Critical gradients and plasma flows in the edge of Alcator C-Mod

B. LaBombard, J.W. Hughes, N. Smick, A. Graf, K. Marr, R. McDermott, M. Reinke, M. Greenwald, B. Lipschultz, J.L. Terry, D.G. Whyte, S.J. Zweben, Alcator C-Mod Team

Invited talk BI1.00001
Presented at the 49th Annual Meeting of the APS Division of Plasma Physics
November 12–16, 2007
Orlando, Florida
Edge Plasma Region -- interface between open and closed magnetic field lines; plays key role in tokamak performance...

- Steep gradient region, L-mode and H-mode ‘pedestals’
  Plasma performance tied to pedestal height

- Power and particle exhaust
  Width of scrape-off layer sets divertor heat fluxes
  ELM phenomena, quasi-coherent modes, ...

- Impurity control
  Impurity ‘screening’, plasma flows, inward pinches, ...
Edge Plasma Region -- interface between open and closed magnetic field lines; plays key role in tokamak performance...

- Steep gradient region, L-mode and H-mode ‘pedestals’
  Plasma performance tied to pedestal height

- Power and particle exhaust
  Width of scrape-off layer sets divertor heat fluxes
  ELM phenomena, quasi-coherent modes, ...

- Impurity control
  Impurity ‘screening’, plasma flows, inward pinches, ...

Questions & Research Goals:

- Underlying physics that sets the transport levels, gradients, SOL widths?
- Connections among transport, plasma flows, magnetic topology, ...
  (e.g. L-H power threshold)
- First-principles, predictive model for edge plasma?
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...

- Edge plasma ~ a system at ‘critical gradient’ near LCFS
  Intermittent, bursty transport in the ‘far SOL’
  Small change in LCFS gradient => large change in fluxes
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...

- **Edge plasma ~ a system at ‘critical gradient’ near LCFS**
  - Intermittent, bursty transport in the ‘far SOL’
  - Small change in LCFS gradient => large change in fluxes

- **Electromagnetic plasma turbulence sets 'critical gradient' near LCFS**
  - Pressure gradients 'clamped' at a value of $\alpha_{MHD}$, dependent on collisionality
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...

- **Edge plasma ~ a system at ‘critical gradient’ near LCFS**
  - Intermittent, bursty transport in the ‘far SOL’
  - Small change in LCFS gradient => large change in fluxes

- **Electromagnetic plasma turbulence sets 'critical gradient' near LCFS**
  - Pressure gradients 'clamped' at a value of $\alpha_{MHD}$, dependent on collisionality
  
  **Old view:** $\Gamma_\perp = -D_\perp \nabla_\perp n$, $D_\perp \sim$ Bohm
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...

- **Edge plasma ~ a system at ‘critical gradient’ near LCFS**
  - Intermittent, bursty transport in the ‘far SOL’
  - Small change in LCFS gradient => large change in fluxes

- **Electromagnetic plasma turbulence sets 'critical gradient' near LCFS**
  - Pressure gradients 'clamped' at a value of $\alpha_{MHD}$, dependent on collisionality

  Old view: $\Gamma_\perp = D_\perp \nabla \perp n$, $D_\perp \sim$ Bohm

  New view: $\nabla \perp nT$ highly constrained!
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...

- **Edge plasma** ~ a system at ‘critical gradient’ near LCFS
  - Intermittent, bursty transport in the ‘far SOL’
  - Small change in LCFS gradient => large change in fluxes

- **Electromagnetic plasma turbulence** sets 'critical gradient' near LCFS
  - Pressure gradients 'clamped' at a value of $\alpha_{MHD}$, dependent on collisionality

  Old view: $\Gamma_\perp = D_\perp \nabla_\perp n$, $D_\perp \sim$ Bohm

  New view: $\nabla_\perp nT$ highly constrained!

- **Strong (near-sonic) plasma flows** just outside the LCFS
  - Set toroidal rotation 'boundary condition' on confined plasma
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...

- **Edge plasma** ~ a system at ‘critical gradient’ near LCFS
  Intermittent, bursty transport in the ‘far SOL’
  Small change in LCFS gradient => large change in fluxes

- **Electromagnetic plasma turbulence** sets 'critical gradient' near LCFS
  Pressure gradients 'clamped' at a value of $\alpha_{MHD}$, dependent on collisionality

  Old view: $\Gamma_\perp = D_\perp \nabla_\perp n$, $D_\perp \sim$ Bohm

  New view: $\nabla_\perp nT$ highly constrained!

- **Strong (near-sonic) plasma flows** just outside the LCFS
  set toroidal rotation 'boundary condition' on confined plasma
  Ballooning-like transport drive mechanism
  Rotation direction depends on x-point topology (LSN/USN)
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...

- **Edge plasma** ~ a system at ‘critical gradient’ near LCFS
  Intermittent, bursty transport in the ‘far SOL’
  Small change in LCFS gradient => large change in fluxes

- **Electromagnetic plasma turbulence** sets 'critical gradient' near LCFS
  Pressure gradients 'clamped' at a value of $\alpha_{MHD}$, dependent on collisionality

  - Old view: $\Gamma_\perp = D_\perp \nabla_\perp n$, $D_\perp \sim$ Bohm
  - New view: $\nabla_\perp nT$ highly constrained!

- **Strong (near-sonic) plasma flows** just outside the LCFS
  set toroidal rotation 'boundary condition' on confined plasma
  Ballooning-like transport drive mechanism
  Rotation direction depends on x-point topology (LSN/USN)
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...

- **Edge plasma ~ a system at ‘critical gradient’ near LCFS**
  - Intermittent, bursty transport in the ‘far SOL’
  - Small change in LCFS gradient => large change in fluxes

- **Electromagnetic plasma turbulence sets 'critical gradient' near LCFS**
  - Pressure gradients 'clamped' at a value of $\alpha_{MHD}$, dependent on collisionality
  - Old view: $\Gamma_\perp = D_\perp \nabla_\perp n$, $D_\perp \sim$ Bohm
  - New view: $\nabla_\perp nT$ highly constrained!

- **Strong (near-sonic) plasma flows just outside the LCFS**
  - Set toroidal rotation 'boundary condition' on confined plasma
  - Ballooning-like transport drive mechanism
  - Rotation direction depends on x-point topology (LSN/USN)

- **Potential link between 'critical gradient' behavior and SOL flows/rotation**
  - L-mode: attainable value of $\alpha_{MHD}$ depends on LSN/USN topology
Experiments in C-Mod and elsewhere have revealed important clues about transport physics at the SOL interface...

- **Edge plasma** ~ a system at ‘critical gradient’ near LCFS
  Intermittent, bursty transport in the ‘far SOL’
  Small change in LCFS gradient => large change in fluxes

- **Electromagnetic plasma turbulence** sets 'critical gradient' near LCFS
  Pressure gradients 'clamped' at a value of $\alpha_{MHD}$, dependent on collisionality
  
  Old view: $\Gamma_\perp = D_\perp \nabla_\perp n$, $D_\perp \sim$ Bohm
  New view: $\nabla_\perp nT$ highly constrained!

- **Strong (near-sonic) plasma flows** just outside the LCFS
  set toroidal rotation 'boundary condition' on confined plasma
  Ballooning-like transport drive mechanism
  Rotation direction depends on x-point topology (LSN/USN)

- **Potential link** between 'critical gradient' behavior and SOL flows/rotation
  L-mode: attainable value of $\alpha_{MHD}$ depends on LSN/USN topology

Connection to X-point dependence of L-H power threshold: *plasma rotation*
Evidence from L-mode Plasmas:

(1) A weak pedestal in the “Near SOL” is seen
Evidence from L-mode Plasmas:

1. A weak pedestal in the “Near SOL” is seen.
Evidence from L-mode Plasmas:

1. A weak pedestal in the “Near SOL” is seen
2. As central density is raised, density profiles flatten in Far SOL
Edge Plasma ~ a system at ‘critical gradient’ near LCFS

Evidence from L-mode Plasmas:
(1) A weak pedestal in the “Near SOL” is seen
(2) As central density is raised, density profiles flatten in Far SOL
Evidence from L-mode Plasmas:

1. A weak pedestal in the “Near SOL” is seen
2. As central density is raised, density profiles flatten in Far SOL
Evidence from L-mode Plasmas:

1. A weak pedestal in the “Near SOL” is seen.
2. As central density is raised, density profiles flatten in Far SOL.

Edge Plasma ~ a system at ‘critical gradient’ near LCFS
Evidence from L-mode Plasmas:

1. A weak pedestal in the “Near SOL” is seen
2. As central density is raised, density profiles flatten in Far SOL

Diagnostics

Lα Array

=> infer ionization profiles and cross-field fluxes in Near SOL
Evidence from L-mode Plasmas:

1. A weak pedestal in the “Near SOL” is seen
2. As central density is raised, density profiles flatten in Far SOL
3. Fluxes through LCFS increase exponentially

Diagnostics

$L_\alpha$ Array

=> infer ionization profiles and cross-field fluxes

Cross-Field Particle Flux

$1\text{mm outside LCFS}$

factor of $\sim 20$

$L$-mode profiles

$\bar{n}_e/n_G$

$0.43$

$0.37$

$0.28$

$0.23$

$0.17$
Evidence from L-mode Plasmas:

1. A weak pedestal in the “Near SOL” is seen.
2. As central density is raised, density profiles flatten in Far SOL.
3. Fluxes through LCFS increase exponentially, yet ‘pedestal’ density gradient changes modestly...

Diagnostics:

- Scanning Probe
- Lα Array
  - => infer ionization profiles and cross-field fluxes

Graphs:

- Density Gradient
- Cross-Field Particle Flux

Alcator C-Mod

Line-Averaged Density (10^{20} m^{-3})

1mm outside LCFS

Factor of ~20

Factor of ~2.5
Evidence from L-mode Plasmas:

1. A weak pedestal in the "Near SOL" is seen
2. As central density is raised, density profiles flatten in Far SOL
3. Fluxes through LCFS increase exponentially, yet ‘pedestal’ density gradient changes modestly...

Diagnostics

- \( \Gamma_\perp = -D_\perp \nabla_\perp n \)
- \( D_\perp = f(...) \)

Flux-gradient model ~ a poor choice

Critical-gradient model ~ a better choice?

\( \nabla_\perp n \sim \nabla_\perp n|_{\text{crit}} = f(...) \)
Edge Plasma ~ a system at ‘critical gradient’ near LCFS

Evidence from L-mode Plasmas:
(1) A weak pedestal in the “Near SOL” is seen
(2) As central density is raised, density profiles flatten in Far SOL
(3) Fluxes through LCFS increase exponentially, yet ‘pedestal’ density gradient changes modestly...

“Critical gradient” sensitive to topology?!
\(|\nabla_{\perp} n|_{\text{crit}}\) reduced for “unfavorable” \(B_x \nabla B\)?

Flux-gradient model ~ a poor choice
\[ \Gamma_{\perp} = -D_{\perp} \nabla_{\perp} n; \ D_{\perp} = f(...) \]

Critical-gradient model ~ a better choice?
\[ \nabla_{\perp} n \sim \nabla_{\perp} n|_{\text{crit}} = f(...) \]
Evidence from L- and H-mode Plasmas:

Coherent structures (“blobs”, “ELMs”) intermittently “peel-away” from LCFS and freely propagate into and across Far SOL...
Evidence from L- and H-mode Plasmas:

Coherent structures ("blobs", "ELMs") intermittently "peel-away" from LCFS and freely propagate into and across Far SOL...

Results from Gas-Puff Imaging (GPI) at outer midplane of C-Mod:
Evidence from L- and H-mode Plasmas:

Coherent structures ("blobs", "ELMs") intermittently "peel-away" from LCFS and freely propagate into and across Far SOL...

Results from Gas-Puff Imaging (GPI) at outer midplane of C-Mod:

... a behavior suggestive of critical-gradient fluctuation dynamics
Evidence from L- and H-mode Plasmas:

Coherent structures (“blobs”, “ELMs”) intermittently “peel-away” from LCFS and freely propagate into and across Far SOL...

Results from Gas-Puff Imaging (GPI) at outer midplane of C-Mod:

... a behavior suggestive of critical-gradient fluctuation dynamics

Turbulence Imaging ~ Wednesday, C-Mod Orals: PO3.0008  J.L. Terry  
PO3.0009  S.J. Zweben
Evidence from L- and H-mode Plasmas:

Coherent structures (“blobs”, “ELMs”) intermittently “peel-away” from LCFS and freely propagate into and across Far SOL...

Results from Gas-Puff Imaging (GPI) at outer midplane of C-Mod:

... a behavior suggestive of critical-gradient fluctuation dynamics

=> Observations point to a ‘critical gradient’ phenomenon in Near SOL

H-mode physics: *Exceed peeling-ballooning boundary, get ELMs*

L-mode physics?
Physics of edge turbulence may be understood in terms of EMFDT, a basis for first-principles 3-D transport simulations†

Physics: ElectroMagnetic parallel inductance, finite $\tilde{B}$, parallel resistivity, Fluid (gyro-fluid) Drift non-linear drift-wave, curvature, 3-D Turbulence toroidal geometry, x-point effects

Turbulence character & transport level is affected by two key dimensionless parameters:

Poloidal Beta Gradient $\alpha_{MHD} \sim q^2 R \frac{\nabla P}{B^2}$

Inverse Collisionality Parameter $\Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2}$

Physics of edge turbulence may be understood in terms of EMFDT, a basis for first-principles 3-D transport simulations†

<table>
<thead>
<tr>
<th>Physics:</th>
<th>ElectroMagnetic</th>
<th>Fluid (gyro-fluid) Drift</th>
<th>3-D Turbulence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>parallel inductance, finite $\tilde{B}$, parallel resistivity, non-linear drift-wave, curvature, toroidal geometry, x-point effects</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Turbulence character & transport level is affected by two key dimensionless parameters:

- **Poloidal Beta Gradient**: $\alpha_{MHD} \sim q^2 R \frac{\nabla P}{B^2}$
- **Inverse Collisionality Parameter**: $\Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2}$

---

Physics of edge turbulence may be understood in terms of EMFDT, a basis for first-principles 3-D transport simulations†

Physics: **ElectroMagnetic Fluid (gyro-fluid) Drift 3-D Turbulence**
- parallel inductance, finite $\tilde{B}$, parallel resistivity,
- non-linear drift-wave, curvature,
- toroidal geometry, x-point effects

**Turbulence character & transport level is affected by two key dimensionless parameters:**

<table>
<thead>
<tr>
<th>Poloidal Beta Gradient</th>
<th>$\alpha_{MHD} \sim q^2 R \frac{\nabla P}{B^2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverse Collisionality Parameter</td>
<td>$\Lambda = \frac{1}{q} \left( \frac{\lambda_{el}}{R} \right)^{1/2}$</td>
</tr>
</tbody>
</table>

**Electron Heat Diffusivity [3]**

![Results from DALFTI code](image)

$\chi_e$ vs. $\alpha_{MHD}$

$\Rightarrow$ strong dependence on $\alpha_{MHD}$ for $\alpha_{MHD} > 0.2$

Physics of edge turbulence may be understood in terms of EMFDT, a basis for first-principles 3-D transport simulations†

Physics: ElectroMagnetic Fluid (gyro-fluid) Drift 3-D Turbulence

parallel inductance, finite $\tilde{B}$, parallel resistivity, non-linear drift-wave, curvature, toroidal geometry, x-point effects

Turbulence character & transport level is affected by two key dimensionless parameters:

Poloidal Beta Gradient

$$\alpha_{MHD} \sim q^2 R \frac{\nabla P}{B^2}$$

Inverse Collisionality Parameter

$$\Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \sim \left( \frac{L_n}{R} \right)^{1/4} \alpha_d$$

Electron Heat Diffusivity [3]

results from DALFTI code

$$\chi_e \sim 10^{10} \alpha_{MHD}$$

$\Rightarrow$ strong dependence on $\alpha_{MHD}$ for $\alpha_{MHD} > 0.2$

'Phase Space' of EMFDT [4]

$\alpha_{MHD}$ vs $\alpha_d$

Ideal MHD Instability

Density Limit

H-Mode

L-Mode

$\leq$ increasing collisionality

transport depends on location in $(\alpha_{MHD}, \alpha_d)$ 'phase-space'


Physics of edge turbulence may be understood in terms of EMFDT, a basis for first-principles 3-D transport simulations†

Physics: ElectroMagnetic Fluid (gyro-fluid) Drift 3-D Turbulence parallel inductance, finite $\tilde{B}$, parallel resistivity, non-linear drift-wave, curvature, toroidal geometry, x-point effects

Turbulence character & transport level is affected by two key dimensionless parameters:

Poloidal Beta Gradient $\alpha_{MHD} \sim q^2 R \frac{\nabla P}{B^2}$

Inverse Collisionality Parameter $\Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \sim \left( \frac{L_n}{R} \right)^{1/4} \alpha_d$

Electron Heat Diffusivity [3]

\[
\chi_e \propto \alpha_{MHD} \quad \text{for} \quad \alpha_{MHD} > 0.2
\]

results from DALFTI code

‘Phase Space’ of EMFDT [4]

$\alpha_{MHD}$ vs $\alpha_d$

Ideal MHD Instability

Inaccessible

Density Limit

Transport Increasing

H−Mode

L−Mode

$\alpha_{MHD}$ increasing collisionality

transport depends on location in $(\alpha_{MHD}, \alpha_d)$ ‘phase-space’


Hypothesis: ‘Critical gradient’ behavior is consequence of EMFDT, combined with \textit{particle \& power balance constraints}
Hypothesis: ‘Critical gradient’ behavior is consequence of EMFDT, combined with particle & power balance constraints.

a) Transport is a strong function of EMFDT 'control parameters'

\[ \alpha_{\text{MHD}} \sim q^2 R \frac{\nabla P}{B^2} \; ; \; \Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \]
Hypothesis: ‘Critical gradient’ behavior is consequence of EMFDT, combined with particle & power balance constraints

a) Transport is a strong function of EMFDT 'control parameters'

\[ \alpha_{MHD} \sim q^2 R \frac{\nabla_q^P}{B^2} ; \quad \Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \]

b) Heat fluxes set by input power, particle fluxes set by fueling
Hypothesis: ‘Critical gradient’ behavior is consequence of EMFDT, combined with particle & power balance constraints

a) Transport is a strong function of EMFDT 'control parameters'
\[ \alpha_{MHD} \sim q^2 R \frac{\nabla \cdot P}{B^2} ; \quad \Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \]

b) Heat fluxes set by input power, particle fluxes set by fueling

Tendency toward a ‘critical gradient’ in the Near SOL may naturally arise from EMFDT combined with the range of particle/power fluxes available in experiments
Hypothesis: ‘Critical gradient’ behavior is consequence of EMFDT, combined with particle & power balance constraints

a) Transport is a strong function of EMFDT 'control parameters'

\[ \alpha_{MHD} \sim q^2 R \frac{\nabla\perp P}{B^2} ; \quad \Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \]

b) Heat fluxes set by input power, particle fluxes set by fueling

Tendency toward a ‘critical gradient’ in the Near SOL may naturally arise from EMFDT combined with the range of particle/power fluxes available in experiments

Experimental Test:

Edge plasma states that are accessible to experiments should ~map to the two-parameter 'phase-space',

\[ \alpha_{MHD} \sim q^2 R \frac{\nabla\perp P}{B^2} ; \quad \Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \]

independent of dimensional parameters \( (B_T, I_p, \bar{n}_e) \)
Plasma states near separatrix are indeed found to occupy a well-defined region in the phase space of EMFDT†

Discharges with different dimensional parameters: $B_T, I_p, \bar{n}_e$

Low-power Ohmic L-mode discharges
Density: $0.14 < n/n_G < 0.53$
Lower single-null
Forward $I_p, B_T$

†Nuclear Fusion 45 (2005) 1658.
Plasma states near separatrix are indeed found to occupy a well-defined region in the phase space of EMFDT†

Discharges with different dimensional parameters: $B_T$, $I_p$, $\bar{n}_e$ ...occupy in a similar band in $\alpha_{MHD}$, $\Lambda$ space

Low-power Ohmic L-mode discharges
Density: $0.14 < n/n_G < 0.53$
Lower single-null
Forward $I_p$, $B_T$

$\rho = 2$ mm

$\alpha_{MHD}$
~ $\nabla nT_e / I_p^2$

$\Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2}$
$\leqslant$ increasing $\bar{n}_e$

†Nuclear Fusion 45 (2005) 1658.
Plasma states near separatrix are indeed found to occupy a well-defined region in the phase space of EMFDT†

Discharges with different dimensional parameters: $B_T$, $I_p$, $\bar{n}_e$

...occupy in a similar band in $\alpha_{MHD}$, $\Lambda$ space

Low-power Ohmic L-mode discharges
Density: $0.14 < n/n_G < 0.53$
Lower single-null
Forward $I_p$, $B_T$

\[ \rho = 2 \text{ mm} \]

\[ I_P \text{ (MA)} \]
- \( \Delta 1.0 \)
- \( \Diamond 0.8 \)
- \( \triangle 0.5 \)

\[ \alpha_{MHD} \sim \frac{\nabla nT_e}{I_p^2} \]

\[ \Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \]

A region of high $\alpha_{MHD}$ at high density is inaccessible, owing to an explosive growth of cross-field transport

†Nuclear Fusion 45 (2005) 1658.
Plasma states near separatrix are indeed found to occupy a well-defined region in the phase space of EMFDT\textsuperscript{†}

Discharges with different dimensional parameters: $B_T, I_p, \bar{n}_e$ ...occupy in a similar band in $\alpha_{MHD}, \Lambda$ space

Low-power Ohmic L-mode discharges
Density: $0.14 < n/n_G < 0.53$
Lower single-null
Forward $I_p, B_T$

Next:
Examine SOL profiles at fixed $\Lambda$

\textsuperscript{†}Nuclear Fusion 45 (2005) 1658.
Pressure gradients near the separatrix appear to clamp at similar values of $\alpha_{MHD}$ when normalized collisionality is held fixed.

Look at pressure profile data from discharges with $\Lambda \sim 0.25$, 2 mm from separatrix.

![Graph showing $I_p$ (MA) vs. $B_T$ (tesla) with three q95 values: 6.5, 5, and 3.5.](image)

![Graph showing $|\nabla nT_e|$ vs. Distance into SOL (mm) with $I_p$ (MA) and $B_T$ (T) values.](image)
Pressure gradients near the separatrix appear to clamp at similar values of $\alpha_{MHD}$ when normalized collisionality is held fixed.

Look at pressure profile data from discharges with $\Lambda \sim 0.25$, 2 mm from separatrix.

$I_p$ Scan:
Pressure gradients scale roughly as $I_p^2$ => similar $\alpha_{MHD}$.
Pressure gradients near the separatrix appear to clamp at similar values of $\alpha_{MHD}$ when normalized collisionality is held fixed.

Look at pressure profile data from discharges with $\Lambda \sim 0.25$, 2 mm from separatrix.

$\nabla nT_e \parallel$ 

$I_p$ Scan:
Pressure gradients scale roughly as $I_p^2$ 
$\Rightarrow$ similar $\alpha_{MHD}$

$B_T$ Scan:
No sensitivity to toroidal field
Pressure gradients near the separatrix appear to clamp at similar values of $\alpha_{MHD}$ when normalized collisionality is held fixed.

Look at pressure profile data from discharges with $\Lambda \sim 0.25$, 2 mm from separatrix.

$I_p$ Scan:
Pressure gradients scale roughly as $I_p^2$
=> similar $\alpha_{MHD}$

$B_T$ Scan:
No sensitivity to toroidal field

=> Pressure gradient near separatrix set by a 'critical poloidal beta gradient'
New Experiments -- Extended Range of Currents and Fields

Range of dimensional parameters: $B_T, I_p$

Density scans: $0.1 < n/n_G < 0.5$

Lower single-null topology
New Experiments -- Extended Range of Currents and Fields
Pressure gradients near sep. consistently scale as $I_p^2$

Range of dimensional parameters: $B_T, I_p$

Density scans: $0.1 < n/n_G < 0.5$
New Experiments -- Extended Range of Currents and Fields
Pressure gradients near sep. consistently scale as $I_p^2$

Range of dimensional parameters: $B_T$, $I_p$

Density scans: $0.1 < n/n_G < 0.5$

$\nabla nT_e \parallel \frac{\alpha_{MHD}}{I_p^2}$

$\frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2}$

=> All discharges have same 'critical poloidal beta gradient'
EMFDT collisionality ($\Lambda$) contains ‘correct’ $q_{95}$ normalization...
edge states are $\sim$invariant when mapped to ($\alpha_{MHD}$, $\Lambda$) space

\[ \alpha_{MHD} \]

Plot versus inverse collision frequency
$\alpha_{MHD}$ values look like a function of $I_p$
EMFDT collisionality ($\Lambda$) contains ‘correct’ $q_{95}$ normalization... edge states are ~invariant when mapped to ($\alpha_{MHD}$, $\Lambda$) space

\[ \rho = 1 \text{ mm} \]

\[ \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \sim 1/\nu_{ei}^{1/2} \]

Plot versus inverse collision frequency

$\alpha_{MHD}$ values look like a function of $I_p$

$\Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2}$

Plot versus $\Lambda$

mapping is ~invariant
EMFDT collisionality ($\Lambda$) contains ‘correct’ $q_{95}$ normalization... edge states are ~invariant when mapped to ($\alpha_{MHD}$, $\Lambda$) space

\[ \Lambda = \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \]

Plot versus inverse collision frequency
\[ \alpha_{MHD} \] values look like a function of $l_p$

Plot versus $\Lambda$
mapping is ~invariant

=> Strong evidence that electromagnetic plasma turbulence is setting the ‘critical gradient’ behavior seen in the Near SOL
H-mode pedestals show a similar ‘critical gradient’ behavior†...
...peak pressure gradients scale as $I_p^2$

H-mode pedestals show a similar ‘critical gradient’ behavior†...
...peak pressure gradients scale as $I_p^2$

● Pedestal gradients are ‘stiff’, unaffected by strong gas puffing

Electron pressure profiles from EDA H-modes (no ELMs)

Pedestal physics ~ Wednesday, C-Mod Orals: PO3.0004 - J. W. Hughes

H-mode pedestals show a similar ‘critical gradient’ behavior†...
...peak pressure gradients scale as $I_p^2$

Pedestal gradients are ‘stiff’, unaffected by strong gas puffing

Despite absence of ELMs, peak pressure gradients scale as $I_p^2$, yielding similar values of $\alpha_{MHD}$ for the same edge collisionality

H-mode pedestals show a similar ‘critical gradient’ behavior†...  
...peak pressure gradients scale as $I_P^2$

Pedestal gradients are ‘stiff’, unaffected by strong gas puffing

Despite absence of ELMs, peak pressure gradients scale as $I_P^2$, yielding similar values of $\alpha_{MHD}$ for the same edge collisionality

$\Rightarrow$ Physics of L- and H-mode pedestals is linked

L-mode pedestal is precursor to H-mode, may yield insights on L-H transition (e.g., topology-dependence)

Magnetic x-point topology is found to affect ‘critical gradient’

Range of dimensional parameters: $B_T, I_p$

- $q_{95} = 6.5$
- $q_{95} = 5$
- $q_{95} = 3.5$

Density scans: $0.1 < n/n_G < 0.5$

Lower and upper-null topologies
Magnetic x-point topology is found to affect ‘critical gradient’
Pressure gradients near sep. consistently scale as $I_p^2$

... but value depends on lower / upper X-point topology

Range of dimensional parameters: $B_T, I_p$

Density scans: $0.1 < n/n_G < 0.5$
Magnetic x-point topology is found to affect ‘critical gradient’
Pressure gradients near sep. consistently scale as $I_p^2$

... but value depends on lower / upper X-point topology

Range of dimensional parameters: $B_T, I_p$

Edge plasma states again align in EMFDT phase-space, but in two bands

Density scans: $0.1 < n/n_G < 0.5$

Lower null achieves higher values of $\alpha_{MHD}$ compared to upper null at high collisionality
Magnetic x-point topology is found to affect ‘critical gradient’
Pressure gradients near sep. consistently scale as $I_p^2$

... but value depends on lower / upper X-point topology

Edge plasma states again align in EMFDT phase-space, but in two bands

Lower null achieves higher values of $\alpha_{MHD}$ compared to upper null at high collisionality.
Magnetic x-point topology is found to affect ‘critical gradient’
Pressure gradients near sep. consistently scale as $I_p^2$

... but value depends on lower / upper X-point topology

Range of dimensional parameters: $B_T$, $I_p$

<table>
<thead>
<tr>
<th>$q_{95}$</th>
<th>$B_T$ (tesla)</th>
<th>$I_p$ (MA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>3.5</td>
<td>4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Density scans: $0.1 < n/n_G < 0.5$

Edge plasma states again align in EMFDT phase-space, but in two bands

Lower null achieves higher values of $\alpha_{MHD}$ compared to upper null at high collisionality

Differences may be related to SOL flows, which is next topic...
Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport†

Mach probes ~ Wednesday, C-Mod Oral: PO3.00011  N. Smick

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport†

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport†

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport.

\[ B \times \nabla B \]

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport†

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport†

- Strong co-current flows in high-field SOL for $Bx\nabla B$ toward X-pt

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport†

- Strong co-current flows in high-field SOL for $B_x \nabla B$ toward X-pt

Edge CXRS ~ Wednesday, C-Mod Posters: NP8.00078 R.M. McDermott
NP8.00079 K. Marr
NP8.00085 A. Graf

Near-sonic parallel plasma flows circulate confined plasma
-- a consequence of ballooning-like transport†

- Strong co-current flows in high-field SOL for $B_x \nabla B$ toward X-pt

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport

- Strong co-current flows in high-field SOL for $B_x \nabla B$ toward X-pt
- Largest flow velocities are seen in the high-field SOL

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport†

- Strong co-current flows in high-field SOL for $B_x \nabla B$ toward X-pt
- Largest flow velocities are seen in the high-field SOL
- Toroidal flow inside separatrix tracks behavior in high-field SOL

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport†

- Strong co-current flows in high-field SOL for $B_x \nabla B$ toward X-pt
- Largest flow velocities are seen in the high-field SOL
- Toroidal flow inside separatrix tracks behavior in high-field SOL
- Low-field SOL flows affected by toroidal rotation inside separatrix

Near-sonic parallel plasma flows circulate confined plasma -- a consequence of ballooning-like transport

Strong co-current flows in high-field SOL for $B \times \nabla B$ toward X-pt

- Largest flow velocities are seen in the high-field SOL
- Toroidal flow inside separatrix tracks behavior in high-field SOL
- Low-field SOL flows affected by toroidal rotation inside separatrix

SOL flows set a flow ‘boundary condition’ on the confined plasma

$\Rightarrow$ tends to spin in the co-current direction for ‘favorable’ $B \times \nabla B$

Highest $\alpha_{MHD}$ are coincident with increased co-current flow... 
...corresponding to ‘favorable’ $Bx\nabla B$ direction

- Favorable $Bx\nabla B$ -- enhanced $\alpha_{MHD}$ at high collisionality

Independent of Forward/Reversed field

$\Rightarrow$ not a divertor/wall geometry effect
Highest $\alpha_{MHD}$ are coincident with increased co-current flow... ...corresponding to ‘favorable’ $Bx\nabla B$ direction

- Favorable $Bx\nabla B$ -- enhanced co-current flow/rotation at high collisionality
Highest $\alpha_{MHD}$ are coincident with increased co-current flow...
...corresponding to ‘favorable’ $Bx\nabla B$ direction

- Favorable $Bx\nabla B$ -- enhanced co-current flow/rotation at high collisionality

$\Rightarrow$ Connections: transport-driven SOL flows, topology, gradients, L-H threshold$^\dagger$

Highest $\alpha_{MHD}$ are coincident with increased co-current flow...
...corresponding to ‘favorable’ $B_x \nabla B$ direction

- Favorable $B_x \nabla B$ -- enhanced co-current flow/rotation at high collisionality

$\Rightarrow$ Connections: transport-driven SOL flows, topology, gradients, L-H threshold

Underlying physics not yet revealed: flow shear? collisionality dependence?

This is a ripe area for future investigations...

Summary

- Edge plasma (L and H-mode) ~ a system at ‘critical gradient’ near LCFS
  Small change in LCFS gradient => large change in fluxes
  Bursty transport, ELMs, ‘blobs’ peeling away from LCFS,...

  => not a simple \( D_n \nabla n, \chi T \) transport paradigm
Summary

- Edge plasma (L and H-mode) ~ a system at ‘critical gradient’ near LCFS
  Small change in LCFS gradient => large change in fluxes
  Bursty transport, ELMs, ‘blobs’ peeling away from LCFS,...
  => not a simple $D\nabla n, \chi \nabla T$ transport paradigm

- Evidence that electromagnetic turbulence sets ‘critical gradient’ ($\alpha_{MHD}$)
  L-mode edge states map to a 2-D dimensionless ‘phase space’ ($\alpha_{MHD}, \Lambda$)
  Mapping is invariant of machine parameters for fixed magnetic topology:
    $0.4 < I_p < 1.1 \text{ MA}, \ 2.7 < B_T < 6T, \ 0.1 < \bar{n}_e/n_G < 0.5$
  => makes contact with first-principles EMFDT simulations
    -- a strong endorsement for continued numerical simulation development
Summary

- Edge plasma (L and H-mode) ~ a system at ‘critical gradient’ near LCFS
  Small change in LCFS gradient => large change in fluxes
  Bursty transport, ELMs, ‘blobs’ peeling away from LCFS,...
  => not a simple $D\nabla n, \chi\nabla T$ transport paradigm

- Evidence that electromagnetic turbulence sets ‘critical gradient’ ($\alpha_{MHD}$)
  L-mode edge states map to a 2-D dimensionless ‘phase space’ ($\alpha_{MHD}, \Lambda$)
  Mapping is invariant of machine parameters for fixed magnetic topology:
  $0.4 < I_p < 1.1$ MA, $2.7 < B_T < 6$T, $0.1 < \bar{n}_e/n_G < 0.5$
  => makes contact with first-principles EMFDT simulations
  -- a strong endorsement for continued numerical simulation development

- SOL flows (ballooning drive) impose a toroidal rotation ‘boundary condition’
  => Confined plasma ‘spins-up’ in co-current direction for $B_x\nabla B$ toward x-point
### Summary

- **Edge plasma (L and H-mode) ~ a system at ‘critical gradient’ near LCFS**
  - Small change in LCFS gradient => large change in fluxes
  - Bursty transport, ELMs, ‘blobs’ peeling away from LCFS,...
  - => **not** a simple $D \nabla n$, $\chi \nabla T$ transport paradigm

- **Evidence that electromagnetic turbulence sets ‘critical gradient’ ($\alpha_{MHD}$)**
  - L-mode edge states map to a 2-D dimensionless ‘phase space’ ($\alpha_{MHD}$, $\Lambda$)
  - Mapping is invariant of machine parameters **for fixed magnetic topology:**
    - $0.4 < I_p < 1.1$ MA, $2.7 < B_T < 6$T, $0.1 < n_e/n_G < 0.5$
  - => makes contact with first-principles EMFDT simulations
    -- a strong endorsement for continued numerical simulation development

- **SOL flows (ballooning drive) impose a toroidal rotation ‘boundary condition’**
  - => Confined plasma ‘spins-up’ in co-current direction for $Bx \nabla B$ toward x-point

- **With $Bx \nabla B$ toward x-point, edge plasma attains higher $\alpha_{MHD}$ values**
  - Strongly correlated with co-current plasma rotation
  - => Rotation/flow is another phase space parameter ($\alpha_{MHD}$, $\Lambda$, $M$,...)
Summary

- Edge plasma (L and H-mode) ~ a system at ‘critical gradient’ near LCFS
  Small change in LCFS gradient => large change in fluxes
  Bursty transport, ELMs, ‘blobs’ peeling away from LCFS,...
  => not a simple $D\nabla n, \chi \nabla T$ transport paradigm

- Evidence that electromagnetic turbulence sets ‘critical gradient’ ($\alpha_{MHD}$)
  L-mode edge states map to a 2-D dimensionless ‘phase space’ ($\alpha_{MHD}, \Lambda$)
  Mapping is invariant of machine parameters for fixed magnetic topology:
    0.4 < $I_p$ < 1.1 MA, 2.7 < $B_T$ < 6T, 0.1 < $n_e/n_G$ < 0.5
  => makes contact with first-principles EMFDT simulations
    -- a strong endorsement for continued numerical simulation development

- SOL flows (ballooning drive) impose a toroidal rotation ‘boundary condition’
  => Confined plasma ‘spins-up’ in co-current direction for $B_x \nabla B$ toward x-point

- With $B_x \nabla B$ toward x-point, edge plasma attains higher $\alpha_{MHD}$ values
  Strongly correlated with co-current plasma rotation
  => Rotation/flow is another phase space parameter ($\alpha_{MHD}, \Lambda, M,...$)
  => Connection to L-H power threshold being lower for $B_x \nabla B$ toward x-point