RMP-driven transport in the pedestal

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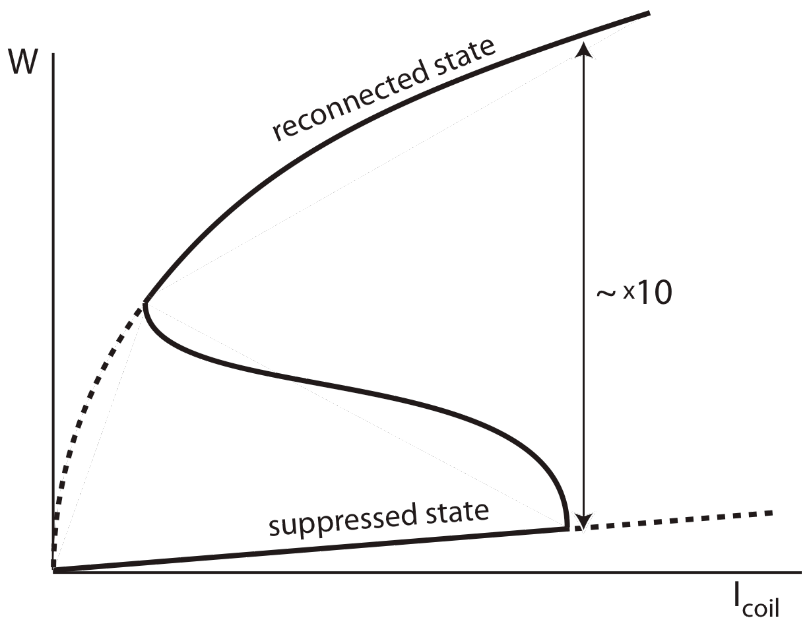
Outline

- 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

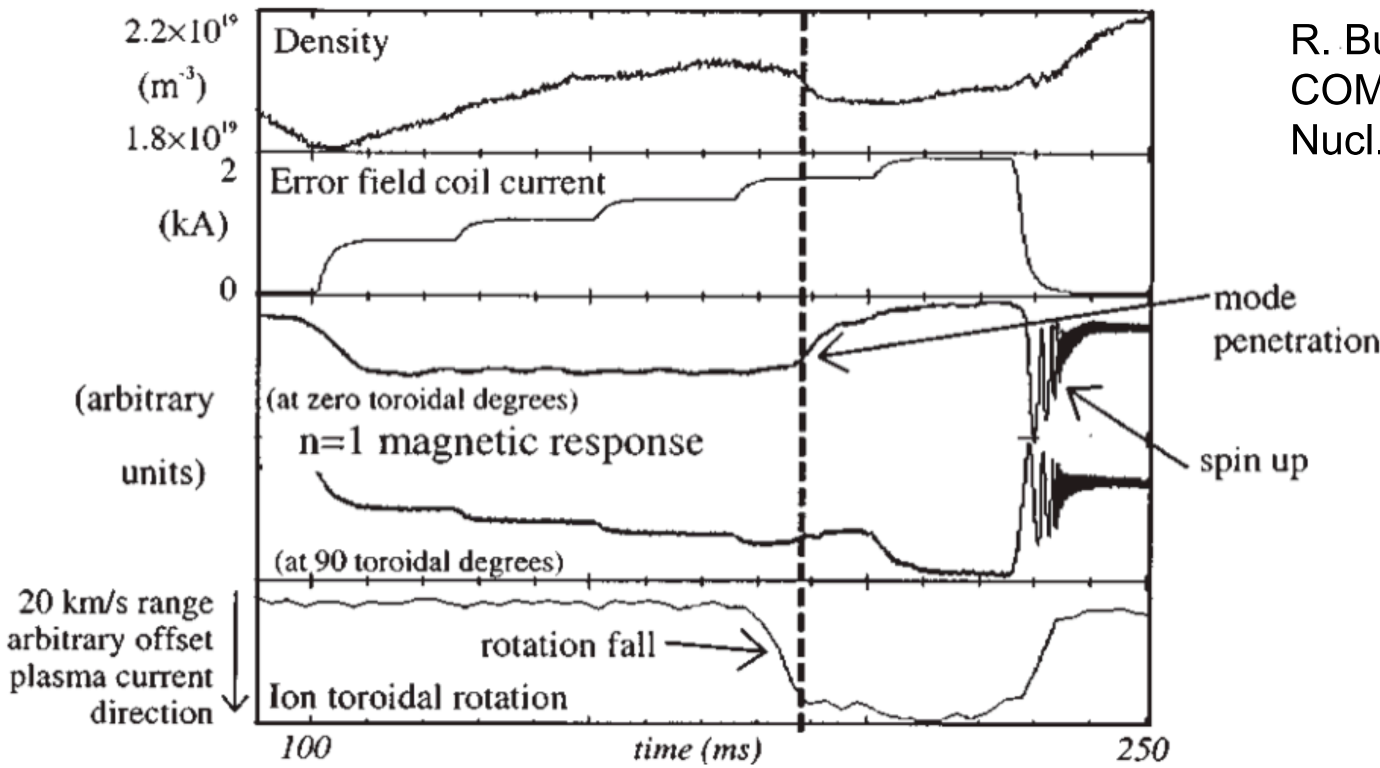
There are 2 possible solutions in the presence of an RMP



- 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).

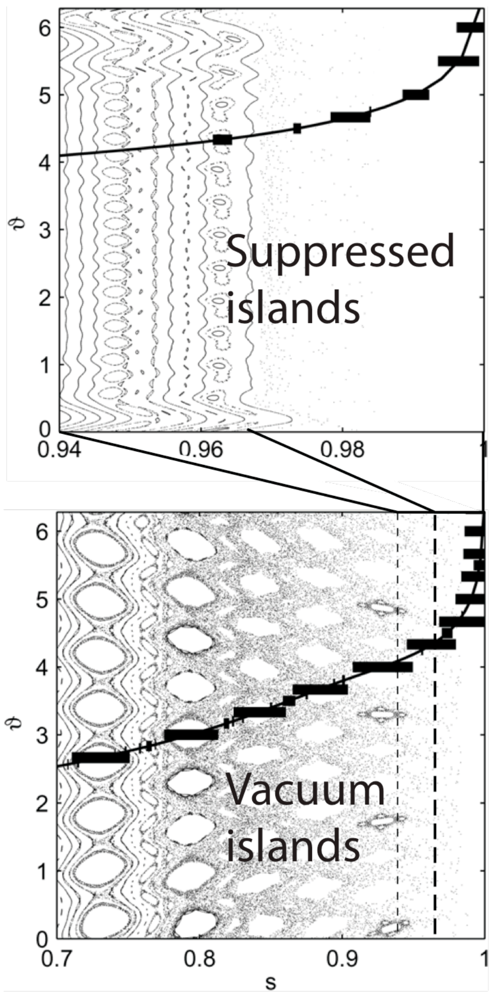
How can we find which state is realized in an experiment?

- 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

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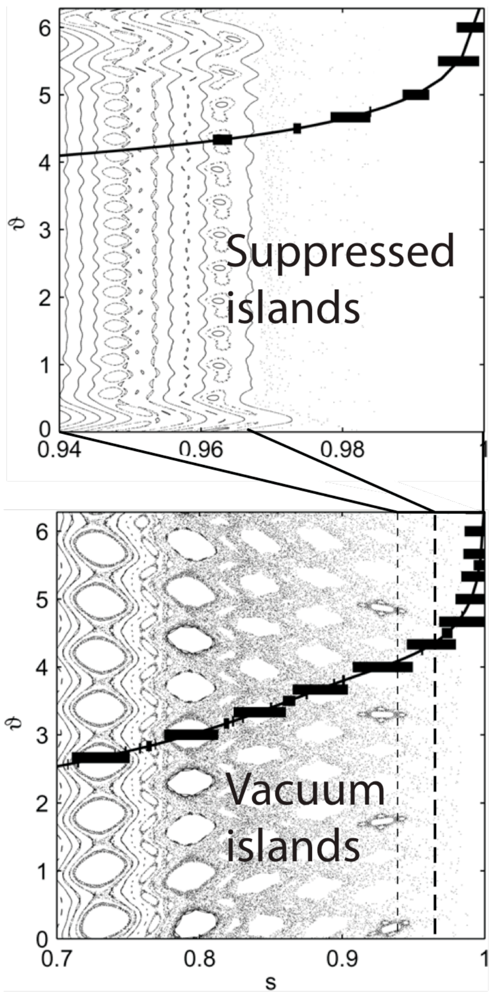

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- There is generally no sign of *edge* locking or unlocking in RMP H-mode experiments.

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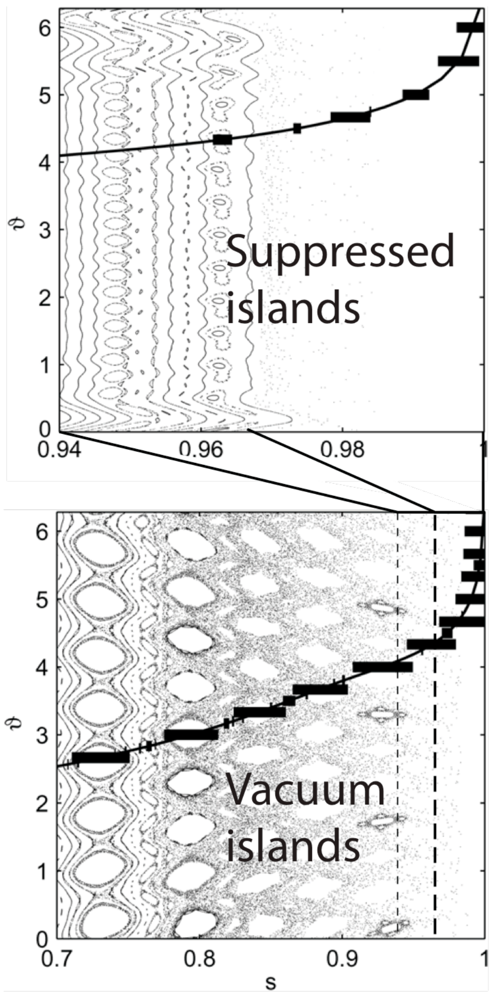


MF Heyn, IB Ivanov, SV Kasilov et al. Nucl. Fusion 2008

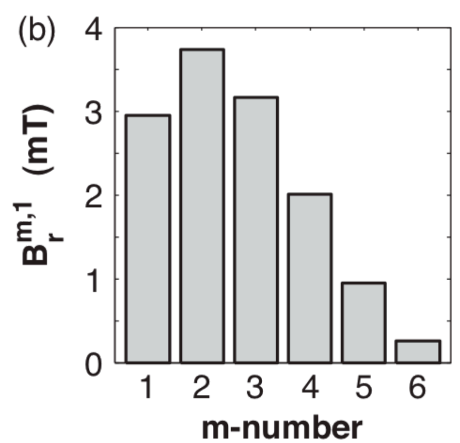
- There is generally no sign of *edge* locking or unlocking in RMP H-mode experiments.
- There are 3 possible explanations:
  1. In the edge, island growth occurs continuously, without a locking bifurcation.
  2. The edge is always locked;
  3. The edge is never locked;

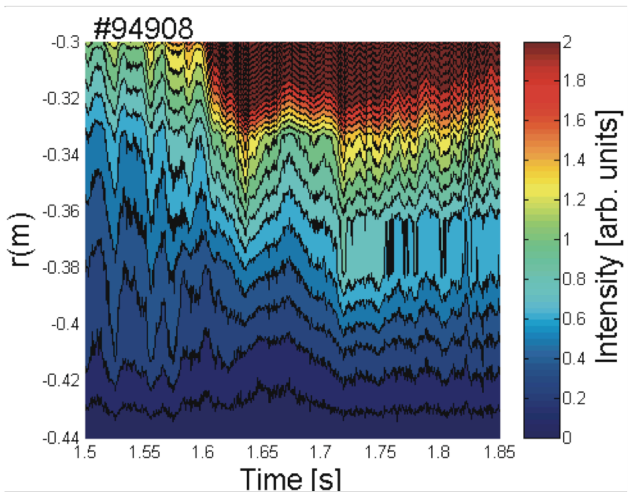
There are two questions

- 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

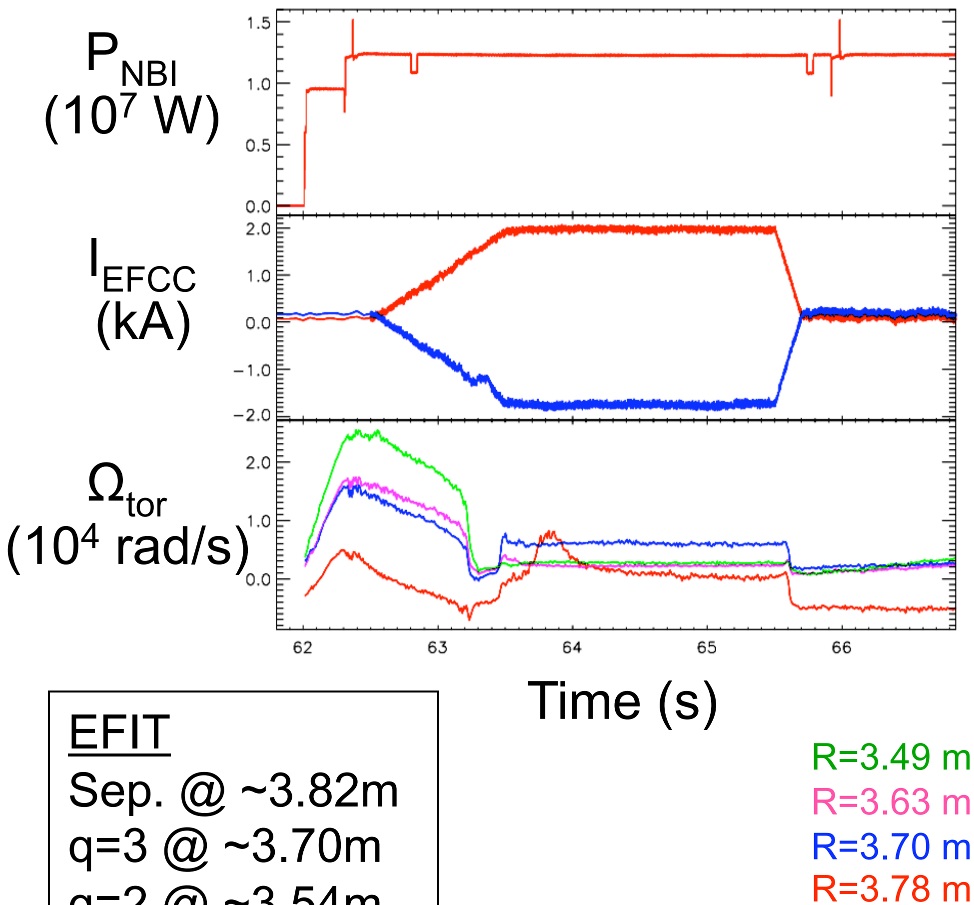




Y. Liang and TEXTOR group, EPS 2004

- 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.

In JET, evidence of edge locking seen following 2/1 locked mode



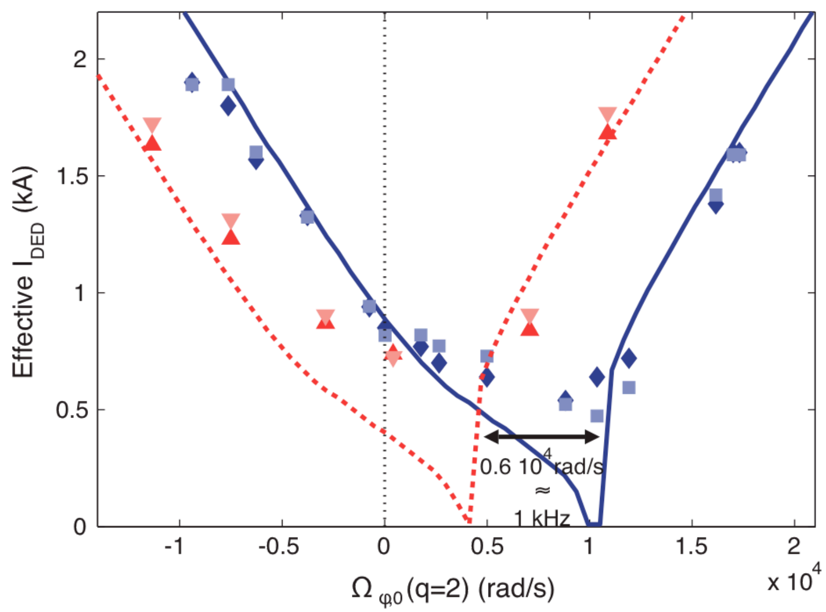
<u>EFIT</u>
Sep. @ ~3.82m
q=3 @ ~3.70m
q=2 @ ~3.54m

<u>Three stages</u>

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

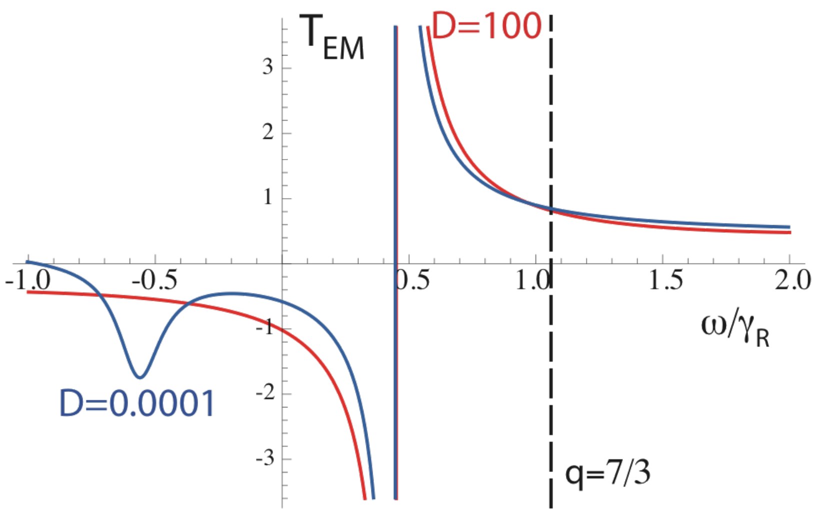


Koslowski, NF 2003; De Bock, NF 2008

- 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.

Theoretical results

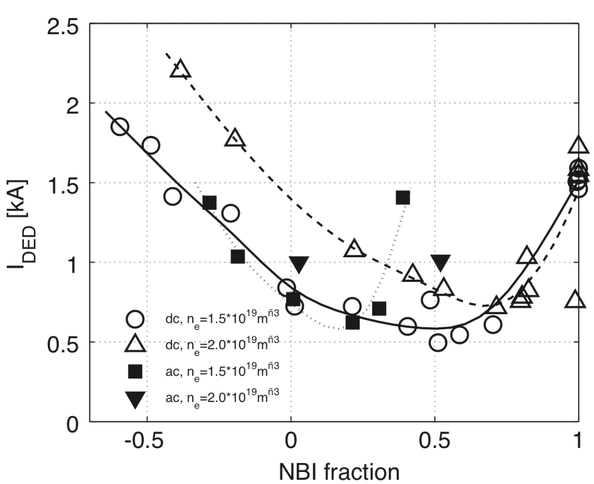
RMP brake the electron rotation

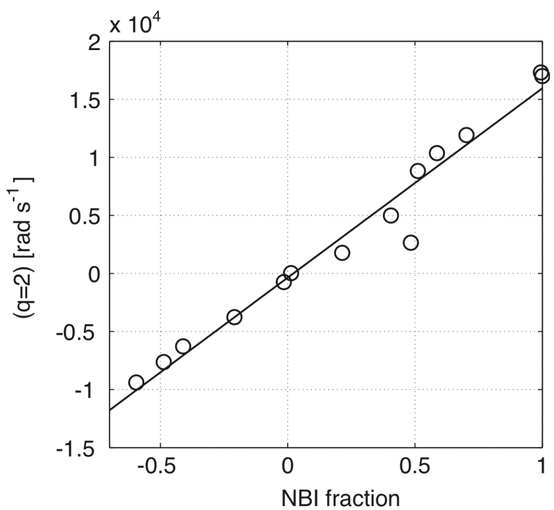


$$\partial_t \Omega + \mathbf{v}\cdot\nabla\Omega - \nabla_{||}J = \mu\nabla^4\varphi.$$
$$\partial_t p + \mathbf{v}\cdot\nabla p - \nabla_{||}J = D\nabla^2 p;$$
$$\partial_t\psi + \mathbf{v}\cdot\nabla\psi - \nabla_{||}p = \eta J;$$
$$\Omega=\nabla^2\varphi$$

•It follows that edge LM can occur either through changes in ω or changes in ω_*

(Waelbroeck, Phys.Plasma 2003).





Koslowski,
Nucl. Fusion '06

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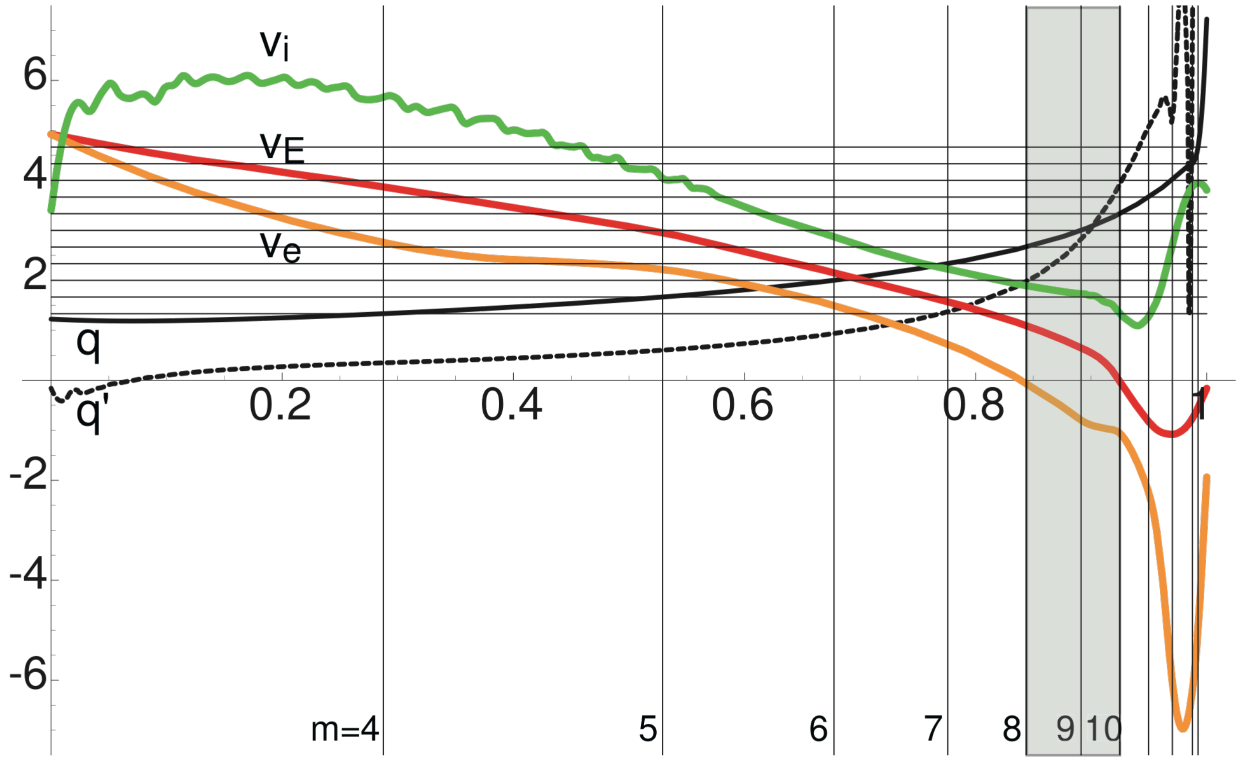
In the pedestal, braking the electrons accelerates the ions.

- 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

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Suppressed RMPs cause particle transport

- The radial current that mediates the braking force exerted by RMPs also causes particle transport:

  $\partial_t \Omega + \mathbf{v}\cdot\nabla\Omega - (\mu_0 v_A{}^2/B_0)\, \nabla_{||}J = \mu\nabla^2\Omega.$

  $\partial_t n + \mathbf{v}\cdot\nabla n - \nabla_{||}J/e = D\nabla^2 n;$

  where $\Omega=\nabla\mathrm{x}\,\mathbf{v}$ is the vorticity.

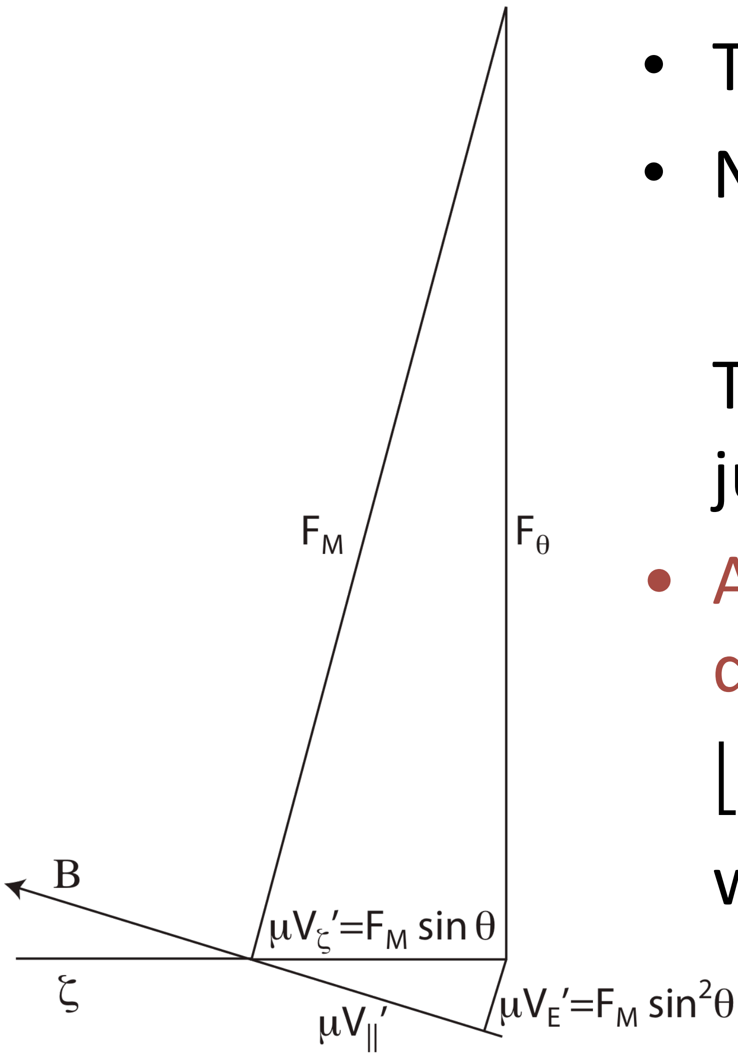
- Poloidal averaging yields the fluxes. In steady state,

  $\Gamma_V = \langle B_r J\rangle/nm_i = \mu\, d\langle\Omega\rangle/dr.$

  $\Gamma_n = \langle v_r n\rangle + \langle B_r J\rangle/eB_0 = D d\langle n\rangle/dr;$

  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 $\lfloor n \rceil$.
- Neglecting the convective transport,

  $$\lfloor <n> \rceil / n_0 = (\mu / D) \; \lfloor d<v_\theta>/dr \rceil / \omega_{ci}$$

  The density jump is μ/D times the jump in the *velocity gradient*.
- Accounting for poloidal rotation damping, we find

  $$\lfloor <n> \rceil / n_0 = (\mu / D)(\rho_\theta / L_n)^2 \, (\delta v_\theta / v_*),$$

  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? (~ ρ_θ^2, may be addressed by JET)
- "non-resonant" transport (cf NTV) may be dominant.
- An unfavorable ρ_* scaling could defeat RMP ELM suppression.
- According to EPED model, RMP need to act on pedestal width as well as gradients.

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