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?

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JET results:

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

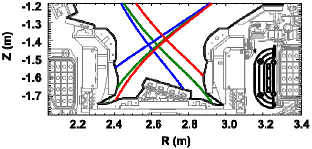


Fig 1a (above): Divertor geometry used in JET (horizontal=blue; corner=green; vertical=red). The cryogenic pump is also pictured in black.

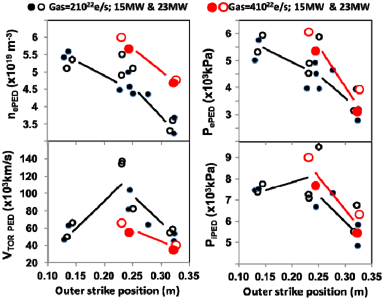


***Fig 5:** Clockwise from top to bottom: pedestal density, electron and ion pedestal pressure and toroidal velocity at the top of the pedestal for the three divertor configurations at different power and gas injection rate.*

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

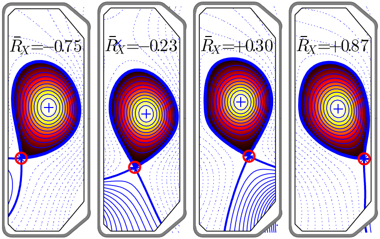


FIG. 1. Representative plasma geometries, varying $\bar{R}_X$, in LSN (lower row) and USN (upper row) configurations.

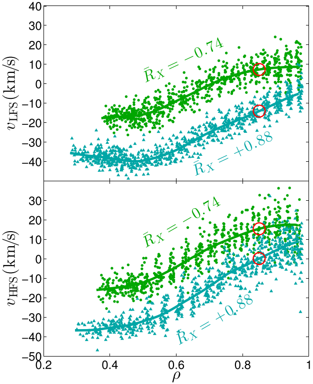


FIG. 6. LFS and HFS carbon velocity measurement points (dots) and fitted profiles (lines) for an HFS ($\bar{R}_X = -0.74$) and LFS ($\bar{R}_X = +0.88$) X-point. The approximate core-edge boundary location $\rho = 0.85$ is marked with red circles. CXRS measurement error bars are comparable to point scatter.

T. Stoltzfus-Dueck et al., *Physics of Plasmas* **22**, 056118 (2015).

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, $\rho_\mathrm{p}/L_\perp \sim \mathcal{O}(1)$
  - **transport by neutral particles**

Neutral momentum transport

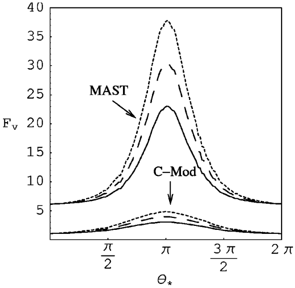
- Low concentration, but high mobility
  - Can affect momentum transport strongly
- **Result: E_r is determined by major radius of neutrals**
  - Control possible
  - e.g. fueling location[1]
- Neutrals may be concentrated near X-point
  - Move X-point to change location of neutrals
- Consider intrinsic rotation (i.e. no torque) and steady state
  - ITER-relevant case
  - Momentum flux ($\propto n_\mathrm{n}$) vanishes, independent of n_n

[1] H-mode access in MAST easier with inboard gas-puff: A.R. Field et al., *PPCF* **46**, 981 (2004).

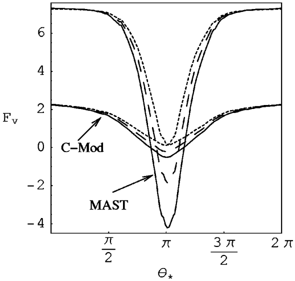
Analytical results

- Analytical results: P. Helander, T. Fülöp, and P. J. Catto, *Physics of Plasmas* **10**, 4396 (2003).

Pfirsch-Schlüter



banana



$V_\zeta \propto \frac{dT_i}{d\psi} F_V$, neutral density is localized to θ_*

Neutral momentum flux

- Charged particle momentum equation, no torque, steady state

$$\langle e_a \boldsymbol{\Gamma}_a \cdot \nabla\psi \rangle = \underbrace{\left\langle R\hat{\phi} \cdot \nabla \cdot \boldsymbol{\pi}_a \right\rangle}_{\approx 0} - \sum_b \left\langle R\hat{\phi} \cdot \mathbf{R}_{a,b} \right\rangle$$

- For neutrals, viscosity balanced by friction on ions

$$0 = \left\langle R\hat{\phi} \cdot \nabla \cdot \boldsymbol{\pi}_{\mathrm{n}} \right\rangle - \left\langle R\hat{\phi} \cdot \mathbf{R}_{\mathrm{n,i}} \right\rangle$$

- Require ambipolar flux

$$0 = \sum_{a\&\mathrm{n}} \langle e_a \boldsymbol{\Gamma}_a \cdot \nabla\psi \rangle \approx \left\langle R\hat{\phi} \cdot \nabla \cdot \boldsymbol{\pi}_{\mathrm{n}} \right\rangle$$

$$\Rightarrow \left\langle R\hat{\phi} \cdot \boldsymbol{\pi}_{\mathrm{n}} \cdot \nabla\psi \right\rangle = 0 \quad \text{with no external torque}$$

- Gives constraint for E_r

Short mean-free-path neutral kinetic equation

- Neutral dynamics is dominated by charge exchange with ions

$$\mathbf{v} \cdot \nabla f_{\mathrm{n}} = C_{\mathrm{CX}}(f_{\mathrm{n}}) \approx \frac{1}{\tau}\left(\frac{n_{\mathrm{n}}}{n_{\mathrm{i}}} f_{\mathrm{i}} - f_{\mathrm{n}}\right)$$

  where $\tau^{-1} = n_{\mathrm{i}} \langle \sigma v \rangle_{\mathrm{CX}}$
- Solve perturbatively in short CX mean-free-path
  - $\lambda_{\mathrm{n}} \approx 0.8\,\mathrm{cm}$ for $n_i = 10^{20}\,\mathrm{m}^{-3}$, $\sigma_{\mathrm{CX}} = 6 \times 10^{-15}\,\mathrm{cm}^2$
- f_{n} is calculated in terms of f_{i}
- Momentum flux moment of f_{n} written as moment of f_{i}

[P.J. Catto, P. Helander, J.W. Connor, and R.D. Hazeltine, *Phys. Plasmas* **5**, 3961 (1998)]

Solution for ion distribution

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

[2] M. Landreman, F.I. Parra, P.J. Catto, D.R. Ernst, and I. Pusztai, *PPCF* **56**, 045005 (2014).

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

$$\frac{n_\mathrm{n}}{n_\mathrm{i}} \gtrsim 3 \cdot 10^{-7} \frac{L_\mathrm{n}}{L} \frac{n^2_{\mathrm{i}[10^{19}/\mathrm{m}^3]} q^2}{B^2_{[\mathrm{T}]} T_{\mathrm{i}[\mathrm{keV}]}} \sim 10^{-6} - 10^{-4}$$

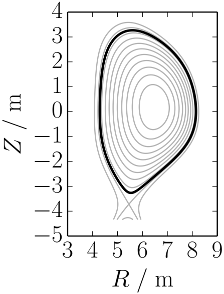
  - Ion distribution is not directly affected by neutrals

$$\frac{n_\mathrm{n}}{n_\mathrm{i}} \lesssim 0.08 \frac{L_\mathrm{n}}{R} \frac{n_{\mathrm{i}[10^{19}\mathrm{m}^{-3}]} \sqrt{T_{\mathrm{i}[\mathrm{keV}]}}}{B_{[\mathrm{T}]}} \sim 10^{-3}$$

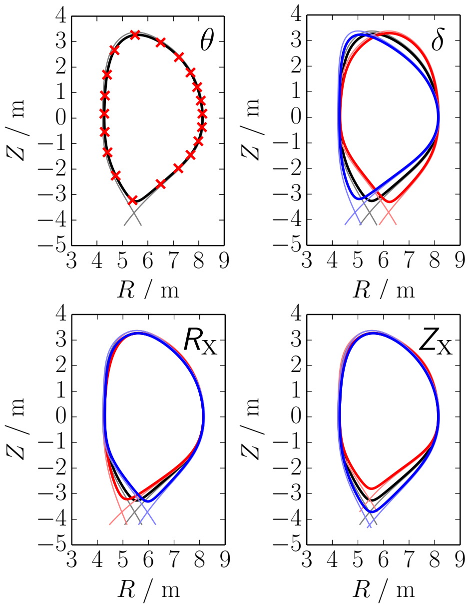
  - Short neutral CX mean-free-path, $\lambda_\mathrm{CX} \ll L$
  - Local neoclassical solutions $L \gg \rho_{p\mathrm{i}}$ (no pedestal)

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 $n_\mathrm{i} = 10^{20}\,\mathrm{m}^{-3}$, $T_\mathrm{i} = 300\,\mathrm{eV} \Rightarrow \nu_* = 6.95$
- Scanning magnetic geometry and/or neutral location



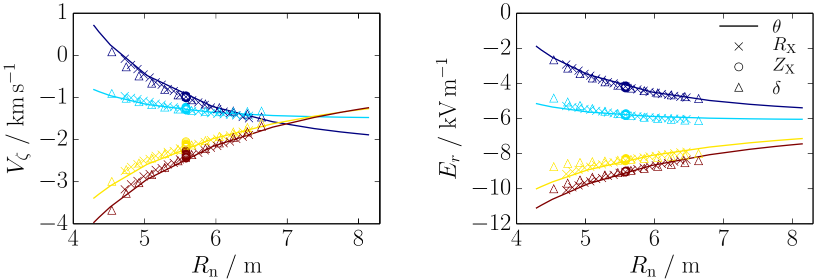
Baseline geometry



- $\boldsymbol{\theta}$: baseline geometry, neutrals located at different poloidal angles
- $\boldsymbol{\delta}$, $\mathbf{R_X}$ and $\mathbf{Z_X}$: 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]

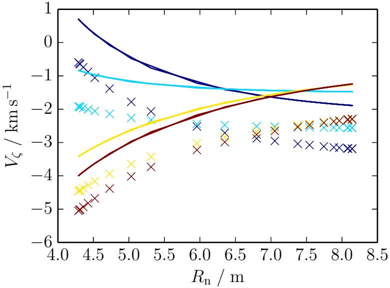


Baseline parameters: cyan $n = 10^{20}\,\mathrm{m}^{-3}$, $T_i = 300\,\mathrm{eV}$, $\nu_* = 6.95$
Others: blue $\nu_* = 0.695$; yellow $\nu_* = 69.5$; red $\nu_* = 695$
$1/L_T = 10\,\mathrm{m}^{-1}$, $1/L_n = 0$
(arbitrary choices, but $V_\zeta \propto 1/L_T$ and E_r is simply offset by a/L_n)

[3] J. Omotani, I. Pusztai, T. Fülöp (2016) "Plasma rotation from momentum transport by neutrals in tokamaks" *arXiv:1604.08028*

Impurity rotation

- We can also add an impurity species, here trace Carbon ($Z = 6$, $n_{\mathrm{C}}/n_{\mathrm{e}} = 0.0004$)
- Show scan in poloidal position of neutrals:



Lines Deuterium; Crosses Carbon

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

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

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

J. Omotani, I. Pusztai, T. Fülöp (2016) "Plasma rotation from momentum transport by neutrals in tokamaks" *arXiv:1604.08028*

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 $\Phi_0(\psi)$