Multi-Diagnostic Study of the QC Mode on Alcator C-Mod

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QCM Diagnostics

Phase Contrast Imaging (PCI)
chord-integrated $n_e$ fluctuations
($\tilde{n}, k_R, k_\theta$)

Fast Scanning Probe (FSP)

Langmuir Probe
($\tilde{n}/n, \delta \phi / \phi, k_\theta, \Gamma_n, R$)

Reflectometry (REF)
Measures $n_e$ fluctuations at midplane ($\tilde{n}/n, R$).

Magnetic Probe
($\delta B_\theta / B_\theta, k_\theta, R$)

Four tips

3.8 mm

5.9 mm

Two coils

Flux Surface

Fast Scanning Probe (FSP)

B-field

North

West

East

South
Magnetic Pick-Up Coils (MPC)
Measure fluctuations in B.
Different toroidal locations \((k_\phi, n)\).

Fast Diode Array (FDA) Measures \(D_\alpha\) fluctuations.

High radial resolution \((R, k_R)\).
\(D_\alpha\) fluctuations are dependent on \(\tilde{n}_e\).
QCM Diagnostics (cont’d)

Beam Emission Spectroscopy (BES)
Measures $n_e$ and $D_\alpha$ fluctuations ($\bar{n}/n$, $k_\theta$, $k_R$, $R$).

Electron Cyclotron Emission (ECE)
Usually measures $T_e$. Sensitive to $n_e$ in edge due to optical thinness.

Light collection cones see light from Hydrogen DNB as well as ambient $D_\alpha$. Can be used with BES channels to measure $k_\theta$. Views vary with $B$. 32 channels.
Location (R), Width (ΔR), and Amplitude (δn/n, δφ/φ, δB/B)

**Measure**
- δn/n, δφ/φ
- R, ΔR
- δB/B

**Calculate/Relate**
- Particle flux
- QCM to $\nabla P$, B-curvature
- EM character

**Conclude**
- QCM’s role in steady-state
- Type of instability behind QCM
QCM Measured in $D_\alpha$

EDA and QCM begin

Beam On

Beam in $D_\alpha$

Beam on FFT (.77-.80s)

Beam off FFT (.80-.83s)

BES detects mode in both beam and background light. Both can be used to constrain mode location.

QCM in background

QCM Mode

$<R_{\text{mid}}>$

FWHM = 5 ± 3 mm. $\tilde{n}_e/n_e \sim 26\%$. 

Sampsell, APS '02

PCI Data

BES Data

FFT v. Time

1021024013, 0.772s, Ch. 3
QCM Width, Amplitude, Location

**RF EDA**
- Amplitude is peaked at or just inside separatrix
- FWHM = 4 ± 0.3 mm.

**Ohmic EDA**
- FWHM = 1 ± 0.2 mm.
- $\tilde{n}_e / n_e \sim 35\%$.

**Reflectometer**
- FWHM ~ 1.3 ± 0.2 mm.
- $\tilde{n}_e / n_e \sim 30\%$.

Abel-inverted profile

**Terry, APS ‘03**

**Y. Lin, RR ‘01**

**Fast diode array (FDA) data**

**Reflectometer**

**Probe data**
FDA and BES both see non-zero coherence amplitude ~7 mm outside of separatrix. Consistent with particle transport.
Frequency (f) and Phase Differences ($\delta \phi_{\phi,\theta,R}$)

Wave-numbers and phase velocities $k_{\phi,\theta,R}, v_{\phi,\theta,R}$

Measure $f, \delta \phi_{\phi,\theta,R}$

Calculate/Relate

Type of instability driving QCM

Interplay of edge rotation, flows, shear, and transport

Coupling of edge and core rotation

Conclude
QCM Frequency Coupled to Rotation?

QCM frequency is often correlated with central rotation.

Sweeping from/to higher frequency at transitions.

Increase in core rotation typical at transition into H-mode.

Magnetic Probe Data

QCM frequency may be physically tied to edge rotation. Some rotation data and theory suggest edge and core rotation are often coupled. The QCM phase velocities are from the pedestal region, where high shear is expected.

Snipes, APS ‘02
Large poloidal correlation length allows cross-diagnostic cross-correlations between BES and ECE. This gives extensive $k_\theta$ vs $\theta$ about the midplane.

$k_\theta$'s at midplane fall into 0.8 - 2.0 cm$^{-1}$ range, $v_\theta$'s in 3 - 5 km/s range. $v_\theta$ falls in between core and SOL rotation velocities, consistent with shear.

Flux surface constrained ($k \cdot B = 0$) propagation predicts less $k_\theta$ variation
Comparisons of BES and PCI Data

Data from PCI chords used to calculate $k_R$’s. Top/bottom flux surface angles give $k_\theta$’s.

Need runs with multi-diagnostic presence to see shot-to-shot variation. Scanning probe, measuring at $z = +10$ cm, could help.
QCM Caused by Resistive Ballooning Instability?

Gyrokinetic “flux tube” simulations (GS2) [1], non-linear sims. of ballooning turbulence [2], and most recently BOUT simulations [3] all indicate that ballooning could produce QCM.

Comparing to Simulations

Compare QCM width vs. pedestal width
- theory and some measurements suggest they’re comparable, other measurements find a narrower QC

Look for high frequency companions, such as predicted by BOUT
- digitization rate is being increased to 3+ MHZ for several of the diagnostics

BOUT: x-point ballooning
Instability drives QCM-like osc.
⇒ beats against an e-GAM
⇒ Alfvén wave (δφ osc.)

Summary and Next Steps

Summary

Amplitude ($\tilde{n}/n$): Max $\tilde{n}/n$’s at ~25-35%

Location (R): 1-5 mm inside LCFS

Width ($\Delta R$): REF, FSP ~ 1-2 mm
FDA, BES ~ 4-5 mm
Consistent with gradient

Outside LCFS: REF, FSP ~ 1-2 mm
FDA, BES ~ 7 mm
Consistent with transport

Frequency ($f$): Correlated with rotation

Velocity ($v_\theta$): Consistent with shear

Wavenumber ($k$): Largely follows flux expansion. Near-midplane measurements still to be resolved.

Next Steps

Improved particle loss measurements and calculations (both for plasma and for QCM).

Collect simultaneous R/$\Delta R$ data, refine $\Delta R$ analysis. Establish R/$\Delta R$ scaling with pedestal.

Study poloidal & toroidal phase velocities, coincident with rotation measurements. Compare to simulated QCM phase velocities.

More QCM with multi-diagnostic presence, especially those with poloidal separation. Look at scalings with plasma shape.
An Enhanced D$_\alpha$ (EDA) H-mode is a steady-state, high confinement regime of the C-Mod tokamak. It is characterized by:

- Rise in edge D$_\alpha$ emission (relative to other H-modes)
- “Clamping” of density accumulation
- No ELM’s.
- Strong reduction of impurity accumulation
- ~ 10-20% decrease in energy confinement
- An oscillation in the edge density, electric potential, and magnetic field. Called the Quasi-Coherent Mode (QCM), this oscillation corresponds strongly to, and may be responsible for, the increased particle transport that allows the H-modes to maintain steady-state confinement.

Greenwald, APS ‘00