Neutral Regulated Flow in the Edge Plasma

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Transport by Neutrals

- Plasma rotation stabilises resistive wall modes, affects pedestal stability
- Flow shear important for L-H transition, pedestal performance
- Intrinsic rotation crucial for future machines with burning plasma, since external torque from heating will be negligible
- Edge rotation sets boundary condition for core rotation, so affects whole plasma
  - Current experimental interest [1]
- Neutrals important in the plasma edge
  - Known to affect plasma performance [2]
- Due to high cross-field mobility, neutrals important for momentum transport, even at low concentration $n_\mathrm{n}/n_\mathrm{i} \sim 10^{-4}$
- Determining radial transport of toroidal angular momentum fixes radial electric field and plasma flow

Neutral Closure

- Simple model for charge-exchange collisions, constant cross-section

$$\frac{\partial f_\mathrm{n}}{\partial t} + \boldsymbol{v}\cdot\nabla f_\mathrm{n} = \langle\sigma v\rangle_\mathrm{X}\left(n_\mathrm{n} f_\mathrm{i} - n_\mathrm{i} f_\mathrm{n}\right)$$

- Steady state, $\partial f_\mathrm{n}/\partial t = 0$, charge-exchange collisions dominate

$$f_\mathrm{n}^{(0)} = \frac{n_\mathrm{n}}{n_\mathrm{i}} f_\mathrm{i}; \quad \boldsymbol{v}\cdot\nabla f_\mathrm{n}^{(0)} = -\langle\sigma v\rangle_\mathrm{X} n_\mathrm{i} f_\mathrm{n}^{(1)} \quad \Rightarrow \quad f_\mathrm{n}^{(1)} = -\tau_\mathrm{X}\boldsymbol{v}\cdot\nabla\left(\frac{n_\mathrm{n}}{n_\mathrm{i}} f_\mathrm{i}\right)$$

  where $\tau_\mathrm{X} = \left(\langle\sigma v\rangle_\mathrm{X} n_\mathrm{i}\right)^{-1}$
- For small neutral density $n_\mathrm{n}/n_\mathrm{i} \lesssim 10^{-3}$, ion distribution unperturbed, taken as input

Neutral Momentum Flux

- With f_n, calculate average radial flux of toroidal angular momentum

$$\left\langle R\hat{\boldsymbol{\zeta}}\cdot\boldsymbol{\pi}_\mathrm{n}\cdot\nabla\psi\right\rangle = \left\langle R\hat{\boldsymbol{\zeta}}\cdot m_\mathrm{i}\int d^3v\left(\boldsymbol{v}\boldsymbol{v} - \frac{1}{3}v^2\boldsymbol{I}\right) f_\mathrm{n}\cdot\nabla\psi\right\rangle$$
$$\approx \left\langle\frac{R}{n_\mathrm{i}}\frac{\partial n_\mathrm{n}}{\partial\psi}\int d^3v\left(\nabla\psi\cdot\boldsymbol{v}\right)^2\left(\hat{\boldsymbol{\zeta}}\cdot\boldsymbol{v}\right) f_\mathrm{i}\right\rangle$$

  where radial gradient of n_n dominates, and dropping $f_\mathrm{n}^{(0)}$ term
- Pick magnetic geometry and flux surface, solve local drift kinetic equation numerically with PERFECT [3], get guiding centre distribution $f_\mathrm{i,gc}$
- Particle distribution f_i is then

$$f_\mathrm{i}(\boldsymbol{r}) = f_\mathrm{i,gc}^\mathrm{M}(\boldsymbol{R}) + \delta f_\mathrm{i,gc}(\boldsymbol{R})$$
$$\approx f_\mathrm{i,gc}^\mathrm{M}(\boldsymbol{r}) - \boldsymbol{\rho}\cdot\nabla f_\mathrm{i,gc}^\mathrm{M}(\boldsymbol{r}) + \delta f_\mathrm{i,gc}(\boldsymbol{r})$$

  with $\boldsymbol{r}$ particle position, $\boldsymbol{R}$ guiding centre position and $\boldsymbol{\rho} = \boldsymbol{R} - \boldsymbol{r}$ gyro-radius vector
- Inputs: temperature, density gradients
  - Density gradient only affects electric field, not flow
- Constraint that steady-state momentum flux vanish, $\left\langle R\hat{\boldsymbol{\zeta}}\cdot\boldsymbol{\pi}_\mathrm{n}\cdot\nabla\psi\right\rangle = 0$, fixes radial electric field and plasma flow

Controlling Edge Flow

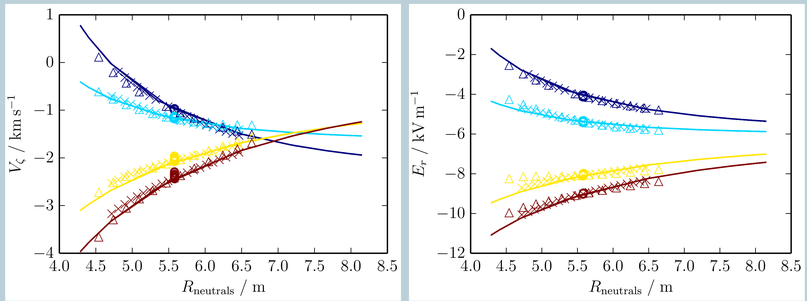

Figure 1: Toroidal flow velocity (left) and radial electric field (right) at outboard midplane. Lines show scan in poloidal position. Markers show scans in R_X (×), Z_X (○), δ (△). Colours show collisionality: cyan baseline $n_\mathrm{i} = 10^{20}\mathrm{m}^{-3}$ and $T_\mathrm{i} = 300\mathrm{eV}$, blue 10 times lower, yellow and red 10 and 100 times higher. Absolute values calculated assuming gradient scale $L_\mathrm{T} = 10\,\mathrm{cm}$

- Two kinds of scan:
  1. Geometry fixed to reference case, poloidal position of neutrals varied, representing different fuelling locations
  2. Neutrals localised at X-point, representing target recycling or private-flux-region fuelling, geometry changed in various ways
- Most important parameters: major radius where neutrals are localised, R_neutrals, and plasma collisionality
- Toroidal flow generally counter-current, stronger for higher collisionality
- Electric field always inwards, stronger for higher collisionality
- Effect of collisionality enhanced when R_neutrals smaller
- Position of X-point, R_X and Z_X, and triangularity, δ, affect flow, electric field only by changing R_neutrals: changes to geometry make little difference
- Agrees well with previous analytical work [4], in appropriate limit

Effect of Geometry

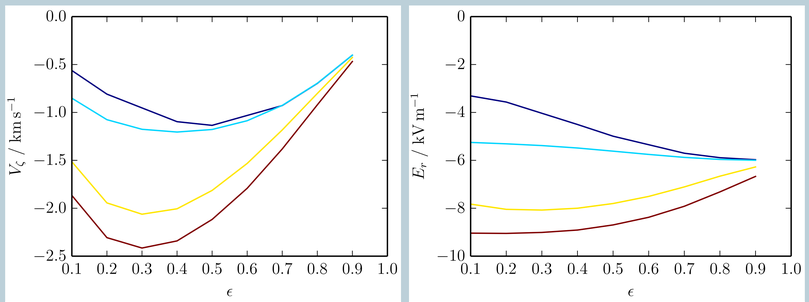

Figure 2: Toroidal flow velocity (left) and radial electric field (right) at outboard midplane versus inverse aspect ratio ϵ. Colours show collisionality as in Figure 1. Absolute values assuming $L_\mathrm{T} = 10\,\mathrm{cm}$

- Lowest order shaping parameters, inverse aspect ratio ϵ and elongation κ, affect flow and electric field directly, not just through R_neutrals as in Figure 1
- As ϵ varies there is extremum in the toroidal flow
- Collisionality dependence of flow and electric field suppressed for large ϵ
- κ does not affect electric field, but toroidal flow decreases in magnitude as κ increases

Model ITER Equilibria

- Use analytical equilibria given in [5]
- Geometry specified by fixing shape of boundary surface.
- Parameters are inverse aspect ratio ϵ, elongation κ, triangularity δ and X-point position $(R_\mathrm{X}, Z_\mathrm{X})$
- Also two constraints, we use the plasma current and toroidal β
- Scales set by R_0, major radius of plasma centre, and B_0, vacuum toroidal field at R_0
- Boundary points of the plasma are:
  - Inner point at $((1-\epsilon)R_0, 0)$
  - Outer point at $((1+\epsilon)R_0, 0)$
  - High point at $((1-\delta\epsilon)R_0, \kappa\epsilon R_0)$
  - Lower X-point at $(R_\mathrm{X}, Z_\mathrm{X})$
- ITER-like baseline case has
  - $\epsilon = 0.32$, $\kappa = 1.7$, $\delta = 0.33$
  - $R_\mathrm{X} = (1 - 1.1\delta\epsilon)R_0$, $Z_\mathrm{X} = -1.1\kappa\epsilon R_0$
  - $I_\mathrm{P} = 15\,\mathrm{MA}$, $\beta_\mathrm{t} = 0.05$
  - $R_0 = 6.2\,\mathrm{m}$, $B_0 = 5.3\,\mathrm{T}$
- Safety factor q constant when geometry changed, instead of I_P

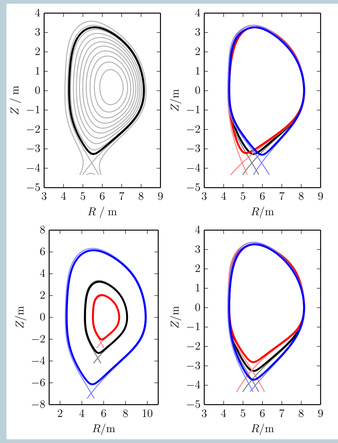

Figure 3: Flux surface shapes, clockwise from top left: baseline ITER equilibrium, changing R_X, changing Z_X, changing ϵ. Black/grey show baseline case. Thick lines show $\psi_\mathrm{N} = 0.95$ surface used for simulations

Conclusions

- Framework to investigate effect of neutrals on edge flow and electric field
- Find counter-current rotation and inward radial electric field
- Flow and electric field largely determined by major radius where the neutrals are localised, R_neutrals, and plasma collisionality
- Only lowest order shaping parameters, inverse aspect ratio ϵ and elongation κ, have significant effect in themselves

Future Work

- Include reaction of ion distribution to neutrals, allowing higher neutral concentrations
- Investigate interaction between neutral transport and global neoclassical effects driven by steep gradients

[1] T Stoltzfus-Dueck, A N Karpushov, O Sauter, B P Duval, B Labit, H Reimerdes, W A J Vijvers, and Y Camenen. X-point-position-dependent intrinsic toroidal rotation in the edge of the TCV tokamak. *Physical Review Letters*, 114:245001, Jun 2015.

[2] E Joffrin, J Garcia, P Tamain, E Belonohy, H Bufferand, P Buratti, C Challis, E Delabie, P Drewelow, D Dodt, et al. Impact of divertor geometry on ITER scenarios performance in the JET metallic wall. In *25th IAEA Fusion Energy Conference (FEC 2014)*, 2014.

[3] M Landreman, F I Parra, P J Catto, D R Ernst, and I Pusztai. Radially global δf computation of neoclassical phenomena in a tokamak pedestal. *Plasma Physics and Controlled Fusion*, 56(4):045005, 2014.

[4] P Helander, T Fülöp, and P J Catto. Controlling edge plasma rotation through poloidally localized refueling. *Physics of Plasmas*, 10(11):4396–4404, 2003.

[5] A J Cerfon and J P Freidberg. "One size fits all" analytic solutions to the Grad-Shafranov equation. *Physics of Plasmas*, 17(3), 2010.

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