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Structure of the Quasi-Coherent Mode in Alcator C-Mod

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Introduction The Enhanced D_α H-mode (EDA) [1] on Alcator C-Mod has come to be defined by the presence of a short wavelength quasi-coherent mode (QCM) [2] observed in the frequency range of 50 – 250 kHz on density, poloidal field, and electrostatic potential fluctuations, which is believed to be responsible for enhanced particle transport in the edge. This enhanced particle transport keeps impurities from accumulating in the plasma core without the large intermittent heat loads on the divertor produced by large edge localized modes (ELMs) found in other devices. The steep edge pressure gradients in EDA H-mode are calculated to be stable to medium n coupled ideal peeling/ballooning modes when the edge bootstrap current is taken into account [3], suggesting that the QCM is a resistive mode. The QCM has been localized to the foot of the steep gradient edge region through scanning Langmuir probe and reflectometer measurements [4]. The mode structure of the QCM has been measured with toroidally displaced magnetic coils fixed to outboard limiters and with a fast radially scanning pair of poloidally displaced magnetic probes. The measured structure of the QCM compares well with calculations of a resistive X-point ballooning mode using the BOUndary plasma Turbulence code BOUT [5]. Changes in the measured QCM frequency as the H-mode evolves are comparable to either a strong mode coupling to the core toroidal ion rotation or coupling to a weak neoclassical poloidal edge ion rotation.

Scanning Probe Measurements

The poloidal mode structure of the QCM was measured with a pair of poloidally separated (5.6 mm) poloidal field pick-up coils on the end of a fast scanning probe that can be inserted into the plasma edge 10 cm above the outboard midplane. The probe can scan in and out of the plasma in 100 ms or be left to dwell at a fixed radius for the length of the data acquisition fast window (~0.5 s at 1 MHz sampling rate). By scanning the probes, the radial decay of the QCM can be measured, which gives a measure of the radial wavenumber of the mode. The perturbed field decays exponentially with radius from the mode rational surface with a radial wavenumber $k_r \approx 1.2 - 1.5$ cm^{-1}. While the measured RMS perturbed field reaches 0.4 to 1 Gauss, the perturbed field at the last closed flux surface (LCFS) extrapolates to 5 to 6 Gauss.

By setting the probe to dwell at a fixed radius, the phase difference between the two poloidally displaced coils in the probe head gives a continuous measure of the local poloidal mode structure (Figure 1). Initially, the QCM appears at about 200 kHz shortly after the L-H transition with a local poloidal wavenumber of $k_\theta \approx 2$ cm^{-1}. As the H-mode evolves, the QCM frequency decreases to about 85 kHz and k_θ also decreases to about 1.5 cm^{-1}. The poloidal wavenumber estimated from the Phase Contrast Imaging (PCI) diagnostic near the top and bottom of the plasma are found to be 4 – 5 cm^{-1}[6], indicating a poloidal variation of

k_θ given by $k_{\theta_2} = k_{\theta_1} \frac{B_{\theta_1}}{B_{\theta_2}}\left(\frac{R_1}{R_2}\right)^2$, for a field-aligned perturbation with $\vec{k}\cdot\vec{B}=0$. Using EFIT this ratio can be calculated all along the LCFS to yield a flux surface averaged $\langle k_\theta \rangle_\psi \approx$ 4.8 cm^{-1}. For a poloidal circumference given approximately by $C_\theta = 2\pi a\sqrt{\frac{1+\kappa^2}{2}}$, the flux surface averaged poloidal mode number then becomes $\langle m \rangle_\psi = \langle k_\theta \rangle_\psi C_\theta / 2\pi \approx 140$.

Independent measurements with two sets of three toroidally separated (3.8 cm) poloidal field pick-up coils 10 cm above and below the outboard midplane on each of two outboard limiters indicate that the QCM has a range of toroidal mode numbers from $15 < n < 20$ (Figure 2). Within the errors, these independent measurements indicate that the QCM is a field-aligned perturbation resonant in the very edge of the plasma just inside the LCFS but well outside $q_{95} \approx 4$, in agreement with the reflectometer and Langmuir probe measurements.

Calculations with the BOUT code agree reasonably well with the observed mode structure and indicate that $k_\theta \approx 1.3$ cm^{-1} and $n = 24$ for one case. Comparisons of the radial decay of the calculated magnitude of the poloidal magnetic field perturbation at the outboard coil location indicate good agreement with the measured peak RMS value of $\tilde{B}_\theta(wall) \approx 1G$. The good agreement lends confidence that the resistive X-point ballooning mode is a good theoretical description of the mode.

QCM and Plasma Rotation

The local poloidal phase velocity of the QCM on the outboard side, given by $v_\theta = \omega / k_\theta$, changes from about -6 km/s to -3 km/s in the electron diamagnetic drift direction as the H-mode evolves to a steady state in Figure 1. Using instead the flux surface averaged $\langle k_\theta \rangle_\psi$, the flux surface averaged change in the phase velocity becomes $\langle \Delta v_\theta \rangle_\psi \approx 1.1 \times 10^5$ cm/s. Assuming the QCM frequency is shifted by the rotation of the bulk plasma ions, this can be compared to the edge neoclassical ion poloidal rotation velocity given approximately by [7] $v_{\theta i}^{neo} \approx \frac{1}{2} v_{Ti} \rho_i \frac{K_1}{L_T}$, where $v_{Ti} = \sqrt{2T_i / m_i}$, $\rho_i = m_i c v_{Ti} / (Z_i e B)$, $L_T^{-1} = d \ln T_i / dr$ and K_1 is a coefficient of order unity that is negative (ion rotation direction) above a collisionality of $\nu_{*i} \geq 5$, for the low impurity fractions of C-Mod ($Z_{eff} \approx 1.5$). Using 1 mm radial resolution edge Thomson scattering data, the neoclassical ion poloidal rotation scales quantitatively in the same way, as a function of time, as the QCM frequency when $K_1 \approx -0.18$, for a calculated edge $\nu_{*i} \approx 6$. Since the toroidal rotation in the edge is small, based on Mach probe measurements, the change in the QCM frequency and the flux surface averaged $\langle m \rangle_\psi$ can be used to calculate the change in the poloidal rotation velocity $\Delta v_{\theta mag} = C_\theta \Delta f_{QCM} / \langle m \rangle_\psi$.

The poloidal rotation determined from magnetic fluctuations is compared to the neoclassical poloidal ion rotation $v_{\theta i}^{neo} / K_1$ (Figure 4). The slope of the fit then gives $1/K_1$, which yields K_1 = - 0.15, which is very close to the value calculated in Ref. 7 for these collisionalities.

If, on the other hand, bulk plasma ion poloidal rotation is taken to be zero, the change in the QCM frequency could be due to strong coupling to the core toroidal plasma rotation, even though the edge plasma does not rotate toroidally, in much the same way that edge m=4, n=1 modes are coupled to m=1, n=1 sawtooth precursors and rotate with the core ion toroidal rotation velocity [8]. Then, the change in QCM frequency would be given by $\Delta f_{QCM} = \Delta v_{\varphi i} n/(2\pi R)$, where $\Delta v_{\varphi i}$ is the change in the ion toroidal rotation velocity. Figure 4 shows that Δf_{QCM} is proportional to the core $\Delta v_{\varphi i}$ from x ray crystal spectrometer measurements of injected argon impurities, but the n number given by the slope is $n_s \sim 8$, which is much lower than the measured n numbers of 15 < n < 20. So, the change in QCM frequency corresponds to typically 40% of the core ion toroidal rotation velocity.

Another possible explanation of the change in QCM frequency could be a change in the $\vec{E} \times \vec{B}$ velocity due to a change in the radial electric field as the steep gradient of the initial ELM-free H-mode relaxes somewhat in EDA H-mode, which would reduce the frequency in the electron direction. However, evidence from some EDA discharges where the edge gradient relaxes substantially due to impurities shows an increase in QCM frequency. Both the measured toroidal and the calculated neoclassical poloidal ion rotation track these changes in QCM frequency. In some EDA H-modes with internal transport barriers, however, the core toroidal ion rotation velocity changes sign from the ion to the electron direction in the middle of the EDA phase [9] and yet the QCM frequency does not track the toroidal rotation and remains approximately constant after the initial drop in frequency just after the L-H transition, while the calculated neoclassical poloidal ion rotation tracks the change in QCM frequency. The QCM frequency also changes by up to 40% in phase with large sawteeth, dropping at the sawtooth crash and increasing with the rise of the core temperature.

Conclusions

The QCM in EDA H-mode has a short wavelength with flux surface averaged poloidal mode numbers $130 < \langle m \rangle_{\psi} < 150$ and toroidal mode numbers 15 < n < 20. The measured change in QCM frequency agrees well with neoclassical predictions of a relatively small poloidal rotation velocity of 1 – 2 km/s in the ion direction in the high collisionality steep gradient edge region. The change in QCM frequency could also be explained by a frequency shift of about 40% of the core toroidal rotation frequency due to some strong mode coupling effect, but the QCM frequency does not track the toroidal rotation in some ITB discharges.

References

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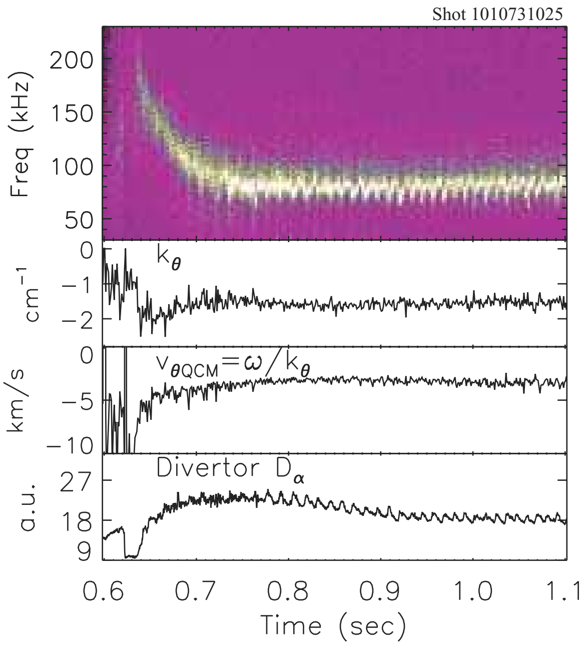

Fig. 1 Poloidal wavenumber and phase velocity from the double magnetic scanning probe dwelling 1.5 cm outside the LCFS. Note the change in QCM frequency from about 200 kHz to 80 kHz as the H-mode evolves.

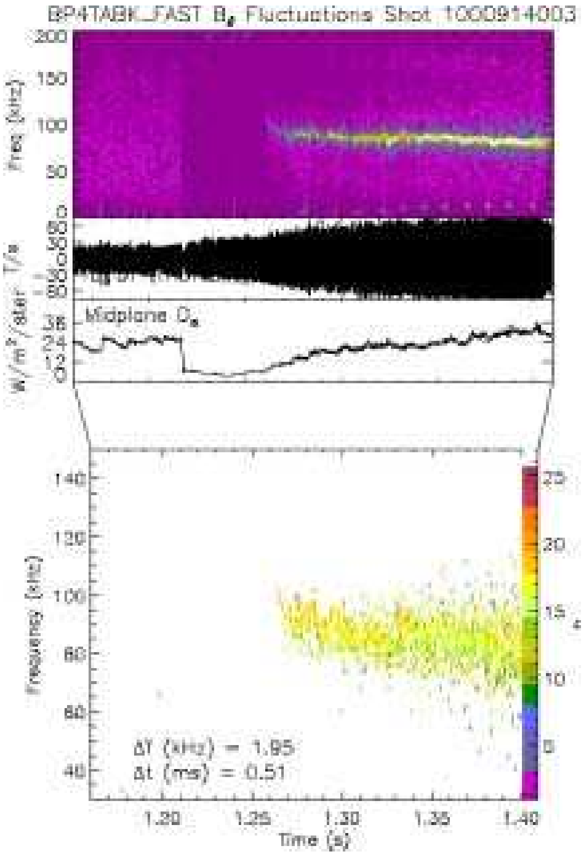

Fig. 2 Toroidal mode number color spectrum of a QCM show 15 < n < 18.

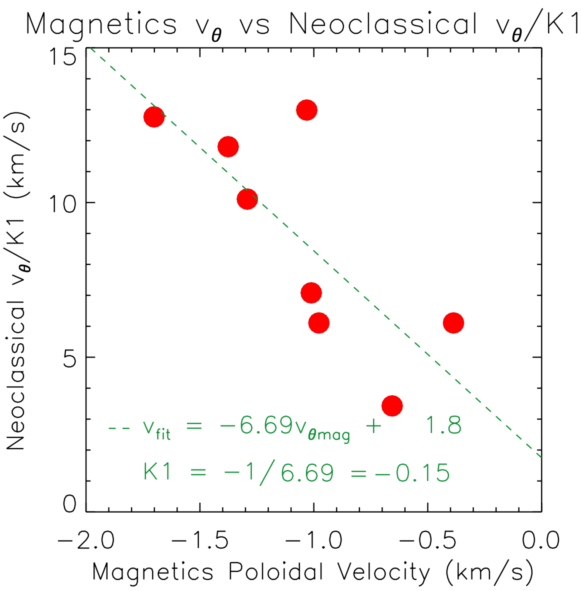

Fig. 3 Neoclassical poloidal velocity divided by the K1 parameter increases linearly with the poloidal velocity calculated from magnetic fluctuation measurements.

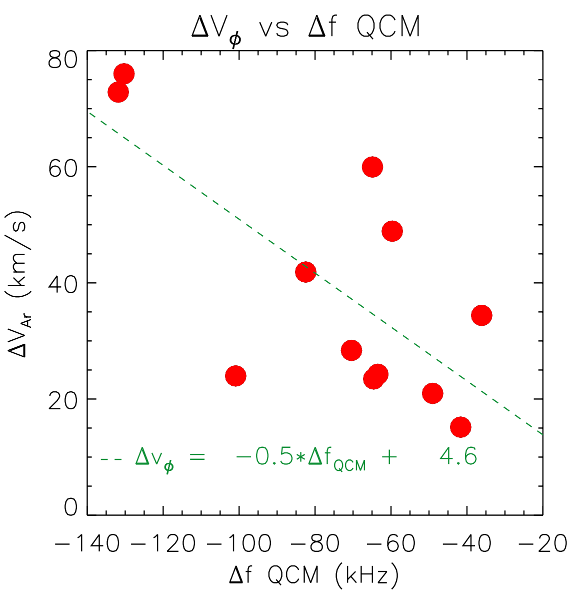

Fig.4 Change in Ar toroidal rotation velocity scales with change in QCM frequency.