Progress in Performance and Understanding of Steady ELM-free I-modes on Alcator C-Mod

A. E. Hubbard,
E.S. Marmar, S.-G. Baek, R. M. Churchill, I. Cziegler[1], A. Dominguez, M.J. Greenwald, N. Howard, J.W. Hughes, B. LaBombard, Y. Lin, B. Lipschultz, M.L. Reinke, J.E. Rice, P. Snyder[2], J.L. Terry, C. Theiler, A.E. White, J. R. Walk, D.G. Whyte, S.J. Wukitch and the Alcator C-Mod Team

MIT Plasma Science and Fusion Center

[1]Univ. California, San Diego

[2]General Atomics

EX/1-3, 24th IAEA Fusion Energy Conference,
San Diego, CA, October 9, 2012

Progress in <u>Performance</u> and <u>Understanding</u> of Steady ELM-free I-modes on Alcator C-Mod

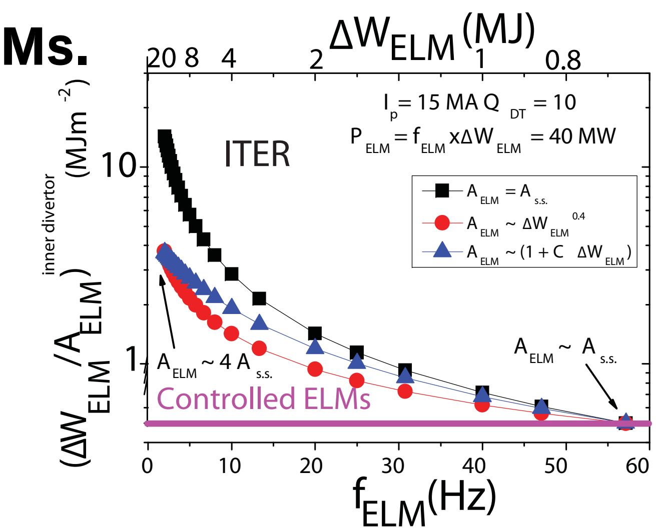
Alcator C-Mod

- **Key features of the I-mode regime.**
- **Progress in performance and duration.**
- **Advances in pedestal turbulence and transport.**
- **Extrapolation of I-mode scenarios to ITER.**

Standard H-mode regime has important drawbacks

Alcator C-Mod

- H-mode features **simultaneous formation of edge density and temperature barriers** or “pedestal”.
- **Energy confinement** roughly doubles over L-mode, a major advance which has made it the standard operating regime for present tokamaks.
- BUT, increased **particle confinement** leads to some serious issues:
  1. **Impurities can accumulate**, a particular concern with metallic PFCs, seeding to reduce divertor loading, and for He ‘ash’ – all of which are expected in ITER operation.
  2. **Pedestals rise to stability limit, triggering ELMs.** Edge instabilities are *needed* to expel particles. ELM heat pulses are unacceptable in ITER! **ELM mitigation or avoidance is needed, and a serious challenge, for ITER and *even more for fusion reactors*.** Approaches include RMP, pellets, and ELM-free regimes such as QH-mode.

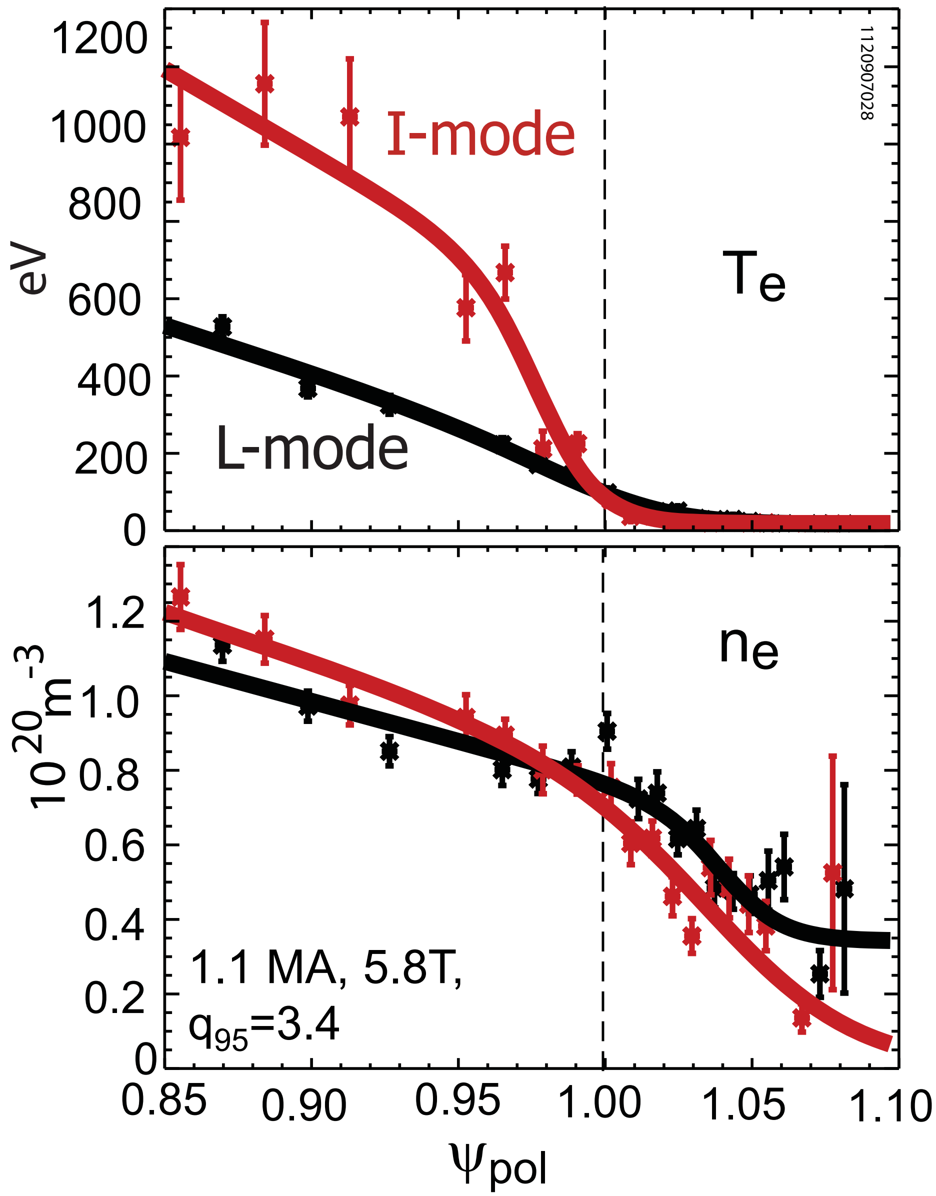


Loarte, FEC 2010

- **An energy transport barrier without a particle barrier (but with controllable density) would be ideal.**

I-mode regime has T_e and T_i pedestal, without density barrier.

Alcator C-Mod



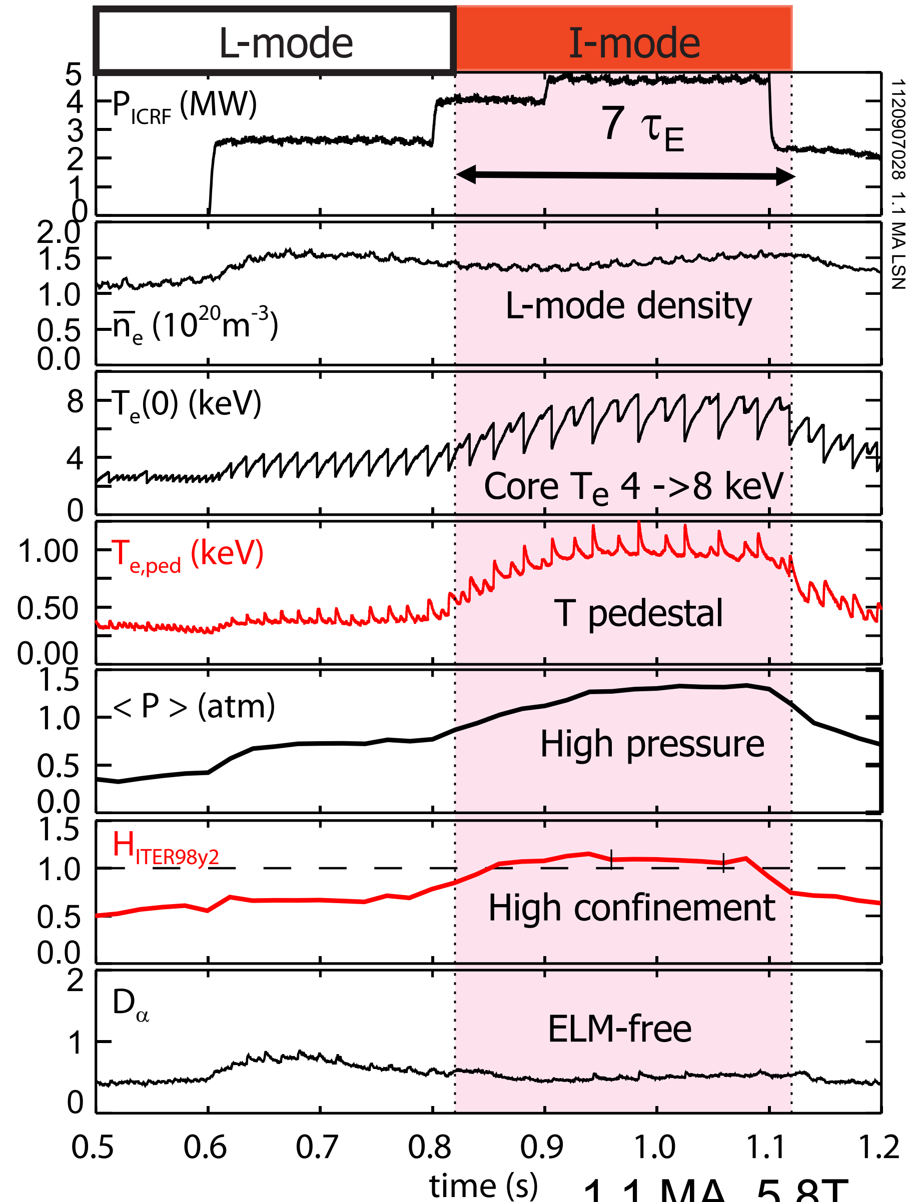
- Steep T_e pedestal – up to 1 keV, ∇T >100 keV/m.
  - T_i pedestals are similar.
- Leads to higher T_e, T_i and pressures across profile.
- L-mode density profile, with broad SOL.

I-mode has also been observed on ASDEX Upgrade. Ryter EPS 2011

A. Hubbard, FEC 2012 EX/1-3

I-mode is a stationary, high energy confinement, ELM-free regime

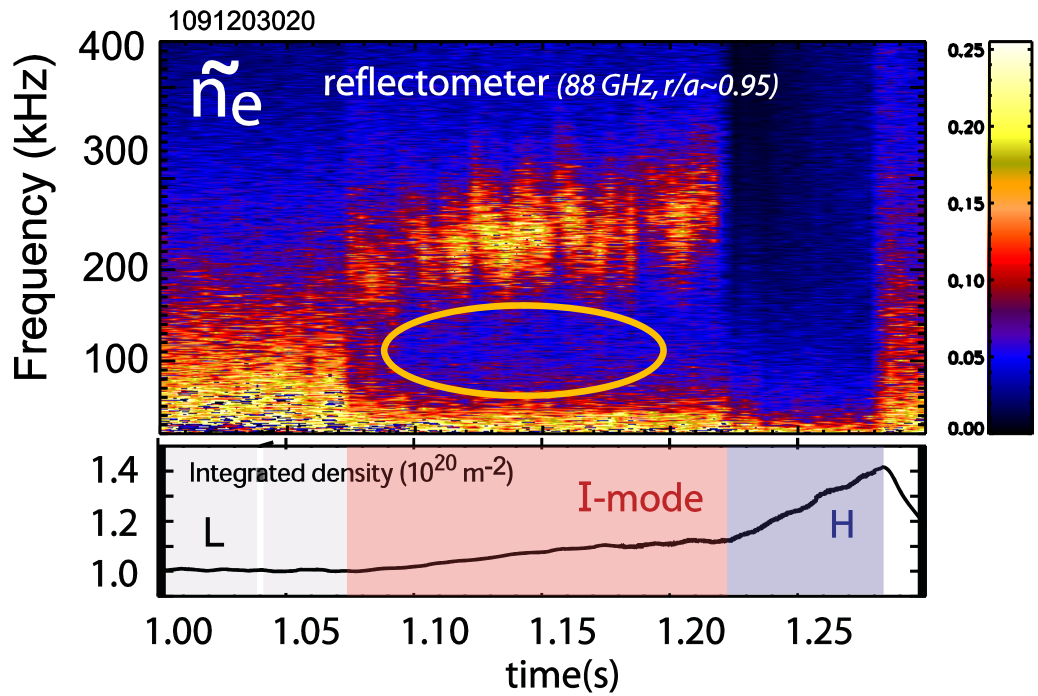
- **Steady I-modes can be maintained for many τ_E,** often limited only by plasma and heating pulse duration.
- Energy confinement is comparable to, can even exceed, H-mode scalings.
  Whyte, Nucl. Fusion 2010
- **I-modes usually ELM-free.**
  - Small ELMs are occasionally seen, but are not needed for steady density and pressure.
- L-mode particle confinement, compatible with high Z PFCs, and with impurity seeding.

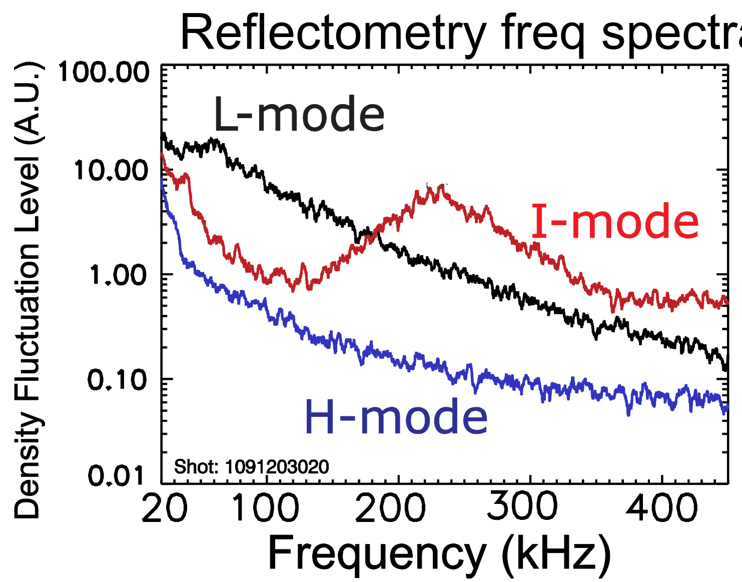


1.1 MA, 5.8T, q_{95}=3.4

Characteristic changes in edge fluctuations at L-I transitions

- As the T pedestal forms, see
  - A DECREASE in edge broadband turbulence (n and B) in mid-f range (~60-150 kHz)
  - Usually a PEAK in turbulence at higher f "weakly coherent mode" (~ 200-400 kHz).
- At the H-mode (particle barrier) transition, remaining turbulence drops suddenly, density rises.





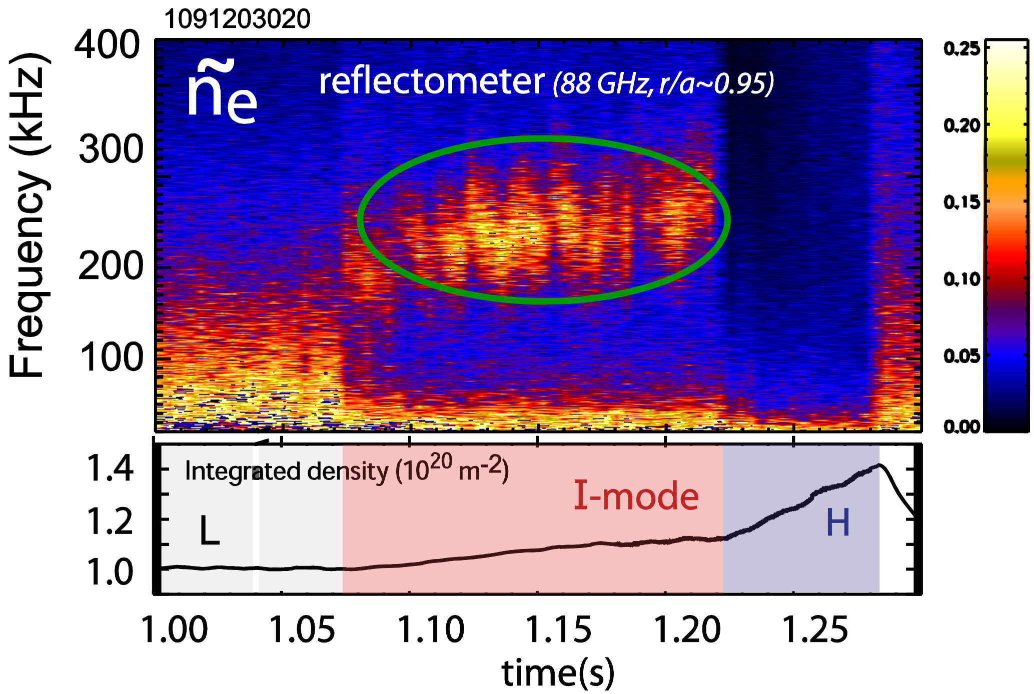
1.3MA, 5.8T
q_{95}=3.1

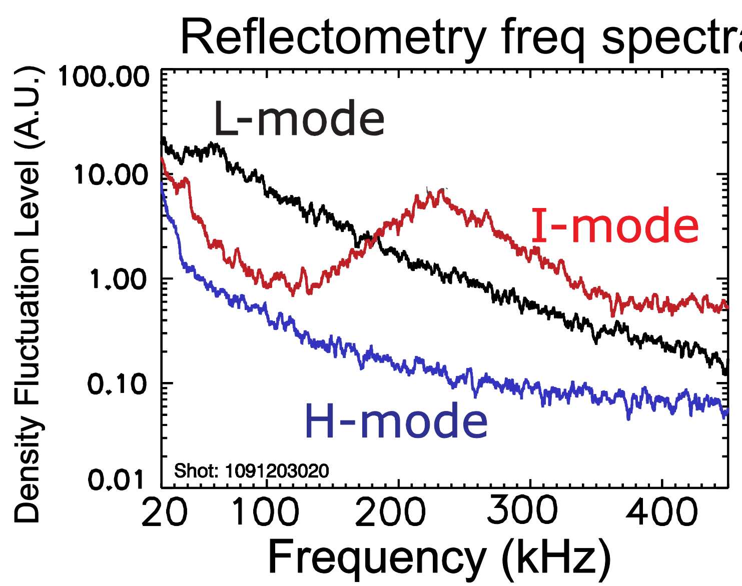
Characteristic changes in edge fluctuations at L-I transitions

Alcator C-Mod

- As the T pedestal forms, see
  - A DECREASE in edge broadband turbulence (n and B) in mid-f range (~60-150 kHz)
  - Usually a PEAK in turbulence at higher f "Weakly Coherent Mode" (~ 200-400 kHz).

- At the H-mode (particle barrier) transition, remaining turbulence drops suddenly, density rises.





1.3MA, 5.8T
q_{95}=3.1

Parameter space for I-mode has been greatly expanded since 2010 FEC

Alcator C-Mod

- Now > 230 I-modes in C-Mod database (vs 90 in 2010), plus >100 more from summer 2012 campaign, which ended a week ago.
- Robust regime, obtained over a wide range of parameters:

I_p = 0.8 -1.3 MA

B_T = 3.0 - 6.1 T

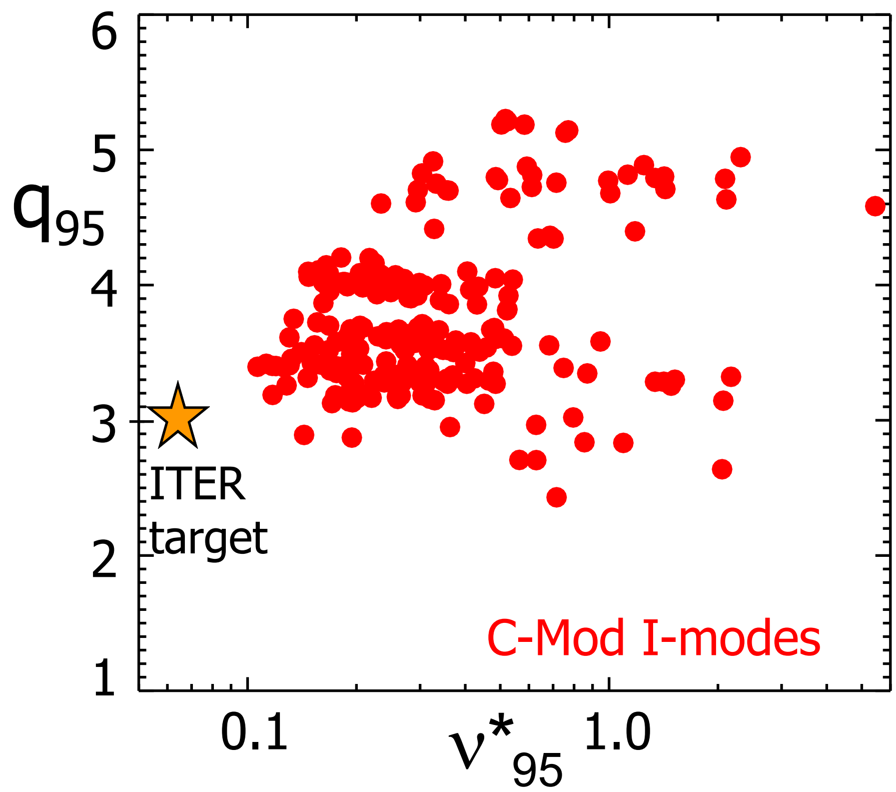
q_{95} =2.5 -5.3

$\bar{n}_e$ =0.85-2.3x10^{20} m^{-3}

ICRF power =1- 5.5 MW

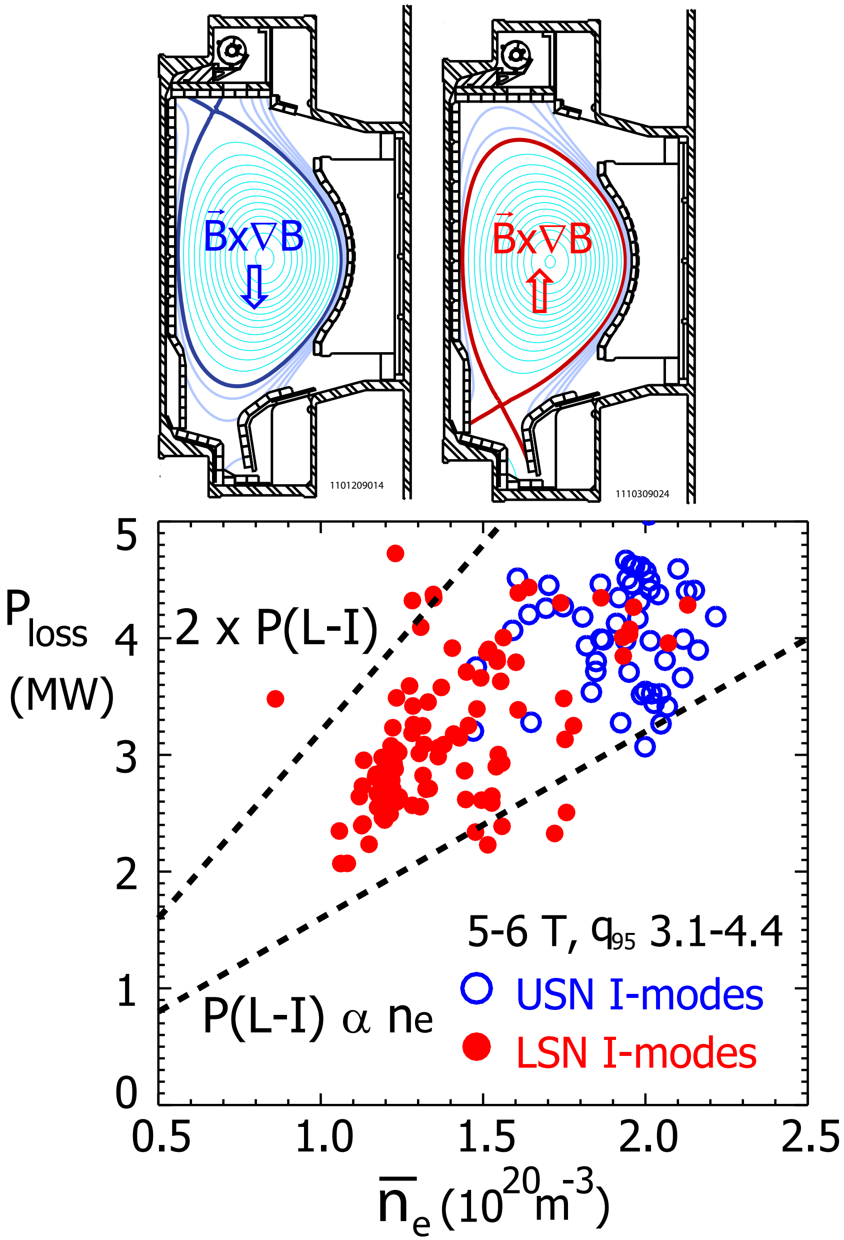
ν^* = 0.1- 5.4

Note that B_T, n_e and q_{95} span ITER ranges.



All C-Mod experiments use Molybdenum PFCs, RF heating, no momentum or core particle input.

Increased power and density ranges for I-mode in Lower Null configuration



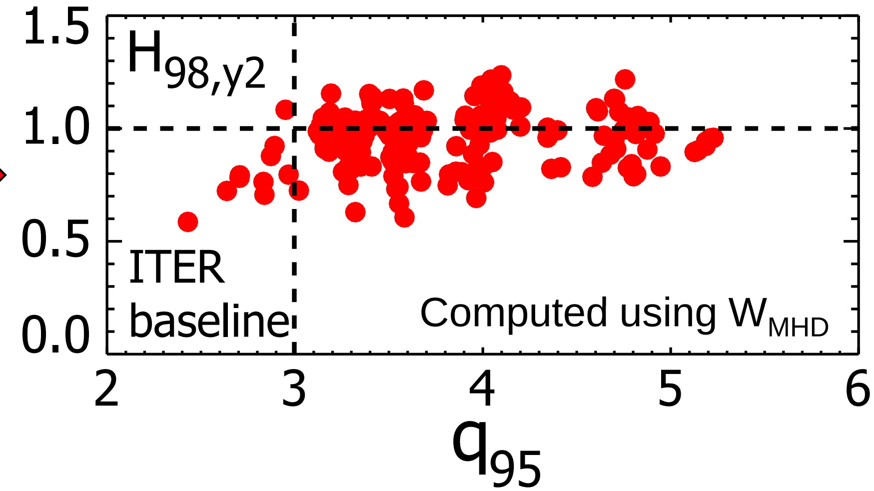
- I-mode is generally achieved with Bx∇B drift away from X-pt.
  - Some cases, reported in 2010, with "favourable" drift towards X-pt, but limited to low power.
- Configuration with LSN, reversing B_T and I_p, enables I-mode at lower density, and over much higher power range (> 2x) than USN, up to max available power. *Due to shape, or closed divertor?*
- This in turn has led to more robust, longer duration I-modes, in most cases without transitions to L or H-mode as long as heating is maintained.

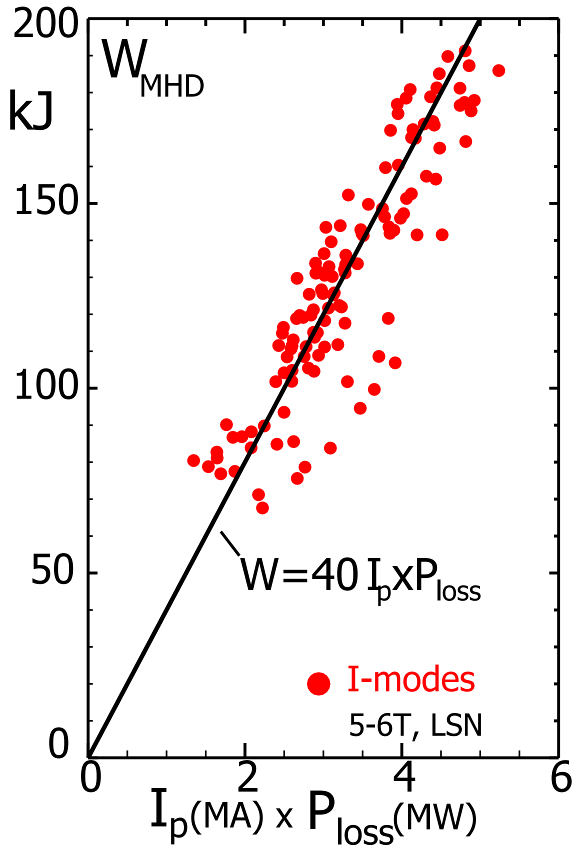
A. Hubbard, FEC 2012 EX/1-3

I-mode has H-mode-like energy confinement, but with little power degradation

Alcator C-Mod

- **H_{98y2} = 0.7-1.2,** comparable to H-modes. But, scatter indicates differences in τ_E scaling.
- **A key difference is much less degradation with power!**

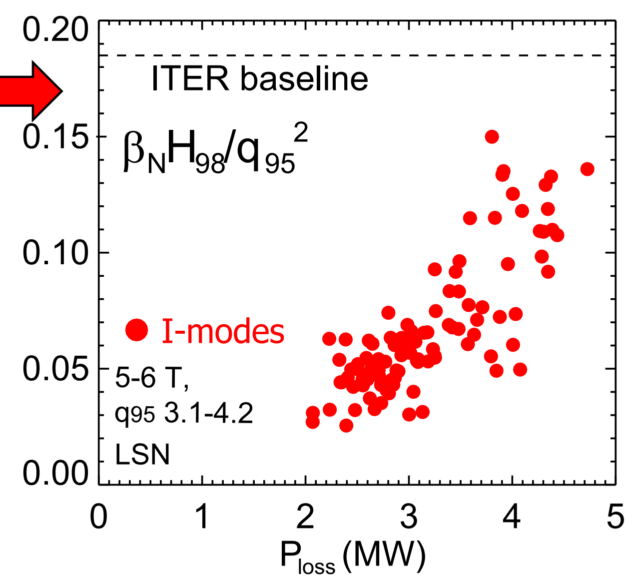




$\beta_N H_{98}/q_{95}^2$, also increases with power, approaching ITER requirements.

- Limited so far by available power.
- NTMs are observed in some cases.

Y. Lin, P4-22, Wed pm

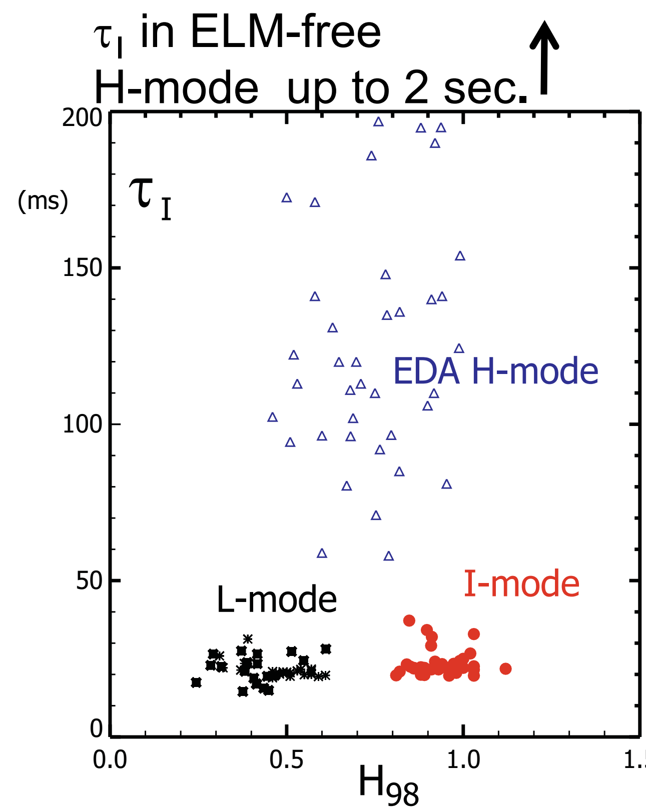


Low impurity confinement of I-mode has several advantages

Alcator C-Mod

- **Impurity particle confinement τ_I,** measured using Ca injection, remains near L-mode levels, and **is much lower than in H-modes.**

- Important implications for operating scenarios and divertor power handling:
  - Intrinsic impurities do not accumulate; core radiation is generally lower than H-mode.
  - Compatible with metal walls, ICRH.
  - Boronization is not essential.
  - Regime highly compatible with impurity seeding to reduce divertor flux; Neon seeding is routinely used on C-Mod.



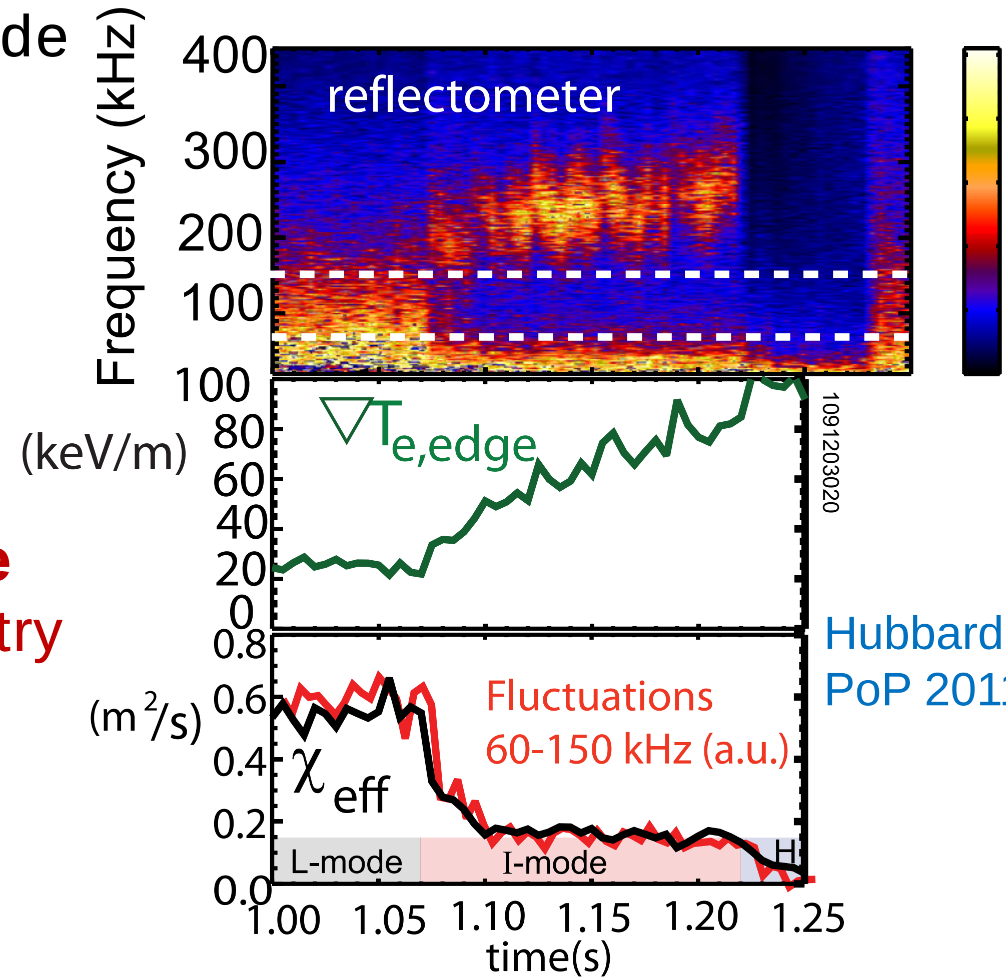
We have begun to explore divertor heat loading in I-modes.

- Peaking of outer footprint similar to H-mode. J. Terry, PSI 2012
- Reversed drifts, flows lead to more equal power sharing between divertor targets.

Advances in pedestal turbulence and transport.

Edge T barrier and decrease in mid-f turbulence are key signatures of L-I transitions

- At transition from L to I-mode **edge ∇T steepens**, at near-constant P_{net} and edge n_e
  $\Rightarrow$ **Edge χ_{eff} is decreasing.** Quantified by edge power balance calculations.
- **Edge χ_{eff} correlates well to the drop in mid-f turbulence** (~60-150 kHz) from reflectometry
  - Sharpest drop at low q_{95}.
  - Analysis of v_{ExB} shows spectral changes are not dominated by Doppler shifts.
- Further drops are seen in both turbulence and χ_{eff} at I-H transitions.



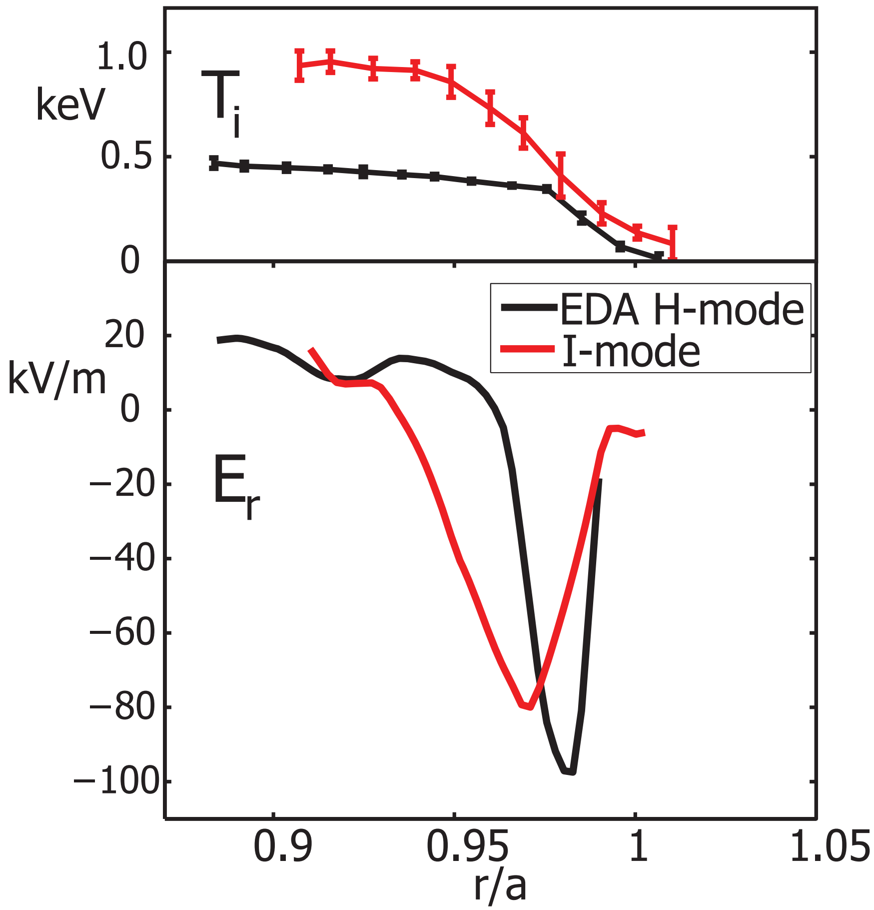
Hubbard PoP 2011

Consistent with this mid-freq turbulence playing a key role in thermal transport.

Temperature pedestal is associated with an E_r well, as in H-mode

Alcator C-Mod

- E_r profile is measured by Boron CXRS.
- A clear E_r well develops in I-mode along with the T_i pedestal, which is comparable to that in T_e.



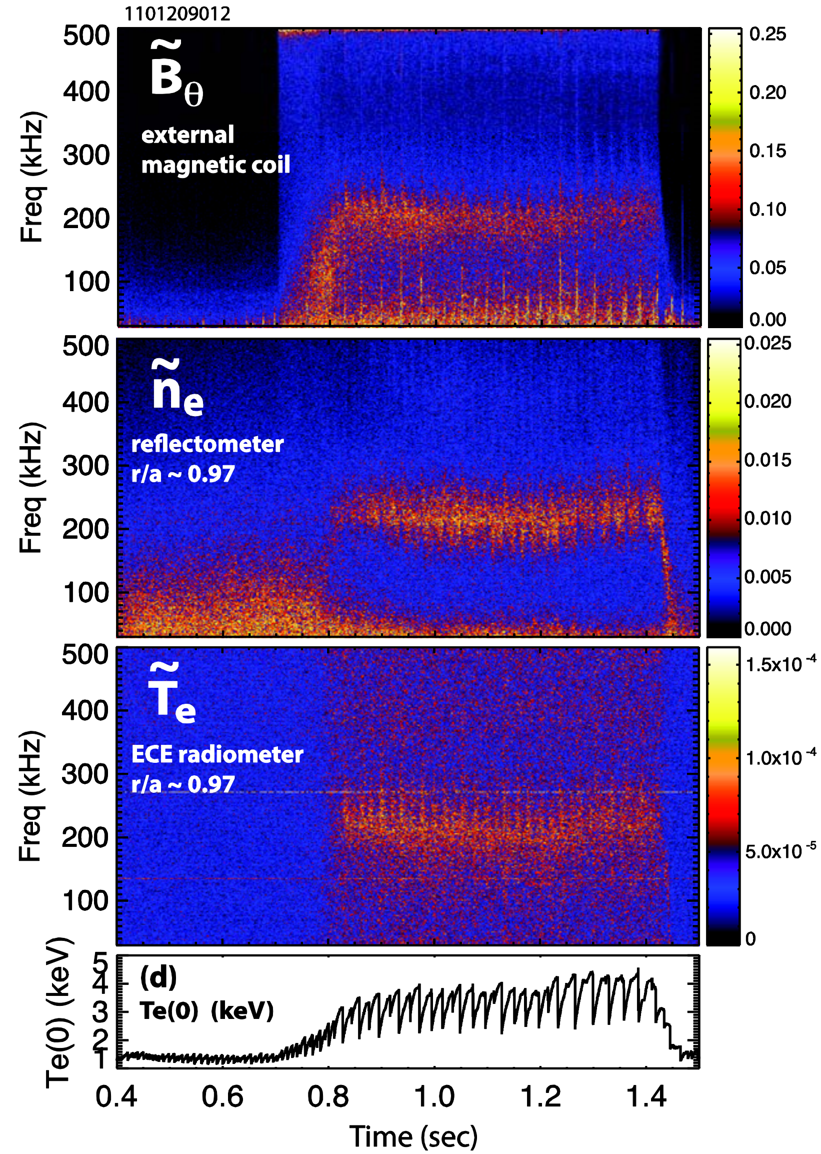
- E_r well can have depth approaching H-modes (up to 80 kV/m), but is wider. **=>ω_{ExB} about 1/3 to 1/2 that of typical H-Modes.**
- This would be consistent with reduction, not suppression, of turbulence.
- Wider pedestal, lower ∇n, j_{boot} are favorable for p-b stability (ELITE). Hughes, EX/P4-15, Wed pm.
- Big difference to H-mode is little effect on **particle** transport. ***WHY? Is something else driving particle flux?***

Weakly Coherent Mode seen in density, magnetics, ECE, localized to barrier region

- In *most* I-modes, a higher frequency turbulence feature appears, simultaneous with mid-freq reduction. **f_0 ~200-400 kHz,** **$\Delta f/f$ ~0.3-1**, increasing with q_{95}
  - Some exceptions, in cases with high q_{95} or marginal power, low ∇T.

- Fluctuations seen in **B** (magnetics), **Density** (Reflectometry, Gas Puff Imaging, PCI, and **Electron Temperature** (ECE). **$\delta T_e/T_e$ 1-1.6% < $\delta n_e/n_e$ 6-13%.**

- Refl, ECE and GPI all localize the mode to within1-2 cm of the separatrix, ie region of T pedestal. **(0.9 < r/a < 1.0)**

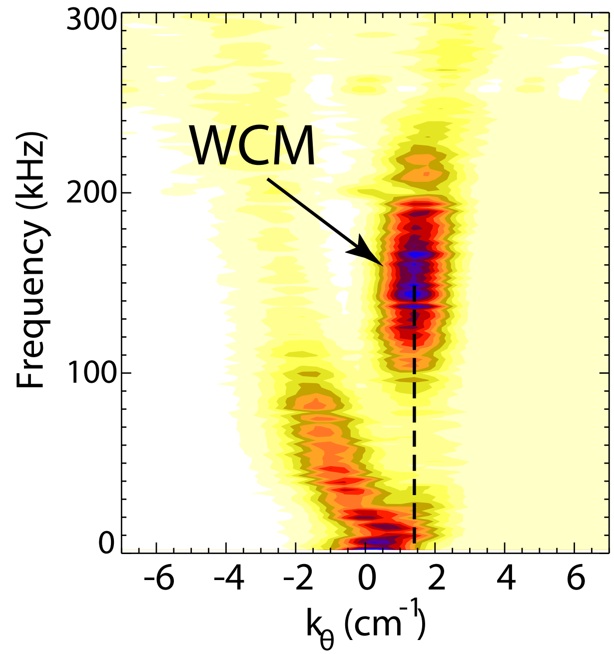


A. White, Nucl. Fusion 2011

Weakly Coherent Mode seen in density, magnetics, ECE, localized to barrier region

Alcator C-Mod

- In *most* I-modes, a higher frequency turbulence feature appears, simultaneous with mid-freq reduction. **f_0 ~200-400 kHz,** **$\Delta f/f$ ~0.3-1**, increasing with q_{95}
  - Some exceptions, in cases with high q_{95} or marginal power, low ∇T.
- Fluctuations seen in **B** (magnetics), **Density** (Reflectometry, Gas Puff Imaging, PCI, and **Electron Temperature** (ECE). **$\delta T_e/T_e$ 1-1.6% < $\delta n_e/n_e$ 6-13%.**
- Refl, ECE and GPI all localize the mode to within1-2 cm of the separatrix, ie region of T pedestal. **(0.9 < r/a < 1.0)**



- **2-D Gas Puff Imaging** reveals WCM details:
  - **k_{pol} ~ 1.5 cm^{-1}** ($k_\perp \rho_s$~ 0.1)
  - Propagation in **electron diamagnetic direction,** in lab and plasma frames.

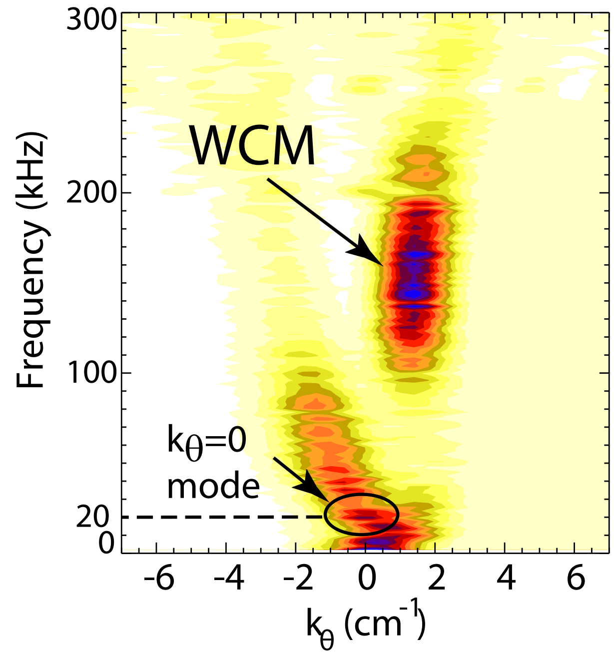
Weakly Coherent Mode seen in density, magnetics, ECE, localized to barrier region

Alcator C-Mod

- In *most* I-modes, a higher frequency turbulence feature appears, simultaneous with mid-freq reduction. **f_0 ~200-400 kHz,** **$\Delta f/f$ ~0.3-1**, increasing with q_{95}
  - Some exceptions, in cases with high q_{95} or marginal power, low ∇T.

- Fluctuations seen in **B** (magnetics), **Density** (Reflectometry, Gas Puff Imaging, PCI, and **Electron Temperature** (ECE). **$\delta T_e/T_e$ 1-1.6% < $\delta n_e/n_e$ 6-13%.**

- Refl, ECE and GPI all localize the mode to within1-2 cm of the separatrix, ie region of T pedestal. **(0.9 < r/a < 1.0)**



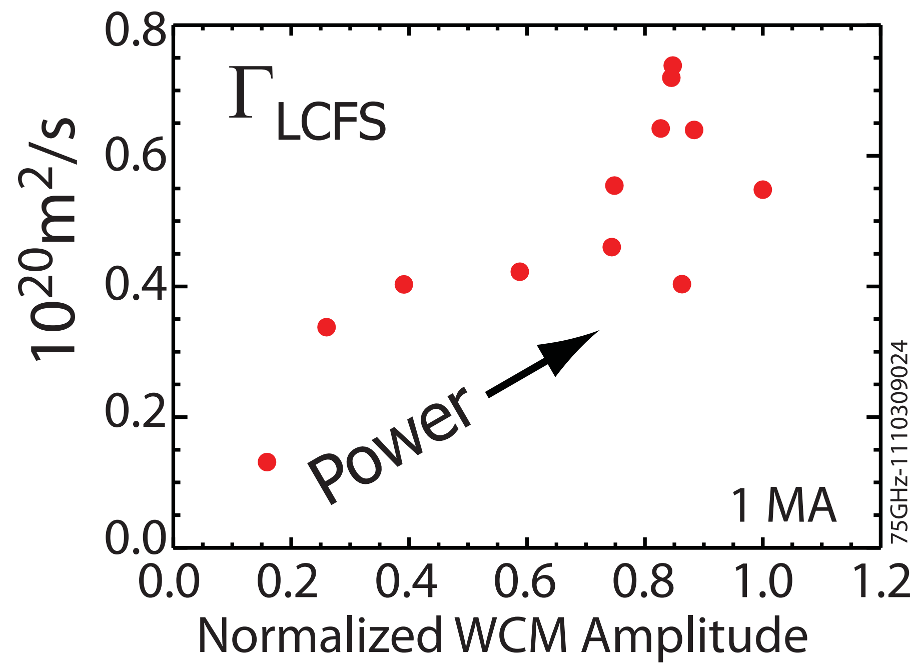
- **2-D Gas Puff Imaging** reveals WCM details:
  - **k_{pol} ~ 1.5 cm^{-1}** ($k_\perp \rho_s$~ 0.1)
  - Propagation in **electron diamagnetic direction,** in lab and plasma frames.

- Also a k=0 feature in v_θ at GAM freq, ~20 kHz, which interacts with WCM. I. Cziegler, to be reported at APS.

Amplitude of WCM correlates with edge particle flux

Alcator C-Mod

- Analysed power steps within I-mode discharges.
- Relative amplitude of WCM from edge reflectometer.
- Edge particle flux Γ_{LCFS} derived from absolutely calibrated D_α imaging near the outboard midplane.



- Correlation with Γ_{LCFS} is consistent with the WCM playing a key role in driving particle transport, perhaps helping avoid transition to H-mode.
  - Analogous to role of QC mode in EDA H-mode.

A. Dominguez, MIT Ph.D. 2012
Submitting to Nuclear Fusion

Extrapolation of I-mode scenarios to ITER.

Initial extrapolation from C-Mod indicates I-mode *may* be an attractive ITER scenario

Key assumptions:

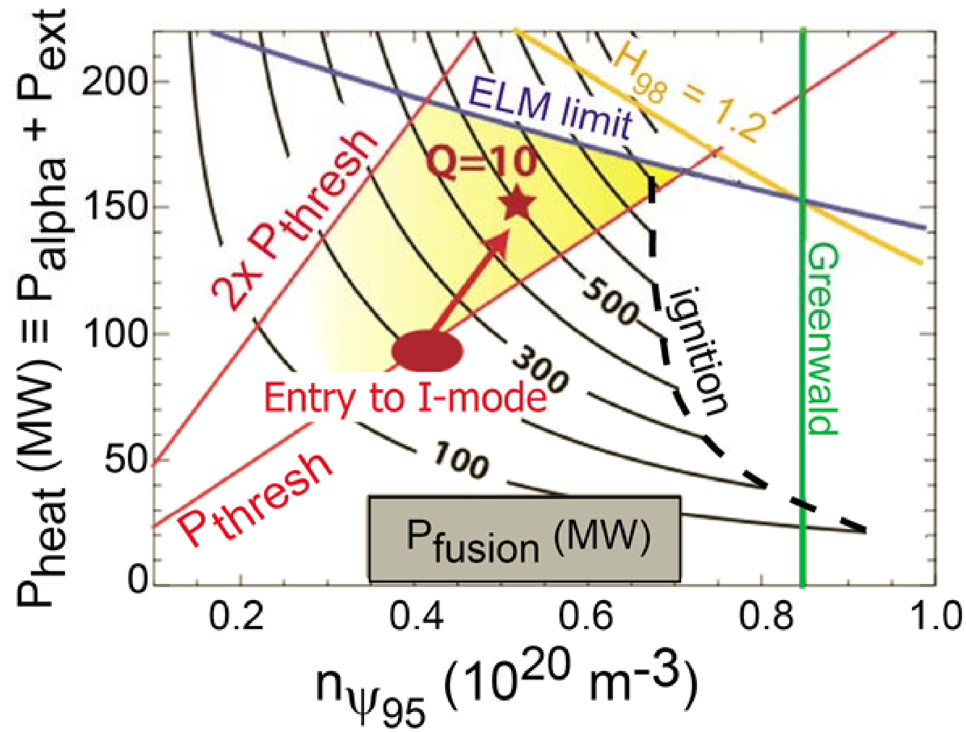
- Match C-Mod R/a, B, q_{95}, shape, and n_e profile shape. Reverse B, I_p, LSN.
- $P_{L\Rightarrow I}$ = 1.8 MW x $n_{e,20}$ x (S_{ITER}/S_{CMod})
- L-mode temperature profile scaled to force H_{89}=1.
- I-mode core and pedestal T(r) scaled from C-Mod data, using $\nabla T_{core} \propto (P_{heat}/S)^{1/2}$ (~H-mode), $\nabla T_{pedestal} \propto (P_{heat}/S)/n_{\Psi 95}$.

Constraints:

- H_{98}<1.2, $n<n_{Greenwald}$
- $P_{L\Rightarrow I} < P_{heat} < 2\ P_{L\Rightarrow I}$
- $Pressure_{\psi 95}$<H-mode (no ELMs)

Whyte APS 2011

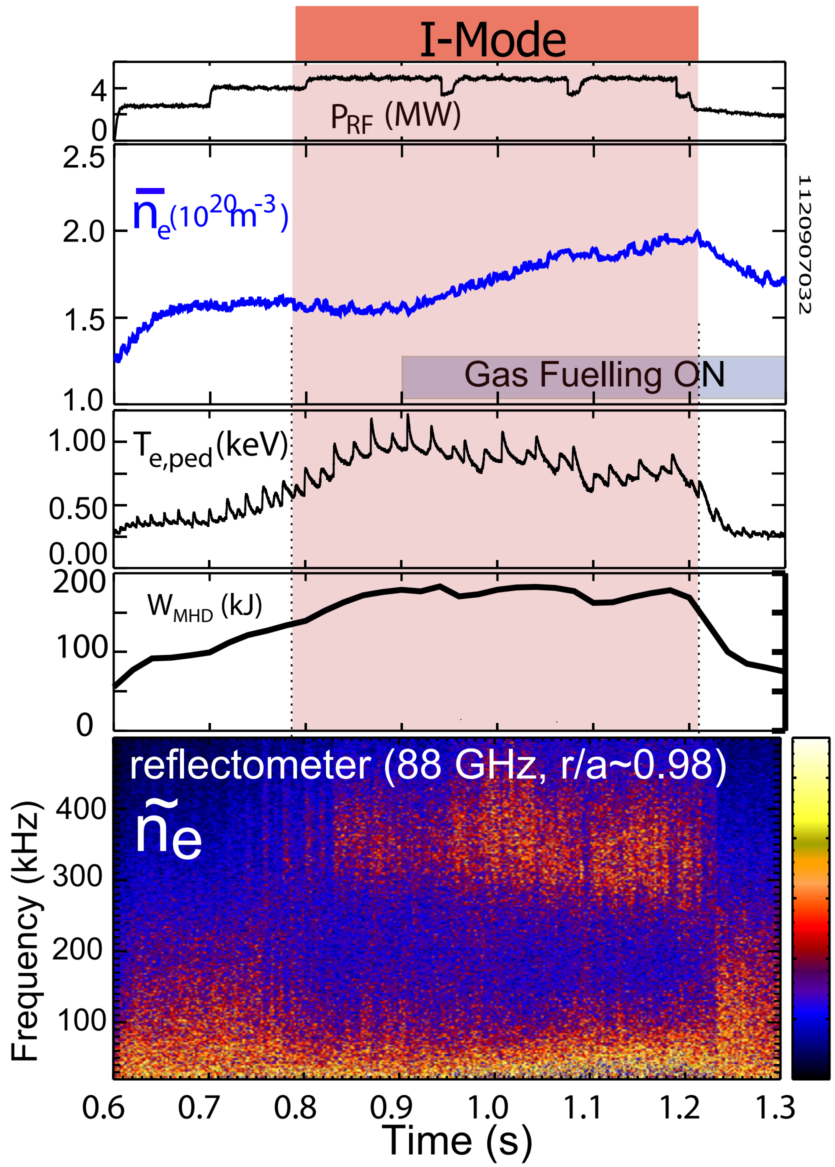
Will need multi-machine expts to verify size, n_e, other scalings!

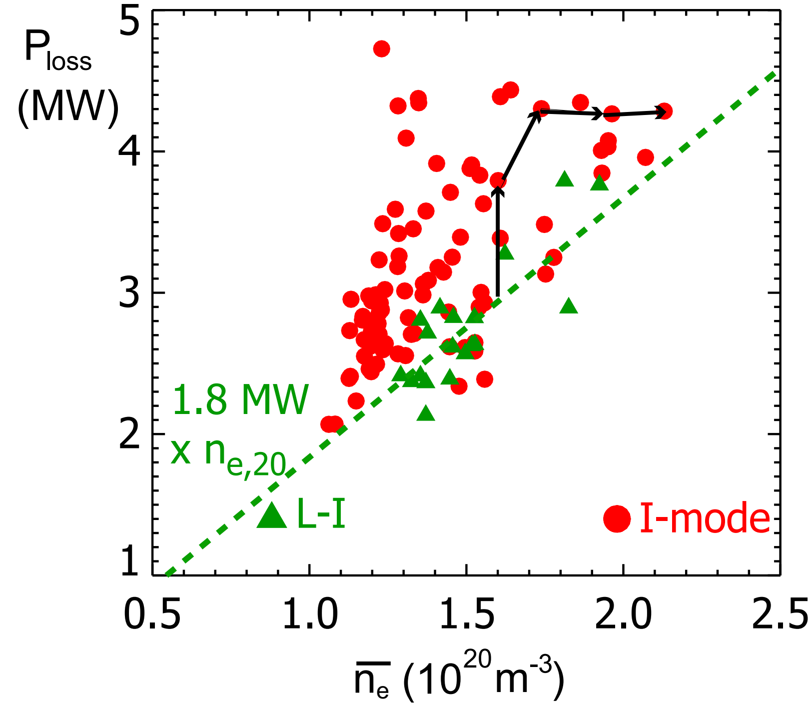


- Access to I-mode appears possible at nebar~ 5e19 m^{-3}.
- Achieve Q=10 by raising n_e. *Can density be controlled to control P_{fus}?*

Gas fueling into I-modes on C-Mod enables higher densities

Alcator C-Mod

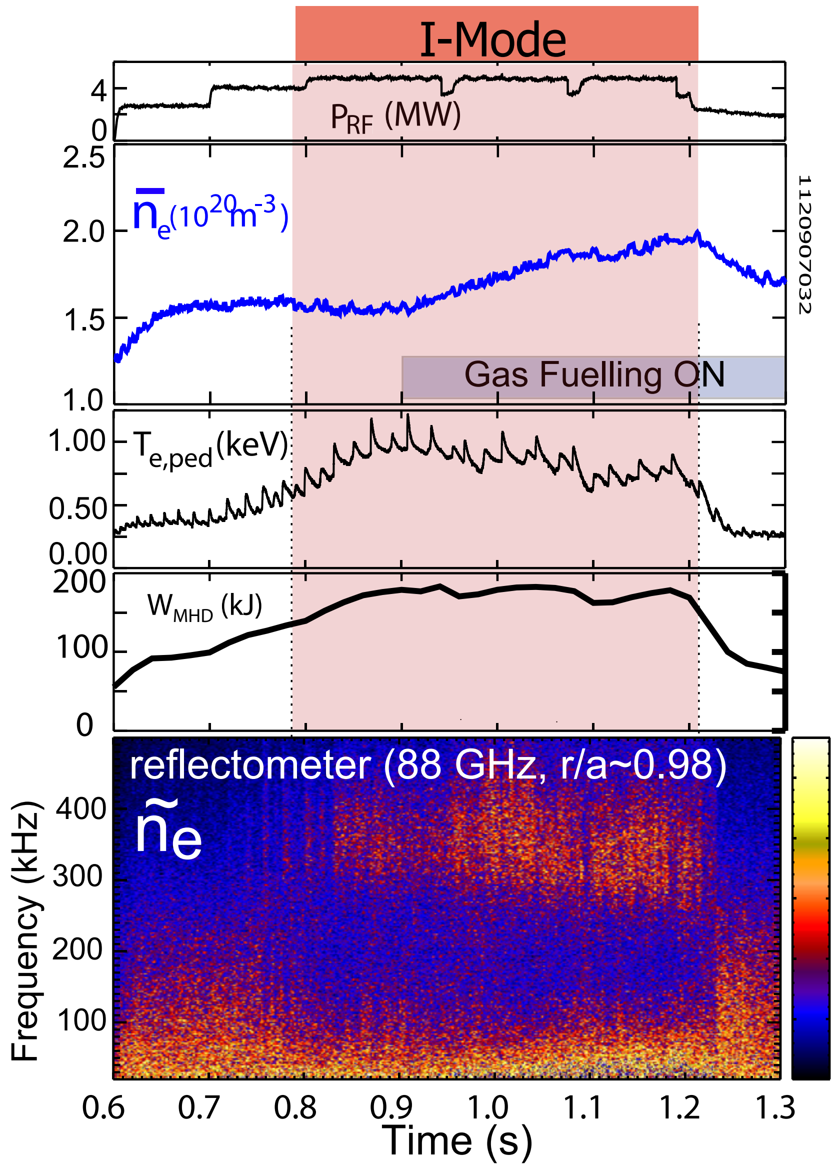


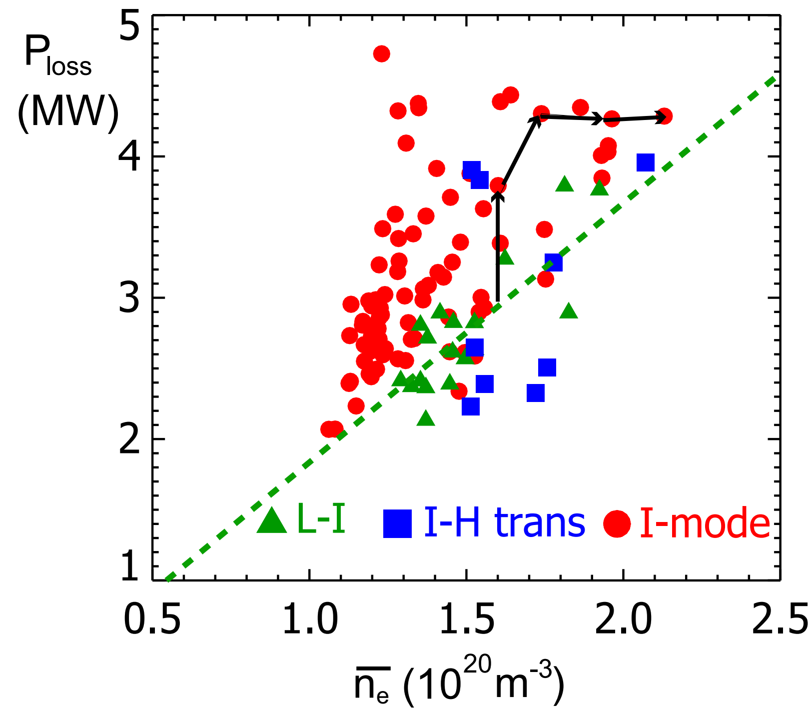


- Gas fuelling into hot I-mode raised n_e by 30%, to 2e20 m^{-3}, with nearly constant stored energy, and H_{98}>1.

Gas fueling into I-modes on C-Mod enables higher densities

Alcator C-Mod





- Gas fuelling into hot I-mode raised n_e by 30%, to 2e20 m^{-3}, with nearly constant stored energy, and $H_{98}>1$.
- This is *higher* n_e and power than many I-H transitions occur.

→ Implies I-mode can be maintained as long as power is sufficient to maintain T_e pedestal, drive WCM

I-mode is an attractive regime for fusion

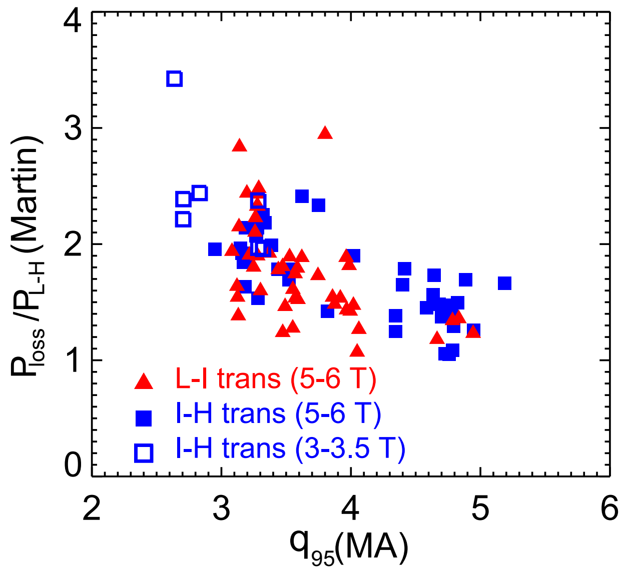
Alcator C-Mod

- **I-mode regime features thermal transport barrier, but with L-mode density profiles and impurity confinement, and without a need for ELMs.**
  - Energy confinement ~ H_{98y2}, but with little power degradation.
- C-Mod configuration with X-point towards closed lower divertor, upwards Bx∇B drift, enables **stationary I-modes without transitions, over a wide range of power and plasma parameters,** many spanning ITER's.
  - Density can be increased by fueling established I-modes, while maintaining high confinement.
- Measurements of **edge turbulence, profiles and transport** show
  - Decrease in mid-freq fluctuations correlates with pedestal χ_{eff}.
  - Weakly Coherent Mode in n_e, B, T_e correlates with particle flux.
- **Initial extrapolations of C-Mod results to ITER are encouraging.** *Further experiments, on other tokamaks as well as C-Mod, are urgently needed to confirm access and confinement scalings, and are planned.*

Additional material

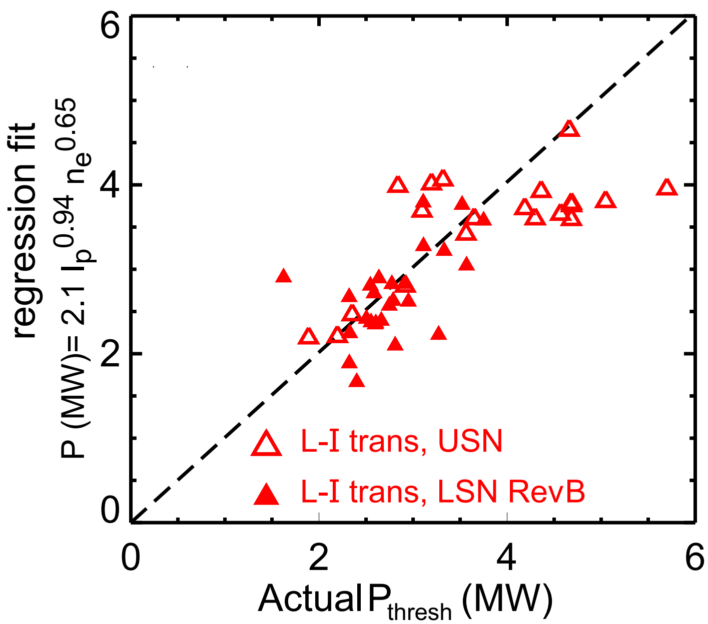
Thresholds for L-I transitions increase with both current and density

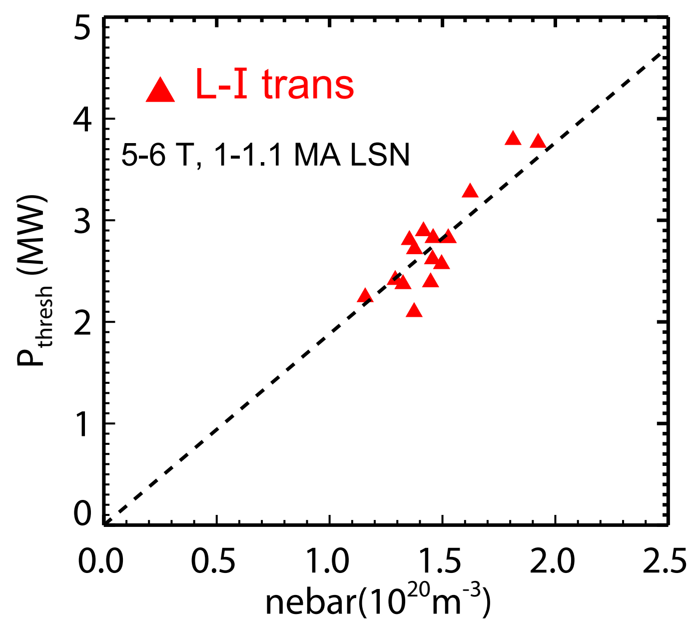
Alcator C-Mod



- Thresholds for L-I transition are generally above L-H scalings for "favorable" drift.
- P (L-I) increases with current as well as density. Regression fit to 2011 dataset gave **$P\ (MW) = 2.1\ I_p^{0.84}\ n_e^{0.85}$.**
- At fixed I_p, find near **linear n_e dependence.**

- **Recent experiments should enable more complete threshold scalings , including B_T.**

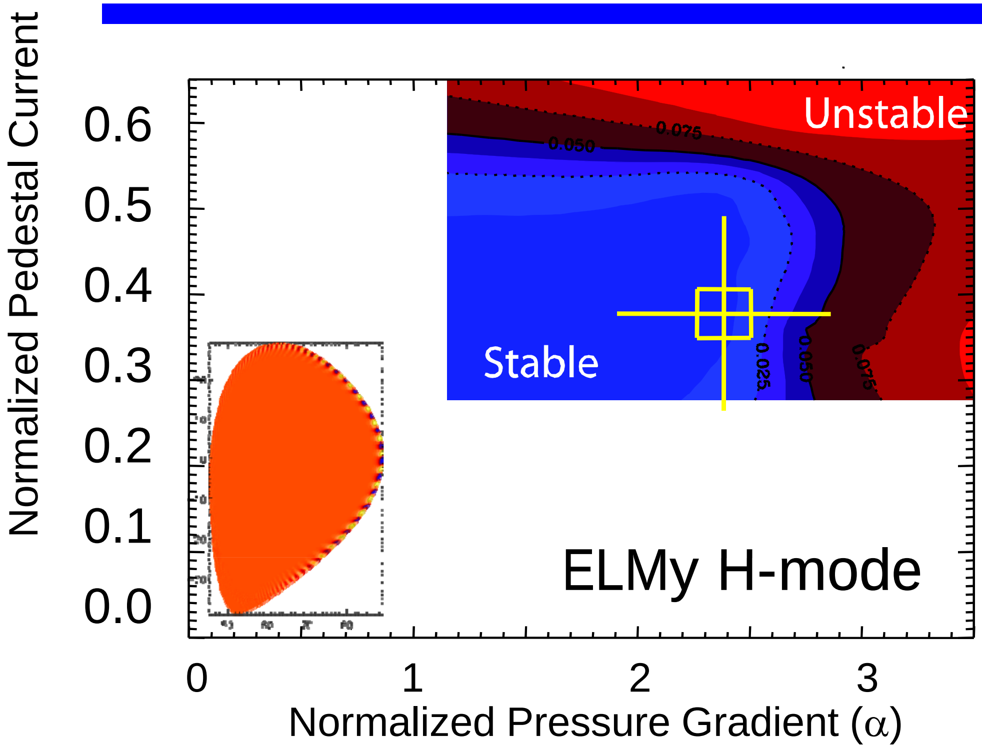


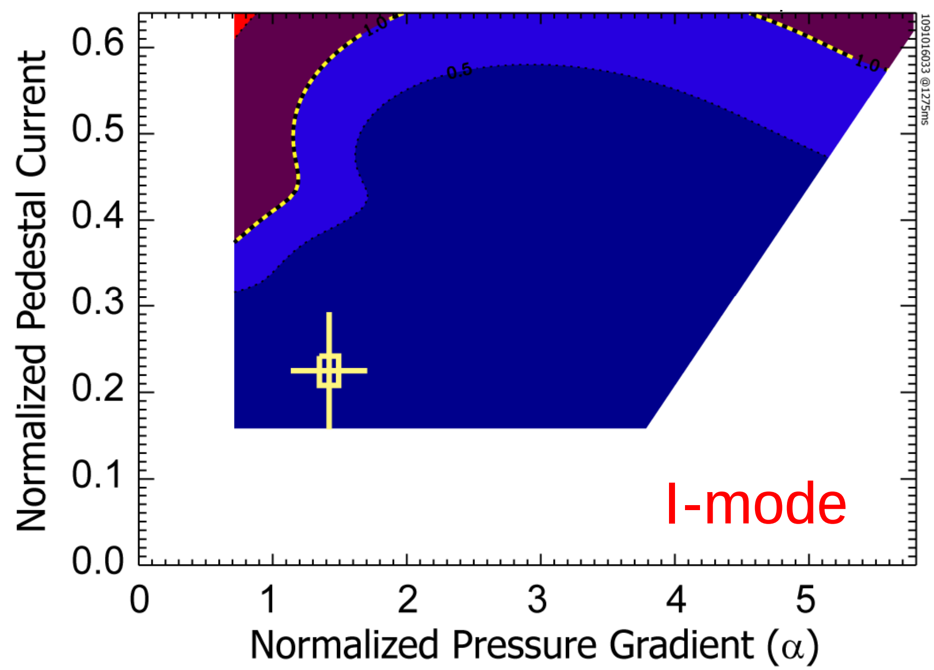


Hubbard
Nucl. Fusion
October 2012

Typical I-mode pedestal calculated to be deeply stable to peeling-ballooning modes (ELITE)

Alcator C-Mod

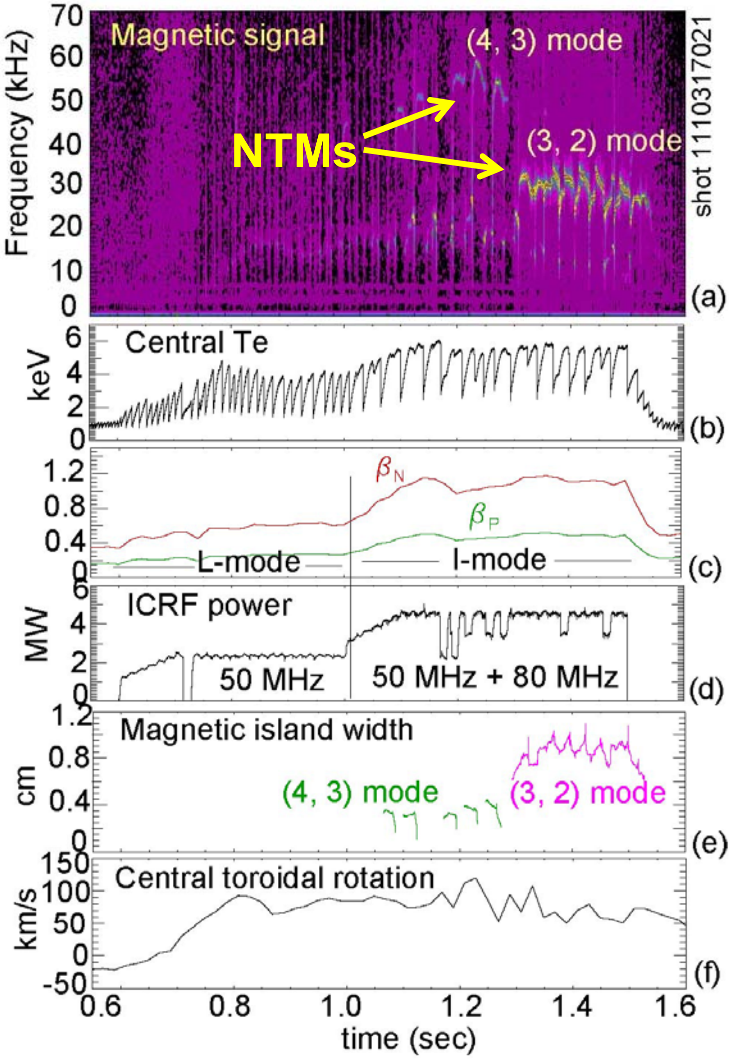




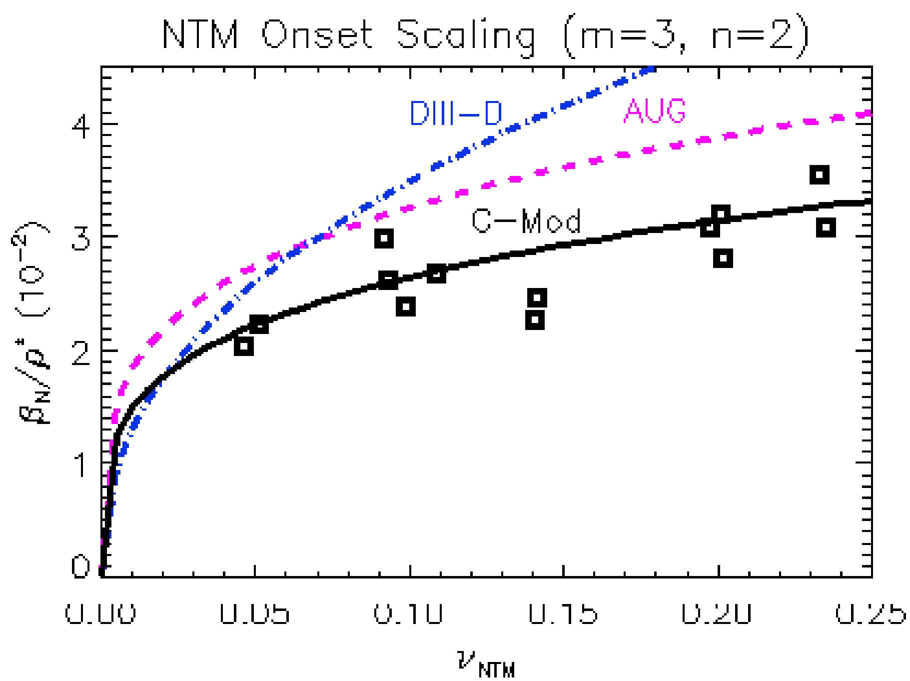
- Peeling-ballooning instability thought responsible for ELM trigger in Type-I ELMing H-mode   Groebner, EX/11-4
- I-mode: Reduced density & pressure gradients are favorable for staying below p-b stability boundary   Hughes, EX/P4-15
  - I-Mode has wider pedestal, lower pedestal j_{boot}
  - Small ELMs have been seen in a minority of I-mode discharges, however this is not intrinsic to the regime, and can be avoided.

EX/P4-22, Y. Lin *et al*, "NTMs in high performance ICRF heated I-mode plasmas on C-Mod"

Alcator C-Mod



- Neo-classical tearing modes (NTMs) have been observed in ICRF heated high-performance I-mode plasmas in C-Mod.
- The NTMs are triggered by large sawtooth crashes, and their **onset criteria, in terms of β_N/ρ^* and $\nu_{NTM}=(\nu i/\varepsilon)/\omega e^*$, are found to be similar to those from DIII-D and ASDEX upgrade.**

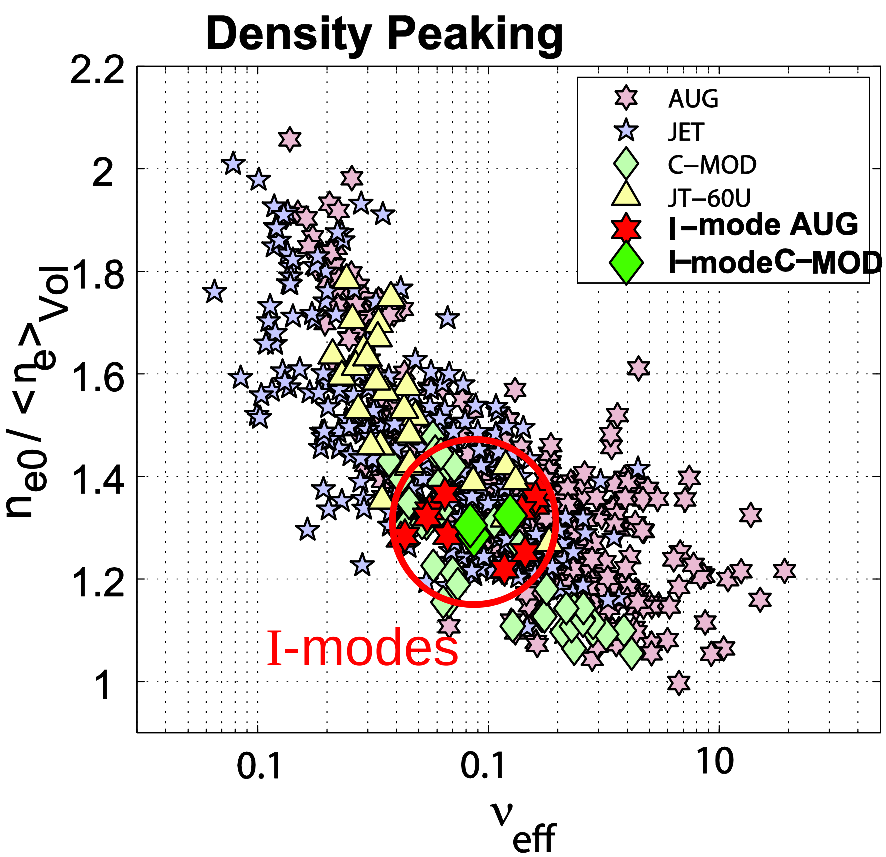


- Bt0 = 5.1 T, Ip = 1 MA, ne0 = 1.2 ×10^{20} m^{-3}.
- ICRF @ 50 MHz → D(^{3}He) mode conversion heating and flow drive;
- ICRF @ 80 MHz → D(H) minority heating.

A. Hubbard, FEC 2012 EX/1-3

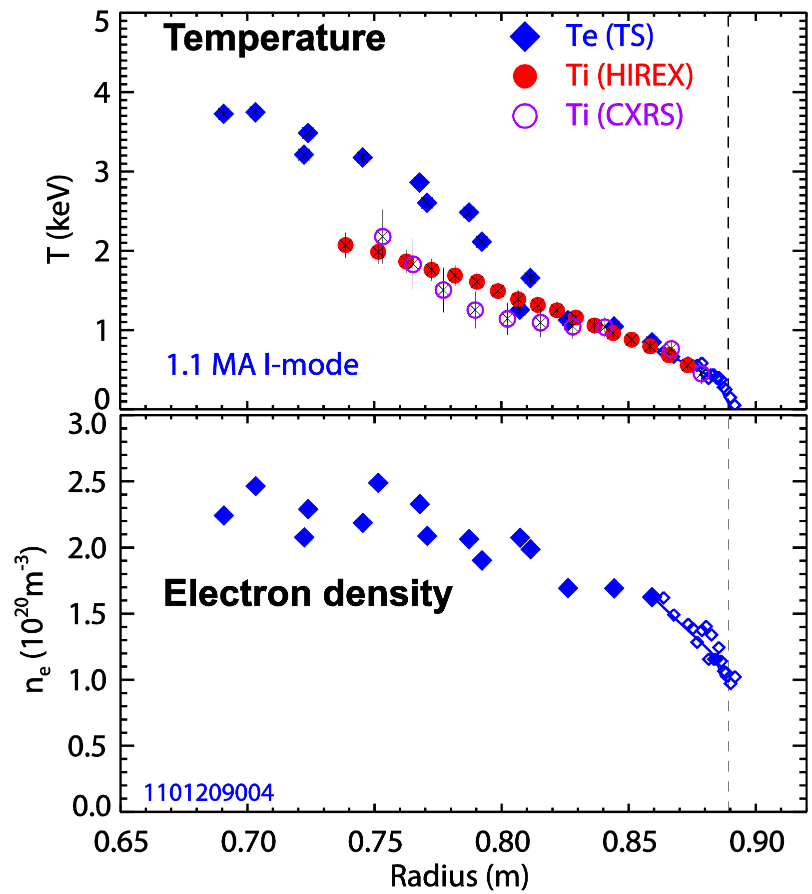
Core density peaking in I-mode is comparable to low ν* H-modes.

Alcator C-Mod



Multi-machine H-mode database, Angioni *et al*, PPCF 2009

- While there is not a steep density pedestal in I-mode, $n_{e0}/<n_e>$ is similar to prior H-mode scalings which show increased peaking at low ν*.

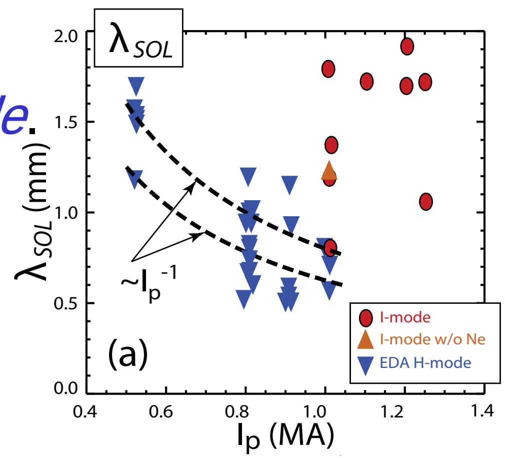


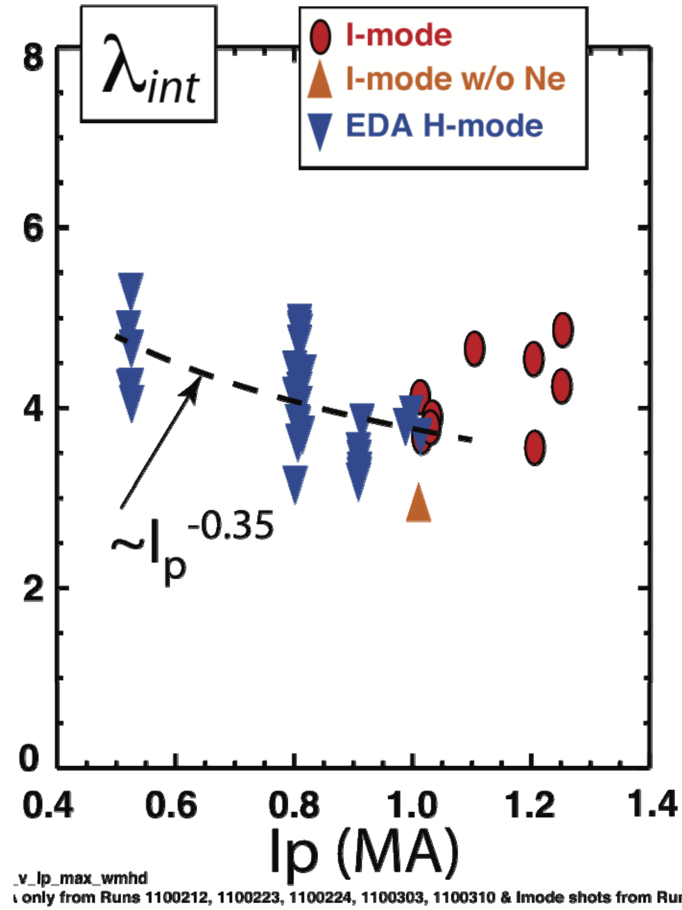
A. Hubbard, FEC 2012 EX/1-3

We have begun to explore divertor response in I-mode regime vs H-mode

Alcator C-Mod

- IR measurements in outer divertor show overall peaking of heat flux footprint is similar in I-mode and H-mode, for highest confinement shots at given I_p, ie $\lambda_{Int}^{I\text{-}mode} \sim \lambda_{Int}^{H\text{-}mode}$
  - But, *larger λ_{SOL} in I-mode*. *Does I_p dependence follow H-mode trend?*





- Recent I-mode experiments with increased density, and a wider range of currents, powers and seeding levels, should enable better characterization of both divertor physics and pedestal, confinement dependences on P_{tot} vs P_{net}.

J. Terry, PSI 2012
To appear in J. Nucl. Mat.