Important issues in confinement transition physics, pedestal dynamics and pedestal structure: the ultimate keys to accessing and sustaining high confinement

Jerry Hughes, MIT PSFC

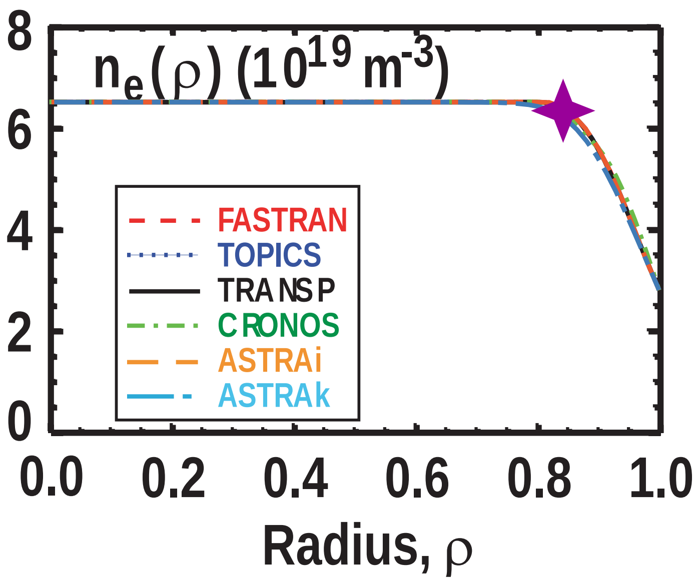
With acknowledgments to

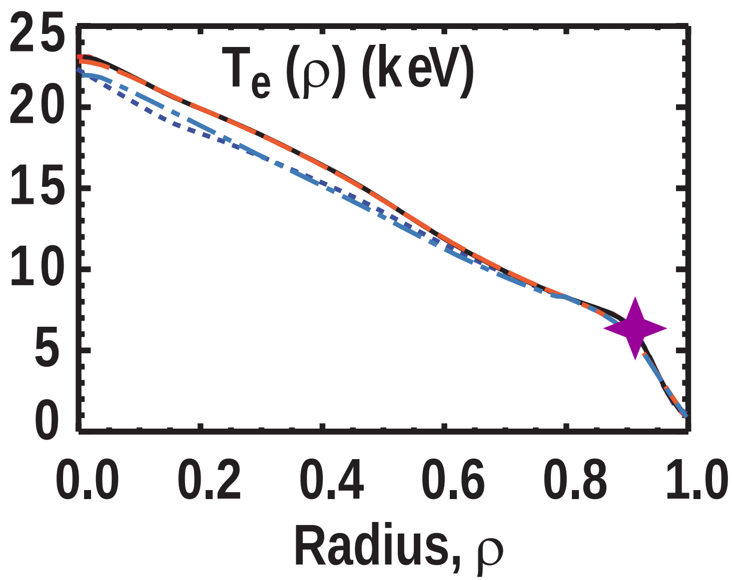
M. Beurskens, J. Callen, J. Canik, A. Diallo, E. Davis, D. Eldon, W. Fundamenski, P. Gohil, R. Groebner, A. Hubbard, K. Kamiya, J. Lore, C. Maggi, R. Maingi, Y. Ma, Y. Martin, T. Osborne, A. Pankin, C. Roach, S. Saarelma, P. Sauter, P. Schneider, S. Smith, P. Snyder, F. Sommer, A. Sontag, A. Webster, M. Willensdorfer, G. Xu, X. Xu

13th International Workshop on H-mode Physics and Transport Barriers, Oxford, UK
10—12 October 2011

Accessing high quality H-mode on ITER will be crucial to its success

- However, when we talk about access to high performing H-mode, we are really talking about *the edge pedestal*
  - Core profile stiffness dictates that global performance in H-mode is highly dependent on the edge pedestal
  - Confidence has grown that modeling can project core transport and confinement, if only pedestal is known

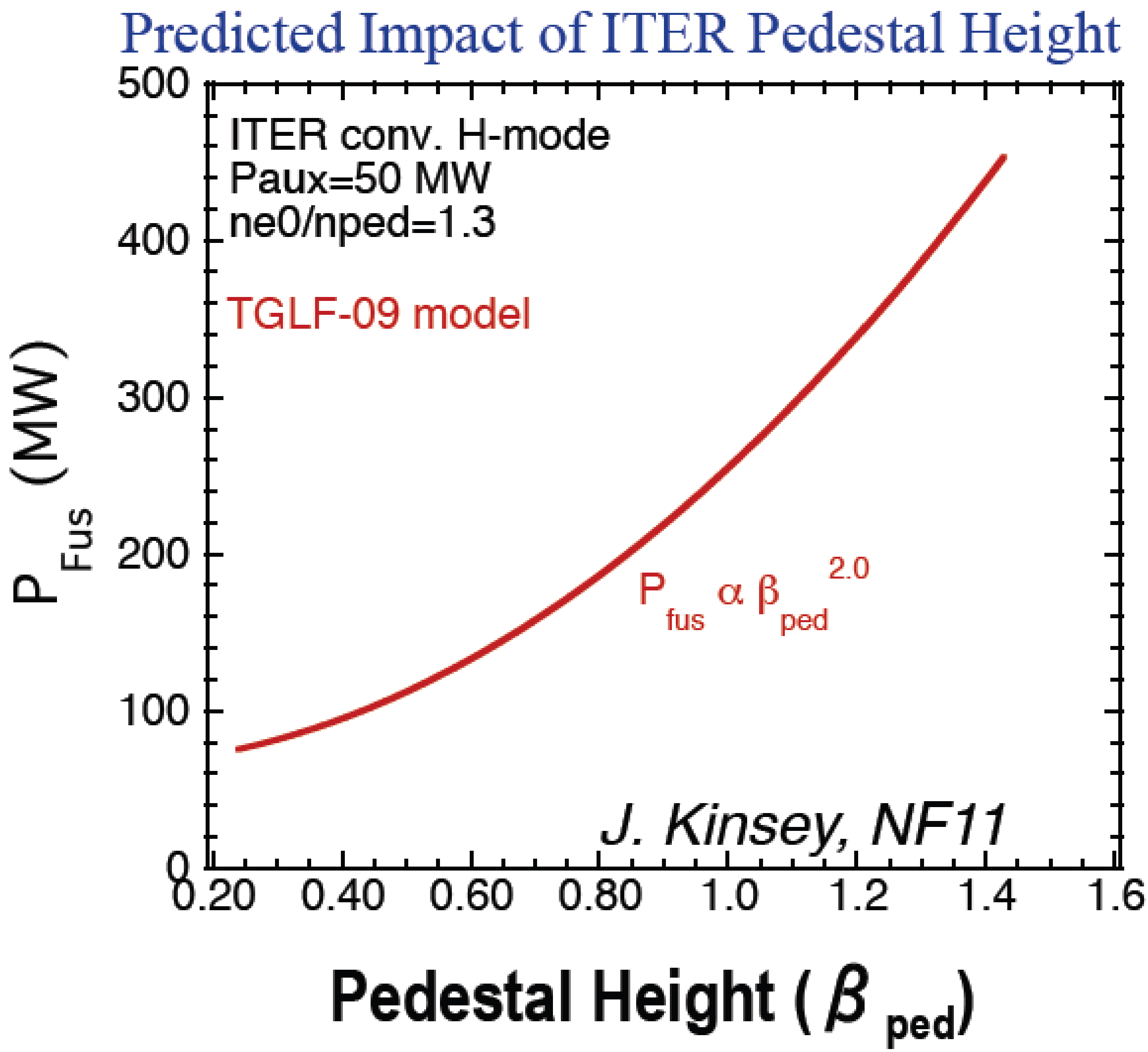




Modeling steady state discharges in ITER

Murakami, NF11

Modeling suggests impact of pedestal on fusion performance is not small



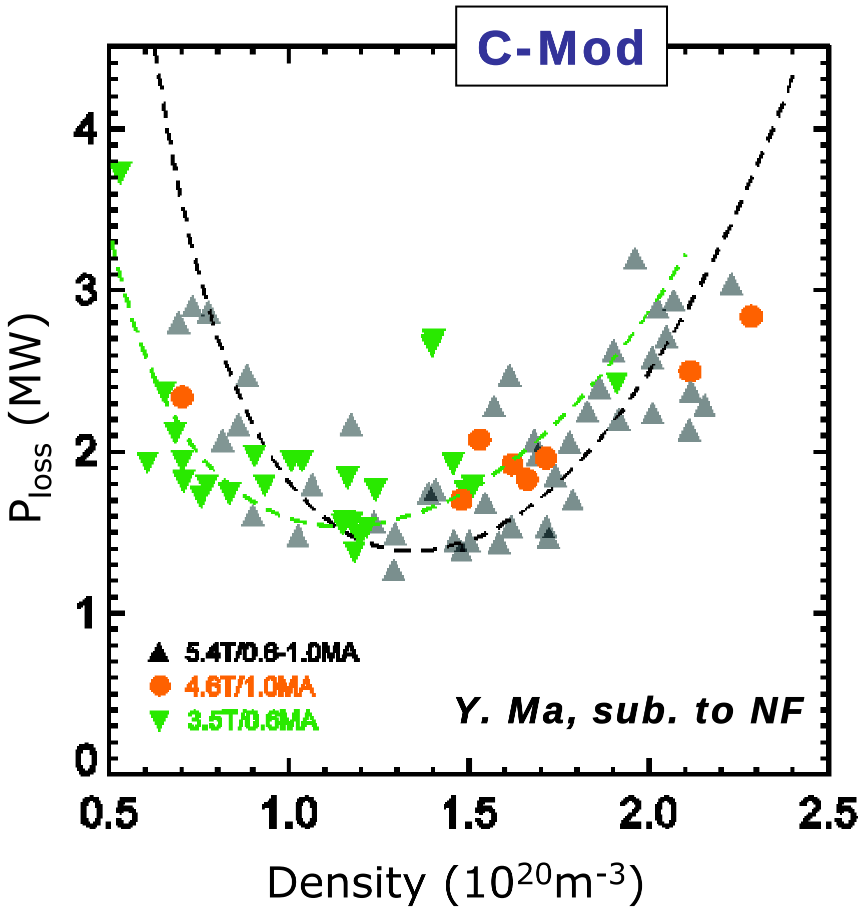
Questions we would like to answer:

1. What are the access conditions for high confinement, and how do we extrapolate to ITER?
   - ITER has finite available input power.
   - Is it enough to trigger L-H transition at the desired *values* of B_T, I_P, n, A, Z, etc.?
   - Will there be enough power to access and sustain H_{98}=1?
2. Can we understand factors determining pedestal structure and improve *predictive capability?*
   - *Both transport and MHD stability*
3. What can we learn from the dynamics of barrier formation, and pedestal transients?

I. ACCESS CONDITIONS FOR HIGH CONFINEMENT

Scaling laws for H-mode power threshold serve as guidelines at best

- Latest power law from multi-machine database gives
  - $P_{th} \sim n^{0.72} B_T^{0.80} S^{0.94}$
- But density dependence is non-monotonic on many devices!
- Additional dependence of P_{th} on main ion A,Z can also be observed *– Gohil, P1.6*
  - *Important for the non-active He phase of ITER*
- Even the B_T dependence seems to break down in some cases
- Then there are the “hidden variables”, e.g. neutrals or divertor configuration . . .



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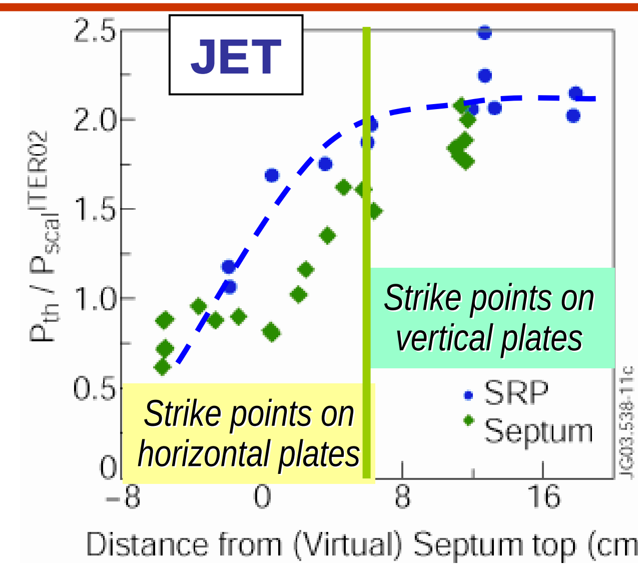
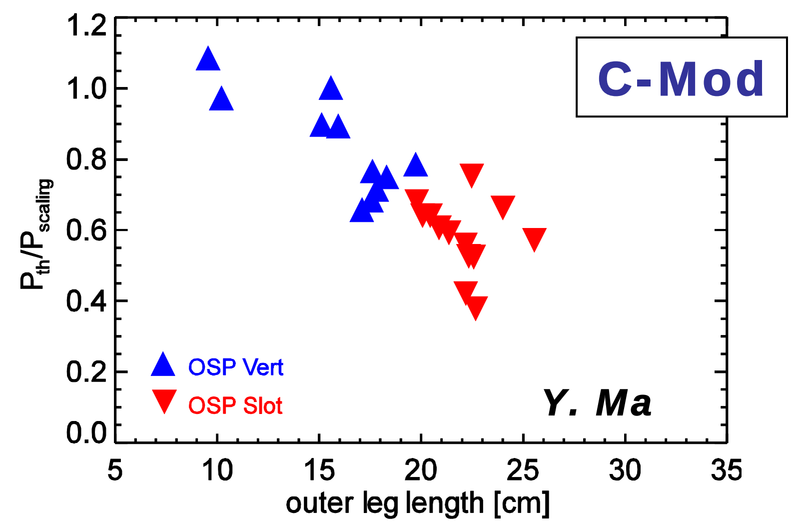


Y. Andrew, PPCF04



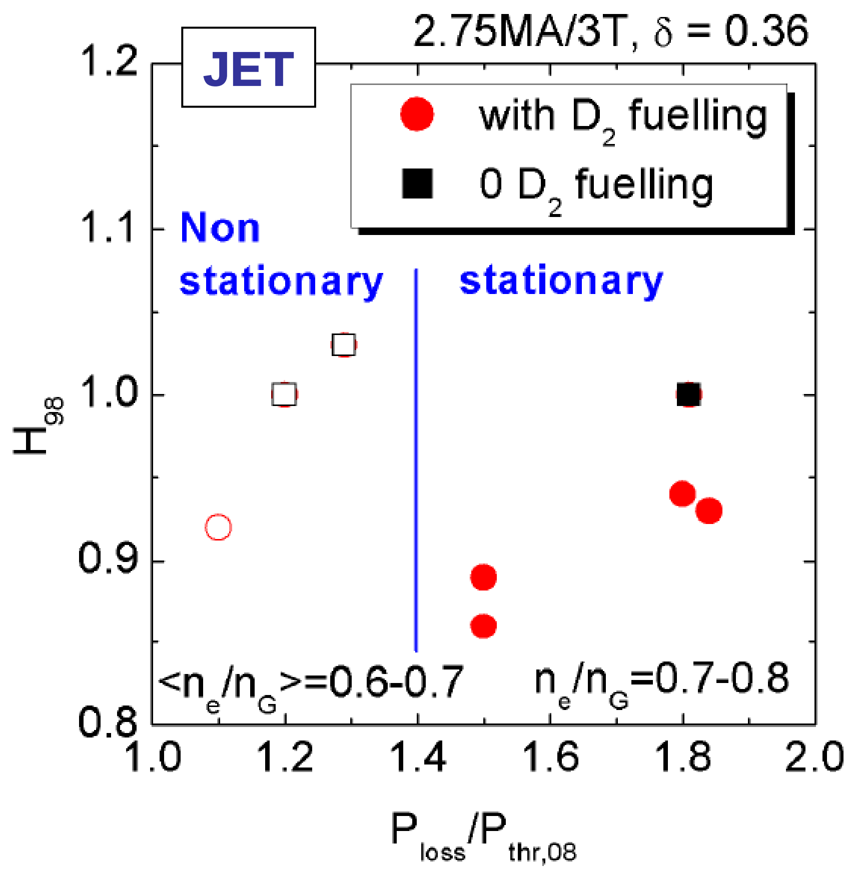
H-mode access and H_{98}=1 sustainment is a non-trivial problem

- L-H transition criteria likely have a rich physical origination
  - Suppression of background turbulent transport must be accomplished → critical thresholds in local profiles?
  - Local profiles set by mixture of core, near-separatrix and SOL transport processes . . . complex
  - Dynamics of turbulence and flow fields could be important
- Many posters at the workshop examine the L-H threshold
  - Three preview talks in this session
    - G. Xu, P3.2, "The role of zonal flows for the L-H transition at marginal input power in the EAST tokamak"
    - W. Fundamenski, P3.14, "A new model of the L-H transition in tokamaks"
    - P. Sauter, P3.21, "Evidence for the role of the ion channel in the L-H transition at low density in ASDEX Upgrade"
  - Others:

P1.6 P. Gohil
P3.3 W. Weymiens
P3.10 R. Chen
P3.11 K. Miki
P3.12 L. Guazzotto
P3.19 F. Ryter
P3.13 N. Yan
P3.24 D. Battaglia
P3.27 E. Solano
P3.28 A. Hubbard
P3.29 J.-W. Ahn
P3.35 B. Chatthong
P5.23 Y. Sechrest
P5.24 S. Zoletnik

H-mode access and H_{98}=1 sustainment is a non-trivial problem

- Unlike most current devices, ITER will not operate with large $P_{in}/P_{th,scaling}$
- The impact of low power ratios on confinement has been studied on multiple machines, through an ITPA-organized activity
  - *(Y. Martin, P1.7)*
- Results can depend on desired n/n_G, radiated power distribution, other factors
  - See also *Beurskens, P3.25; Urano, P3.17; Ahn, P3.29; Lebedev, P3.34*



Maggi, P3.22

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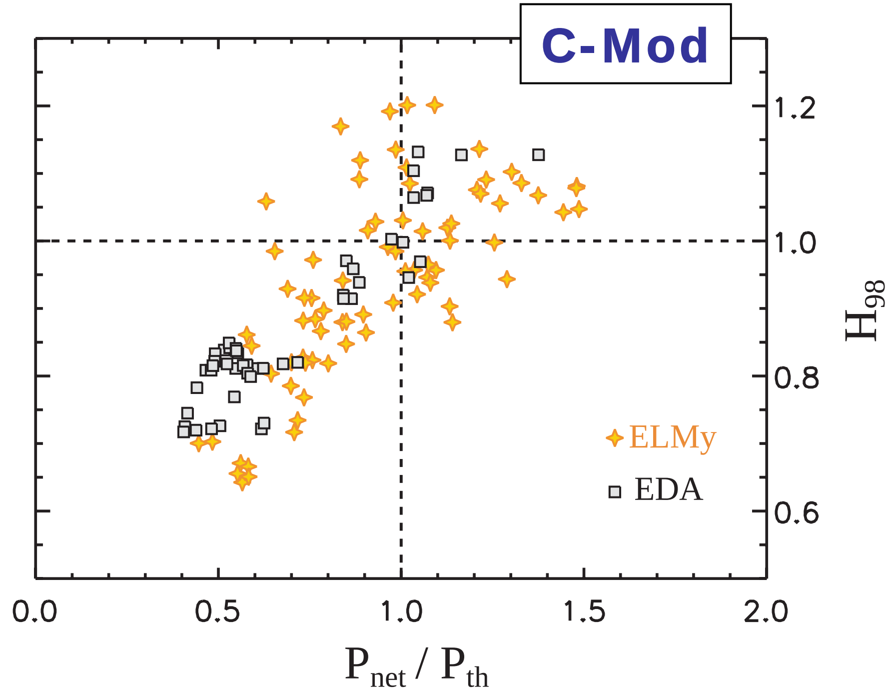

J. Hughes, NF11

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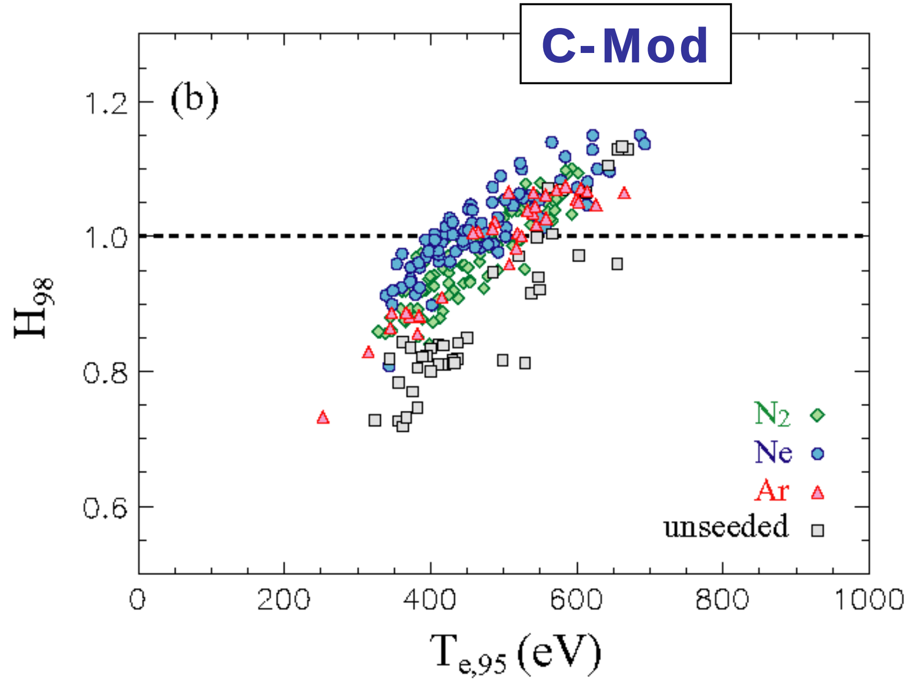

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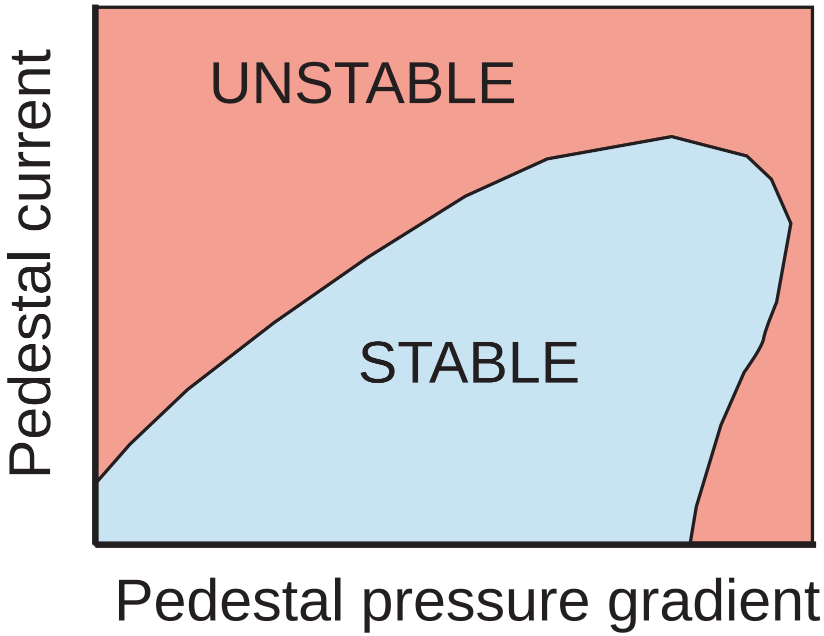
Baseline H-mode confinement depends robustly on pedestal

II. PEDESTAL STRUCTURE AND DEVELOPMENT OF PREDICTIVE CAPABILITY

Steps toward obtaining predictive capability for the H-mode pedestal

- *Developing predictive capability for the H-mode pedestal:* an overarching theme for pedestal research
  - **Focus of DoE FES Joint Research Target (JRT) for FY11**
  - **Goal:** *improve our knowledge of the physics processes that control the H-mode pedestal by applying models of these mechanisms to experimental data.*
- Significant experimental resources devoted to pedestal studies on Alcator C-Mod, DIII-D and NSTX
- Increased collaborations among facilities, and with theory/modeling groups
  - *GA Theory, Georgia Tech, LLNL, MIT, PPPL, Tech-X, UC Irvine, UCSD, U. Colorado, U. Toronto, U.Wisconsin*
- Some physics mechanisms evaluated
  - Neoclassical transport - Paleoclassical transport
  - Electron temperature gradient (ETG) modes
  - Peeling-ballooning (PB) stability - Kinetic ballooning modes (KBM)
  - Resistive ballooning modes - Neutral fuelling

Ultimate limits on pedestal growth increasingly well understood



- Growth of pedestal ultimately constrained by intermediate wavelength MHD instabilities
  - *Snyder P3.4, X. Xu P2.22, Webster, P3.33*
- *Peeling-ballooning modes* driven by edge pressure gradient and current
- Manifest as Type-I ELMs
- Calculations for linear growth rates increasingly well benchmarked (GATO, ELITE, BOUT++)
- Predictive capability? Couple stability calculations to analytic or computational pedestal models for width/gradient

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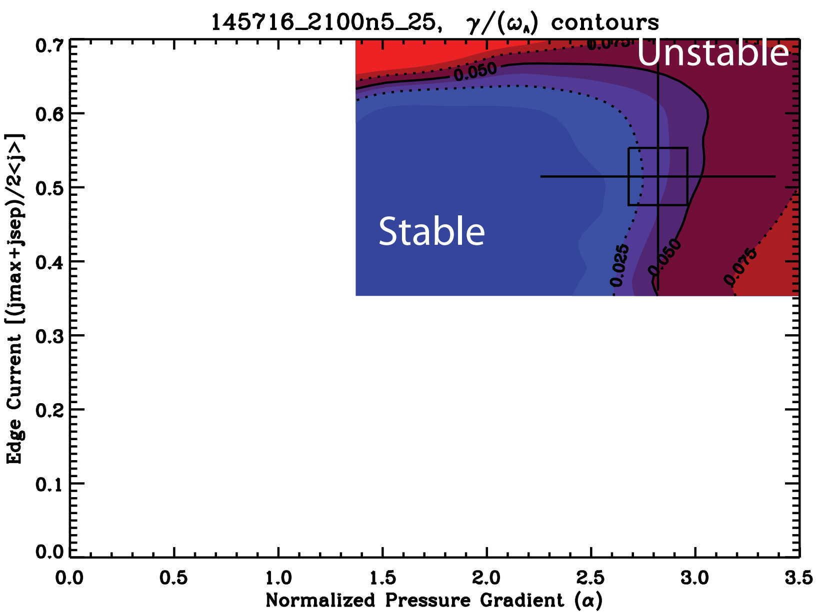

DIII-D, ELITE

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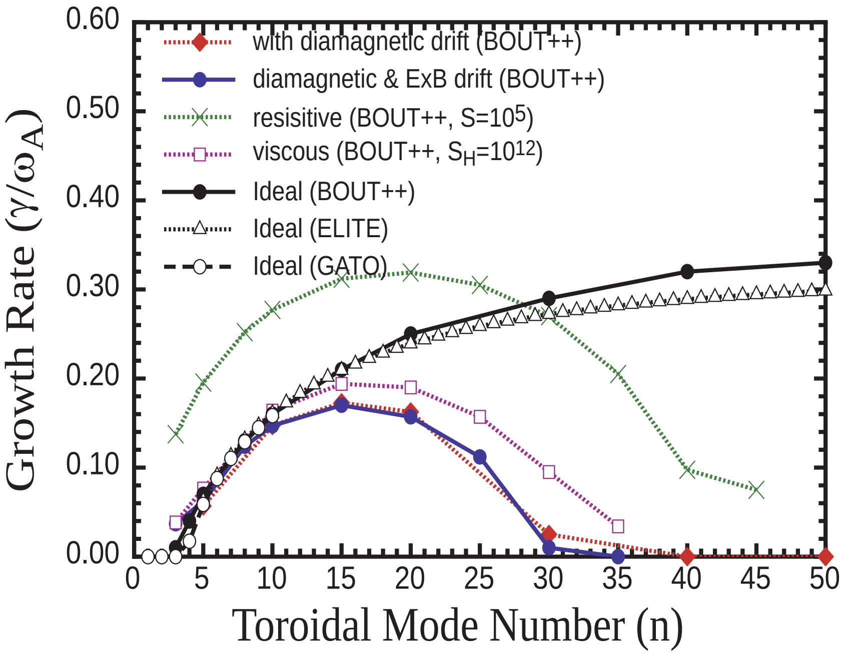

X. Xu, NF11

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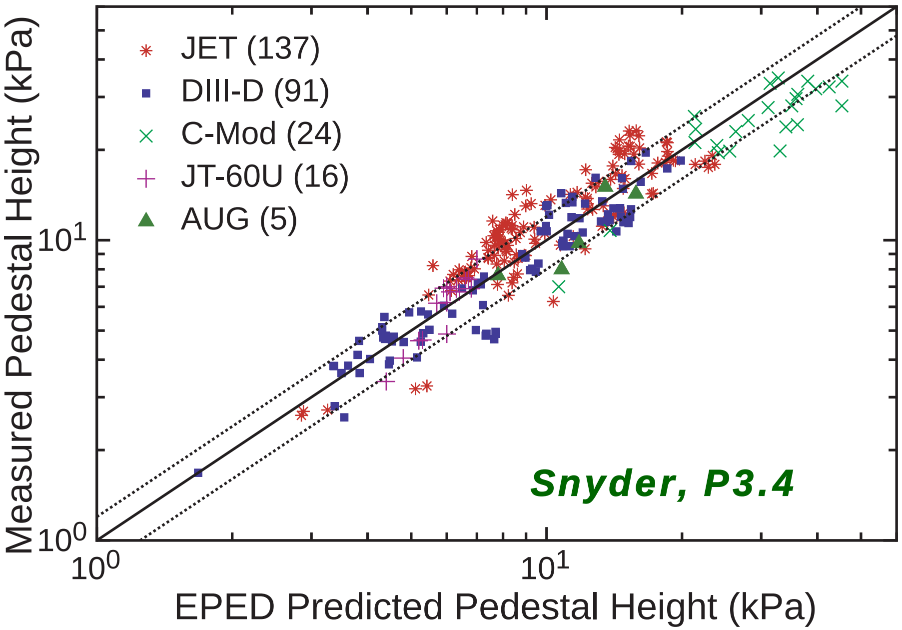
EPED class of models is an example of a testable pedestal prediction

- EPED1.x model couples peeling-ballooning stability limits to pedestal width model
  - **Dominant empirical dependence:** $\Delta_\psi \sim \beta_{pol}^{1/2}$
  - *Kinetic ballooning modes* are the width limiting mechanism in EPED 1.6x
- Confidence level has increased to the point that predictions are made *before* experiment

Comparison of EPED Model to 273 Cases on 5 Tokamaks



- Tests of EPED have expanded to include large range of device size, discharge type
  - EPED used to interpret recent DIII-D/C-Mod identity experiment
  - Comparisons of baseline and hybrid discharges in JET, with weak and strong shaping

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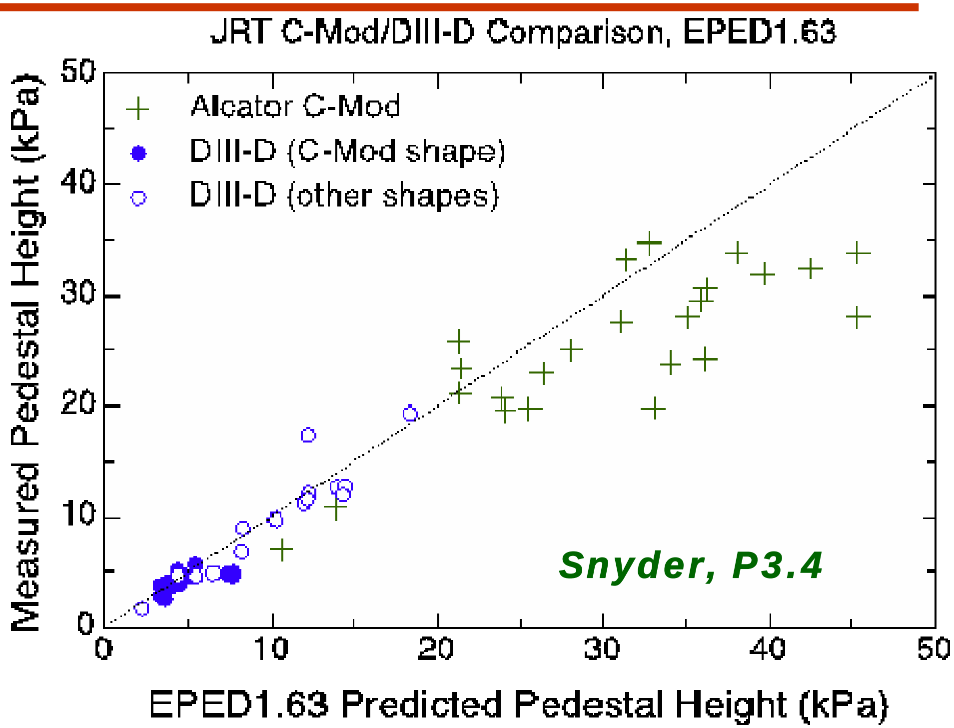

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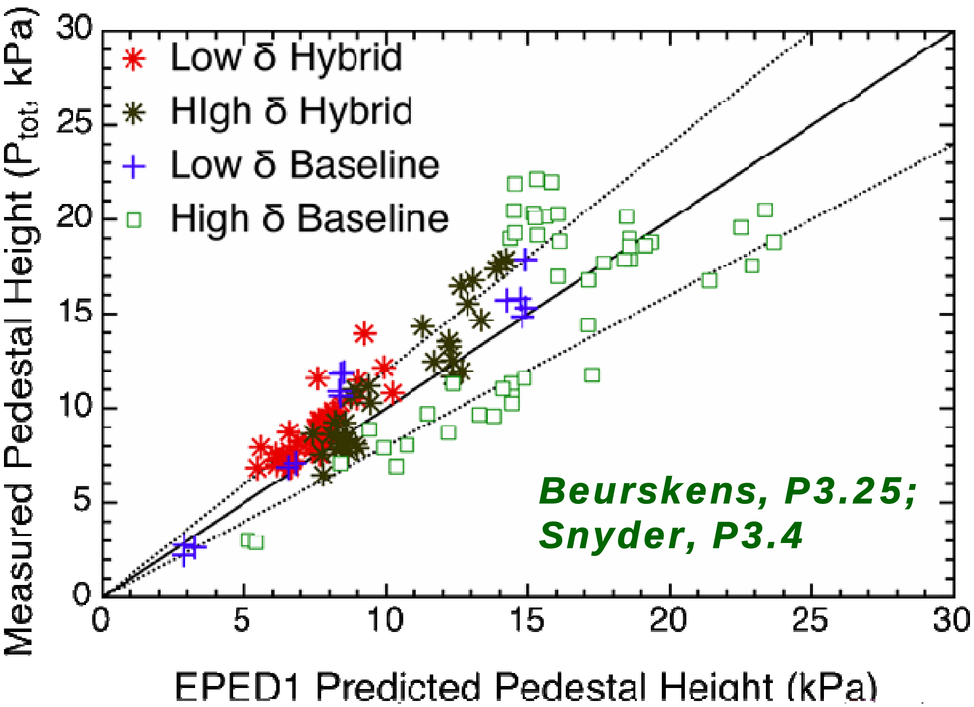

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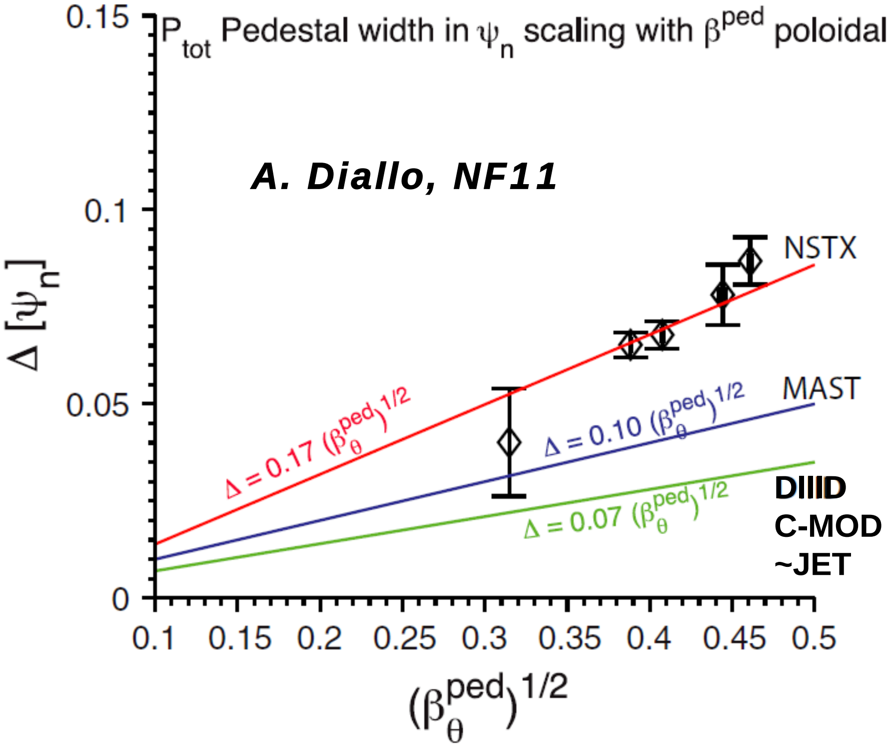
EPED shows promise when compared to experiment, but what issues remain?

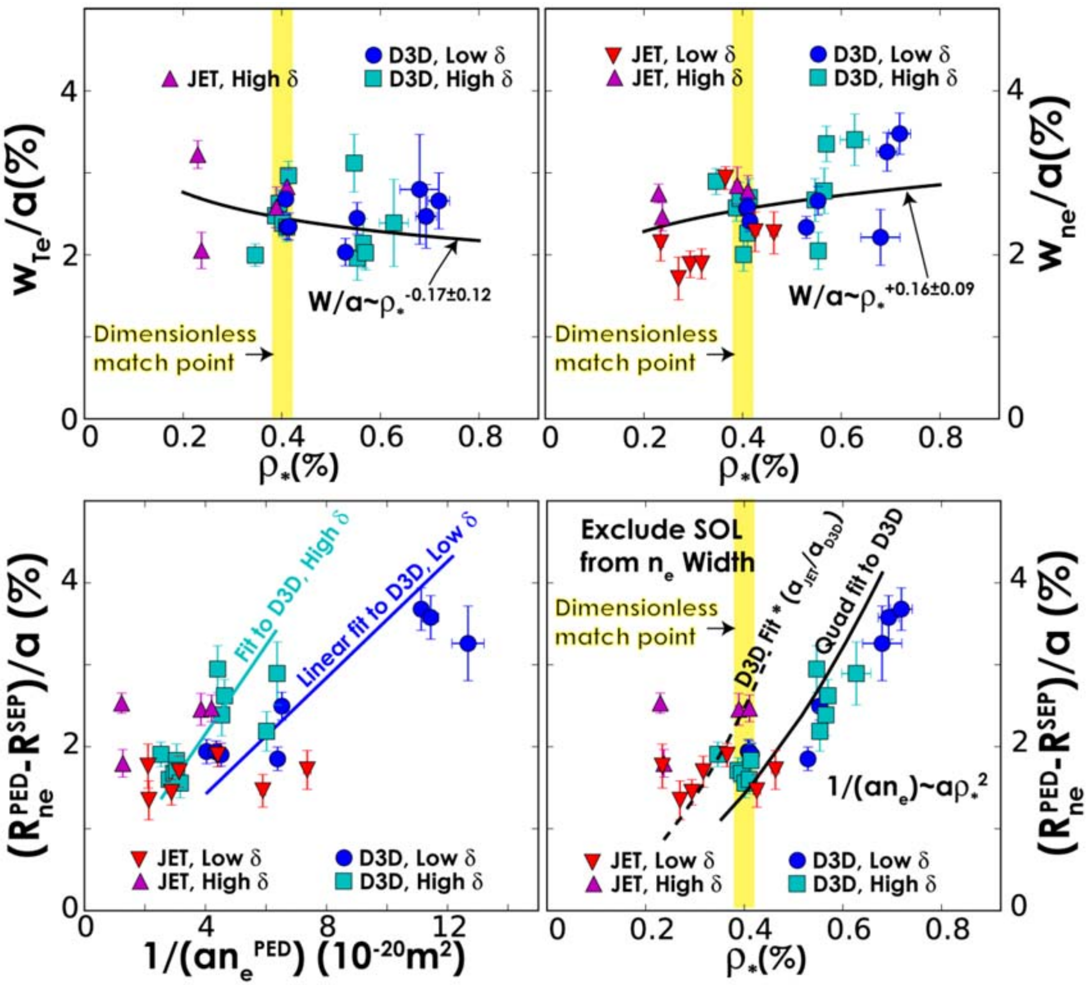


- Success of EPED hinges on $\Delta \sim C_0 \beta_p^{1/2}$
  - Can we rule out other width models?
- Is the KBM the dominant mechanism limiting the width?
  - Can we see the KBM in either experiment or modeling?
  - Or identify cases where the KBM constraint breaks down?
    - Lithiumized H-modes in NSTX?
    - Dependence of pedestal evolution on fueling rate in JET? – *Beurskens, P3.25*

- Mechanisms that limit n, T gradients independently of p are not included
  - ITER performance will be sensitive *e.g.* to how the pedestal and core fuel
- EPED provides ultimate pressure limit for a given width model in ELMy H-mode
  - What about ELM-suppressed regimes?

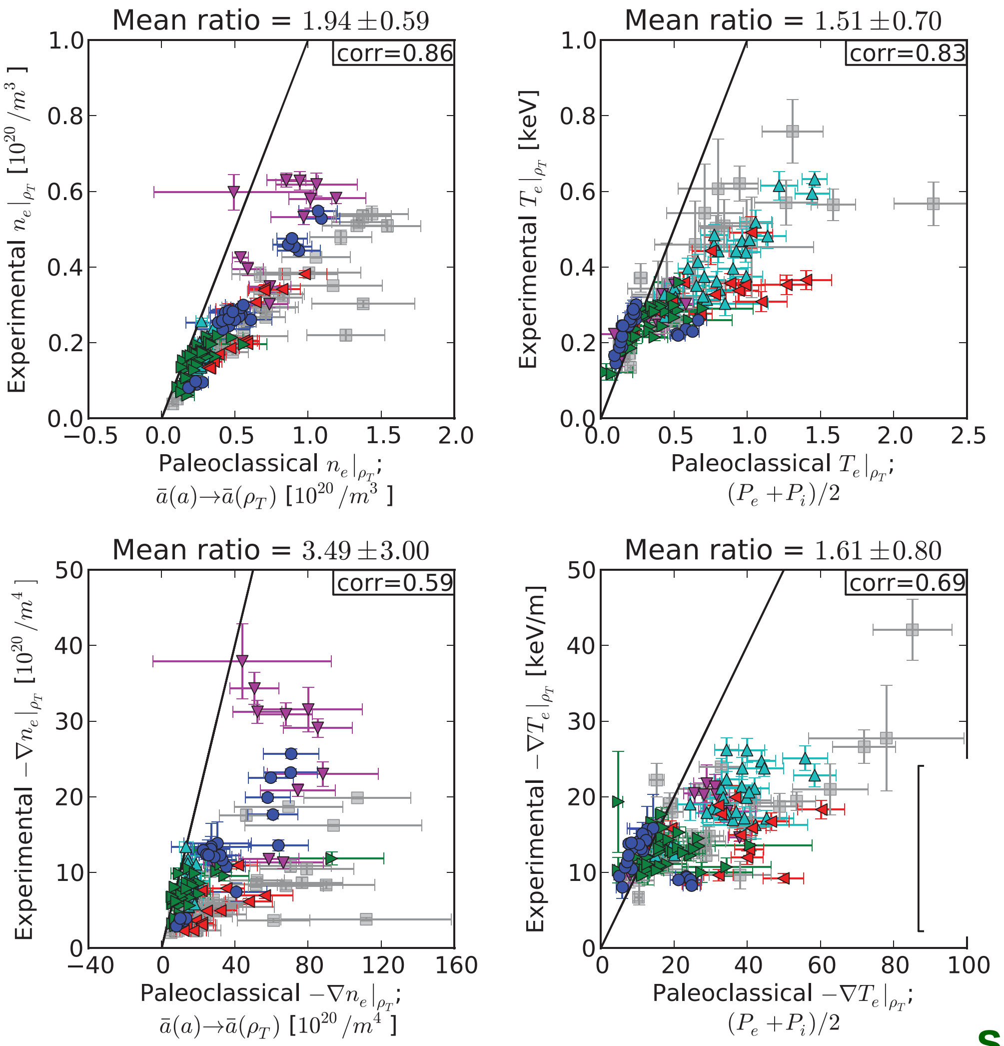
Multi-machine studies used for non-dimensional pedestal width scalings

Osborne, P.3.15; see also Beurskens, PoP11



- JET/DIII-D matching experiment finds near independence of pedestal width with ρ^*
  - *Inconsistent with models of shear suppression of drift wave turbulence predicting $\Delta\sim\rho^{*(1/2)}$*
- Slightly positive scaling of Δn_e with ρ^* associated with a shift in the n_e pedestal relative to T_e pedestal seen on DIII-D
- Neutral fueling effect?
- Extensions of width study to AUG, C-Mod are ongoing
  - *Schneider P3.5*

What can theory and simulation reveal about transport-limited pedestal?

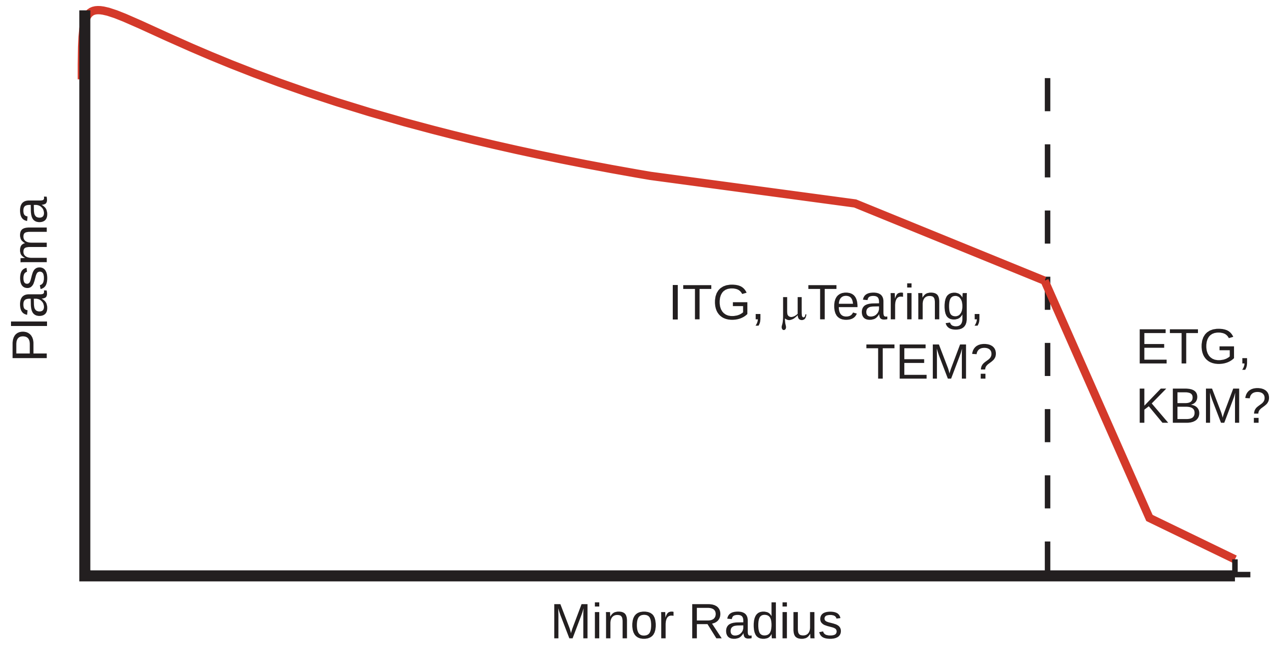


- Pedestal model based on paleoclassical processes gives irreducible level of transport
- ← Comparisons with DIII-D database performed
- *Model gradients ≥ exp. gradients*
  - Consistent with P.C. setting minimum level of transport
- P.C. predictions of pedestal profiles of χ_e, n_e compare favorably in analyzed DIII-D and NSTX discharges
  - *Callen, sub. PRL; Canik, PoP11*

Smith, P3.1; Callen, P3.18

What can theory and simulation reveal about transport-limited pedestal?

- Calculations of neoclassical transport (*e.g.* with XGC0) show that additional anomalous transport is required to relax pedestal gradients
- Predictions from paleoclassical-based model can yield similar results – *Smith, P3.1*
- Not surprising. Experimentalists see turbulence everywhere, and most of it probably drives some sort of transport



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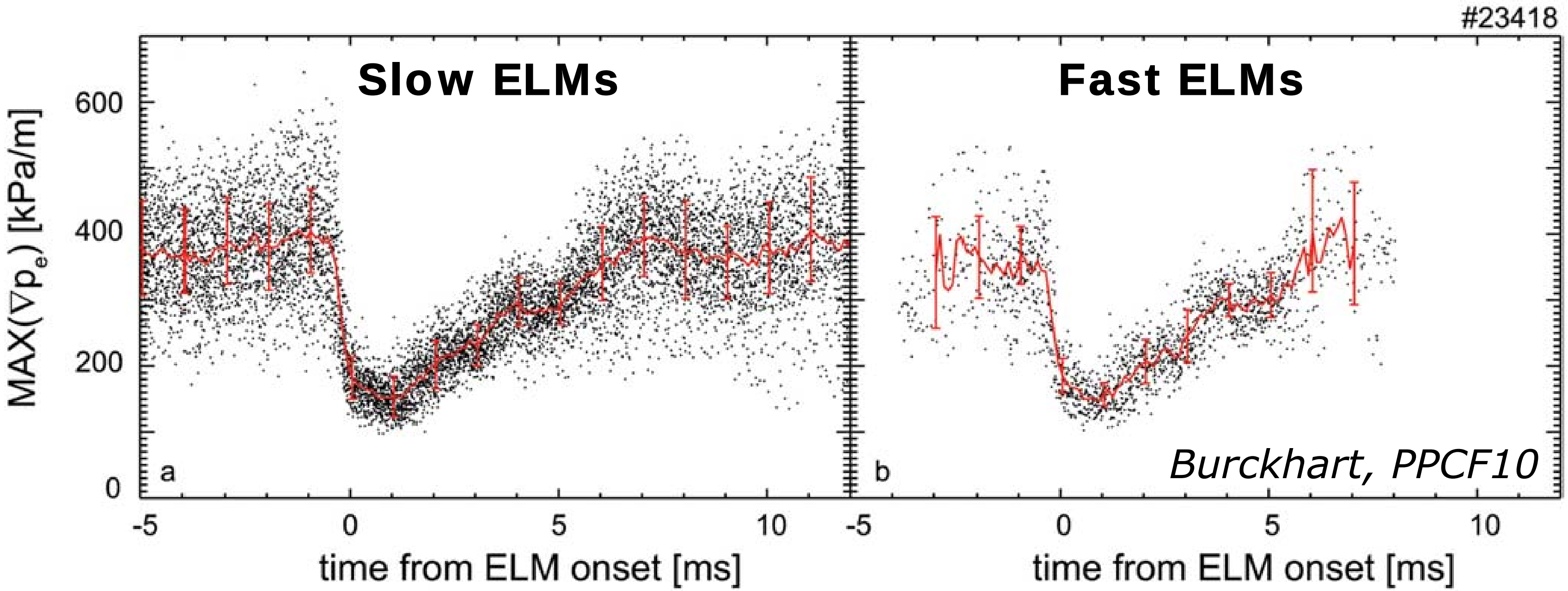
- BOUT++ has been used to identify potential unstable resistive ballooning modes in C-Mod EDA H-modes – *Xu, P2.22*
- Gyrokinetic simulations implemented in a number of codes are extended into the pedestal region
  - GYRO (eigenvalue code) and GEM (initial value code) are benchmarked on a common DIII-D case – *Wang/Xu P3.32*
    - ITG modes dominant inside ψ_n~0.96
    - Mix of Alfvenic and drift wave modes in the pedestal
    - KBM is difficult to resolve
  - GS2 (local GK code) simulations on MAST identify a transition between microtearing modes and KBMs at the pedestal - *Saarelma, P2.23; Roach, P3.36*

III. DYNAMICS OF PEDESTAL FORMATION, FLUCTUATION EVOLUTION

What can transients in the pedestal teach us?

- High time and spatial resolution diagnostics, combined with repeatable ELM-cycles, yield extensive information about pedestal evolution
  - *e.g. Eldon, P5.18; Osborne, P3.15; Beurskens, P3.25*
- Time scales of evolution, pedestal structure, can answer questions about physical processes limiting pedestal



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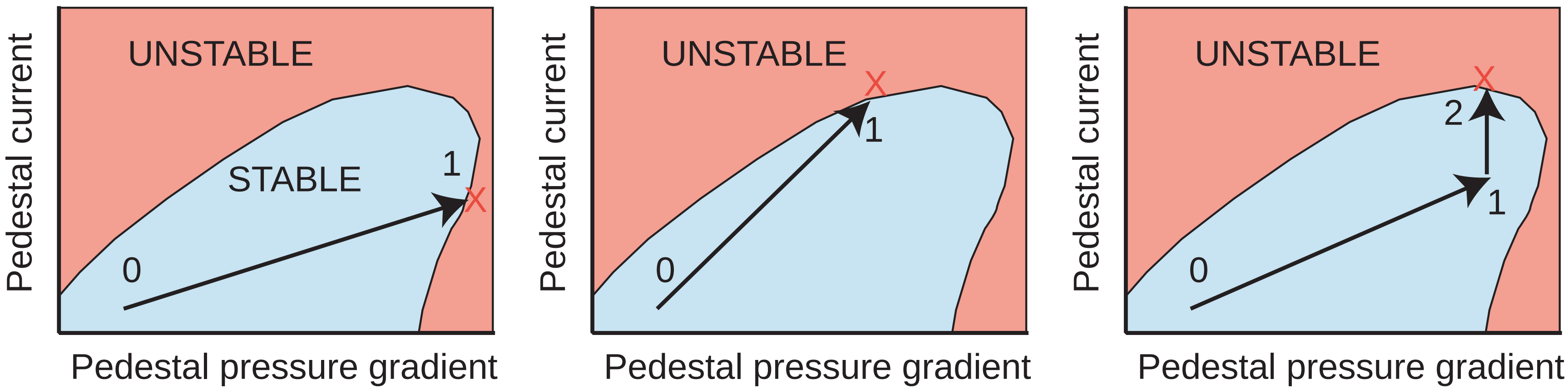
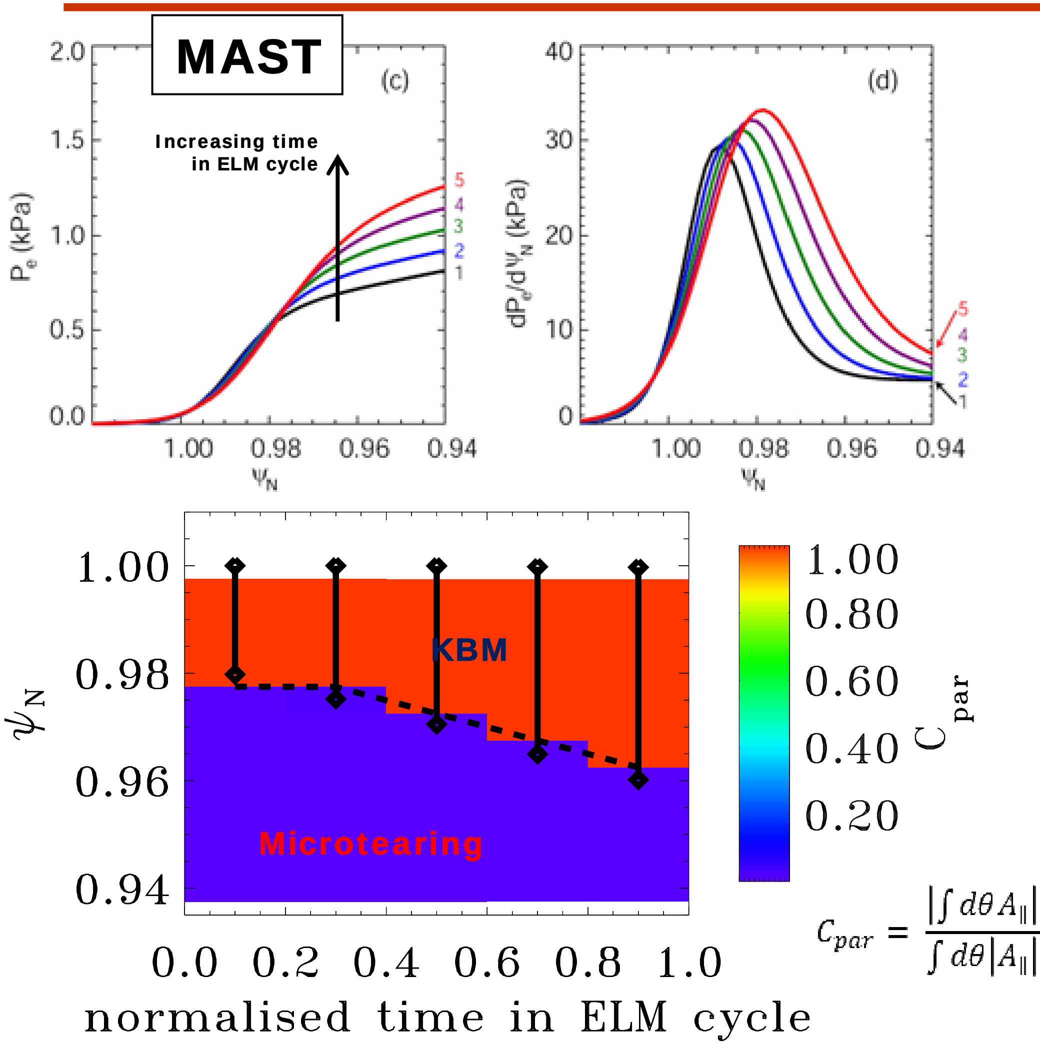


High ν^* ballooning? | Low ν^* peeling? | Moderate ν^* 2-phase?

Gyrokinetic tests of the KBM and associated width evolution



Saarelma, P2.23; Roach, P3.36

- MAST: $(dp/d\psi)_{max}$ almost constant through the ELM cycle as pedestal *widens*
  - Entire pedestal ideal MHD n= ∞ ballooning and kinetic ballooning mode unstable
  - Finite n limit decreases during the ELM cycle and meets the experimental value just before an ELM.
- EPED idea that KBMs limit $dp/d\psi$ and the finite n modes limit the width seems ok.
- Pressure pedestal evolution qualitatively similar on AUG (Burckhart, PPCF10), DIII-D *(Osborne, P3.15)*, NSTX *(Diallo, P5.22)*
- But, on JET, pressure width is fixed or decreasing during ELM cycle *(Saarelma, P2.23; Beurskens, P3.9)*

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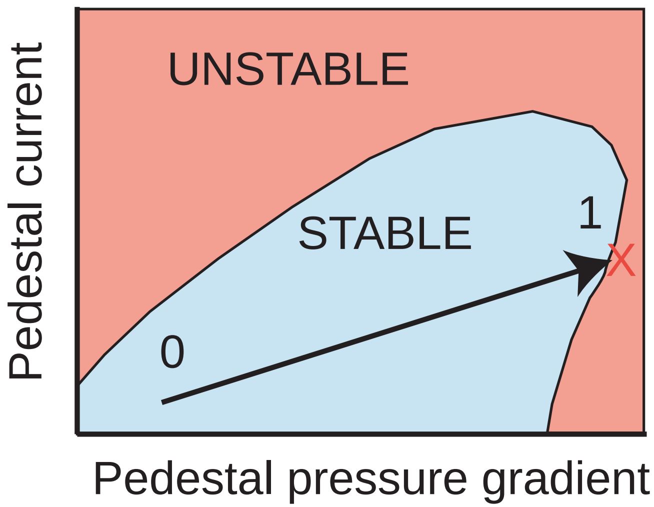

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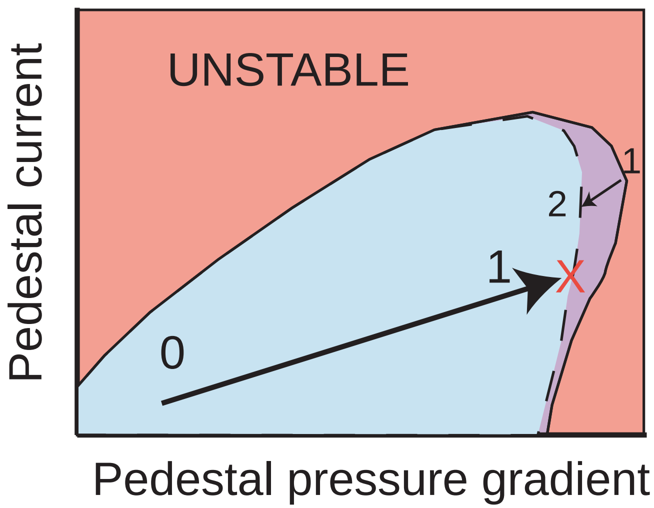

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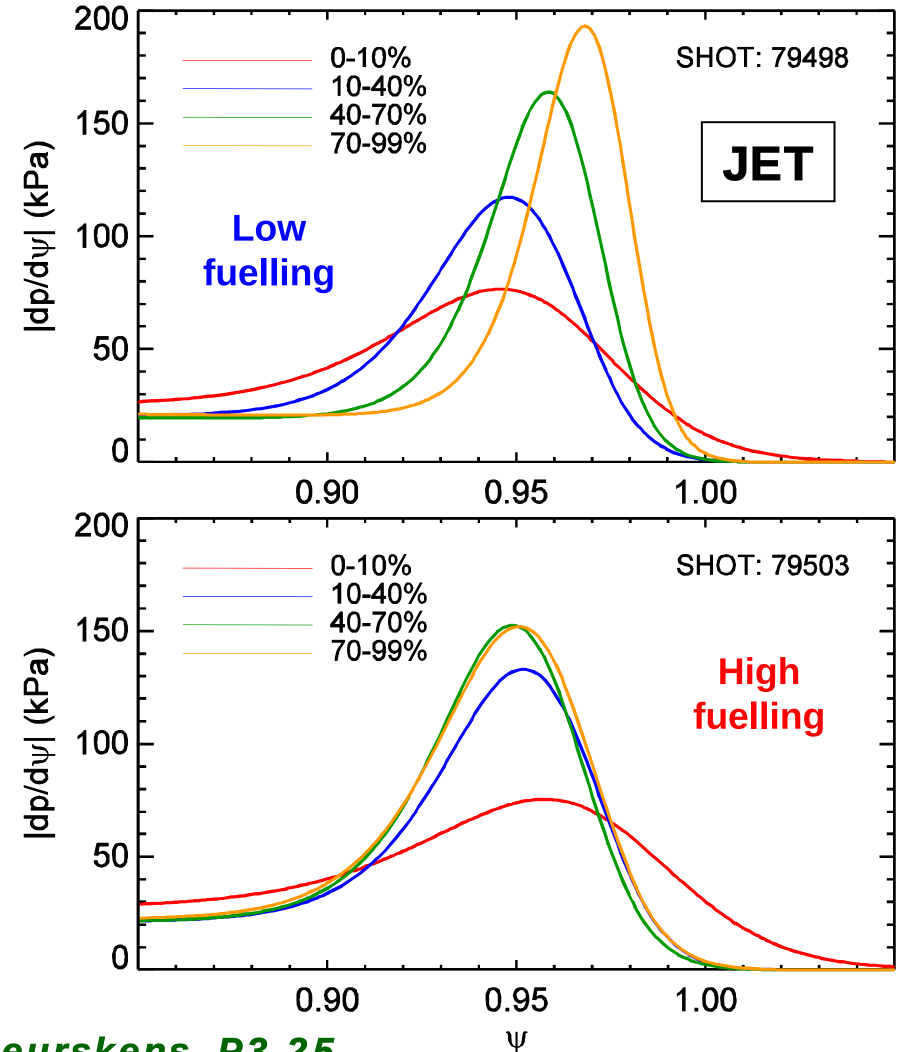

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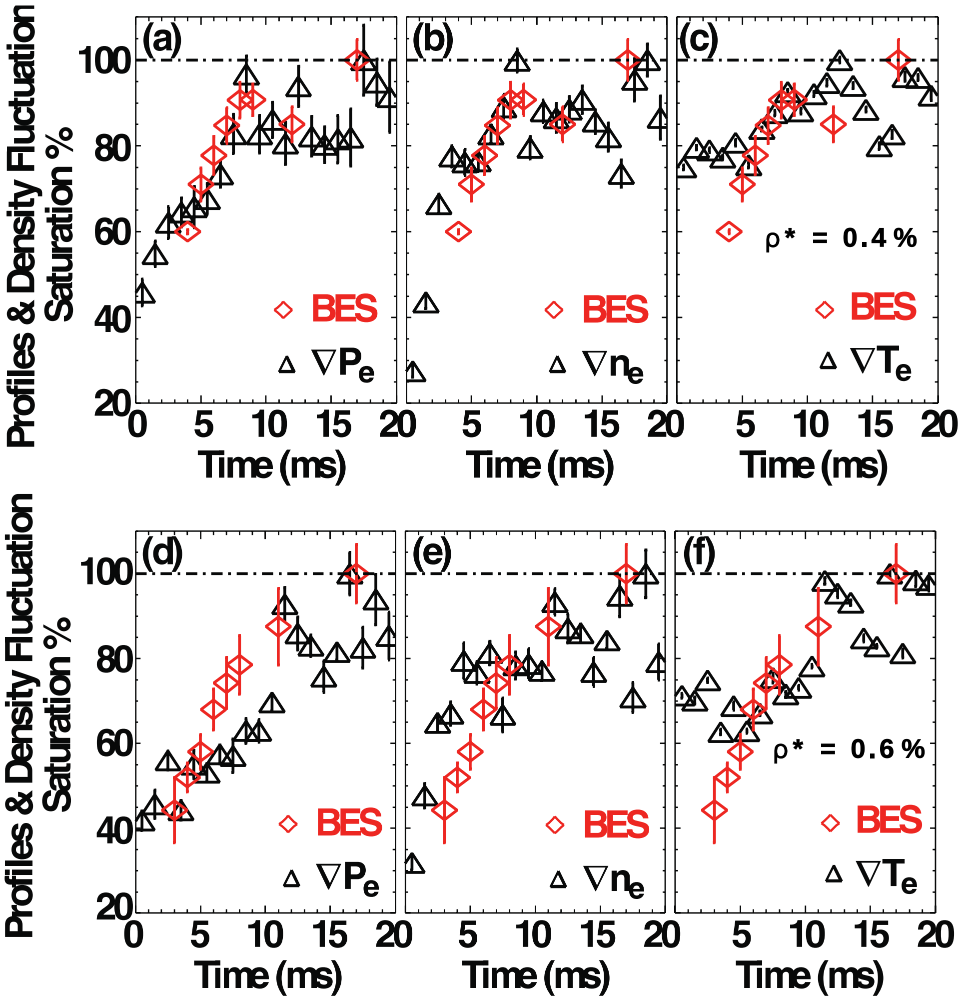
Pedestal saturation: Looking for signatures in the turbulence



Yan, PoP11

- DIII-D: Correlation between broadband turbulence and pressure gradient observed between ELMs
  - Relative dn/n in pedestal increases to ~ 80% within a few ms, then saturates, or increases more slowly
  - Similar trend observed for electron pressure gradient
- Cause and effect? Does broadband turbulence stop pressure rise?
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- Additional KBM candidate found in QH-mode, replacing EHO

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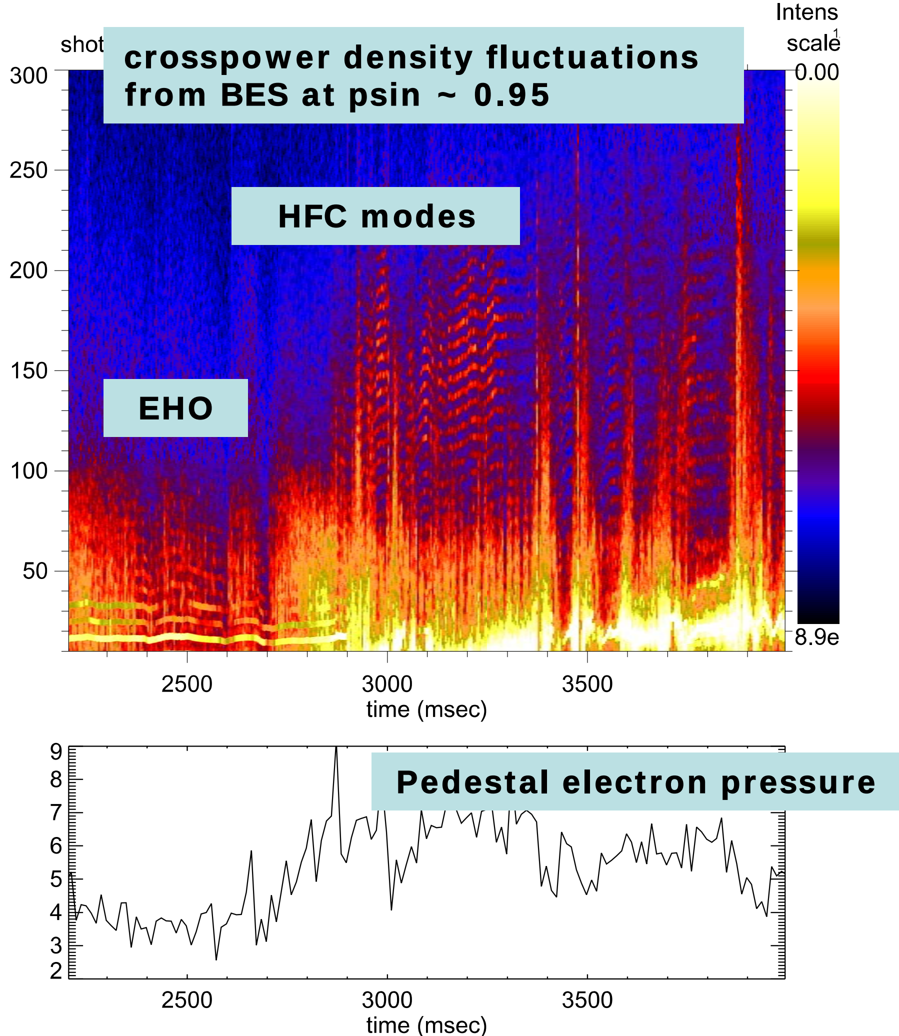

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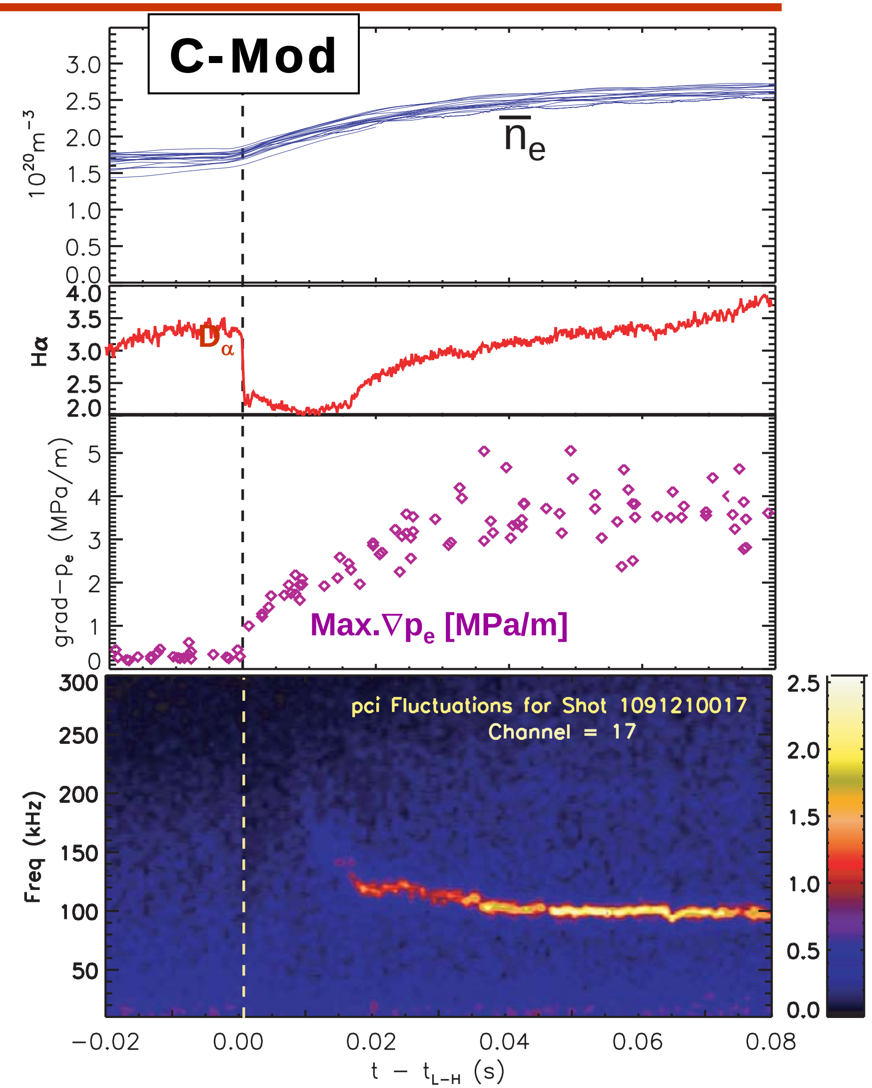
Similar techniques can be used to study the evolution of pedestal following L-H

- Evolution of pedestal and fluctuations diagnosed in EDA H-modes on C-Mod
  - Quasi-coherent mode (QCM) amplitude saturation correlates with pedestal gradients achieving stationary values
- Time scales of pedestal evolution important to characterize, model for ITER
  - Affects alpha heating rate, H-mode sustainment
  - Time to first unmitigated ELM?
- Pedestal evolution studies can also give insight into transport processes that set pedestal structure
  - ***Pankin, P5.4; Willensdorfer, P3.23, Diallo, P5.22; Zoletnik, P5.24***

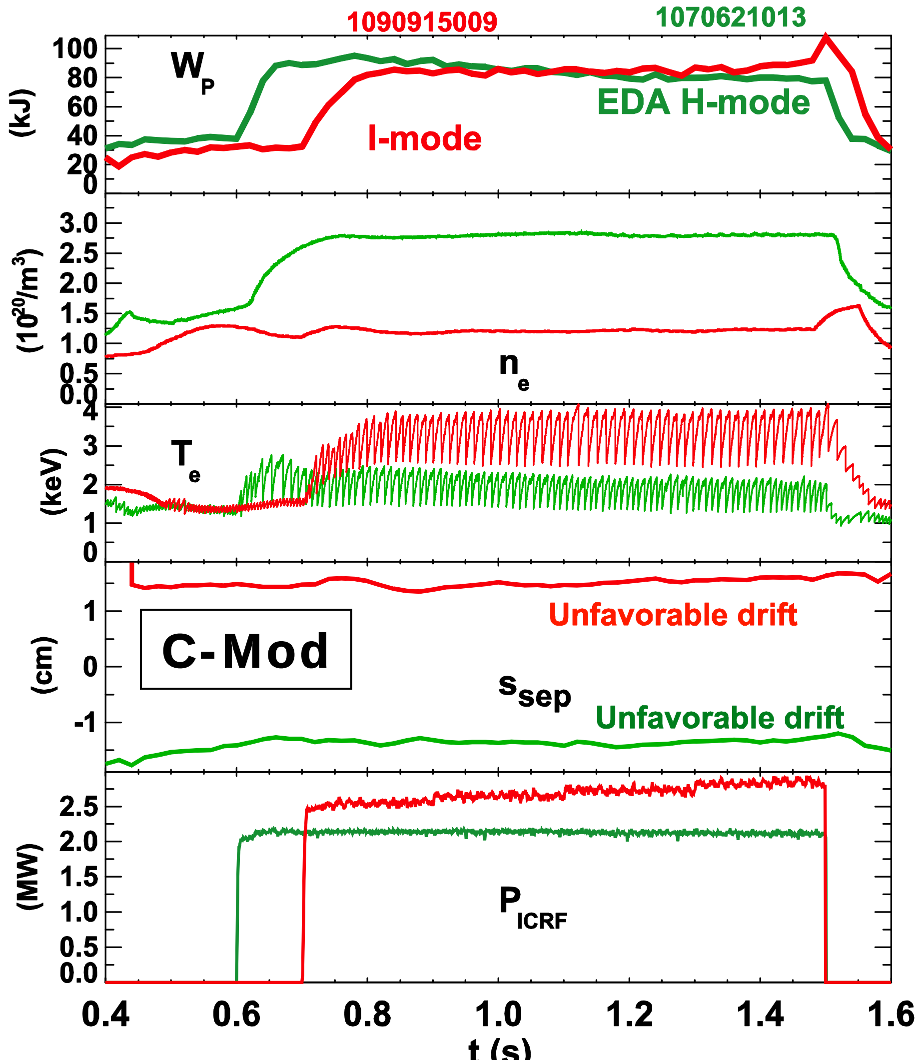


Other interesting questions about the H-mode pedestal and confinement

- How does pedestal fuel?
  - Pinch vs. diffusive particle transport vs. neutral penetration
  - A fundamental predictive capability for the density pedestal is highly desirable, as the ITER edge will be thick to neutrals like no existing device
  - *Canik, P3.6; Stacey, 5.14*
- How does species mix affect pedestal and confinement?
  - *Urano, P3.17*
- Effects of edge rotation and rotation shear on the pedestal
  - ITER will not have driven rotation, like today's NBI-heated devices
  - Some of the most dramatic changes in pedestal structure are associated with changes in pedestal Ω or $d\Omega/d\psi$
  - *Sontag, P3.7; Maingi, P3.16; Kamiya, P3.20*
- Are there differences associated with dominant electron vs. ion heating?
  - *Sommer, P1.8; Lore, P3.8*

Other interesting questions about the H-mode pedestal and confinement

- How do we explain (and exploit) pedestals in regimes where particle and thermal transport are partially decoupled
  - (e.g. I-mode, QH-mode, EP H-mode)?
  - Increasing the ratio of particle to thermal transport → high confinement with ELMs naturally suppressed
  - *Garofalo, P1.2; Maingi, P3.16; Hubbard, P3.28*



DISCUSSION POINTS

Improving understanding of pedestal structure: possible discussion points

- Confident area: peeling-ballooning modes provide upper bound on pedestal pressure
- What limits the radial extent of the pedestal?
  - Why does transport blow up inside ψ~0.93—0.97?
  - Is KBM-like description of $\Delta_\psi \sim \beta_{pol}^{1/2}$ good enough?
  - Are there better candidate mechanisms for determining width, say yielding a $\Delta_R \sim R$ dependence?
- Pedestal height limits in ELM-suppressed regimes → will they extrapolate favorably to ITER?
- Can we model the time scales of pedestal evolution following L-H? Between ELMs?
- Models often do not treat density, temperature profiles independently
  - But they must in order to explain cases like I-mode
- Pedestal fueling and particle transport is not well understood in H-mode plasmas
  - What interpretative modeling and experimental diagnosis is needed?
- Details of turbulence suppression and transport reduction in barrier are critical for understanding. What are the dominant modes and where?

Improving understanding of L-H transition: possible discussion points

- L-H transition trigger: is it just shear suppression of turbulence, or is there something more?
- Can local quantities uniformly describe L-H trigger, in the same way that pedestal pressure sets core confinement in H-mode?
- What of the interplay of turbulence and flows leading up to the transition? How prevalent are limit-cycle oscillations?
- Relating local L-H triggers to power requirements
  - Is there simple theory that can do this?
  - Is there any theory that can do this?

Preview Talks

- A. Diallo
  - "Observation of Turbulence Correlation in the Pedestal during the Inter-ELM phase in NSTX" (P5.22)
- W. Fundamenski
  - "A new model of the L-H transition in tokamaks" (P3.14)
- G. Xu
  - "The role of zonal flows for the L-H transition at marginal input power in the EAST tokamak" (P3.02)
- P. Sauter
  - "Evidence for the role of the ion channel in the L-H transition in ASDEX Upgrade" (P3.21)

End of talk

Threshold conditions for transitions to I-mode and H-mode with unfavourable ion drift direction

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J. W. Hughes, Y. Ma, E. S. Marmar, Y. Lin, M. L. Reinke
MIT Plasma Science and Fusion Center

Poster presented at
13th International Workshop on H-mode Physics and Transport Barriers
10-12 October 2011,
Oxford, UK

This workshop presentation contains unpublished results, some of a preliminary nature. Please do not distribute further, or include material in other presentations, without contacting the authors first.

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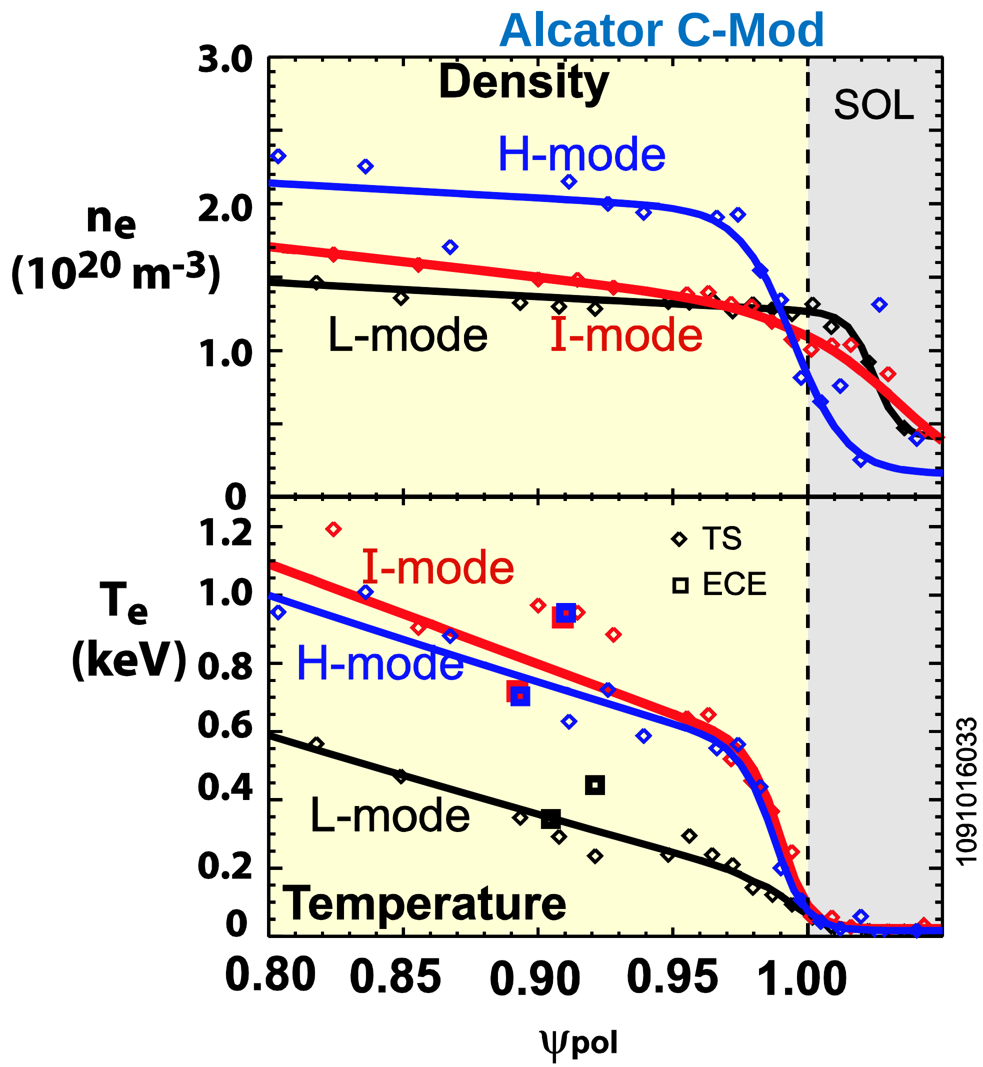
Overview of I-mode regime

- In plasmas with **unfavorable ion B×∇B drift, away from the active X-point,** as input power is raised, typically get separation of thermal and particle transport barriers.
- First, in **I-mode regime***, get only a thermal/temperature barrier.
- At still higher power, get transition to traditional **H-mode**, with also a particle/density barrier.

* Note: This phenomenon, first observed transiently, was referred to as "slow transitions" or "Improved L-Mode" in prior H-mode workshop presentations [Hubbard HMW 2007, HMW2009], and on ASDEX Upgrade [Ryter 1998].

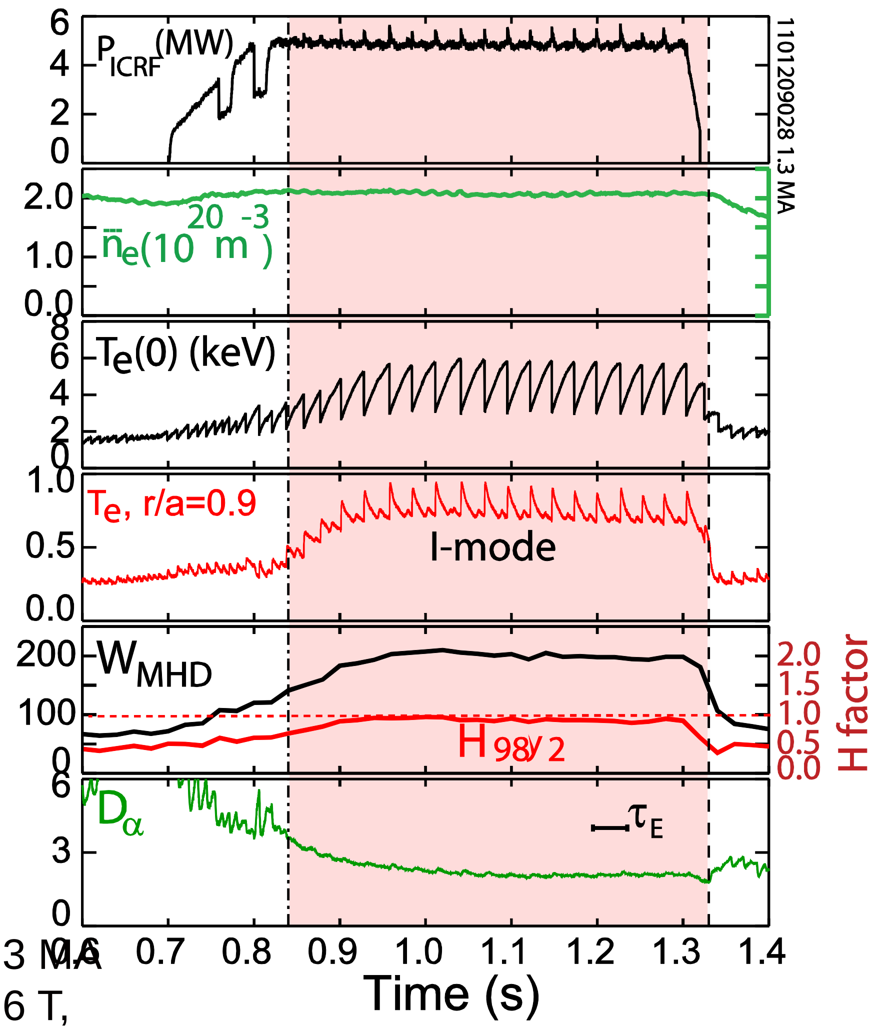
I-mode regime has T_e and T_i pedestal, without density barrier.



- Steep T pedestal (electrons and ions) leads to increased core T, stored energy.
- L-mode density profile, broad SOL.

- H-mode has similar T pedestal, but much higher and steeper density pedestal.

I-modes have now been maintained in steady state



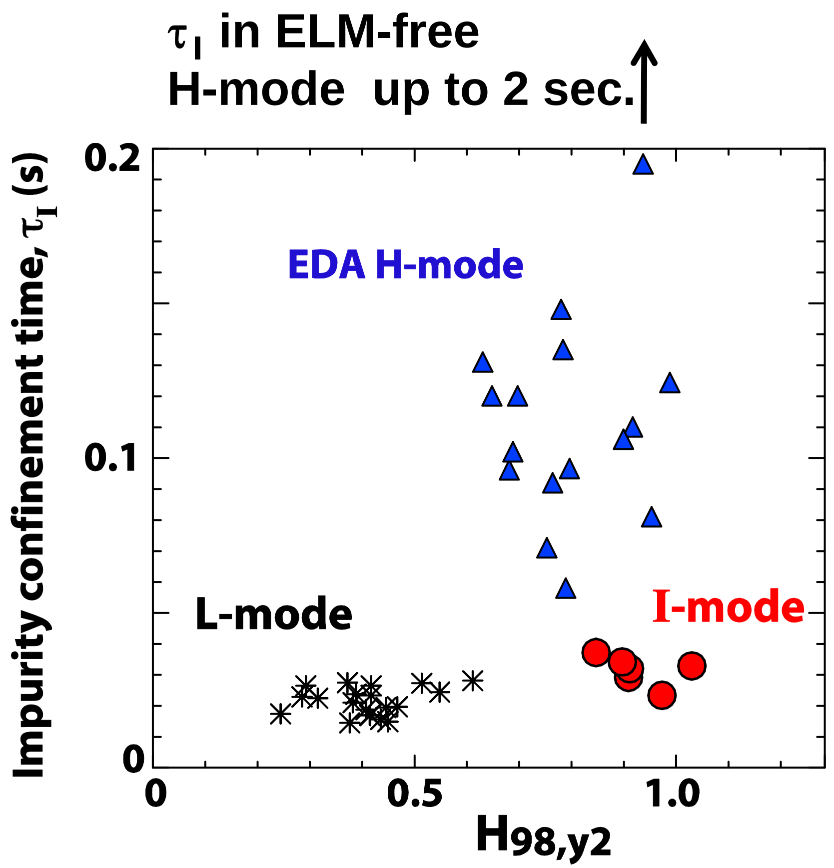
1.3 MA
5.6 T,
USN

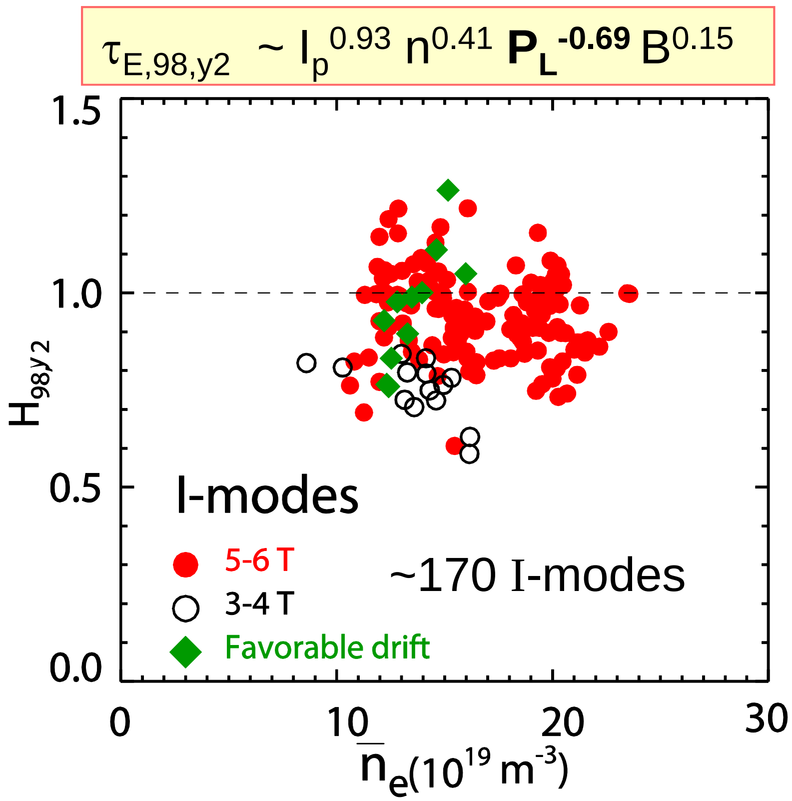
- **I-modes maintained on C-Mod with steady conditions for many τ_E,** in many cases limited by plasma and heating pulse duration.
- Usually **ELM-free.**

- Steady I-modes have also been observed on ASDEX Upgrade

[Ryter EPS 2011, Hubbard EPS 2011]

I-mode regime combines L-mode like particle transport with thermal confinement ~ H-mode





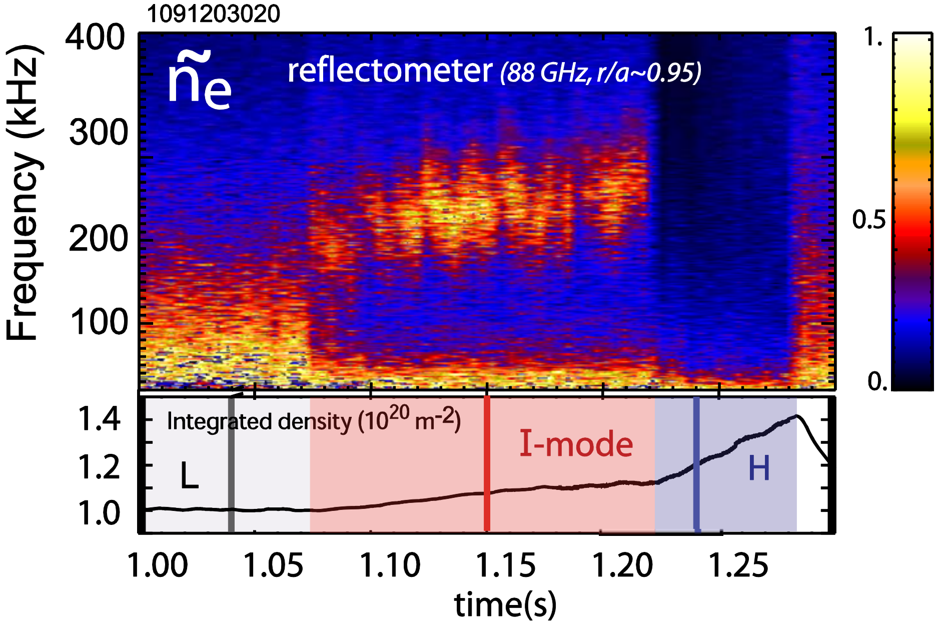
τ_I measured with laser ablation of Ca.

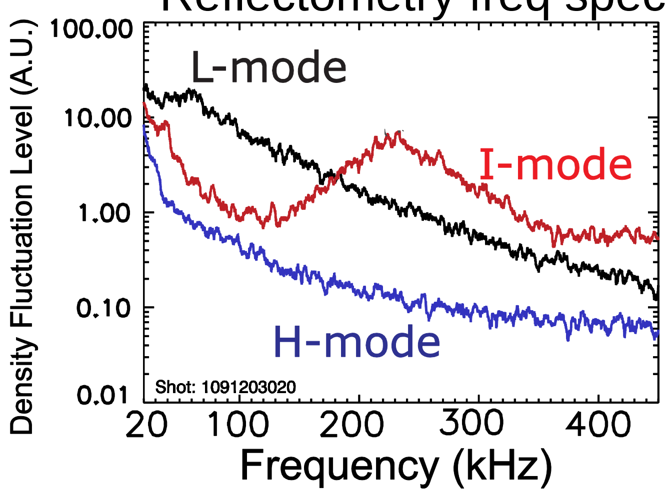
[Whyte, NF 2010]

Wide data set shows **$H_{98,y2}$ 0.7-1.2**, But some differences in τ_E scaling, notably **much lower power degradation.**

Changes in edge fluctuations at L-I and I-H transitions

- At **L-I transition**, as the T pedestal forms, see
  - DECREASE in edge broadband turbulence (n and B) in mid-f range (~60-150 kHz)
  - PEAK in turbulence at higher f "weakly coherent mode" (~ 250 kHz)
- At the **I-H-mode** (particle barrier) transition, remaining turbulence drops suddenly, n_e rises. Suggests WCM is contributing to particle transport in I-mode.

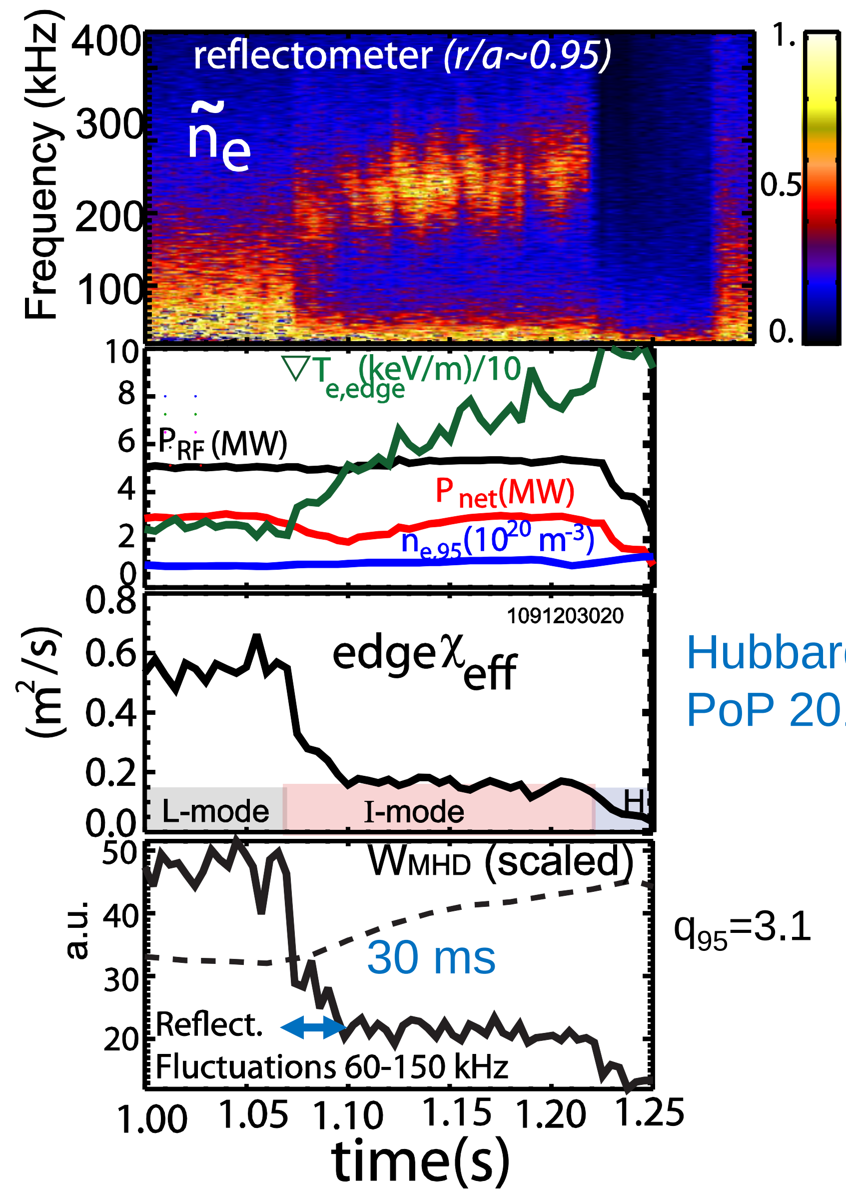




1.3MA, 5.8T
q_{95}=3.1

Edge thermal transport is correlated with mid-f turbulence

- Edge ∇T is steepening at L-I transition, at near-constant P_{net} and edge n_e
  $\Rightarrow$ **edge χ is decreasing.**
- Little or no change in D_α, Ly_α, density profiles or impurity confinement indicates that **particle transport is NOT changing significantly.**
- Decrease in edge χ from L to I-mode correlates on C-Mod to the drop in mid-f turbulence. (~60-150 kHz)
  - Sharpest drop at low q_{95}.
  - Analysis of v_{ExB} shows spectral changes are not dominated by Doppler shifts.



Hubbard PoP 2011

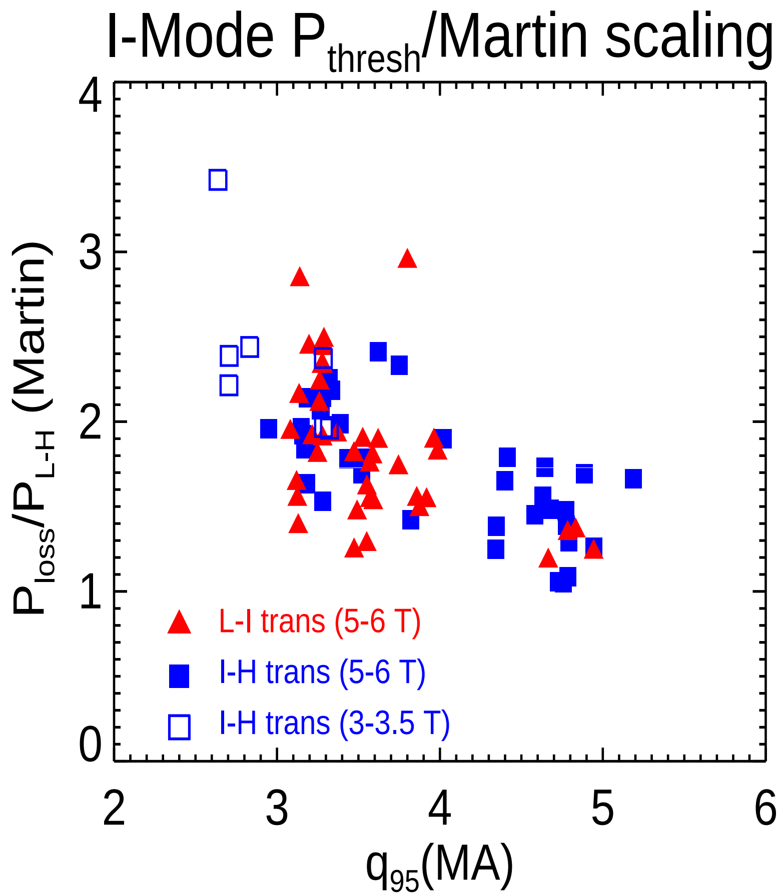
q_{95}=3.1

L-I and I-H Power Thresholds

- In unfavorable drift, thresholds for L-I and I-H transitions:
  - Are generally higher than L-H thresholds with favorable drift.
  - Scale very differently than usual L-H scalings (developed for favorable drift).
  - Have a lot of overlap

- Key questions:
  - *What physics determines L vs I vs H regime?*
  - *How to reliably obtain and stay in I-mode, avoiding H-mode transition? How wide is the "power window"?*
  - *Is there hysteresis?*

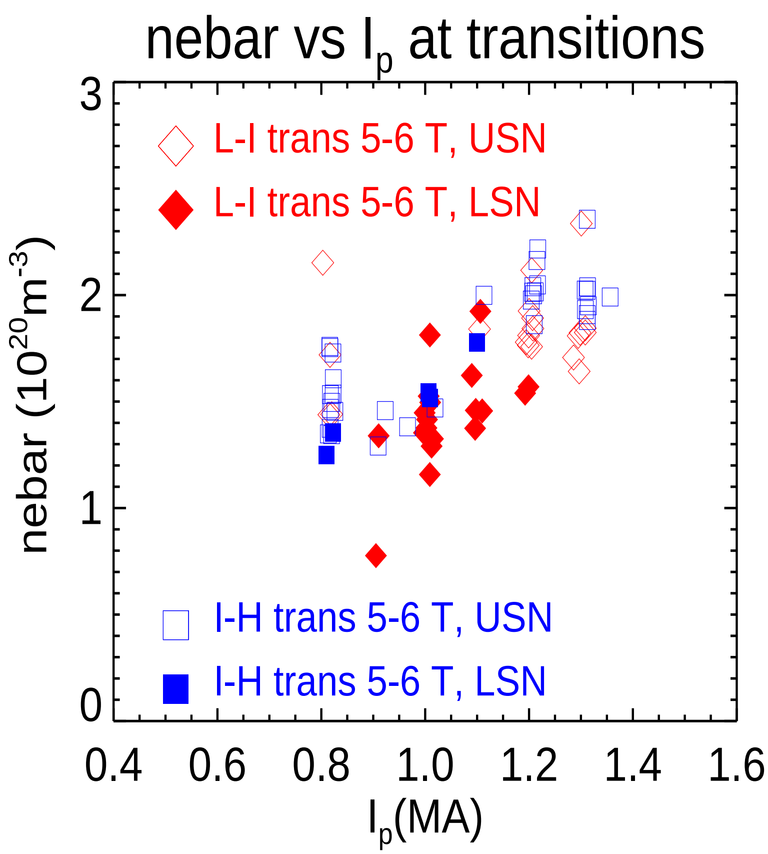
Transition thresholds do not fit ITER L-H scalings



- Strong q_{95} dependence (higher P_{thresh} at higher I_p).
- Large scatter at given q_{95}, indicating other dependences are different.
- Large overlap between L-I and I-H thresholds; scalings [eg Martin 2008] do not predict which regime a plasma will be in at given power.

New power scalings for transitions with unfavorable drift are needed!

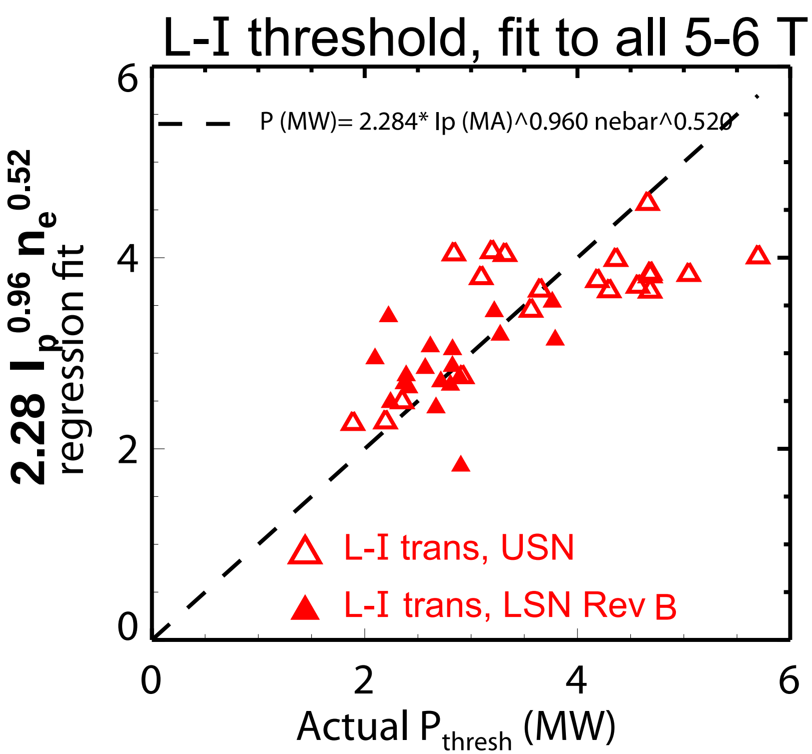
Wide database of I-modes and transitions on C-Mod

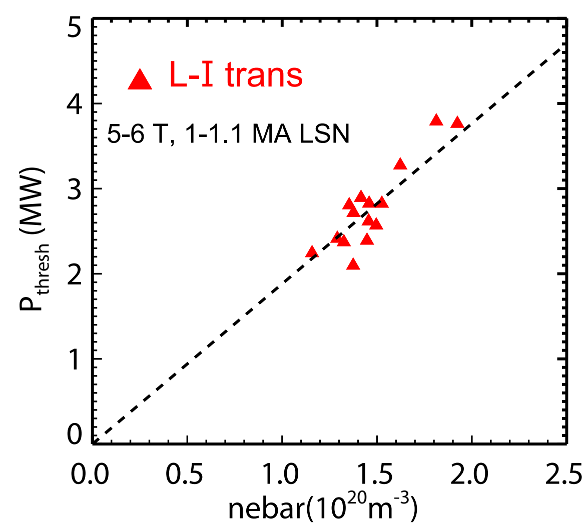


- Unfavorable drift: Both USN, and LSN, reversed B_T.
- ICRF Heating; D(H) minority and D(He^3) mode conversion.
- B_T 3-6 T; **For this study, restricted to 5-6 T since most discharges in this range**:
  - 169 I-mode time slices
  - 39 L-I transitions
  - 40 I-H transitions.
- I_p 0.8-1.35 MA.
- Average n_e 0.8-2.4 $x10^{20}$ m^{-3}
  - n_e and I_p have some correlation, so hard to separate dependences.
  - Also LSN discharges (closed divertor) have lower n_e.

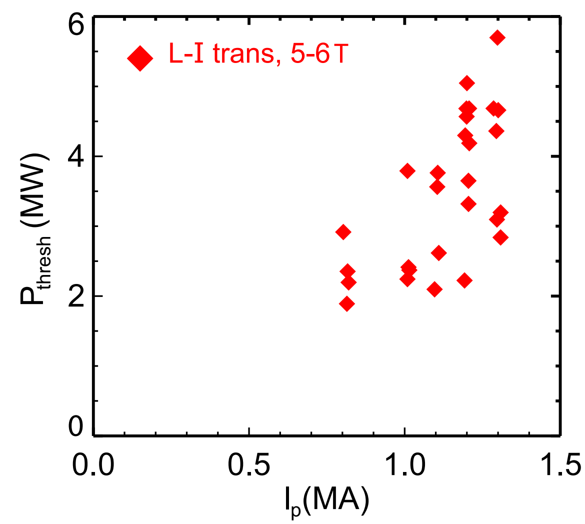
L-I power threshold increases with I_p *and* n_e

- Regression over all transitions gives **P_{loss} (L-I) ~ $I_p\ n_e^{0.5}$**
  - Fit underpredicts the highest current and density thresholds.



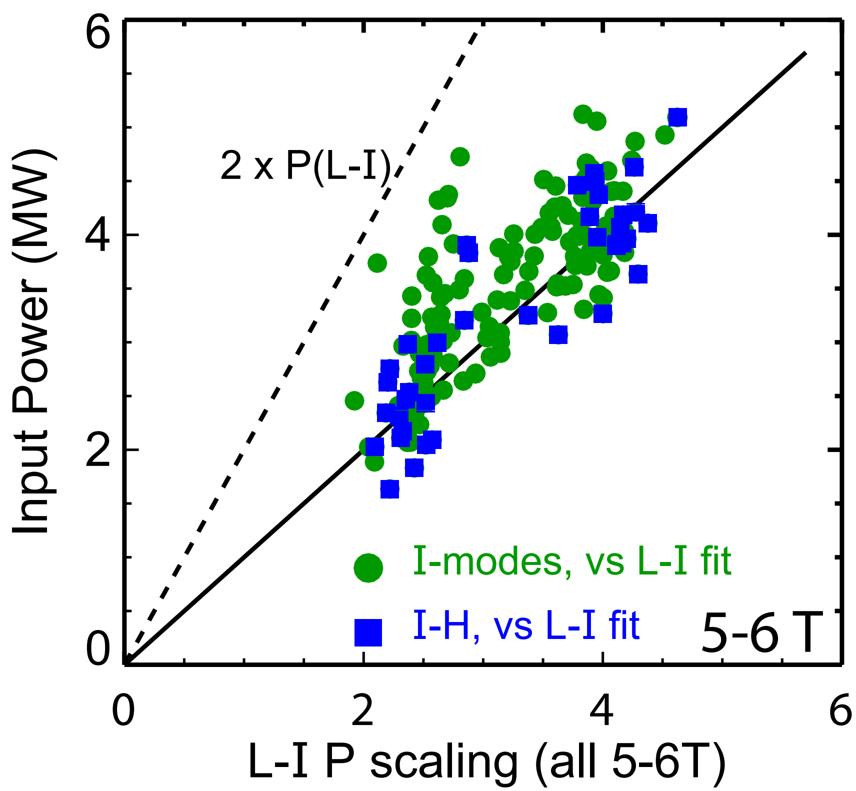


Density scan at fixed I_p, shape (1 MA LSN) shows **~linear n_e dependence**



Plasma current dependence (all 5-6 T transitions)

Power “window” in I-modes up to 1.8x L-I threshold

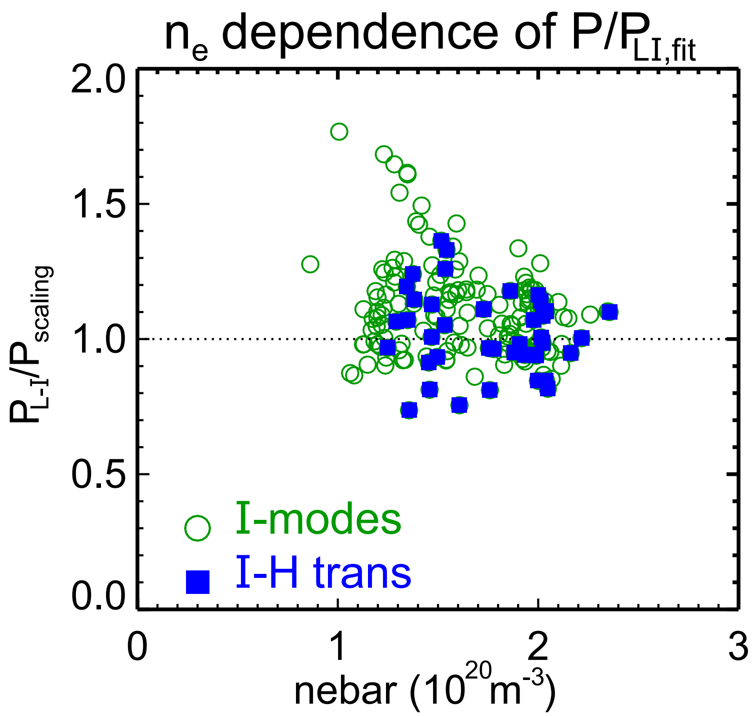


- Divided power in I-modes by new “L-I scaling”.
  - Range up to 1.5 in USN discharges, 1.8 in LSN discharges.
- BUT I-H “thresholds” (blue points) are scattered randomly, often LOWER power than I-modes without transition (green).

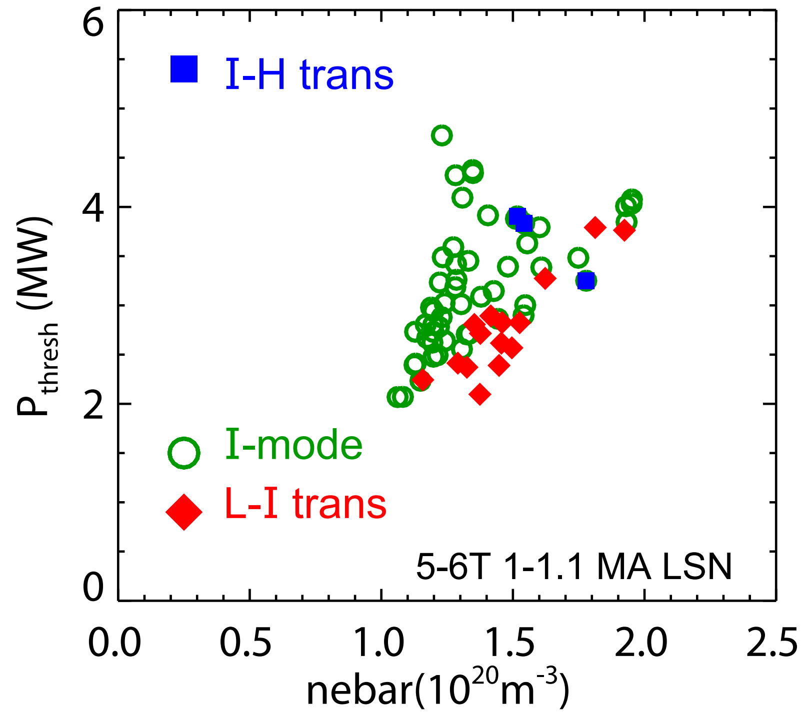
- **I-H threshold conditions, scaling are not yet clear!**

I-H threshold, power "window" may *decrease* with density

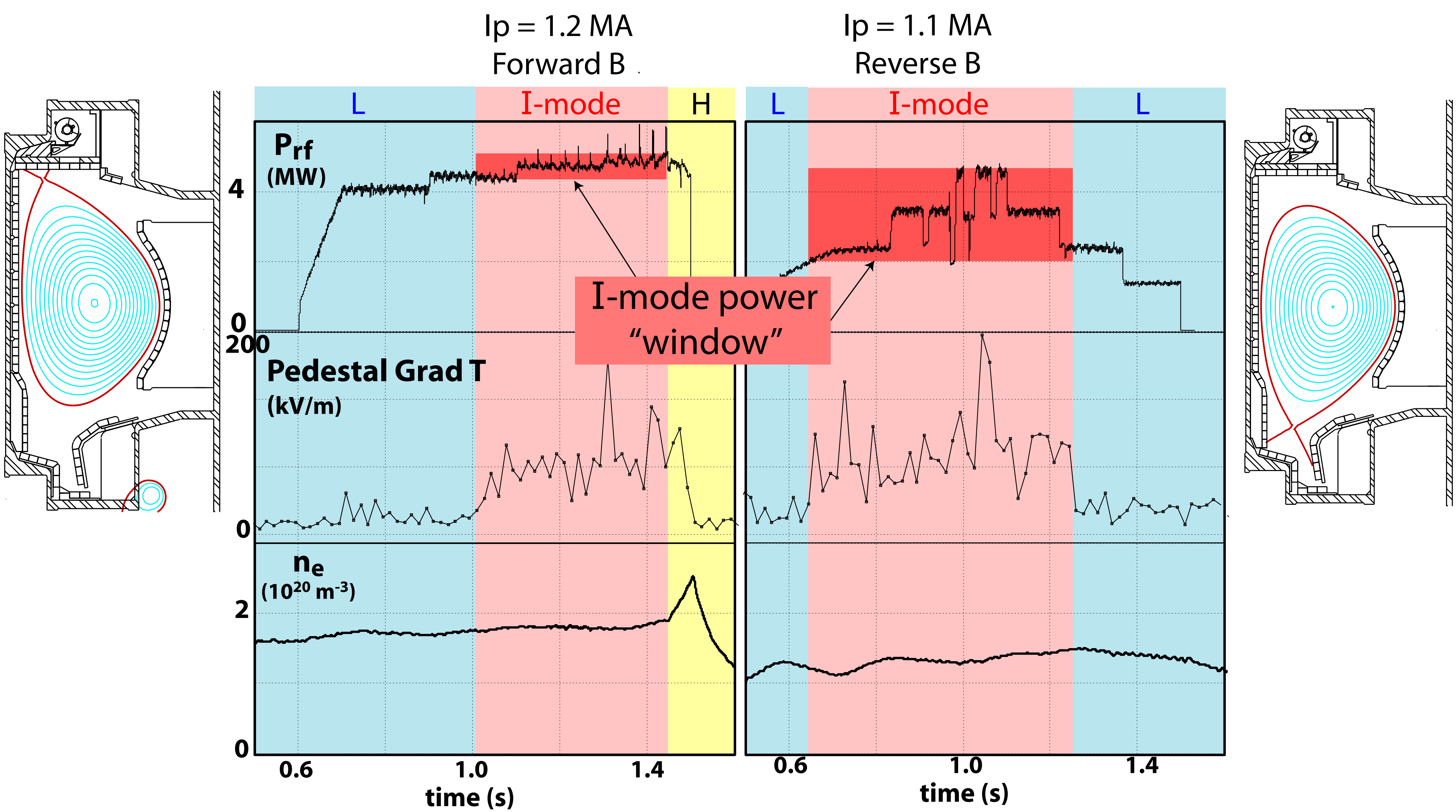
- Full data set shows I-mode power range vs L-I scaling is highest at low density. BUT I-H transitions are still scattered.



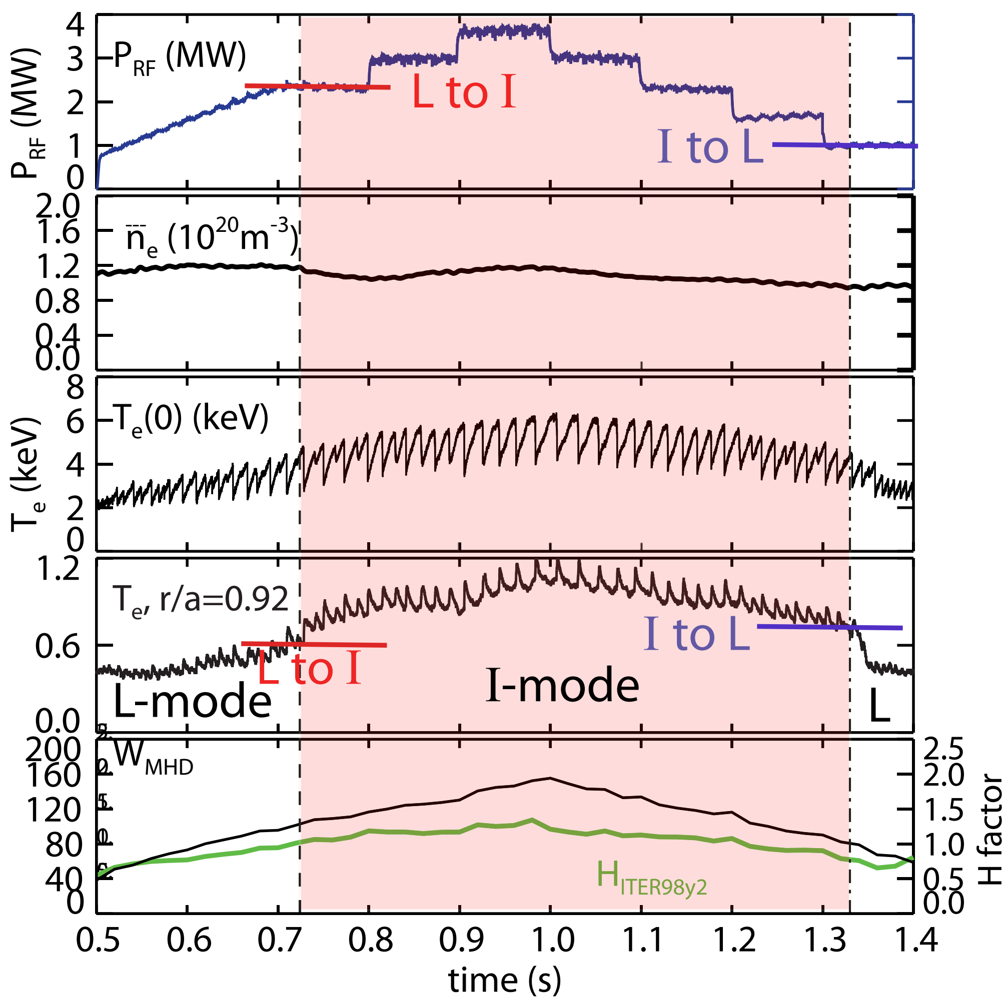
- Restricted data set (1 MA, LSN) reduces scatter.
  - P(L-I) *increases* with n_e.
  - I-mode P range, and P(I-H) *decrease* w n_e



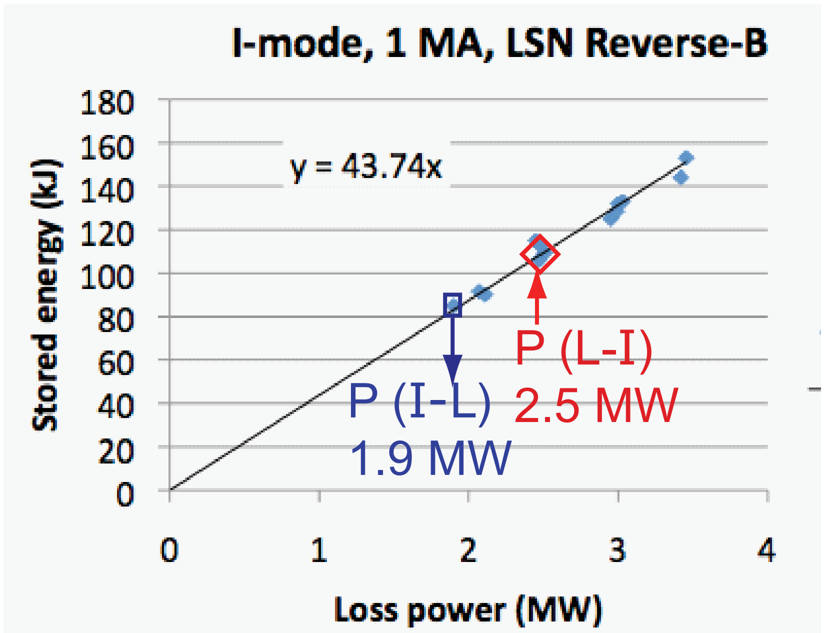
Highest I-mode 'power window' so far obtained in LSN, Reverse B_T, moderate density



I-L back-transitions exhibit modest power hysteresis



- Transitions back to L-mode at much lower ICRF power than L-I transition.
- $P_{loss}=P_{tot}-dW/dt$ was about 25% lower.

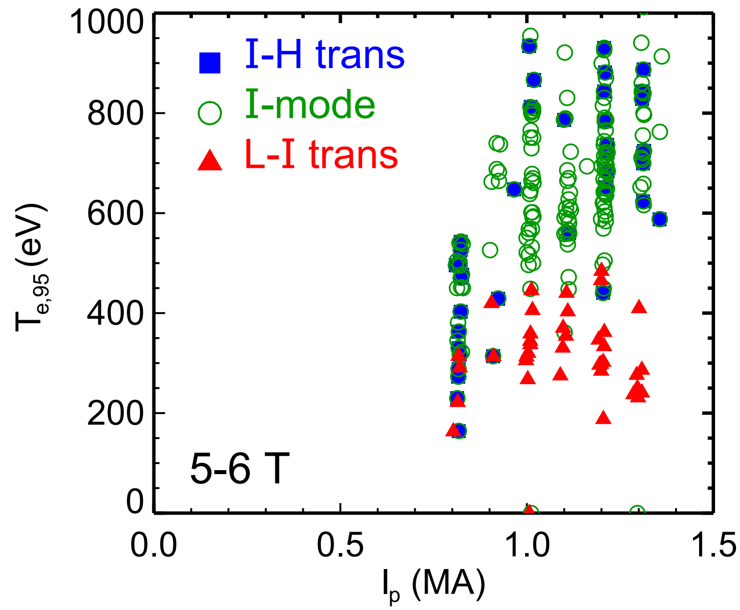


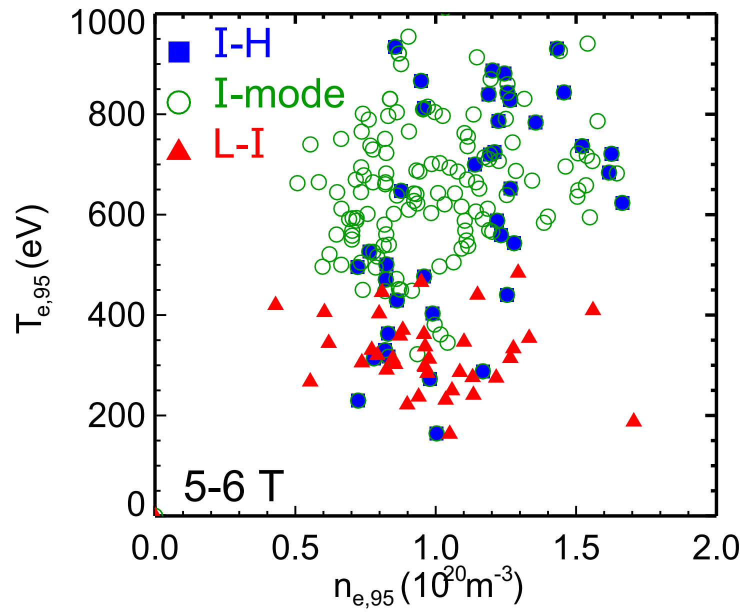
Note: Linear W vs P in I-mode → no power degradation!

Local conditions at transitions to I and H-mode

- Past studies on C-Mod and elsewhere have found local conditions at transition thresholds can be a better way to characterize thresholds, give more insight into physics.
- On C-Mod and elsewhere, edge temperature (T_e, T_i and/or grad T) tends to organize L-H transitions with favorable drift [eg, Hubbard1998, Groebner 1998]
- On C-Mod, $T_{e,95}$ for usual L-H ~ 100-200 eV, higher below “low n_e limit”. [Hubbard 1998, Ma 2011]
- *How do thresholds in unfavorable drift compare?*

Database study finds edge T_e *may* describe L-I threshold, but not I-H.

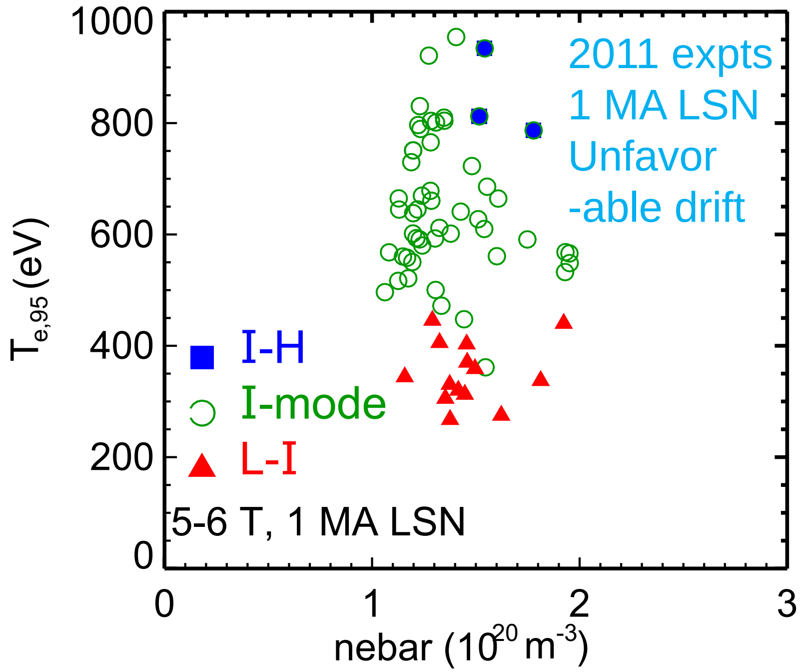


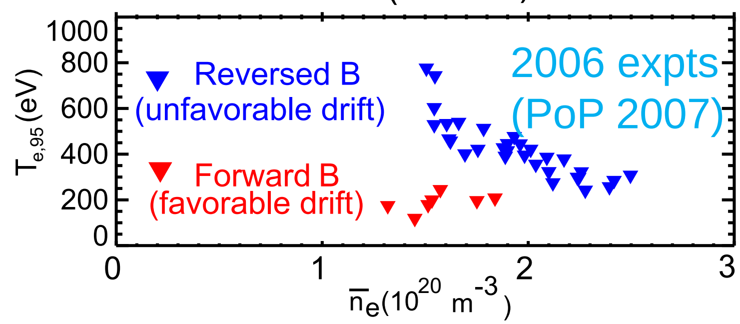


- Used parameters from fits to core and edge ECE and TS.
- Averaged over sawtooth heat pulses, which can be large at high power and often trigger transitions. For full 5-6 T dataset, find $T_{e,95}$ (L-I) ~ 250-400 eV, independent of I_p and n_e.
  - Roughly double the $T_{e,95}$ found in studies with favourable drift (see below).
- Does not organize I-H transitions well.

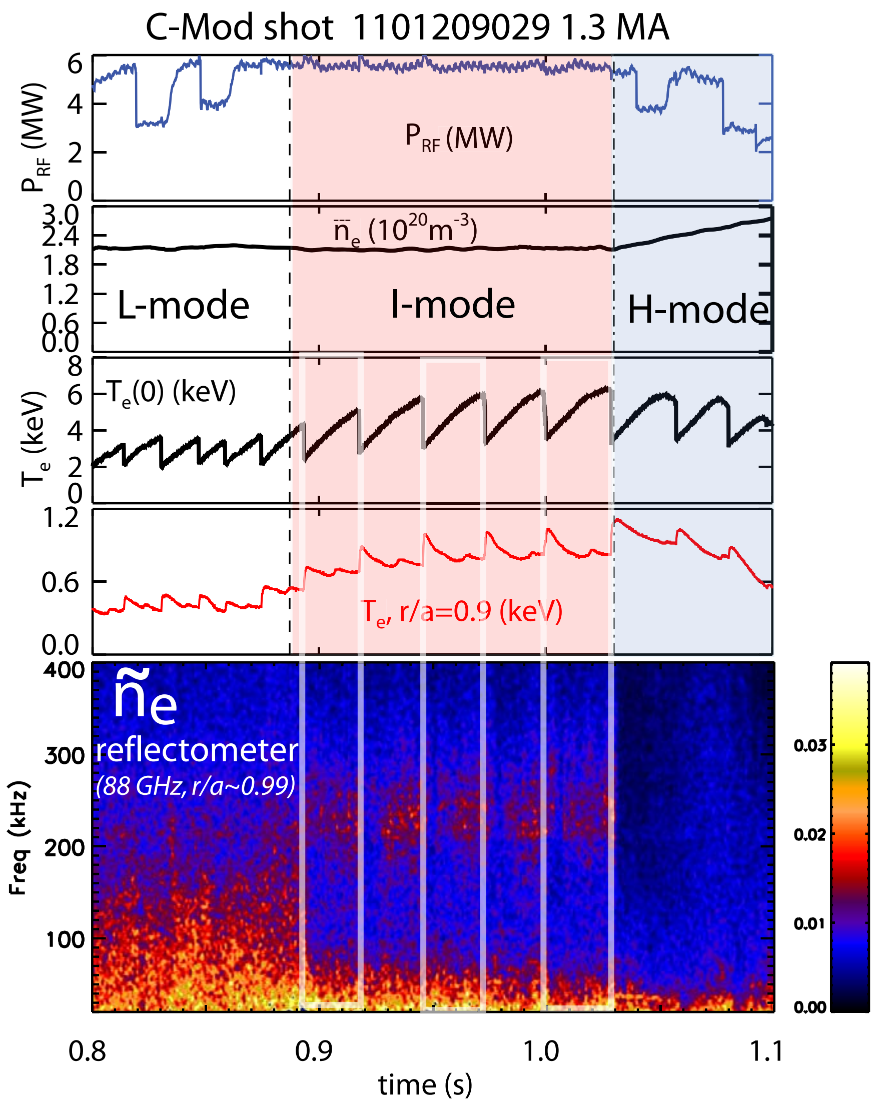
At fixed I_p & shape, I-mode edge T_e range decreases with n_e

- Subset of 1.-1.12 MA LSN discharges, narrow shape range.
- As with power, scatter is much reduced; suggests decreasing I-mode window with n_e. Pressure limit?
- Consistent with prior study of H-mode transitions with unfavorable drift which extended to higher n_e range. [Hubbard PoP 2007].





Sawtooth heat pulses affect I-mode dynamics, transitions



- Heat pulses can be large with high power ICRH, especially at low q_{95}, and in I-mode due to high T_e.
- Pulses often trigger L-I and I-H transitions, and affect WCM amplitude and freq.
  - Off-axis ICRH can delay H-mode transition.
- More detailed transition studies and analysis will need to look at *instantaneous* heat flux and edge profiles, which will be higher than average.
  - A diagnostic challenge
  - TS upgrade this year will help.

CONCLUSIONS

- Transitions to I-mode and H-mode with unfavorable Bx∇B drift are generally higher than, and scale quite differently than, usual L-H transitions with favorable drift.
- **L-I thresholds**
  - Increase with both plasma current and density. Regression fit gives **P_{loss} (L-I) ~ I_p $n_e^{0.5}$**; single current scan shows ~linear n_e dependence.
  - Occur at $T_{e,95}$ ~250-400 eV, independent of current and density. Possible threshold parameter linked to edge temperature or related quantity?
  - Sawtooth heat pulses play a role in triggering and dynamics

- **I-H thresholds**
  - Occur at power as much as 1.8 x L-I threshold and scalings.
  - But, highly scattered, in both power and local parameters (eg T_e). Not yet clear what determines I vs H-mode regime.
  - I-mode power window (and I-H threshold) may depend inversely on n_e.

- **I-L back transition** shows modest hysteresis (ie lower power than L-I transition).

FUTURE WORK

The initial analysis presented here motivates new experiments and analysis to answer questions raised. These will include:

- **Controlled density scans to clarify scaling of L-I and particularly I-H mode thresholds.**
  - *Does I-mode "window" really shrink at high density? How does this depend on Ip, Bt, shape? Can we increase power at low density or via fuelling?*

- **Intermachine comparisons to identify underlying physics variable, size scaling.** Planned in 2012 on AUG, D3D, encouraged on others.
  - *How do I-mode thresholds and confinement scale with size?*
  - *What determines density range? (n/n_G, collisionality….)*
  - *Will I-mode be accessible on ITER??*

- **More precise determination of edge profiles at and during transitions,** including role of sawtooth heat pulses and relation with edge fluctuations.

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