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
- Neutrals important in the plasma edge
- Known to affect plasma performance
- Due to high cross-field mobility, neutrals important for momentum transport, even at low concentration $n_i/n_e \sim 10^{-3}$
- 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
  $$\frac{df_e}{dt} + \mathbf{v} \cdot \nabla f_e = \left( -\sigma v \right) \frac{n_i}{n_e} (n_i f_e - n_i f_i)$$
- Steady state, $\partial f_e/\partial t = 0$, charge-exchange collisions dominate
  $$f_e^{(i)} = \frac{n_i}{n_e} f_i \quad \mathbf{v} \cdot \nabla f_i^{(i)} = -\left( \sigma v \right) \frac{n_i}{n_e} f_i \Rightarrow f_i^{(i)} = f_e = \frac{n_i}{n_e} f_i$$
  where $\gamma = \frac{n_i}{n_e}$
  - For small neutral density $n_i/n_e \leq 10^{-3}$, ion distribution unperturbed, taken as input

Neutral Momentum Flux

- With $f_e$, calculate average radial flux of toroidal angular momentum
  $$\int \left( R^2 \mathbf{\nabla} \cdot \mathbf{R} \mathbf{\nabla} \right) f_e = \left( R^2 \mathbf{\nabla} \cdot \mathbf{R} \mathbf{\nabla} \right) f_i + \frac{d}{dt} \left( \frac{1}{2} \mathbf{R} \mathbf{\nabla} \cdot \mathbf{R} ight)$$
  $$\approx \frac{d}{dt} \frac{d}{dt} \left( \frac{1}{2} \mathbf{R} \mathbf{\nabla} \cdot \mathbf{R} ight)$$
  where radial gradient of $n_i$ dominates, and dropping $f_e^{(i)}$ term
- Pick magnetic geometry and flux surface, solve local drift kinetic equation numerically with PERFECT [3], get guiding centre distribution $f_e^{(i)}$
- Particle distribution $f_i$ is then
  $$f_i(r) = f_i^{(i)}(R) + \delta f_i(R)$$
  $$\approx f_i^{(i)}(R) - \rho \left( R \mathbf{\nabla} f_i^{(i)}(r) + \delta f_i^{(i)}(r) \right)$$
  with $r$ particle position, $R$ guiding centre position and $\rho = R - r$ gyroradius-vector
- Inputs: temperature, density gradients
  - Density gradient only affects electric field, not flow
- Constraint that steady-state momentum flux vanish, $\left( R^2 \mathbf{\nabla} \cdot \mathbf{R} \mathbf{\nabla} \right) f_i = 0$, fixes radial electric field and plasma flow

Effect of Geometry

- Lowest order shaping parameters, inverse aspect ratio $\epsilon$ and elongation $\kappa$, affect flow and electric field directly, not just through $R_{\text{tor}}$, as in Figure 1
- $\epsilon$ varies there is extremum in the toroidal flow
- Collisionality dependence of flow and electric field suppressed for large $\epsilon$
- $\kappa$ does not affect electric field, but toroidal flow decreases in magnitude as $\kappa$ increases

Controlling Edge Flow

- 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, $R_{\text{tor}}$, 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 $R_{\text{tor}}$ smaller
- Position of X-point, $R_x$ and $Z_{\text{X}}$, and triangularity, $\delta$, affect flow, electric field only by changing $R_{\text{tor}}$, changes to geometry make little difference
- Agrees well with previous analytical work [4], in approximate limit

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

Model ITER Equilibria

- Use analytical equilibria given in [5]
- Geometry specified by fixing shape of boundary surface
- Parameters are inverse aspect ratio $\epsilon$, elongation $\kappa$, triangularity $\delta$ and X-point position $(R_X, Z_X)$
- Also two constraints, we use the plasma current and toroidal $\beta$
- Scales set by $R_0$, major radius of plasma centre, and $B_o$, 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 $(1 - \delta) R_0, x \pi R_0$
  - Lower X-point at $(R_X, Z_X)$
- ITER-like baseline case has
  - $\epsilon = 0.32$, $\kappa = 1.7$, $\delta = 0.33$
  - $R_0 = 1.1 \text{m} R_0$, $Z_0 = -1.1 \pi R_0$
  - $I_p = 15 \text{MA}$, $\beta_i = 0.05$
  - $B_0 = 6.2 \text{mT}$, $B_0 = 5.3 \text{T}$
- Safety factor $\nu$ constant when geometry changed, instead of $I_p$

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, $R_{\text{tor}}$, and plasma collisionality
- Only lowest order shaping parameters, inverse aspect ratio $\epsilon$ and elongation $\kappa$, have significant effect in themselves

Figure 1: Toroidal flow velocity (left) and radial electric field (right) at outboard midplane. Lines show scan in poloidal position. Markers show scans in $R_X$, $Z_X$, $\delta$ ($\epsilon$). Colours show collisionality: cyan baseline $n_i = 10^{22} \text{m}^{-3}$ and $T_i = 300 \text{eV}$, blue 10 times lower, yellow and red 10 and 100 times higher. Absolute values calculated assuming gradient scale $L_T = 10 \text{cm}$

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

Figure 3: Flux surface shapes, clockwise from top left: baseline ITER equilibrium, changing $R_X$, changing $Z_X$, changing $\epsilon$. Black/grey show baseline case. Thick lines show $\gamma\beta = 0.95$ surface used for simulations


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