THE EFFECT OF THE RADIAL ELECTRIC FIELD ON NEOCLASSICAL PHENOMENA IN A TOKAMAK PEDESTAL

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OUTLINE

- Effect of scale: background ion temperature profile
- Ion orbits in the presence of strong radial electric field
- Poloidal flow of background ions in the pedestal
- Enhancement of the poloidal impurity flow and bootstrap current in the banana regime pedestal
The key feature of a subsonic pedestal directly affecting particle orbits is the strong radial electric field needed to sustain ion pressure balance.
In the core plasma gradients are so weak that ion departures from a flux surface are not important and we can consider any given flux surface a closed system.

In the pedestal, gradients are as large as $1/\rho_{\text{pol}}$ and therefore these departures affect the equilibrating of the neighboring flux surfaces. Thus, it is the entire pedestal region that is a closed system rather than its individual flux surfaces.

That is, $T_i$ must vary slowly compared to $\rho_{\text{pol}}$. 

*Kagan & Catto PPCF 2008*
The $T_i$ gradient for the bulk ion in a DIII-D ECH H-mode pedestal is small relative to gradients in electron temperature and density.

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**DIII-D: Edge $T_i$ for bulk ion He$^{++}$**

The thermal ion full banana width is computed to be $2\rho_0 = 10$ mm for He$^{++}$ at the top of the density pedestal.

The smooth spline fits to the data (solid lines) end at the LCFS as computed by EFIT. Note the clear break in slope for $T_i$ beyond the LCFS.

In a nominally identical companion discharge we measured $T_i$ for the minor C$6^+$ impurity constituent. The $T_i$ profile for C$6^+$ has a very similar slope to that for He$^{++}$, but is $\sim 150$ eV greater in this region, probably because this discharge had an increase in $\beta_N$ of $\sim 10\%$ compared with the one shown here.

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IMPURITY FLOW MEASUREMENTS AT ALCATOR C-MOD:

Observation: In the banana regime pedestal, the boron impurity poloidal flow is larger than that predicted by conventional formulas.

These impurities are highly collisional and their mean free path is too short for their kinetic energy to be affected by the electric field.

It may only be the friction with background ions that the electric field manifests itself through

Relation between the background and impurity poloidal ion flows:

\[ V_{zp}^{pol} = V_{ip}^{pol} - \frac{cIB_{pol}}{eB^2} \left( \frac{1}{n_i} \frac{\partial p_i}{\partial \psi} - \frac{1}{Zn_z} \frac{\partial p_z}{\partial \psi} \right) \]

If \( V_{ip}^{pol} \) goes smaller or even negative it no longer competes with the diamagnetic terms, thereby resulting in a relatively large \( V_{zp}^{pol} \). Such a change in \( V_{ip}^{pol} \) should alter the bootstrap current as well.
ION ORBITS IN PEDESTAL

\[
\dot{\theta} \approx \left[ v_\parallel + c I \phi'(\psi) \right] / B \hat{n} \cdot \nabla \theta
\]

ExB drift is of order \( v_{th} (\rho / \rho_{pol}) << v_\parallel \), but due to the geometrical factors its contribution to the poloidal velocity is comparable to that of \( v_\parallel \)
TRAPPED PARTICLE REGION

In the absence of orbit squeezing (S=1), ExB drift has the following effects:

1) Increases the depth of the effective potential well – now particles with no magnetic moment can be trapped.
2) Shifts the axis of symmetry of the trapped particles region.

For small enough \( \varepsilon \) the trapped particle fraction decays exponentially as \(|u|\) grows. Accordingly, some neoclassical phenomena disappear in the large electric field limit.

Notice, that \( u \approx (\rho_{pol}/\rho)v_{E} \gg v_{E} \) and therefore particle dynamics can be qualitatively changed even by the ExB drift much less than \( v_{i} \).
In the pedestal, the pitch angle scattering component of the collision operator is not sufficient to retain transitions across the trapped-passing boundary!
NEOCLASSICAL ION HEAT FLUX

Moment approach: 
\[
\langle \vec{q} \cdot \nabla \psi \rangle = -\frac{McIT}{Ze} \int \frac{d^3v}{B} \left( \frac{Mv^2}{2T} - \frac{5}{2} \right) v \| C \{ g - h \}
\]

Evaluating the integrals we find 
\[
\langle \vec{q} \cdot \nabla \psi \rangle = 1.35n_i \nu_B \frac{T \meas{T} \sqrt{\varepsilon S}}{\Omega_0^2 M} \frac{\partial T}{\partial \psi} G(u),
\]

where

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{chart.png}
\caption{G}
\end{figure}

Kagan & Catto PPCF 2010
Similarly to the ion heat flux we calculate the parallel ion flow to obtain

\[ V_{i||} = -\frac{cI}{B} \left( \frac{\partial \phi}{\partial \psi} + \frac{1}{Ze_i} \frac{\partial p}{\partial \psi} \right) - 1.17 \frac{I}{\Omega_0 M} \frac{\partial T}{\partial \psi} J(u) \]

Poloidal flow changes direction at \( u/v_i \approx 1.2! \)

*Kagan & Catto PPCF 2010*
IMPURITY MEASUREMENTS AT C-MOD YET AGAIN

Marr et al, PPCF 2010 & Kagan et al submitted to PPCF
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ENHANCEMENT OF THE BOOTSTRAP CURRENT IN THE BANANA REGIME PEDESTAL

The calculation of the bootstrap current runs the same as in the conventional case with the new expression for the parallel ion flow in place of the old one

\[ J_{BS} \approx -1.46 \varepsilon^{1/2} \frac{cIB}{B^2} \left[ \frac{Z^2 + 2.21Z + 0.75}{Z(Z + 1.414)} \right] \left[ \frac{dp}{d\psi} - \frac{(2.07Z + 0.88)n_e}{Z^2 + 2.21Z + 0.75} \frac{dT_e}{d\psi} - 1.17 J(u) \frac{n_e}{Z_i} \frac{dT_i}{d\psi} \right] \]

\[ Z \to \infty : \quad J_{BS} \approx -1.46 \varepsilon^{1/2} \frac{cIB}{B^2} \left[ \frac{dp}{d\psi} - 1.17 J(u) \frac{n_i}{Z_i} \frac{dT_i}{d\psi} \right] \]

governed by poloidal ion flow

Analogously to the impurity case, poloidal ion flow going negative results in a bootstrap current larger than that predicted by the conventional theory

Kagan & Catto PRL 2010
MORE INTUITIVE PICTURE

Electric field acts in the direction to increase the difference between the ion and electron net flow velocities. In response, friction between the species increases as well, reducing the effect by the usual $\sqrt{\epsilon}$ factor, but the resultant current is still enhanced.

*Kagan & Catto PRL 2010*
SUMMARY

- Background ion temperature profile cannot be as steep as that of the density

- In the banana regime pedestal ion orbits are modified by a strong radial electric field, thereby calling for reexamination of conventional neoclassical theory

- In particular, neoclassical poloidal ion flow changes direction as compared to its core counterpart
  - Poloidal impurity flow is enhanced (observed at C-Mod)
  - Bootstrap current in the pedestal is larger than one might expect based on conventional consideration