Intrinsic edge rotation as governed by momentum transport due to neutrals

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Edge rotation

- Flow shear suppresses turbulence
- Rotation stabilizes MHD modes (e.g. resistive wall mode, neoclassical tearing mode)
- Edge sets the boundary condition for core rotation profile

**Need to understand momentum transport in edge**

- Neutrals present inside separatrix, large cross-field mobility

**Role of neutrals?**
Role of neutrals?

JET results:

- Pedestal toroidal rotation is higher in “corner” divertor configuration, and it is affected by fueling

![Diagram of divertor geometry](image_url)

*Fig 1a (above): Divertor geometry used in JET (horizontal=blue; corner=green; vertical=red). The cryogenic pump is also pictured in black.*

![Graphs showing pedestal characteristics](image_url)

*Fig 5: Clockwise from top to bottom: pedestal density, electron and ion pedestal pressure and toroidal velocity at the top of the pedestal for the three divertor configurations at different power and gas injection rate.*

E. Joffrin et al., *25th IAEA Fusion Energy Conference (2014).*
Effect of geometry? TCV data

TCV results:

- Rotation profile shifts by changing X-point location

FIG. 1. Representative plasma geometries, varying $\tilde{R}_X$, in LSN (lower row) and USN (upper row) configurations.

FIG. 6. LFS and HFS carbon velocity measurement points (dots) and fitted profiles (lines) for an HFS ($\tilde{R}_X = -0.74$) and LFS ($\tilde{R}_X = +0.88$) X-point. The approximate core-edge boundary location $\rho = 0.85$ is marked with red circles. CXRS measurement error bars are comparable to point scatter.

Momentum transport and $E_r$

- Standard neoclassical theory, for low flow (i.e. subsonic)
  - Viscosity is small, higher order quantity
  - Particle fluxes automatically ambipolar to lowest order, independent of $E_r$
  - Need $f_i$ very accurately to set $E_r$

- At the edge other effects can give sizable momentum transport
  - Ion orbit losses
  - Toroidal field ripple or resonant magnetic perturbations
  - Sharp profile variations, $\rho_p/L_\perp \sim O(1)$
  - Transport by neutral particles

Background

Istvan Pusztai 2016 Vienna
Neutral momentum transport

- Low concentration, but high mobility
  - Can affect momentum transport strongly

**Result:** $E_r$ is determined by major radius of neutrals
  - Control possible
  - e.g. fueling location

- Neutrals may be concentrated near X-point
  - Move X-point to change location of neutrals

- Consider intrinsic rotation (i.e. no torque) and steady state
  - ITER-relevant case
  - Momentum flux ($\propto n_n$) vanishes, independent of $n_n$

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Analytical results


\[ V_\zeta \propto \frac{dT_i}{d\psi} F_V, \text{ neutral density is localized to } \theta_* \]
Neutral momentum flux

- Charged particle momentum equation, no torque, steady state

\[ \langle e_a \Gamma_a \cdot \nabla \psi \rangle = \langle R\hat{\phi} \cdot \nabla \cdot \pi_a \rangle - \sum_b \langle R\hat{\phi} \cdot R_{a,b} \rangle \approx 0 \]

- For neutrals, viscosity balanced by friction on ions

\[ 0 = \langle R\hat{\phi} \cdot \nabla \cdot \pi_n \rangle - \langle R\hat{\phi} \cdot R_{n,i} \rangle \]

- Require ambipolar flux

\[ 0 = \sum_{a\&n} \langle e_a \Gamma_a \cdot \nabla \psi \rangle \approx \langle R\hat{\phi} \cdot \nabla \cdot \pi_n \rangle \]

\[ \Rightarrow \langle R\hat{\phi} \cdot \pi_n \cdot \nabla \psi \rangle = 0 \quad \text{with no external torque} \]

- Gives constraint for \( E_r \)
Short mean-free-path neutral kinetic equation

- Neutral dynamics is dominated by charge exchange with ions

\[ \mathbf{v} \cdot \nabla f_n = C_{\text{CX}}(f_n) \approx \frac{1}{\tau} \left( \frac{n_n}{n_i} f_i - f_n \right) \]

where \( \tau^{-1} = n_i \langle \sigma v \rangle_{\text{CX}} \)

- Solve perturbatively in short CX mean-free-path
  - \( \lambda_n \approx 0.8 \text{ cm} \) for \( n_i = 10^{20} \text{ m}^{-3}, \sigma_{\text{CX}} = 6 \times 10^{-15} \text{ cm}^2 \)
  - \( f_n \) is calculated in terms of \( f_i \)
  - Momentum flux moment of \( f_n \) written as moment of \( f_i \)

Solution for ion distribution

- Use PERFECT code\textsuperscript{2} to compute $f_i$
  - neglect finite orbit-width effects here (radially local)
- Inputs to each PERFECT call:
  - magnetic geometry
  - ion temperature gradient $d_{\psi}T_i$
  - radial electric field $d_{\psi}\Phi_0$
- Outer loop iterates to find $d_{\psi}\Phi_0$, calling PERFECT to compute $f_i$

Neutral momentum transport

- Neoclassical $f_i$ from PERFECT + Short mean-free-path neutral solution → Momentum flux carried by neutrals

- Iterate to find $E_r$ so that momentum flux vanishes

- Limitations
  - Neutrals dominate momentum transport
    \[
    \frac{n_n}{n_i} \gtrsim 3 \cdot 10^{-7} \frac{L_n}{L} \frac{n_i^{19/m^3} q^2}{B^2_{[T]} T_{i[keV]}} \sim 10^{-6} - 10^{-4}
    \]
  - Ion distribution is not directly affected by neutrals
    \[
    \frac{n_n}{n_i} \lesssim 0.08 \frac{L_n}{R} \frac{n_i^{19/m^3} \sqrt{T_{i[keV]}}}{B_{[T]}} \sim 10^{-3}
    \]
  - Short neutral CX mean-free-path, $\lambda_{CX} \ll L$
  - Local neoclassical solutions $L \gg \rho_{pi}$ (no pedestal)
Simulations

- Investigate effect of poloidally localized neutral density
- ITER-like parameters, near separatrix
  - Model equilibria [Cerfon & Freidberg]
  - Simulate $\psi_N = 0.95$ surface
  - Baseline parameters $n_i = 10^{20} \text{ m}^{-3}$, $T_i = 300 \text{ eV} \Rightarrow \nu_\star = 6.95$
- Scanning magnetic geometry and/or neutral location
• $\theta$: baseline geometry, neutrals located at different poloidal angles

• $\delta$, $R_X$ and $Z_X$: neutrals located at bottom of the flux surface (close to X-point), triangularity, and the horizontal and vertical position of the X point is varied, respectively.
Results: major radius of neutrals determines $E_r$, rotation

- All 4 types of scan collapse, $R_n$ determines the behavior\(^3\)

Baseline parameters: cyan $n = 10^{20} \text{m}^{-3}$, $T_i = 300 \text{eV}$, $\nu_* = 6.95$
Others: blue $\nu_* = 0.695$; yellow $\nu_* = 69.5$; red $\nu_* = 695$
$1/L_T = 10 \text{m}^{-1}$, $1/L_n = 0$
(arbitrary choices, but $V_\varsigma \propto 1/L_T$ and $E_r$ is simply offset by $a/L_n$)

Impurity rotation

- We can also add an impurity species, here trace Carbon ($Z = 6, \frac{n_C}{n_e} = 0.0004$)
- Show scan in poloidal position of neutrals:

![Graph showing impurity rotation](image)

Lines Deuterium; Crosses Carbon

Baseline parameters: cyan $n = 10^{20} \text{ m}^{-3}$, $T_i = 300 \text{ eV}$, $\nu_* = 6.95Z_{\text{eff}}$

Others: blue $\nu_* = 0.695Z_{\text{eff}}$; yellow $\nu_* = 69.5Z_{\text{eff}}$; red $\nu_* = 695Z_{\text{eff}}$
Summary

- Calculate $E_r$ and rotation when neutral viscosity dominates
- Major radius of neutrals controls solution
- Ways to influence edge rotation:
  - move X-point
  - change fueling location

Future work

- Experimental modeling
  - Rotation measurements
  - Inboard vs. outboard fueling?
  - Move X-point (but same target configuration)?

- Theory/code developments
  - Allow for torque from neutral beam injection
  - Higher neutral density
    - Affects ion distribution function
  - Density pedestal
    - Requires radially-global solution
    - Non-linear solve to obtain $\Phi_0(\psi)$