The Quasi-Coherent Signature of Enhanced D_α H-mode in Alcator C-Mod

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Abstract The steady-state H-mode regime found at moderate to high density in Alcator C-Mod, known as Enhanced D_α H-mode (EDA), appears to be maintained by a continuous quasi-coherent (QC) mode in the edge steep gradient region. Large amplitude density and magnetic fluctuations with typical frequencies of ~100 kHz are driven by the QC mode. These fluctuations are measured in the steep edge gradient region by inserting a fast scanning probe containing two poloidally separated Langmuir probes and a poloidal field pick-up coil. As the probe approaches the plasma edge, clear magnetic fluctuations were measured within ~ 2 cm of the last closed flux surface (LCFS). The mode amplitude falls off rapidly with distance from the plasma center with an exponential decay length of $k_r \approx 1.5\ cm^{-1}$, measured 10 cm above the outboard midplane. The root-mean-square amplitude of the fluctuation extrapolated to the LCFS was $\tilde{B}_\theta \approx 5$ G. The density fluctuations, on the other hand, were visible on the Langmuir probe only when it was within a few mm of the LCFS. The potential and density fluctuations were sufficiently in phase to enhance particle transport at the QC mode frequency. These results show that the quasi-coherent signature of the EDA H-mode is an electromagnetic mode that appears to be responsible for the enhanced particle transport in the plasma edge.

1. Introduction

The Enhanced D_α H-mode [1-3] (EDA) is a steady-state high confinement regime found in the Alcator C-Mod [4] tokamak that combines good core energy confinement with lower edge particle confinement. Under these conditions, the energy is well contained in the core, but the impurities, which enter from the edge, do not accumulate. Instead, the density is controlled, providing a clean, high energy confinement plasma. This regime is particularly well suited to a steady-state next step device. The EDA H-mode is best recognized by a steady quasi-coherent (QC) mode whose oscillation frequency is typically in the range of 100 – 150 kHz, which is observed only when the plasma is in the EDA H-mode phase of the discharge. The QC mode is not found in ELM-free H-mode, Type III ELMy H-mode, or in L-mode. Up to now, the mode was observed on density and potential fluctuation diagnostics including an edge reflectometer [5], a Phase Contrast Imaging (PCI) system [6], and fast scanning Langmuir probes [7]. In this paper, for the first time, measurements have been made of the large magnetic component of this quasi-coherent mode. This large mode in the edge appears to be responsible for the enhanced edge particle transport that characterizes the EDA H-mode. Similar quasi-coherent density fluctuations in the 50 - 180 kHz range were also observed in H-modes in PDX [8] and in PBX-M [9]. Edge transport has been associated with similar modes in DIII-D, though they were assumed to be electrostatic because no magnetic component was measured at the wall [10].

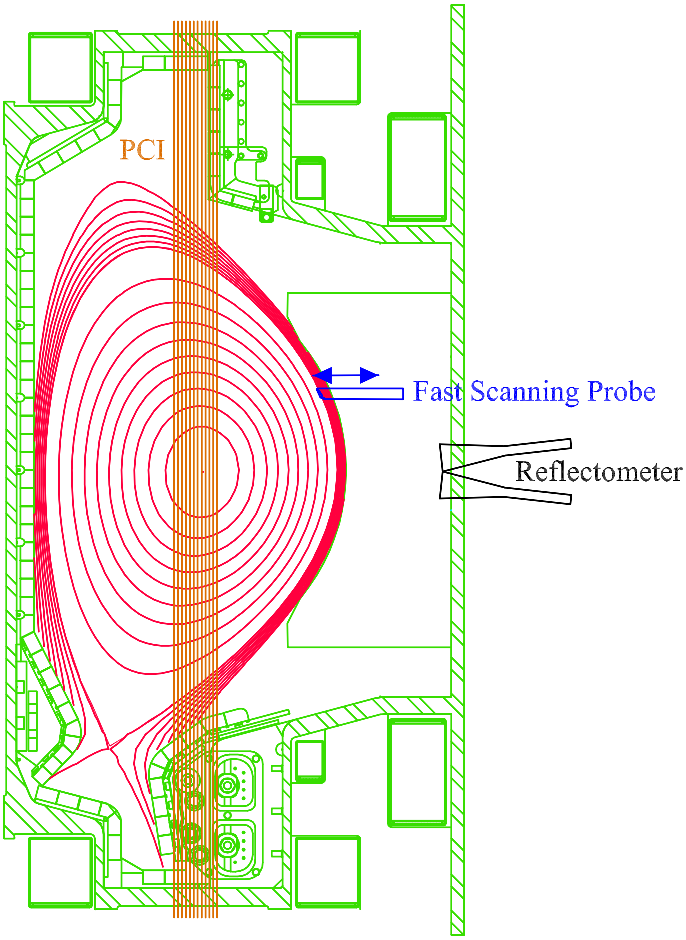

Figure 1. Poloidal cross-section of Alcator C-Mod showing the locations of the Phase Contrast Imaging system, the Fast Scanning Probe and the reflectometer. These diagnostics are not all at the same toroidal location.

2. Diagnostics

Figure 1 shows a poloidal cross-section of Alcator C-Mod with the locations of the diagnostics used in this paper. Two fast scanning probe heads were employed. One head has two imbedded Langmuir probes and one magnetic field pick-up coil oriented in the poloidal direction. The probe head is made of boron nitride, which is a low Z insulator that can withstand high heat flux from the plasma and allow high frequency magnetic fields to penetrate to the enclosed pick-up coil. The head is 2 cm in diameter with two 1.5 mm diameter molybdenum Langmuir probe wires cut flush with the probe surface and separated by 4 mm poloidally to resolve short wavelength modes. The probe normally scans in and out of the plasma in 100 ms and is limited to a depth of a few mm within the LCFS to avoid overheating the probe or causing disruptions (Figure 2). The center of the magnetic pick-up coil was located 9 mm behind the plasma-facing tip of the probe. The coil was wound of 36 AWG (ϕ=0.12 mm) high temperature Kulgrid ceramic-coated nickel clad copper wire [11] onto a boron nitride bobbin. It has a diameter of 5.8 mm, a length of 4 mm, and a total surface area NA = 1.76×10^{-3} m^2. The coil signal is high-pass filtered with a 3 dB point of 1 kHz to avoid low frequency noise pick-up. The second probe head was similar except that it was made of molybdenum and had four Langmuir probes with a probe spacing of 6.35 mm. The four probes are labeled North, South, East, and West. The North and South probes are separated poloidally with the North above the South probe. The East and West probes are halfway between the North and South probes and are separated along a field line. All of these signals were sampled at 1 MHz with 256 K of samples per shot and up to three scans into the plasma were made per discharge. The probe can also be scanned to a fixed depth and then dwell at that position throughout the data-taking window. The probe was located 10 cm above the outboard midplane of the plasma (Figure 1).

Additional density fluctuation measurements were made with ordinary-mode 88 GHz and 110 GHz reflectometer channels [12] and a Phase Contrast Imaging (PCI) system (Figure 1). The reflectometer channels have reflecting layers at densities of 9.6×10^{19} m^{-3} and 1.5×10^{20} m^{-3}, which are in the steep gradient region at the plasma edge in H-mode. The PCI system measures density fluctuations along 12 chords passing vertically through the core of the plasma. The radial separation of the chords, which was varied from 0.25 – 1 cm, allows measurements to be made of an apparent major radial wave number of the QC fluctuations up to 10 cm^{-1} with a resolution of about 1.7 cm^{-1}.

3. Quasi-Coherent mode measurements

To allow relatively deep probe penetration into the hot plasma edge, low power Ohmic H-modes were chosen to make the probe measurements. The toroidal field was ramped down to ~3.2 T to reduce the H-mode threshold. Once in the H-mode, the field was raised to ~4.2 T to reach the q range preferred for EDA H-mode ($q_{95} > 3.5$) at a plasma current of 0.77 MA in lower single null deuterium plasmas [6]. The L-mode target density of $\bar{n}_e \approx 1.3 \times 10^{20}$ m^{-3} was just above the density threshold for obtaining EDA H-mode rather than ELM-free H-mode and the final H-mode densities were $\bar{n}_e \approx 3.5 \times 10^{20}$ m^{-3}.

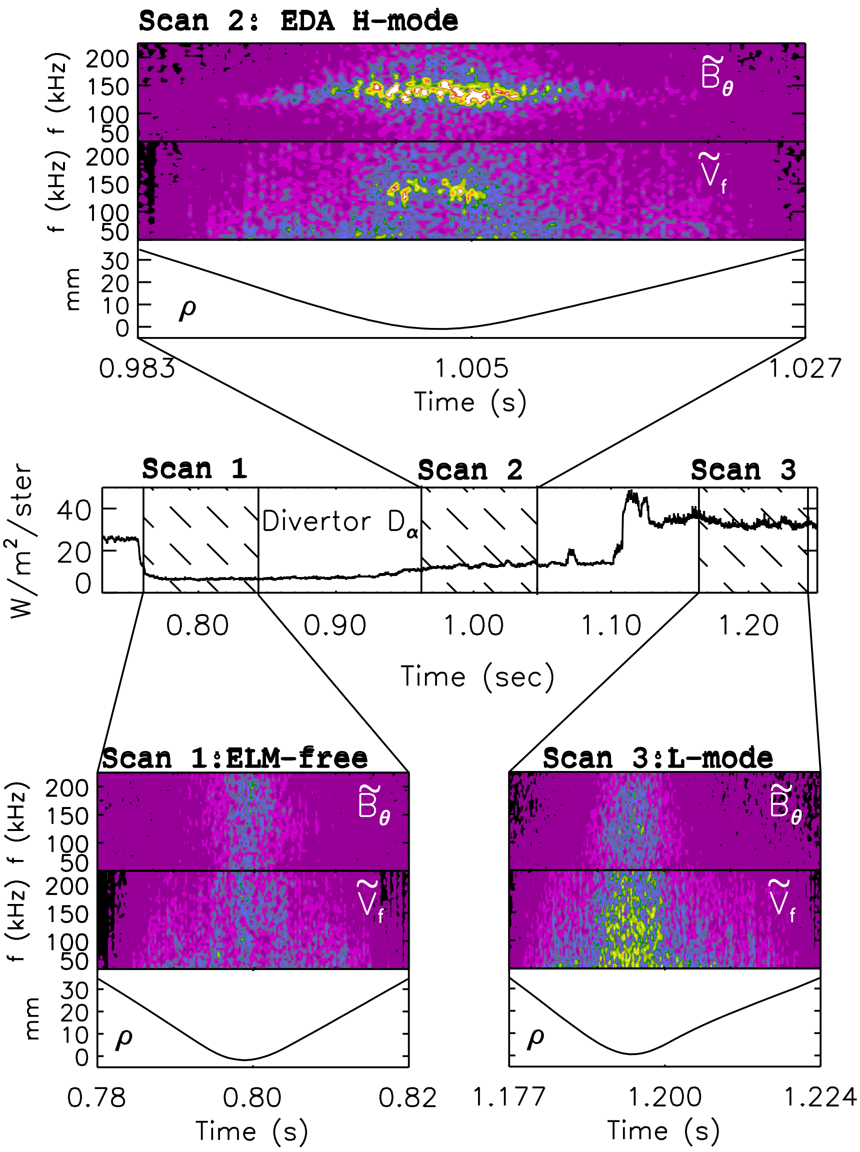

Figure 2. Fast Fourier Transforms versus time of the magnetic probe and Langmuir probe floating potential signals together with the probe tip position, ρ, relative to the EFIT calculated last closed flux surface for three scans of the probe. Scan 1 is in ELM-free H-mode, scan 2 is in Enhanced D_α H-mode, and scan 3 is in L-mode. Brighter color indicates larger amplitude. A divertor D_α trace is also shown to indicate the phases of the H-mode.

Figure 2 shows auto-power spectra as a function of time of the magnetic and Langmuir probe signals during three scans of the probe. The first scan was into an ELM-free H-mode phase and shows low level broadband fluctuations. The second scan was in an Ohmic EDA H-mode phase and shows a clear quasi-coherent mode (QC) in the 100 – 150 kHz range as the probe head approached the last closed flux surface (LCFS). The third scan was in an Ohmic L-mode phase and it shows an increased level of broadband fluctuations, but the QC mode is not present. The QC mode is observed only when the discharge is in an

EDA H-mode phase. The probe tip position relative to the EFIT calculated LCFS is also shown, indicating that the probe tip just reaches the LCFS. The QC mode was measurable on the magnetic probe from about 2 cm outside the LCFS and the amplitude increased rapidly as the coil came closer to the LCFS. The oscillating mode was observed on the Langmuir probes only when the tip of the probe was within a few mm of the LCFS.

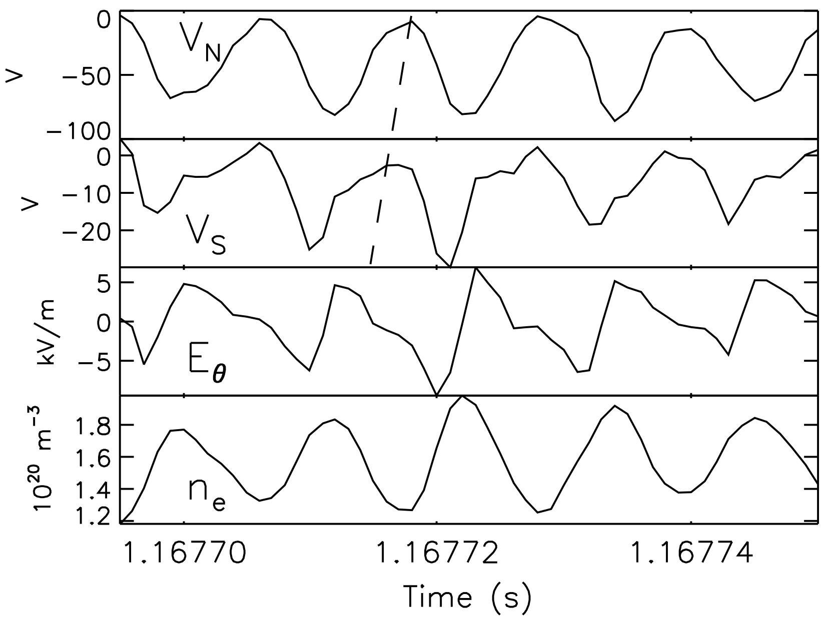

Figure 3. Raw signals from the north and south Langmuir probes showing QC mode fluctuations. The dashed line shows that the mode appears first on the south probe then on the north probe indicating that the mode propagates in the electron diamagnetic drift direction. The third and fourth traces are the poloidal electric field and the electron density showing that they are sufficiently in phase to drive substantial particle transport.

In a different set of discharges, using a similar probe head with four Langmuir probes and without a magnetic probe, it was possible to measure both the electric field and density fluctuations associated with the QC mode. The north and south probes were separated by 6.35 mm along the poloidal direction and the east and west probes were oriented along a field line between the north and south probes. The phase difference between the floating potentials of the north and south probes (Figure 3) shows that the mode propagates from the south probe toward the north probe, which is in the electron diamagnetic drift direction. Due to a slight (~1 mm) misalignment of the south probe from the flux surface of the north probe, the extremely rapid decay of the mode with distance from the fluctuating layer, and that the probe may have disturbed the mode, the amplitudes are not comparable. For an estimate of the particle transport, we assume that the temperature fluctuation is small compared to the potential fluctuation. The electric field fluctuation can be estimated by normalizing the south and north probe floating potential signals with the average of the root-mean-squares of the two signals. The phase of this electric field fluctuation can then be compared with the electron density determined from the average of the ion saturation current measurements from the east and west probes. Note that the density perturbation is very large with the local $\tilde{n} / n \sim 30\%$. Since the electric field and density fluctuations are ~ 60° out of phase, the QC mode appears to drive substantial particle transport. Taking the time average of the product of the density and electric field fluctuations for a number of probe sweeps gives an average E × B driven particle flux density of $\langle \tilde{n} \cdot \tilde{v} \rangle \approx 4 \times 10^{21}$ particles/(m^2 s), which is comparable to previous estimates [13]. This is a large particle flux that is comparable to the total fueling rate measured in typical H-mode discharges [14] if this level of mode-induced flux occurs over half of the total plasma surface area. These data show that the QC mode appears to be responsible for the enhanced edge particle transport of the EDA H-mode.

The rapid radial decay of the QC magnetic fluctuation amplitude can be used to determine the poloidal wavenumber of the mode. Since the magnetic pick-up coil is outside the fluctuating current layer, Laplace's equation, $\nabla^2 \Psi = 0$, will apply. In a slab approximation, which is appropriate for the observed wavelength, we can write $\Psi = \Psi_0 \exp(i(k_\theta x + k_\varphi z) - k_r r)$, where x is the distance in the poloidal direction, z is in the toroidal direction, and r is in the radial direction. Then, $\nabla^2\Psi = (-(k_\theta{}^2 + k_\varphi{}^2) + k_r{}^2)\Psi = 0$. Now, for a field-aligned perturbation, $\vec{k} \cdot \vec{B} = 0$ and $k_\varphi = k_\theta B_\theta / B\varphi \approx k_\theta / 5$, which gives $k_r \approx k_\theta$. That is, the decay length normal to the surface is approximately the same as the poloidal wavenumber. Figure 4 shows the radial decay of the magnetic fluctuations in the frequency band of the QC mode for one scan of the magnetic probe in an Ohmic EDA H-mode. The amplitude falls off exponentially with radius and the ingoing and outgoing scans of the probe nearly overlay one another, indicating that the probe did not significantly disturb the mode amplitude. The exponential fits to the ingoing and outgoing scans both give a best fit to a wavenumber of $k_\theta = 1.5$ cm^{-1}. The toroidal field on axis at the time of this scan was 3.2 T. The extrapolated amplitude of the mode at the LCFS is between 4.5 and 5.1 Gauss. This corresponds to $\tilde{B}_\theta / B_\theta \approx 9 \times 10^{-4}$.

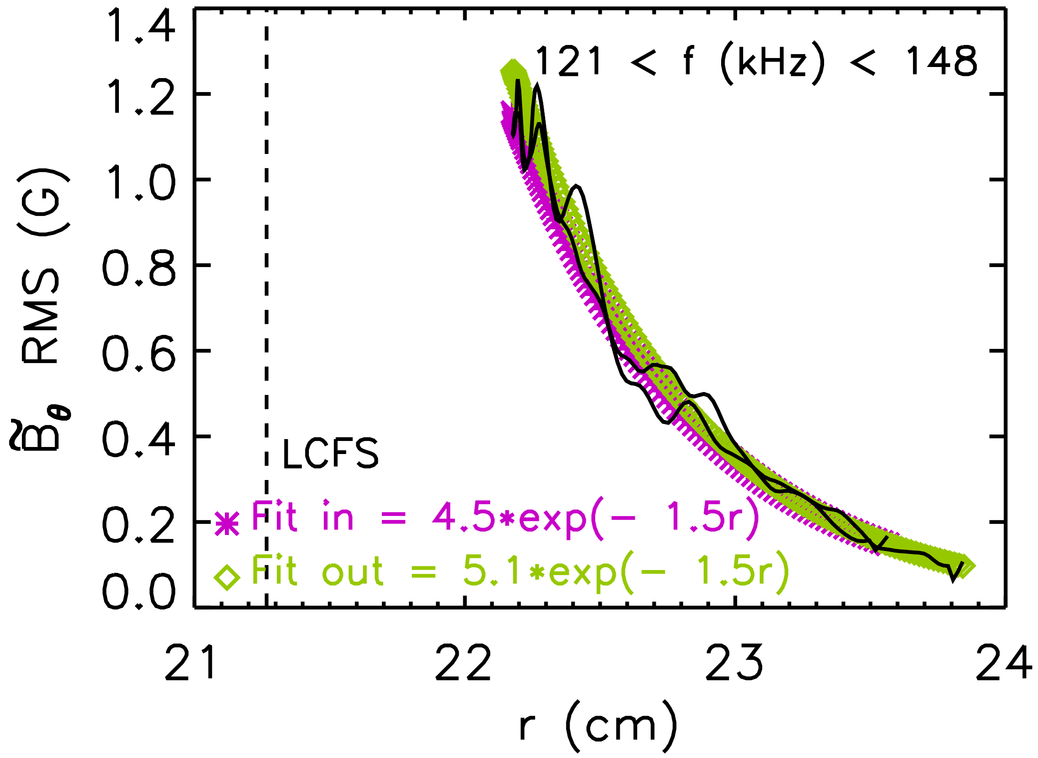

Figure 4. Radial decay of the magnetic fluctuations from a fast scanning probe scan into an EDA H-mode in the frequency range of the QC mode showing an exponential decay with a decay length of 1.5 cm^{-1}. The ingoing and outgoing scans nearly overlay one another and extrapolate to a magnetic perturbation of 4.5 to 5.1 Gauss at the last closed flux surface (LCFS).

Measurements of the phase difference between poloidally separated Langmuir probe signals also give a measure of the poloidal scale of the QC mode. The phase difference shown in Figure 3, for example, gives a $k_\theta \approx 1.2\ cm^{-1}$ at a toroidal field of 2.6 T on axis. The wavelength of the QC mode has also been measured with the PCI system and was found to scale inversely proportional to the toroidal field [15]. Because of the PCI geometry (Figure 1), the wavelengths that are calculated from phase differences between different vertical chords are along a major radius and are projections of the poloidal wavenumber of the mode. The PCI wavenumbers near the top and bottom of the plasma are in the range of 4 – 7 cm^{-1} for toroidal fields from 3.5 – 5.4 T. If the QC perturbation is field-aligned, the flux expansion between the magnetic probe location (1) and the PCI location (2) together with the flux surface angle to the horizontal at the PCI location can explain the difference in the poloidal wavenumber and the apparent major radial wavenumber through the relation

$k_{R_2} = k_{\theta_1} \frac{B_{\theta_1}}{B_{R_2}} \frac{R_1^2}{R_2^2}$, where k_{R2} is the apparent major radial wavenumber at location 2, $k_{\theta 1}$ is the poloidal wavenumber at location 1, $B_{\theta 1}$ is the poloidal field at location 1, B_{R2} is the major radial field component at location 2, and R_1 and R_2 are the major radii of locations 1 and 2, respectively. Evaluating this expression, the wavenumbers inferred from the PCI and the magnetic and Langmuir probes agree within the uncertainties of the measurements.

The scanning magnetic probe can also be set to scan into a certain depth and dwell throughout the data acquisition time so that measurements can be made at a fixed location near the LCFS. Figure 5 shows an example comparing auto-power spectra versus time of the magnetic probe signal and a 110 GHz edge reflectometer signal. In this case, the magnetic probe was inserted to a probe tip position of about 12 mm outside the LCFS, which means the center of the pick-up coil was about 21 mm outside the LCFS. The QC mode is clearly visible on both the magnetic probe and the reflectometer signal in the 100 – 140 kHz range. The magnetic fluctuations drop just after the L-H transition at 0.76 s, then the QC mode appears at 0.79 s and persists throughout the EDA H-mode.

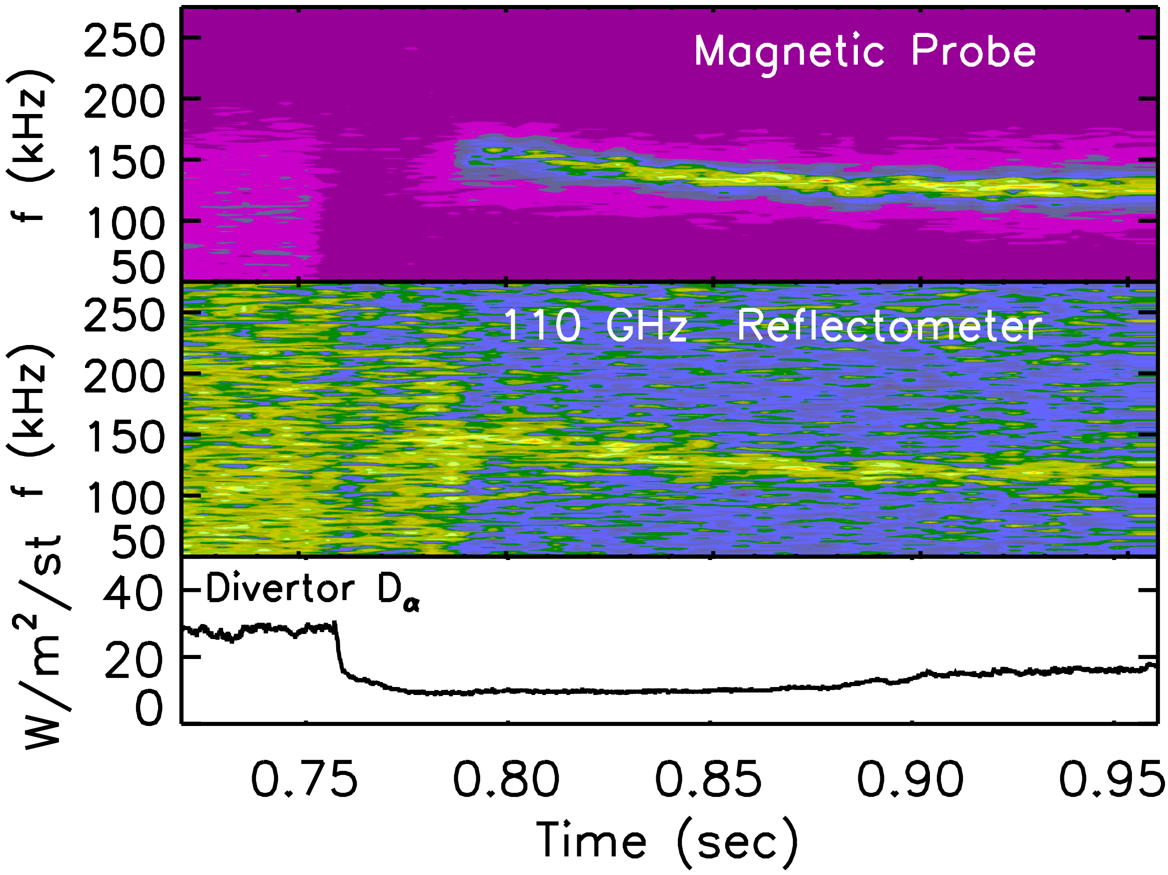

Figure 5. Auto-power spectra versus time of the magnetic probe signal and a 110 GHz edge reflectometer signal during an EDA H-mode. The L-H transition is visible on the divertor D_α signal at 0.76 s. The QC mode appears on both signals at 0.79 s at 150 kHz, then the frequency decreases with time to about 120 kHz. Brighter color indicates larger fluctuation amplitude.

4. Conclusions

Measurements with a fast scanning magnetic and Langmuir probe agree with previous edge reflectometer and Phase Contrast Imaging measurements showing that there is a quasi-coherent mode typically in the 100 – 150 kHz frequency range that is present only during the Enhanced D_α H-mode phase of C-Mod discharges. The amplitude of the magnetic QC perturbation is ~ 5 Gauss extrapolated to the last closed flux surface and it falls off exponentially with radius with a decay length of typically 1.5 cm^{-1}. If the perturbation is field-aligned, the wave-vector tangential to the surface corresponds to a toroidal mode number $n \approx k_\theta R B_\theta / B_\varphi \approx 30$. Due to the highly shaped plasma cross-section, poloidal mode numbers are more difficult to determine. The large magnetic amplitude of the perturbation indicates its strong electromagnetic character. The high mode numbers suggest that it may be a ballooning mode, though no measurements are available to confirm whether or not the amplitude has a ballooning character.

The Langmuir probe measurements localize the QC mode to within the steep gradient region near the LCFS. The floating potential perturbation is observed only within a few mm of the EFIT calculated LCFS. The phase difference between poloidally separated Langmuir probes shows that the mode is propagating in the electron diamagnetic drift direction. The QC mode appears to drive substantial particle flux in the edge with a time-averaged particle flux density of order 4×10^{21} particles/m^2/s, which implies a QC mode-induced particle flux that is the same order as the total fueling rate. This indicates that the QC mode is likely to be responsible for the enhanced edge particle transport in EDA H-mode.

Acknowledgements

The authors would like to thank all the members of the Alcator C-Mod team who have kept the machine running well and without whose help these results would not have been possible. The first author would also like to thank Dr. S. M. Wolfe for valuable discussions.

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