A Tour Of Transport on the Alcator C-Mod Tokamak

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Outline

• The C-Mod Experiment
• Transport Geography
  – Far-SOL and Near-SOL
  – Density Limits and Transport
  – L-H Thresholds
    ◊ Self-generated Flows and the $\nabla B$ Drift Effect
  – H-mode – Types and Transport
  – Pedestal Scaling and Stability
  – Critical Gradients and Marginal Stability
  – ITBs – Creation and Control
• Future Directions
C-Mod Is A Compact High-Field Tokamak

- C-Mod Parameters \((R = 0.67m, a = 0.22m)\)
  - \(B_T = 2 – 8 T\)
  - \(I_P = 0.2 – 2 MA\)
  - \(n_e = 0.2 – 15.0 \times 10^{20} m^{-3}\)
- We tend to run at higher collisionality and lower \(\beta\) (though much higher pressure) than low-field devices.
  - \(T_e \sim T_i\)
- Auxiliary heating is with ICRF
  - No core particle source
  - No core momentum source
- LHCD experiments just begun
- All metal first wall (PFC)
C-Mod Cutaway and Equilibrium
Two Regimes Observed In Scrape-Off Layer (SOL)

- **Near-SOL**: steep gradients, Te high
- **Far-SOL**: flat profiles, Te 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 Far-SOL

- Normalized fluctuation level & auto-correlation time increase in far-SOL
- PDF gets more skewed toward larger events.
Fluctuations Are Filamentary With Very Large Amplitude

- Field aligned perturbations have been seen in images of confined plasmas for decades.
- Recent diagnostic advances have allowed these to be visualized, with good spatial and time resolution.
Blobby Transport in Far-SOL

- Fast CCD camera images, 4 msec framing time
- D2 gas puff $\Rightarrow$ localization
- Large "blobs" dominate far-SOL
- Blobs move poloidally and radially
- Correlation length, correlation time, propagation velocity consistent with probe measurements
Average Fluctuation Velocity Tends to be Poloidal in the Confined Region and Radial in the SOL
Simulations Are Providing Insights Into Edge Turbulence

- Nonlinear electromagnetic models identify 2 principal control parameters (Rogers, Drake, Scott, Hallatschek…)
  - Normalized pressure gradient ($\alpha_{\text{MHD}}, \beta$)
  - Normalized collisionality ($\alpha_D, \hat{C}$)
- At higher collisionalities, transport increases sharply when critical $\alpha_{\text{MHD}}$ is exceeded.

![Graph showing transport increases dramatically](image)

*Rogers, Drake, Zeiler PRL 1998*

*DRB Code: 3D, electromagnetic Braginskii fluid*
Data From Fast Scanning Probe Supports Theory (!)

- Measured in near-SOL
- Scans of \(I_p, B_T\) and \(n_e\)
- Plotting vs theory-based parameters groups data.
- SOL profiles appear to follow contours defined by simulations.
- Strongly suggests that drift-Alfven resistive ballooning dominates transport in this region

\[
\alpha_{MHD} \sim \frac{nT_e q^2 R}{B^2 L_{\perp}}
\]

\[
\alpha_d \sim \frac{1}{q} \left( \frac{\lambda_{ci}}{R} \right)^{1/2} \left( \frac{R}{L_{\perp}} \right)^{1/4}
\]
Turbulent Transport Increases Sharply With Density/Collisionality

- $D_{\text{EFF}} = \Gamma / \nabla n$, $V_{\text{EFF}} = \Gamma / n$
- Turbulence driven convection can compete with parallel transport
- Loss of “stabilizing” influence of parallel transport
- Destruction of shear layer
- $n_e/n_G$ is a proxy for collisionality and other variables

![Graph showing $D_{\text{eff}}$, $V_{\text{eff}}$, and $\lambda_{ei}/L$ versus $n_e/n_G$ at 2 mm into SOL with data points for different $I_p$ values.](image)
That is: As density increases, high transport region moves inward across separatrix.

Seen as increase in auto-correlation time and fluctuation level.

Blobs are formed in “core” regions.

Warm plasma is convecting out; replaced by cold neutrals.

Edge Cools.
Density Limit As Transport Phenomena

- Temperature collapse begins before \( \frac{n}{n_G} \sim 0.8 \)
- Potential well disappears and is replaced by moderate hill
- Proceeds about 3 cm into closed field-line domain (15% of r/a)
- Note: Cooling will precipitate H-L transition, MARFEs, detachment, radiation collapse if they have not already occurred.
- Threshold condition? – need to understand interaction of turbulence, profiles, MHD – feedback loops
We’re Trying To Understand The L-H Transition Based On Local Physics

- Despite many years of study, there is still no widely accepted theory for L/H transition/threshold.
Some Agreement With Theory Emerging?

- Previous studies: qualitative agreement with drift-Alfven turbulence simulations (Rogers, et al., 1998)
- Simulation physics embodied in analytic formalism by Guzdar (2002)

$$\Theta \equiv \frac{T_e}{L_n^{1/2}} = 0.45 \frac{B_T^{2/3} Z_{eff}^{1/3}}{(R A_i)^{1/6}}$$

- This approach is controversial in the edge turbulence community
SOL Flows, Core Rotation and the L-H Transition: Some Unexpected Connections

• "Fasten your seatbelts, it's going to be a bumpy ride."
Strong Self-Generated Core Rotation Observed In C-Mod

- C-Mod has no external momentum drive (OH + ICRF + LH)
- Has diagnostics to measure core rotation without heating beam
- Rotation a robust feature
- Seen in JET, DIII-D, Tore-Supra as well.
Source Of Rotation Seems To Be At Edge

- Core rotation responds to change in edge – L/H transition
- Time histories used to obtain transport coefficients.
- Momentum is observed to diffuse and convect inward.
Core and SOL Flows are Well Correlated

- Note: Core and SOL flows track but are not identical.
- We still need to investigate momentum transport in pedestal.
SOL Flows Show Same Topology Dependence as Core Rotation

- Change in core flows with topology is in same direction and same magnitude as SOL flow
- Core flows exhibit the same extreme sensitivity to edge topology! – each mm counts
- SOL flows are near sonic on high-field side.
- Double null balance is critical
Symmetrizing Flows Driven By Ballooning Transport are Co or Counter Depending on Topology

These flow patterns are observed with the inner wall probes

Plasma From Ballooning Transport Flows Along Field Lines to Populate High-Field SOL

- Much higher fluctuation levels (\perp transport) on low field side – ballooning
- When high-field side is connected (SN), shows similar plasma density
- When not connected (DN), no plasma
- For SN, symmetrizing flows are responsible for high-field plasma
These Observations May Actually Explain Something Important

- 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

Asdex 1989
The Effect the $\nabla B$ Drift Direction on the H-Mode Threshold is 0th Order and Requires a Robust Explanation

- Size of effect suggests looking for large asymmetries.
- Only occur near separatrix or beyond.
Observed Flows May Be That Explanation

- To reach given level of core flow (shear) requires more pressure (power) for unfavorable drift direction

Two “contributions” to the flows

1. Topology dependent SOL flows as described above
2. Pressure dependent rotation in both L and H-Mode
   - Net rotation is Sum of Two Effects
   - (Observed in core and SOL)
Change in Power Threshold Follows Changes in SOL Flows

- Inconsistent results reported with DN may be the result of this extreme sensitivity

- Experimental data straddles topology-insensitive theory
L-H Story In Words…

• Significant parallel flows are driven in the SOL as a result of poloidally asymmetric cross-field transport (ballooning).
• 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 and couple to toroidal rotation in the confined plasma.
• 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.
• So these two effects add or subtract depending on the topology, perhaps leading to $\nabla B$ drift effect on threshold.

• How does momentum couple through edge?
• How does this work quantitatively with the details of ExB stabilization and such?
Very High Resolution Diagnostics
Enable Pedestal Studies

- Instrumental resolution for $T_e$, $T_i$, $n_e$, $L_\alpha$, approaching 1 mm
- Pedestal widths: 2-6 mm

Pedestal Similarity Experiments Suggest Dominance Of Plasma Physics

• Carefully prepared discharges – match $\varepsilon$, $\delta$, $\kappa$, $q$, $\nu^*$, $\rho^*$, $\beta$ at top of pedestal
• Entire pedestal profile is matched
• Suggests a dominant role for plasma physics
• Atomic physics sub-dominant
Pedestal Width Can’t Be Easily Characterized

- Pedestal width is of order the poloidal gyro-radius
- But no clear trend is observed
- Multi-machine studies have not found simple parametric dependence
- Scales are not clearly separated in edge ($\rho_i$, $L_{no}$, $L_s$...)
Pedestal Scaling (a Crucial Parameter for Predicting the Performance of Future Machines)

- Pedestal pressure scales like $I_p^2$
- Width shows relatively little variation over wide parameter range
- Pedestal height (density and temperature) each scale with $I_p$
- $\eta_e$ in the range 1-2
Transport Probably Plays an Important Role in Pedestal Structure

- MHD-induced ELMs can limit pedestal gradient
- Small ELMS on C-Mod consistent with peeling-ballooning model
- But... ballooning like scaling observed in EDA data (no ELMs)
- Pressure gradient limit is soft – increases with $P_{\text{INPUT}}$
- Dependence on $\nu^*$ consistent with drift-Alfven-resistive-ballooning theories

\[ |\nabla p_e|_0 \propto I_p^2 P_{\text{SOL}}^{1/2} \]
Several Types Of H-Modes Seen On C-Mod

- At moderate heating power the “standard” H-mode is EDA (Enhanced Dα)
- EDA has good energy confinement but no impurity accumulation and no large ELMs
- At higher pressure and lower $\nu^*$ small ELMs appear
Confinement in EDA H-modes Is Almost As Good As In ELM-free H-modes
In EDA H-modes, Edge Transport Is Apparently Regulated By A Steady Quasi-Coherent Mode

- Seen with PCI, Reflectometry, BES, GPI, Magnetics, Probes, HECE
Strong Evidence For QC Mode As Cause Of Transport

- QC mode always seen in EDA
- Calculate $D_{\text{eff}}$ by dividing particle flux by local gradient
  - $L_y\alpha$ measurement + $T_e$, $n_e$ from Thomson Scattering provides local particle source rate.
  - Integrated to give ion flux in steady state.
- Similar result seen for impurities and flux calculated from probe data $\langle \tilde{n} \cdot \tilde{\phi} \rangle$
QC Mode Appearance Correlated With Changes In Impurity Transport

- Both injected and intrinsic impurity confinement is correlated with appearance of QC mode
- $\tau_I \sim 3 \times \tau_E$ in EDA
- $\tau_I \gg \tau_E$ in ELM-free
- Impurity density pedestal much wider in EDA

Density Fluctuations

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QC Mode Is Short-Wavelength, Field Aligned Perturbation

- Standard magnetics diagnostics are too far from plasma to see mode reliably
EDA/QC Mode Obtained More Easily At High Triangularity

- $\delta$ Scan shows “dithering” between EDA and ELM-free
EDA/QC Mode Obtained At Higher $q_{95}$

- $I_p$ and $B_T$ scans show $q_{95}$ threshold for EDA/ELM-free boundary
- EDA obtained at lower $q$ in hydrogen plasmas
- Consistent with resistive ballooning; diamagnetic stabilization important when:
  \[ \frac{qR}{L_{||}} \frac{\sqrt{m_i/m_e}}{2q(1+T_i/T_e)} \approx 1 \]
- With $L \sim qR$ and $T_i = T_e$; critical $q \propto m_i^{0.5}$
Testing Predictions of BOUT Code: $\omega$, $k$ Match

- GPI, BES show QC radial extent at limit of resolution < 4 mm
- Probe measurements find 1-2 mm but may perturb flux tube
- Important test of BOUT prediction
At Higher Pressure And Lower Collisionality, Small ELMs Take Over

- Small ELMs appear when $\beta_N > 1.2$
- Coexist with QC
- At higher pressures, QC disappears entirely
- Increased particle flux is seen with divertor probes
- ELMs make no observable perturbation in global parameters Stored Energy or Particle content
ELMs: Triangularity And Collisionality

$n_{e,95}$ vs $T_{e,95}$, $q_{95} = 3.5$

$v^* = 0.2$

$v^* = 0.5$

$v^* = 1$

$v^* = 2$

$v^* = 5$

Te (eV)

Te (eV)

$n_{e,95}$ ($10^{20}$ m$^{-3}$)

$n_{e,95}$ ($10^{20}$ m$^{-3}$)

discrete ELMs

Steady EDA

EDA+ELMs

EDA/ELM-free Boundary Is Consistent With MHD Calculations

- Using measured edge $n_e$ and $T_e$ profiles, reconstructed equilibria
- $J_{\text{BOOTSTRAP}}$ calculated
- ELITE code calculates stability boundary for intermediate $n$ peeling-ballooning modes
- Calculation correctly sorts plasmas
- Suggests that EDA provides just enough transport to reduce pressure gradient to below stability boundary
Global Transport is Strongly Correlated with Edge Temperature Across Transport Regimes

Greenwald 1996
Core Temperature Gradient Is Given By Boundary Temperature

Greenwald 1996
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
What is Expected Theoretically?

- Free energy in plasma gradients can drive turbulence and transport
- Transport is predicted to be strong if microstability threshold is exceeded
- Theory predicted ITG instability for

\[
\frac{R}{L_{T_i}} \equiv \frac{R \nabla T_i}{T_i} > \frac{R}{L_{T_{CRIT}}}
\]
Data From Confinement Database Shows
Same (lack of) Trend
We Are Approaching Quantitative Agreement via Non-Linear Gyrokinetic Simulations

Note: There is still a lot of unvalidated physics in these codes.
Internal Barriers Created With Off-Axis ICRF

• Broadened temperature profile remains nearly unchanged while density peaks (break in slope of ECE $T_e$ profile shows up in 2002 data)

• Electron and impurity densities rise inside the heating radius until radiative collapse, unless controlled

• Modest on-axis ICRF heating (< 0.6 MW) arrests density rise

33 - 35 ms intervals
218 radial channels
~ 1 mm spacing

$\left( R - R_0 \right) / a$

$P_{RF}$ (MW)

$\frac{n_e \sqrt{Z_{eff}}}{m^{-3}}$

Magnetic axis

H-Mode Transition

ITB Forms

Barrier foot

Edge

2 MW Off-axis RF

0.6 MW On-axis RF

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Thermal Diffusivity Drop Across Entire Core

- Peak in pressure gradient implies drop in thermal diffusivity
- Barrier “strength” is controlled via on-axis heating
Incremental Diffusivity Drop In Very Narrow Layer

Heat pulse slows as it propagates through the barrier

- Incremental thermal diffusivity is measured using heat-pulse propagation from sawtooth crash
- Time to peak increases as heat-pulse traverses barrier
- Suggests that barrier itself is sub-critical – turbulence is completely suppressed.
Barrier Formation And Control Understood As Stabilization Of ITG Via Modification of $L_T$.

- Supported by recent experiments.
- Barrier saturation and control via TEM destabilization
- ITBs In C-Mod Not Dominated By ExB Stabilization
Core Fluctuations Increase When Barrier Is Weakened By On-Axis Heating

(Basse)

(Phillips)

Particle Transport in ITB In Quantitative Agreement With TEM Predictions

- Synthetic PCI diagnostic built for gs2 calculations
- By properly treating experimental details, good agreement was obtained

(Ernst, Long)
ITB Foot Location Controlled by $B_T$ and $I_P$ (magnetic shear effect?)

- Efficient, off-axis current drive may allow creation of large-volume ITBs
Future Plans:
Facility Upgrades Will Allow Important Transport Questions To Be Addressed

- LHCD – control of magnetic shear
- Cryopump – extend collisionality regime
LHCD Should Allow Steady-state Control Of Magnetic Shear

- Shear is predicted to be important for ITG, TEM, ETG stability (linear and nonlinear dependences are complicated)
- One of only a very few “free” parameters that (are predicted to) determine R/L_T
- Experiment: Test ITG models by evaluating change in R/L_T and fluctuations as we modify Ŝ.
Impact of Collisionality on Transport Has Become An Important Issue

- Physics Issues – nonlinear regulation of turbulence
  - ITG - Nonlinear effects through change in electron dynamics
  - Reduction of instability drive (ITG) predicted to be more important than zonal flow damping?
  - TEM – Drives and dissipation? Effects on particle transport and density profile?
- Previous results at higher collisionality ($v^* = 0.2 \rightarrow 1$)
  - $B \tau_E \sim v^{*-1.0 \pm 0.2}$ in H-mode; $B \tau_E \sim v^{*-0.4 \pm 0.1}$ in L-mode
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Cryopump Should Allow Operation at Significantly Lower Collisionality

- At fixed pressure, a small change in density can have a large effect on $\nu^*$
- Should provide more overlap with other experiments
- Test predictions of nonlinear simulations – apparent contradiction with high-collisionality results

(Mikkelsen)

![Graph showing total heat flux normalized against R/L_T with linear and critical gradients, and actual $\nu_e$ & $\nu_i$.]
Summary

• The C-Mod transport program tries to take advantage of its unique parameters
  – $T_i = T_e$, no core momentum or particle sources
  – Dimensionless similarity with large low-field devices
• Diagnostics
  – Especially high-resolution edge diagnostics
  – Broad range of profile and fluctuation measurements
• We stress connections across spatial domains