New insights on boundary plasma turbulence and the Quasi-Coherent Mode in Alcator C-Mod using a Mirror Langmuir Probe

B. LaBombard, T. Golfinopoulos, J.L. Terry, D. Brunner, E. Davis, M. Greenwald, J.W. Hughes and the Alcator C-Mod Team

Plasma Science and Fusion Center, MIT

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A “Mirror Langmuir Probe” bias system\textsuperscript{1} is a powerful new tool to investigate $n$, $T_e$, $\Phi$ profiles and turbulence.

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MLP was installed on a C-Mod scanning-probe and tested at the end of C-Mod’s FY12 run campaign.

Initial experiments produced exciting new observations of edge plasma turbulence, including identifying the mode structure of C-Mod’s Quasi-Coherent Mode.

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A first-principles understanding of this physics is an important step towards unfolding the transport of the boundary layer.

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**Outline:**
- What is a Mirror Langmuir Probe (MLP) bias system?
- MLP bias system on a C-Mod scanning probe
  - High fidelity measurements of \(\tilde{n}\), \(\tilde{T}_e\), and \(\tilde{\Phi}\) (~1 MHz)
  - L-mode, H-mode and ELMs
- Quasi-Coherent Mode investigation
  - \(\tilde{n}\), \(\tilde{T}_e\), \(\tilde{\Phi}\), \(\tilde{B}_\theta\) and \((f, k_\theta)\) spectra at ~100 kHz, clearly identifying mode type

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QCM is a drift-wave with interchange drive and EM components

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Mirror Langmuir Probe
An electronic device that adjusts its $I-V$ response in real time to match that of an actual Langmuir probe

- Fast-switching voltage bias applied to actual Langmuir Probe (LP) and Mirror Langmuir Probe (MLP)

$V_{\text{bias}}$: 3-State Voltage Waveform

$V_+$
$V_f$
$V_-$

$0.9 \mu s$

time

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V_- & \\
0.9 \mu s & \\
\end{align*}

I-V Response

Mirror Langmuir Probe I-V Model:

\[ I = I_{\text{sat}} \{ \exp[\left( V - V_f \right)/T_e] - 1 \} \]

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Three Key Results:
(1) Real-time \( I_{sat} \), \( T_e \), and \( V_f \) signals (1 MHz) which ‘mirror’ that of Real LP
(2) Optimum “triple probe bias” waveform is continuously maintained.
(3) \( I_{sat} \), \( T_e \), and \( V_f \) data are obtained from a single electrode.

MLP bias has been implemented on each of 4-electrodes on a C-Mod horizontal scanning probe drive.

High heat-flux geometry

MLP simultaneously measures $\tilde{n}$, $\tilde{T}_e$, $\tilde{\Phi}$ on all 4 electrodes ($\sim$1 $\mu$s)
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MLP simultaneously measures $\tilde{n}$, $\tilde{T}_e$, $\tilde{\Phi}$ on all 4 electrodes (~1 μs)

Enables new capabilities:
- High resolution $n$, $T_e$, $\Phi$ profiles
- Fluctuations and transport

Particle flux
$$\Gamma_r = \langle \tilde{n} \tilde{E}_\theta \rangle / B$$

Heat fluxes
$$Q_{er} = (5/2) \langle \tilde{P}_e \tilde{E}_\theta \rangle / B$$
$$= (5/2) T_e \Gamma_r + (5/2) n \langle \tilde{T}_e \tilde{E}_\theta \rangle / B$$

convection conduction

Turbulence mode structure
$k_\theta$- resolved $\tilde{n}$, $\tilde{T}_e$, $\tilde{\Phi}$
and relative phase angles

Momentum fluxes
$$\langle \tilde{V}_r \tilde{V}_{\|} \rangle \quad \langle \tilde{n} \tilde{V}_r \tilde{V}_{\|} \rangle \quad \langle \tilde{V}_r \tilde{V}_\theta \rangle \quad \langle \tilde{n} \tilde{V}_r \tilde{V}_\theta \rangle$$
MLP bias has been implemented on each of 4-electrodes on a C-Mod horizontal scanning probe drive.

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Focus of this talk

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Turbulence mode structure
$k_\theta$-resolved $\tilde{n}, \tilde{T}_e, \tilde{\Phi}$ and relative phase angles

Momentum fluxes
$$\langle \tilde{V}_{r\parallel} \tilde{V}_{\parallel} \rangle, \langle \tilde{n} \tilde{V}_r \tilde{V}_{\parallel} \rangle, \langle \tilde{V}_{r\theta} \tilde{V}_\theta \rangle, \langle \tilde{n} \tilde{V}_r \tilde{V}_\theta \rangle$$
MLP Working Example: Probe scan to separatrix in L-mode plasma

Data from NW electrode

Real-time signals of $I_{\text{sat}}$, $V_f$, and $T_e$ reported by Mirror Langmuir Probe

22,000 measurements of $I_{\text{sat}}$, $V_f$, and $T_e$ from a single electrode
MLP Working Example:
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MLP system automatically adjusts bias to optimum value ($\Delta V \sim 4xT_e$)

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22,000 measurements of $I_{sat}$, $V_f$, and $T_e$ from a single electrode
Fluctuations in signals are not noise! These are plasma fluctuations.

Data from NW electrode

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MLP Working Example: Probe scan to separatrix in L-mode plasma

Data from NW electrode

Same data on expanded time scale

Real-time signals of $I_{sat}$, $V_f$, and $T_e$ reported by Mirror Langmuir Probe

Immediate observation: $I_{sat}$ and $T_e$ fluctuations tend to track one another
MLP Working Example: Probe scan to separatrix in L-mode plasma

Data from NW electrode

Real-time signals of $I_{sat}$, $V_f$, and $T_e$ reported by Mirror Langmuir Probe

1 $\mu$s time resolution adequate to resolve plasma dynamics
MLP Working Example: Probe scan to separatrix in L-mode plasma

Post-processing computation of $I_{sat}$, $V_f$, and $T_e$ from I-V data yield nearly identical signals, but with no slew-rate limitations.
Use Fitted I-V data for all physics analyses

Compute:
Plasma potential \( \Phi = \alpha_{sh} T_e + V_f \)
Plasma density \( n = I_{sat} / (2q Area \ C_s) \)
MLP Working Example: Boundary profiles in H and L-mode

Data from NE electrode
MLP Working Example: Boundary profiles in H and L-mode

Fluctuations and profiles resolved with unprecedented detail

- Each profile contains 18,000 measurement points (in + out scan, 16 ms)

Data from NE electrode

ELM-free H-mode

Density

Electron Temperature

Plasma Potential

Floating Potential

L-mode (after H-L)

Density

Electron Temperature

Plasma Potential

Floating Potential
MLP Working Example: Boundary profiles in H and L-mode

- Each profile contains 18,000 measurement points (in + out scan, 16 ms)
- Smoothing over 200 \( \mu \text{s} \) window yields high resolution, ‘time-averaged’ profiles

ExB shear layer clearly resolved

Data from NE electrode
MLP Working Example: ELMs

Data from NE electrode
MLP Working Example: ELMs

Time evolution of ELMs is readily resolved.

- Multiple ELM events, $\sim25\,\mu$s evolution timescale, easily resolved

Data from NE electrode

H-mode with a few ELMs

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Electron Temperature

Plasma Potential

Floating Potential

ELM

Time evolution of ELMs is readily resolved.
MLP Working Example: ELMs

Time evolution of ELMs is readily resolved.

- Multiple ELM events, ~25 μs evolution timescale, easily resolved
- Nearly identical signals observed on different electrodes

Time evolution of ELMs is readily resolved.
Goal: **Unambiguously identify QC mode type (drift wave, interchange, ...)**

Measurements:
- $k_\theta$-resolved $\tilde{n}$, $\tilde{T_e}$, $\tilde{\Phi}$, $\tilde{B}_\theta$ and relative phase angles
- Phase propagation relative to $V_{ExB}$, $V_{de}$
- Radial width of mode layer

Results from $\tilde{B}_\theta$ probe: QCM has strong $B_\theta$, $J_//$ components

Spectra from $\tilde{B}_\theta$ pickup coils

- Frequency Spectrum
- Poloidal Wavenumber Spectrum

$\tilde{B}_\theta$ magnetic probe

Probe Position

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Results from $\widetilde{B}_\theta$ probe: QCM has strong $B_\theta$, $J_{\parallel}$ components

- $k_\theta \sim 1.5 \text{ rad/cm}$; perturbation $\sim$ field-aligned [1] $\vec{k} \cdot \vec{B} \approx 0$

Results from $\tilde{B}_\theta$ probe: QCM has strong $B_\theta$, $J_\parallel$ components

- $k_\theta \sim 1.5$ rad/cm; perturbation ~field-aligned \[1\] $k \cdot B \approx 0$
- QCM propagates in electron diamagnetic direction (lab frame)
- Near LCFS: $B_r \sim 0.3$ mT Equivalent filament current ~10 amps

$=>$ peak amplitude $J_\parallel \sim 25$ amps/cm$^2$

Experimental setup: Mirror Langmuir Probe investigation of Quasi-Coherent Mode

Goals: ● Plunge probe across QCM mode layer
Record $k_\theta, \tilde{n}, \tilde{T}_e, \tilde{\Phi}$ response
Determine mode layer width (？)
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● Does probe ‘kill the mode’? Use electrodes spaced in minor radius direction to assess probe perturbation effects
MLP passes through mode layer -- reveals density fluctuation with frequency and wavenumber of QCM

- Mode exists near LCFS
- Frequency, poloidal wave number and propagation in electron diamagnetic direction -- consistent with $B_\theta$ probe, PCI (and GPI)
- Probe appears to pass through mode
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- Probe perturbs plasma at peak insertion (see $P_{rad}$ jump)
  Post mortum: leading edge of probe head showed melt damage
- Must examine other electrodes to see if probe is perturbing mode...

Spectra from North-South electrodes

Cross-Power Spectrum, $S(f,k_\theta)$

- Frequency $[kHz]$ -1.0 0 1.0
- Poloidal Wavenumber $[rad/cm]$ -1.0 0 1.0
- Probe Position
- Probe appears to pass through mode
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Radial extent of QCM fluctuation is mapped out separately by each electrode as they pass through the layer.

Note: $I_{sat}$ power normalized to same peak value for in-going scan.

- Time delay is seen among probes, consistent with their radial positions.
- At peak insertion, $P_{rad}$ jumps up -- probe-induced impurity injection;
  
  $I_{sat}$ power envelopes are different on out-going scan.
Narrow QCM layer width from ion saturation current fluctuations is consistent with Gas-Puff Imaging (GPI)

- $I_{\text{sat}}$ and $\tilde{I}_{\text{sat}}$ power profiles align, despite being recorded at different times by different probes.
- Conclusion: QCM is \textit{not} being attenuated by probe.
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- Radial width of Quasi-Coherent Mode layer is $\sim 3$ mm FWHM
Quasi-coherent mode lives at separatrix, in steep gradient region with positive radial electric field. 

Profiles from East electrode:

- QCM exists in region of positive $E_r$ (i.e. with $E_x B$ in ion diam. dir.)
Quasi-coherent mode lives at separatrix, in steep gradient region with **positive radial electric field**.

- QCM exists in **region of positive** $E_r$  
  *(i.e. with ExB in ion dia. dir.)*

- From power balance: $T_e \sim 50$ eV at LCFS  
  *(used here to set $\rho = 0$ location)*
Quasi-coherent mode lives at separatrix, in steep gradient region with **positive radial electric field**

Profiles from East electrode

- QCM exists in **region of positive** $E_r$ (i.e. with $E_xB$ in ion dia. dir.)

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- Profiles deeper into plasma are unreliable
Quasi-coherent mode lives at separatrix, in steep gradient region with positive radial electric field

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QCM spans LCFS

$=>$ consistent with QCM kicking impurities out confined plasma onto open field lines
Quasi-coherent mode propagates at electron diamagnetic drift velocity in the plasma frame

Velocities computed from East electrode profiles

\[ V_{dpe} = \frac{\nabla_{r} n T_e \times b}{nB} \]
\[ V_{de} = \frac{T_e \nabla_{r} n \times b}{nB} \]
\[ V_{ExB} = \frac{b \times \nabla_{r} \Phi}{B} \]

- \( V_{dpe}, V_{de} \) are in opposite directions to \( V_{ExB} \) in mode layer

- \( V_{dpe}, V_{de} \) are stronger than \( V_{ExB} \) in mode layer

- QCM propagates in \( e^- \) dia. direction in the plasma frame

QCM frequency is quantitatively consistent with \( k_{\theta} \sim 1.5 \) rad/cm mode propagating with velocity between \( V_{dpe} \) and \( V_{de} \) in the plasma frame.
Snapshot of QCM reveals large amplitude, \( \sim \) in-phase, density, electron temperature and potential fluctuations.

Profiles from East electrode:

- **Density**
- **Electron Temperature**
- **Plasma Potential**

\( I_{\text{sat}} \) Fluctuation Power \( 80 \text{ kHz} < f < 120 \text{ kHz} \)

\[
\frac{\Delta n}{\langle n \rangle} \sim 30\% \quad \frac{\Delta T_e}{\langle T_e \rangle} \sim 45\% \quad \frac{\Delta \Phi}{\langle T_e \rangle} \sim 45\%
\]
Snapshot of QCM reveals large amplitude, ~in-phase, density, electron temperature and potential fluctuations

Cross Power Spectrum: **Density** and **Potential**

Potential lags **Density** with a phase angle of ~ 16 degrees

=> Drift wave
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\[ V_r = \langle \tilde{n} \tilde{E}_\theta \rangle / \langle n \rangle B \approx 10 \text{ m/s} \quad \Rightarrow \text{Drives transport} \]
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Simple Boltzmann electron response?

Compute \( n_B \) required to satisfy

\[ n_B = \langle n \rangle \exp \left( \frac{\Phi - \langle \Phi \rangle}{T_e} \right) \]

\( n_B \) is ~1.5x larger than measured \( \tilde{n} \)

Not a simple Boltzmann response
Snapshot of QCM reveals large amplitude, ~in-phase, density, electron temperature and potential fluctuations.

Cross Power Spectrum: Density and Potential

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Not a simple Boltzmann response

But Boltzmann response is not expected, considering large \( \tilde{T}_e \) and EM character of wave...
Analysis of $\tilde{n}$, $\tilde{\Phi}$, $\tilde{T}_e$, $\tilde{p}_e$ indicates interchange drive and inductive $\tilde{E}_{//}$ components contribute to QCM
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- Phase order is $\tilde{n}(0^\circ)$, $\tilde{p}_e(5^\circ)$, $\tilde{T}_e(9^\circ)$, $\tilde{\Phi}(16^\circ)$
  => drift wave
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- Large electron pressure fluctuation $\frac{\tilde{p}_e}{\langle p_e \rangle} \sim 1.7 \frac{\tilde{\Phi}}{\langle T_e \rangle}$
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$$\frac{\tilde{p}_e}{\langle p_e \rangle} \sim 1.7 \frac{\tilde{\Phi}}{\langle T_e \rangle}$$
- Look at linearized vorticity equation $^1$ (i.e., $\nabla \cdot \mathbf{J} = 0$)

$$\frac{nM_i}{B^2} \frac{\partial}{\partial t} \nabla_\perp^2 \tilde{\Phi} = \nabla_{//} \tilde{\mathbf{J}}_{//} - \frac{2k_{//}}{BR} \tilde{p}_e$$

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- Look at linearized vorticity equation$^1$ (i.e., $\nabla \cdot J = 0$) for interchange drive

  $$\frac{nM_i}{B^2} \frac{\partial}{\partial t} \nabla^2 \tilde{\Phi} = \nabla_{//} \tilde{J}_{//} - \frac{2k_{//} \tilde{p}_e}{BR}$$

  $$k_{//} \approx \frac{\pi}{L_{//}}$$

  $$\frac{\omega \rho_s^2 k_{//}^2}{k_{//} C_s \langle T_e \rangle} \frac{\tilde{\Phi}}{\langle T_e \rangle} : \frac{\tilde{J}_{//}}{enC_s} : \frac{2k_{//} \rho_s}{k_{//} R} \frac{\tilde{p}_e}{\langle p_e \rangle}$$

  $\tilde{p}_e$ term is significant

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  $$\frac{nM_i}{B^2} \frac{\partial}{\partial t} \nabla^2 \tilde{\Phi} = \nabla_{//} \tilde{J}_{//} - \frac{2k_{//}}{BR} \tilde{p}_e$$

  $$k_{//} \approx \frac{\pi}{L_{//}}$$

  $$\frac{\omega \rho_s^2 k_{//}^2}{k_{//} C_s \langle T_e \rangle} \frac{\tilde{\Phi}}{\langle T_e \rangle} = \frac{\tilde{J}_{//}}{enC_s} : \frac{2k_{//} \rho_s}{k_{//} R} \frac{\tilde{p}_e}{\langle p_e \rangle}$$

  0.3 ~ 0.2

  from $\tilde{B}_\theta$ probe

  $\tilde{p}_e$ term is significant

  => Interchange drive is important

\(^1\)B. Scott, PPCF, 39 (1997) 1635.
Analysis of $\tilde{n}$, $\tilde{\phi}$, $\tilde{T}_e$, $\tilde{p}_e$ indicates interchange drive and inductive $\tilde{E}_{//}$ components contribute to QCM

Look at linearized parallel Ohm's law\(^1\)

**Inductive** $E_{//}$

\[
\frac{en}{e} \frac{\partial}{\partial t} \tilde{A}_{//} + \frac{m_e}{e} \frac{\partial}{\partial t} \tilde{J}_{//} = \nabla_{//} \tilde{p}_e - en \nabla_{//} \tilde{\phi} + 0.71 n \nabla_{//} \tilde{T}_e - en \eta_{//} \tilde{J}_{//}
\]

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- Look at linearized parallel Ohm's law\(^1\)
  
  inductive $\tilde{E}_{//}$

\[
\begin{aligned}
  \frac{en}{e} \frac{\partial}{\partial t} \tilde{A}_{//} &+ \frac{m_e}{e} \frac{\partial}{\partial t} \tilde{J}_{//} = \nabla_{//} \tilde{p}_e - en \nabla_{//} \tilde{\Phi} + 0.71 n \nabla_{//} \tilde{T}_e - enr_{//} \tilde{J}_{//} \\
  \text{small}
\end{aligned}
\]

inductive $\tilde{E}_{//}$

\[
\begin{aligned}
  \omega \frac{C_s}{k_{//} k_{//} \rho_s V_A^2} \left( \frac{\tilde{J}_{//}}{en C_s} \right) : \left[ \frac{\tilde{p}_e}{\langle p_e \rangle} - \frac{\tilde{\Phi}}{\langle T_e \rangle} + 0.71 \frac{\tilde{T}_e}{\langle T_e \rangle} \right]
\end{aligned}
\]

\(^1\)B. Scott, PPCF, 39 (1997) 1635.
Analysis of $\tilde{n}$, $\Phi$, $\tilde{T}_e$, $\tilde{p}_e$ indicates interchange drive and inductive $E_{//}$ components contribute to QCM

- Look at linearized parallel Ohm’s law

\[
\begin{align*}
\frac{en}{t} \frac{\partial \tilde{A}_{//}}{\partial t} + \frac{m_e}{e} \frac{\partial \tilde{j}_{//}}{\partial t} &= \nabla_{//} \tilde{p}_e - en \nabla_{//} \Phi + 0.71 n \nabla_{//} \tilde{T}_e - en \nabla_{//} \tilde{j}_{//}
\end{align*}
\]

inductive $E_{//}$

\[
\omega \frac{C_s}{k_{//} \rho_s^2 V_A^2} \left( \frac{\tilde{j}_{//}}{en C_s} \right) : \left[ \frac{\tilde{p}_e}{\langle p_e \rangle} - \frac{\tilde{\Phi}}{\langle T_e \rangle} + 0.71 \frac{\tilde{T}_e}{\langle T_e \rangle} \right] \approx 0.9 \frac{\tilde{p}_e}{\langle p_e \rangle}
\]

\[
\tilde{p}_e \text{ leads } \Phi \text{ by } 11 \text{ deg.}
\]

$\approx 0.22$

$\Rightarrow$ force balance implies inductive contribution

\[^{1}\text{B. Scott, PPCF, 39 (1997) 1635.}\]
Analysis of $\tilde{n}$, $\tilde{\Phi}$, $\tilde{T_e}$, $\tilde{p_e}$ indicates interchange drive and inductive $\tilde{E}_//$ components contribute to QCM

- Look at linearized parallel Ohm’s law\(^1\)

inductive $E_//$

$$en \frac{\partial}{\partial t} \tilde{A}_// + \frac{m_e}{e} \frac{\partial}{\partial t} \tilde{J}_// = \nabla_// \tilde{p}_e - en \nabla_// \tilde{\Phi} + 0.71n \nabla_// \tilde{T_e} - enr_// \tilde{J}_//$$

small

$$\omega \frac{C_s}{k_// k_{\perp}^2 \rho_s V_A} \left( \frac{\tilde{J}_//}{enC_s} \right) : \left[ \frac{\tilde{p}_e}{\langle p_e \rangle} - \frac{\tilde{\Phi}}{\langle T_e \rangle} + 0.71 \frac{\tilde{T_e}}{\langle T_e \rangle} \right] \approx 0.9 \frac{\tilde{p}_e}{\langle p_e \rangle}$$

$\sim 0.06$

$\sim 0.22$

$\Rightarrow$ force balance implies inductive contribution

with 1cm x 1cm flux tube, $\tilde{J}_// \sim 25$ amps/cm\(^2\) (Mag Probe)

\(^1\)B. Scott, PPCF, 39 (1997) 1635.
Analysis of $\tilde{n}$, $\tilde{\Phi}$, $\tilde{T}_e$, $\tilde{p}_e$ indicates interchange drive and inductive $\tilde{E}_\parallel$ components contribute to QCM

Look at linearized parallel Ohm’s law:

$$en \frac{\partial}{\partial t} \tilde{A}_\parallel + \frac{m_e}{e} \frac{\partial}{\partial t} \tilde{J}_\parallel = \nabla_\parallel \tilde{p}_e - en \nabla_\parallel \tilde{\Phi} + 0.71n \nabla_\parallel \tilde{T}_e - enr_\parallel \tilde{J}_\parallel$$

Inductive $E_\parallel$

$$\omega \frac{C_s}{k_{\perp} k_{\parallel}^2 \rho_s^2 V_A^2} \left( \frac{\tilde{J}_\parallel}{enC_s} \right) : \left[ \frac{\tilde{p}_e}{\langle p_e \rangle} - \frac{\tilde{\Phi}}{\langle T_e \rangle} + 0.71 \frac{\tilde{T}_e}{\langle T_e \rangle} \right] \approx 0.9 \frac{\tilde{p}_e}{\langle p_e \rangle}$$

$\tilde{n}$ leads $\tilde{\Phi}$ by 16 deg.

$\tilde{T}_e$ leads $\tilde{\Phi}$ by 7 deg.

$\tilde{p}_e$ leads $\tilde{\Phi}$ by 11 deg.

$\nabla_\parallel \tilde{p}_e - en \nabla_\parallel \tilde{\Phi} + 0.71n \nabla_\parallel \tilde{T}_e - enr_\parallel \tilde{J}_\parallel$ small

with 1cm x 1cm flux tube, $\tilde{J}_\parallel \sim 25$ amps/cm$^2$ (Mag Probe)

$\tilde{p}_e$ leads $\tilde{\Phi}$ by 11 deg.

$\nabla_\parallel \tilde{p}_e - en \nabla_\parallel \tilde{\Phi} + 0.71n \nabla_\parallel \tilde{T}_e - enr_\parallel \tilde{J}_\parallel$ small

QCM has significant inductive component

Mirror Langmuir Probe is a powerful new tool for investigating boundary $n$, $T_e$, $\Phi$ profiles and turbulence

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Fluctuations and profiles resolved with unprecedented detail:

- High spatial resolution profiles, ELM dynamics,...
MLP is revealing new insights on Alcator C-Mod’s Quasi-Coherent Mode in ohmic EDA H-mode plasmas.

- QCM spans LCFS region with a mode width of ~ 3mm
  - Drives transport directly across LCFS
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  - EM signature
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- Contributions of interchange and inductive \( E// \) components in:

\[
\frac{nM_i}{B^2} \frac{\partial}{\partial t} \nabla^2 \Phi = \nabla_// \tilde{J}_// - \frac{2k_//}{BR} \tilde{p}_e
\]

Vorticity

// electron force balance

\[
\frac{\omega L_{//}}{\rho_s e n \left( \frac{k_//^2 + k_r^2}{L_{//}} \right)} \approx \frac{\tilde{p}_e}{\langle p_e \rangle} - \frac{\tilde{\Phi}}{\langle T_e \rangle} + 0.71 \frac{\tilde{T}_e}{\langle T_e \rangle}
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\]

\[
\omega_{L_{\parallel}} \left( \frac{\tilde{j}_e}{\rho_{s} V_A^2 e n \left( \frac{k_\perp^2 + k_r^2}{L_{\parallel}} \right)} \right) \approx \frac{\tilde{p}_e}{\langle p_e \rangle} - \frac{\tilde{\Phi}}{\langle T_e \rangle} + 0.71 \frac{\tilde{T}_e}{\langle T_e \rangle}
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Vorticity // electron force balance

Thank you for your attention.