New Insights into Short-Wavelength, Coherent Edge Fluctuations on Alcator C-Mod


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Abstract. Two new research tools – a Mirror Langmuir Probe (MLP) and a “Shoelace” antenna – have been employed to diagnose and actively perturb fluctuations in the Alcator C-Mod tokamak edge plasma. Both tools elucidate the physics associated with the Quasi-Coherent Mode (QCM, $k_\perp \sim 1.5 \text{ cm}^{-1}$, $f \sim 50 – 200 \text{ kHz}$), the edge fluctuation responsible for the increased particle flux which sustains the steady-state Enhanced D$_\alpha$ H-mode. In particular, the MLP has been used to characterize the QCM with unprecedented detail, showing it to be primarily a drift wave, with curvature also playing an important role. In addition, the Shoelace antenna coupled inductively to a fluctuation localized in the edge plasma and resonant at the QCM $k_\perp$ and frequency, representing the first time a drift-wave-like fluctuation has been driven actively in the tokamak edge.

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1. Introduction

The ability to achieve steady-state, high-performance confinement regimes in future reactors rests upon creating edge conditions that are thermally insulating but permeable to outward flow of impurities, including high-Z particles from plasma facing components, as well as helium ash. In many present-day, low-power-density experimental reactors, edge localized modes (ELMs) – whose behavior is well-described by a peeling-ballooning cycle\cite{1} – provide such a mechanism. However, the intermittent, bursting nature of these fluctuations leads to unacceptably-large transient heat loads on plasma facing components; this is true even for ratios of stored energy to surface area present in the ITER design\cite{2,3,4}, and the situation is expected to worsen still on a full-scale reactor\cite{5}. As such, identifying steady-state confinement regimes that are stable to ELMs and find alternative means of exhausting impurities is of critical importance for the successful operation of any tokamak reactor scenario.

Two steady-state, high-performance, ELM-free regimes have been identified on the Alcator C-Mod tokamak\cite{6}: enhanced D_α (EDA) H-mode\cite{7,8,9} and I-mode\cite{10,11}. These may be grouped into a larger family of small or no-ELM regimes\cite{12}, including the Quiescent H-mode found on DIII-D and later observed on ASDEX-Upgrade and JET\cite{13,14,15}, the High-Recycling Steady regime on JT-60U\cite{16,17,18}, and the long-pulse Low and High Enhanced Recycling regimes on EAST\cite{19,20}, with the latter three bearing similarities to EDA H-mode. The unifying observation across all such regimes is the presence of one or more continuous, coherent edge fluctuations which replace ELMs to enhance particle transport, and which do not significantly degrade energy confinement.

Two new tools developed at the Alcator C-Mod tokamak have been used to study these edge fluctuations both passively and actively. The Mirror Langmuir Probe (MLP)\cite{21} is an intelligent bias control system which mimics the Langmuir probe response in real time using an analog computer, optimizing rapid switching over bias states and turning each individual probe into a triple probe with 0.9 \(\mu\)s time resolution. When applied to probes on a reciprocating head, the MLP simultaneously provides both fluctuations and time-averaged values of quantities of electron temperature, \(T_e\), and density, \(n_e\), and plasma potential, \(\Phi\), across the entire edge plasma. Applied to a stationary probe, the real-time approximations of these measurements are useful for feedback applications.

The Shoelace antenna\cite{22} induces currents in the edge plasma that mimic those of the intrinsic edge coherent modes, matching both the perpendicular wave number and frequency of the Quasi-Coherent Mode (QCM), the fluctuation that regulates edge particle transport in EDA H-mode, as well as the Weakly-Coherent Mode (WCM), which plays the same role in I-mode. In initial experiments attempting to couple to the QCM, the antenna drove a weakly-damped resonance in the edge plasma centered at the QCM frequency, with measured signatures in density and field; interestingly, the resonance persisted even in plasmas without an intrinsic QCM.

The discussion below reports recent experiments using these two devices. First, the QCM is reviewed in Section 2. The methodology and experimental results of the Mirror Langmuir Probe are then described in Section 3, and of the Shoelace antenna in Section 4. Finally, the work is summarized in Section 5, and an outline of future work is provided.
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Figure 1: Overview of typical ohmic EDA H-mode used in these studies. Spectrograms of (a) PCI and (b) Mirnov coil signals, measuring \( \tilde{n}_e \) and \( \tilde{B}_0 \); pairs of parameter traces showing (c) line-averaged density, \( \bar{n}_e \) (blue), and toroidal magnetic field, \( B_t \) (orange); (d) plasma current, \( I_p \) (blue), and \( q_{95} \) (orange); and (e) \( D_\alpha \) light (blue) and radiated power (orange). \( B_t \) and \( I_p \) are negative when their directions are clockwise looking down from above the tokamak.

2. The Quasi-Coherent Mode

The Quasi-Coherent Mode (QCM) is the edge fluctuation that is responsible for exhausting impurities in the enhanced \( D_\alpha \) (EDA) H-mode confinement regime \[7, 23, 9\], allowing this confinement regime to achieve a steady-state without ELMs \[24\]. Instances of fluctuations on other tokamaks strongly reminiscent of the QCM include the coherent modes of the high-recycling regimes on JT-60U and EAST \[16, 18, 19, 20\]. Similarity studies conducted on the DIII-D tokamak also yielded a QCM, though it did not result in an ELM-free EDA H-mode \[25\], while the low particle confinement H-mode accessed on JET bears similarities to EDA \[26\].

The QCM has strong signatures in density, temperature, potential, and magnetic field, and has been characterized by numerous diagnostics, including gas-puff imaging \[24, 27\], phase contrast imaging (PCI) \[28\], beam emission spectroscopy \[29\], reflectometry \[30\], and reciprocating Langmuir probes and Mirnov coils \[31, 21\]. It has a perpendicular wave number of \( k_{\perp} \sim 1.5 \text{ cm}^{-1} \), and is nominally field-aligned \[31, 28\]. This corresponds to a perpendicular wavelength that is long relative to the drift wave dispersion length scale, \( k_{\perp} \rho_s \sim 0.1 \), but short compared to the minor radius, \( k_{\perp} a \approx 33 \). The laboratory frame frequency band of the mode is typically between 50 and 200 kHz, though it may exceed these bounds under particular experimental conditions, for example, with the application of lower hybrid power \[32\]. The phase velocity in the laboratory frame points in the electron diamagnetic drift direction.

EDA H-modes prefer stronger shaping, higher \( q_{95} \), and higher edge collisionality and \( |\nabla p| \) \[33\]; however, the boundary of EDA parameter space is not sharp in these parameters \[9\]. To allow better access to the edge plasma by the MLP, and to minimize the gap between the plasma and the Shoelace antenna, no RF heating was used in the discharges explored below. The recipe for achieving an EDA H-mode with only ohmic heating typically involves ramping the toroidal field down to around 3 T to reduce the H-mode threshold, and then back up to reach the higher \( q_{95} \) values generally preferred by the QCM \[31\]; however, a stationary EDA H-mode was also achieved even at a field of \( \lesssim 3 \text{ T} \), without the subsequent ramp up.

Figure 1 shows spectrograms of PCI and Mirnov coil signals, as well as parameter traces, from one such ohmic EDA H-mode obtained during these studies. The QCM

\[ \rho_s = c_s/\Omega_i, \text{ where } c_s \text{ is the sound speed and } \Omega_i \text{ the ion gyro frequency} \]
features prominently in both the poloidal field and line-averaged density spectra, setting in at \( \sim 1.04 \) s into the discharge, just after the transition to H-mode at around 1.02 s. The eponymous rise in \( D_\alpha \) light, associated with increased recombination from enhanced particle transport, accompanies the appearance of the QCM.

Comparisons between ICRF-heated and ohmic EDA H-modes showed no significant difference in the global aspects of the two scenarios \([8]\). Nonetheless, it has been conjectured that details of the QCM may vary between the two cases. This is a subject that merits further scrutiny, but will not be approached here.

## 3. The Mirror Langmuir Probe

### 3.1. Background and Methodology

The Mirror Langmuir Probe (MLP) approach transforms an individual electrode into a triple probe \([34, 35, 21]\). This is accomplished by rapidly switching the probe bias voltage through a large negative (ion saturation), a near-floating, and a large positive (electron collection) state, with the entire cycle through all three states completed in 0.9 \( \mu \)s for a 1.1 MHz sampling rate. This is fast enough to resolve turbulent and coherent fluctuations in the edge, typically band-limited to below 500 kHz on Alcator C-Mod. The three voltage set points are optimized via real-time feedback by an analog computer which “mirrors” the actual \( I/V \) characteristic of the Langmuir probe, adjusting the three parameters in the probe current model,

\[
I_p = I_s \left[ e^{\frac{V-V_f}{T_e}} - 1 \right],
\]

where \( I_p \) is the current through the MLP, \( I_s \) is the saturation current, \( V_f \) is the floating potential, \( T_e \) is the electron temperature (in eV), and \( V \) is the applied voltage. The direct parameters of this model are \( I_s, V_f, \) and \( T_e \). The electron density, \( n_e \), is extracted from the saturation current using the Bohm sheath condition, while the local plasma potential, \( \Phi \), is calculated from the plasma sheath drop model \([36]\).

Figure 2a illustrates the operation of the MLP. The top trace shows the rapid scanning of the probe voltage through the three bias states, highlighted by the red, green, and blue lines bounding and bisecting the trace. The critical function of the MLP circuitry is to adjust these bias states from one cycle to the next to ensure a well-optimized and rapid assessment of the entire \( I/V \) characteristic. The current trace appears beneath the voltage, followed by the values of \( n_e, V_f, \) and \( T_e \) calculated in real time by the MLP circuitry (thin colored lines) and those fit to Eq. 1 (thick black lines). An independent measurement of these parameters is made available every 0.9 \( \mu \)s. While the fitted values are preferred for data analysis, the comparison reveals the high-quality of the MLP system’s real-time determination of \( I/V \) parameters.

Two probe-head geometries used in conjunction with the MLP drive circuitry are shown in Figure 2b. Both configurations employ four tungsten probes, spaced to resolve the wave numbers of the edge fluctuations of interest. Each probe is driven by a separate MLP circuit, yielding four independent sets of measurements of \( n_e, T_e, \) and \( \Phi \). The electrodes of the Langmuir-Mach probe sit on a single flux surface, and are designed for high heat flux. The other probe design, with radially-spaced electrodes, allows separate measurements of fluctuations and profiles at the front and in the wake of the plunging probe head, helping to determine whether the probe perturbs the
local plasma (for example, by extinguishing a fluctuation due to an injection from a melting tip). The head, itself, is plunged via a pneumatic driver, traversing an in-going and out-going scan in about 20 ms that covers the SOL (typically $\sim 1 - 2 \text{ cm}$), and can briefly penetrate the LCFS by several mm under lower-heating-power conditions.

Because of its ability to provide simultaneous measurements of both the fluctuating and background profile components of $\Phi$, $T_e$, and $n_e$, the MLP is uniquely suited to diagnose fluctuations in the plasma edge. The relative phases and magnitudes of the three measured quantities provide an excellent means of discriminating the underlying mode physics. Moreover, the ability to measure profile conditions at the precise location in which the fluctuation is immersed facilitates comparison to theoretical models, while direct measurement of transport helps to determine the effect of the fluctuation on edge confinement. Because the probes are mounted on reciprocating heads, local measurements are available both at flux surfaces where the mode is unstable, as well as where it is stable. In addition, the probe resolves wave numbers and phase velocities in both the laboratory and plasma frames, giving a robust measurement of the mode dispersion relation.

### 3.2. Results and Discussion

Figure 3a shows data from the MLP extracted from an edge plasma bearing a QCM [21]. The discharge corresponds to that shown in Figure 1. The plot at left shows $n_e$, $T_e$, $\Phi$, and $I_s$ gathered from one of the four available electrodes. The fluctuations...
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Figure 3: (a) Profiles of $n_e$, $T_e$, and $\Phi$, as well as $I_s$ fluctuation power in the band from 80 to 120 kHz as estimated by the RMS amplitude, obtained by the MLP “West” electrode from a discharge with a QCM. (b) (i) $E \times B$, “adiabatic” ($V_{dpe}$), and “isothermal” ($V_{de}$) electron diamagnetic drift velocities calculated from MLP profiles; (ii) sum of $E \times B$ and diamagnetic drift velocities; (iii) lab-frame frequency of the drift wave dispersion relation, superimposed with a spectrogram of the fluctuation power recorded during the probe’s scan. $\rho$ is the distance from the LCFS. Compare to Figure 13 in [21], which shows slightly different analysis using data from the “East” electrode.

around the mean are not noise, but direct measurements of the plasma fluctuations, themselves; the thick, black lines plot the smoothed, time-averaged profiles. The ion saturation current fluctuation power profile clearly places the QCM within a 3 mm (full-width at half-maximum) layer which spans the last-closed flux surface (LCFS), commensurate with the well-established role played by the QCM in regulating transport in the pedestal. The radial electric field points outward at this location, against the orientation of the pressure gradient, with the consequence that the electron diamagnetic and $E \times B$ drift directions oppose one another. This means that the mode rotates in the electron diamagnetic drift direction not only in the laboratory, but also the plasma frame, an insight not demonstrated prior to the availability of these results, and only achieved by the simultaneous measurement of profile and fluctuations afforded by the MLP. Were profile and fluctuations measured separately, an alignment error of only 5 mm would lead to the conclusion that the mode propagates in the ion, rather than the electron, diamagnetic drift direction in the plasma frame, a discrepancy which underscores the value of the MLP data.

The probe has also revealed that the isothermal and adiabatic limits of the drift-wave dispersion relation [37] bracket the QCM frequency band, suggesting that the QCM sits in a region of stationary drift, where the shear vanishes from the combined diamagnetic and
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$\mathbf{E} \times \mathbf{B}$ flows. This is illustrated in Figure 3b, which shows the electron diamagnetic drift velocity under the isothermal ($V_{de} \equiv T_e \nabla n_e \times \mathbf{B}/(n_e e B^2)$) and adiabatic ($V_{dpe} \equiv \nabla p_e \times \mathbf{B}/(n_e e B^2)$) assumptions, together with the $\mathbf{E} \times \mathbf{B}$ velocity, and compares the frequency predicted by the drift-wave dispersion relation with the spectrum measured by the probe.

The MLP registered strong fluctuations on the order of $\Delta n_e/\bar{n}_e \sim 30\%$ and $\Delta T_e/\bar{T}_e \sim \Delta \Phi/T_e \sim 45\%$ for the QCM. Crucially, around the separatrix, the phase difference between potential and density fluctuations was also determined, with $\tilde{\Phi}$ lagging $\tilde{n}_e$ by $\sim 16^\circ$, as shown by the time traces and Lissajous curve in Figure 4. This near-Boltzmann response is nonetheless large enough to produce an outward radial flow at 10 m/s, corresponding to a particle flux of $\Gamma \sim 1.4 \times 10^{21}$ m$^{-2}$s$^{-1}$. The small phase lag between $\tilde{\Phi}$ and $\tilde{n}_e$ further establishes the identification of the QCM as drift-wave-like [38, Sec. IV]. At the same time, MLP measurements indicate a significant interchange component in the mode drive, and recent data indicate that further up the pedestal, the phase difference between $\tilde{\Phi}$ and $\tilde{n}_e$ may increase. The importance of curvature in the QCM physics is also expected given the QCM’s ballooning nature [24].

4. The Shoelace Antenna

4.1. Background and Methodology

Complementing the MLP’s passive diagnosis of the QCM is an attempt to drive the mode directly using a “Shoelace” antenna [22, 39, 40].

Exciting coherent drift waves has been explored elsewhere in the literature, by electrostatic means on the linear machines, MIRABELLE and VINETA [41, 42] and the toroidal device, TORPEX [43], and also inductively on VINETA [44]. This work showed that drift modes may be driven both electrostatically and inductively, and that in both cases, the coupling occurs when driven parallel current filaments are phase-matched in both frequency and wave number (i.e. spatiotemporally) to the mode eigenfunction; in these experiments, the wave parameters belonging to the natural drift wave spectrum in the device were highly reproducible and had already been well-characterized experimentally. Interestingly, not only could the strongly-coherent driven mode be made to dominate the fluctuation spectrum, but it also suppressed the background, incoherent turbulence, and reduced cross-field transport beneath its fully-turbulent level.

On tokamaks, electrostatic probes have been used to interact with broadband edge turbulence [45, 46], showing both feedback stabilization and destabilization of background fluctuations depending upon driver phase settings. However, use of such probes to continuously interact with target fluctuations is limited to relatively low-temperature plasmas due to the high heat load experienced in the edge plasma.

The inspiration for exciting the QCM inductively derives from the fact that the QCM possesses a magnetic signature [31]; it was conjectured that an antenna which mimics the current pattern that produces this magnetic signature could couple to the QCM. The design of the antenna and its power system builds off of experience obtained in Alcator C-Mod’s Active MHD program [47, 48, 49, 50, 51, 52, 53, 54, 55], but the comparatively short wavelength of the QCM (relative to toroidal Alfvén eigenmodes on C-Mod) presents technical challenges unique to the task of exciting this particular edge mode, as described below.
Figure 4: 200 µs of fluctuation signals from the MLP “West” electrode, displayed as (a) time traces of $n_e$ (top), $T_e$ (middle), and $\Phi$ (bottom), and (b) parametric, or “Lissajous,” figure plotting $\tilde{n}_e/\langle n_e \rangle$ against $\tilde{\Phi}/\langle T_e \rangle$ ($T_e$ in eV and $\langle \rangle$ denotes averaging over the entire time bin). A Boltzmann relation between $\tilde{n}_e$ and $\tilde{\Phi}$, shown by the purple line in the $\tilde{n}_e$ trace panel, largely reproduces the measured data (in blue), while the near linear distribution of points in the Lissajous figure illustrates that the phase difference between the traces is small, though non-zero. Compare to Figures 14 and 15 in [21], which shows slightly different analysis using data from the “East” electrode.

Figure 5a shows a photograph of the “Shoelace” antenna built for this purpose mounted inside the Alcator C-Mod vacuum vessel. The molybdenum winding zigzags back and forth across the support structure, climbing upward once and then back down to form 19 “rungs” in each of two layers. The rungs are nominally field-aligned, and are spaced to reproduce the measured perpendicular wave number of the QCM, $k_\perp = 1.5 \pm 0.1$ cm$^{-1}$ [31, 28, 24, 21]. But this means that the antenna vacuum field falls off rapidly, with a radial e-folding length $\sim k_\perp^{-1} = \frac{2}{3}$ cm. This necessitates placing the antenna rungs very close to the plasma, only $\sim$3 mm in the shadow of the main limiter at closest approach. To accommodate the high heat flux incident on the antenna structure, and attendant thermal expansion, the winding is pretensioned to 220 N (50 lbs) by spring-loaded winding posts.

Additionally, the rapid radial fall-off of the vacuum field must be offset by driving as much current through the antenna as the available power system will allow. This is accomplished by a custom matching network, which couples two commercial 50-Ω amplifiers at an arbitrary and rapidly tunable frequency (better than 1 MHz/s slew rate) in the band between 45 and 300 kHz [39], providing $\sim$2 kW of radio-frequency (RF) source power at an end-to-end efficiency of 85% or better, and resulting in an antenna current $\geq$80 A. A phase lock
system also provides the ability to lock to the measured fluctuation signal of a QCM in real time.

4.2. Results and Discussion

Figure 5b presents measurements from antenna operation. The cross-coherence – the cross-power between the antenna current and a diagnostic signal, normalized by the product of the autopowers of the two signals, \( C_{xy} = P_{xy} / \sqrt{P_{xx} P_{yy}} \) – is shown for three fluctuation diagnostics: a phase contrast imaging (PCI) chord measuring \( \tilde{n}_e \), a polarimetry chord with signal primarily \( \propto \tilde{n}_e \), and a Mirnov coil sensitive to \( \tilde{B}_\theta \). The antenna is energized for the duration of the discharge’s 1 s flat-top; its frequency is modulated between 90 and 140 kHz in a triangular waveform with a 100 ms period. It excites a \( \tilde{B}_\theta \) fluctuation throughout the discharge that is coherent with the antenna current; however, immediately after the transition to H-mode, a coherent density response is also observed. The density response first appears prior to the onset of an intrinsic QCM, and is maintained throughout the EDA phase of the H-mode.

Analysis of the coherent \( \tilde{n}_e \) and \( \tilde{B}_\theta \) responses shows that they are approximately field-aligned, \( k_\perp \gg k_\parallel \), and assume the same \( k_\perp = 1.5 \text{ cm}^{-1} \) as that imposed by the antenna. Moreover, while the antenna has no structurally-preferred perpendicular launch direction, the driven mode selects a laboratory-frame phase velocity in the electron diamagnetic drift direction. This is demonstrated in Figure 6b and g, which show a fit of the perpendicular wave number across multiple PCI chords for both a forward- and reversed-field discharge. As the electron diamagnetic drift velocity changes direction between the two field orientations, so, too, does the direction of \( k_\perp \) change. The mode is also strongly guided by field lines, evidenced by the fact that it is observed only by diagnostics which map to the antenna along field lines on the last closed flux surface.

The plasma response to the antenna is strongly peaked at the QCM center frequency, as is apparent from Figure 6i-e and h-j. The resonance is well-characterized by a simple pole with a weak normalized damping rate, \( \gamma/\omega = 5-10\% \). The absolute magnitude of the driven fluctuations may be estimated at \( \tilde{n}_e \sim 10^{16} \text{ m}^{-2} \) (line-averaged density) and \( 4 \times 10^{-6} \text{ T} \) at the Mirnov coil (extrapolating to a value in excess of \( 10^{-4} \text{ T} \) at the LCFS). These values are on the same order as those of the intrinsic QCM. Figure 6b also shows that the antenna drives a resonant fluctuation of smaller, but similar, magnitude even when there is no intrinsic QCM present in the background. This is noteworthy since it suggests that a similar damped drift-wave resonance is available both in EDA and ELM-free H-modes, and that, in EDA H-mode, a source of free energy is coupled to this mode. From the ballooning nature of the QCM, we may speculate that this free energy derives from a curvature-driven instability appearing further up the pedestal, coupling to and exciting a damped drift-wave at the LCFS, which, in turn, is responsible for expelling particles across the plasma boundary and sustaining the H-mode. However, additional experiments are needed to determine whether such a scenario is, indeed, the mechanism underlying the QCM.

5. Conclusion and Future Work

Two new tools – the Mirror Langmuir Probe and the Shoelace antenna – have been employed on the Alcator C-Mod tokamak to explore edge coherent modes by passive
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Figure 5: (a) The Shoelace antenna mounted inside Alcator C-Mod. (b) Short-time magnitude squared coherence between the antenna current and PCI, polarimeter, and Mirnov coil fluctuation signals. The $\bar{n}_e$, $D_\alpha$, and radiated power traces are plotted beneath. Photo in (a) from Figure 1 in [39]. Compare (b) to Figure 9b in [22], which shows data from a different discharge.

and active means. The MLP gives multiple, simultaneous measurements of fluctuation and profile data for $n_e$, $T_e$, and $\Phi$ at high temporal and spatial resolution. This has provided characterization of the quasi-coherent mode, as well as other edge fluctuations, with unprecedented detail, revealing the mode to be predominantly drift-wave-like in character, with a significant contribution from interchange forcing.

The Shoelace antenna has driven a resonance at the QCM perpendicular wave number and frequency, the first-ever instance of an inductive antenna driving a drift-wave-like mode in a tokamak. The driven mode is weakly-damped, with amplitude comparable to that of the intrinsic QCM, and is strongly guided by field lines. The resonance can be driven even in the absence of an intrinsic mode, suggesting that the antenna might be able to reproduce QCM-like transport, at least on mapped field lines, even in discharges which are stable to this edge fluctuation.

Several new features will be available to the MLP and Shoelace antenna in the 2015 experimental campaign. A high-speed linear servo motor will replace the pneumatic drive for the reciprocating probe. In conjunction with a feedback system using the real-time estimates of $T_e$ provided by the MLP, this feature will allow the probe to scan to a desired set of flux or probe surface conditions, before retracting automatically, enhancing the robustness and repeatability of the system.

Mirror Langmuir Probe bias control will also be deployed on probes situated in the
Figure 6: Data pertaining to the characterization of the mode driven by the Shoelace antenna. (a) PCI spectrogram; (b) outer-midplane value of $k_\perp$ for the driven mode extracted from data across the outer-most 21 PCI chords assuming a field-aligned mode; (c) peak amplitude in the spectrum together with the product of the transfer function and the antenna current for a PCI chord and (d) a Mirnov coil, and finally, (e) peak frequency in the PCI and Mirnov spectra superimposed with the antenna frequency. (f)-(j) present the same analysis (except that only the outer-most 14 PCI chords are used in the estimation of $k_\perp$), but from a reversed-field discharge; the direction of $k_\perp$, and hence the laboratory-frame phase velocity, inverts under this reversal. Compare to Figures 14 and 17 in [22], which show data from a different discharge.
divertor, providing the opportunity for real-time feedback control of divertor conditions, which may be used, for example, to achieve and maintain detachment.

The Shoelace antenna power system has also been upgraded from 2 to $\geq 8$ kW of source power, exploiting the flexible matching network’s ability to couple the antenna load to 50-Ω drivers. Not only does this improve the robustness of the coherent mode, but it also facilitates studying nonlinear interaction between intrinsic fluctuations and the antenna, including mode-locking, frequency pulling, and background turbulence suppression [42, 44]. In addition, a larger vacuum field perturbation allows the antenna to reach further across the SOL and into the edge plasma, meaning that it may drive significant edge currents even at larger gaps between the outer wall and the plasma. This greater operational flexibility will allow the antenna to run in a variety of new conditions, including those with RF heating and current drive power.

Critically, the Shoelace antenna has also been rewound at a new, shallower pitch, which will allow the antenna rungs to be field-aligned for equilibria in which the antenna maps to the MLP. As a result, the MLP will be able to characterize the antenna-driven fluctuation, and assess whether the antenna drives transport, as does the QCM. A positive result would suggest a pathway toward active control of edge transport using RF actuators, the demonstration of was one of the principle motivations behind the creation of the Shoelace antenna.

Both the Shoelace antenna and the MLP will also be used to examine the weakly coherent mode (WCM, $f = 200 - 500$ kHz, $k_\perp \sim 1.5$ cm$^{-1}$, $k_\perp \rho_s \sim 0.1$ [11, 27]), which is the particle exhaust channel in the I-mode confinement regime [58, 59]. Low-RF-power I-mode discharges suitable for probe scans have already been run with successful MLP operation; in the 2015 experimental campaign, deeper traversals of the MLP, together with systematic parameter scans, will help to better characterize the WCM, particularly with respect to fluctuation-induced transport, as well as the background plasma in which the mode is immersed. The Shoelace antenna, phase-matched in $k_\perp$ and $\omega$ to the WCM, will contribute to these studies with first-of-a-kind active measurements of the mode, and will examine whether the WCM might also be driven actively to enhance edge transport.

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