Plasma edge/SOL transport simulations including quasilinear stochastic transport due to resonant magnetic perturbations

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Outline

1. Motivation and goal

2. Characterizing/reduce additional transport channels to 2D
   • Electron: quasilinear stochastic transport
   • Ion: viscous transport

3. Initial 2D UEDGE simulation of DIII-D RMP

4. Summary
Edge magnetic stochastic may be generated during RMP from non-axisymmetric coils in DIII-D.
Goal: quantify transport behavior in presence of stochastic magnetic field; apply to DIII-D

- Incorporate stochastic electron transport in 2D edge transport code

- Rozhansky reports (NF 50, 34004, 2010) stochastic electron model can explain ASDEX-U and MAST density pumpout

- Can such a model explain DIII-D density pumpout?
In a stochastic field, competition between non-ambipolar electron and ion transport leads to an additional net flux

- Ambipolarity requires electron & ion transport to balance \( \nabla \cdot J = 0 \)

- General transport relations

\[
\begin{align*}
J_e &= \sigma_e (E_e - E) \\
J_i &= \sigma_i (E - E_i) \\
eE_i &= \frac{dn_i}{T_i} + k_{ii} \frac{dT_i}{dr} \\
eE_e &= -\frac{dn_e}{T_e} - k_{ee} \frac{dT_e}{dr} - k_{ei} \frac{dT_i}{dr}
\end{align*}
\]

- The conductivity and diffusivities are related via

\[
\sigma_j = Z_j e^2 n_j D_j / T_j
\]

- Net flux requires 2 transport mechanisms: one for ions and one for electrons

Am bipolar electric field & flux

\[
E_A = \frac{\sigma_e E_e + \sigma_i E_i}{\sigma_e + \sigma_i}
\]

\[
\Gamma_A = \frac{J_i}{e} = -\frac{J_e}{e} = \frac{E_e - E_i}{1/\sigma_e + 1/\sigma_i}
\]
Viscous ion transport can generate a competing non-ambipolar transport mechanism (for small $\delta B/B$)

- Viscous transport is nonambipolar due to the difference in gyroradius

$$\Gamma_{\Pi} = \hat{b}_0 \times (\nabla \cdot \Pi) / ZeB.$$ 

- Anomalous ion viscous flux will generate the ion flux (in UEDGE)

$$\Gamma_{\Pi} = -\frac{\hat{b}_0}{ZeB} \times \nabla \cdot mn \nabla v \sim \frac{\rho_i^2}{T} (\nabla \cdot n \mu \nabla) \left( \nabla_\perp Ze \phi + \frac{\nabla_\perp p}{n} \right)$$

- Below a critical magnetic field perturbation strength, particle transport will dominate heat transport

$$\left( \frac{\delta B}{B} \right)^2 < \frac{\sigma_{\mu,i}}{\sigma_{st,e}} \left( \frac{\delta B}{B} \right)^2 \simeq \frac{\mu_i \rho_i^2}{q RV_T e L_E^2}$$

where $L_E = \phi/\phi'$

- Neoclassical viscous forces also generates additional ion flux$^1$

Stochastic B-field transport – a partial reference list

• **Theory of transport in a stochastic magnetic field**

• **Calculations of transport in ELM-suppressed discharges without E-field**

• **Calculations including E-field & ion viscous transport channel**
Drift-kinetic equation describes electron motion in a stochastic magnetic field

- Drift kinetic equation
  \[ \partial_t f + \mathbf{u} \cdot \nabla f + \frac{Z_e}{m} E_\parallel \nabla_u f = 0 \]  
  (1)

- Expand solution in perturbation strength \( \delta = \delta B_1 / B \)
  \[ f = f_0 + \delta f_1 + \delta^2 f_2 + .... \]

- the flux takes a local diffusive form
  \[ \Gamma_{n,fl} \simeq -|u| D_{fl} \cdot (\nabla + Z_e E_0 \partial_w) f_0 \]

- Electron flux is larger than ion by \( V_{te} / V_{ti} \sim (m_i / m_e)^{1/2} \)
Changes to UEDGE includes added terms for stochastic electron particle and heat flow

a) Current continuity eqn has added term owing to electron stochastic particle flux:

\[ \Gamma_e \rightarrow \Gamma_e + \Gamma_{e-st} \]

\[ \Gamma_{e-st} = - \sigma_{st}( E_r + [T_e/e] \{d \ln n_e/dr + k d \ln T_e/dr\})/e \]

b) Radial heat conduction eqn adds enhance heat flux terms

\[ q_{e,r} \rightarrow q_{e,r} + (5/2)T_e \Gamma_{e-st} - \chi_{e-st} n_e T_e d \ln T_e/dr \]

\[ \chi_{e-st} = \sigma_{st} T_e/(ne^2k), \quad k = 0.3 \]

Implementation of stochastic electron terms parallels that of Rozhansky et al., Nucl. Fusion 50 (2010) 034005
Application: profiles from DIII-D RMP experiment

T. Evans et al., Nucl. Fusion 48 (2008) 024002; DIII-D shot 126442
Without RMP effect, UEDGE simulation temperature profiles exhibit pedestal; modest density pedestal.

Density

Temperatures ($\chi_{e,I}$ similar to D on left)

Without RMP
Particle flux across separatrix includes core (neutral beam) current and neutral ionization source.

Continuity equation:

$$\text{div}(\Gamma) = S_i$$

$$\Gamma(r) = \Gamma(r_{cb}) + \text{Int } S_i$$
Stochastic conductivity, $\sigma_{st}$, is determined by $\delta B^2$ quasilinear estimate

$$\sigma_{st} = 2\pi qR(n_e e^2/T_e)(\delta B/B)^2$$

where A is a parameter used to account for, trapped electrons, flux limits, and $\delta B$ shielding.

For DIII-D, significant density pumpout observed for $\delta B/B \sim 3 \times 10^{-4}$

We vary A and find significant pumpout for $A \sim 1/30$
With a stochastic magnetic field zone representing the RMP, both $n_e$ and $T_e$ reduction found.
Balanced stochastic electron flux & ion viscous flux, plus enhanced electron thermal diffusivity explain results

- Radial particle fluxes, $\Gamma_{i,e}$, must be ambipolar: $\Gamma_i = \Gamma_e$

  $$\Gamma_i = \Gamma_{\text{turb}} + n_i \mu_i (E_r - E_{i-\text{neo}})$$

  $$\Gamma_e = \Gamma_{\text{turb}} - n_e \mu_{e-\text{st}} (E_r - E_{e-\text{st}})$$

- Thus, $\Gamma_i = \Gamma_e$ yields

  $$E_r = (\mu_i E_{i-\text{neo}} + \mu_{e-\text{st}} E_{e-\text{st}}) / (\mu_i + \mu_{e-\text{st}})$$

- Finite $\mu_{e-\text{st}}$ modifies $E_r$ to preserve ambipolarity

- Electron diffusivity is increased (Rechester-Rosenbluth)

  $$\chi_e \rightarrow \chi_e + \chi_{e-\text{st}}$$

- Electron energy work term

  $$v_{e-\text{st}} \text{ grad}(P_e)$$

  though not included here, is negative and should decrease $T_e$ somewhat further if valid
Details: in stochastic zone, electron-stochastic & ion-neoclassical fluxes match; $E_r$ increases to drive $\Gamma_{i-neo}$
Summary

• Qualitative: incorporating separate electron & ion loss channels
  – Electrons – stochastic particle and thermal transport
  – Ions – radial particle (turbulent) viscosity
  – Different channels made ambipolar by reduction in $E_r$ (div $J = 0$)

• Quantitative: comparison to DIII-D
  – For same $\sigma_{st}$, find similar $n_e$ reduction, but also $T_e$ reduction (difference in ion viscosity models?)
  – Effects found at reduced $\sigma_{st}$ from quasilinear (~1/30); from trapped electrons, flux limits, and shielding?
  – Inward shift of $\sigma_{st}$ layer returns steep $n_e$ profile at separatrix