B_0 = - \Delta \Lambda_{RF} R_T^2 / R_0 \Lambda r \sin \theta_T$

Selective Detrapping by ELD / TTMP



Change of current due to detrapping $\Delta j_\parallel = -e v_{\parallel T}$
Fraction of momentum absorbed on trapped particles leading to detrapping $\Delta v_\parallel/(v_{\parallel T} - \omega/k_\parallel)[\nu_{RF}/(\nu_C + \nu_{RF})]$
Averaged $\Delta j_\parallel = -e v_{\parallel T} \Delta v_\parallel/(v_{\parallel T} - \omega/k_\parallel))[\nu_{RF}/(\nu_C + \nu_{RF})]$

The change in current is of the same order as if it was directly absorbed on passing particles $\kappa = \xi_T \Big/ \left(\xi_T - \omega v / k_\parallel\right) \nu_{RF} \Big/ \left(\nu_{RF} + \nu_C\right)$

Particle Flux by Wave Particle Interactions

Wave-particle change ψ, and produce a flux of trapped particles across the flux surfaces (for symmetric detrapping).

$$\Gamma^{(i_t)}_{\psi:RF} = \frac{n_\phi}{Z_i e\omega\Delta\psi}\int_{i_t:\Delta\psi}\frac{\partial W^{(i_t)}_{RF}}{\partial t}F_i\sqrt{g}\,dW\,d\Lambda\,dP_\phi = \frac{n_\phi}{Z_i e\omega\Delta\psi}P^{(i_t)}_{\psi:RF}$$

and passing particles $\Delta\psi_{res} = \frac{\Delta W_{RF}}{Ze}\left[\frac{n_\phi}{\omega}\frac{B_\theta^2}{B^2} - \frac{m_\theta R}{\omega r}\frac{B_\theta B_\phi}{B^2}\right]_{res}$

Corresponding flux of passing particles

$$\Gamma^{(i_p)}_{\psi:RF} = \frac{1}{Z_i e\Delta\psi}\int_{i_p:\Delta\psi}\frac{\partial W^{(i_p)}_{RF}}{\partial t}\left[\frac{n_\phi}{\omega}\frac{B_\theta^2}{B^2} - \frac{m_\theta R}{\omega r}\frac{B_\theta B_\phi}{B^2}\right]_{res}F_i\sqrt{g}\,dW\,d\Lambda\,dP_\phi =$$

$$\frac{1}{Z_i e\Delta\psi}\left[\frac{n_\phi}{\omega}\frac{B_\theta^2}{B^2} - \frac{m_\theta R}{\omega r}\frac{B_\theta B_\phi}{B^2}\right]_{res}P^{(i_t)}_{\psi:RF}$$

Particle transport

The electron flux $\Gamma_{\psi}^{(e)} \approx \Gamma_{\psi:D}^{(ei)} + \Gamma_{\psi:D}^{(ee)} + u_{e_t i_p}^{(0)} L_t^{(e_t i_p)} + u_{e_t e_p}^{(0)} L_t^{(e_t e_p)} + \Gamma_{\psi:RF}^{(e)}$

The wave-particle interactions affect directly the electron transport by the RF-induced electron transport, $\Gamma_{\psi:RF}^{(e)}$ but also indirectly by the RF induced transport of ions through the change in $u_{ei}^{0} \approx u_{ii}^{0}$ which has only an effect of the order $(m_e/m_i)^{0.5}\,\Gamma_{\psi:RF}^{(i)}$.

For thin orbits

$$\Gamma_{\psi:D}^{(e)} + \Gamma_{\psi:d}^{(e)} \approx n_{et}\int_S \frac{dS}{|\nabla\psi|}\int_{\substack{trapped\\ \psi_T=\psi}} \left\{ \frac{-1}{4e^2}\left(2\left\langle \dot{\sigma}_{P_\phi P_\phi}^{(ei)}\right\rangle + \left\langle \dot{\sigma}_{P_\phi P_\phi}^{(ee)}\right\rangle\right)\left(\frac{1}{n}\frac{\partial n}{\partial\psi} + \left(\frac{W}{T_e}-\frac{3}{2}\right)\frac{1}{T_e}\frac{\partial T_e}{\partial\psi}\right) - \left(L_t^{(ei)} + \frac{1}{2}L_t^{(ee)}\right)u_i^{(0)}\right\} f_e d^3 v_e$$

In absence of RF this is the similar as the neoclassical transport

$$\Gamma_{\psi}^{(e)} \approx \frac{m_e^2 R_0^2}{2e^2}\frac{RB_\theta}{Z_i e B_0}\int_S \frac{dS}{|\nabla\psi|}\left\{-\left(C_{ei}\left(l_e^{-2} l_i^2\right) + C_{ee}\right)\left(1+\frac{T_i}{T_e Z_i}\right)\frac{1}{n}\frac{\partial n}{\partial\psi} + \right.$$

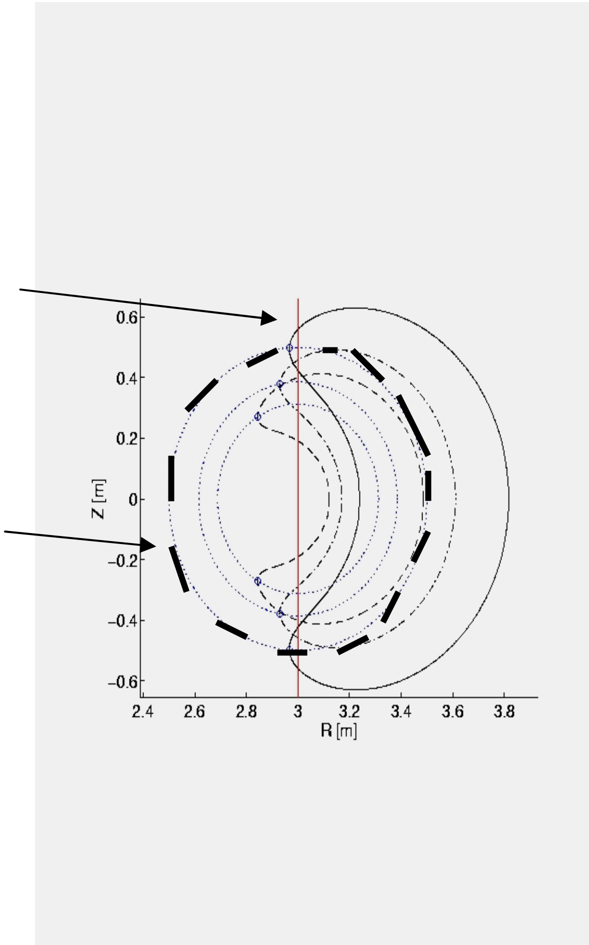
$$\left. + \left\{\frac{1}{2T_e}\left(C_{ei}\left(l_e^{-2} l_i^2\right) + C_{ee}\right)\left(\frac{2\gamma_\alpha}{Z_i}\frac{\partial T_i}{\partial\psi}\right) + \left(C_{ei}\left(l_e^{-2} l_i^2\right) + C_{ee}\right)\frac{\gamma_b}{T_e}\frac{\partial T_e}{\partial\psi}\right\}\frac{1}{2T_e}\right\} + \Gamma_{\psi:RF}^{(e)}$$

Neoclassical transport in a nut shell

The changes of the toroidal velocity as passing electrons collide with trapped ions, give the bootstrap current

trapped ion

passing electron



$$m_e R_0 \frac{n_e \partial u_{e_p i_t}^{(0)}(\psi)}{\partial t} = \frac{\partial P_\phi^{(e_p i_t)}}{\partial t}$$

$$= -\frac{\partial P_\phi^{(i_t e_p)}}{\partial t} = -Z_i e \Gamma_{\psi:C}^{(i_t e_p)} \approx -e\Gamma_{\psi:C}^{(e_t i_p)}$$

$$J_{bs} = -e n_e u_{e_p i_t}^{(0)}(\psi) \approx \frac{e^2 n_e \Gamma_{\psi:C}^{(e_t i_p)}}{m_e R_0 \nu_{e_p i_p}}$$

The passing electrons spins up and the trapped ions are transported out.
ν_{ei} is the parallel friction between electron and ions

Momentum balance of passing particles

The current is obtained from the toroidal velocity of the electrons

$$n_{ep} m_e R_0 \Delta V \frac{\partial u_e^{(0)}(\psi)}{\partial t} = \int_{\substack{e_p:\Delta\psi \\ \text{passing}}} \left\{ \left\langle \frac{\partial P_\phi^{(e_p i_p)}}{\partial t} \right\rangle + \left\langle \frac{\partial P_\phi^{(e_p e_t)}}{\partial t} \right\rangle + \left\langle \frac{\partial P_\phi^{(e_p i_t)}}{\partial t} \right\rangle + \left\langle \frac{\partial P_\phi^{(e_p e_p)}}{\partial t} \right\rangle + \right.$$

$$\left. m_e \left[\frac{R_0^2}{R_{res}} \frac{\partial \upsilon_{\phi:RF}(\psi)}{\partial t} \right]_{res} \right\} F_e \sqrt{g}\, dW d\Lambda dP_\phi + \int_{\substack{e_t:\Delta\psi \\ \text{trapped}}} m_e(\psi) R_0 \frac{\partial u_{d:trp}^{(0)}}{\partial t} F_e \sqrt{g}\, dW d\Lambda dP_\phi$$

Change in momentum by passing colliding with trapped is the same as trapped particle colliding with passing, related to fluxes

$$n_{ep}(\psi) \int_S \frac{dS}{|\nabla \psi|} \int_{\substack{\text{passing} \\ \text{electrons}}} \left\{ \left\langle \frac{\partial P_\phi}{\partial t} \right\rangle^{(e_p i_p)} + m_e R_0 \left[\frac{R_0}{R} \frac{\partial \upsilon_{\phi:RF}(\psi)}{\partial t} \right]_{res} \right\} f_e d^3\upsilon +$$

$$m_e n_{et}(\psi) R_0 \int_S \frac{dS}{|\nabla \psi|} \int_{\substack{trapped \\ electrons}} \frac{\partial \upsilon_{\phi:dtrp}(\psi)}{\partial t} f_e d^3\upsilon \approx -e\left(\Gamma_{\psi:D}^{(ei)} + \Gamma_{\psi:D}^{(ee)} + u_i^{(0)} L_t^{(ei)} + u_i^{(0)} L_t^{(ee)} \right)$$

Electron current

$$J_{\phi e} \approx \frac{e^2\left(\Gamma^{(ei)}_{\psi:D} + \Gamma^{(ee)}_{\psi:D} + u_i^{(0)} L_t^{(ei)} + u_i^{(0)} L_t^{(ee)}\right)}{L_p^{(ei)}} +$$

Bootstrap current
RF changes u_i

$$\frac{en_{ep}(\psi)}{L_p^{(ei)}} \int \frac{dS}{|\nabla \psi|} \int_{\substack{passing\\electrons}} \left[\frac{n_\phi}{\omega} \frac{B_\phi^2}{B^2} - \frac{m_\theta R}{\omega r} \frac{B_\theta B_\phi}{B^2} \right]_{res} \frac{R_0}{R_{res}} \frac{\partial W_{RF}}{\partial t} f_e d^3 \upsilon_e$$

Normal RF-driven current

$$+\frac{en_{et}(\psi)}{L_p^{(ei)}} \int_S \frac{dS}{|\nabla \psi|} \int_{\substack{trapped\\electrons}} R_0 \frac{\partial \upsilon_{\phi:dtrp}(\psi)}{\partial t} f_e d^3 \upsilon_e$$

RF- current driven by detrapping

The bootstrap current is affected by the wave-particle transport through the shift $u_i^{(0)}$, radial electric field.

Wave particle induced ion transport or prompt ion losses or reduced electron transport increases the bootstrap current whereas wave induced electron transport reduces bootstrap current.

Recovered fraction of current due to absorption on trapped particles

The fraction of recovered current through changes in the bootstrap current becomes

$$\frac{\Delta J_{\phi bs}}{\Delta J_{\phi RF}} \approx \frac{\left(L_t^{(ei)} + L_t^{(ee)}\right)}{Z_i L_t^{(ii)}} \frac{P_t}{P_p}$$

which is of the order $(m_e/m_i)^{0.5}$.

The additional bootstrap current due to wave particle interactions depends only on the total momentum absorbed by ions and electrons, and thus on the direction of the wave through n_ϕ and m_θ.

Thus, the bootstrap current absorbed on trapped and passing particles counteract ion current drive and enhance electron current drive.

Summary

Orbit averaged Monte Carlo operators have been developed for toroidal plasma, consistent with neo-classical transport. This is achieved by shifting the parallel velocity of the test particles and using the collision operators developed by Chandrasekhar´s for Maxwellian plasmas.

The shift is non-linear with respect to ∇T_i and losses beneficial for transport barrier and produce radial electric field stronger than the neoclassical one. The non-linearity may lead to bifurcation.

The coupling between the electron and ion distribution functions can be modelled in the banana regime by shifting the velocity between trapped and passing particles.

Summary

The net particle transport is strongly affected whether the RF-power is absorbed on electrons or ions; absorption on electrons gives rise to a factor $(m_i/m_e)^{0.5}$ larger effect on the transport.

The RF-induced transport affect the bootstrap current, and is independent whether the power is absorbed on electrons or ions, but depends on the direction of the waves.

The recovered bootstrap current will enhance electron current drive and reduce ion current drive. But it is only of the order $(m_e/m_i)^{0.5}$.

Due to the universality of the relation between changes in the invariants W, Λ and P_ϕ by wave-particle interactions the relation between the wave induced fluxes, bootstrap current, radial electric field and neoclassical particle fluxes holds also for wave induced anomalous transport that does not destroy the flux surfaces.

Summary

Large fraction of the power absorbed on trapped particles can be recovered by selective detrapping for ELD/TTMP.

The selective detrapping depends on the strength of the wave particle interactions compared to pitch angel scattering, thus more important for high-energy particles, for which the collision frequency becomes lower.

The selective detrapping may partly explain the stronger current drive observed in FWCD experiments than modelled in absence of this effect.

Selective detrapping can be important for FWCD and mode conversion current drive with large upshift of $k_{||}$ due to large m_{θ}. Detoriated by high collision frequency for particles with low velocity.