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

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

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A new ‘Mirror Langmuir Probe’ diagnostic, combined with a double-coil scanning magnetic probe, is used to interrogate Alcator C-Mod’s Quasi-Coherent Mode (QCM) with unprecedented detail. In ohmic EDA H-modes, the QCM is found to reside in a region of positive radial electric field, with a radial width (~3 mm) that spans open and closed field line regions. Large amplitude, in-phase sinusoidal bursts (~100kHz) in density, electron temperature and plasma potential are observed, with potential lagging density by ~16 degrees, producing an outward radial transport velocity of ~10 m/s. Mode propagation corresponds to the sum of local $E \times B$ and electron diamagnetic drift velocities. Poloidal magnetic field fluctuations project to current filaments carrying peak current densities of ~25 amps/cm$^2$. An evaluation of parallel electron force balance (Ohm’s law) over a fluctuation cycle indicates a significant electromotive component. Interchange drive is also a contributor in the current continuity (vorticity) equation. Thus the QCM is primarily a separatrix-spanning electron drift-wave with interchange and electromagnetic contributions.

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I. INTRODUCTION

Boundary plasma turbulence and transport critically affect the overall performance of a tokamak – setting the H-mode pedestal height and width [1], producing ELMs and coherent modes [2-4], determining fuel and impurity transport, defining the maximum density that can be achieved [5], regulating the power exhaust channel width [6-8] and influencing plasma-material impact on divertor/first-wall components. Significant progress has been made in recent years towards understanding a number of these boundary plasma phenomena – all made possible by high-quality measurements from boundary plasma diagnostic systems. Scanning Langmuir probe diagnostics have proven essential to this research, providing high-resolution plasma profile measurements and local, multiple-point, high-bandwidth measurements of ion saturation current, electron temperature and floating potential. These measurements have also allowed higher-order quantities, such as plasma flow, fluctuation-induced fluxes and Reynolds stresses to be estimated and studied [9-26]. In addition, scanning magnetic probes have proven essential to interrogate poloidal magnetic field fluctuations associated with high $k_\theta$ modes [27-29].

Langmuir probe diagnostics tend to suffer from two important limitations, however. First, they cannot survive for very long in the high heat flux environment of a tokamak edge plasma. As a result, Langmuir probes are usually relegated to study only low power density regions of the boundary layer. Second, measurements that would be truly of most interest – density ($n$), electron temperature ($T_e$) and electric potential ($\Phi$) at sufficient bandwidth to fully resolve plasma turbulence and at a specific point in space – are very difficult to make for technical reasons. Such measurements require the full $I-V$ characteristic (i.e., spanning from ion saturation to electron collection) from a single electrode to be cyclically recorded over time scales shorter than plasma fluctuation times, which are typically on the order of a few microseconds. Lacking

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“New insights on Quasi-Coherent Mode using a Mirror Langmuir Probe”, B. LaBombard et al.
this ability, separate measurements of ion saturation current, electron temperature and floating potential are usually made from independent electrodes that do not sample the same plasma flux tube. These results are combined to estimate point-localized values of $n$, $T_e$, and $\Phi$. Unfortunately, this approach does not allow the relative amplitude and phase relationships to be followed with high fidelity – quantities that are critically needed both to identify the underlying character of the turbulence (e.g., interchange versus drift wave) and also to compute transport fluxes that arise from correlations among fluctuating fields (e.g., particle and energy fluxes, Reynolds stresses).

Recognizing the tremendous potential that scanning Langmuir probes have to interrogate the physics of boundary plasma transport and turbulence, the Alcator C-Mod team has developed new techniques to push back against these two limitations. First, high heat-flux tolerant Langmuir probe electrode and head geometries have been developed for fast-scanning probes, employing tungsten and molybdenum components [30]. Second, a new fast-switching, self-adaptive Mirror Langmuir Probe (MLP) bias scheme has been developed [31,32], which samples the full $I-V$ characteristic of a single Langmuir electrode fast enough to resolve the plasma turbulence (i.e., under 1 µs).

During Alcator C-Mod’s FY2012 run campaign (ending September 2012), we assembled these new tools on C-Mod’s horizontal fast-scanning probe system – deploying a Mirror Langmuir Probe (MLP) bias drive on each of four electrodes on a high-heat flux Langmuir-Mach probe head. The results were very impressive. The diagnostic proved capable of recording high-bandwidth (1.1 MHz) $n$, $T_e$, and $\Phi$ measurements across the scrape-off layer and slightly inside the last closed flux surface (LCFS) in C-Mod’s high power density plasmas ($n \sim 1.5 \times 10^{20} \text{m}^{-3}$, $T_e \sim 80 \text{ eV}$, $q/\sim 1 \text{ GW m}^{-2}$), revealing plasma fluctuations and high-resolution, time-averaged...
profiles with unprecedented detail. An initial survey of H-mode, ELMy H-mode and L-mode plasmas clearly demonstrated the utility of the diagnostic and immediately uncovered interesting phenomena: tracking ELM evolution and identifying a small amplitude quasi-coherent mode (QCM) as a potential ELM precursor.

Recognizing the power of this new system, we promptly initiated a set of experiments to target the Quasi-Coherent Mode (QCM) associated with Alcator C-Mod’s EDA H-modes [2] – looking to identify the underlying physics (mode structure, location, phase relationships, fluctuation energetics). The experimental investigation was very successful, identifying the mode structure of the QCM for the first time – an electron drift wave with significant interchange drive and inductive EMF contributions.

This paper summarizes the research that has led to these important conclusions. The paper also introduces and describes the MLP bias technique in some detail, since this experimental investigation is the first time the method has been employed for physics studies. Section II discusses the implementation of the MLP concept, presenting typical bias waveforms, plasma profiles and fluctuations obtained in ohmic L-mode. Section III shows the use of the MLP in H-mode plasmas, highlighting its ability to record high-resolution time-averaged profiles, resolve ELMs and discern evidence that a small amplitude QCM may be acting as an ELM precursor. Experiments targeting the mode structure of the QCM are reported in Section IV. A double-coil scanning magnetic probe is used to measure poloidal magnetic field fluctuations associated with the QCM and to estimate the fluctuating parallel currents associated with the QCM layer. Phase-contrast imaging (PCI) and gas-puff imaging (GPI) provide independent measurements of the QCM. A specially-designed, four electrode Langmuir probe head, the ‘QCM probe,’ is used to record the mode’s radial width, deduce $E_xB$ and diamagnetic flow profiles and record the relative phase relationships, poloidal wavenumbers and amplitudes.

“New insights on Quasi-Coherent Mode using a Mirror Langmuir Probe”, B. LaBombard et al.
of the fluctuating quantities of interest: \( n \), \( T_e \), and \( \Phi \). In C-Mod’s non-auxiliary-heated (i.e. ohmic) EDA H-mode plasmas, it is found that the QCM has large amplitude, approximately in-phase fluctuations in all three quantities and that it spans the last closed flux surface (LCFS) with a radial width of \( \sim 3 \) mm. The mode exhibits a small phase lag of \( \Phi \) relative to \( n \) (\( \sim 16 \) degrees) and propagates in the electron diamagnetic direction in the plasma frame – hallmarks of an electron drift wave, as is well established in the literature [33]. The small phase lag produces an outward radial transport \( (V_r \sim 10 \, \text{m/s}) \), which is modest in comparison to the mode’s large amplitude \( (\Delta \Phi / \langle T_e \rangle \sim 45\%) \). This level of fluctuation-induced transport across the LCFS is consistent with what is needed to affect impurity confinement time and to enhance plasma particle loss – essential functions that the QCM provides in EDA H-modes. Section V discusses the fluctuation measurements within the context of fluid drift turbulence [34, 35], establishing that interchange drive in the vorticity equation and inductive parallel electric field in parallel Ohm’s law are significant contributors to the wave dynamics. As briefly outlined in Section VI, these new observations present some significant challenges to present models for the QCM, none of which accurately describe the QCM phenomenon. The principal findings from this work are restated in Section VII.

II. MIRROR LANGMUIR PROBE

A. Mirror Langmuir Probe bias technique

A Mirror Langmuir Probe (MLP) [31, 32] is an electronic device that automatically adjusts its \( I-V \) response in real time to match that of an actual Langmuir probe (LP). The MLP operates essentially as an analog computer, synchronized to a fast-switching, three-state bias waveform (see Fig. 1) via a digital timing system. The MLP system uses high-bandwidth (\( \sim 200 \) MHz) circuitry composed of rf transistors, operational amplifiers and analog multipliers to
generate an $I$-$V$ response with three adjustable parameters. These represent ion saturation current ($I_{\text{sat}}$), floating potential ($V_f$) and electron temperature ($T_e$) of a Langmuir probe,

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

This model is appropriate for an electrode immersed in the strong magnetic field of a fusion plasma where the angle between the particle collection surface and the field line exceeds ~10 degrees, avoiding anomalous ion collection and sheath expansion effects [36]. The bias waveform is applied simultaneously to the LP and MLP. During times when the bias voltage is settled and switching transients are minimized (colored bands in Fig. 1), a feedback system compares the LP and MLP current response and ‘corrects’ the MLP $I$-$V$ model, if necessary, by cyclically adjusting its ‘fitting parameters’: $I_{\text{sat}}$ during large negative bias (blue), $V_f$ during a near-floating state (green), and $T_e$ during electron collection (red). The three parameter update cycle is completed every 0.9 µs. The resulting time history of $I_{\text{sat}}, V_f$ and $T_e$ therefore ‘mirrors’ the actual values in the plasma, as long as plasma conditions seen by the LP do not change significantly on a ~1 µs time scale.

A key feature of the MLP system is its automatic optimization of the three-state bias waveform. The system performs a running averaging of the real-time $I_{\text{sat}}$ and $T_e$ signals over a ~1 ms time window ($<I_{\text{sat}}>$, $<T_e>$). The peak-to-peak amplitude of the voltage waveform is adjusted dynamically so that it is maintained at 4 times $<T_e>$. In addition, voltage drop due to a 50 ohm source impedance is compensated and coupling capacitance is adjusted as needed according to $<I_{\text{sat}}>$.

Thus the MLP plays the role of an expert Langmuir probe drive system; it continuously maintains the optimum bias waveform that is required to sample the complete $I$-$V$ characteristic.
as local plasma conditions change. At the same time, the Langmuir probe’s current and voltage data are digitized at 10 MHz, synchronized with the MLP bias waveform. This provides samples of the $I-V$ response at the most important times – times when the steps in voltage are completely settled (see black dots in Fig. 1). These digitized data are the primary output of the diagnostic; they allow independent computations of $n$, $T_e$, and $\Phi$ directly from the $I-V$ data – just as one would process data from a standard Langmuir probe system. The real-time MLP output signals of $I_{sat}$, $V_f$ and $T_e$ are nevertheless a useful byproduct of this expert biasing system; they track values of $I_{sat}$, $V_f$ and $T_e$ computed from the digitized $I-V$ data with remarkable fidelity (as discussed further below). The real-time MLP signals may therefore be used for real-time plasma control – regulating via feedback the electron temperature in a dissipative divertor experiment, for example, or even controlling the plunge depth of a scanning probe drive, based on the plasma conditions experienced by the electrodes.

B. Horizontal scanning probes

Alcator C-Mod’s horizontal scanning probe system supports a number of probe head geometries (see Fig. 2). Three different probe heads were used in the experiments reported here: (1) a high heat-flux handling Langmuir-Mach probe, with four tungsten electrodes forming a pyramidal structure and lying on the same magnetic flux surface (2) a ‘QCM probe,’ with tungsten wire electrodes spaced in minor radius to lie on different flux surfaces and (3) a double-coil, ‘magnetic probe’ with poloidal magnetic field pick up coils spaced in the poloidal direction. The construction of the two-coil probe is very similar to a single-coil probe that was used previously to interrogate the quasi-coherent mode [29]. Four separate MLP bias drives were connected to the electrodes on the Langmuir-Mach and QCM heads. These systems operate independently but are synchronized in time so as to produce simultaneous measurements of $n$, $T_e$,
$T_e$, and $\Phi$ on each of the four electrodes.

Two other diagnostics systems were used to record the QCM in these experiments: a phase-contrast imaging system (PCI) and a gas-puff imaging system (GPI). The PCI system [37] measures line-integrated density fluctuations along 32 vertical chords. The location of the outermost chords used in this investigation is shown graphically in Fig. 2. The GPI system [38] is a 2D 9x10 array of optical fibers, viewing a 4 cm (radial) x 4.4 cm (vertical) area near the outboard midplane with an in-focus spot size of 3.7 mm for each fiber (see graphic in Fig. 2). This system uses an array of 90 avalanche photodiodes to record fluctuations in He I 587.6 nm line emission with a 2 MHz sample rate. A local He gas puff is used to provide spatial localization of the measurement along the view chords.

C. MLP in operation

Figures 3 and 4 show typical time traces that result from applying the MLP system to a scanning Langmuir-Mach probe head. Data from the “NW” electrode are shown as it is scanned to the LCFS in an ohmic L-mode discharge (line-averaged density, $\bar{n}_e = 1.2 \times 10^{20}$ m$^{-3}$, plasma current, $I_p = 0.8$ MA and toroidal magnetic field, $B_T = 5.3$ tesla). The in-and-out plunge of the probe shown in Fig. 3 takes 20 msec to traverse ~15 mm. Over this time, the MLP system reports 22,000 measurements of $I_{sat}$, $V_f$, and $T_e$. The time-averaged electron temperature at the LCFS is ~ 60 eV; large excursions in $T_e$ are detected (±20 eV). The self-adapting feature of the MLP bias waveform is illustrated in the top two panels of Fig. 3: peak-to-peak voltage bias is increased and then decreased to follow the overall $T_e$ envelope experienced by the Langmuir probe. The asymmetric voltage waveform ($V^+, V^-$) also produces the desired effect: collecting roughly equal magnitudes of positive and negative currents ($I^+, I^-$) such that during the zero bias...
state \((V_0)\) an approximate “floating condition” \((I_0 \sim 0)\) is continuously maintained as the probe plunges through the plasma.

The MLP system is able to track large transients. A burst event, resulting in more than a factor of two increase in both \(I_{sat}\) (0.25 to 0.6 amps) and \(T_e\) (40 to 90 eV), is highlighted in the bottom panels of Fig. 3. An immediate observation, which is evident in all the data collected thus far, is that fluctuations in \(I_{sat}\) and \(T_e\) are highly correlated in boundary plasma turbulence – as expected when intermittent convective transport events provide the dominant transport mechanism.

Figure 4 shows the burst event of Fig. 3 on an expanded time scale. Digitized samples of the voltage bias and resulting currents collected by the Langmuir probe (top two panels) are now resolved. Black curves labeled ‘Fit’ are overlayed on top of the real-time MLP \(I_{sat}\), \(V_f\), and \(T_e\) values. These are computed from a post-processing analysis of the digitized \(I-V\) data, satisfying the exponential model of Eq. (1). The MLP system does a remarkably good job of computing \(I_{sat}\), \(V_f\), and \(T_e\) values in real time. But due to slew rate limitations, the MLP system does have some trouble following largest amplitude transients. For this reason, all data analyses presented in the remainder of this paper use the \(I_{sat}\), \(V_f\), and \(T_e\) values derived from fitting to the digitized \(I-V\) data.

Local plasma density at an electrode tip is computed using a simple Bohm sheath condition,

\[
n = I_{sat} / (−2 e A C_s ) \quad ; \quad C_s = \sqrt{2eT_e / m_i} ,
\]

with the approximation \(T_i = T_e\) (units of eV). \(A\) is the electrode’s projected area along magnetic field lines. Local plasma potential is computed from a sheath potential drop model [39],

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“New insights on Quasi-Coherent Mode using a Mirror Langmuir Probe”, B. LaBombard et al.
\[ \Phi = \alpha_{sh}T_e + V_f; \quad \alpha_{sh} = \frac{1}{2} \ln \left[ m \left( 1 - \gamma_{se} \right)^2 / 4\pi m_e \right] . \] 

(3)

\( \alpha_{sh} \) is primarily a function of secondary electron emission coefficient, \( \gamma_{se} \). To account for secondary electrons, we use tabulated values of \( \gamma_{se} \) for pure tungsten [40] and compute the appropriate value of \( \alpha_{sh} \) for a Maxwellian distribution of primary electrons at the measured temperature, \( T_e \) (see Fig. 2-1 in [41]). \( \alpha_{sh} \) varies from 2.8 to 1.4 in a deuterium plasma as \( T_e \) ranges from 5 to 100 eV. It is estimated that a 10% error in the energy parameterization of \( \gamma_{se} \) (i.e., \( E_p^I \) in ref. [40]) would yield a 5% error in \( \alpha_{sh} \). This propagates to a 5% error in the computed fluctuation amplitudes of \( \Phi \) using Eq. (3). While we must keep in mind that a systematic error of this magnitude is possible for \( \Phi \), it does not affect the primary conclusions made in this paper.

III. H-MODE, L-MODE AND ELMs

Armed with this new diagnostic, we explored boundary plasma profiles in a few low-power, ohmic H-modes, in which the scanning Langmuir-Mach probe could be scanning inside the LCFS without damage. The recipe for obtaining these discharges is to operate at a reduced magnetic field, with \( q_{95} \) near 3. Figure 5 shows time traces from a discharge that exhibited short phases of ELM-free H-mode, H-mode with intermittent ELM events and L-mode. Plasma conditions were \( I_p = 0.8 \) MA, \( B_T \) ramping from 3.6 to 4.5 tesla (reversed \( I_p \) and \( B_T \)) with upper single null topology and line-integrated density varying among confinement regimes, as indicated in Fig. 5. The Langmuir-Mach probe was scanned three times. Its position with respect to the LCFS is shown in the bottom panel.
Figure 6 shows the resulting profiles in density, electron temperature, plasma potential and floating potential obtained from the ‘NE’ electrode of a Langmuir-Mach probe head. A total of 18,000 measurements of each parameter are obtained during the in-going and out-going probe motion. These data are plotted against $\rho$, which is the distance from the LCFS mapped to the outer midplane, deduced from a reconstruction of the plasma equilibrium using C-Mod’s magnetic sensors [42] and the EFIT plasma equilibrium code [43]. Unfortunately, due to a known interaction between midplane partial flux loops and differing current distributions in individual toroidal field coils that depend on temperature, mapping errors as large 6 mm can sometimes occur at the location of the scanning probe. To correct for possible error, we use the measured $T_e$ profile combined with SOL power balance considerations (discussed further in Sec. IV.E). These tell us that the LCFS should have an electron temperature of roughly 50 eV in these discharges. The profiles in Fig. 6 (and also Figs. 12 and 13 in Sec. IV) have been shifted to be consistent with this constraint. At the point of peak insertion, the Langmuir-Mach probe records $n \sim 1.8 \times 10^{20}\text{m}^{-3}$ and $T_e \sim 80$ eV corresponding to a parallel heat flux density of $q_\parallel \sim 1.4$ GW m$^{-2}$.

The level of detail contained in these profiles is unprecedented: clear differences in H-mode and L-mode profiles are immediately evident in both fluctuation levels and profile shapes. Smoothing over a 200 $\mu$s time window produces the black traces shown in Fig. 6, yielding high spatial resolution profiles that fully resolves the plasma potential profile on a sub-millimeter scale and the associated $ExB$ shear layer. In H-mode, the plasma potential is more positive and much more sharply peaked compared to L-mode; its maximum value resides near the location of the LCFS in both cases.
ELM events show up as spikes in the profile. The time trace of an ELM event recorded near the LCFS in the middle panel of Fig. 6 is examined in Fig. 7. The ELM, which apparently passes over the electrode on a ~25 µs time scale, is easily resolved by the MLP system. Independent measurements of $n, T_e, \Phi$ and $V_f$ from ‘NE’ and ‘SE’ electrodes are overlayed and show excellent correspondence throughout the ELM evolution. Subtle differences are evident, however. Prior to the ELM event, an oscillatory feature is seen, particularly on the floating potential. A cross-power spectrum between $I_{sat}$ signals recorded on the NE and SE electrodes reveals the frequency and $k \theta$ of the mode, consistent with a low-amplitude quasi-coherent mode (QCM, $f \sim 130$ kHz, $k \theta \sim 1.7$ rad/cm), propagating in its usual electron diamagnetic direction. Phase contrast imaging records a similar fluctuation at the same time, as can be seen in Fig. 5. The observations suggest that the QCM may be acting as an ELM precursor in these discharges. Extensive ELM precursor measurements have been made in a number of devices using magnetic pickup loops [44], gas puff imaging [45,46] and ECE imaging [47,48]. But, as demonstrated in the next section, the MLP system has the added ability to follow three dynamical quantities simultaneously: $n, T_e, \Phi$. This may allow ELM precursor mode types and structures to be identified in future experiments.

IV. QUASI-COHHERENT MODE INVESTIGATION

The Quasi-Coherent Mode (QCM) plays a central role in Alcator C-Mod’s EDA H-mode plasmas [2,49], enhancing particle and impurity transport across the LCFS. EDA H-modes with a strong QCM are stationary; their density and impurity contents are maintained constant in time without ELMs. The QCM performs the essential task of regulating the pedestal such that its pressure and current profiles are stable against peeling-ballooning modes [50].
Extensive measurements of the QCM with reflectometry [51], phase-contrast imaging [37], electrostatic [52] and magnetic probes [29], beam emission spectroscopy [53] and gas-puff imaging [38,54] have clearly established the QCM to be an approximately field-aligned perturbation \((k_\theta \sim 1.5 \text{ rad/cm at the outer midplane})\) located near the plasma edge on the low-field side of the torus. Direct measurements with probes have shown that it drives outward radial plasma flux. Initial measurements with a scanning probe and reflectometry [51] indicated that the mode lives approximately halfway up the density pedestal and has a narrow radial width – on the order of 1 to 3 mm. However, there were two concerns with these data: (1) the probe might be destroying the mode, rather than passing through it and (2) large amplitude fluctuation measurements with reflectometry are notoriously challenging to interpret, casting some uncertainty on the mode width measurement.

Candidate explanations for the underlying physics and mode structure of the QCM have been identified. Initial modeling with BOUT [37] tentatively identified the QCM as a resistive-ballooning, x-point mode with its frequency in the lab frame set by the \(E\times B\) motion in the mode layer; a negative radial electric field was required in order to account for the mode’s propagation in the electron diamagnetic drift direction. It was pointed out by Myra \textit{et al.} [55] that drift-Alfvén waves may be a candidate for the QCM. They can become destabilized by the distorted flux-tube geometry associated with the x-point, with electron inertia and resistivity being the primary contributors (curvature drive was not included in the analysis). Such a mode would naturally propagate in the electron diamagnetic drift direction in the plasma frame. Other QCM-like mode possibilities include a pressure-driven ‘surface wave’ observed in modeling by Rogers and Drake [56] as an ideal stability boundary is approached (with diamagnetic correction) and, most recently, a separatrix-spanning QCM-like mode observed by Russell \textit{et al.} using SOLT [57],
which lives in a region of low $E \times B$ shear near the LCFS and spawns ‘blobs’ that propagate into the scrape-off layer.

Unfortunately, experimental uncertainties and ambiguities have made it difficult to clearly identify the physics of the QCM, in particular, determining the true radial width of the mode layer, the precise location of the mode relative to the LCFS and the mode’s propagation direction in the plasma frame. The goal of our experimental investigation was to answer these questions and to use the new capabilities of the MLP to measure amplitude and phase relationships among $n$, $T_e$ and $\Phi$ fluctuations. This would allow us to: (1) clearly distinguish the mode type (e.g., interchange vs. drift) and (2) identify the dominant dynamics of the mode (e.g., density fluctuation vs. pressure fluctuation). In order to assess electromagnetic contributions, measurements of poloidal magnetic field fluctuations were also made with a double-coil magnetic probe head.

A. Double-coil magnetic probe

Time traces from an ohmic H-mode discharge ($\bar{n}_e = 1.1$ to $3.6 \times 10^{20}$ m$^{-3}$, $I_p = 0.73$ MA, $B_T = 3.5$ to 4.2 tesla, normal direction of field and current, lower single-null) used to investigate the QCM are shown in Fig. 8. The toroidal field is ramped down, initiating a transition to a brief ELM-free H-mode followed by an EDA phase in which a QCM is detected by the phase contrast imaging diagnostic. In this case, the QCM is not strong enough to completely arrest the density rise, but it does affect the slope. The double-coil magnetic probe is scanned two times, with the position of the coil center with respect to the LCFS indicated. A discharge on the previous day, in which the MLP system was used to record $T_e$ profiles, has been used to correct for errors in EFIT mapping of the LCFS. A correction of 6 mm has been applied in this case. Spectral power-weighted frequencies and poloidal wavenumbers are shown in the lower panels of Fig. 8 as the
probe approaches its peak insertion during the first scan. These are derived from a cross-power spectrum analysis of the two coil signals (‘A’ and ‘B’). A frequency and wavenumber resolved snapshot of the cross-power spectrum at 1.1469 s is shown in the top panel of Fig. 9. The poloidal wavenumber is deduced from the phase delay between the ‘A’ and ‘B’ probe signals over a 1.6 ms time window [58] (middle panel of Fig. 9). The measured amplitude of the poloidal field fluctuation is on the order of ~0.05 mtesla at the location of the coils.

**B. Magnetic field and parallel current fluctuations**

Using a simple filament model, it is possible to estimate the amplitude of the radial magnetic field perturbation and parallel current fluctuation in the QCM layer. We make use of measurements presented below (see Fig. 13) that locate the QCM at the LCFS and define its radial mode width (FWHM) to be ~ 3 mm, based on the measured envelope of ion saturation current fluctuation power.

Consider the radial ($B_r$) and poloidal ($B_y$) vacuum magnetic fields produced from an infinite, regular array of poloidally-spaced filaments lying in a plane with alternating currents of magnitude $I$ [59],

$$B_y = \frac{\mu_0 I}{2b} \frac{\sinh(\pi r/b) \cos(\pi y/b)}{\sinh^2(\pi r/b) + \sin^2(\pi y/b)}$$  \hspace{1cm} (4a)$$

$$B_r = \frac{\mu_0 I}{2b} \frac{\cosh(\pi r/b) \sin(\pi y/b)}{\cosh^2(\pi r/b) - \cos^2(\pi y/b)}.$$ \hspace{1cm} (4b)

The plane in which the filaments are embedded is taken to approximate locally the poloidal flux surface of the QCM layer. $b$ is the poloidal spacing between filaments, $r$ is the radial distance from the mode layer and $y$ is the poloidal coordinate (MKS units). The filaments are located at $[r=0, y=0 \pm nb; n=0,1,2,3\ldots]$. Here we take $b = \pi / k_\theta \sim 0.02$ meters, corresponding to a half poloidal wavelength of the QCM. This filament pattern, with static currents of alternating sign...
and magnitude \( I \), effectively models the midplane magnetic fluctuation signal of the QCM seen in the lab frame as the pattern moves with the phase velocity of the mode. From Eq. (4a), the amplitude of the poloidal field perturbation, \( B_y = \sim 0.05 \) mtesla, measured at a distance of \( r = 16 \) mm from the mode layer, projects to a current fluctuation amplitude,

\[
I = B_y \frac{2b}{\mu_0} \sinh(\pi r / b) = \sim 9.8 \text{ amps.} \tag{5}
\]

The corresponding radial field in the mode layer \((r = 0, y = b/2)\) is

\[
B_r = \frac{\mu_0 I}{2b} = \sim 0.3 \text{ mtesla.} \tag{6}
\]

Earlier measurements of the QCM using a single coil magnetic probe [29] recorded a poloidal field fluctuation amplitude of 0.17 mtesla at a distance of 10 mm from the LCFS. Using the filament model, this projects to a similar \( B_r \sim 0.4 \) mtesla.

Based on measurements of the mode width (see Fig. 12) and poloidal half wavelength at the midplane, the cross sectional area of the current channel is \( \sim 0.5 \) cm x 2 cm, leading to an average current density of approximately \( \sim 10 \) amps/cm\(^2\). Approximating the current density profile has having a half-cosine shape in the radial and poloidal directions, the current density fluctuation amplitude at the center of the mode layer is \( J_{//} \sim 10\pi^2 / 4 \sim 25 \) amps/cm\(^2\).

**C. QCM probe**

Previous observations of the quasi-coherent mode with a scanning probe suggested a very narrow mode layer radial width (\( \sim 1.5 \) mm [49,51]). However, there was concern that the probe might be attenuating the mode. The ‘QCM probe’ (see Fig. 2) was specially designed to test for a probe perturbation effect, with electrodes (‘N’, ‘S’, ‘E’, and ‘W’) positioned at different minor radii. The idea was to map out the fluctuation profile on each electrode as it scanned through the
mode. If the widths deduced by each probe are observed to be the same then that could be taken as strong evidence that the probe body was not affecting the mode width.

We connected four separate MLP bias systems to the QCM probe electrodes and plunged the probe into a quasi-coherent mode. Figure 10 shows time traces from the ohmic discharge that was used ($\bar{n}_e = 1.4 \times 10^{20}$ m$^{-3}$, $I_p = 0.73$ MA, $B_T = 2.9$ to 3.2 tesla, normal direction of field and current, lower single-null), exhibiting a transition to an EDA H-mode phase at 1.15 s. A single probe plunge was executed at 1.2 s. The top panels of Fig. 11 show the resulting frequency and poloidal wavenumber-resolved power spectra deduced from $I_{sat}$ data on North and South electrodes. These are consistent with the PCI data and suggest that the probe punched through the mode layer. Examination of the four separate time traces of ion saturation current fluctuation power ($I_{sat}$ PWR, $80 \text{ kHz} < f < 120 \text{ kHz}$) reported by the electrodes indicates that the probe body is not affecting the mode width – at least not during the in-going scan. The $I_{sat}$ PWR traces are normalized to have the same amplitude on the in-going scan; during the out-going scan their amplitudes appear to have changed. At the time of peak probe insertion (1.2 s), the core radiated power begins a step change. Inspection of the probe after the experiment revealed that the tip of the molybdenum head had melted. We therefore restrict our attention to the in-going data in the remainder of the paper.

A phase-angle resolved cross power spectrum between density and potential fluctuations ($80 \text{ kHz} < f < 120 \text{ kHz}$) recorded by the East electrode is shown in the bottom time-trace panel of Fig. 11. This plot reveals that potential lags density by $\sim 10$ to $\sim 40$ degrees, with a phase delay of $\sim 16$ degrees at a time of maximum fluctuation amplitude (Fig. 15). There is a hint that the phase lag is higher ($\sim 40$ degrees) on the inboard side of the mode layer compared to the outboard ($\sim 10$ degrees). But this will require further experimentation to verify the trend and its reproducibility.
Frequency and poloidal wavenumber resolved $I_{sat}$ cross-power spectra deduced from the North and South electrodes at 1.1964 s confirm that it is the same mode detected by PCI and GPI diagnostics: $f \sim 105$ kHz, $k_\theta \sim 1.5$ radians/cm at the outboard midplane, propagating in the electron diamagnetic drift direction in the lab frame.

**D. Radial mode width measurement**

The radial mode width of the QCM can be obtained by simply plotting profiles of ion saturation current fluctuation power ($I_{sat}$ PWR, $80$ kHz < $f$ < $120$ kHz) obtained by the four electrodes during the in-going scan. This is done in Fig. 12. However, as a further consistency test, we do not rely on the computed $\rho$ location of each electrode; variations in electrode alignment and geometry can cause variations in the location of the centroid of the current collecting areas. Instead, we ‘adjust’ the $\rho$ coordinate of each electrode, if needed, so as to make all the time-averaged ion saturation current profiles ($I_{sat}$) overlay. The vertical scale factors for E, S and N $I_{sat}$ values have been adjusted so as to achieve this alignment (top panel in Fig. 12). These same adjusted $\rho$ values are used to plot profiles of $I_{sat}$ PWR in the second panel in Fig. 12, normalizing each curve to have the same peak value. Apart from some deviation in the North electrode inside $\rho = 0$, the curves overlay well, indicating that we have a reliable measure of the QCM width. Visual inspection indicates the width to be $\sim 3$ mm (FWHM) at the outer midplane.

In Fig. 12, the radial profile of $I_{sat}$ PWR obtained from the probes is compared with a profile of normalized light intensity fluctuation power ($\delta I/I$) from the GPI system. The radial widths are consistent, although the GPI has insufficient spatial resolution to quantify the width. It should be noted that the GPI profile has been shifted 5 mm outward in $\rho$ coordinate in order to
align the peaks in the profiles. The magnitude of this shift is consistent with known offset errors in EFIT reconstructions and alignment uncertainties of the GPI system.

**E. Mode location and phase velocity in plasma frame**

The MLP system’s ability to record mode fluctuation amplitude and time-averaged $n$, $T_e$, and $\Phi$ profiles from a single electrode (see Fig. 13) allows the location of the mode layer to be determined with respect to the LCFS. Based on the measured $T_e$ profile, power balance considerations require that the electron temperature at the LCFS be in the range of 50 and 60 eV, i.e., this produces a power loss via electron parallel conduction on open field lines that accounts for the power entering into the scrape-off layer (ohmic input power minus radiation). In Fig. 13, the profiles are shifted so that $\rho=0$ corresponds to the location where the time-averaged $T_e$ (black curve) is 50 eV, placing the peak in the $I_{sat}$ fluctuation power profile roughly at the LCFS. Shifting the profiles to align $T_e = 60$ eV at $\rho=0$, would place the peak fluctuation power about 2 mm into the scrape off layer. In any case, these data tell us that the QCM lives at the location where $T_e$ is $\sim 50$ eV and, as a result, the mode must span the LCFS. This result is consistent with the idea that the mode kicks plasma and impurity ions onto open field lines. It should be pointed out that a QCM fluctuation has not been seen on divertor probes in C-Mod – neither in ion saturation current, floating potential or currents flowing to grounded electrodes. Thus the QCM does not involve connection to wall surfaces along open field lines. Taken together, this new information from the MLP, combined with the fact that the mode is seen only on low-field side indicates that it is a ballooning-like perturbation located very close to the LCFS.
Profiles of $E \times B$ velocity ($V_{E \times B}$) and two electron diamagnetic velocities ($V_{dpe}$, $V_{de}$), computed from the time-averaged $n, T_e$, and $\Phi$ data from the East probe, are shown in panel (a) of Fig. 13. $V_{dpe}$ includes the electron pressure gradient while $V_{de}$ includes density gradient only,

\begin{align}
    V_{E \times B} &= \frac{b \times \nabla \Phi}{B} ; \\
    V_{dpe} &= \frac{\nabla n T_e \times b}{nB} ; \\
    V_{de} &= \frac{T_e \nabla n \times b}{nB} .
\end{align} \tag{7}

At the location of the peak amplitude of the QCM, $V_{E \times B}$ is in the ion diamagnetic direction and therefore cannot, by itself, account for the electron diamagnetic-directed motion of the mode seen in the lab frame. Instead, the frequency of the QCM and its direction of propagation in the lab frame is quantitatively consistent with the mode propagating at the electron diamagnetic velocity in the plasma frame. This is seen in panel (c) of Fig. 13, which overlays the QCM frequency spectrogram ($I_{sat}$ data from East probe) with a computation of the frequency of a mode with $k_\theta = 1.5$ rad/cm, propagating at $V_{dpe}$ (red) or $V_{de}$ (blue) in the plasma frame. These data are very strong, direct evidence that the QCM is an electron drift wave.

**F. Time snapshot of QCM fluctuation**

A 200 µs time segment of $n, T_e$, and $\Phi$ data from the East probe, recorded during the peak amplitude of the QCM fluctuation (data from Fig. 13), is shown in Fig. 14. These data reveal a wealth of information about the QCM – we are now looking directly at the fluctuation dynamics of $n, T_e$, and $\Phi$ for the first time. Large-amplitude, approximately in-phase fluctuations of all three quantities are seen, with normalized peak-to-peak amplitudes: $\Delta n/<n> \sim 30\%$, $\Delta T_e/<T_e> \sim 45\%$ and $\Delta \Phi/<T_e> \sim 45\%$. Cross-power spectral analysis of $n$ and $\Phi$ data from the East probe indicates that $\Phi$ lags $n$ by $\sim 16$ degrees. This phase lag produces a fluctuation-induced
outward radial transport velocity of $V_r \sim 10$ m/s, or a particle flux density through the LCFS of $\sim 1.4 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$.

Assuming the transport occurs only on the low-field side (as the QCM only exists there), this flux density alone would result in a particle confinement time of $\sim 50$ ms, sufficient to arrest impurity accumulation. It should be noted that this transport rate is a factor of $\sim 6$ smaller than first reported [49] from multiple electrode measurements of $I_{sat}$ and $V_f$ using a conventional probe head with embedded wire electrodes (not the Langmuir-Mach probe of Fig. 2). Besides not measuring $\Phi$ directly, probe perturbation effects from the head geometry have been identified as a potential source for error in the earlier measurements [60]. Misalignment of electrodes with respect to the local flux surface is also a concern. The ability to record $n$ and $\Phi$ data directly from a single electrode is therefore an important development. Unless the phase delay between $n$ and $\Phi$ can be measured accurately, it is difficult to compute the fluctuation-induced transport for large amplitude, oscillatory modes.

The in-phase oscillation of density and potential seen in Fig. 14 is suggestive of a Boltzmann-like response – reminiscent of a classic drift wave. Is the relationship between $n$, $T_e$, and $\Phi$ simply Boltzmann? To test this idea, a Boltzmann density ($n_B$) is computed from $n$, $T_e$(eV) and $\Phi$ data according to the expression,

$$n_B = \langle n \rangle \exp \left[ \frac{(\Phi - \langle \Phi \rangle)}{T_e} \right],$$  \hspace{1cm} (8)

where $\langle n \rangle$ and $\langle \Phi \rangle$ are time-averaged quantities (200 $\mu$s running average), shown as black traces in Fig. 14. The resulting $n_B$ is shown as a purple time trace in the top panel of Fig. 14. $n_B$ does indeed tend to follow the density, $n$, but its fluctuation amplitude generally exceeds that

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“New insights on Quasi-Coherent Mode using a Mirror Langmuir Probe”, B. LaBombard et al.
which is measured. In any case, we do not expect Eq. (8) to be an appropriate description of the dynamics in the presence of electron temperature fluctuations and possibly electromagnetic contributions (inductive EMF). This motivates a more careful analysis of these fluctuations and a more generalized consideration of the parallel forces acting on the electron fluid (Sec. V).

G. Relative amplitudes and phases of $n$, $T_e$, and $\Phi$ fluctuations

The QCM’s quasi-periodic $n$, $T_e$, and $\Phi$ fluctuations exhibit well-defined relative amplitudes and phases. This can be seen in the plots of Fig. 15, which are constructed from the 200 µs snapshots of $n$, $T_e$, and $\Phi$ shown in Fig. 14. Here, dynamic ‘trajectories’ of normalized fluctuations – density ($\tilde{n} / \langle n \rangle$ - blue), electron temperature ($\tilde{T}_e / \langle T \rangle$ - red) and electron pressure ($\tilde{p}_e / \langle p_e \rangle$ - orange) – are plotted versus normalized potential fluctuation ($\tilde{\Phi} / \langle T_e \rangle$). Depending on the relative phase relationship between these fluctuations and $\tilde{\Phi} / \langle T_e \rangle$, the shapes of the resulting ‘Lissajous figures’ could in principle vary from a straight line (zero phase delay) to an ellipse (90 degrees phase delay). But in this case, the time bases of the vertical axes data relative to the $\tilde{\Phi} / \langle T_e \rangle$ data have been shifted such that each figure collapses onto a straight line. (The individual time-shifts are actually determined by maximizing the time-delay correlation.) For the mode frequency of this QCM, ~105 kHz, the time shift corresponds to a well-defined phase shift, which is indicated in each panel. The observation that the Lissajous figures collapse toward straight lines means that the phase delay is well defined. The largest phase shift is between density and potential (~16 degrees); the smallest phase shift is between electron temperature and potential (~7 degrees).
The relative amplitudes of the fluctuations are also very well defined; these are simply the slopes of the fitted straight black lines shown in Fig. 15. The dashed black lines correspond to a 1:1 proportionality. It is important to note that normalized electron pressure fluctuations are a factor of 1.7 times larger than normalized potential fluctuations. As discussed in Sec. V, this is a strong indicator that interchange drive and inductive EMF effects contribute to the mode dynamics.

H. New understanding of QCM – implication for EDA H-mode pedestal evolution

While the measurements reported here are from ohmic EDA H-modes, it is reasonable to assume that certain key features of the QCM are universal to all discharges, i.e., that the mode is an electron drift wave and that it spans the LCFS. (However, we must be cautious because the radial widths of the QCM in ICRF-heated EDA H-modes are reported by GPI to be typically much larger than the ~3 mm width measured here.) Accepting that the QCM is an electron-drift wave, the observation that the QCM frequency down-shifts during formation of the EDA H-mode [49] implies a specific evolution of the pedestal profile at the location of the mode layer: (1) a decrease in electron pressure gradient and/or (2) an increase in radial electric field, making it more positive (if it is positive) or less negative (if it is negative). The radial location of the mode may also shift, facilitating part or all of these changes. The QCM observations presented here indicate that the QCM is peaked near the LCFS and that the radial electric field at this location is close to zero. Thus the frequency of the QCM may be taken (in this case) as a proxy for the magnitude of the electron pressure gradient, implying that the electron pressure gradient near the LCFS relaxes as the EDA H-mode becomes established. Further experiments with the MLP scanning probe system could easily sort out these details of pedestal/QCM evolution. We look forward to the opportunity to perform such an investigation.
V. FLUCTUATION ANALYSIS

Low frequency plasma fluctuations in the collisional edge plasma of a tokamak can be understood within the context of a fluid drift turbulence model [35,61,62]. Here we follow the work of Scott [34] and consider the magnitudes of the measured \( n, T_e, \Phi \) and \( J_\parallel \) fluctuations relative to their importance in the current continuity (vorticity) and parallel force balance (Ohm’s law) equations. The DALFTE model [34] provides a framework for this discussion since it includes electron temperature fluctuations. As pointed out in Ref. [33], resistive MHD is not able to produce a drift-wave response (\( \tilde{\Phi} \sim \tilde{p}_e \)) because it neglects electron pressure gradients in parallel Ohm’s law. Lacking any information on ion temperature fluctuations, we ignore them. Kinetic corrections to parallel Ohm’s law are also neglected. Our goal here is not to perform a rigorous comparison between model and experiment but to simply provide rough estimates of the relative magnitude of terms (e.g., interchange drive, inductive EMF) in these two conservation equations based on the new MLP measurements.

A. Vorticity equation

The vorticity equation is a statement of conservation of current (\( \nabla \cdot J \)), accounting for fluctuations in ion polarization current, parallel current and diamagnetic current in a curved toroidal geometry. The latter contribution results in an interchange drive, which has its strongest contribution at the outer midplane. In linearized form, the vorticity equation (see Eq. 3.61 in [34]) can be written (in MKS units) as

\[
\frac{n M_i}{B^2} \frac{\partial}{\partial t} \nabla_\perp^2 \tilde{\Phi} = \nabla_\parallel J_\parallel - \kappa \left( \tilde{p}_e \right) \quad ; \quad \kappa(f) = \frac{2}{BR} \left( \sin \theta \frac{\partial}{\partial r} + \cos \theta \frac{\partial}{\partial y} \right) f ,
\]

\( \text{Eq. 9} \)
where the curvature operator, $\kappa(f)$, has been expressed in terms of a poloidal angle $\theta$ (Eq. 10.32 in [34]). Evaluating Eq. (9) at the outer midplane ($\theta = 0$) and Fourier transforming in space and time, the magnitudes of the three terms in Eq. (9) can be compared in a non-dimensional form,

$$\frac{\omega \rho_s^2}{k_i C_s \left( \frac{\pi^2}{w^2} + k_f^2 \right)} \left( \frac{\Phi}{\langle T_e \rangle} \right) : \frac{\bar{J}_i}{en C_s} \sim \frac{2 k_i \rho_s}{k_i R} \left( \frac{\bar{p}_e}{\langle p_e \rangle} \right),$$

(10)

The radial structure of the QCM at the outer midplane is approximated as having a cosine shape $\sim \cos[\pi (r - r_{LFS}) / w]$ with a half-wavelength, $w \sim 0.5$ cm. From magnetic and mirror probe measurements at the midplane, all the parameters in Eq. (10) are known, except for a value of $k_i$, which we approximate as $k_i = \pi / L_{ij}$. $L_{ij}$ is the length of a magnetic field line near the separatrix in the ‘bad curvature’ region, spanning from near the lower x-point to the top of the plasma. Table 1 compiles a list of parameters used to evaluate terms in Eqs. 10 and 14. $T_e$ is in eV.

**TABLE I. Parameters evaluated at location of QCM’s peak amplitude, outer midplane**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{mid}$</td>
<td>0.9 (m)</td>
</tr>
<tr>
<td>$B$</td>
<td>2.3 (tesla)</td>
</tr>
<tr>
<td>$T_e$</td>
<td>45 (eV)</td>
</tr>
<tr>
<td>$n$</td>
<td>$1.4 \times 10^{20}$ (m$^{-3}$)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$6.2 \times 10^5$ (rad / s)</td>
</tr>
<tr>
<td>$\omega_{ci}$</td>
<td>$1.1 \times 10^8$ (rad / s)</td>
</tr>
<tr>
<td>$C_s$</td>
<td>$\sqrt{e T_e / m_i} = 4.6 \times 10^4$ (m / s)</td>
</tr>
<tr>
<td>$V_A$</td>
<td>$\frac{B}{\sqrt{\mu_0 n M_i}} = 3.0 \times 10^6$ (m / s)</td>
</tr>
<tr>
<td>$k_i$</td>
<td>150 (rad / m)</td>
</tr>
<tr>
<td>$w$</td>
<td>0.5 (cm)</td>
</tr>
<tr>
<td>$L_{ij}$</td>
<td>7 (meters)</td>
</tr>
<tr>
<td>$k_{ij}$</td>
<td>$\pi / L_{ij} = 0.45$ (rad / m)</td>
</tr>
<tr>
<td>$\rho_s = C_s / \omega_{ci}$</td>
<td>0.42 (mm)</td>
</tr>
<tr>
<td>$k_{ij} \rho_s$</td>
<td>0.063</td>
</tr>
<tr>
<td>$\frac{m_e}{M C_s} \frac{\omega}{k_{ij}}$</td>
<td>$8.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\frac{\eta_e \bar{J}_i}{k_i T_e}$</td>
<td>0.097</td>
</tr>
<tr>
<td>$\frac{\bar{J}_i}{en C_s}$</td>
<td>$0.25$ (§IV.B)</td>
</tr>
<tr>
<td>$\frac{\bar{p}_e}{\langle p_e \rangle}$ (Fig. 15)</td>
<td>$1.7$</td>
</tr>
<tr>
<td>$\frac{\bar{T}_e}{\langle T_e \rangle}$ (Fig. 15)</td>
<td>$1.1$</td>
</tr>
<tr>
<td>$\frac{\Phi}{\langle T_e \rangle}$ (Fig. 15)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

From these data, terms in the vorticity equation have the magnitudes,
which indicates that all three terms play a role. The QCM is therefore not a simple drift wave. It has a significant interchange drive component. Ion temperature contributions which are ignored here are likely to enhance the interchange drive by a factor of ~2.

B. Parallel Ohm’s law

A linearized form of parallel Ohm’s law (see Eq. 3.76 in [34]) can be written as,

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

which includes inductive EMF, electron inertia, forces due to pressure, potential and temperature gradients along the field lines and collisional resistance to electron current flow. Ampere’s law is used to relate vector potential to parallel current,

$$\tilde{J}_\parallel = -\frac{1}{\mu_0} \nabla_\perp \tilde{A}_\parallel = \frac{k_\parallel^2}{\mu_0} \tilde{A}_\parallel ; \quad k_\perp^2 = k_r^2 + k_\theta^2$$

where $k_r$ and $k_\theta$ vary along the current carrying flux tube as its cross-section changes from midplane to near a poloidal field null. For the purpose of estimation, we take $k_\theta = k_r = \pi / 0.01$ (rad/m), corresponding to a 1 cm x 1 cm square cross section flux tube. With the help of Eq. (13), the relative magnitudes of the four terms in Eq. (12) can be expressed in non-dimensional form,

$$\frac{\omega}{k_\parallel} \frac{C_s}{k_\parallel^2 \rho_s V_A} \left( \tilde{J}_\parallel \right) : \frac{m_e}{M_s} \frac{\omega}{k_\parallel} \left( \tilde{J}_\parallel \right) : \frac{\tilde{p}_e - en\tilde{\Phi}}{\langle p_e \rangle} + 0.71 \frac{\tilde{T}_e}{\langle T_e \rangle} : \eta_\parallel \tilde{J}_\parallel.$$

From the measurements in Fig. 15, the magnitude of the third term evaluates to
\[
\frac{\tilde{p}_e}{\langle p_e \rangle} + \frac{\Phi}{\langle T_e \rangle} + 0.71 \frac{\tilde{T}_e}{\langle T_e \rangle} = 1.48 \frac{\Phi}{\langle T_e \rangle} = 0.22 .
\] (15)

This immediately tells us that the parallel pressure, potential and thermal gradient forces are not balanced among themselves. This imbalance is significant, on the order of the pressure perturbation. Some other term(s) must therefore be providing the overall force balance. Using the data in Table I, all four terms in Eq. (14) evaluate to

\[
0.23 \left( \frac{\tilde{J}_\parallel}{enC_s} \right) : 8.2 \times 10^{-3} \left( \frac{\tilde{J}_\parallel}{enC_s} \right) : 1.48 \frac{\Phi}{\langle T_e \rangle} : 0.095 \left( \frac{\tilde{J}_\parallel}{enC_s} \right)
\] (16)

\[
\sim 0.058 : \sim 0.002 : \sim 0.22 : \sim 0.024
\]

The dominant term in this equation is the third one – unbalanced pressure, potential and thermal gradient forces. Relative to this term, our estimates of the magnitudes of the other terms appear too low to reconcile overall parallel force balance. Inductive EMF is the largest of the remaining terms, but still a factor of 3.8 smaller than the third term. However one must recognize that there is significant wiggle room in these estimates, particularly in the current density. One could imagine that the current density is actually higher than estimated, proportionally increasing all terms except the third one. In addition, the structure of the mode along field lines is not actually known. In any case, these estimates tell us that electron inertia (2\textsuperscript{nd} term) is not a contributor. We also know that resistivity (last term) must play a role in the QCM dynamics in order to account for the phase lag in plasma potential and resulting radial transport of the QCM. The relative magnitudes of the terms in Eq. (15) therefore tell us that inductive EMF contributes to the QCM dynamics at a level that is at least comparable to or larger than resistivity.
VI. CHALLENGE FOR THEORY AND MODELING

While these measurements shed new light on the physics of the QCM, they also raise a challenge for developing accurate theoretical descriptions of the phenomenon. None of the four candidate modes that were highlighted in the introduction of section IV appear to be consistent with the observations. A resistive-ballooning x-point mode, as identified in the initial BOUT modeling [37] work, does not propagate with the electron diamagnetic velocity in the plasma frame. Its electron diamagnetic-directed mode velocity in the lab frame is a consequence of a negative radial electric field in its mode layer. In the drift-Alfvén waves identified in [55], electron inertia was an important component, but this term in an evaluation of parallel Ohm’s law (section V.B) appears to be very small for the QCM. The pressure-driven surface wave candidate [56] is a marginally-stable ideal ballooning mode, not a drift wave. It also has a radial width ($\delta_R$) much larger than the pedestal half width ($k_\theta \sim 1/\delta_R$), yielding a full mode width of $\sim$13 mm. This is not observed for the QCM measurements reported here. The separatrix-spanning QCM-like mode observed in SOLT simulations [57] obtains its electron-diamagnetic directed velocity in the lab frame primarily because of a very strong mean poloidal flow, centered about the LCFS, not because of an electron diamagnetic propagation. Thus while the new measurements reported here do indicate a significant interchange drive and EM component to the QCM (hinting at MHD and ballooning physics), the dominant drift-wave propagation character of the QCM, with its pressure and potential fluctuations nearly in phase, is a challenge for these QCM models.

Clearly more research needs to be done, both in improving models and in providing improved, detailed measurements of the QCM. Work is presently proceeding on both fronts. BOUT++ modeling of the QCM [63], which is obtaining poloidal mode numbers and onset conditions consistent with the mode, is now incorporating two-fluid physics to simulate drift-
wave responses. A new tool to actively probe the QCM, a high- $k\theta$ antenna structure, has also been developed [64], revealing a drift-wave like resonance in the edge of H-mode plasmas. With input from these new tools, improved models of the QCM will likely reveal a more complicated picture than originally anticipated. Perhaps the QCM is excited by an interchange-like mode near the middle of the pedestal (similar to present BOUT++ modeling) and manifests itself as a large amplitude drift-wave like response near the foot of the pedestal, i.e., near the LCFS, consistent with MLP measurements. We look forward to the next chapter in this developing story.

VII. SUMMARY

A Mirror Langmuir Probe (MLP) bias system [31,32] has been implemented on a horizontal scanning probe drive to explore boundary plasma turbulence and the Quasi-Coherent Mode (QCM) [29] associated with Alcator C-Mod’s EDA H-mode [2] for the first time. The MLP is found to be a powerful new technique that enables high-bandwidth measurements (1.1 MHz) of density ($n$), electron temperature ($T_e$) and electric potential ($\Phi$) from a single Langmuir electrode. The system generates a fast-switching, three-state voltage waveform to sample $I$-$V$ characteristics of both a Langmuir probe (LP) and an electronic analog of a Langmuir probe, a ‘mirror Langmuir probe’ (MLP), with a 0.9 $\mu$s cycle time. Using fast feedback, the $I$-$V$ response of the MLP is adjusted in real time to match that of the LP, producing on-the-fly measurements of ion saturation current, electron temperature and floating potential. These quantities are used to dynamically control the amplitude of the voltage bias waveform over a ~1 ms time scale. As a result, the MLP functions as an expert Langmuir probe bias system; it produces accurate digitized samples of a LP’s $I$-$V$ response at optimum voltage biases and at times when step changes in voltage are settled. Using these digitized $I$-$V$ data, $n$, $T_e$, and $\Phi$ values at 1.1 MHz are
computed in a post-processing step, similar to what is done for standard Langmuir probe systems.

An initial survey of L-mode and H-mode plasmas was performed using a four-electrode, high heat-flux tolerant Langmuir-Mach probe head, demonstrating the operation of the MLP system and highlighting its new capabilities. Fluctuations and time-averaged plasma profiles of $n$, $T_e$, and $\Phi$ are recorded with unprecedented detail, clearly resolving sub-millimeter scale features, including a very strong $ExB$ shear layer at the LCFS in ELM-free H-mode. ELMs are detected as large spikes in density and temperature on a $\sim 25 \mu s$ time scale, which are fully resolved on all four electrodes. Prior to the ELM, a small amplitude QCM-like oscillation is detected ($f \sim 130 \, \text{kHz}$, $k_\theta \sim 1.7 \, \text{rad/cm}$), which may play the role of an ELM precursor.

Two different scanning probe heads are used to investigate the structure of the $\sim 100 \, \text{kHz}$ Quasi-Coherent Mode (QCM) that plays a critical role in regulating EDA H-mode pedestals. Low power ohmic H-modes are investigated, in which scanning probes can be inserted past the last-closed flux surface (LCFS). A double-coil, magnetic probe is used to measure poloidal field fluctuations and to estimate the magnitude of radial field fluctuations ($B_r \sim 0.3 \, \text{mtesla}$) and parallel current density fluctuations ($J_{||} \sim 25 \, \text{amps/cm}^2$) at the location of the QCM layer. A specially designed ‘QCM probe’ combined with separate MLP bias systems are used to record $n$, $T_e$, and $\Phi$ fluctuations on four electrodes as the probe head is scanned across the QCM layer. The radial spacing of the electrodes allows an assessment of probe perturbation effects while the poloidal spacing enables poloidal wavenumbers to be deduced. Amplitude and phase relationships among the QCM $n$, $T_e$, and $\Phi$ fluctuations are inferred with high fidelity using time series data from a single Langmuir electrode.
The unique ability to record mode fluctuation amplitude (ion saturation auto-power) and time-averaged $T_e$ profiles from the same electrode has allowed the flux surface location of the QCM to be determined unambiguously for the first time. The peak amplitude of the QCM is found to reside near the LCFS ($T_e \sim 50$ eV). The mode has a radial width of $\sim 3$ mm (FWHM in $I_{sat}$ autopower), spanning the LCFS. The width measurement is consistent with simultaneous measurements of light intensity fluctuations from gas-puff imaging (GPI), although the GPI system has insufficient spatial resolution to quantify widths smaller than $\sim 3.8$ mm. The location and width is consistent with the idea that the QCM kicks plasma and impurities onto open field lines, accomplishing an essential function of ELMs, but with a benign perturbation.

High-resolution $n$, $T_e$, and $\Phi$ profile measurements at the location of the mode layer also enable the propagation velocity of the QCM in the plasma frame to be determined unambiguously for the first time. The mode lives in a region of positive radial electric field; its frequency in the lab frame is found to be quantitatively consistent with a plasma frame phase velocity that is bracketed by two electron diamagnetic drift velocities: one evaluated using electron pressure gradient ($V_{dpe} = \nabla_n n T_e \times \frac{\mathbf{b}}{nB}$) and the other evaluated using density gradient alone ($V_{de} = T_e \nabla_n n \times \frac{\mathbf{b}}{nB}$). This result is compelling evidence that the QCM is an electron drift wave.

A 200 $\mu$s time ‘snapshot’ of the QCM’s $n$, $T_e$, and $\Phi$ fluctuations is examined in detail at the spatial location of peak mode amplitude, revealing nearly in-phase, sinusoidal bursts ($\sim 100$ kHz) in density, electron temperature and plasma potential. The fluctuating fields are found to have well-defined relative phases and amplitudes, with phases relative to density fluctuations $[\tilde{n}(0^\circ), \tilde{\rho}_e(5^\circ), \tilde{T}_e(9^\circ), \tilde{\Phi}(16^\circ)]$ and amplitudes $\tilde{n}/\langle n \rangle \sim 0.65 \tilde{\Phi}/\langle T_e \rangle$, $\tilde{T}_e/\langle T_e \rangle \sim 1.1 \tilde{\Phi}/\langle T_e \rangle$. 

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“New insights on Quasi-Coherent Mode using a Mirror Langmuir Probe”, B. LaBombard et al.
\[ \frac{\dot{p}_e}{\langle p_e \rangle} \sim 1.7 \frac{\Phi}{\langle T_e \rangle} \]. The observation of a small \( \sim 16 \) degree phase delay between potential and density is an independent indicator that the mode is primarily a drift wave.

The large electron pressure fluctuation, \( \frac{\dot{p}_e}{\langle p_e \rangle} \sim 1.7 \frac{\Phi}{\langle T_e \rangle} \), is taken as a hint that interchange drive may contribute to the fluctuation dynamics. The relative magnitudes of terms in the vorticity equation are evaluated using measured plasma parameters, including an estimate of \( \tilde{J}_e / enC_s \) from magnetic probe measurements and approximating \( k || = \pi / L || \) where \( L || \) is the length of a magnetic field line in the bad curvature region. Interchange drive is indeed found to be a significant contributor, even without allowing for a finite ion pressure contribution, which is not measured.

An evaluation of terms in parallel Ohm’s law is also performed. The large measured pressure fluctuation, \( \frac{\dot{p}_e}{\langle p_e \rangle} \sim 1.7 \frac{\Phi}{\langle T_e \rangle} \), implies that a significant parallel inductive electric field must exist to maintain parallel electron force balance. Direct evaluation of the magnitudes of the dominant terms in this equation supports this conclusion. However, one must realize that there is significant wiggle room in these estimates.

In conclusion, we find that the QCM is primarily an electron drift-wave with significant interchange drive and electromagnetic contributions. It spans the LCFS and enhances the radial transport of confined plasma onto open magnetic field lines. These new measurements challenge present theoretical models for the QCM and call for further work in both theory and experiment.

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New insights on Quasi-Coherent Mode using a Mirror Langmuir Probe, B. LaBombard et al.


FIG. 1. (Color online) MLP bias system uses active feedback control to adjust the $I_{sat}$, $T_e$, and $V_f$ ‘control knobs’ on an electronic analog of a Langmuir probe – a Mirror Langmuir Probe – such that it produces an $I$-$V$ characteristic that precisely matches the response of an actual Langmuir probe exposed to a plasma (a). Langmuir and mirror-probe current-voltage responses are compared during the times when the fast-switching 3-bias state voltage waveform settles to fixed values (b). Three different bias states are cyclically sampled every 0.9 µs. The bias voltage values ($V^+$, $V_0$, $V^-$) are adjusted dynamically over time, such that $V^+ - V^-$ is roughly 4 times the electron temperature averaged over a ~1 ms time period. Biases $V$ and $V_0$ sample the ion saturation and floating regions of the $I$-$V$ characteristics, respectively. $V^+$ is chosen such that the probe collects a net positive current that is approximately equal in magnitude to the ion saturation current (c). The Langmuir and Mirror-Langmuir $I$-$V$ responses in panel (c) are shown with different shapes for illustration only. In actual operation, the MLP circuit dynamically adjusts $I_{sat}$, $T_e$, and $V_f$ such that these curves overlay.
New insights on Quasi-Coherent Mode using a Mirror Langmuir Probe, B. LaBombard et al.

High heat-flux electrodes, on same flux surface

Radial-spaced electrodes, on different flux surfaces

FIG. 2. (Color online) Three different probe heads are used on the horizontal scanning probe system to investigate boundary plasma turbulence and the Quasi-Coherent Mode (QCM). Langmuir-Mach and QCM probe heads employ the new MLP bias drive system on each of their four electrodes. Electrodes on the Langmuir-Mach probe lie on the same flux surface and are designed for high heat flux handling. Electrodes on the QCM probe are exposed to plasma on different flux surfaces to interrogate the radial width of the QCM layer. (A mirror image of the QCM probe is shown here so that the electrodes can be seen. The probe tips face into the page and map along field lines to the outer midplane.) A two-coil magnetic probe is used to record poloidal magnetic field fluctuations. The QCM is also recorded on a Phase-Contrast Imaging system (PCI, only outer chords shown) and a Gas-Puff Imaging system (GPI) that samples a region near the outer midplane.
FIG. 3. (Color online) A working example of the MLP system applied to a scanning probe. These data were obtained from the NW electrode of a Langmuir-Mach probe head, scanning into an ohmic L-mode plasma. The upper two panels show the voltage waveform applied and current collected by the NW electrode. Red, green and blue traces correspond to the $V^+$, $V_0$, and $V^-$ portions of the $I$-$V$ response. Real-time outputs of $I_{sat}$, $T_e$, and $V_f$ reported by the MLP are shown in the middle panels. At its peak insertion, the probe reaches the last-closed flux surface. An expanded view of the time traces in the bottom panels shows that fluctuations in $I_{sat}$, $T_e$, and $V_f$ are highly correlated. A burst event where $I_{sat}$ and $T_e$ jump by a factor of 2 is highlighted. This time segment is shown on an expanded time scale in Fig. 4.

“New insights on Quasi-Coherent Mode using a Mirror Langmuir Probe”, B. LaBombard et al.
FIG. 4. (Color online) Expanded timescale of the $I_{\text{sat}}$ and $T_e$ burst event highlighted in Fig. 3. On this scale, the discrete bias states of the probe voltage and current waveforms can be seen (top panels). The 0.9 $\mu$s cycle time is sufficiently fast to resolve the plasma fluctuations. These data are used to independently compute $I_{\text{sat}}$, $T_e$, and $V_f$ values from an exponential fit to the $I$-$V$ measurements (black traces, labeled ‘Fit’). The MLP system does a remarkably good job of computing these values in real time (blue, green, red traces), although due to slew rate limitations, the MLP can lose accuracy during large amplitude transients. For this reason, the ‘Fit’ data are used for all data analyses. Nevertheless, the MLP system is critically important for obtaining these data – it controls the operation of the bias system, dynamically adjusting and producing the optimum three-state bias waveform during the probe’s trajectory through the plasma. The result is high quality $I$-$V$ measurements at the three bias states, cyclically repeating at 1.1 MHz.
FIG. 5. (Color online) As a test the MLP system, a high heat-flux handling Langmuir-Mach probe head with the MLP bias drive was used to investigate boundary plasma conditions in an ohmic discharge that exhibited ELM-free, ELMy and L-mode phases (top panel). During ELMy periods, the phase contrast imaging diagnostic recorded short bursts of activity in the QCM range of frequencies (middle panel). The event highlighted by the purple circle is also picked up on the scanning probe (see Fig. 7), which was plunged three times in this discharge, reaching at or slightly inside the last-closed flux surface (bottom panel).
FIG. 6. (Color online) Plasma profiles obtained from the NE electrode of the Langmuir-Mach probe corresponding to the three probe plunges shown in Fig. 5. Data from in-going and out-going probe motion are overlayed for a total of ~18,000 measurements of each parameter. The coordinate, ρ, is the distance from the last-closed flux surface mapped to the outer midplane. The black curves result from smoothing the raw data over a 200 µs time window. The MLP system records plasma fluctuations, ELMs and high spatial resolution time-averaged profiles with unprecedented detail. The $E \times B$ shear layer in H-mode is clearly resolved, with a plasma potential maximum located at the last-closed flux surface. An ELM event recorded with the probe near the last-closed flux surface (yellow highlight) is examined in detail in Fig. 7.
FIG. 7. (Color online) An ELM event was recorded by NE and SE electrodes on a Langmuir-Mach probe head while it was located near to the last-closed flux surface (see Fig. 6). The ~25 µs burst in density and electron temperature associated with the ELM is easily resolved. A possible ELM precursor oscillation is also detected. Cross-power spectral analysis reveals that the fluctuation propagates in the electron diamagnetic direction with frequency and $k_\theta$ corresponding to a small-amplitude quasi-coherent mode. The short-lived QCM-like mode is also seen by the phase contrast imaging system at this time (see Fig. 5).
FIG. 8. (Color online) A two-coil magnetic probe is used to investigate the QCM in an ohmic EDA H-mode. An 80 kHz QCM begins after a short ELM-free period, as seen on the PCI diagnostic. The magnetic probe is scanned into the plasma at that time. Frequency and poloidal wavenumber of the poloidal field fluctuations agree with that obtained from PCI – a mode propagating in the electron diamagnetic drift direction. Time traces from coils ‘A’ and ‘B’ at 1.1469 seconds (dashed line) are shown in Fig. 9.
FIG. 9. (Color online) At a location approximately 16 mm from the mode layer, coils ‘A’ and ‘B’ measure intermittent bursts in poloidal magnetic field (~ 0.05 mtesla amplitude) that last tens of cycles (bottom two panels), with a time delay corresponding to the poloidal motion and poloidal wavenumber of the mode (top panel). Using a current filament model for the QCM, the amplitude of the radial field component at the mode layer is estimated to be ~ 0.3 mtesla, with an equivalent parallel current amplitude of ~10 amps per filament.
FIG. 10. (Color online) A specially-design probe head, the ‘QCM probe’, combined with the MLP bias drive is used to investigate the QCM mode structure in detail. The probe is plunged across the last-closed flux surface of an ohmic EDA H-mode that exhibits a 105 kHz quasi-coherent mode, as detected on the phase contrast imaging system.
FIG. 11. (Color online) The ‘QCM probe’ is scanned through the QCM layer, recording frequency and $k_\theta$ spectra from North (N) and South (S) probes (top two panels). Ion saturation current autopower from all four electrodes (frequency range $80 \text{ kHz} < f < 120 \text{ kHz}$) shows that the probe head does not affect the mode as it passes through it. During the in-going scan, signal on the East electrode (E) rises and drops. A similar response on North, West and South electrodes is seen, but delayed in time, consistent with their relative spatial locations on the probe head (third panel). The probe does cause a perturbation to the plasma, however, as illustrated in the jump in core radiated power at the time of peak probe insertion (fourth panel). Plasma potential lags density by a phase angle of $\sim 10$ to $\sim 40$ degrees, as recorded by the East electrode (fifth panel). Cross-power $S(f, k_\theta)$ spectra taken at 1.1964 s from North and South electrodes clearly identifies the mode’s frequency and poloidal mode number – it corresponds to the QCM seen by the PCI diagnostic.
FIG. 12. (Color online) Ion saturation current profiles recorded by four electrodes on the ‘QCM probe’ are precisely aligned by adjusting their vertical scales and allowing for small corrections in the flux surface \( \rho \)-mapping (panel A). Using the corrected \( \rho \)-mapping obtained from panel A, ion saturation current autopower (80 kHz < \( f \) < 120 kHz) are plotted in panel B. These are scaled so that their peak values are the same. The fluctuation profiles are seen to overlay, indicating that radial structure of the mode is not being disturbed by the presence of the probe head. We therefore report with confidence that the full-width, half maximum radial mode width of the QCM is \( \sim 3 \) mm in ion saturation current autopower. Gas-puff imaging (GPI) performed at the same time yields a radial mode width (purple diamonds) that is consistent with the probe results (bottom panel), although GPI has insufficient spatial resolution to quantify widths smaller than \( \sim 3.8 \) mm. It is important to note that the GPI fluctuation profile has been shifted in \( \rho \) such that its peak aligns with the peak in the fluctuation power measured by the scanning probe. A schematic of the GPI viewing array and gas-puffing nozzle relative to the plasma is shown in the inset.
FIG. 13. (Color online) The ability to make measurements of plasma density, electron temperature, plasma potential and ion saturation current fluctuation power from the same electrode (top four panels) allows the precise location and phase velocity of the QCM in the plasma frame to be determined. Here, profiles are shifted such that the electron temperature at the last closed flux surface (LCFS, $\rho=0$) is 50 eV – roughly consistent with power balance. The QCM spans the LCFS. $ExB$ and electron diamagnetic velocities are computed from the measured profiles (lower panels). The QCM lives in a region where the $ExB$ is in the ion diamagnetic direction. The frequency of the QCM is consistent with it having a poloidal wavenumber of 1.5 rad/cm and propagating in the electron diamagnetic drift direction in the plasma frame.
FIG. 14. (Color online) Top three panels show a time snapshot of the QCM density ($n$ - blue), electron temperature ($T_e$ – red) and plasma potential fluctuation ($\Phi$ – green), taken with the East probe near the last closed flux surface. $n$, $T_e$ and $\Phi$ exhibit large amplitude excursions ($\Delta n/\langle n \rangle \sim 30\%$, $\Delta T_e/\langle T_e \rangle \sim 45\%$ and $\Delta \Phi/\langle T_e \rangle \sim 45\%$) but remain nearly in-phase throughout. Cross power spectral analysis of the density and potential fluctuation reveal that $\Phi$ lags $n$ by approximately $\sim 16$ degrees, consistent with a drift wave response (bottom panel). The resulting outward radial transport velocity is estimated to be $\sim 10$ m/s. For reference, a computation of a local density fluctuation that would be consistent with a Boltzmann response is plotted in the top panel ($n_B$ – purple). The electron response does not satisfy a simple Boltzmann relationship. A more careful, direct evaluation of the parallel electron force balance equation suggests a significant electromagnetic contribution (i.e., inductive parallel electric field) to the wave dynamics (Sec. V and Fig. 15).
FIG. 15. (Color online) Density, electron temperature and electron pressure time signals from Fig. 14 are time-shifted and plotted versus the potential time signal to reveal the amplitude and phase relationships of the fluctuations. These measurements, combined with the measurements of frequency, poloidal wavenumber and poloidal magnetic field perturbations, allow terms in the vorticity and parallel electron force-balance equation to be evaluated directly (see Sec. V). The large amplitude of the electron pressure perturbation relative to potential indicates both a strong curvature drive and a significant electromagnetic component to the QCM. Thus the mode structure of the QCM is identified as an electron drift-wave with significant interchange drive and electromagnetic contributions.