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

T.D. Rognlien and I. Joseph
Lawrence Livermore National Laboratory

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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

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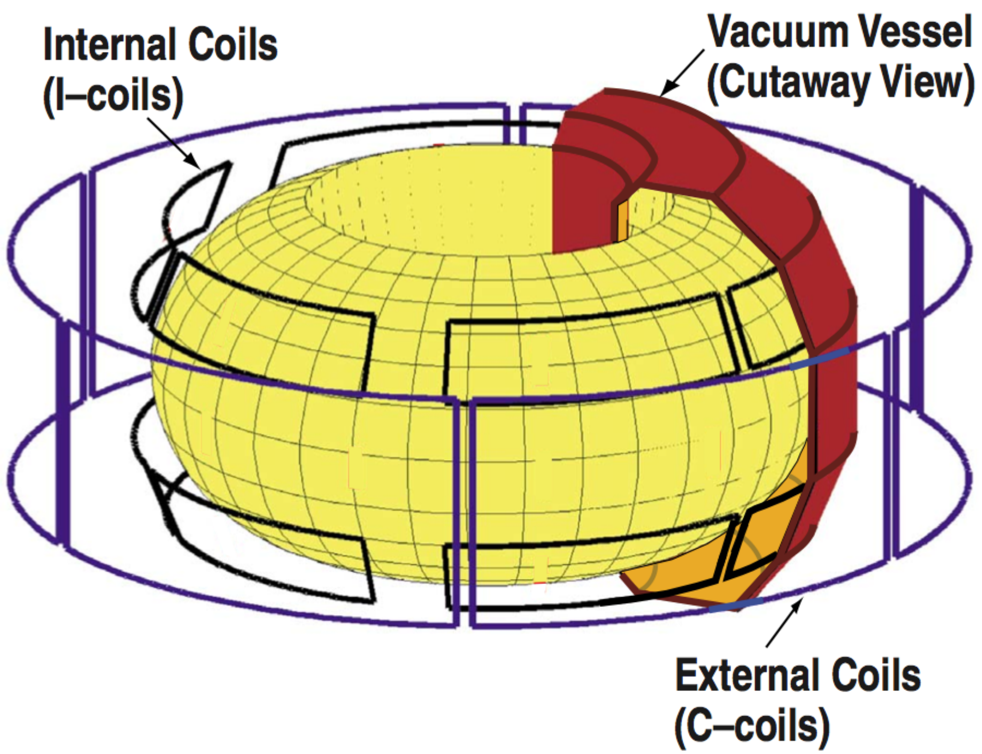
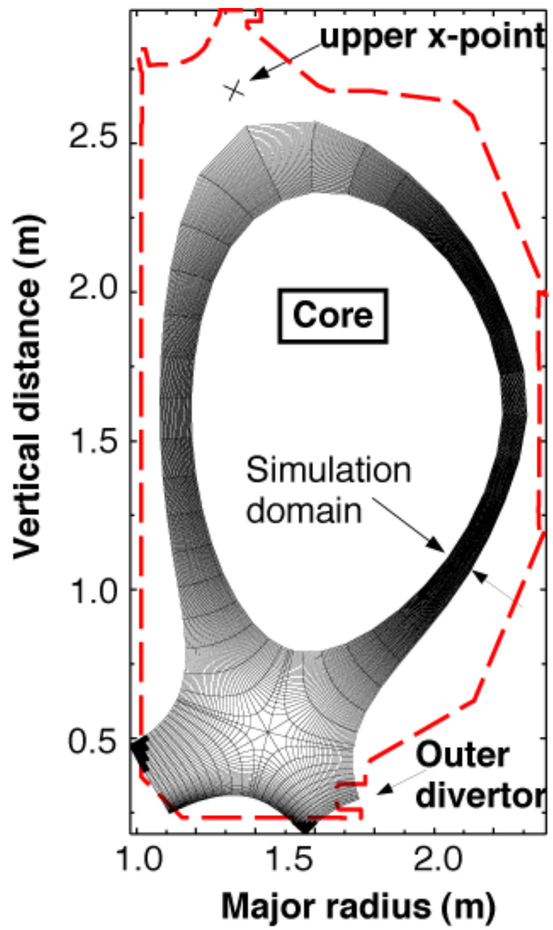
Edge magnetic stochastic may be generated during RMP from non-axisymmetric coils in DIII-D





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**

$$J_e = \sigma_e \left(E_e - E \right)$$

$$J_i = \sigma_i \left(E - E_i \right)$$

$$\frac{eE_i}{T_i} = \frac{dn_i}{dr} + k_{ii} \frac{dT_i}{dr}$$

$$\frac{eE_e}{T_e} = -\frac{dn_e}{dr} - k_{ee} \frac{dT_e}{dr} - k_{ei} \frac{dT_i}{dr}$$

Ambipolar electric field & flux

$$E_A = \frac{\sigma_e E_e + \sigma_i E_i}{\sigma_e + \sigma_i}$$

$$\Gamma_A = \frac{J_i}{e} = -\frac{J_e}{e} = \frac{E_e - E_i}{1/\sigma_e + 1/\sigma_i}$$

  – **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**

Viscous ion transport can generate a competing non-ambipolar transport mechanism (for small δB/B)

- **Viscous transport is nonambipolar due to the difference in gyroradius**

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

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

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

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

$$\left(\frac{\delta B}{B}\right)^2 < \frac{\sigma_{\mu,i}}{\sigma_{st,e}}\left(\frac{\delta B}{B}\right)^2 \simeq \frac{\mu_i \rho_s^2}{qRV_{Te}L_E^2}$$

where $L_E = \phi/\phi'$

- **Neoclassical viscous forces also generates additional ion flux**[1]

[1] M. Z. Tokar, T.E. Evans, T.R. Singh, and B. Unterberg, Phys. Plasmas **15**, 072515 (2008).
V. Rozhansky, E. Kaveeva, P. Molchanov et al., Nucl. Fusion **50**, 034005 (2010).
G. Park, C. S. Chang, I. Joseph, and R. A. Moyer, Phys. Plasmas **17**,102503 (2010).

Stochastic B-field transport – a partial reference list

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

M.N. Rosenbluth, R.Z. Sagdeev, J.B. Taylor, G.M. Zaslavski, Nucl. Fusion **6**, 297 (1966).

J.D. Callen, Phys. Rev. Lett. **39**, 1540 (1977).

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R.W. Harvey, M.G. McCoy, J.Y. Hsu and A.A. Mirin, Phys. Rev. Lett. **47**, 102 (1981)

I. Kaganovich and V. Rozhansky, Phys. Plasmas 5, 3901 (1998).

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

I. Joseph, T.E. Evans, A.M. Runov et al., Nucl. Fusion **48**, 045009 (2008).

H. Frerichs, D. Reiter, O. Schmitz et al., Nucl. Fusion **50**, 034004(2010).

- **Calculations including E-field & ion viscous transport channel**

M.Z. Tokar, T.E. Evans, T.R. Singh, and B. Unterberg, Phys. Plasmas **15**, 072515 (2008).

→ V. Rozhansky, E. Kaveeva, P. Molchanov et al., Nucl. Fusion **50**, 034005 (2010).

G. Park, C.S. Chang, I. Joseph, and R.A. Moyer, Phys. Plasmas **17**,102503 (2010).

V. Rozhansky, P. Molchanov, E. Kaveeva et al., Nucl. Fusion **51**, 083009 (2011).

Drift-kinetic equation describes electron motion in a stochastic magnetic field

- **Drift kinetic equation**

$$\partial_t f + u\hat{\mathbf{b}} \cdot \nabla f + \frac{Ze}{m} E_{\|} \partial_u f = 0 \qquad (1)$$

- **Expand solution in perturbation strength** $\delta = \delta B_1/B$

$$f \;=\; f_0 + \delta f_1 + \delta^2 f_2 + \ldots.$$

- **the flux takes a local diffusive form**

$$\Gamma_{n,fl} \simeq -|u| \mathcal{D}_{fl} \cdot \left(\nabla + Ze\mathbf{E}_0 \partial_w\right) f_0$$

- **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:

$$\Gamma_e \rightarrow \Gamma_e + \Gamma_{e\text{-}st}$$

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

b) Radial heat conduction eqn adds enhance heat flux terms

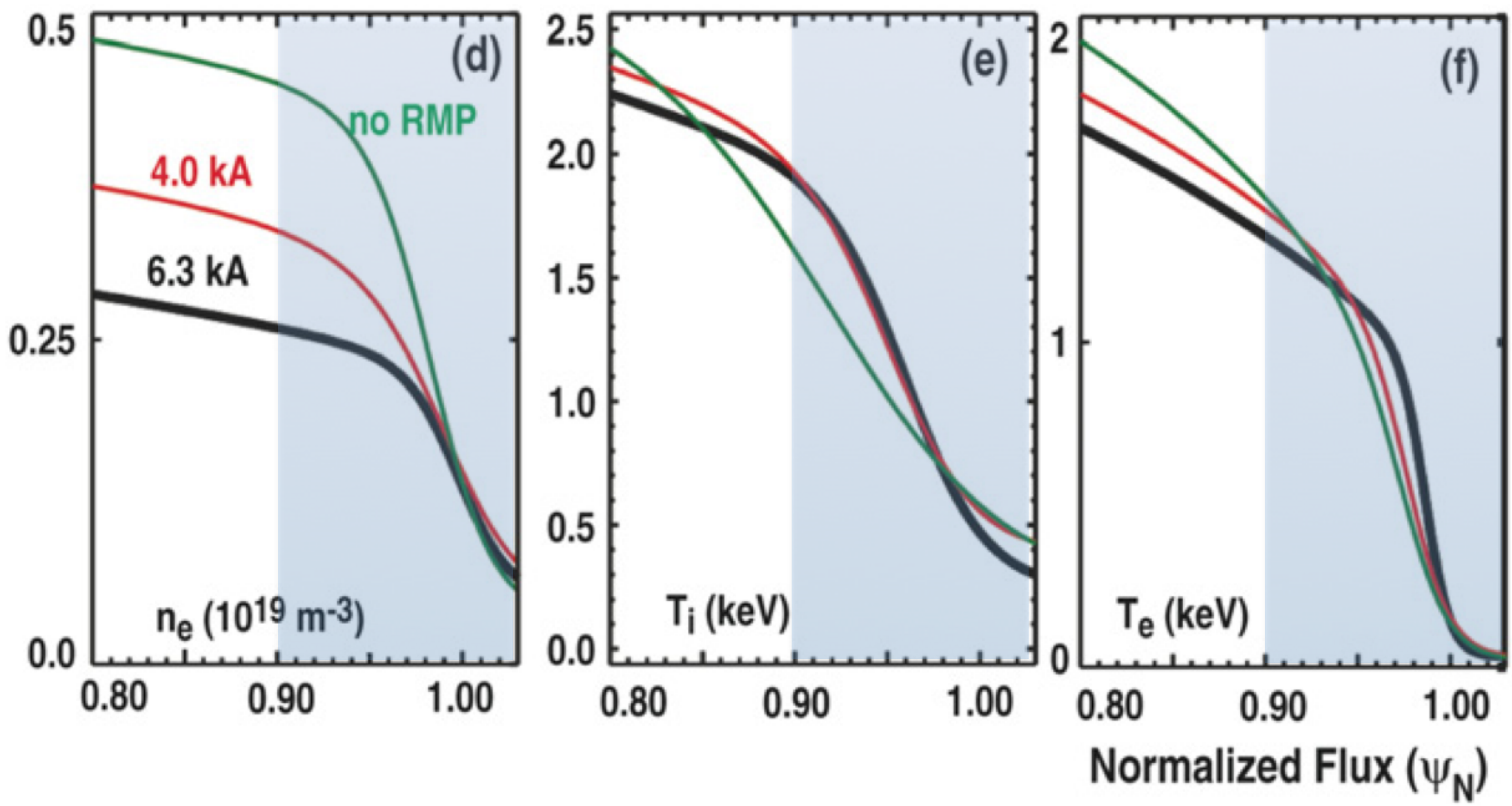
$$q_{e,r} \rightarrow q_{e,r} + (5/2)T_e\Gamma_{e\text{-}st} - \chi_{e\text{-}st} \, n_e T_e \, d \ln T_e/dr$$

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

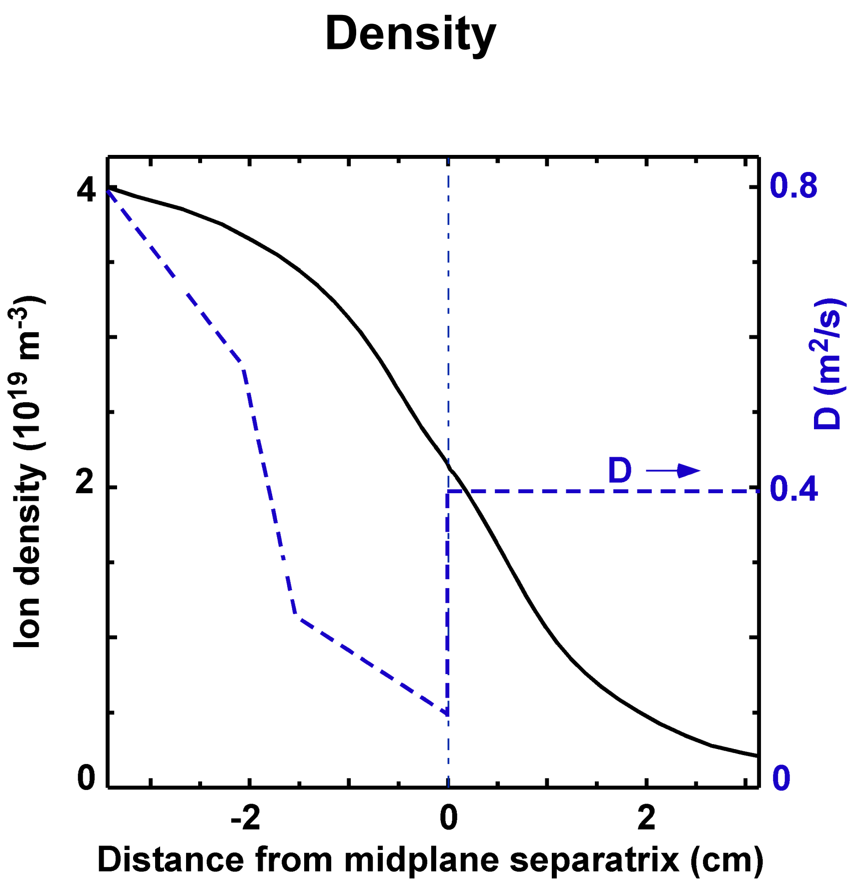
Implementation of stochastic electron terms parallels that of Rozhansky et al., Nucl. Fusion 50 (2010) 034005

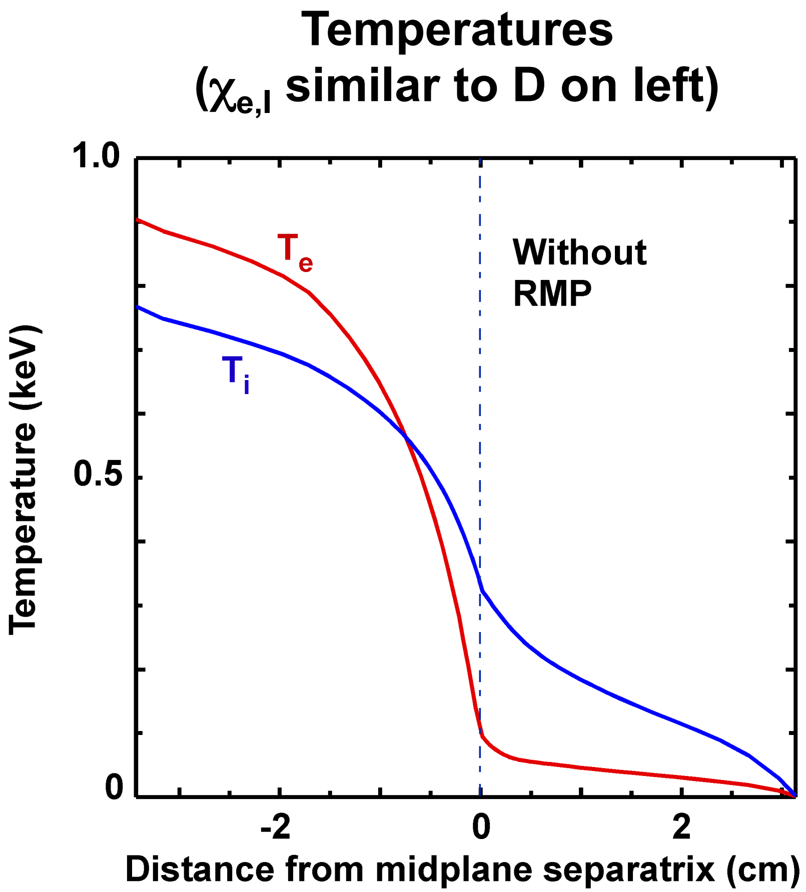
Applicaition: profiles from DIII-D RMP experiment

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





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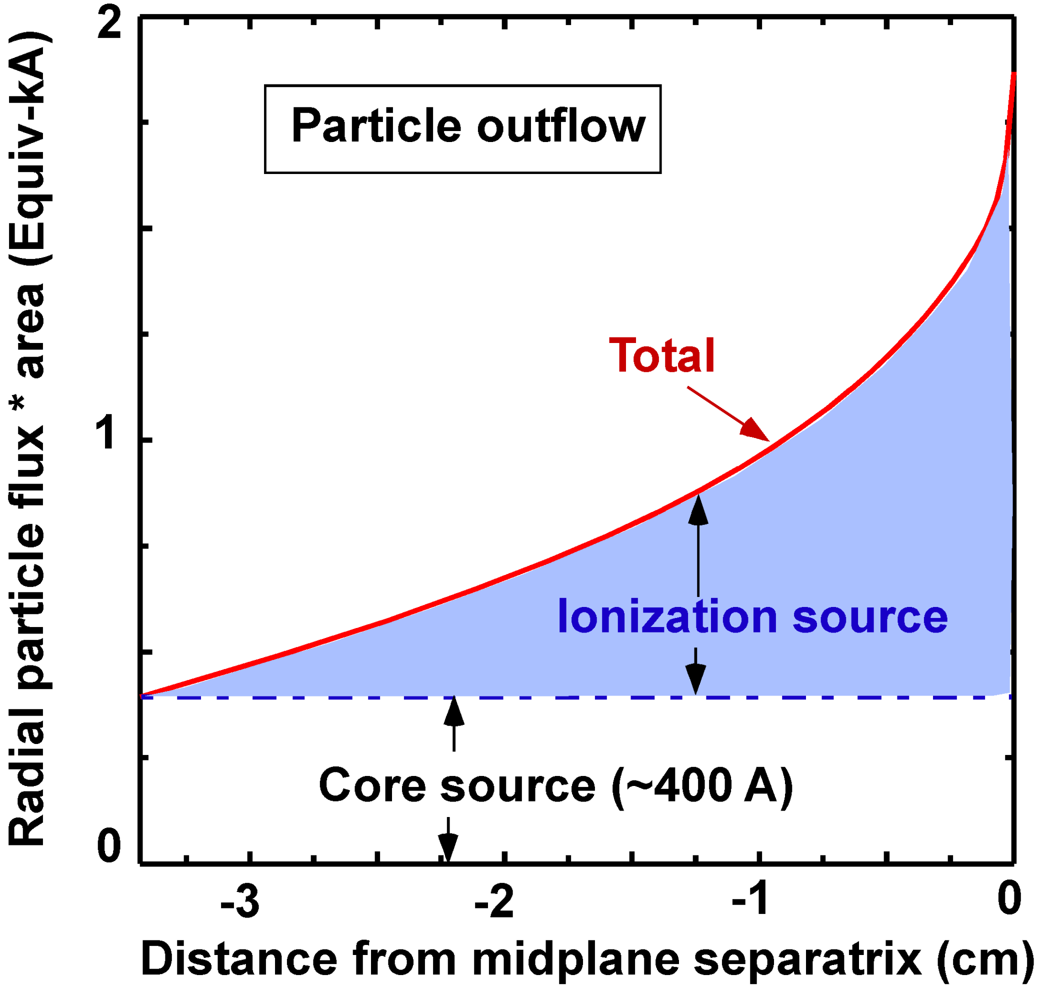
Particle flux across separatrix includes core (neutral beam) current and neutral ionization source



Continuity equation

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

$$\Gamma(r) = \Gamma(r_{cb}) + \mathrm{Int}\ S_i$$

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Stochastic conductivity, σ_{st}, is determined by δB^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 δB shielding.

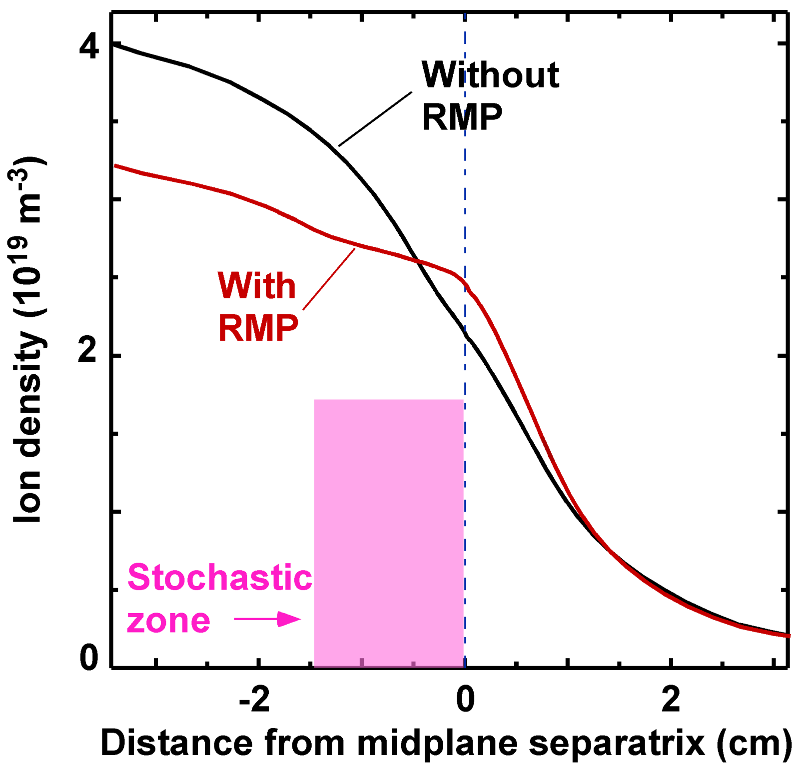
For DIII-D, significant density pumpout observed for

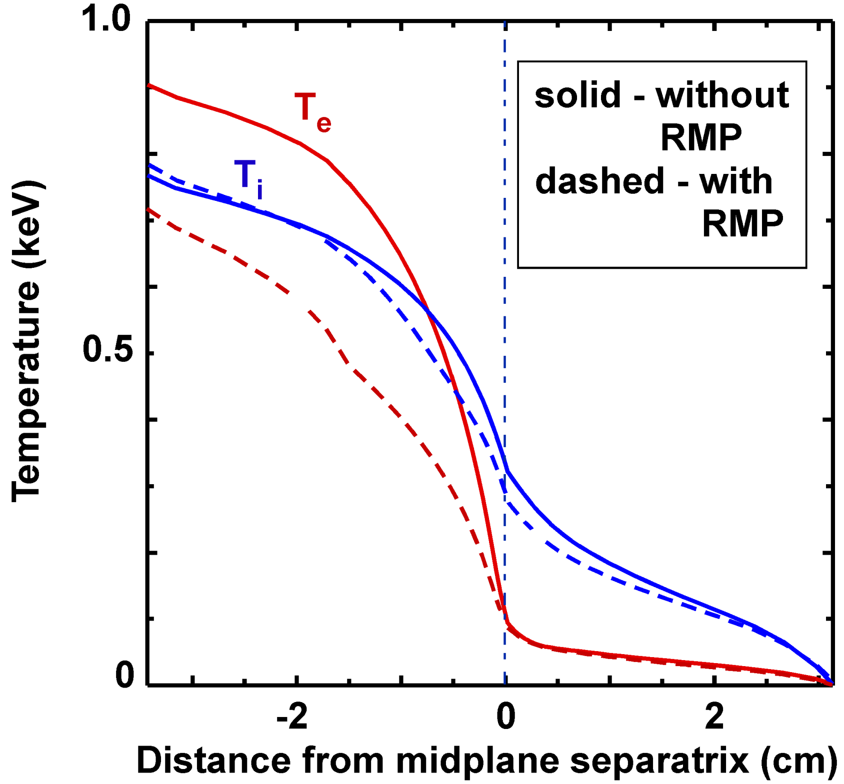
$$\delta B/B \sim 3\times10^{-4}$$

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: $\Gamma_i = \Gamma_e$

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

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

- 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

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

though not included here, is negative and should decrease T_e somewhat further if valid

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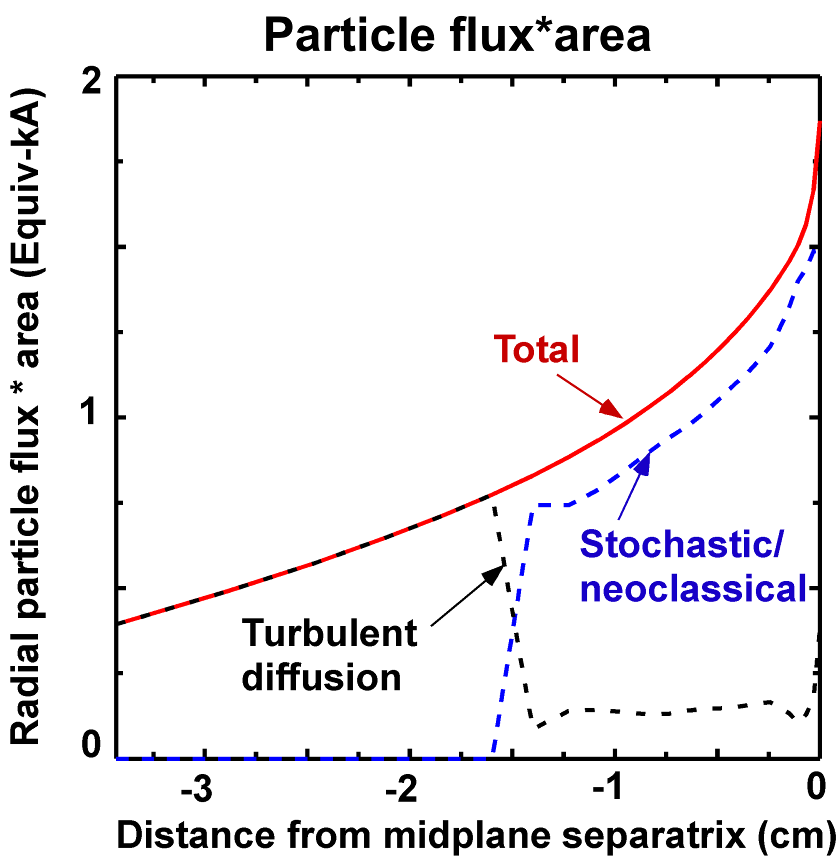
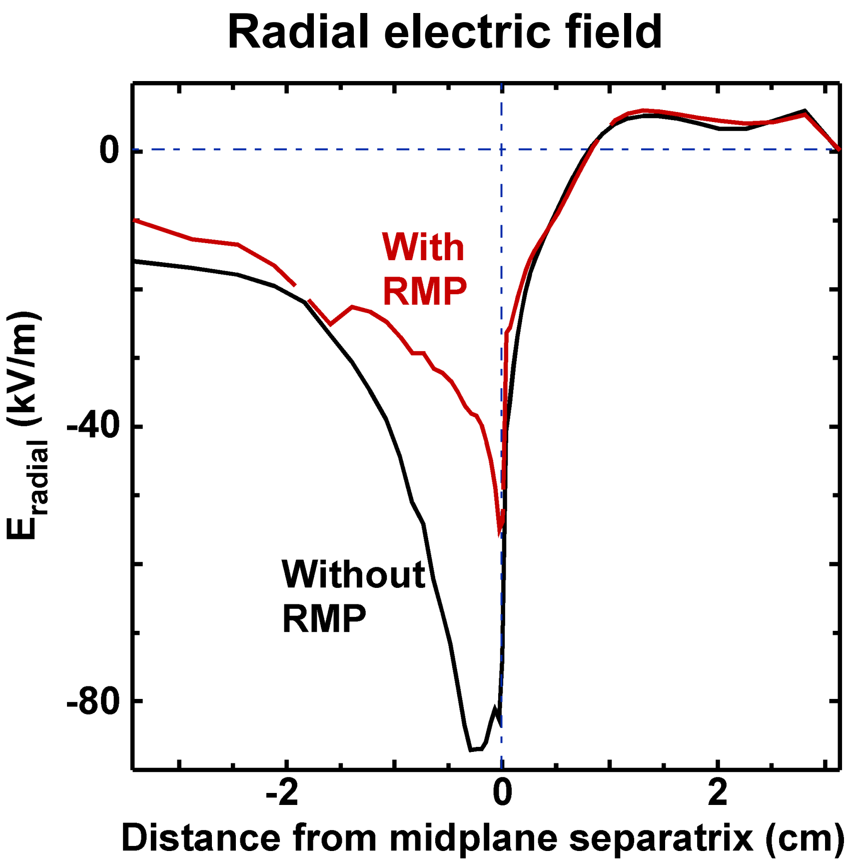
Details: in stochastic zone, electron-stochastic & ion-neoclassical fluxes match; E_r increases to drive $\Gamma_{i\text{-neo}}$





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 σ_{st}, find similar n_e reduction, but also T_e reduction (difference in ion viscosity models?)
  - Effects found at reduced σ_{st} from quasilinear (~1/30); from trapped electrons, flux limits, and shielding?
  - Inward shift of σ_{st} layer returns steep n_e profile at separatrix