Effect of Ion Orbit Loss on Rotation and the Radial Electric Field in the DIII-D Tokamak

by

T.M. Wilks$^1$

with

W.M. Stacey$^1$ and T.E. Evans$^2$

$^1$Georgia Institute of Technology

$^2$General Atomics

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Presentation outline

- Background
- Ion orbit loss and x-transport models
- Radial particle flux
- Deuterium rotation velocities
- Radial electric field
- Discussion
Presentation outline

• Background
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General methodology for radial electric field calculation

Radial particle flow generated by external fueling, IOL, and return current → Torque from radial flow drives rotation → Rotation generates a radial electric field → $E_r$ influences collisionless loss of thermal and fast beam particles → Radial particle flow generated by external fueling, IOL, and return current
Goal of semi-analytical model is to define physics of the radial electric field inside the separatrix.

Present analysis examines causes for Er profile structure in H-mode inside the separatrix due to:

- Background plasma defined by diffusive and non-diffusive transport
- Realistic flux surface geometry
- Thermal ion orbit loss
- Fast ion orbit loss
- Corresponding radial return current
- Inclusion of ion orbit loss in conservation equations
- X-loss and x-transport
- Returning ions from scrape-off layer

Goal: fast, predictive, and self-consistent physical model.
GTEDGE calculates background plasma and edge pedestal boundary conditions:

- Energy and particle balance on core plasma
- 2D neutral calculation using integral transport theory → net ion flux across separatrix
- “Two-point” divertor model → ion densities at divertor plate and outboard midplane
- Model parameters conserve 1) line average density 2) energy confinement time 3) central and edge pedestal temperatures

Goal: fast, predictive, and self-consistent physical model
1D radial profiles calculated for specific edge parameters determined from GTEDGE

Ion orbit loss (fast and thermal):

- 2D magnetic field and flux surface models \(\rightarrow\) collapsed to 1D profile
- 2D x-transport model collapsed to 1D profile

2 species momentum balance requirements (1D profiles):

- Radial particle flux
- Rotation velocities
- Radial electric field

Goal: fast, predictive, and self-consistent physical model
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Conservation equations determine minimum energy for ion loss to overcome electrostatic potential generated from Er in a collisionless plasma

- Canonical angular momentum
- Magnetic moment
- Energy

**Representative $E_{\text{min}}$ Curves**

$$V_0^2 \left[ \left( \frac{B}{B_0} \frac{f_{\phi 0}}{f_{\phi}} \xi_0 \right)^2 - 1 + (1 - \zeta_0^2) \left| \frac{B}{B_0} \right| \right] + V_0 \left[ 2e(\psi_0 - \psi) \left( \frac{B}{B_0} \frac{f_{\phi 0}}{f_{\phi}} \xi_0 \right) \right]$$

$$+ \left( e(\psi_0 - \psi) \right)^2 - \frac{2e(\phi_0 - \phi)}{m} = 0$$

$V_0$ = minimum velocity required for an ion to execute an orbit that crosses the separatrix

$IOL > 0$
X-loss and X-transport model for region with null in $B_\theta$

- Null in poloidal magnetic field causes decrease in poloidal transport

- Competing effects between ExB drift poloidally and curvature drift downwards

- Particles either lost through x-point or x-transported to flux surfaces closer to the separatrix

- X-loss and X-transport in direct competition with fast and thermal IOL

$\Delta \theta$ of x-region defined by $B_\theta \sim \varepsilon B_\phi$
X-transport dominates over ion orbit loss generating a particle pump out

\[ E_r^c = (Z_c e n_c)^{-1} \frac{\partial p_c}{\partial r} - V_{\theta c} B_\phi + V_{\phi c} B_\theta \]

**X-transport drifts right into x-region for \( E_r > 0 \)**
X-transport dominates over ion orbit loss generating a particle pump out

\[ E_r^c = (Z_e n_c)^{-1} \frac{\partial p_c}{\partial r} - V_{\theta_c} B_\phi + V_{\phi_c} B_\theta \]

Experimental Radial Electric Field

X-transport drifts downwards when for \( E_r \sim 0 \), then reverses direction
X-transport dominates over ion orbit loss generating a particle pump out

\[ E_r^c = (Z_c e n_c)^{-1} \frac{\partial p_c}{\partial r} - V_{\theta c} B_\phi + V_{\phi c} B_\theta \]

**Experimental Radial Electric Field**

- **X-transport drifts left out of x-region for** \( E_r < 0 \)

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X-transport dominates over ion orbit loss generating a particle pump out

Minimum energies to x-transport from away from an inner flux surface are low for inner edge
X-transport dominates over ion orbit loss generating a particle pump out

$E_{\text{min}}$ values to be ion orbit lost decrease monotonically towards the separatrix to very low energies.
X-transport dominates over ion orbit loss generating a particle pump out

X-transported ions cascade down to flux surfaces with very low thermal $E_{\text{min}}$ values to be ion orbit lost in far edge.
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- **Radial particle flux**
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Radial particle flux profile decreases close to edge due to particle losses

- Particle flux accounts for fast and thermal IOL
- IOL of fast beam ions ($F_{\text{fast}}$) reduces NBI source
- IOL of thermal ions ($F_{\text{thermal}}$) further reduces thermal ion flux in edge where losses are significant

\[
\frac{\partial \Gamma}{\partial r} = \dot{N}_{nbi}(1 - \alpha F_{\text{fast}}) + n v_{\text{ion}} - \alpha \frac{\partial F_{\text{therm}}}{\partial r} \Gamma
\]

\(\alpha = 0\): no IOL
\(\alpha = 1\): IOL with no return current
\(\alpha = 2\): IOL and return current
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Momentum balance indicates radial flow torque drives rotation

Drive from deuterium radial flux

Interspecies collision frequencies

Drive from carbon impurity radial flux

Viscous drag frequencies
Momentum balance indicates radial flow torque drives rotation.

Drive from deuterium radial flux

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Viscous drag frequencies

Different drive terms derived from poloidal momentum balance
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Rotation generates radial electric field

Radial Electric Field

\[ E_r = \eta j_r - (u \times B)_r + \frac{\nabla_r (p_j + p_k)}{e(n_j + z_k n_k)} \]

\[ = -\eta e_j \Gamma_r \xi_{loss} - \frac{V_{j\theta} B_\phi - V_{j\phi} B_\theta}{1 + n_k m_k / n_j m_j} - \frac{V_{k\theta} B_\phi - V_{k\phi} B_\theta}{1 + n_j m_j / n_k m_k} - \frac{p_j L_{pj}^{-1} + p_k L_{pk}^{-1}}{e(n_j + z_k n_k)} \]
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Discussion and future work

• Calculations for ion orbit loss and related mechanisms have been improved significantly
  — Inherent inclusion in continuity equation with return currents
  — Fast ion losses via NBI
  — Realistic flux surfaces and magnetic fields
  — Retuning particle orbits
  — X-transport and x-loss

• X-transport dominates over x-loss, and particles are subsequently lost via thermal ion orbit loss

• There is still a shortfall between theoretical radial electric field and experiment
  — Look beyond ion orbit loss
  — Effects of non-axisymmetry
Thank you
Select references

1. L.L. Lao et al., NF 30, 6 (1990)
3. V. Rozhansky, PET (2013)
5. J. Mandrekas, “Physics models and user’s guide for the neutral beam module of the SUPERCODE”, GTFR-102 (1992)
7. Stacey, PoP 18, 102504 (2011)
8. Stacey, PoP 19, 112503 (2012)
Backup Slides
1. Experimental data obtained from DIII-D database
   - Sister shots: RMP -123301; H-mode -123302

2. Spline fits for CER system (ions), tanh fits for Thompson system (electrons)
   - Scale length and time derivatives calculated

3. Fits used as inputs to edge pedestal code GTEDGE
   - Balances core plasma and predicts nev2, $T_E$, $T_{ped}$, and $T_c$

4. Experimental and interpreted parameters output from GTEDGE in 25 discrete points between $0.86 < \rho < 1.0$
Revised Miller Model Grid