RMP-driven transport in the pedestal

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MHD Mode-control meeting, November 2010
Outline

• Introduction and motivation for the key questions:
  1. Can locked-mode bifurcations occur in the edge?
  2. How does the transport caused by suppressed islands scale to ITER?

• Selected experimental results
• Theoretical considerations
• Summary
There are 2 possible solutions in the presence of an RMP

- The two solutions are:
  - the suppressed island state (VMEC, IPEC): $w/w_{vac} < 0.1$
  - the reconnected island state (PIES, SURFMN, HINT): $w/w_{vac} \sim 1$

- Which one of these two states is realized in an experiment depends on the history of the plasma (hysteresis).
How can we find which state is realized in an experiment?

- The transition between states is easily observable: it is the surest way to determine the state.

R. Buttery & COMPASS-D group, Nucl. Fusion 1999
The rotation in the edge must lock to create magnetic chaos

MF Heyn, IB Ivanov, SV Kasilov et al.
Nucl. Fusion 2008
The rotation in the edge must lock to create magnetic chaos

- There is generally no sign of *edge* locking or unlocking in RMP H-mode experiments.

MF Heyn, IB Ivanov, SV Kasilov et al. Nucl. Fusion 2008
The rotation in the edge must lock to create magnetic chaos

- There is generally no sign of edge locking or unlocking in RMP H-mode experiments.
- There are 3 possible explanations:
  1. In the edge, island growth occurs continuously, without a locking bifurcation.
  2. The edge is always locked;
  3. The edge is never locked;

MF Heyn, IB Ivanov, SV Kasilov et al. Nucl. Fusion 2008
There are two questions

• Question 1: Can locked-mode bifurcations occur in the edge?
• Question 2: how does the transport caused by suppressed islands scale?
Selected Experimental results
Observed locked mode threshold higher for q=3 than 2

- Observations of q=3 locked-mode onset can yield insight into differences between edge and core locked modes.
- TEXTOR “DED” has similar amplitudes for 3/1 and 2/1 harmonics
- Despite this, the locked mode onset threshold is significantly higher for the q=3 than for the q=2 mode.
- This suggests that edge resonant surfaces are harder to lock.

Y. Liang and TEXTOR group, EPS 2004
In JET, evidence of edge locking seen following 2/1 locked mode

Three stages
1) Slow global braking
2) Dramatic braking, consistent with locking of the 2/1 mode
3) Abrupt spin-up of the edge rotation (R=3.70 m), which is consistent with mode penetration at the edge, causing magnetic chaos
   • A chaotic edge spins up the plasma: K.H. Finken et al., PRL 94
   • Correlated temporally with the flattening of $T_e$ at the edge

Y. Liang, Kirk, E. Nardon, and JET team
TEXTOR msmt of the locking threshold vs. rotation has a shift and an offset

- Shift shows that resonant braking acts on electrons (predicted theoretically, Waelbroeck, PoP 2003)
- The nonzero locked-mode threshold for stationary electrons is unaccounted for theoretically.
- This threshold may account for absence of edge locked-mode at q=8/3 in DIII-D.

Koslowski, NF 2003; De Bock, NF 2008
Theoretical results
RMP brake the electron rotation

\[ \partial_t \Omega + \mathbf{v} \cdot \nabla \Omega - \nabla \parallel J = \mu \nabla^4 \varphi. \]
\[ \partial_t \rho + \mathbf{v} \cdot \nabla \rho - \nabla \parallel J = D \nabla^2 \rho; \]
\[ \partial_t \psi + \mathbf{v} \cdot \nabla \psi - \nabla \parallel \rho = \eta J; \]
\[ \Omega = \nabla^2 \varphi \]

• It follows that edge LM can occur either through changes in \( \omega \) or changes in \( \omega^* \)


Koslowski, Nucl. Fusion ‘06
In the pedestal, braking the electrons accelerates the ions.

• Is the lack of evidence for an 8/3 island due to the lack of rotation, or to the “TEXTOR threshold”? 

Courtesy of T. Osborne
Suppressed RMPs cause particle transport

• The radial current that mediates the braking force exerted by RMPs also causes particle transport:
\[ \partial_t \Omega + \mathbf{v} \cdot \nabla \Omega - \left( \mu_0 v_A^2 / B_0 \right) \nabla \| J = \mu \nabla^2 \Omega. \]
\[ \partial_t n + \mathbf{v} \cdot \nabla n - \nabla \| J / e = D \nabla^2 n; \]
where \( \Omega = \nabla \times \mathbf{v} \) is the vorticity.

• Poloidal averaging yields the fluxes. In steady state,
\[ \Gamma_v = \frac{\langle B_r J \rangle}{n m_i} = \mu \frac{d \langle \Omega \rangle}{dr}. \]
\[ \Gamma_n = \langle \mathbf{v}_r n \rangle + \frac{\langle B_r J \rangle}{e B_0} = D \frac{d \langle n \rangle}{dr}; \]
The particle flux is composed of a convective flux term (Nardon JNM ‘07, Izzo and Joseph NF ‘09) and a magnetic flutter term.
The RMP causes a density jump across the layer

- The RMP causes a jump \([n]\).
- Neglecting the convective transport,
  \[\frac{\langle n \rangle}{n_0} = \left(\frac{\mu}{D}\right) \frac{d\langle v_\theta \rangle/dr}{\omega_{ci}}\]
  The density jump is \(\mu/D\) times the jump in the velocity gradient.
- Accounting for poloidal rotation damping, we find
  \[\frac{\langle n \rangle}{n_0} = \left(\frac{\mu}{D}\right) (\rho_\theta / L_n)^2 (\delta v_\theta / v_\ast),\]
  where \(d\) is the pedestal width.
Summary

• Vacuum island = locked mode.
• There are two key questions regarding RMP:
  1. Can locked-mode bifurcations occur in the edge? Yes!
  2. How does the transport caused by suppressed islands scale to ITER? ($\sim \rho_\theta^2$, may be addressed by JET)
• “non-resonant” transport (cf NTV) may be dominant.
• An unfavorable $\rho_*$ scaling could defeat RMP ELM suppression.
• According to EPED model, RMP need to act on pedestal width as well as gradients.