CORE AND EDGE TRANSPORT IN ALCATOR C-MOD
CONNECTIONS ACROSS THE SEPARATRIX

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BASIC THESIS - CORE/EDGE/SOL CAN'T EASILY BE DECOUPLED

- Different regions of plasma are typically disunified
  - Studied by different groups
  - With different diagnostics
  - And different codes
  - Going to different meetings

- But of course as we all know:
  - There is substantial overlap in the physics
  - These regions have unignorable interactions
OUTLINE – THREE CASE STUDIES

1) If marginal stability sets energy transport, temperature profile couples edge and core physics - profile stiffness

2) SOL flows apparently provide an important boundary condition for core rotation

3) Edge turbulence sets global density limit
CASE 1 – COUPLING THROUGH MARGINAL STABILITY

(Likely applies to more than core temperature profiles)
GLOBAL TRANSPORT IS STRONGLY CORRELATED WITH EDGE TEMPERATURE ACROSS TRANSPORT REGIMES

Greenwald 1996
The critical parameter is related to the temperature gradient.
In fact, temperature profiles are self-similar under a wide variety of conditions.

- ~100 Random C-Mod shots and times selected from 2003-04
  - 1 MA, 5.3 T
  - Temperature picked at peak of sawtooth

- Otherwise
  - All powers, densities
  - On and Off-axis heating
  - L and H-modes

- Temperature Gradient-Length exists with very narrow range
DATA FROM CONFINEMENT DATABASE SHOWS SAME (LACK OF) TRENDS.
THIS EFFECT MAY BE UNDERSTOOD QUANTITATIVELY VIA
NON-LINEAR GYROKINETIC SIMULATIONS

Matching experimental profiles requires non-linear calculations and proper treatment of electron dynamics.

Nonlinear GS2 simulations

Fully kinetic electrons and ions
C-Mod EDA H-mode
\( r_{\text{mid}} = 0.56a \)

Lower \( v_e \) & \( v_i \)
IFS-PPPL model
Standard collisionality
Matching experimental profiles requires non-linear calculations and proper treatment of electron dynamics

Note: There is still a lot of unvalidated physics in these codes.

Mikkelsen 2001
CASE 2 – COUPLING BALLOONING TRANSPORT, SOL FLOWS, CORE FLOW AND THE L/H THRESHOLD
1. The ballooning character of turbulent transport drives SOL flows.

2. The SOL flow responds strongly to changes in magnetic topology.

3. Core flows respond strongly to changes in SOL flows.
   (SOL flows provide the boundary condition for core flows)

4. This topology dependent boundary conditions for plasma flow may be the explanation for the ∇B drift effect on the H-mode threshold.
PLASMA HEATING AND ROTATION MEASUREMENTS WITHOUT NBI ON C-MOD - Provides an Excellent Laboratory to Study These Effects

- Heating is with ICRH + OH
- Changes in core reflect changes in boundary conditions
- SOL flows measured at three locations by fast scanning probes
- Core rotation profiles measured passively with high-resolution x-ray spectrometers
PLASMA FROM BALLOONING TRANSPORT FLOWS ALONG FIELD LINES TO POPULATE HIGH-FIELD SOL

- Much higher fluctuation levels (⊥ transport) on low field side – ballooning
- When high-field side is connected (SN), shows similar plasma density
- When not connected (DN), no plasma
- So for SN plasmas, symmetrizing flows are robust feature of SOL

LaBombard 2004
Symmetrizing flows driven by ballooning transport are co or counter depending on topology.

transport-driven parallel SOL flows:
- Change in core flows with topology is in same direction and same magnitude as SOL flows
- Core flows exhibit the same extreme sensitivity to edge topology! – each mm counts
- SOL flows are near sonic on high-field side.
Core and SOL flows are well correlated

- Note: Core and SOL flows track but are not identical
MOMENTUM IS OBSERVED TO BE TRANSPORTED FROM OUTSIDE INWARD INTO CORE

- Core rotation responds to change in edge – L/H transition
- Momentum is observed to diffuse and convect inward.

EDA

ELM-free

Rice 2003
NET ROTATION IS SUM OF TWO EFFECTS

1. Topology dependent
   SOL flows as described above

2. Topology independent
   component which always increases in co-direction with plasma pressure

Strong co-current toroidal rotation observed following L/H transition
The Effect the $\nabla B$ Drift Direction on the H-Mode Threshold is 0\textsuperscript{th} Order and Requires a Robust Explanation

- The L/H Power threshold is typically ~2x higher when ion $\nabla B$ drift direction is away from X-point in single null topology when compared to case where $\nabla B$ drift direction is toward X-point.

- First reported on Asdex in 1989

- “Universal” result
For fixed conditions (Power, density, current, etc.), edge profiles are similar for both topologies.

Global power threshold can be recast as condition on local edge temperature or gradient.

For unfavorable drift direction, threshold $T_e$ is about 2x higher.

Size of effect suggests looking for large asymmetries – only occur near separatrix or beyond.

Hubbard 1996
For particular discharge conditions, L/H transition is reached when core rotation reaches some critical value.

Relevant physics is likely local shear but measurements not available yet...

For unfavorable drift direction, starting conditions are farther from threshold in this sense.
THIS EFFECT CAN BE SEEN IN DISCHARGE EVOLUTION

- Before transition, evolution occurs on time scale slower than energy or momentum confinement time
- May suggest two stage transition
- First stage involves generation of shear flow
- Second stage: bifurcation corresponding to fluctuation quench
• Core flows (and presumably shear) show remarkable dependence on topology.

• Inconsistent results reported with DN may be the result of this extreme sensitivity.
1. Significant parallel flows are driven in the SOL as a result of poloidally asymmetric cross-field transport.

2. These flows reverse direction with respect to the plasma current depending on whether the x-point is at the top or bottom of the machine.

3. These flows couple to toroidal rotation in the confined plasma.

4. There is a separate effect in which both the SOL and core flows increment in the co-current direction when the plasma pressure (input power) is increased.

5. So these two effects add or subtract depending on the topology.

6. Plasmas with the $\nabla B$ drift in the unfavorable direction have "farther" to go to get to the same state of rotation.

How this connects to the details of ExB stabilization and such is still unknown.
CASE 3 – GLOBAL DENSITY LIMIT DETERMINED BY EDGE TURBULENCE
Disruptive limit from edge cooling $\Rightarrow$ current profile shrinks $\Rightarrow$ MHD unstable

No widely accepted first principles theory available

Not even agreement on critical physics

How about the role of radiation cooling? $P_{RAD} \propto n_e^2 f Z R(T_e)$

- Power and impurity dependence too strong $\Rightarrow$

  $n_{LIM} \propto \sqrt{P_{IN}/(Z_{EFF} - 1)}$

- Threshold mechanisms (MARFEs, detachment, etc) show up well below density limit

- Transport assumptions: ad hoc at best

Hypothesis: Density or collisionality dependent transport $\Rightarrow$ edge cooling
TURBULENT TRANSPORT IN EDGE INCREASES WITH COLLISIONALITY

- Two regimes observed in scrape-off layer (SOL)
  - Near-SOL: steep gradients, $T_e$ high
  - Far-SOL: flat profiles, $T_e$ low

- Particle flux and transport
  - Near-SOL: cross-field transport low
  - Far-SOL: cross-field transport high

- Fluctuation changes character
  - Near-SOL: low amplitude, short correlation times and lengths
  - Far-SOL: large amplitude, bursty, long correlation times
BURSTY TRANSPORT DOMINATES SOL

Normalized RMS fluctuation level & auto-correlation time of $I_{sat}$ increase as distance into SOL increases

Probability distribution functions of emission get more skewed toward larger events, as distance into SOL increases

Terry 2001
WE CAN VISUALIZE THE FAR-SOL FLUCTUATIONS - BLOBS

- Fast CCD camera images, 4 µsec framing time
- D$_2$ gas puff ⇒ localization
- Large "blobs" dominate far-SOL
- Blobs move poloidally and radially
- Correlation length, correlation time, propagation velocity consistent with probe measurements

Terry 2002
Average blob velocity tends to be poloidal in the confined region and radial in the SOL.
AS THE DENSITY LIMIT IS APPROACHED, HIGH TRANSPORT REGIME CROSSES SEPARATRIX AND MOVES INTO MAIN PLASMA

- Has the potential to explain range of density limit phenomena
- Fluctuations can cool edge, eliminate edge shear layer
- Note: Cooling will precipitate MARFEs, detachment if they have not already occurred.
- Threshold condition? – need to understand interaction of turbulence and profiles – feedback loops
As density is raised, the temperature profile collapses

- Edge density profiles inside separatrix are not markedly different.
- Temperature collapse begins before \( n/n_G \sim 0.8 \)
- Floating potential well disappears and is replaced by moderate hill
Magnitudes of transport parameters correlate with $n_e/n_G$

Data at 2 mm into SOL

$D_{eff} = \Gamma/\nabla n$, $V_{eff} = \Gamma/n$

- $n_e/n_G$ is a proxy for collisionality and other variables critical for the limit
- Turbulence driven convection can compete with parallel transport
- Loss of “stabilizing” influence of parallel transport
- Destruction of shear layer?
Non-linear 3D gyro-fluid simulations have found regime of extremely high transport

\[ \alpha = -Rq^2 d\beta / dr \] (normalized pressure gradient)

\[ \alpha_D = \rho_s c_s t_0 / L_n L_0 \]

\[ \propto \left( \frac{T^2}{n L_n} \right) \rightarrow \frac{\lambda}{L_n} \] (inverse \perp collisionality)

Region of ultra-high transport consistent with high density, low temperature

Similar results from Xu, Hallatschek

No quantitative predictions yet

**SOME SUPPORT FROM EDGE TURBULENCE SIMULATIONS**
Edge plasma pushes calculated stability limits

- $\alpha_{\text{MHD}}$ is significant in near SOL
- Unstable region moves inward at higher densities
- Calculations are limited Flux tube, local profiles, no open field lines, separatrix, no profile evolution
- Role of shear layer is uncertain (and not modeled here)
As density rises, edge fluctuations show increasing long-time correlations.

- Computed with reduced range (R/S) analysis
- $H = 0.5 \Rightarrow$ Random
- $H = 1.0 \Rightarrow$ Coherent
- So fluctuations go “global” as density limit is approached?

Carreras 2004
We think there is a plausible case for turbulent transport in the plasma edge as the critical physical mechanism for the density limit.

- The dynamics by which enhanced convective transport destabilizes the entire temperature profile has not been worked out quantitatively.
- Is the result sensitive to details of the turbulence?
- How do these results carry over to other devices (RFP) which see a similar limit?
SUMMARY

• For the examples given, SOL/Edge/Core coupling is 0th order, not perturbative.

• It may not be possible to understand anything fully without understanding everything.

• Though an awful prospect, we need to deal seriously with the coupling problem.