I-mode regime and characterization of the Weakly Coherent Mode (WCM) in Alcator C-Mod

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Summary

I-mode plasmas in Alcator C-Mod

- Enhanced energy confinement with L-like particle confinement
- Low impurity confinement

I-mode is characterized by changes in edge fluctuations:

- A Weakly Coherent Mode (WCM) and a broadband fluctuation suppression
- WCM is localized close to the Te pedestal ($0.95<r/a<1$)
- WCM and Quasi-coherent mode (signature of the Enhanced Dα (EDA) H-modes) have similar radial localization and k_θ but different frequency ramp up. Er well in EDA H-modes is much deeper than in I-mode.
- Broadband suppression is seen to correlate with thermal diffusion at the edge.

Conclusions

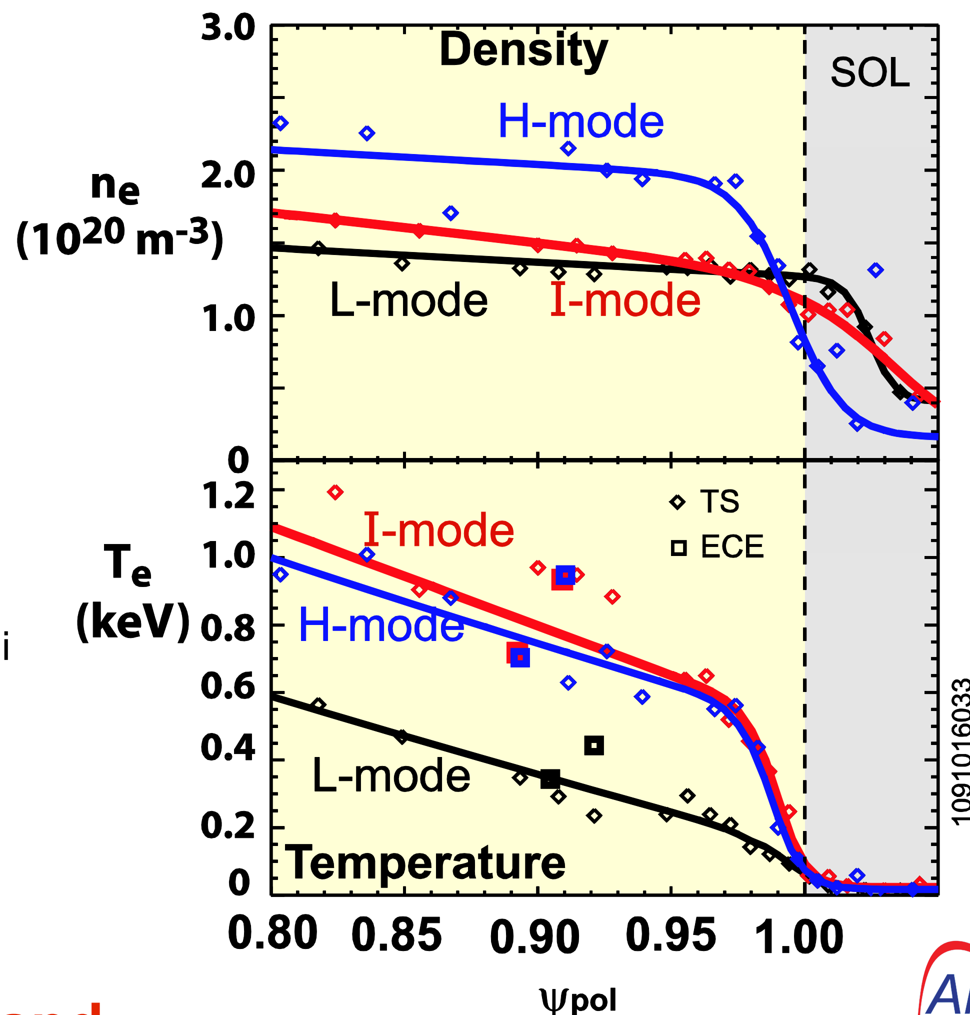
I-Mode regime is characterized by H-mode like energy confinement and L-mode like particle confinement

Low particle confinement

- No density pedestal formation
- Little to no rise in <ne>

Enhanced energy confinement

- $T_{e,i}$ pedestal formation
- Profile stiffness → Core $T_{e,i}$ increase
- $T_{e(ped)}$ measured above 1keV



Whyte, Nucl. Fus.
Hubbard, PoP

Alcator C-Mod

Good case study for energy and particle channel separation.

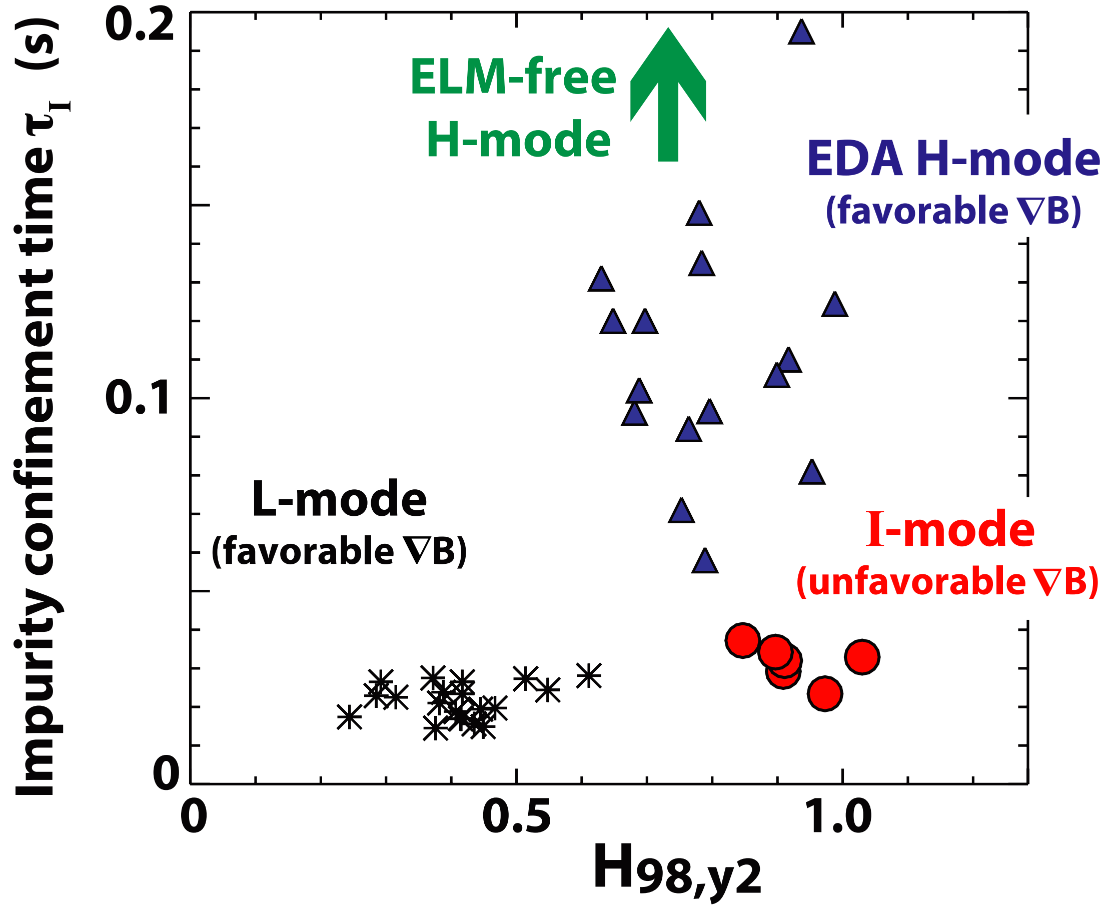
I-Mode impurity confinement is low which is desirable for a reactor regime

Using CaF_2 impurity laser blow off, impurity confinement time has been measured in I-mode plasmas.

I-mode impurity confinement time is similar to L-mode. Lower than EDA H-Mode, and much lower than ELM-free H-mode

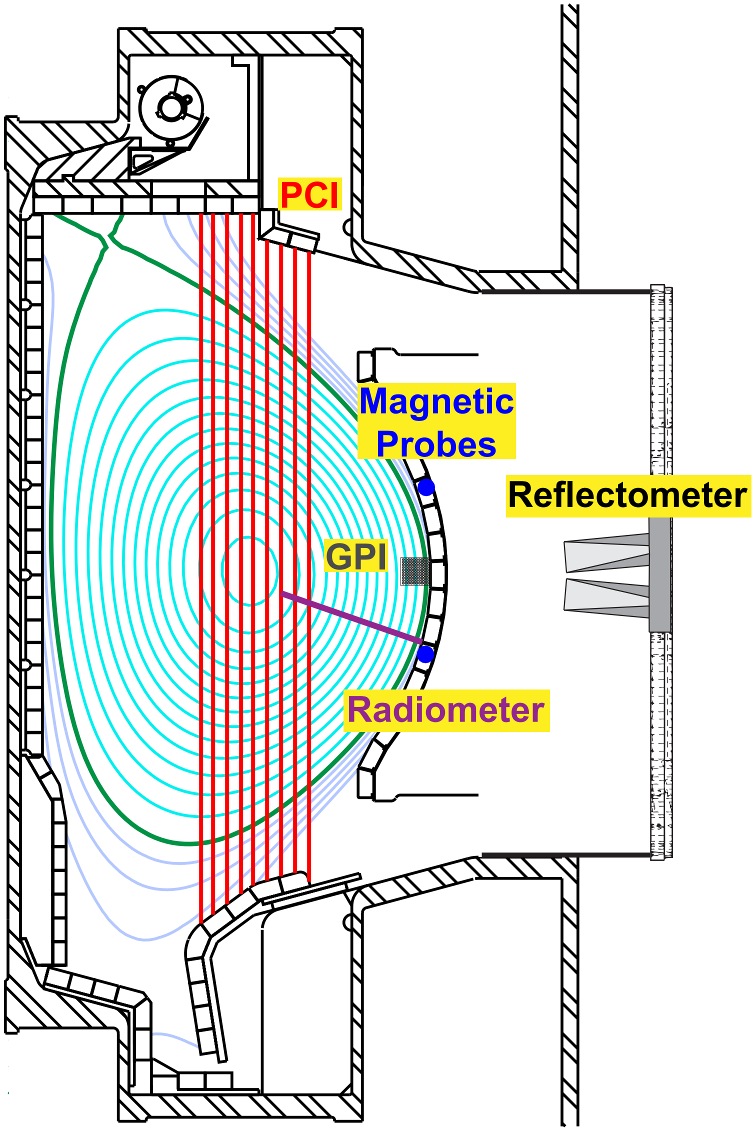
I-modes have been sustained for many confinement times (>10τ_E)

Energy confinement quality measured by H_{98} is equal and greater than H-mode



Impurity transport in L and I-mode plasmas:
N.T. Howard, Core working session, 10:20AM

C-Mod has a comprehensive set of edge fluctuation diagnostics



$\tilde{n}_e/n_e$:

local:

Multichannel reflectometer:
amplitude, power spectra

Gas Puff Imaging (GPI):
2D, amplitude, power spectra, wavenumber spectra

line integrated:

Phase Contrast Imaging (PCI):
amplitude, power spectra, wavenumber spectra

$\tilde{T}_e/T_e$:

High resolution ECE radiometer:
local,amplitude, power spectra

$\tilde{B}_\theta/B_\theta$

Fast magnetic probes:
amplitude, power spectra
toroidal and poloidal mode numbers

Alcator C-Mod

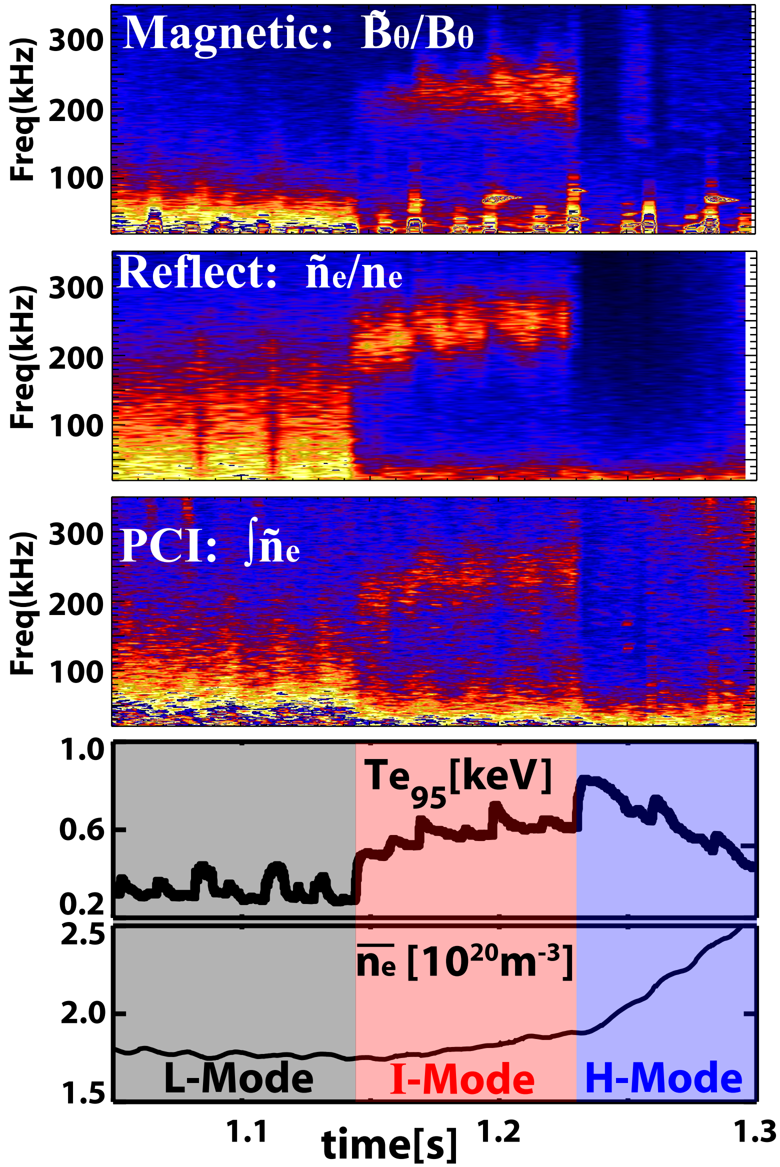
Changes in fluctuations correlate with regime transitions

Weakly Coherent Mode (WCM)

- Fluctuation enhancement seen for f_{cent}~200kHz [100-350kHz]
- Fairly broad ($\Delta f/f_{cent}$~0.5) as compared with other MHD modes seen on C-Mod
- Abruptly disappears at I-H transition

Broadband fluctuation suppression

- $\tilde{B}_\theta$ and $\tilde{n}_e$ decrease observed in the 50-150kHz range.



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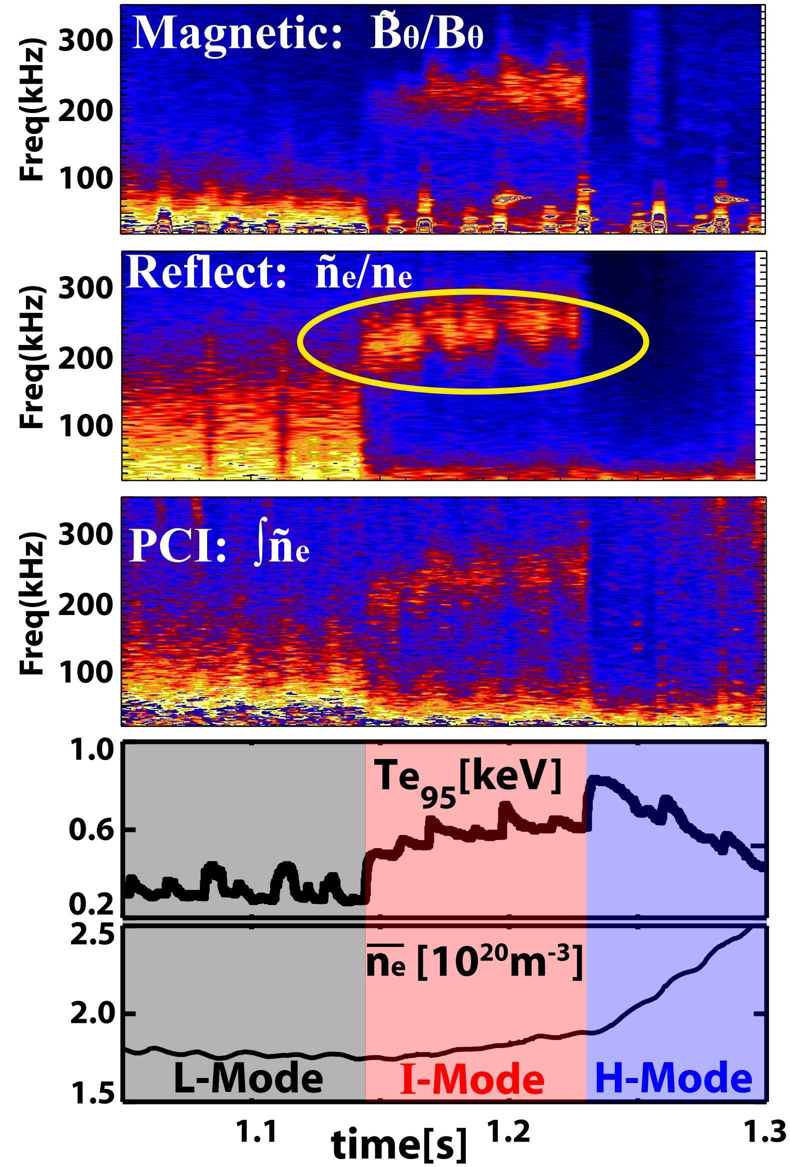

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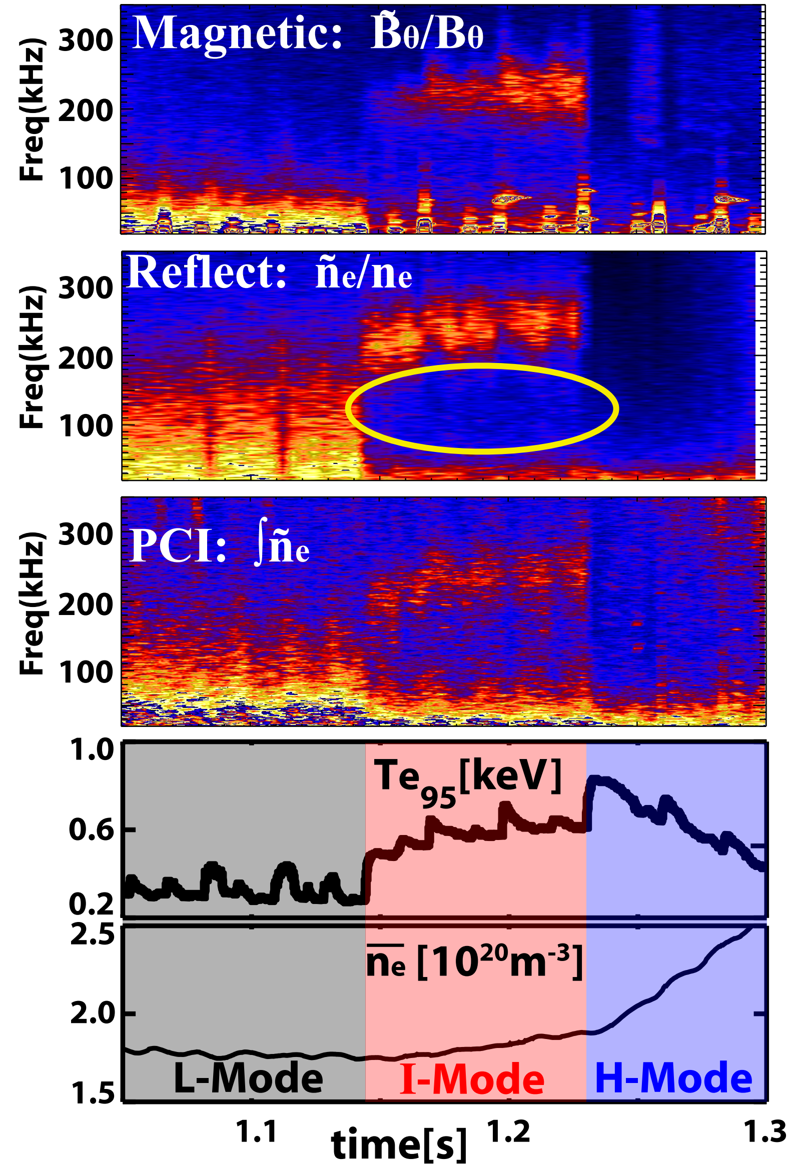

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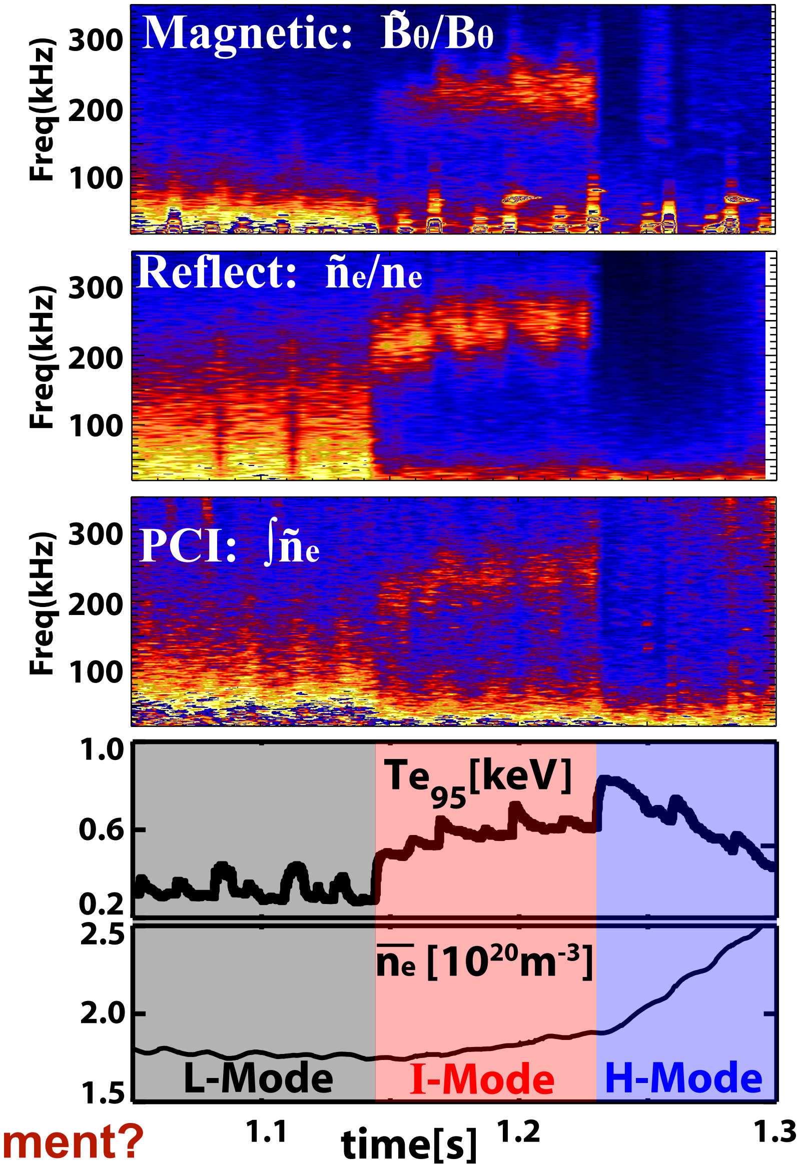
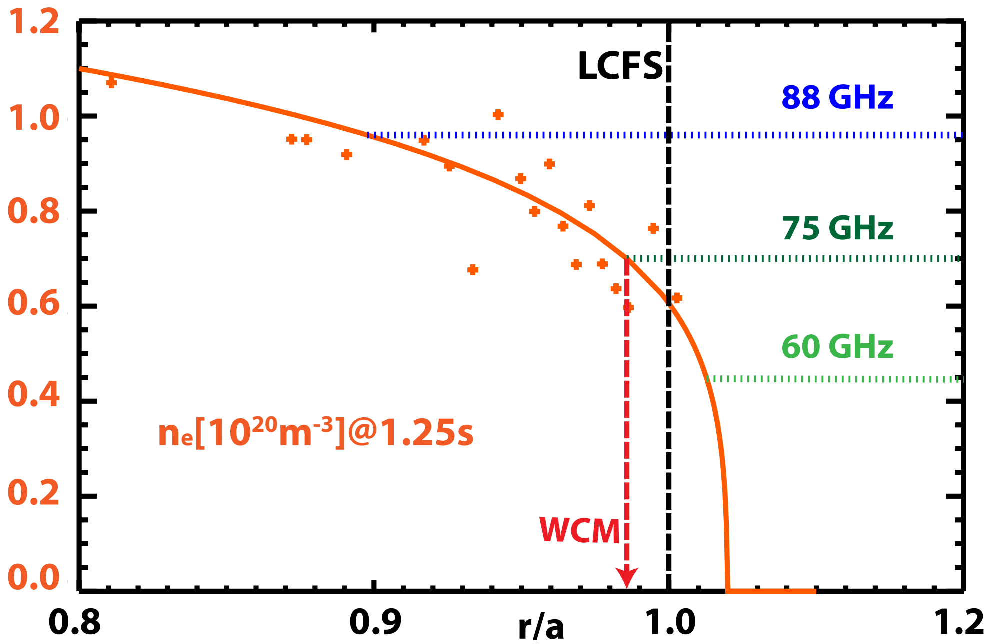


Open question: What is the relationship between these phenomena and I-mode global transport?

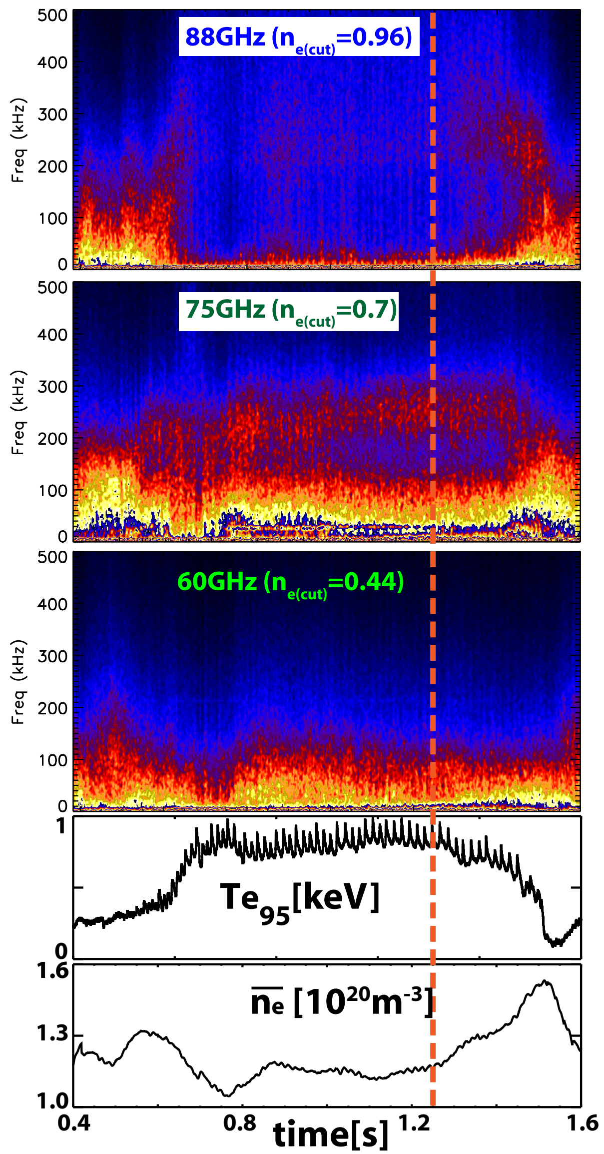
WCM → Particle transport?
Broadband suppression → Enhanced energy confinement?

WCM has been localized at ~0.95<r/a<~1

Reflectometry can be used to radially localize the WCM.
Typically, WCM is observed within ~1cm inside the LCFS
For a=20cm: ~0.95<r/a<~1



GPI has also been used to localize the WCM to the same location of ~0.95<r/a<~1



WCM k_θ~$2cm^{-1}$ in the electron diamagnetic direction

- From GPI and PCI: **k_θ~$2cm^{-1}$ in the electron diamagnetic direction** for all q_{95}

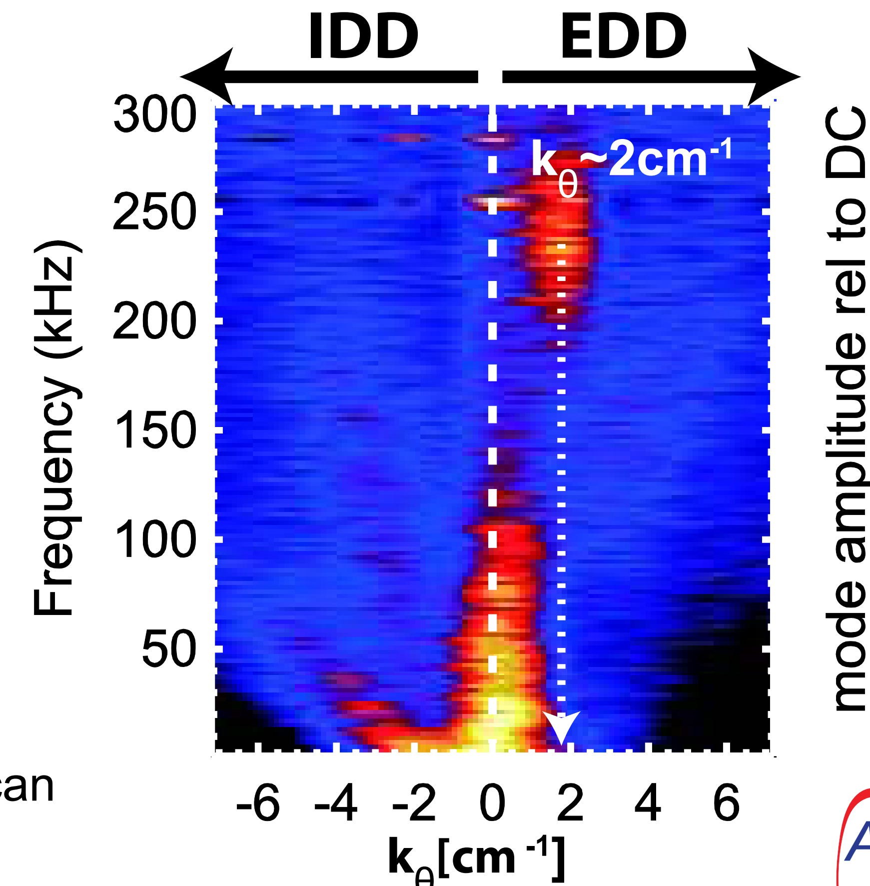
- Using toroidally separated magnetic probes, the k_Φ is measured in the counter-current direction, this is consistent with a mode where:

$$\vec{k} \cdot \vec{B} \sim 0$$

- We can then identify m and n values: m/n~3-6 (low/high q_{95})

- Poloidal phase velocities in the lab frame can be estimated: f_{cent}~[100-350]kHz: $V_{ph(\theta)}$~[3-11]km/s

Gas Puff Imaging measurement



Cziegler, TTF2010

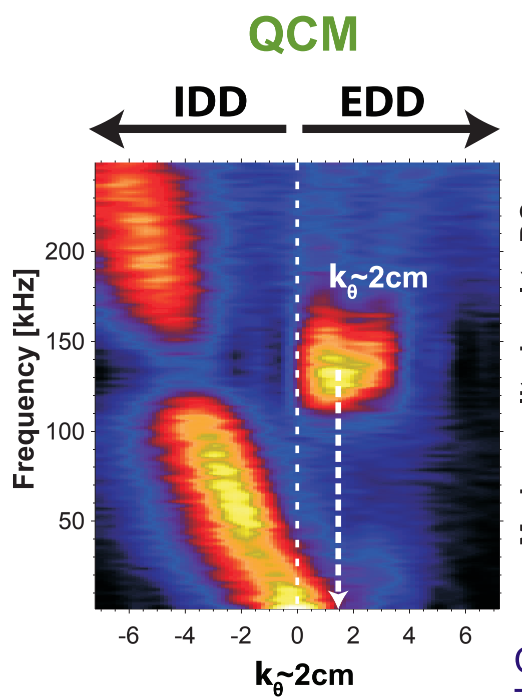
Alcator C-Mod

The WCM has a similar k_θ and radial localization as the QCM.

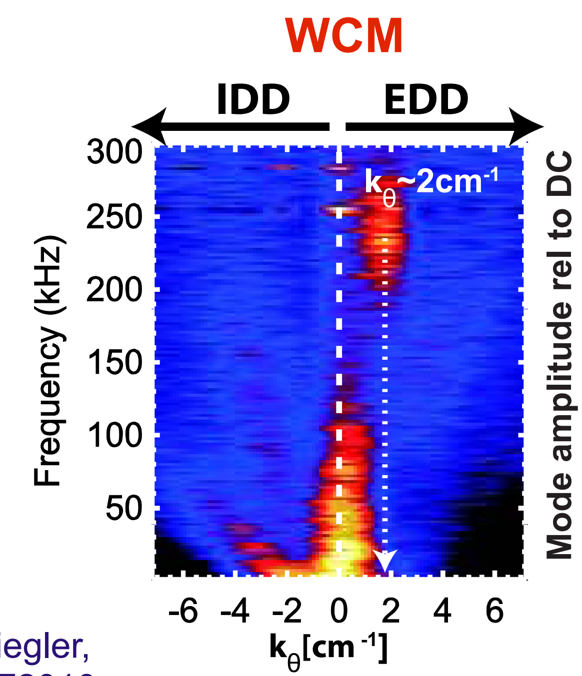
On Alcator C-Mod, the Enhanced Dα (EDA) H-mode is accompanied by a Quasi-coherent mode (QCM)

Similarities between WCM and QCM:

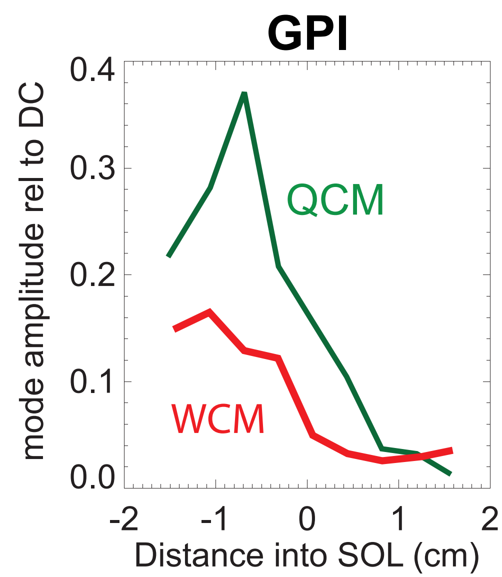
- $k_{\theta(QCM)} \sim 2cm^{-1} \sim k_{\theta(WCM)}$
- Both in the EDD in the lab frame



Cziegler, TTF2010



- Both modes localized near the pedestal region

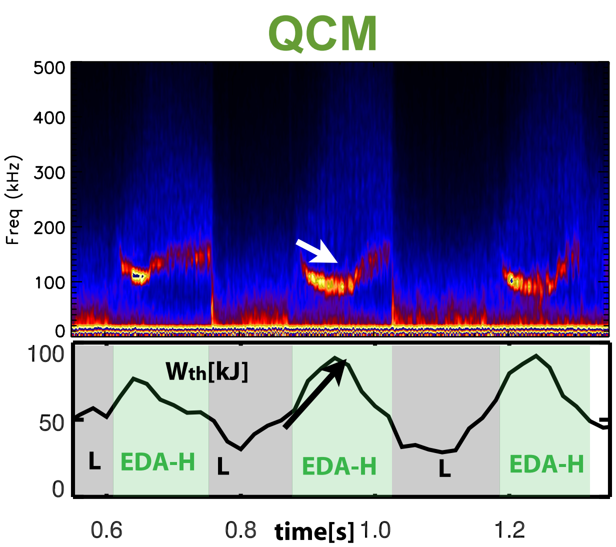


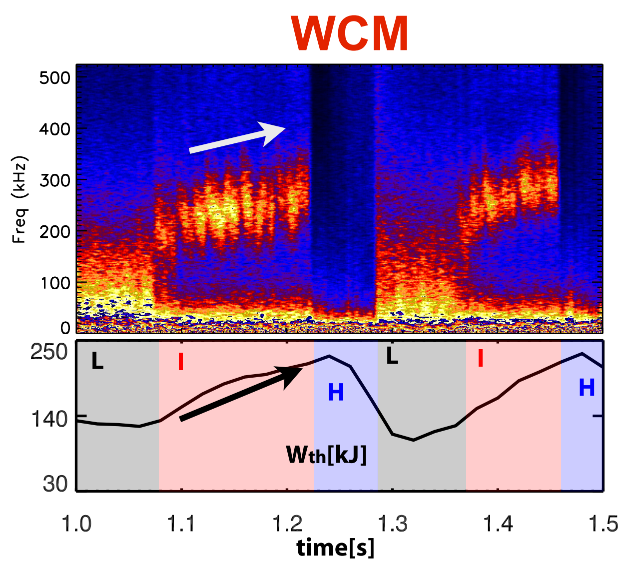
Differences:

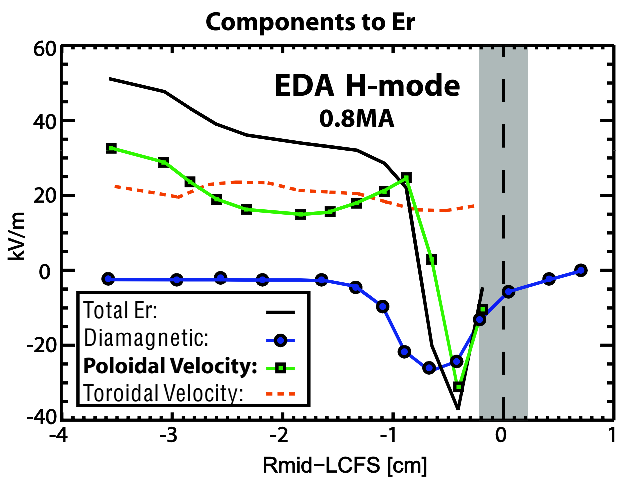
- $\tilde{n}_e/n_{e(WCM)} \sim 7\% < \tilde{n}_e/n_{e(QCM)} \sim 30\%$
- The I-mode lives in a lower collisionality regime:

$\nu^*_{ped(I\text{-}mode)} \sim 0.3 < \nu^*_{ped(EDA\ H\text{-}mode)} \sim 5$

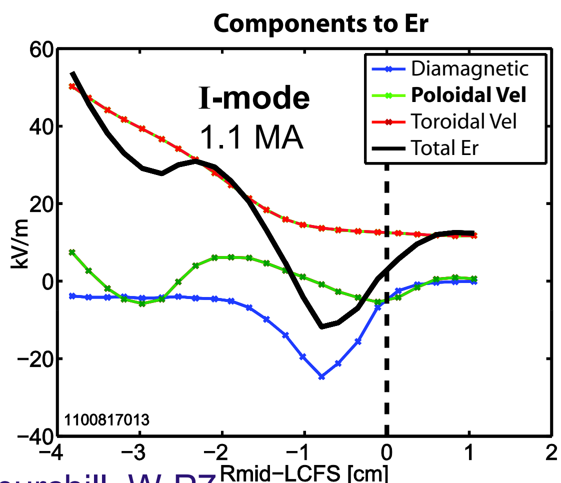
Differences in WCM and QCM frequency ramp up are likely connected to differences in edge Er







McDermott, PoP



Churchill, W-P7
Hubbard, PoP

- typically $f_{cent(QCM)}$ < $f_{cent(WCM)}$
- $\Delta f_{(QCM)}/f_{cent(QCM)}$ < $\Delta f_{(WCM)}/f_{cent(WCM)}$
- Inverse frequency ramp:

$f_{cent(QCM)}$ decreases with W_{th}

$f_{cent(WCM)}$ increases with W_{th}

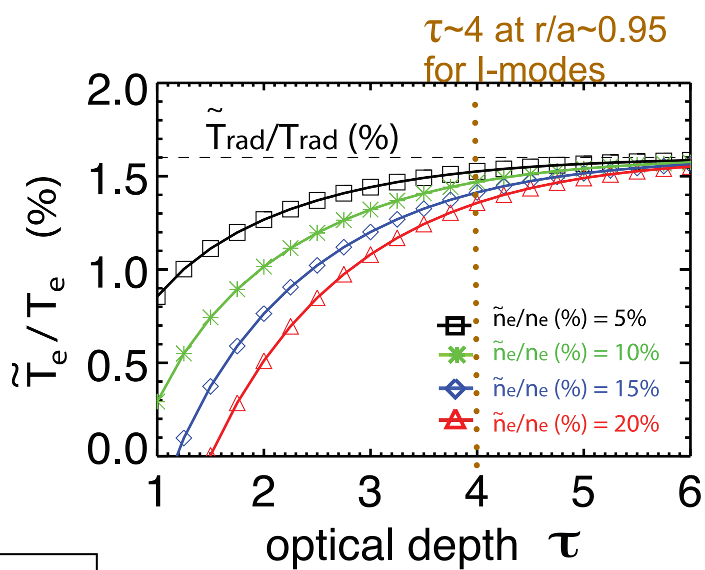
Using boron charge exchange recombination spectroscopy, edge Er terms have been measured:

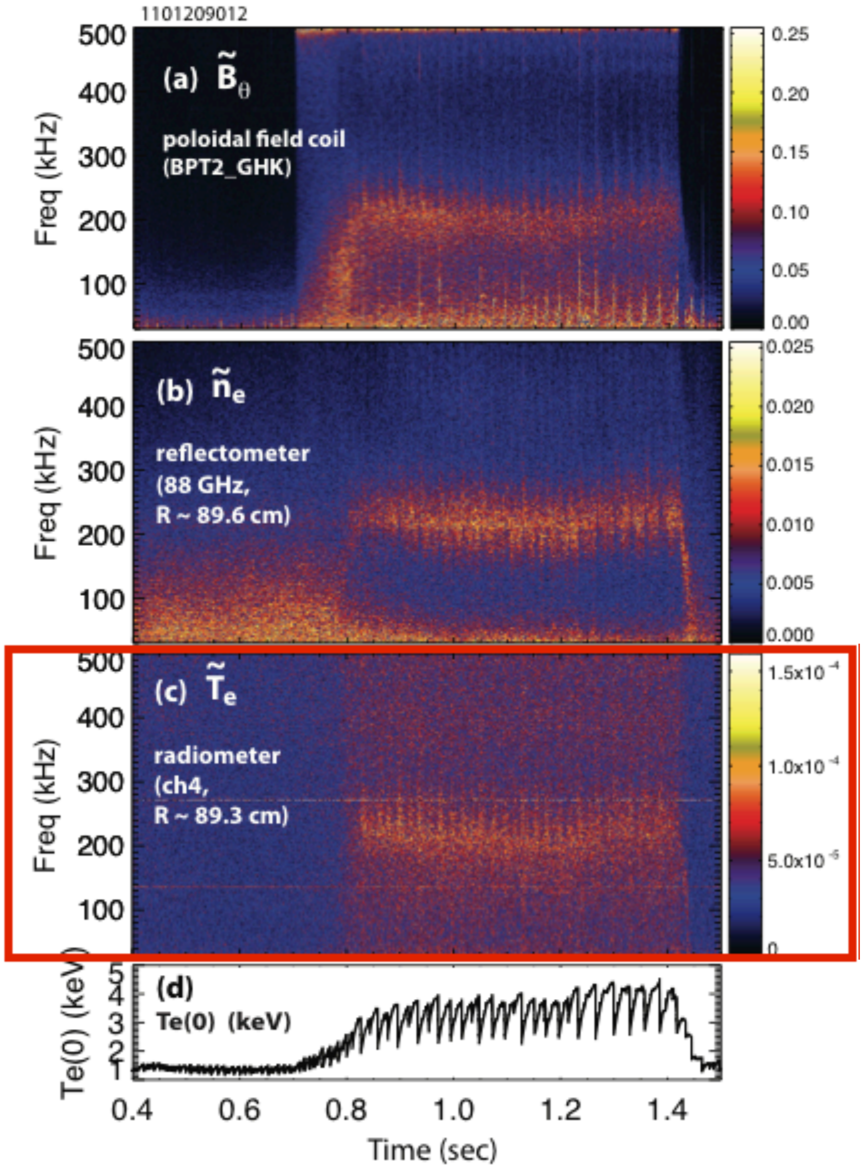
- EDA H-Mode develops a large Er well, such that:
- $v_{ExB(EDA\ H\text{-}mode)}$~10km/s same order as $v_{\theta ph(QCM)}$~3km/s (both EDD)
- I-mode has a moderate Er well with Er~0 at the center
- ExB doppler shift clearly plays larger role in QCM than WCM
- **The differences in the signature modes and pedestal collisionalities set the QCM and WCM clearly apart.**

Measured WCM $\tilde{T}e/Te \sim 1$-$1.5\% < \tilde{n}_e/n_e \sim 7\%$

- WCM Te fluctuations have been observed using a high resolution ECE radiometer
- WCM localized within 1cm inside LCFS (r/a~0.95) where optical depth $\tau \sim 4$.

The $\tilde{T}e/Te$ is then measured confidently in the range: $1\% < \tilde{T}e/Te < 1.5\%$





$\tilde{T}e/Te < \tilde{n}e/ne \sim 7\%$

Consistent with WCM being responsible for particle transport

White, Nucl. Fus., submitted

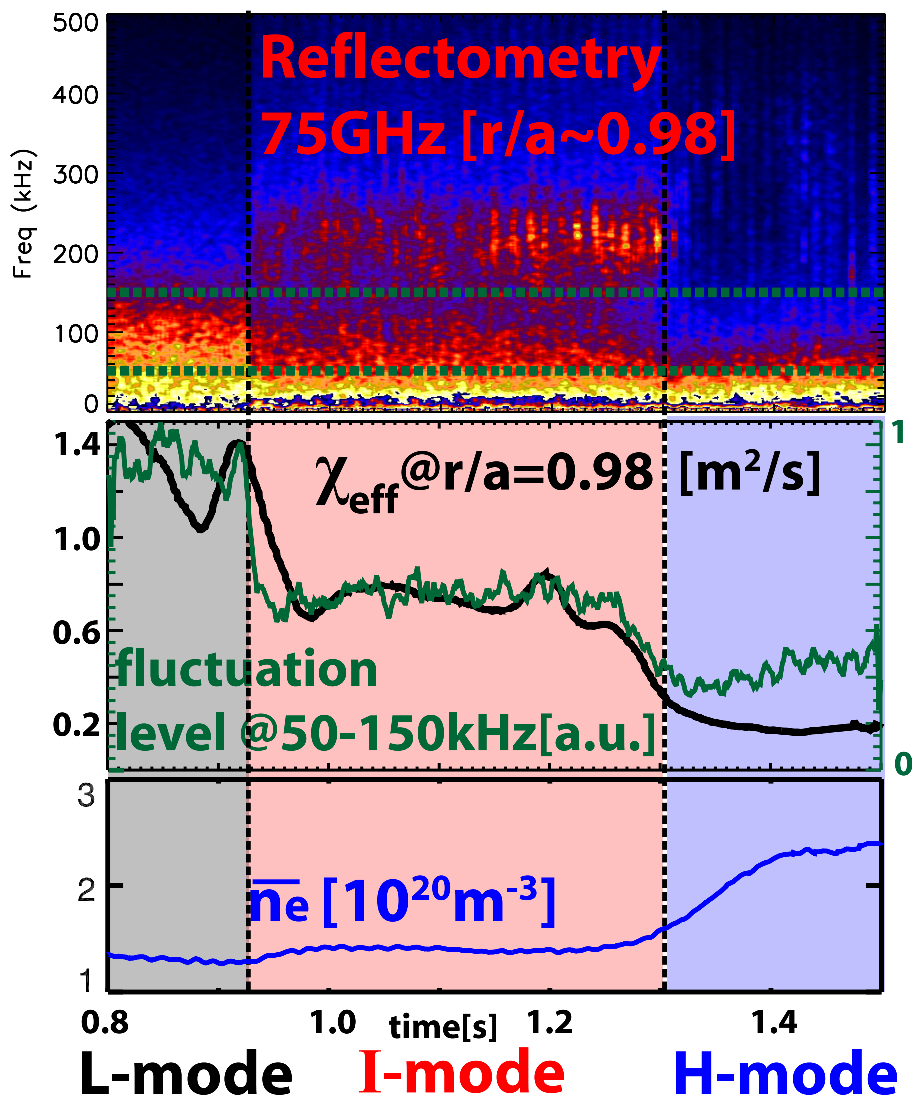
Thermal diffusion at the edge estimated from TRANSP correlates well with fluctuation suppression

Using the power balance code TRANSP:
χ_{eff} at the plasma edge drops at the L-I and I-H transition.

The changes in local thermal diffusion correlate well with decreases in intermediate broadband fluctuations.

$\bar{n}_e$ behavior suggests little change in particle transport in I-L transition.

Analysis of recent experiments plan to provide estimated particle transport across the LCFS



Alcator C-Mod

Conclusions

I-mode regimes have been routinely produced on C-Mod featuring:
High energy confinement, low particle confinement.

Changes in $\tilde{n}e$, $\tilde{T}e$ and $\tilde{B}_\theta$ close to the LCFS accompany the I-mode regime:

- The Weakly Coherent Mode (WCM):
  - radially localized within 0.95<r/a<1
  - f_{cent} ~ 200kHz, f_{FWHM} ~ 80kHz
  - Similar localization and k_θ as QCM but different frequency evolutions likely related to a much weaker Er well in I-mode than in EDA H-mode
  - Observations are consistent with WCM being responsible with maintaining particle transport across LCFS

- Broadband fluctuation suppression (BFS):
  - ~50kHz- ~150kHz range
  - Strong correlation between the BFS and the edge χ_{eff} has been observed coincident with the Te pedestal formation