Alcator C-Mod

Mirror Langmuir Probe observations of edge plasma turbulence and the Quasi-Coherent Mode in Alcator C-Mod

B. LaBombard

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Mirror Langmuir Probe -- a powerful new tool for investigating boundary n, T_e, Φ profiles and turbulence

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Background:

A “Mirror Langmuir Probe” bias system has been implemented on Alcator C-Mod’s horizontal scanning-probe (4 electrodes).

Initial experiments with this diagnostic have yielded exciting new observations of boundary plasma turbulence and C-Mod’s Quasi-Coherent Mode (QCM).

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Outline:

- What is a Mirror Langmuir Probe?
- High fidelity measurements of $\tilde{n}$, $\tilde{T}_e$, and $\tilde{\Phi}$ (~1 MHz)
- Very high resolution 'time averaged' n, T_e, and Φ profiles
- Detailed measurements of $\tilde{n}$, $\tilde{T}_e$, $\tilde{\Phi}$, $\tilde{B}_\theta$ and (f, k_θ) spectra of ~100 kHz QCM - clearly identifying mode type

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QCM is a electron drift-Alfven wave.

Mirror Langmuir Probe[1]

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

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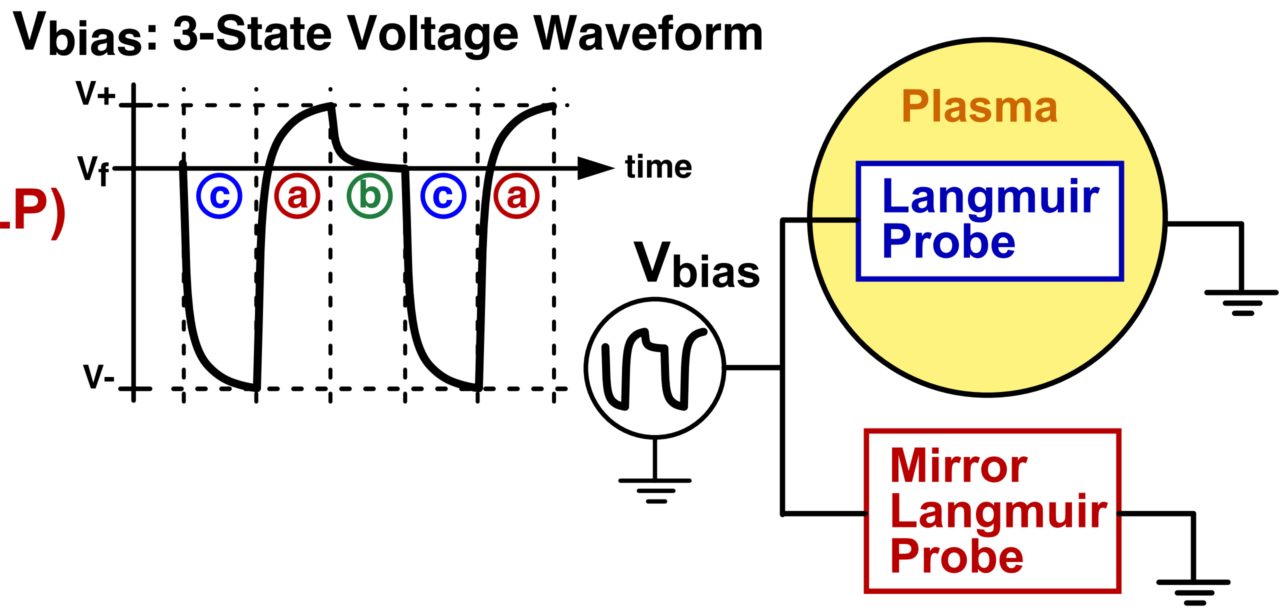
- Fast-switching voltage bias applied to actual Langmuir Probe (LP) and Mirror Langmuir Probe (MLP)



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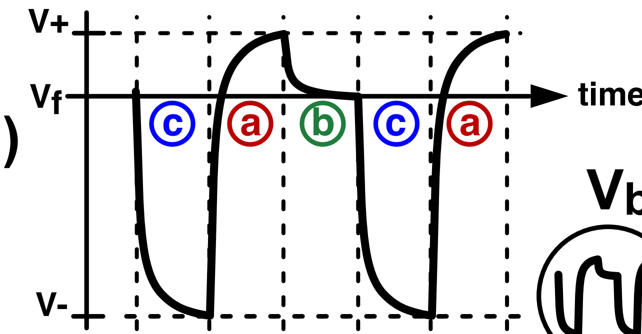
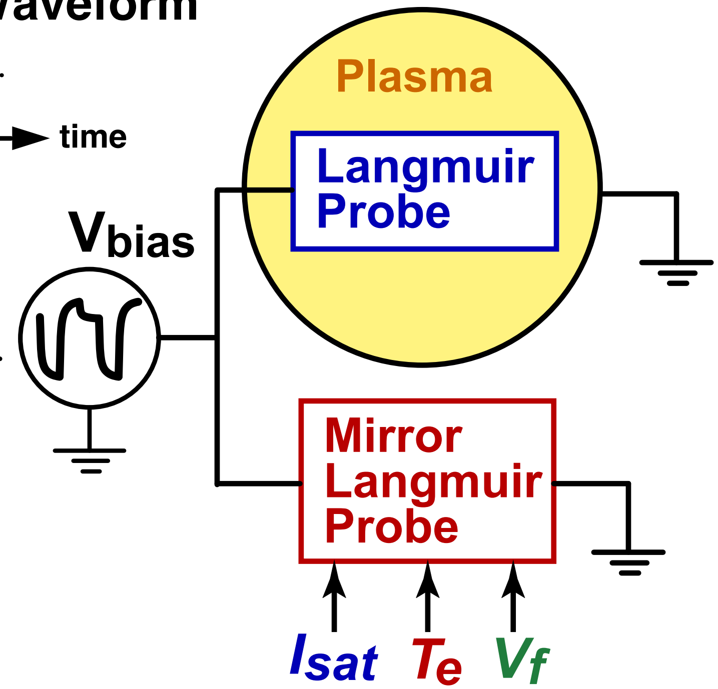
V_{bias}: 3-State Voltage Waveform





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- **Bias amplitude is adjusted dynamically based on real-time T_e signal**

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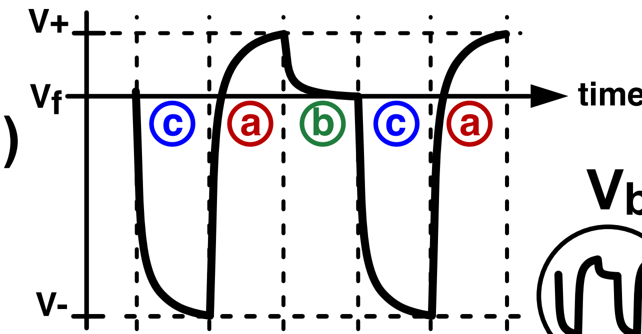

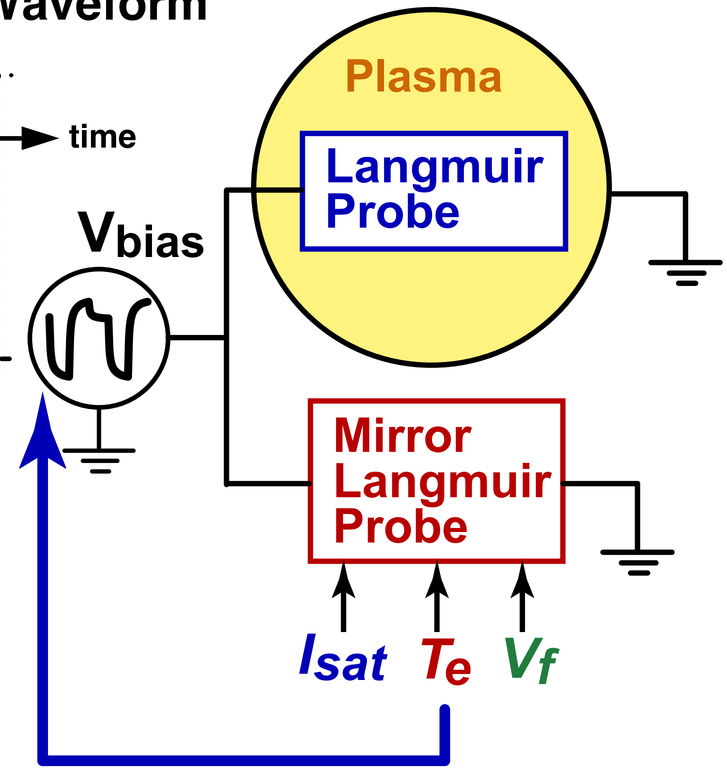

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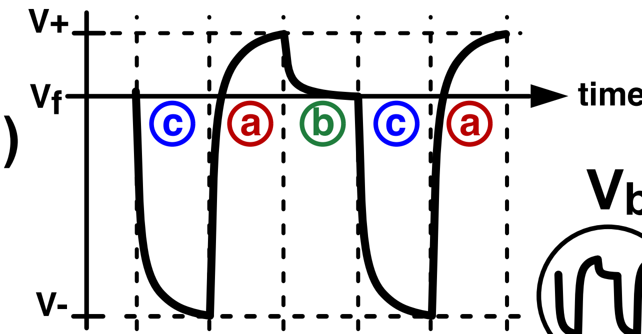

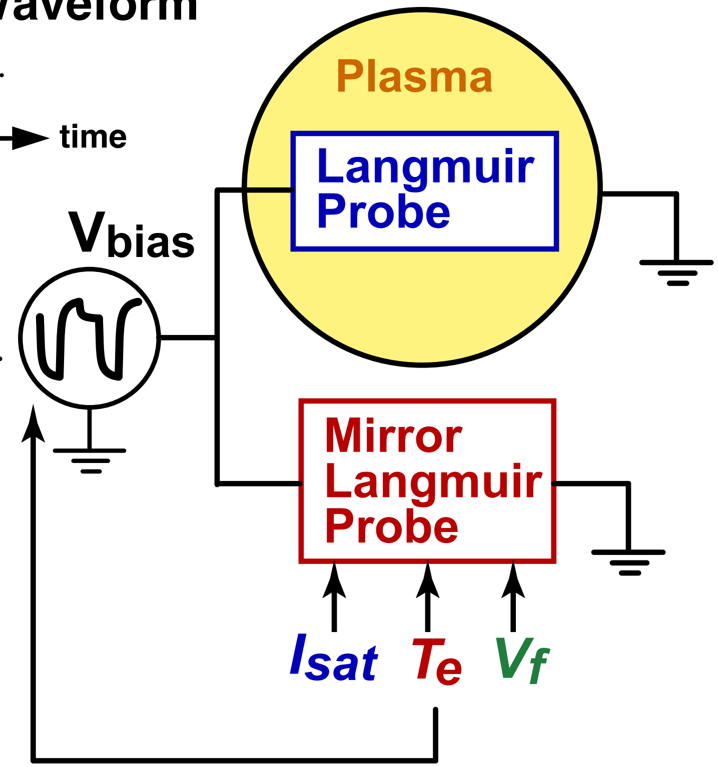

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Result:

- Real-time I_{sat}, T_e, and V_f signals which 'mirror' that of Real LP
- Optimum "triple probe bias" is applied to a single electrode

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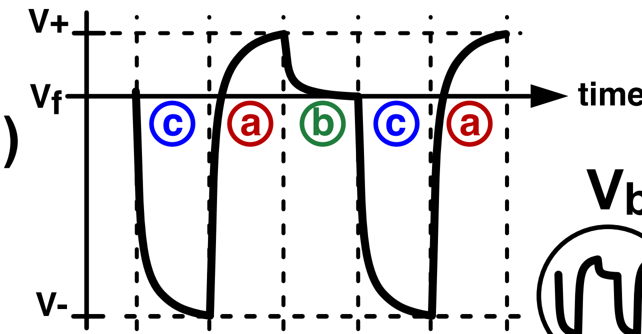

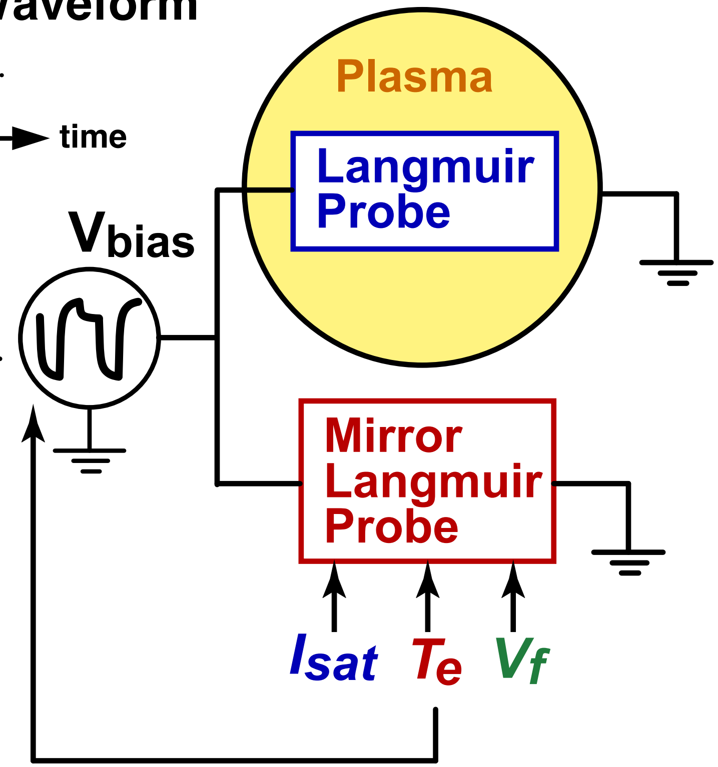

Result:

- Real-time I_{sat}, T_e, and V_f signals which 'mirror' that of Real LP
- Optimum "triple probe bias" is applied to a single electrode

MLP bias operates a single probe as a "triple probe in the time domain"

Important: These data are obtained from a single LP electrode.

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MLP Fast-Switching Voltage Waveform:
Samples I-V characteristic at three bias states in under 1 μs

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Probe Voltage Waveform ⟹

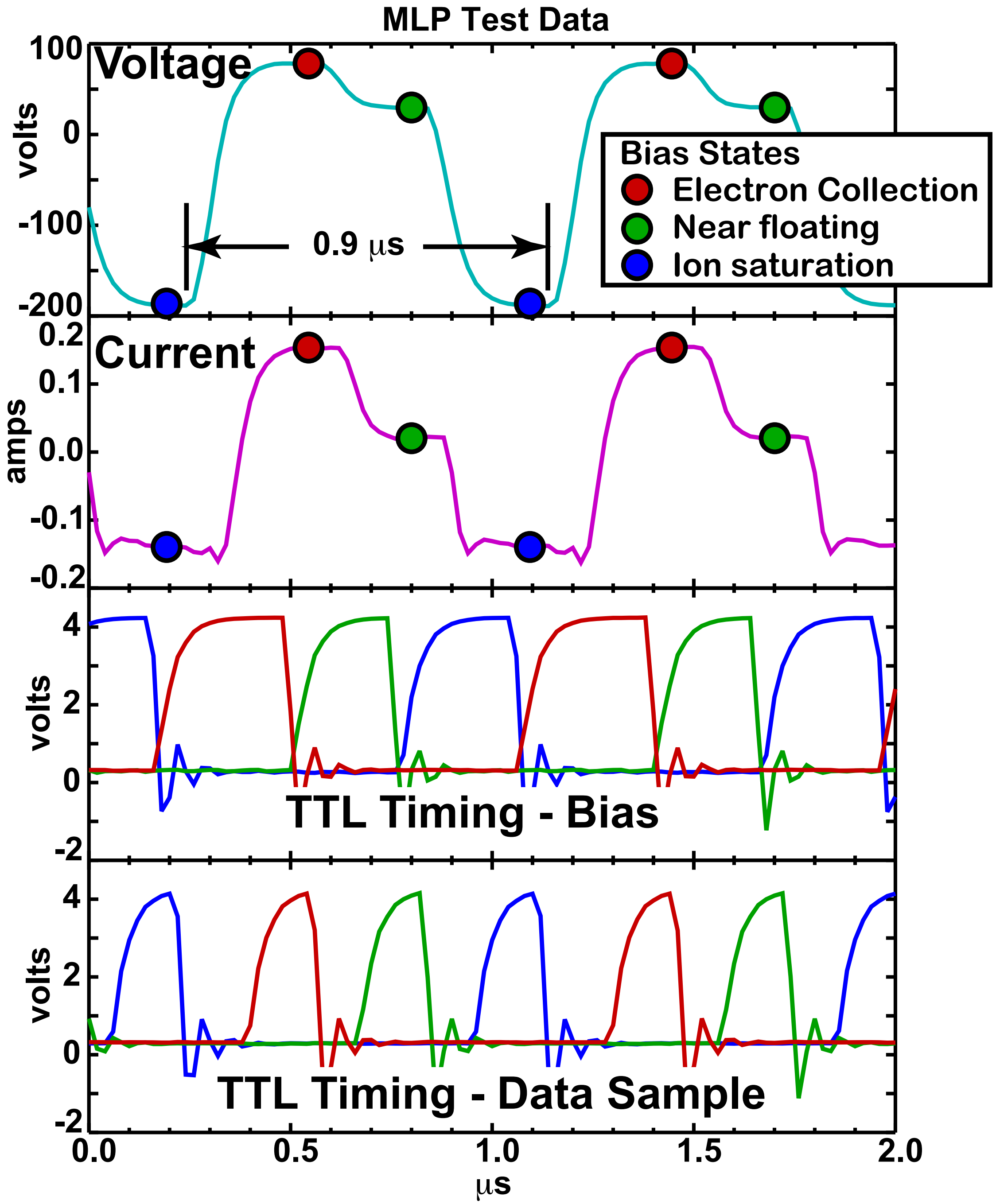
Voltage changes by up to 360V, settling in less than ~ 150ns

Probe Current Response ⟹

TTL Timing Pulses:

Bias Timing ⟹

Data Sample Timing ⟹



MLP waits for switching transients to die away before taking data samples

Working Example:
MLP waveforms from a C-Mod fast-scanning probe

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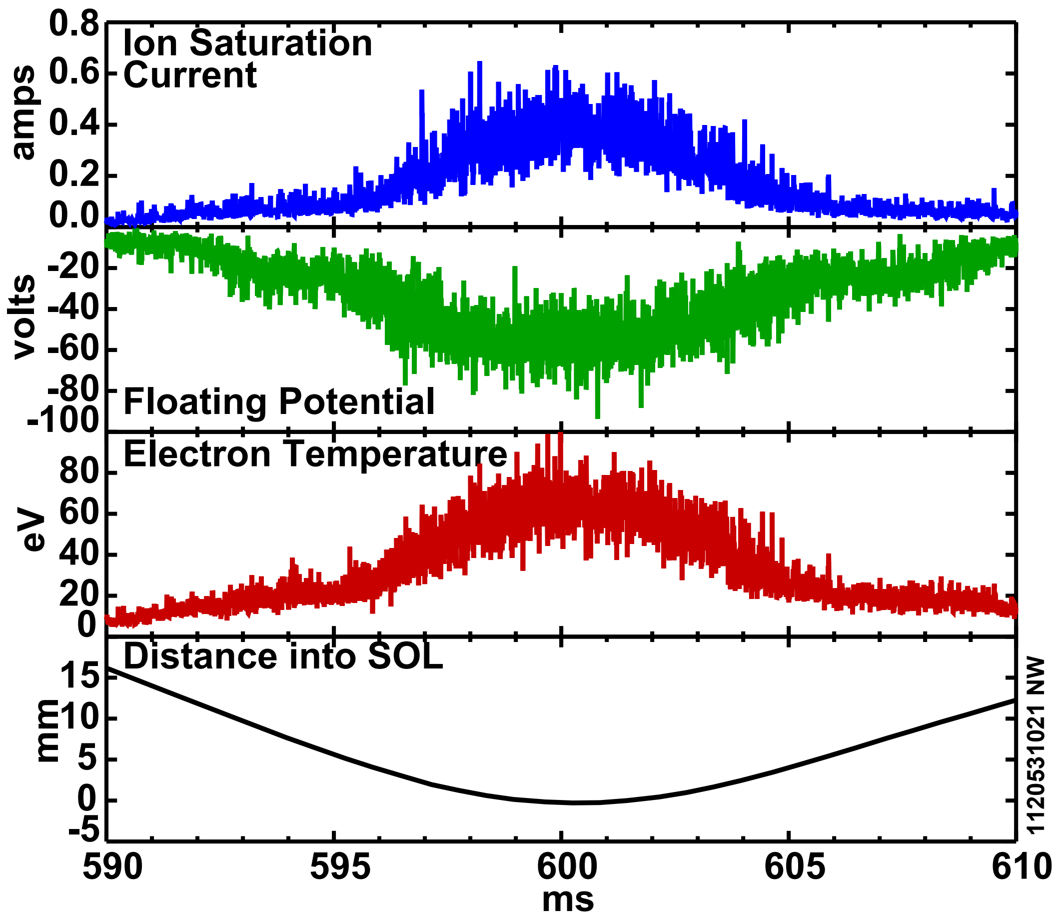
Data from a probe scan to the separatrix in an ohmic L-mode plasma

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

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.

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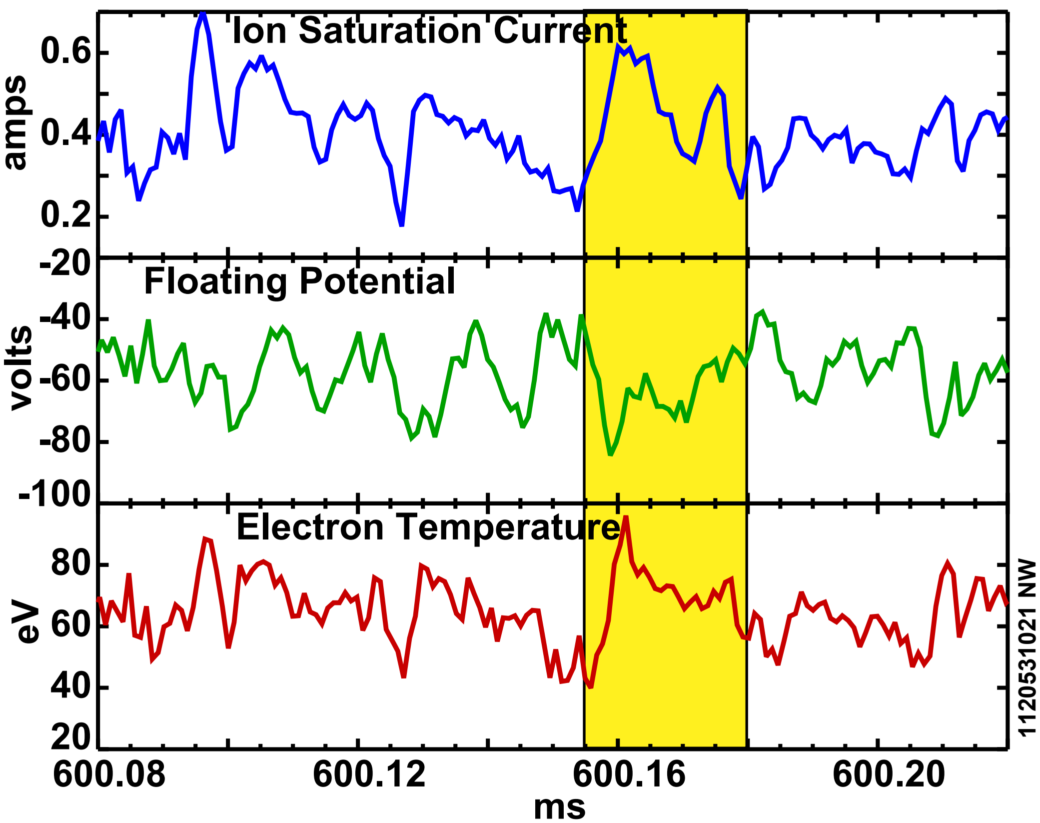
Same data on expanded time scale

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

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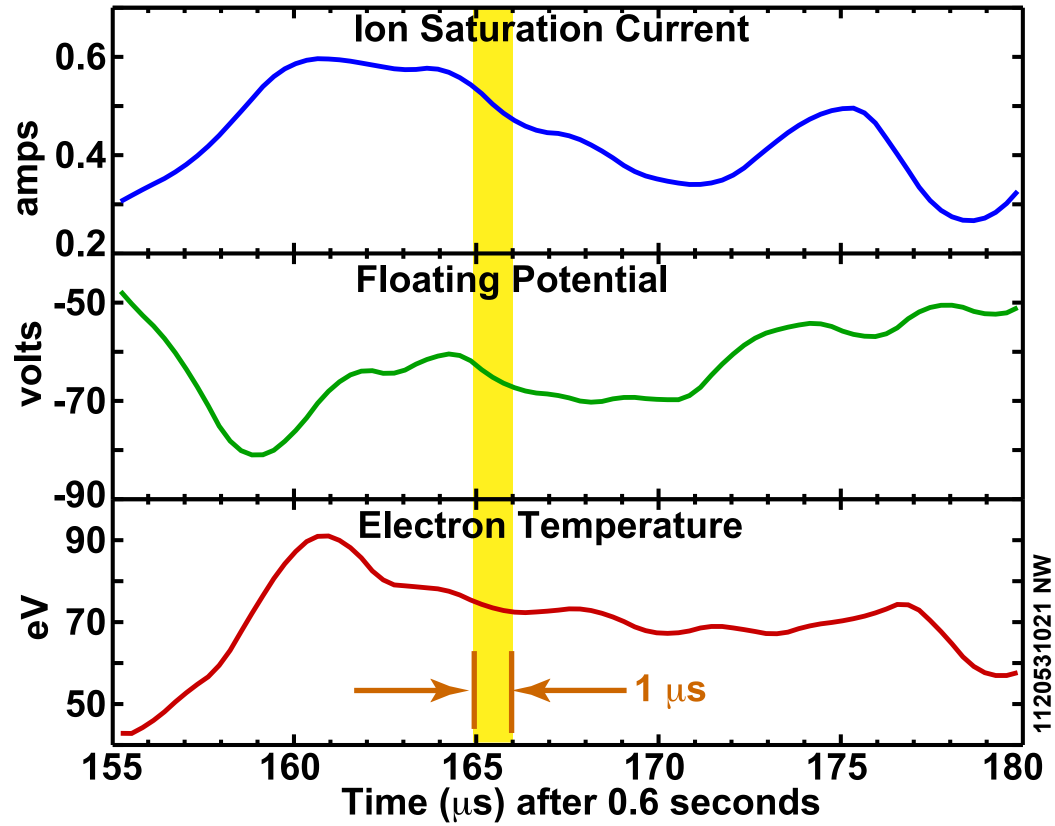
Same data on expanded time scale

1 μs time resolution adequate to resolve plasma dynamics



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Working Example:
MLP waveforms from a C-Mod fast-scanning probe

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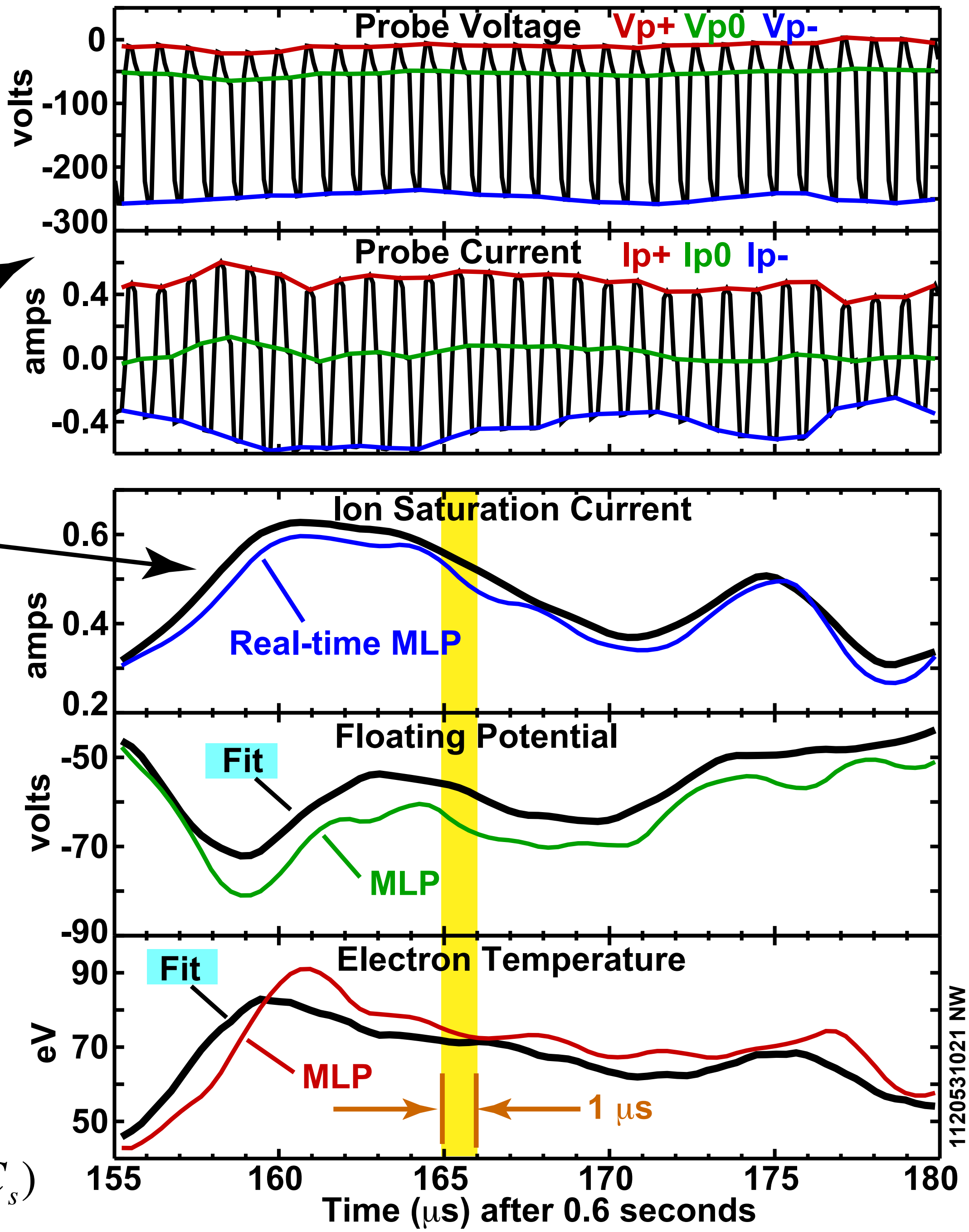
Same data on expanded time scale

1 μs time resolution adequate to resolve plasma dynamics

I-V data are also recorded at high bandwidth

Post-processing Fit



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 Fit data for remainder of talk**

Compute:

Plasma potential $\Phi = \alpha_{sh} T_e + V_f$

Plasma density $n = I_{sat} / (2\, q\, Area\, C_s)$

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Experiment: Investigate structure of Quasi-Coherent Mode using Mirror Langmuir and Magnetic ($\tilde{B}_\theta$) probes

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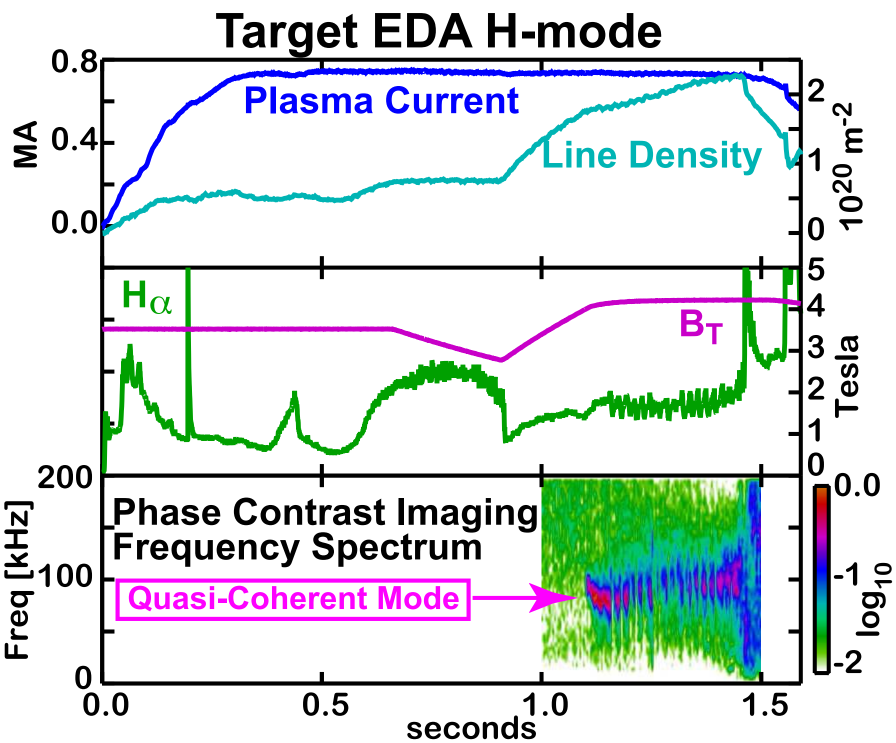

Why study the QCM?

- Coherent edge modes, such as the QCM (in H-mode) and the "weakly coherent mode" WCM (in I-mode) play key roles in pedestal dynamics, including ***regulating particle and impurity confinement without ELMS.***

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

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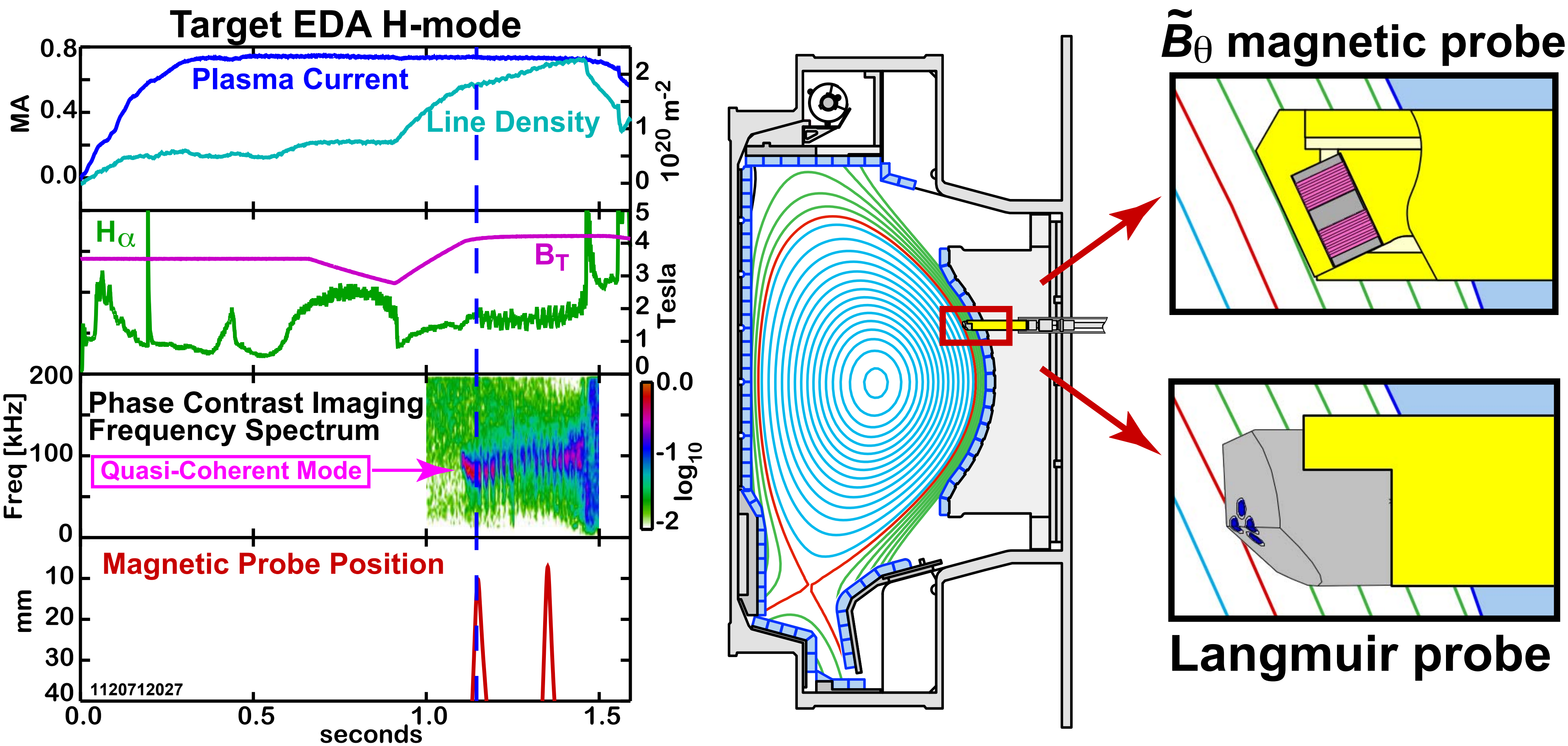


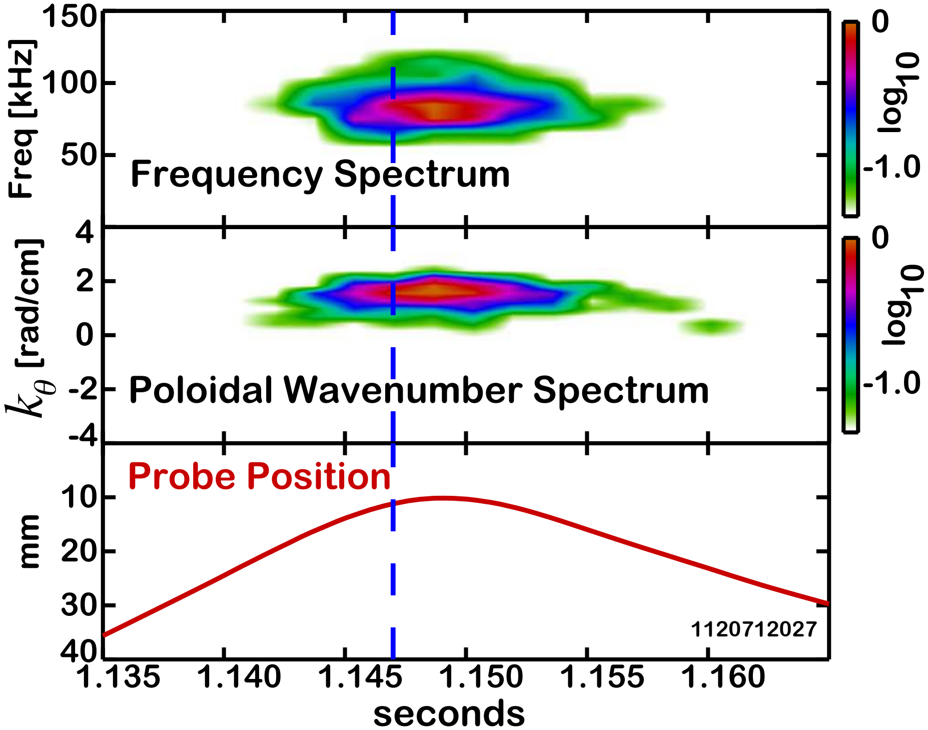
Goal: Unambiguously identify QC mode type (drift wave, interchange, ...)

Measurements:

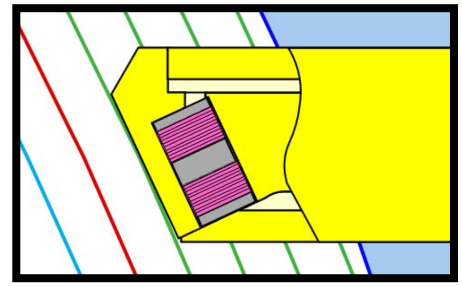
- k_θ-resolved $\tilde{n}$, $\tilde{T}_e$, $\tilde{\Phi}$, $\tilde{B}_\theta$ and relative phase angles
- Phase propagation relative to V_{ExB}, V_{de}
- Radial width of mode layer

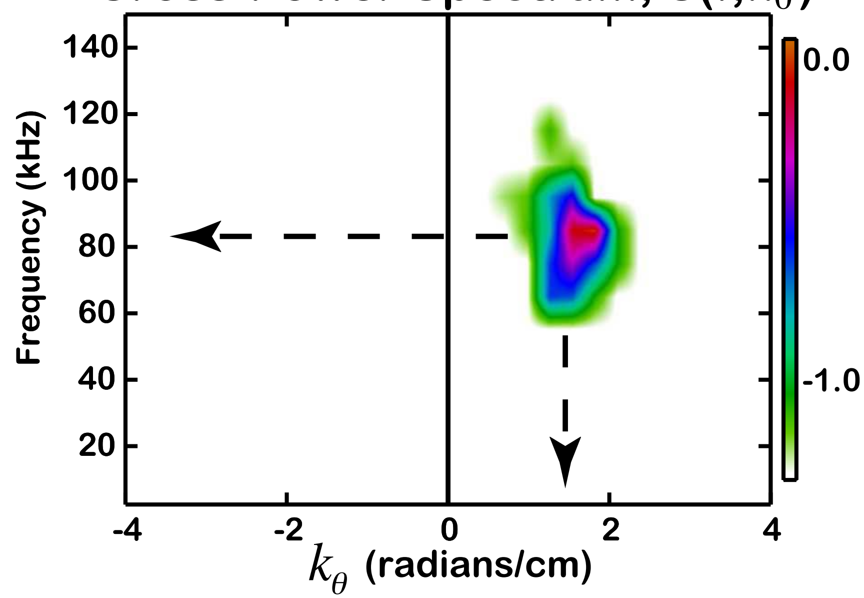
Results from $\tilde{B}_\theta$ probe: QCM has strong B_θ, $J_{//}$ components

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



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





- k_θ ~ 1.5 rad/cm; perturbation ~field-aligned [1] $\underline{k} \cdot \underline{B} \approx 0$

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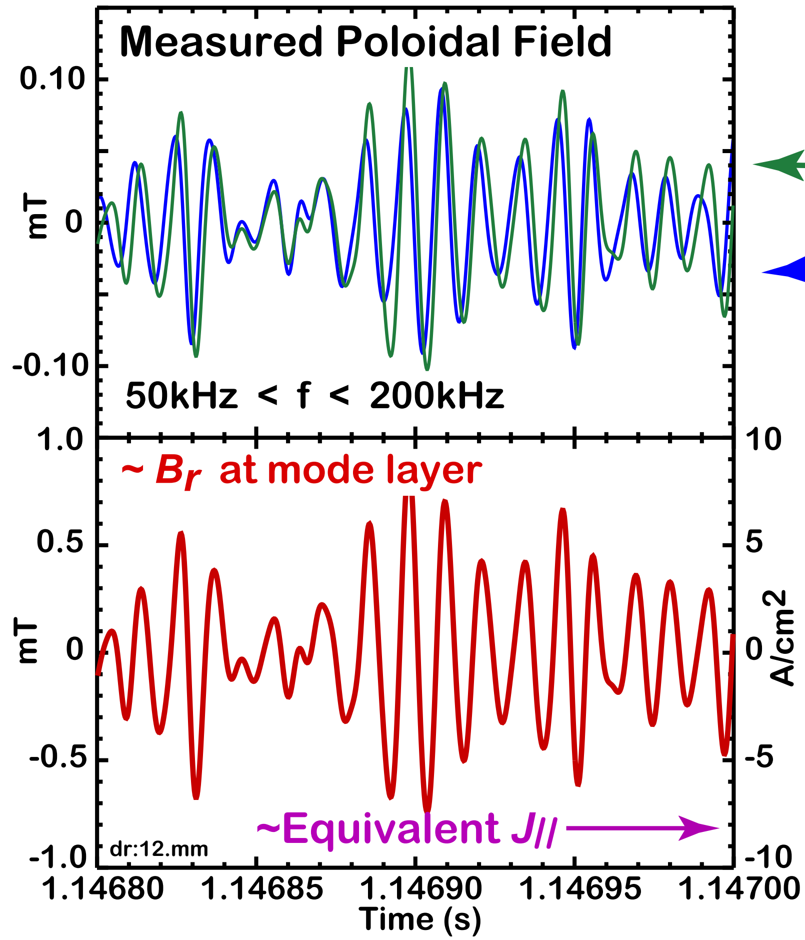

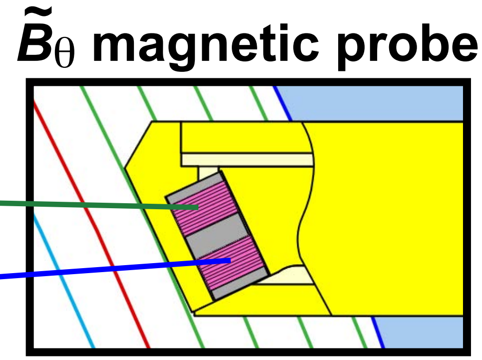

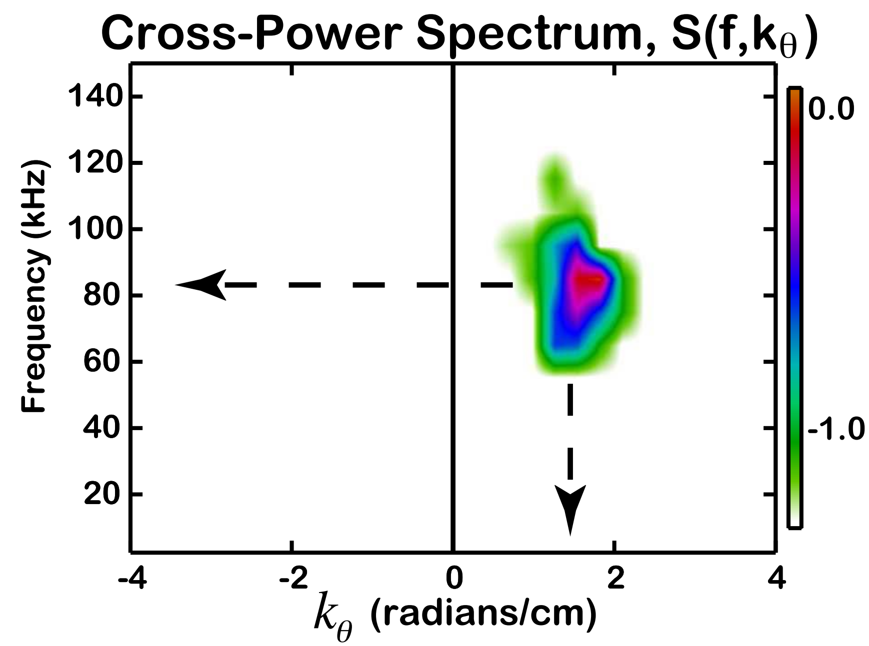

- k_θ ~ 1.5 rad/cm; perturbation ~field-aligned [1] $\underline{k} \cdot \underline{B} \approx 0$
- QCM propagates in electron diamagnetic direction (lab frame)
- At location of QC mode layer: B_r ~ 0.5 mT, $J_{//}$ ~ 5 A/cm^2

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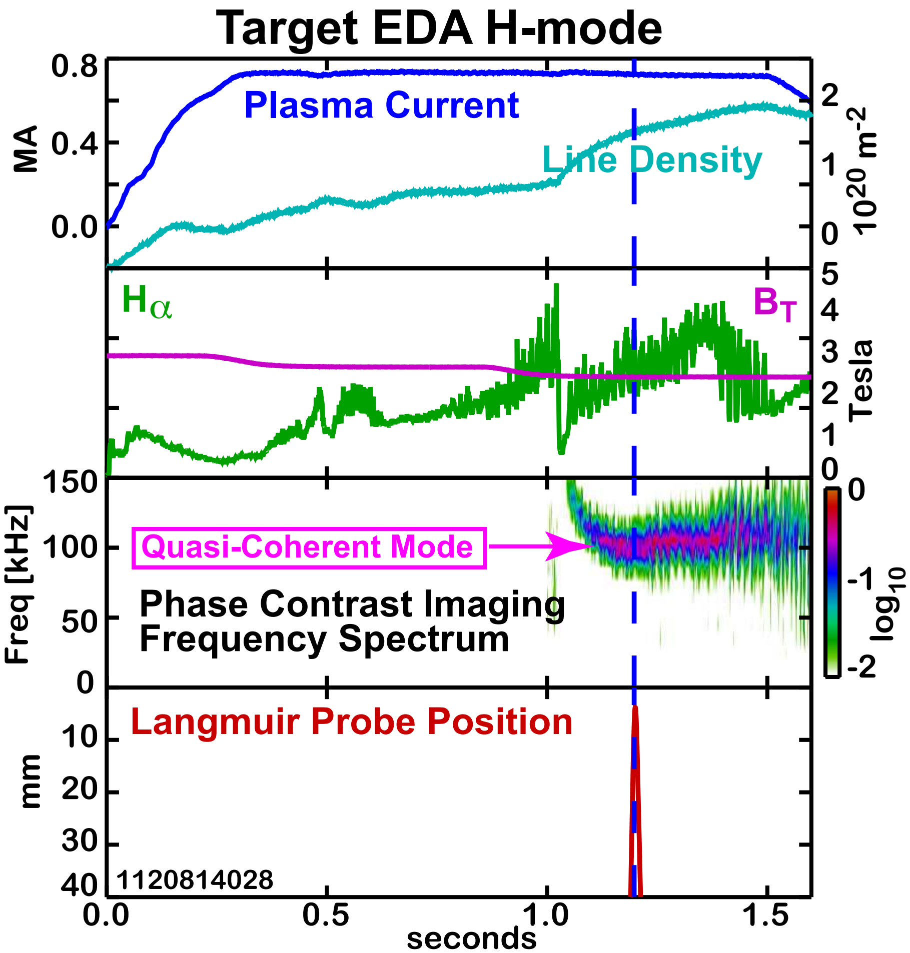
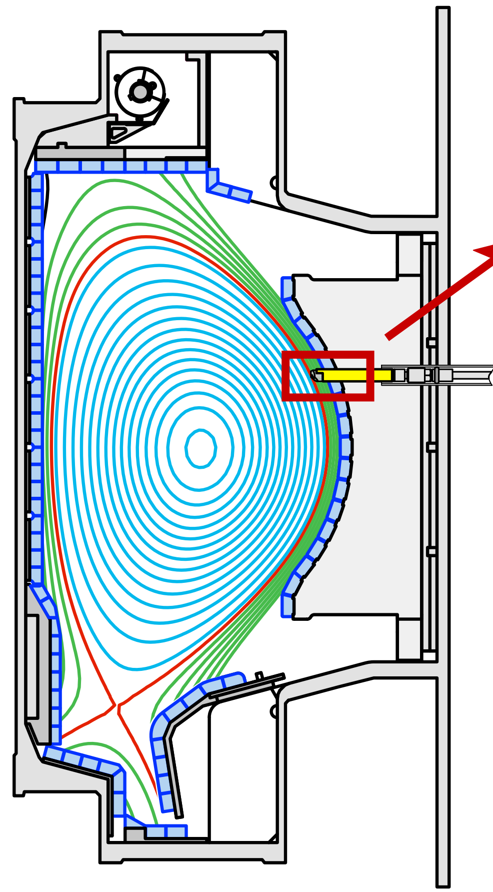
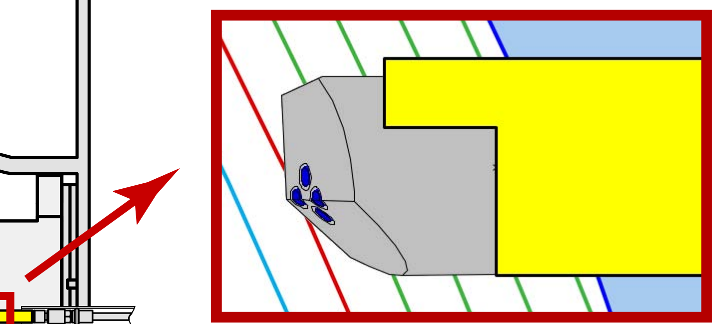
Experimental setup: Mirror Langmuir Probe investigation of Quasi-Coherent Mode





Langmuir probe



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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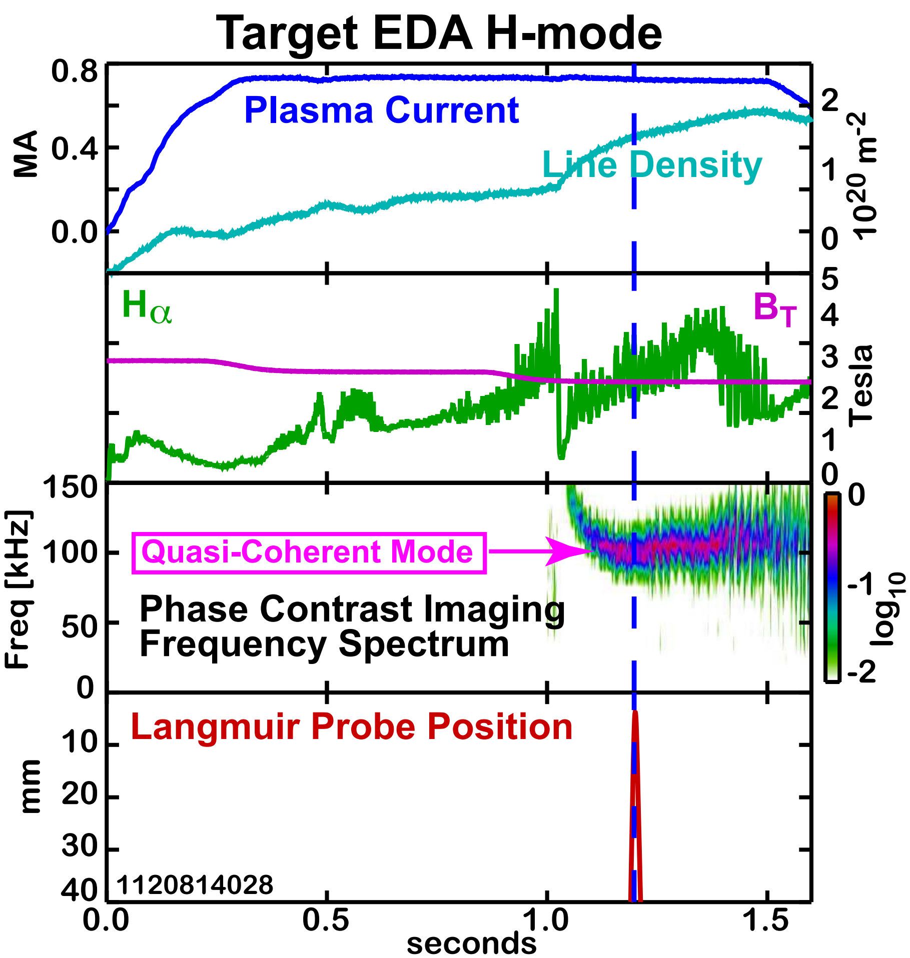

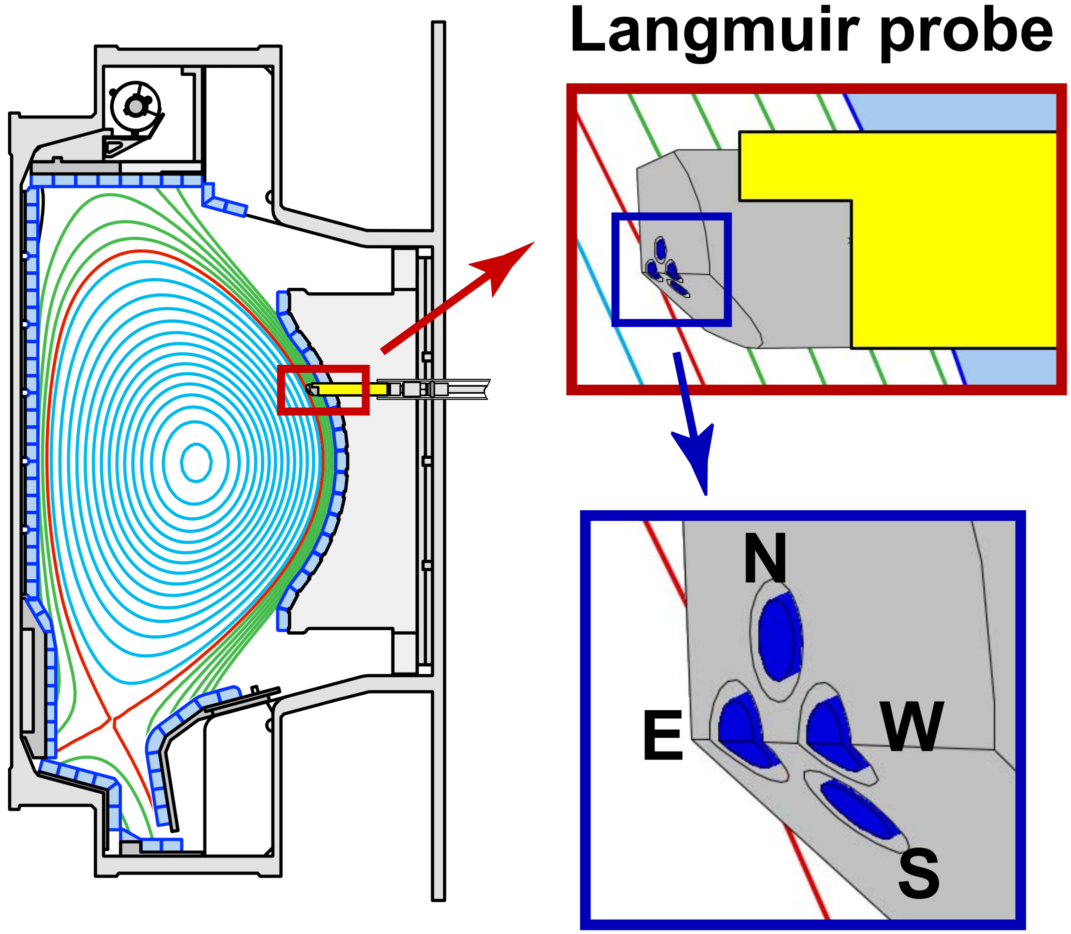

Goals: • Plunge probe across QCM mode layer

Record $k_\theta, \tilde{n}, \tilde{T}_e, \tilde{\Phi}$ response

Determine mode layer width (?)

• Does probe 'kill the mode'? Use electrodes spaced in minor radius direction to assess probe perturbation effects

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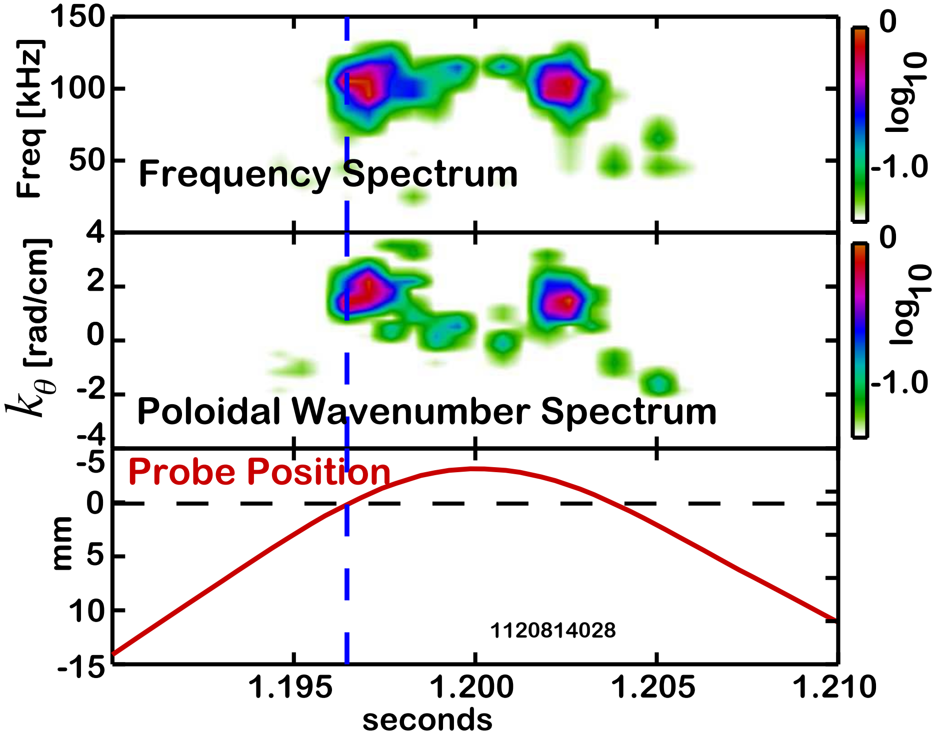
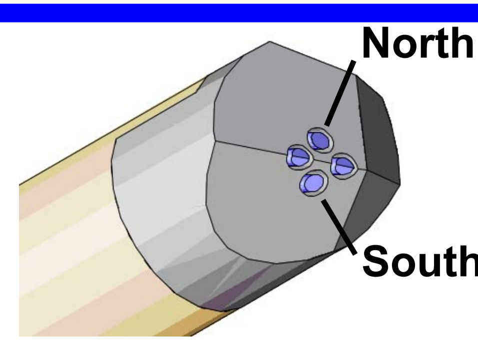
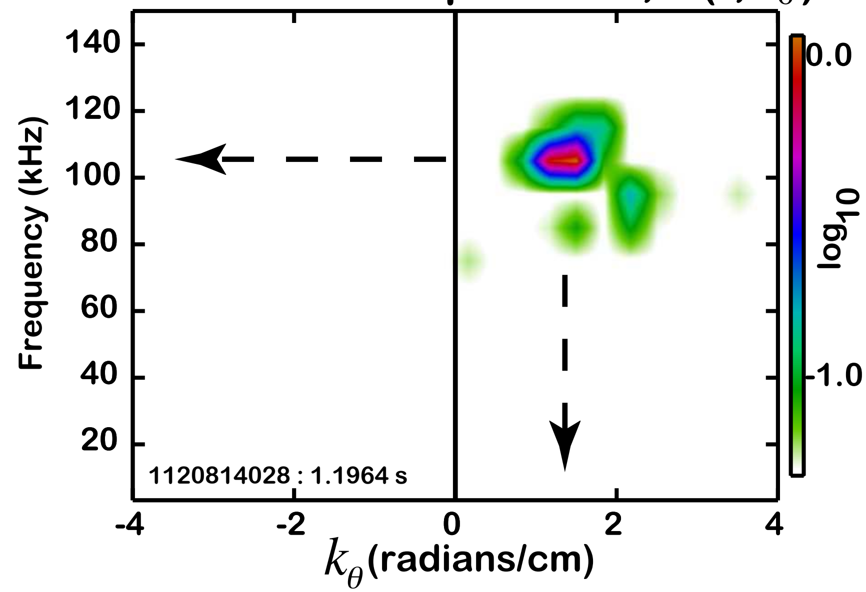
MLP passes through mode layer -- reveals density fluctuation with frequency and wavenumber of QCM

Spectra from North-South electrodes





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



- Mode exists near LCFS
- Frequency, poloidal wave number and propagation in electron diamagnetic direction -- consistent with B_θ probe, PCI (and GPI)
- Probe appears to pass through mode

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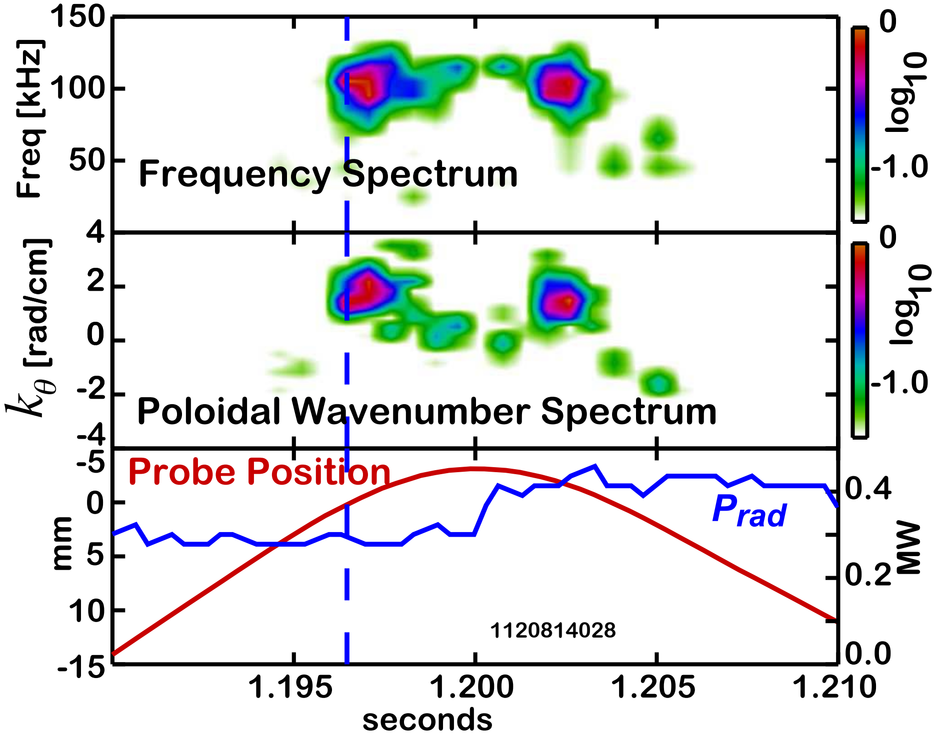

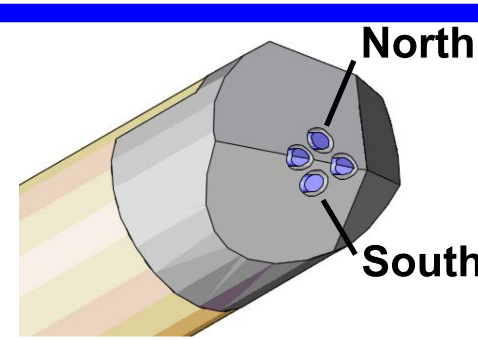

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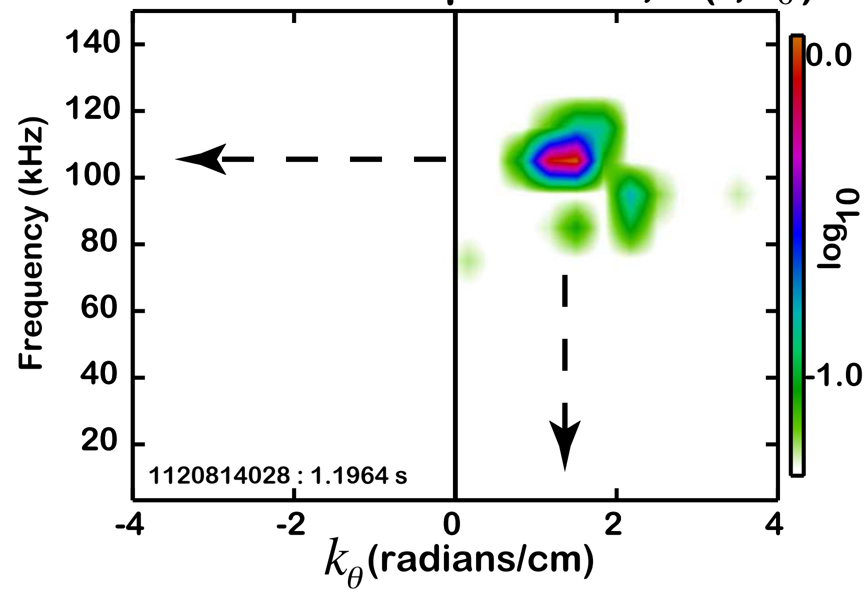
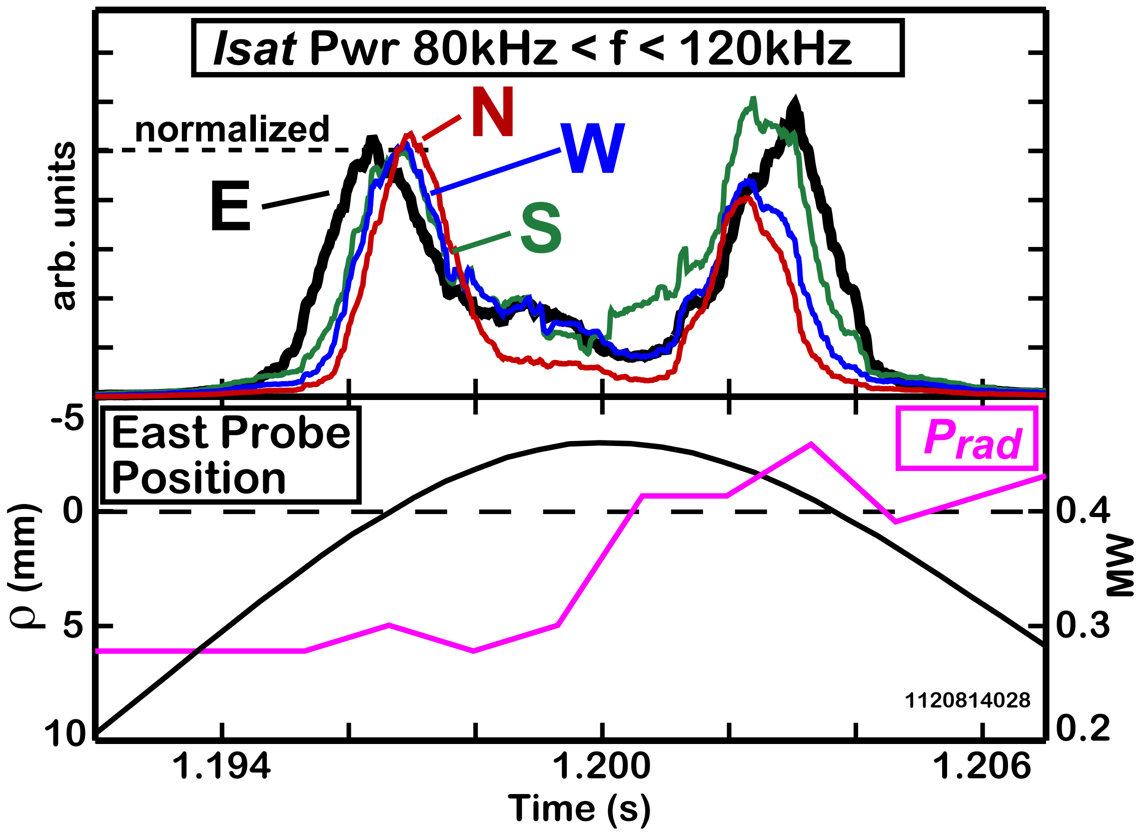
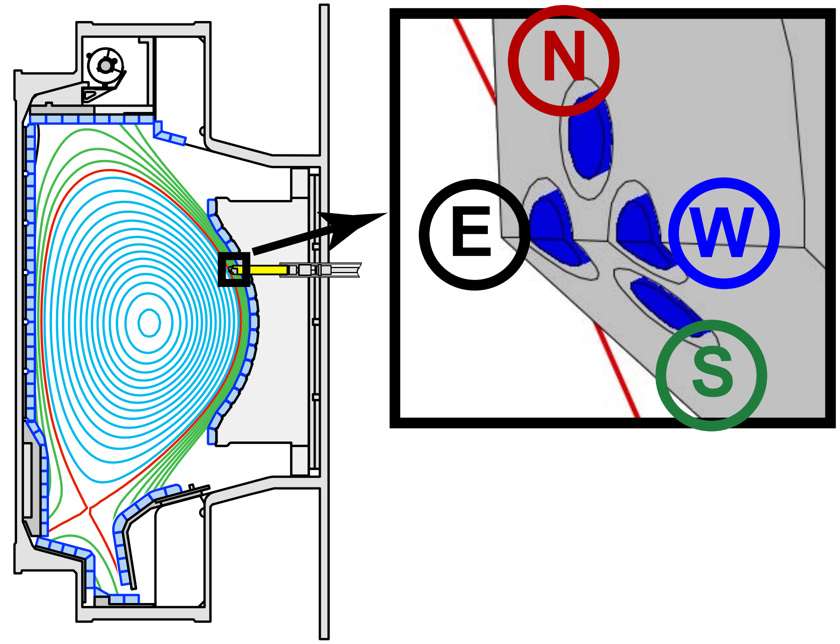


- Mode exists near LCFS
- Frequency, poloidal wave number and propagation in electron diamagnetic direction -- consistent with B_θ probe, PCI (and GPI)
- Probe appears to pass through mode
- Probe perturbs plasma at peak insertion (see P_{rad} jump)
  Post mortum: leading edge of probe head showed melt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

Radial extent of QCM fluctuation is mapped out separately by each electrode as they pass though layer

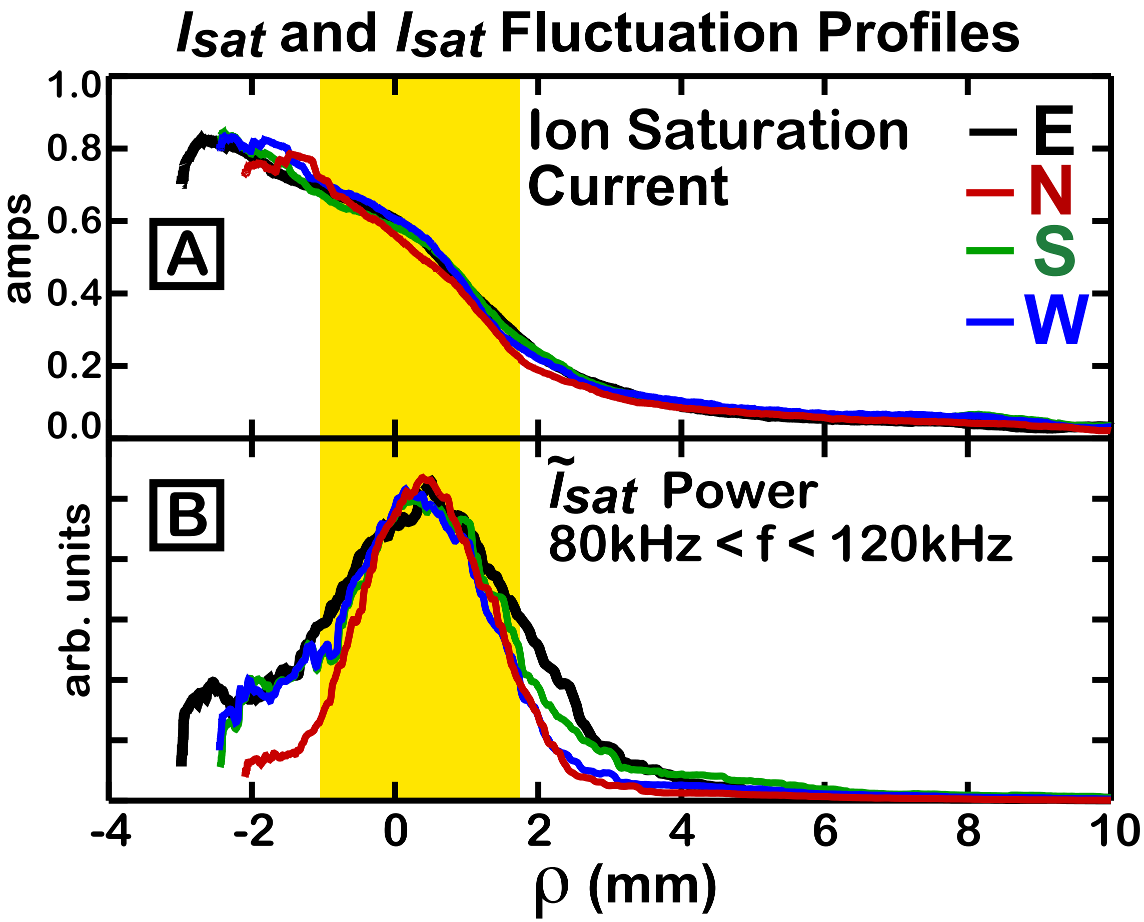


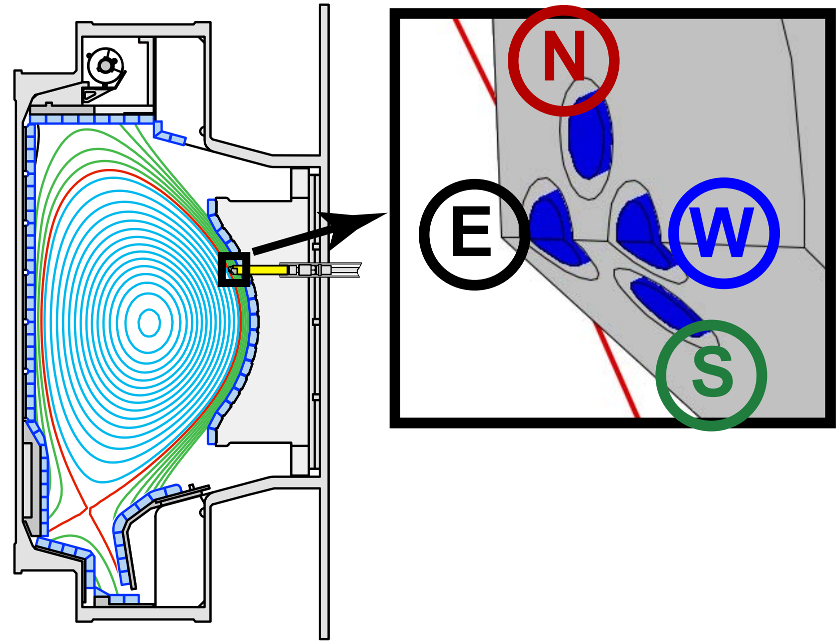


Note: $\tilde{I}_{sat}$ power normalized to same peak value for in-going scan

- Time delay is seen among probes, consistent with their radial positions
- At peak insertion, P_{rad} jumps up -- probe-induced impurity injection
  => electrodes likely affected;
  $\tilde{I}_{sat}$ power envelopes are different on out-going scan

Radial profiles of ion saturation current and QCM fluctuation envelope align from all four electrodes





A I_{sat} scaled and ρ adjusted, such that profiles overlay

B $\tilde{I}_{sat}$ power scaled, such that profiles overlay (using ρ values from **A**)

- I_{sat} and $\tilde{I}_{sat}$ power profiles align, despite being recorded at different times by different probes
- Conclusion: QCM is ***not*** being attenuated by probe

- Radial width of Quasi-Coherent Mode layer is ~ 3 mm FWHM

Quasi-coherent mode lives at separatrix, in steep gradient region with *positive radial electric field*

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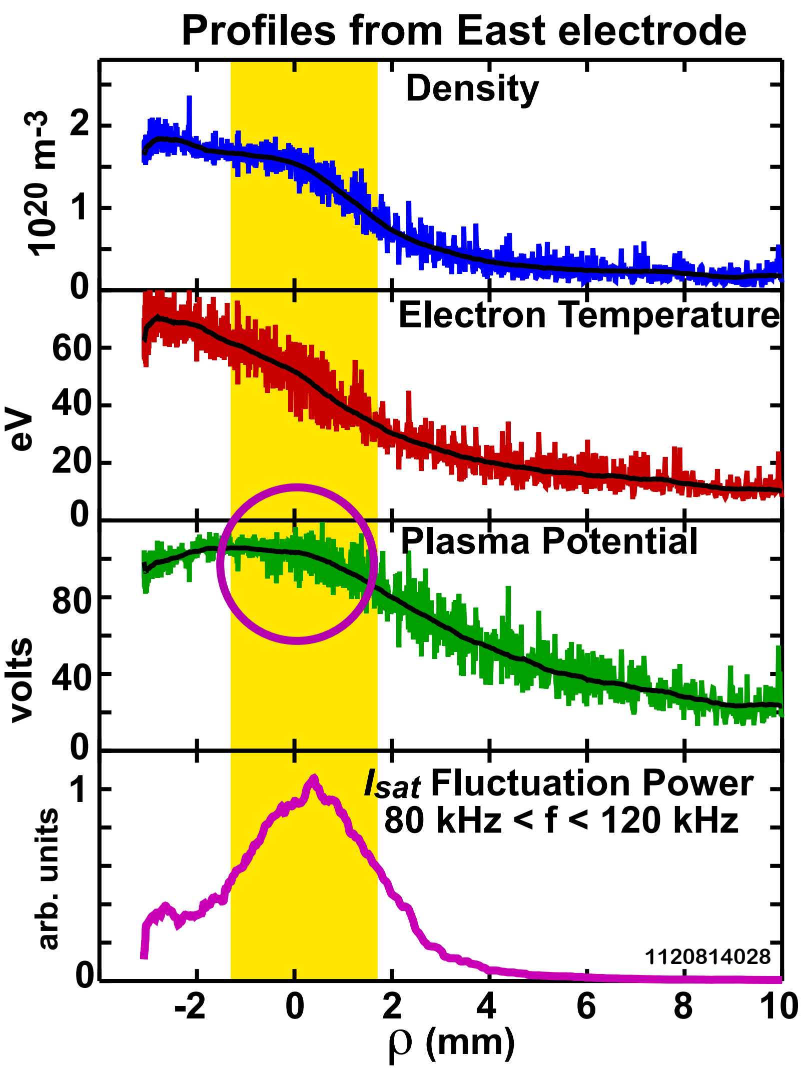
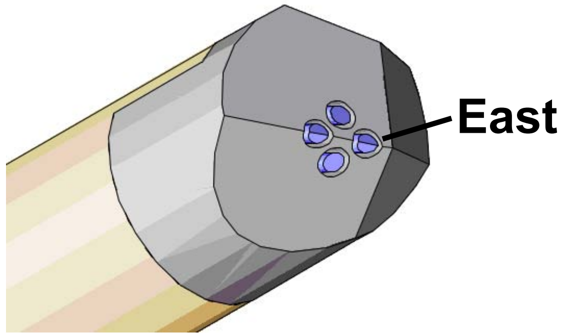
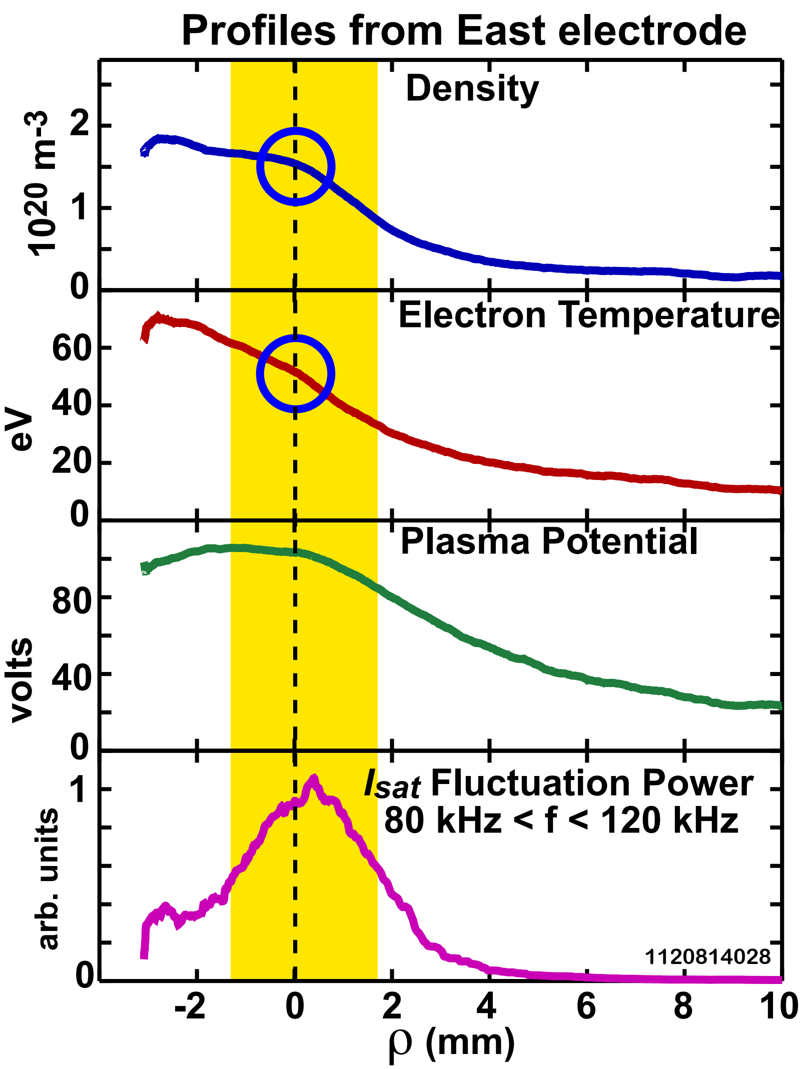
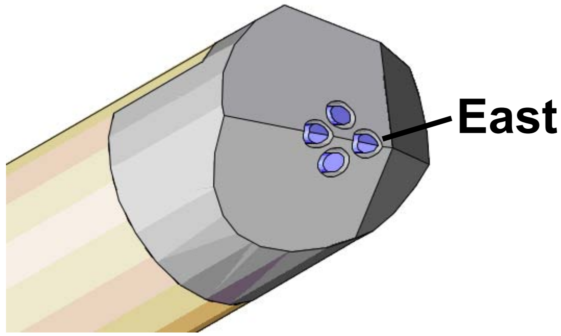




- QCM exists in **region of positive E_r**
  (*i.e.* with ExB in ion dia. dir.)

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 ~ 50 eV at LCFS (used here to set ρ = 0 location)
- Possible break-in-slope at LCFS in n, T_e profiles (needs further study)

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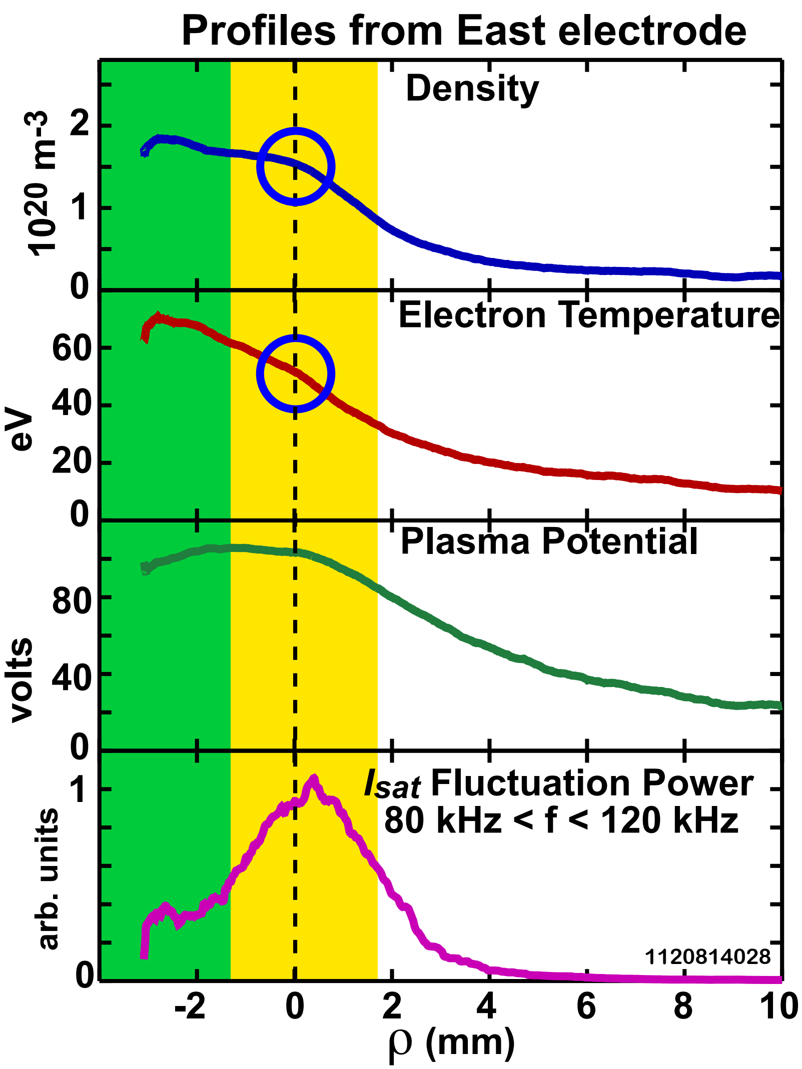

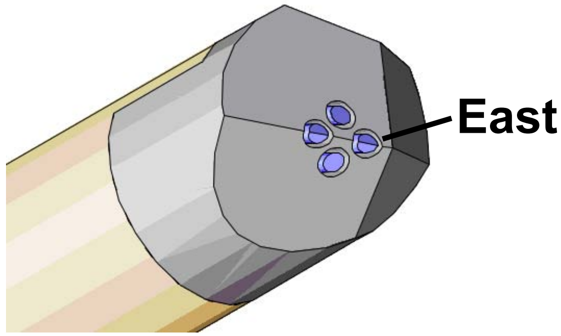

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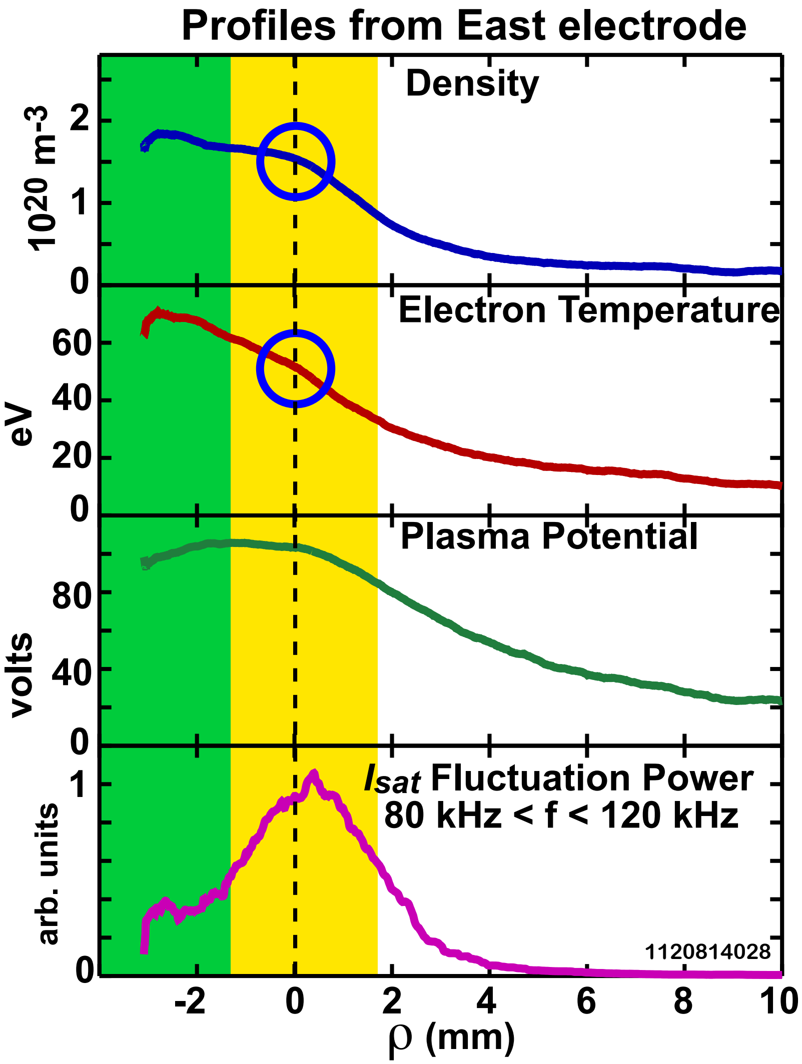
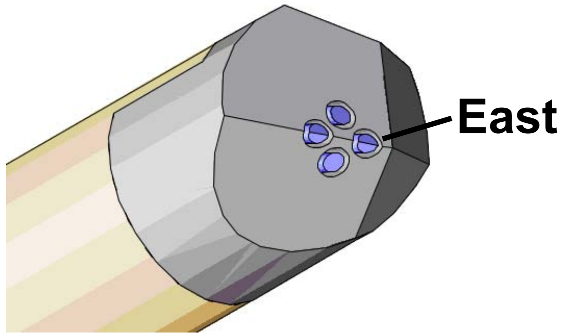
- Possible break-in-slope at LCFS in n, T_e profiles (needs further study)
- Profiles deeper into plasma are unreliable

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 ~ 50 eV at LCFS (used here to set ρ = 0 location)
- Possible break-in-slope at LCFS in n, T_e profiles (needs further study)
- Profiles deeper into plasma are unreliable

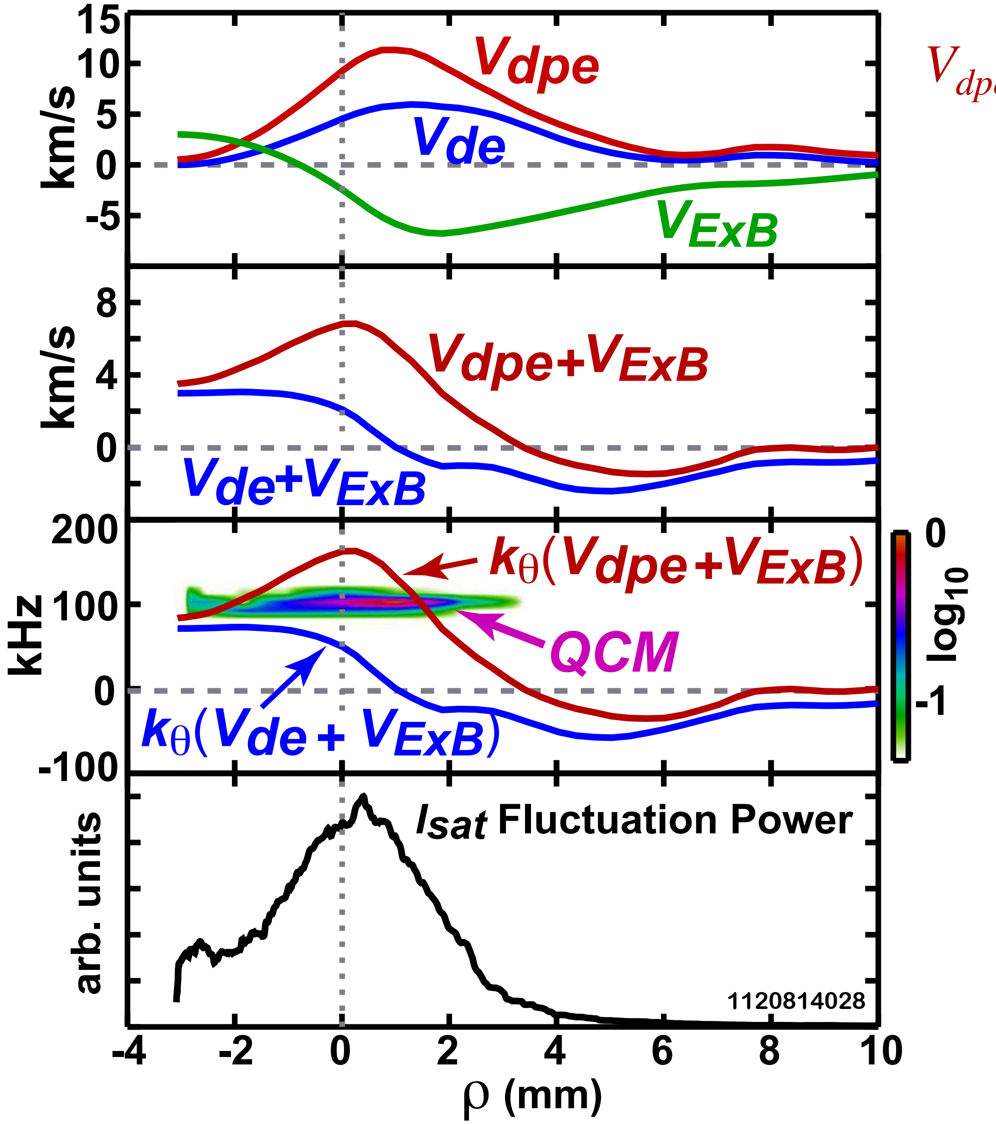
QCM spans LCFS

=> 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

Alcator C-Mod

Velocities computed from East electrode profiles



$$V_{dpe} = \frac{\nabla_r n T_e \times \underline{b}}{nB} \qquad V_{de} = \frac{T_e \nabla_r n \times \underline{b}}{nB} \qquad V_{ExB} = \frac{\underline{b} \times \nabla_r \Phi}{B}$$

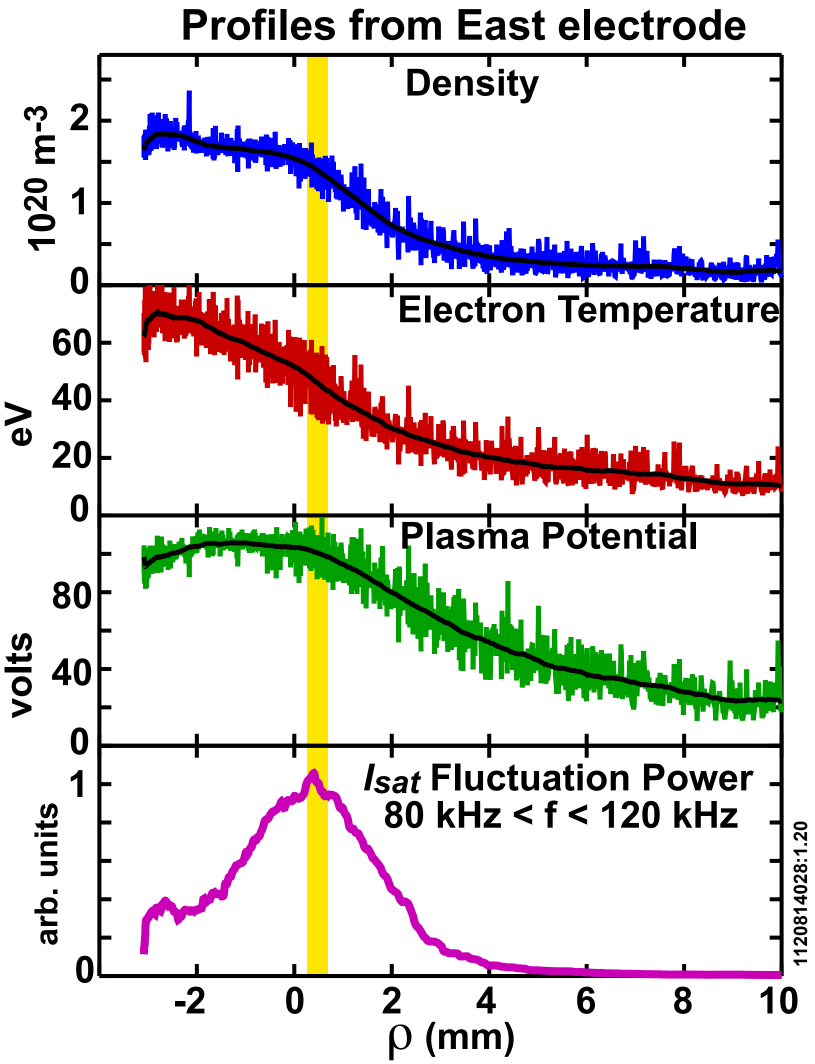
- V_{dpe}, V_{de} are in opposite directions to V_{ExB} in mode layer

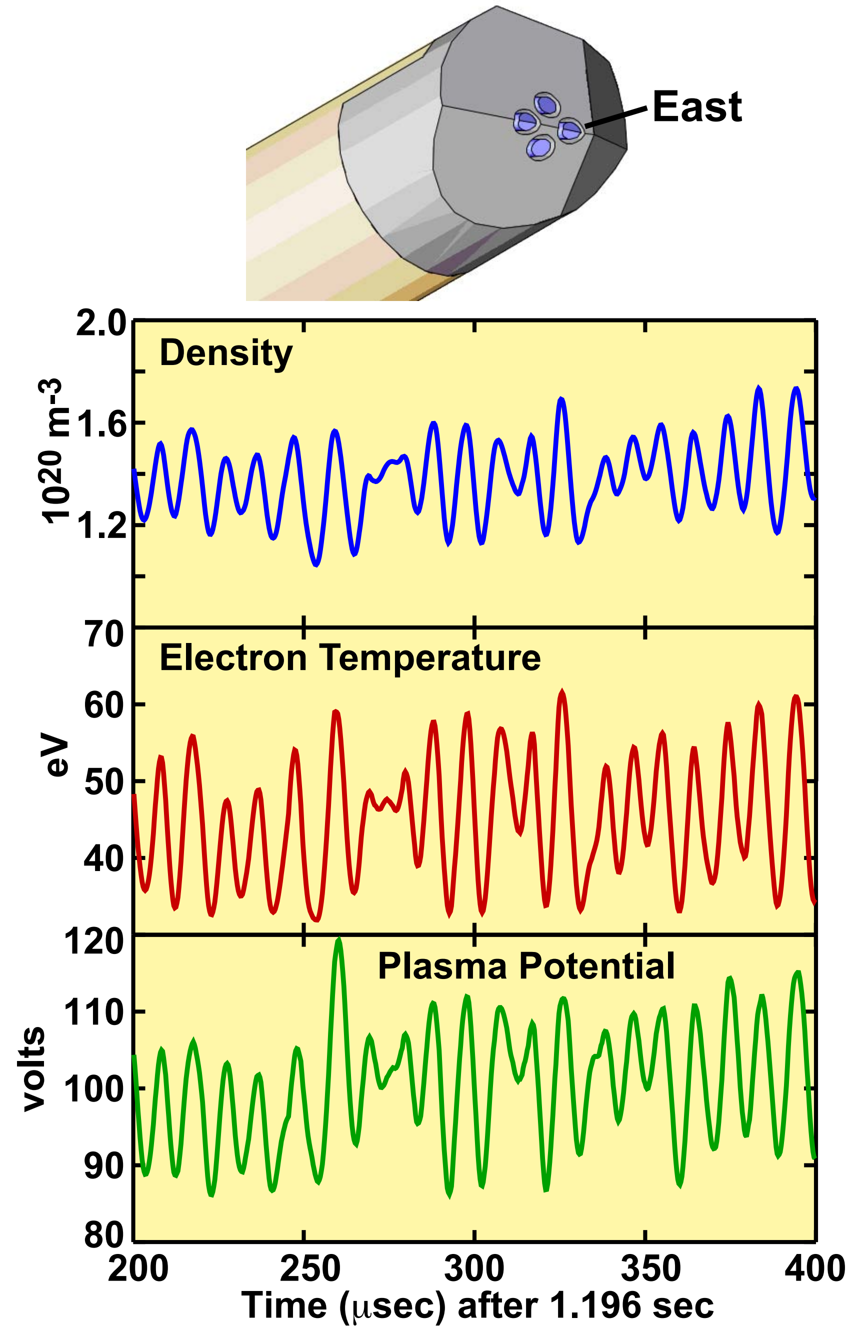
- V_{dpe}, V_{de} are stronger than V_{ExB} in mode layer

- QCM propagates in e^- dia. direction *in the plasma frame*

QCM frequency is quantitatively consist with a k_θ ~ 1.5 rad/cm mode propagating with velocity between V_{dpe} and V_{de} in the plasma frame.

Snapshot of QCM reveals large amplitude, ~in-phase, density, electron temperature and potential fluctuations





$$\frac{\Delta n}{\langle n \rangle} \sim 30\% \qquad \frac{\Delta T_e}{\langle T_e \rangle} \sim 45\% \qquad \frac{\Delta \Phi}{\langle T_e \rangle} \sim 45\%$$

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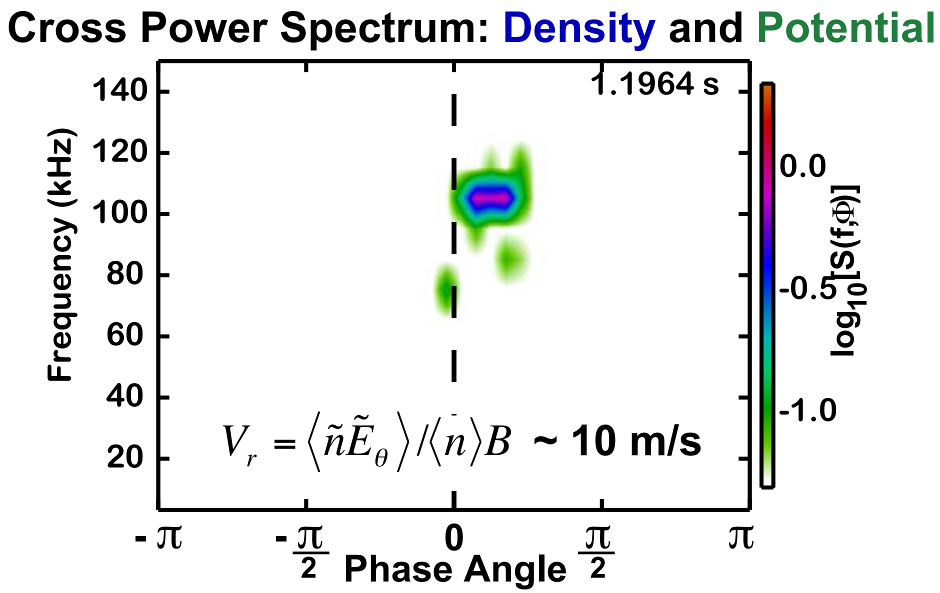
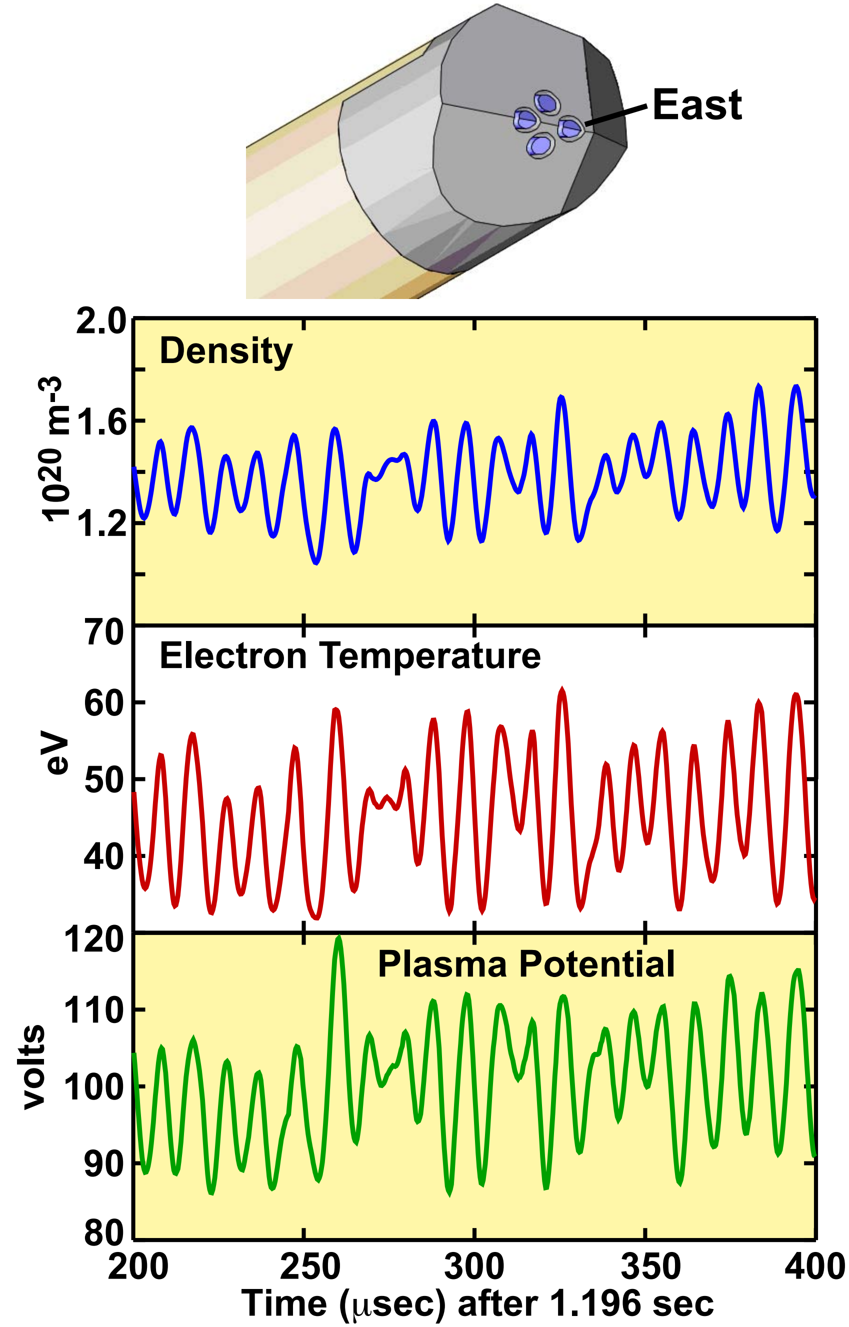
Alcator C-Mod



Potential lags Density with a phase angle of ~ 10 degrees

=> Drift wave



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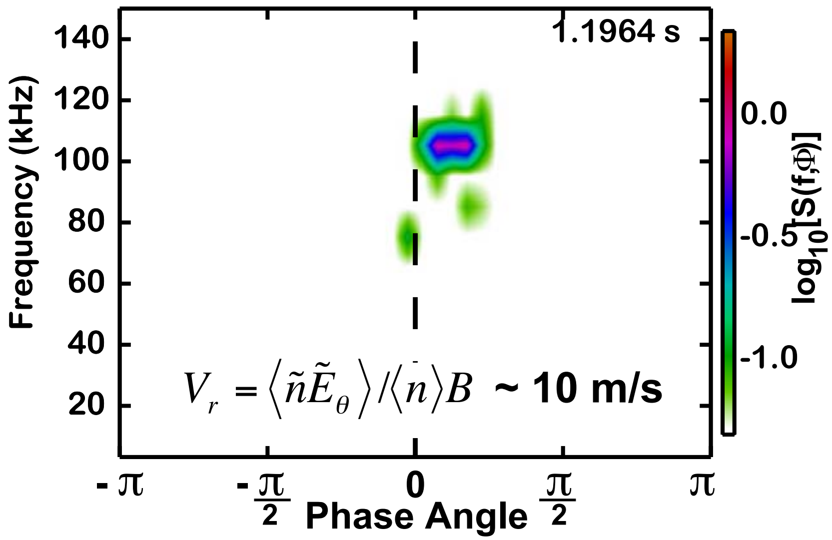
Alcator C-Mod

Cross Power Spectrum: Density and Potential



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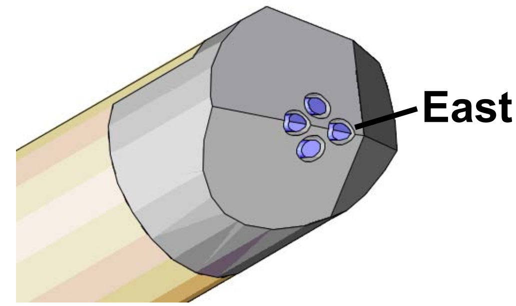
Simple Boltzmann electron response?

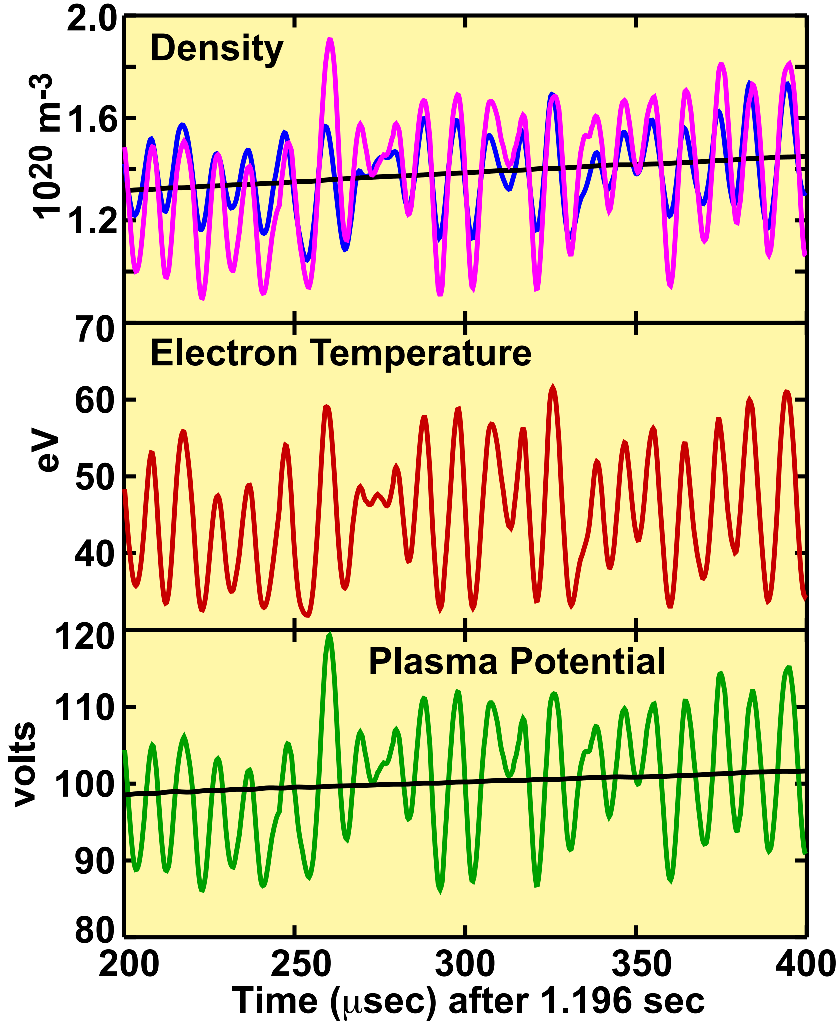
Compute $\tilde{n}_B$ required to satisfy

$$\tilde{n}_B = \langle n \rangle \exp\left(\left(\tilde{\Phi} - \langle \Phi \rangle\right) / \tilde{T}_e \right]$$

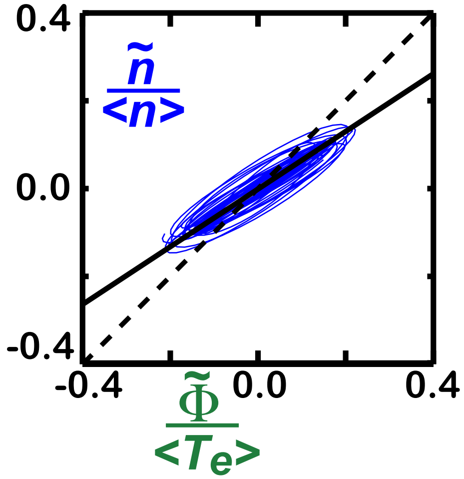
$\tilde{n}_B$ is ~1.5x larger than measured $\tilde{n}$

***Not* a simple Boltzmann response**





Non-Boltzmann response is consistent with measured EM character of the mode -- an electron drift-Alfven wave



- **Density fluctuations are smaller than Boltzmann**

$$\frac{\tilde{n}}{\langle n \rangle} < \frac{\tilde{\Phi}}{\langle T_e \rangle}$$

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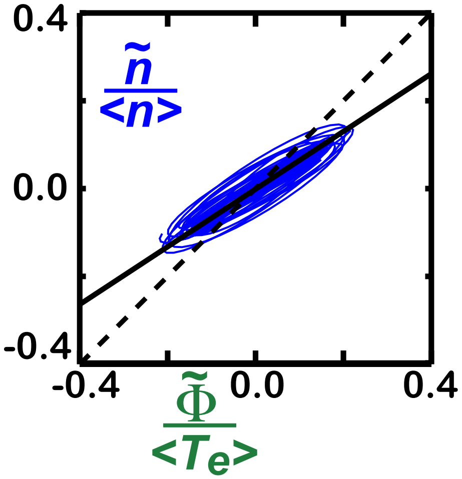

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$$\frac{\tilde{n}}{\langle n \rangle} < \frac{\tilde{\Phi}}{\langle T_e \rangle}$$

- **But parallel electron force balance (Ohm's law) in this case should include electron pressure and inductive $\tilde{E}_{//}$ associated with parallel current fluctuation**[1]

$$\frac{1}{\langle T_e \rangle} \frac{\partial}{\partial t} \tilde{A}_{//} \approx \nabla_{//} \left(\frac{\tilde{n} \tilde{T}_e}{\langle n T_e \rangle} - \frac{\tilde{\Phi}}{\langle T_e \rangle} \right) \qquad k_{//} \sim \frac{1}{qR}$$

$$\frac{qR\mu_0}{k_\perp^2} \frac{\omega}{\langle T_e \rangle} \tilde{J}_{//} \approx \frac{\tilde{n} \tilde{T}_e}{\langle n T_e \rangle} - \frac{\tilde{\Phi}}{\langle T_e \rangle}$$

[1] B. Scott, PPCF, 39 (1997) 1635.

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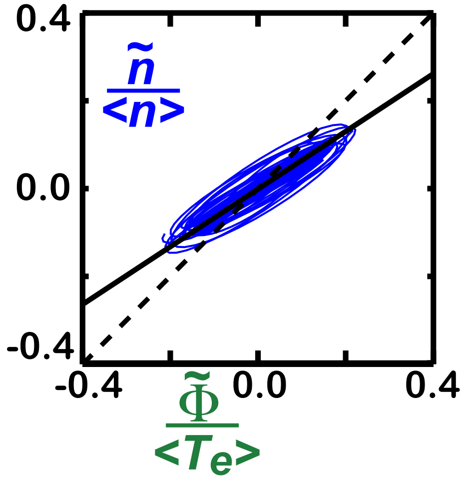
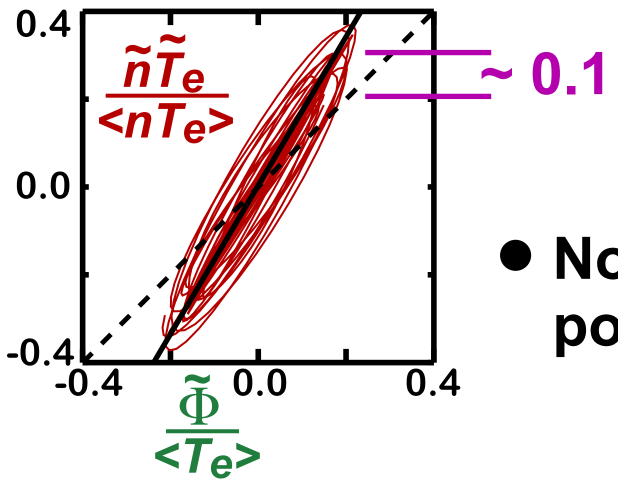
Alcator C-Mod





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- Normalized electron pressure fluctuations exceed potential fluctuations by ~ 0.1 at their maxima

$$\left(\frac{\tilde{n}\tilde{T}_e}{\langle nT_e \rangle} - \frac{\tilde{\Phi}}{\langle T_e \rangle}\right)_{\text{max}} \sim 0.1$$

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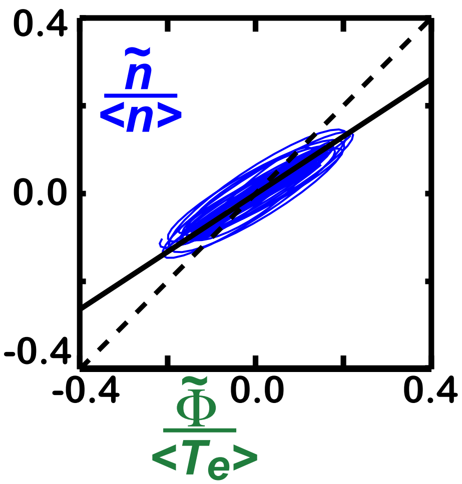

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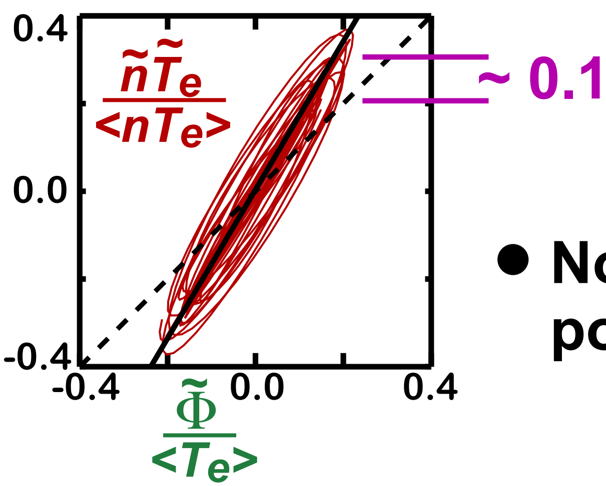

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- Plugging in values for QCM parameters yields: $\tilde{J}_{//}$ ~ 6 A/cm^2

=> Consistent with amplitude of $J_{//}$ inferred from magnetic probe.

QCM is a electron drift-Alfven wave.

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Summary

- **Mirror Langmuir Probe is a powerful new tool for investigating boundary n, T_e, Φ profiles and turbulence**

MLP is revealing new insights on Alcator C-Mod's Quasi-Coherent Mode in ohmic EDA H-mode plasmas:

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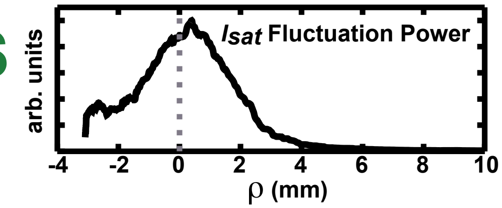
  - Drives transport directly across LCFS



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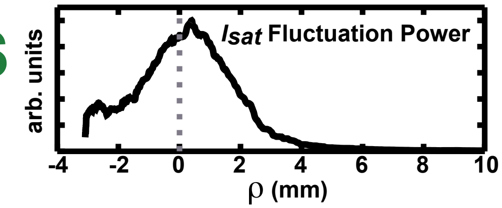

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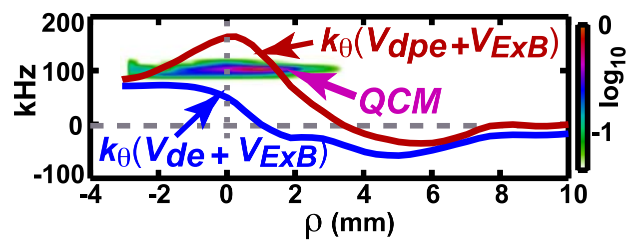

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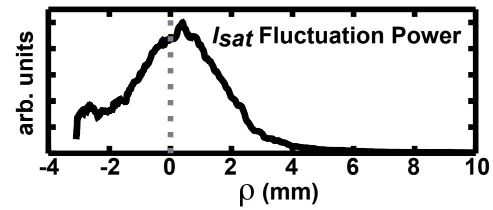

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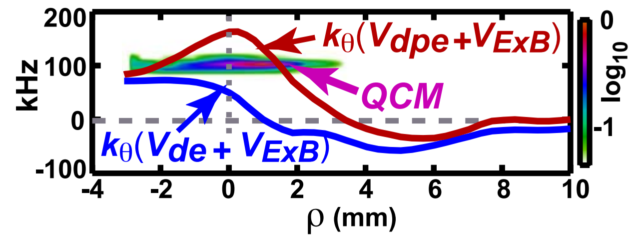
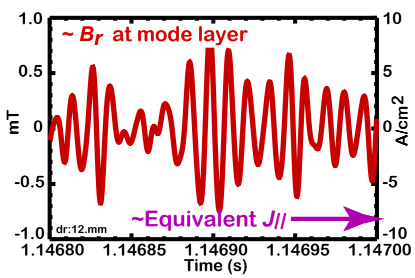
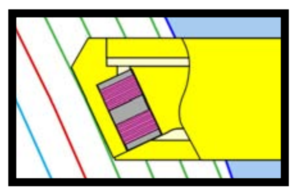


  - EM signature





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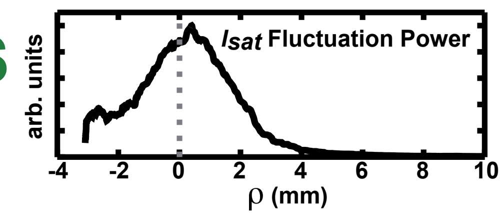

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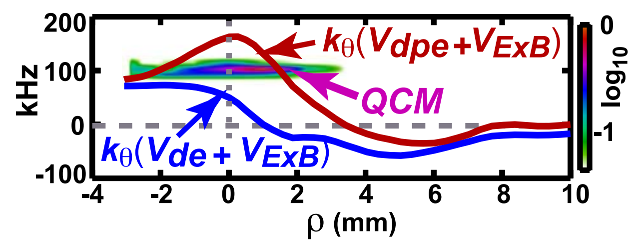

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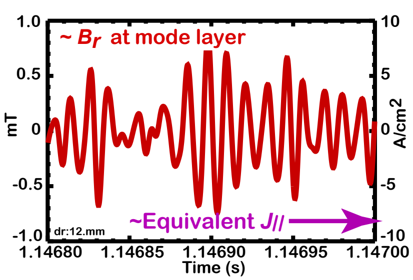
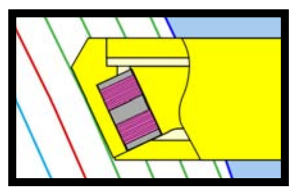
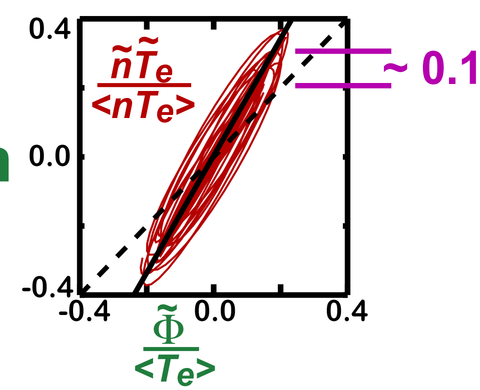




- Measured amplitude of plasma potential, electron pressure and parallel current fluctuations



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