Multi-device Studies of Pedestal Physics and Confinement in the I-mode Regime

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KEY NEW RESULTS

- I-mode has now been obtained on **Alcator C-Mod, ASDEX Upgrade and DIII-D.**
  - Regime is ELM-free, can obtain high normalized energy confinement, with low power degradation, and has low particle confinement.
- Wide ranges of device and dimensionless parameters, including low ν^* and q_{95}.
- Changes in pedestal turbulence, and E_r shear, are observed in all devices.
- L-I threshold increases with n_e, but weak B_T dependence.
- Upper range of power for I-mode increases with B_T, making regime more steady and robust at higher field.

Features of I-mode regime

I-mode regime is characterized by [Whyte 2010]:

1. Edge thermal barrier, increased energy confinement.
2. L-mode particle confinement (no density barrier).
3. Changes in pedestal turbulence.

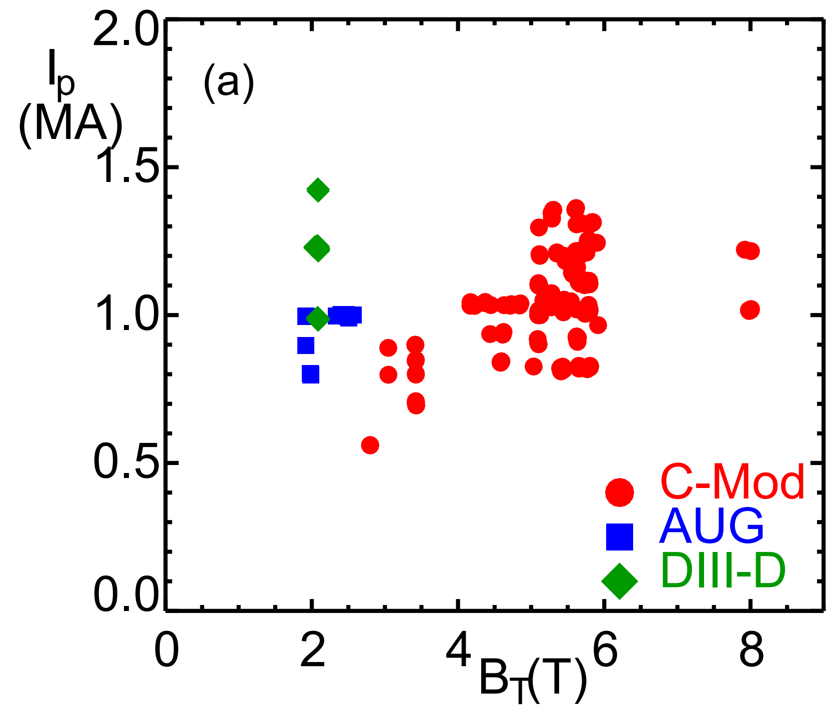
Advantages over H-mode:

- Regime is generally **ELM-Free**, while remaining stationary.
- **Avoids accumulation of impurities** (from PFCs, seeding, 'ash').
- **More favourable dependence of τ_E on power** than L or H-mode.

This has motivated multi-machine studies of regime properties and access conditions, in both Transport and Pedestal ITPA groups.

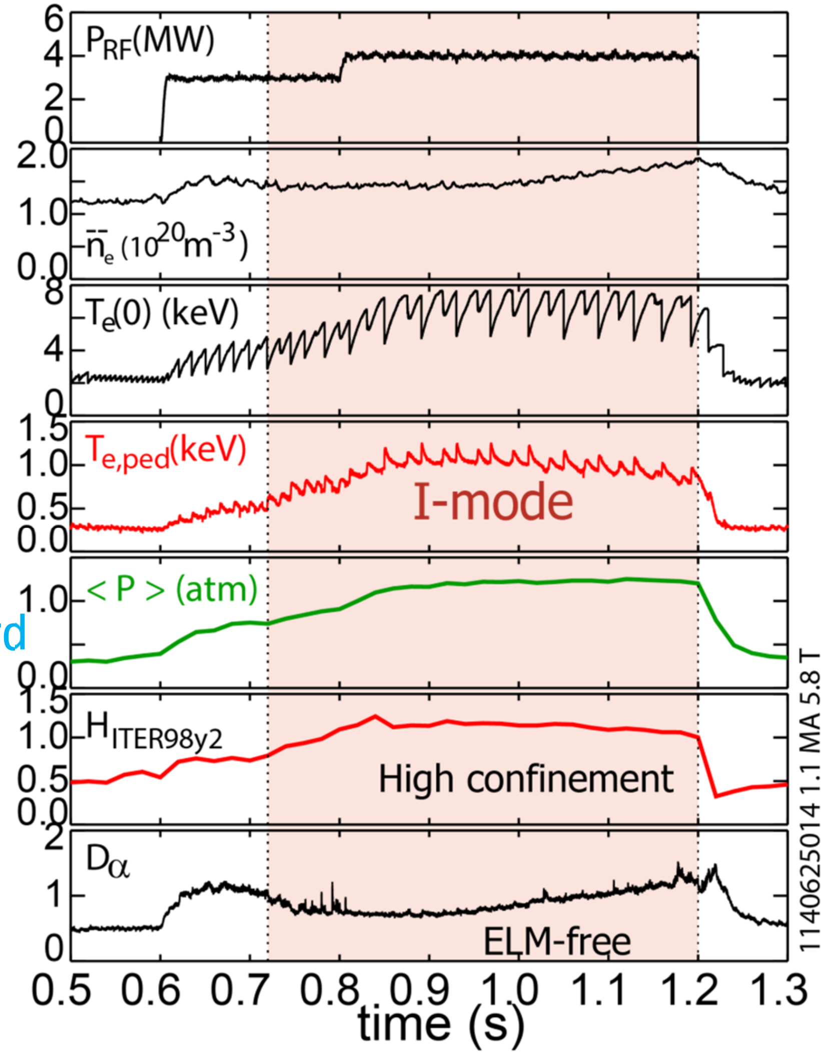
I-mode is now established on Alcator C-Mod, ASDEX Upgrade and DIII-D, over wide parameter ranges.

	C-Mod	AUG	DIII-D
I_p (MA)	0.56-1.4	0.8-1.0	0.96-1.4
B_T (T)	2.8-8.0	1.9-2.5	2.04
q_{95}	2.4-5.2	3.0-4.1	3.5-5.2
$\overline{n}_e$ ($10^{20}m^{-3}$)	0.9-2.3	0.16-0.3	0.22-0.51
P_{loss} (MW)	1.5-5.1	1.6-3.0	2.4-4.1
Heating method	ICRH	NBI, ECH, ICRH	NBI, ECH



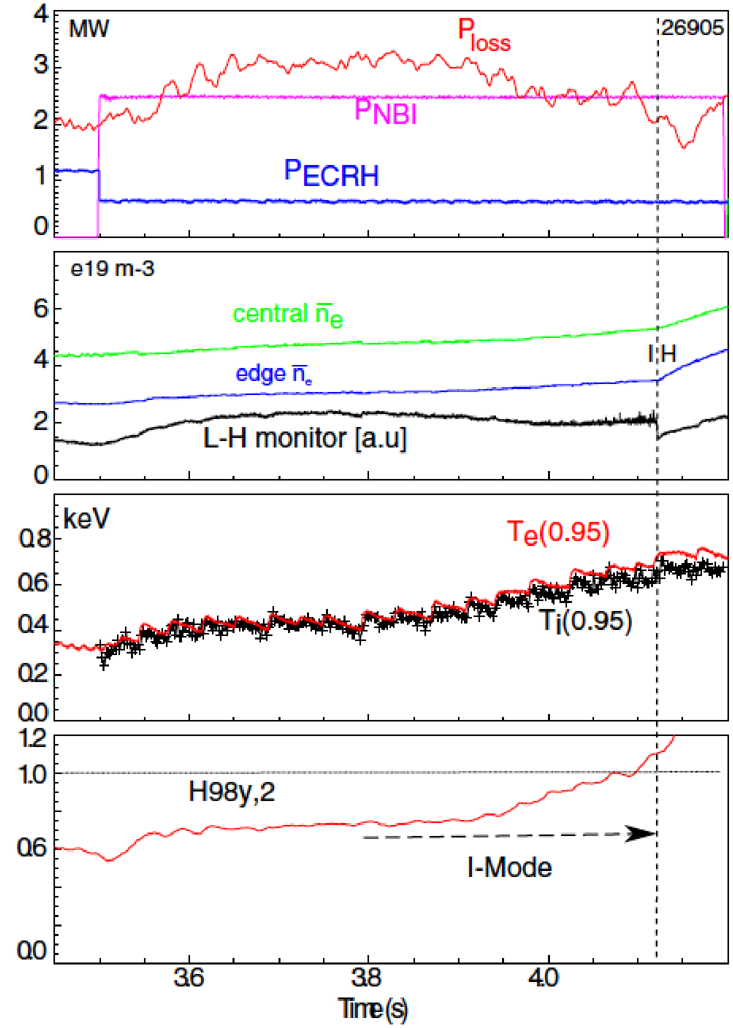
All results in this poster are from **D plasmas**, with ion **B×∇B drift away from active divertor** (ie 'unfavourable' drift for H-mode)

Alcator C-Mod



Hubbard FEC 2012

ASDEX Upgrade

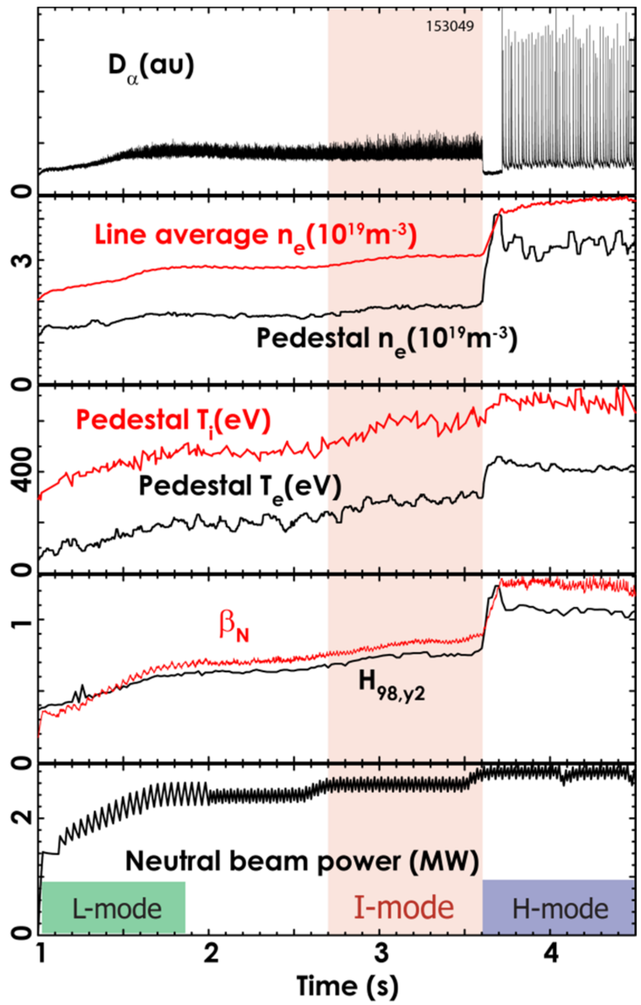


Ryter 2011

- 1.1 MA, 5.8 T, q_{95}=3.4
- LSN, upwards **B**×∇**B** drift.
- **ICRF heating**

- 1 MA, 2.45 T, q_{95}=4.
- USN, **B**×∇**B** drift downward.
- **NBI + ECH heating**.

DIII-D

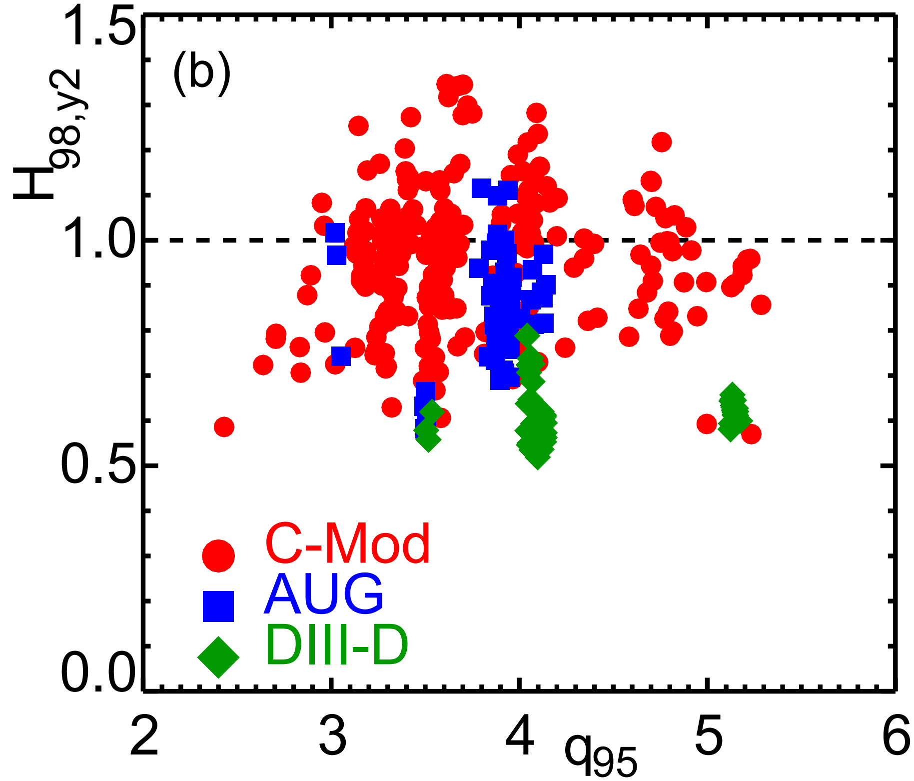


- 0.98 MA, 2.05 T, q_{95}=5.1
- LSN, upwards **B**×∇**B** drift.
- **NBI heating**
- Note T_i > T_e in DIII-D pedestals with NBI.

Energy Confinement

Global energy confinement in I-mode often reaches or exceeds H-mode scalings, over a wide range of q_{95}.

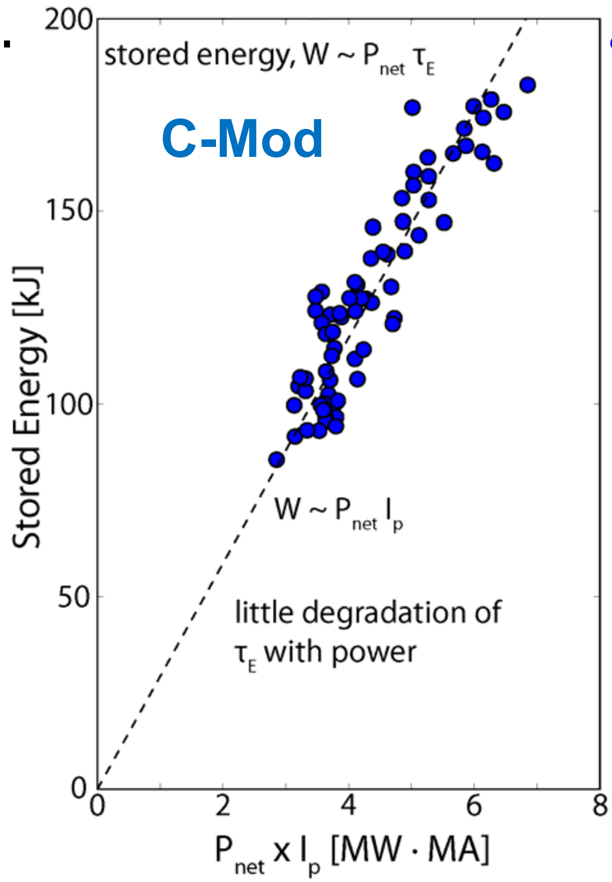
$0.6 < H_{98} < 1.3$



- Note that density in I-mode tends to be lower than H-modes, $\tau_{98} \propto n^{0.4}$.

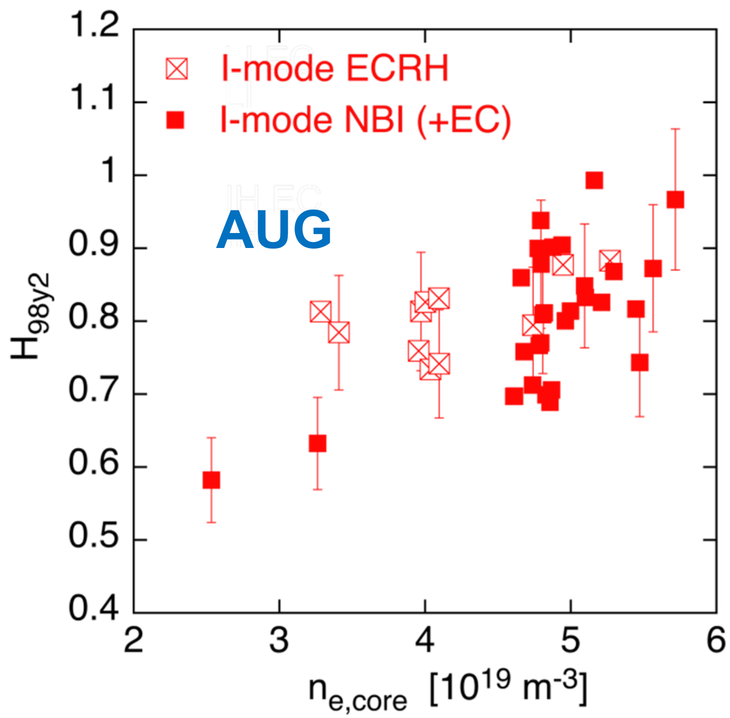
Stored energy increases strongly with input power

- Much less power degradation of τ_E than in H-mode (all devices).



Alcator C-Mod

- AUG and DIII-D find H_{98} independent of heating method.
- H_{98} tends to increase with density (AUG and C-Mod)
  - Due to transition thresholds, n_e and power ranges are correlated.



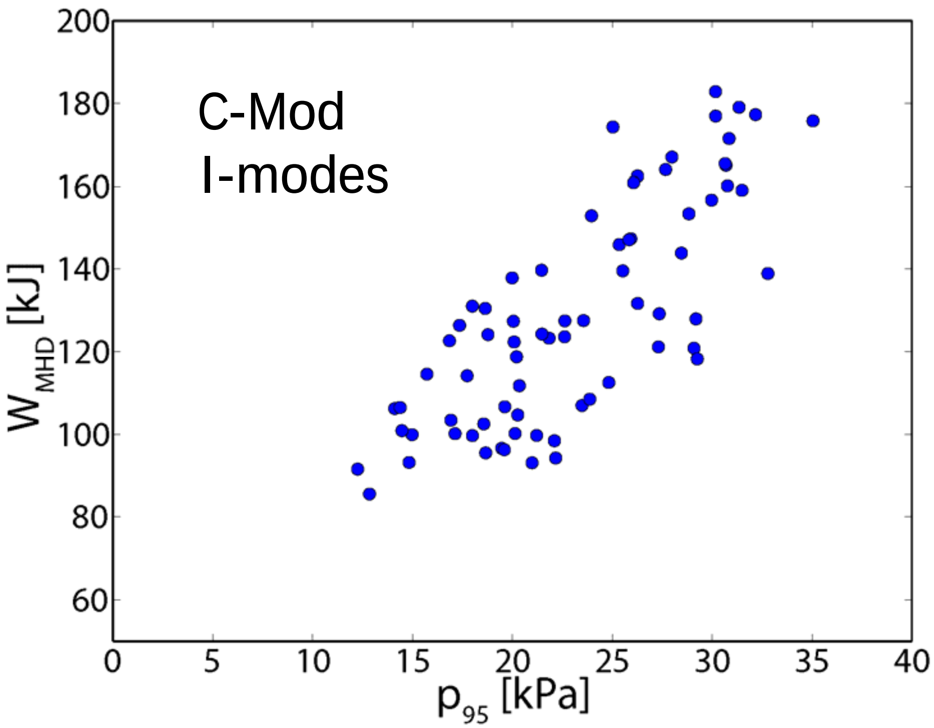
IPP

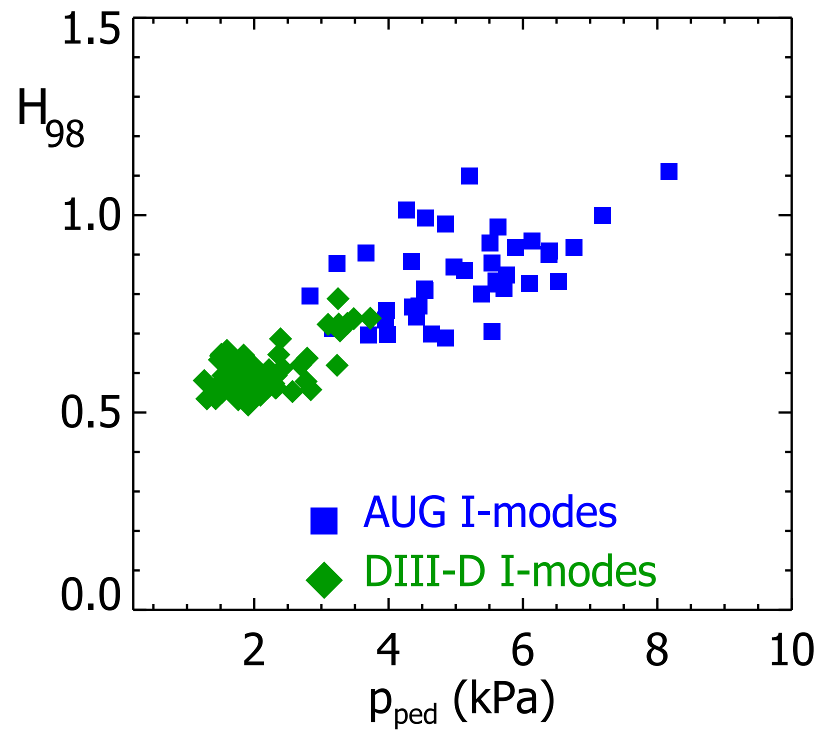
Regression fit to C-Mod data gives

τ_E=0.014 $I_p^{0.68} p\, B_T^{0.77} \boldsymbol{P}^{-0.29}$ [Walk 2014]

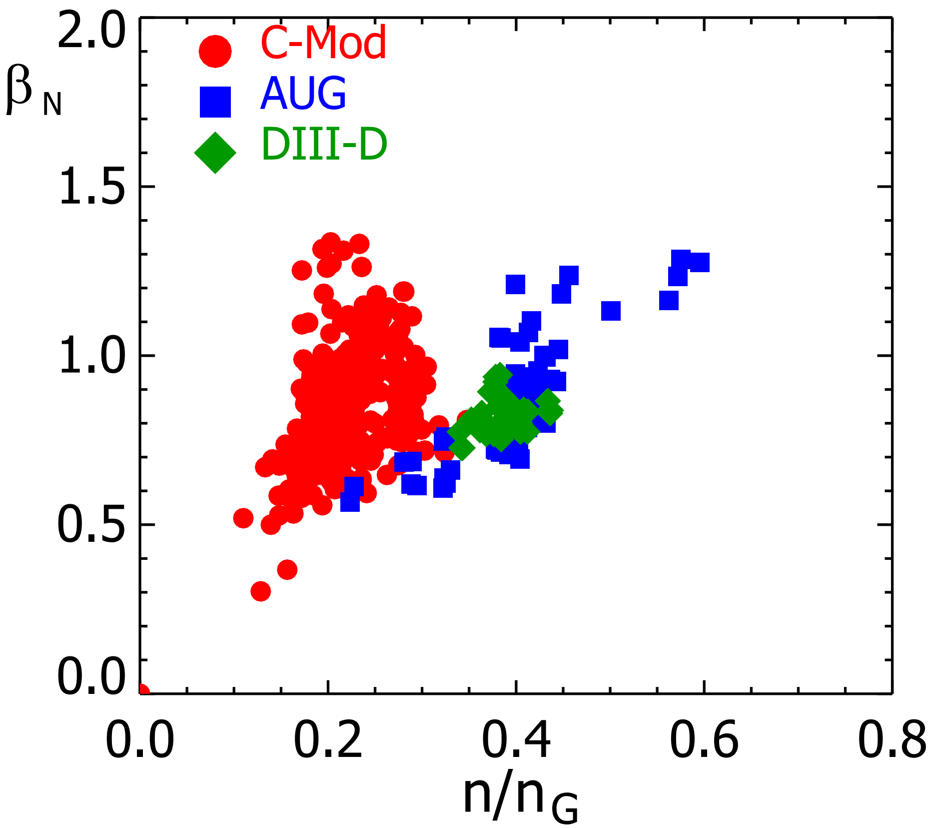
Stored energy and H_{98} are correlated with pedestal pressure

- Consistent with fairly stiff thermal transport in core, most of confinement improvement due to pedestal increase.
- Unlike H-mode, pedestal pressure does not saturate in I-mode at high power, which explains the weak confinement degradation.





Normalized pressure and density so far lower than H-modes



- Achieved β_N is modest, ~1.4.
  - Does not seem to be set by an MHD limit, rather by I-H transitions (AUG, D3D) or available power (C-Mod).
- Density to date up to 60% of Greenwald limit.
  - Also does not seem an intrinsic limit.
  - On C-Mod, density range can be increased by fueling into I-mode, and increases with heating power.

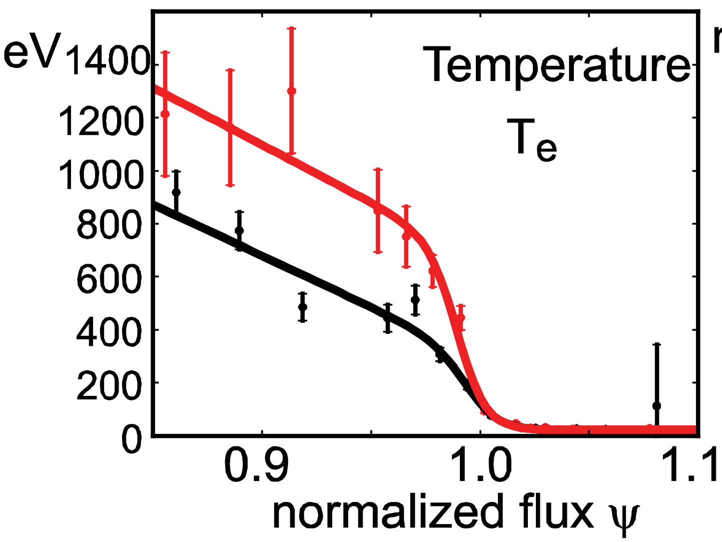
Extending these ranges is a goal of ongoing experiments.

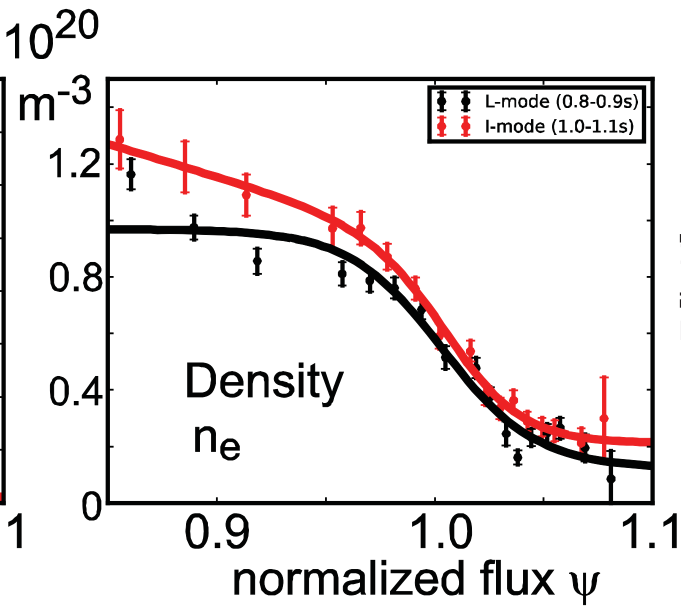
Pedestal Physics

In all devices, a temperature pedestal (T_e and T_i) develops in I-mode, while density profiles remain close to L-mode.

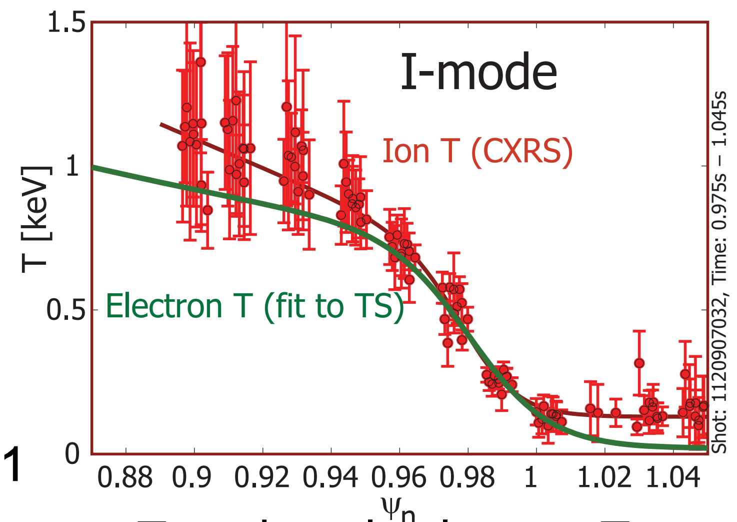
Clear separation, not yet well explained, between thermal and particle transport, motivates detailed measurements of profiles and turbulence.

Alcator C-Mod



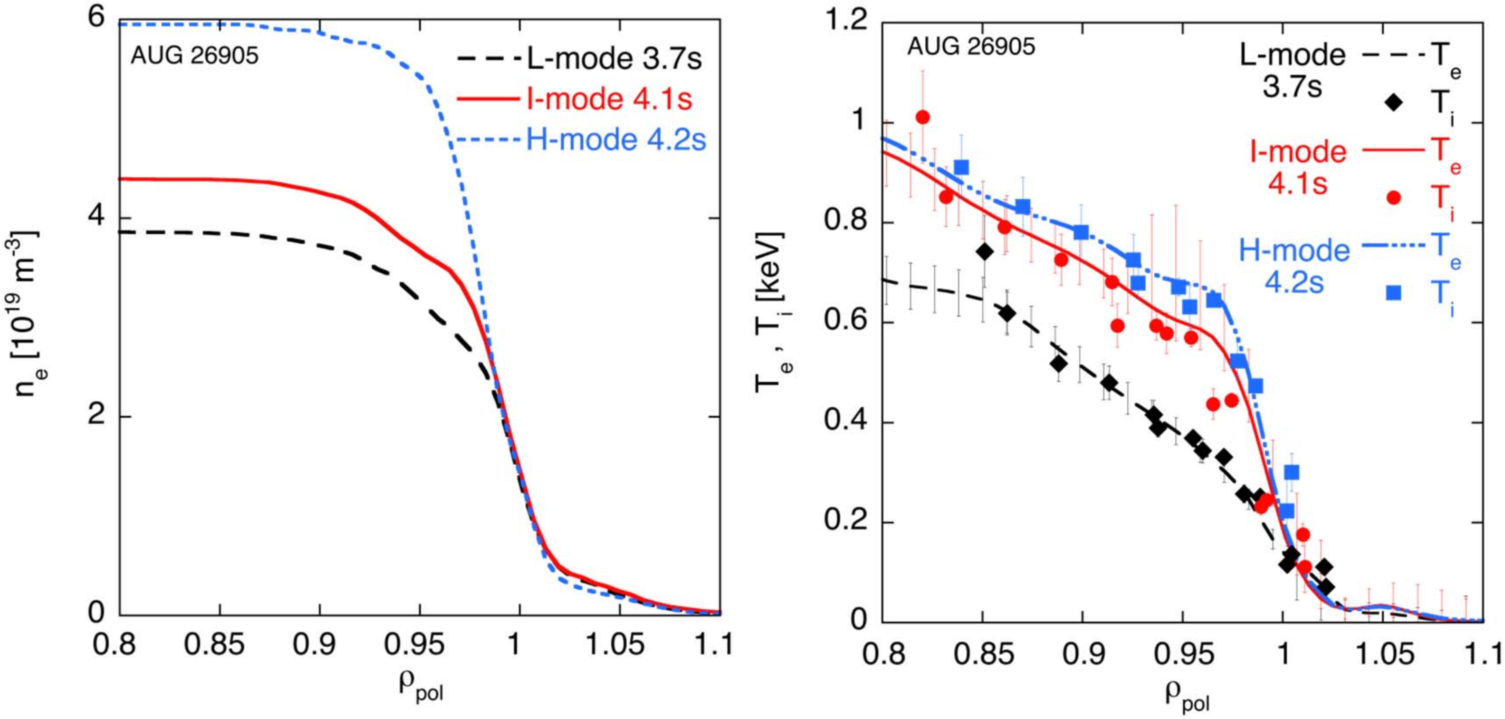


1.1 MA, 5.8 T, q_{95}=3.4

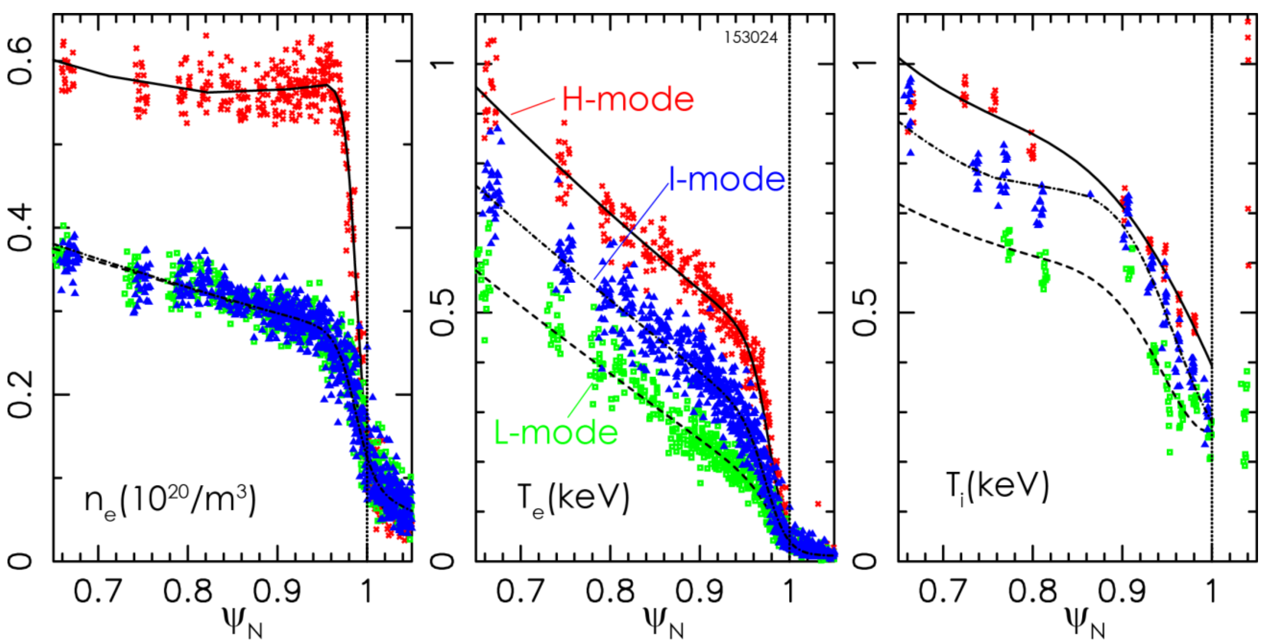


T_i pedestals close to T_e (in similar discharge)

ASDEX Upgrade



- 1 MA, 2.45 T, q_{95}=4
- USN, B×∇B drift downward.
- **2.5 MW NBI heating + 0.7 MW ECH**.
- T_i pedestal ~ T_e.



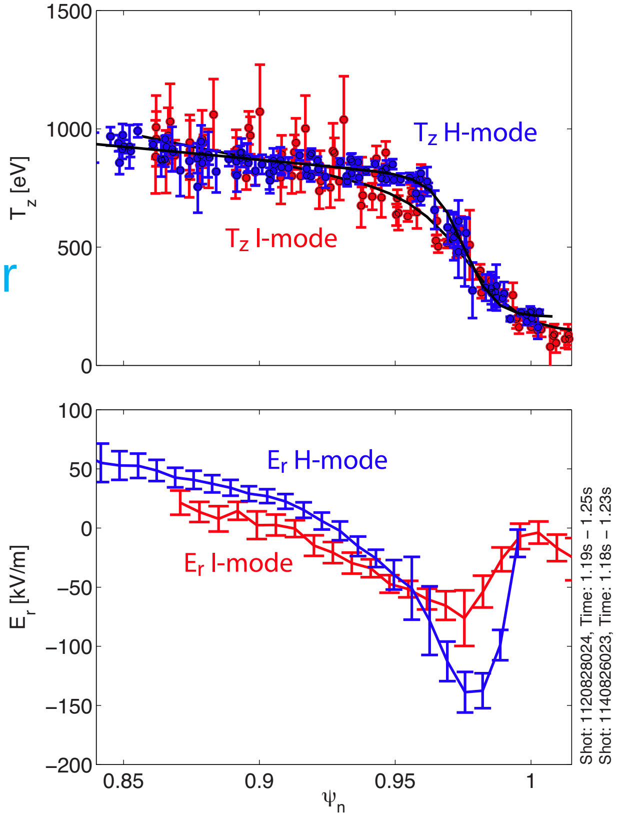
DIII-D

- 1.2 MA, 2.05 T, q_{95}=4.3
- LSN, B×∇B drift upwards
- **3 MW NBI** in I-mode.
- T_i pedestal > T_e.

E_r well develops in T pedestal region, may play role in turbulence reduction

C-Mod: CXRS using B^{5+} measures E_r well during I-mode, to -80 kV/m in this case (variable).

ExB shear is significant, though weaker than in H-modes.



Theiler 2014

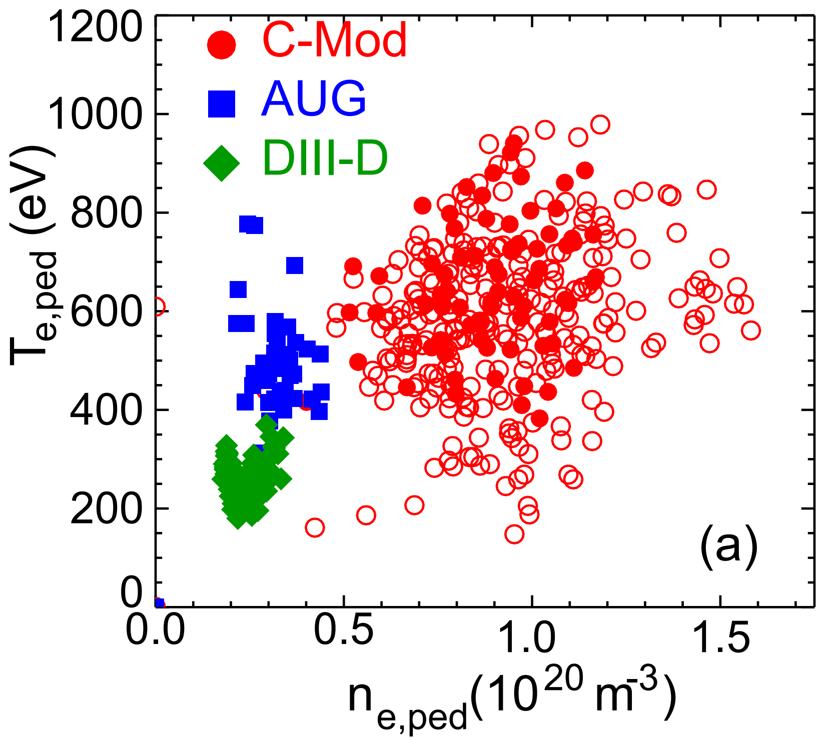
AUG: Doppler reflectometry shows progressively deeper E_r well during I-mode, to -16 kV/m in this case.

CXRS measures E_r as low as -30 kV/m in other I-mode discharges.

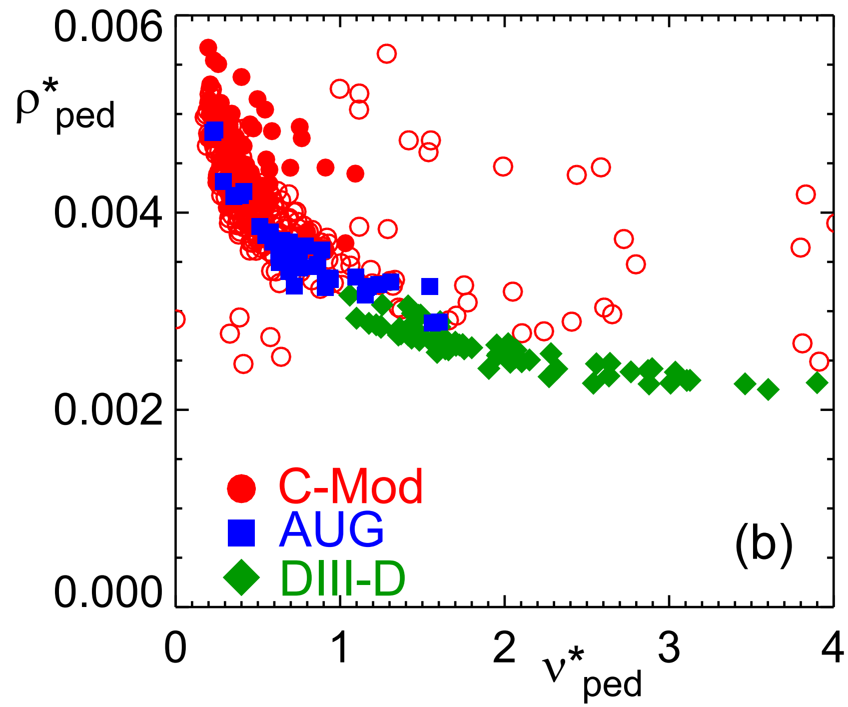
DIII-D: Weaker E_r well, near 0 at minimum, measured by CXRS.

I-mode pedestals span wide parameter ranges, reach low ν^*

- **Devices have distinct T_e, n_e ranges**
- Up to T_{ped}=1 keV, $n_{ped}=1.6\times10^{20}\ m^{-3}$.



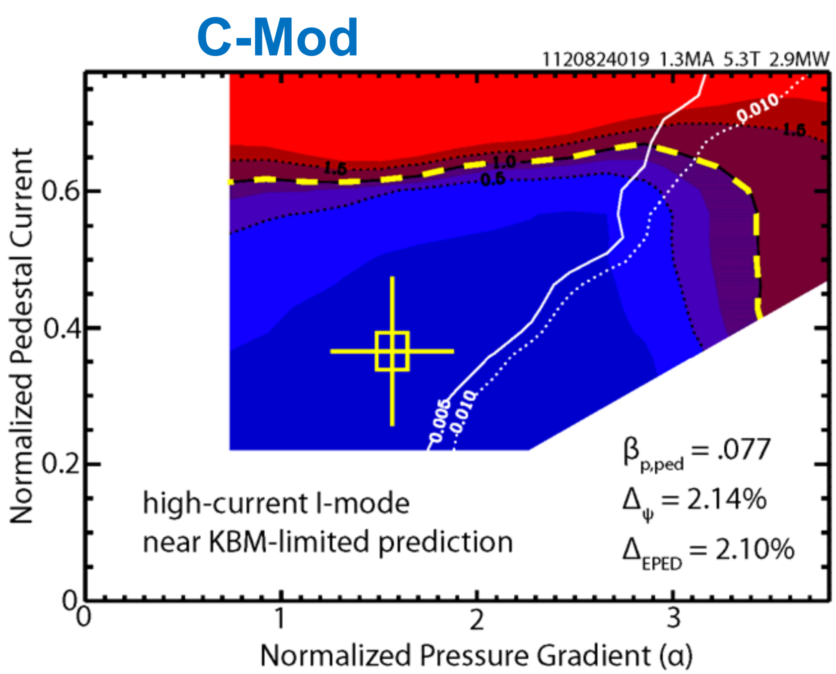
- **Dimensionless parameters overlap.**
- Down to ν^*_{ped}=0.17, $\rho^*_{ped}=2.2\times10^{-3}$
  - no sign of limits in these parameters.

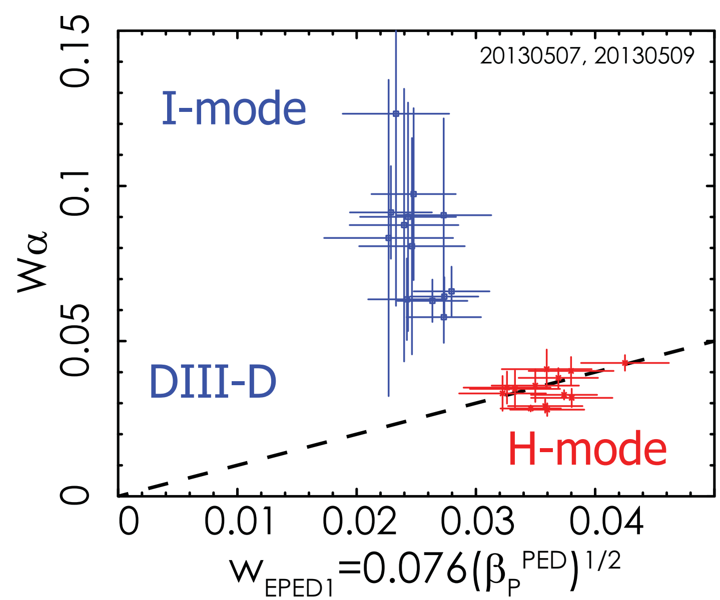


Pedestals are stable to peeling-ballooning MHD and Kinetic Ballooning Mode, explaining lack of ELMs.

- ELITE shows pressure gradient well below limit, room to increase further; Analysis on DIII-D is consistent.
- Pedestal is wider than for ELMy H-modes, exceeds $\beta_p^{0.5}$ scaling in EPED* based on KBM limit (on both DIII-D and C-Mod).

Walk PoP 2014



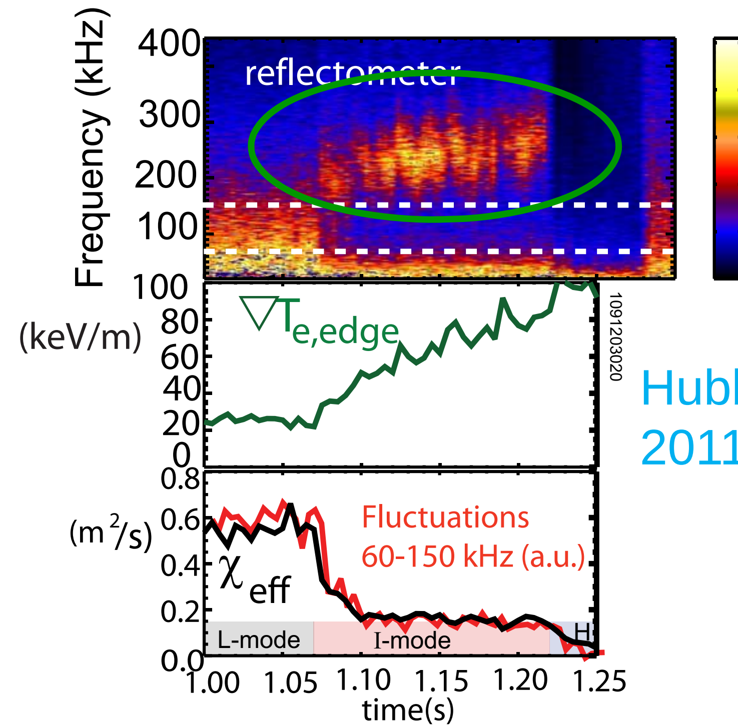


* Snyder 2011

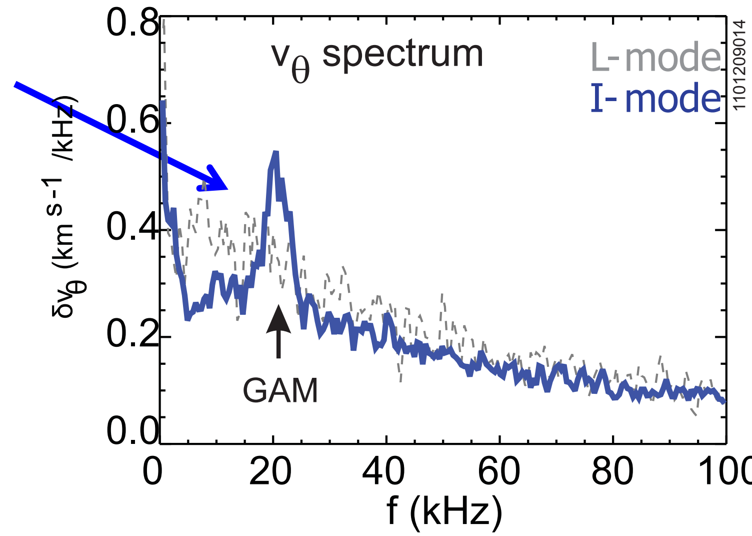
Changes in turbulence and fluctuations occur at L-I transitions in each device

C-Mod

- **As the T pedestal forms**, see
  - A DECREASE in edge broadband turbulence (n and B) in mid-f range (~60-150 kHz), correlated to decreasing χ_{eff}.
  - Usually a PEAK in turbulence (n, T and B) at higher f **"Weakly Coherent Mode".** f_0 ~200-400 kHz, $\Delta f/f$ ~0.3-1, r/a 0.9-1.
  - A **fluctuating poloidal flow at GAM frequency** (~20 kHz), which exchanges energy with mid-f turbulence and broadens WCM.
- CORE transport and turbulence (both δn_e and δT_e) also promptly decrease.



Hubbard 2011

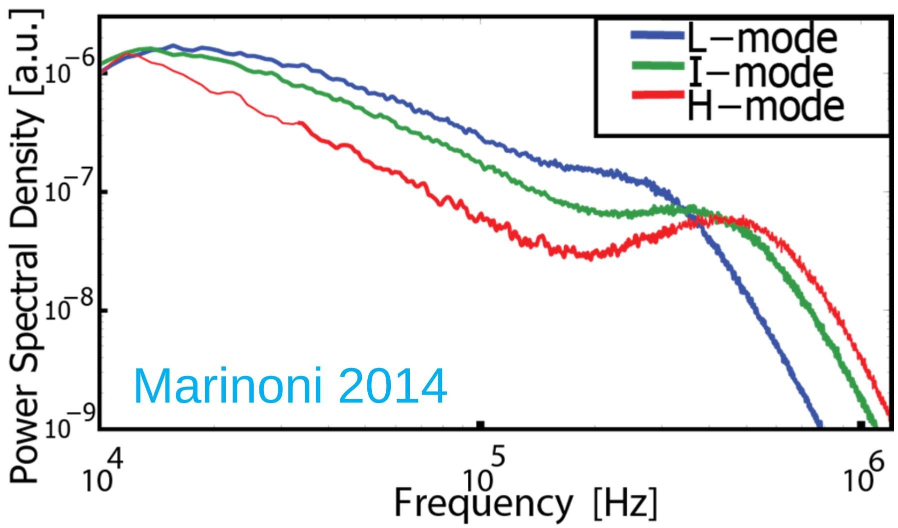


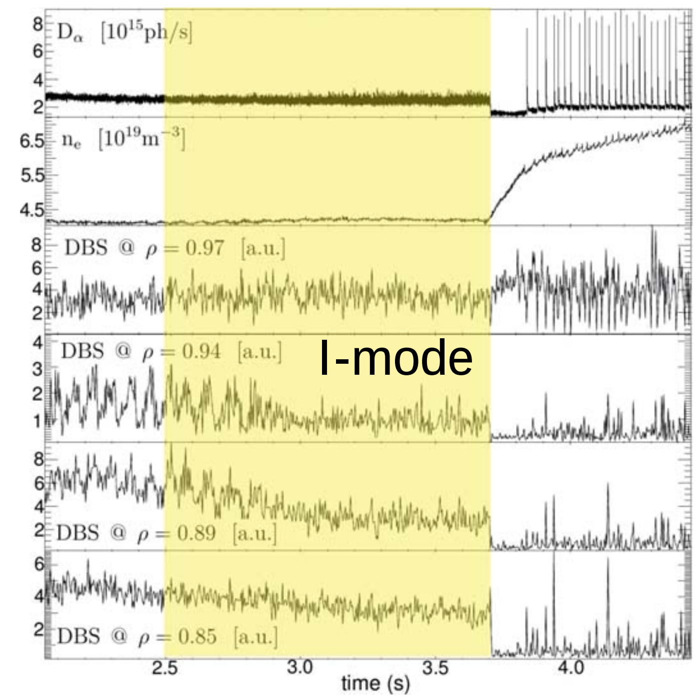
Cziegler 2013

DIII-D

During formation of T_e and T_i pedestal in I-mode, typically see

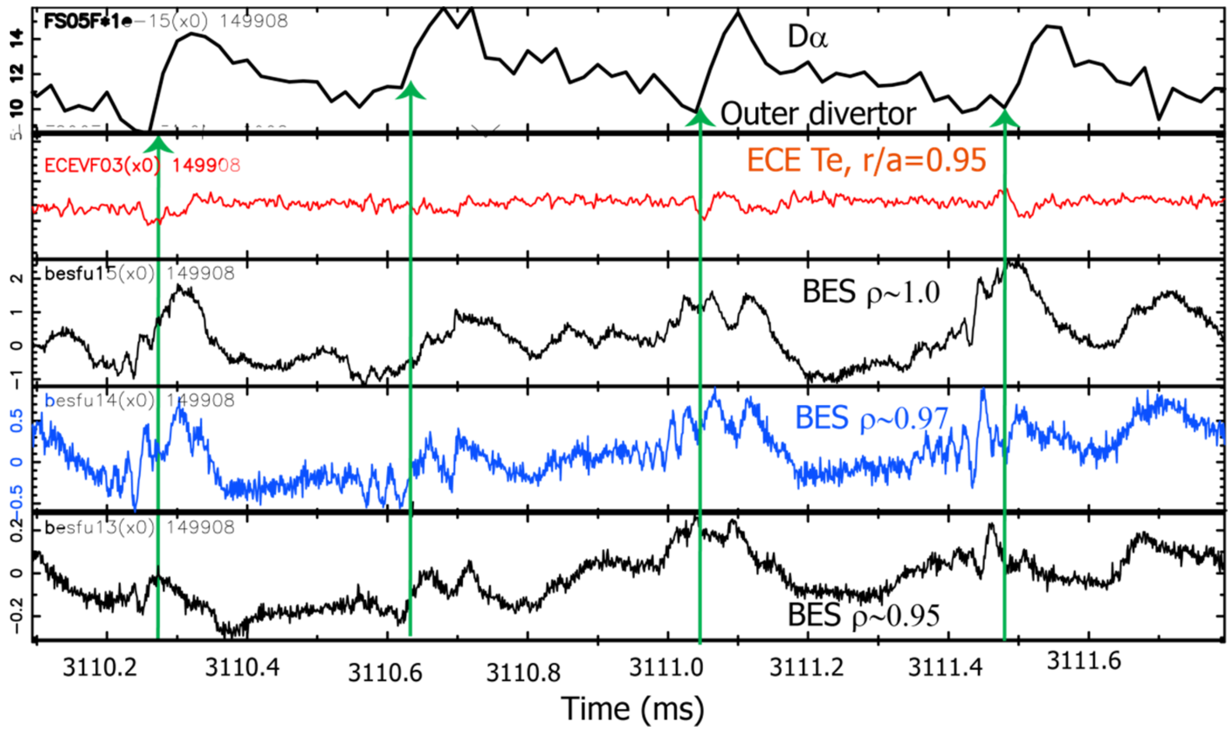
- **PCI:** line integrated n_e fluctuations intermediate between L and H-mode spectra, reduced~150 kHz, develop peak at ~300 kHz.
- **Doppler Backscattering:** Decrease in density fluctuations, localized near pedestal top.
- **BES:** Little change in spectra of ion-scale density fluctuations, up to 40 kHz.





In at least some DIII-D I-mode discharges, small discrete events (few kHz) are seen on BES and ECE. These are correlated with increases in Dα, indicating enhanced particle transport.

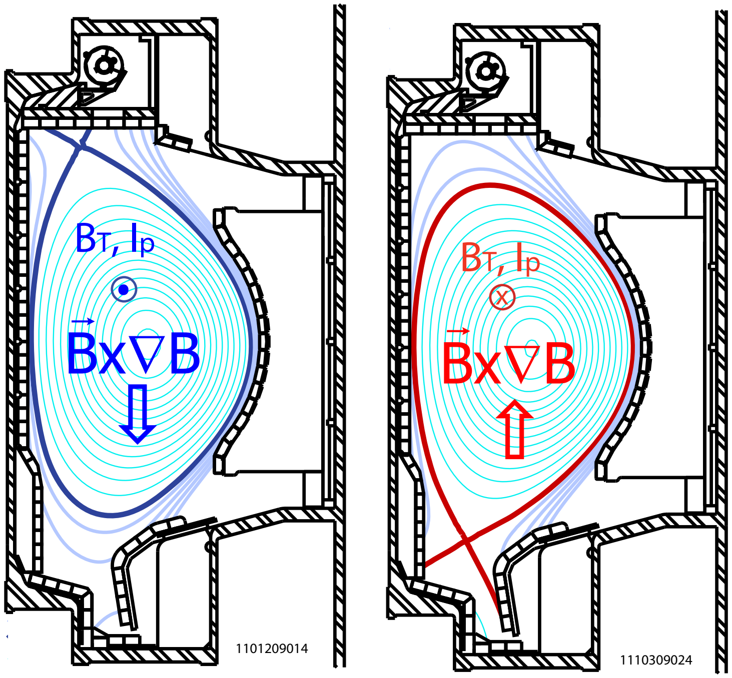
- Origin of these 'ELM-like events is unclear, since as shown above pedestals are far from MHD limits.



DIII-D

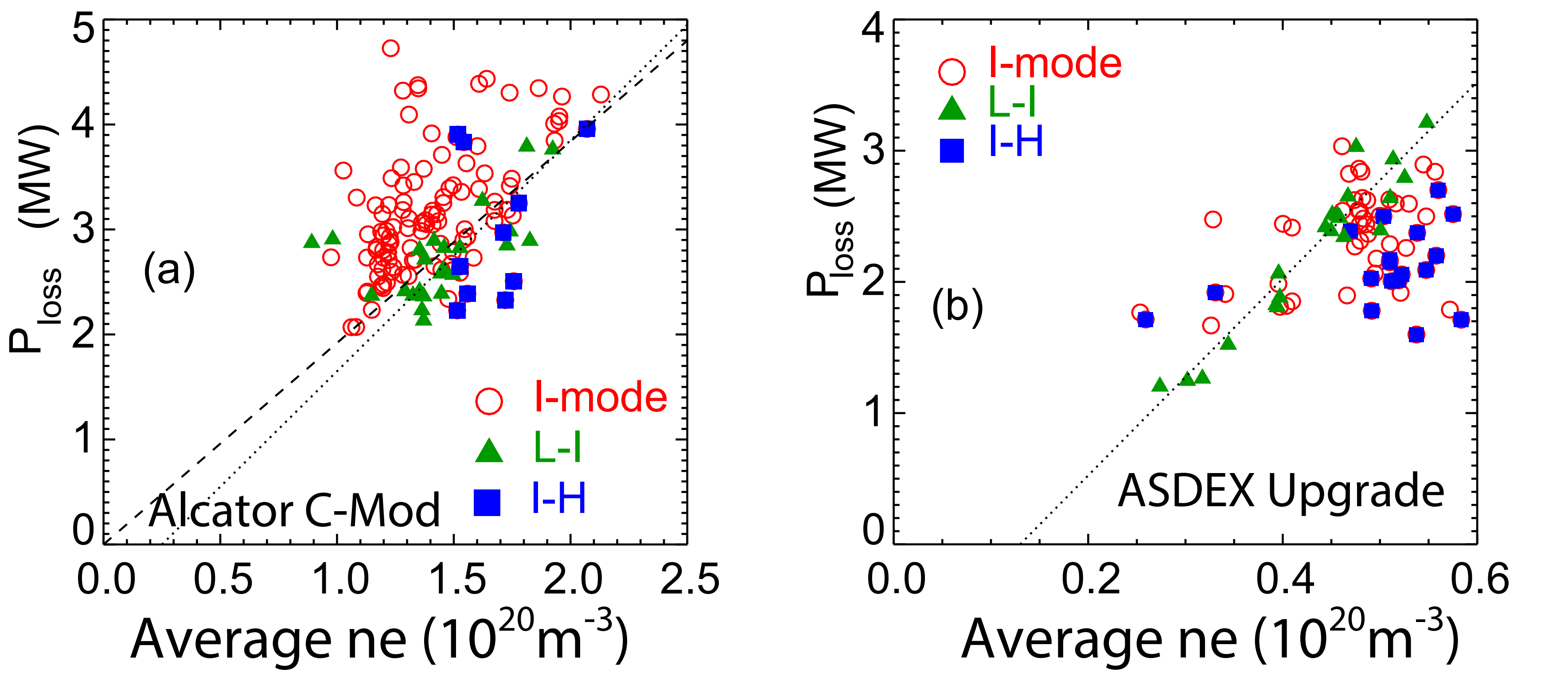
Access to I-mode

- In all devices, I-mode is usually accessed by operating with **B×∇B** drift *away* from X-pt, which raises H-mode threshold. (ie ‘unfavourable’ drift).
- Heating power is gradually increased, while remaining below the H-mode threshold.



- **Since I-mode performance (W and H_{98}) increase strongly with power, thresholds to enter I-mode (L-I transition) while avoiding H-mode (I-H transition) are key to extrapolating the regime.**

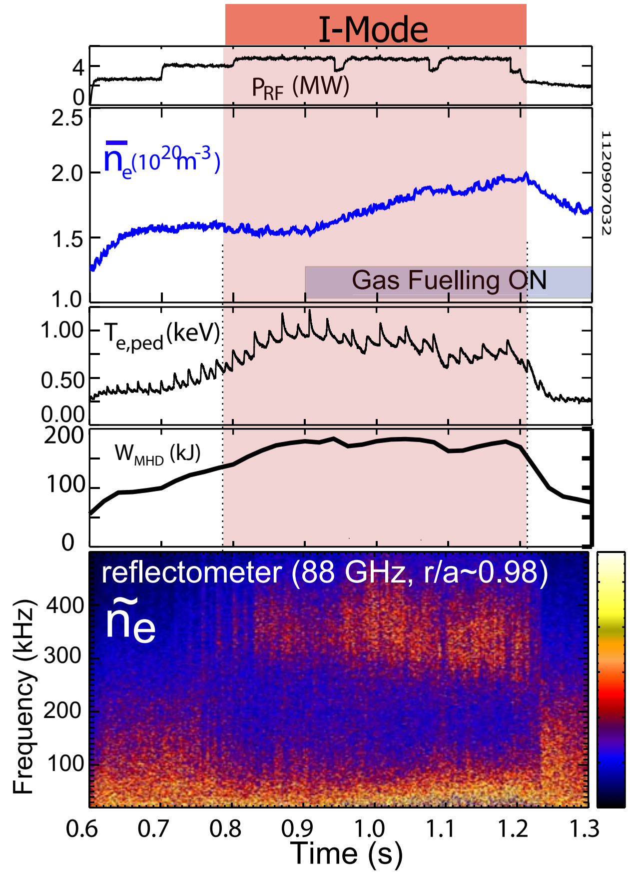
L-I threshold increases with density

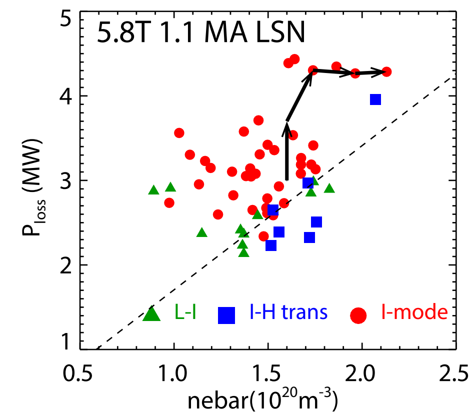


- Density dependence of P(L-I) at least linear, with a small offset on AUG.
  - C-Mod observes a minimum threshold power at $n_e \sim 10^{20}m^{-3}$, analogous to 'low ne limit' for L-H transitions.
- Increase in P(L-I) with plasma current has also been observed on C-Mod. [Hubbard NF 2012]

I-H transitions are complex, depend on both power and n_e

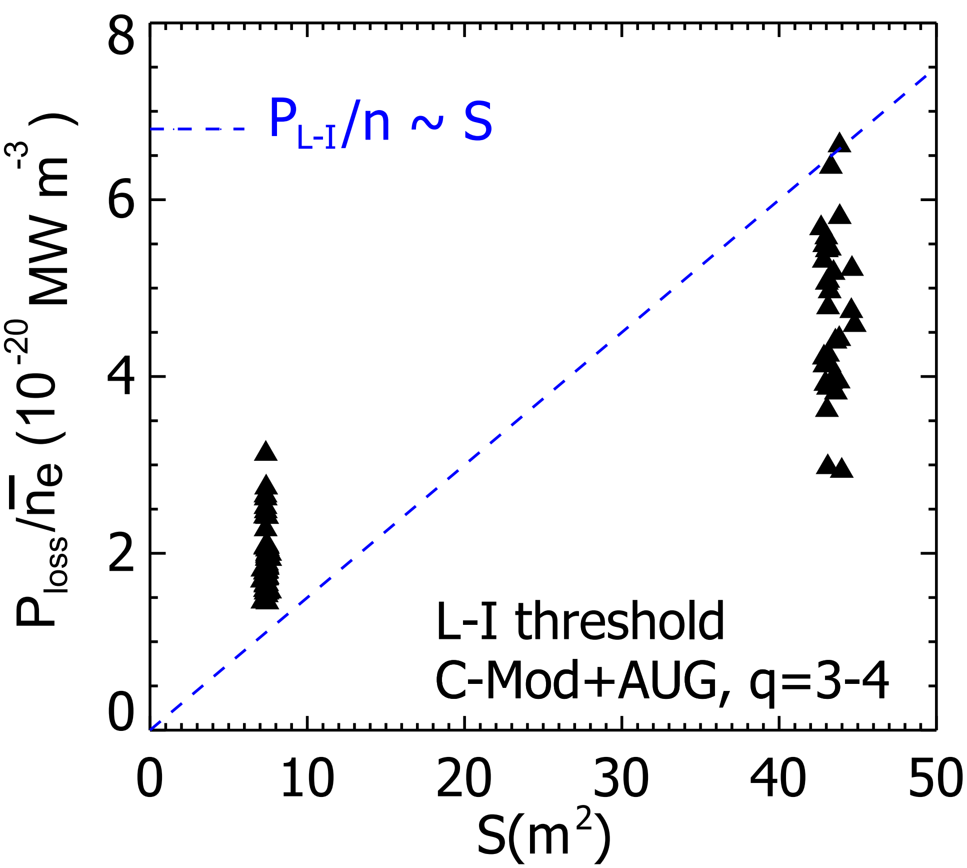
- I-H transitions do *not* always occur at the maximum power of I-modes.
- On C-Mod, maximum density for sustaining I-mode depends on discharge trajectory and power, can be increased by fueling into hot, high power I-mode.
  - Often an I-H transition occurs when P_{RF} *decreases.*





C-Mod

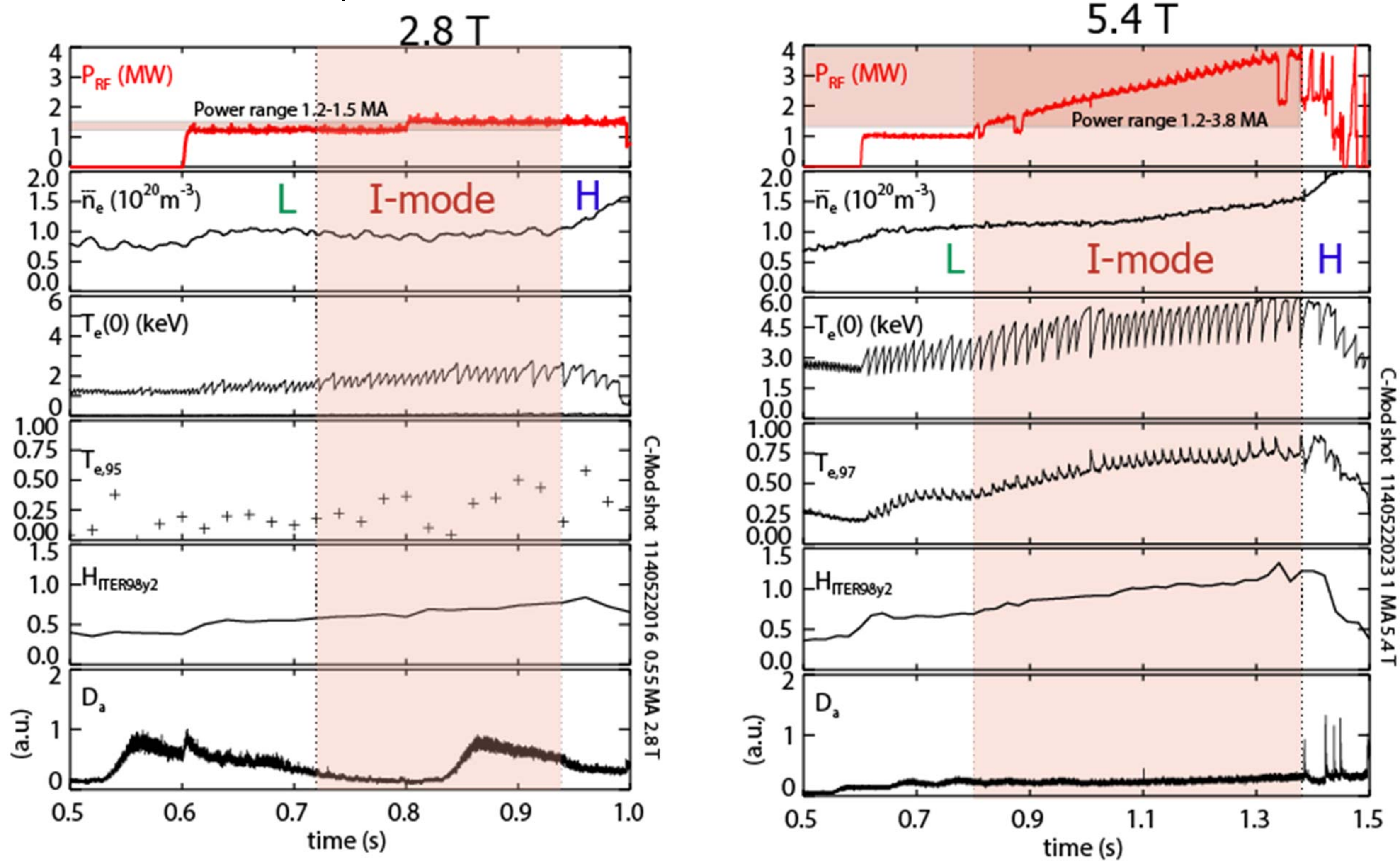
L-I threshold increases less than linearly with device surface area S

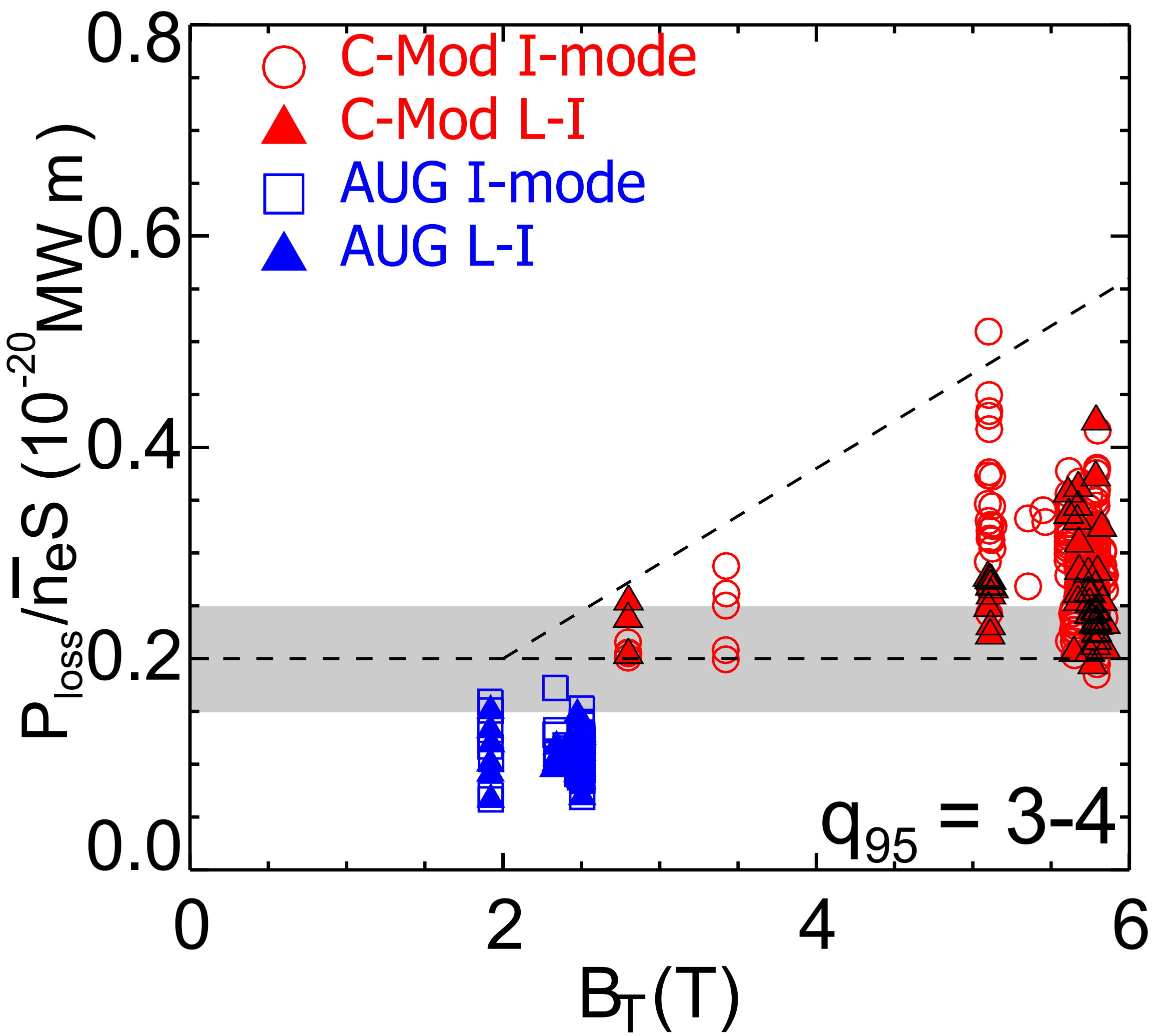


- Linear fit seems too strong, $P(L\text{-}I)/n \sim S^{0.5}$ is a better fit.
  - But, there is scatter in data, and parameters are different between devices; need to check covariances.
- We conservatively use $P/n_e S$ to extrapolate thresholds and power range.
  - If S dependence is weaker, threshold power for larger devices will be lower.

Power range while remaining in I-mode increases strongly with field

Illustrated by C-Mod experiment which compared discharges in same configuration, with B_T=2.8 T and 5.4 T.





Both C-Mod and joint datasets show:

- Weak (no?) scaling of L-I threshold P/nS with B_T.
- Strong (~linear) scaling of *upper* range for I-mode with B_T.

➢ Results in **expanded power range for I-mode at high field.**
  - Consistent with differences seen among devices.
  - Result is encouraging for ITER, at 5.3 T, and for application of I-mode to proposed higher B fusion devices*

*eg, LaBombard, Paper FIP/P7-18, Sorbom 2014.

Extrapolation and key issues

One of the aims of this ITPA joint activity has been to assess possible extrapolation of the I-mode regime to larger devices, especially ITER. Many of the results, obtained with ion grad B drift away from the x-pt, are encouraging:

- I-mode is robust over a wide range of global and dimensionless parameters, extending to low q_{95}, ν^* and ρ^*; no indication of a physics limit which would prevent application to burning plasmas.
- High normalized confinement (H_{98}>1) has been achieved on AUG and C-Mod, though at lower B these discharges often evolve to H-mode.
- L-I threshold power: P/n_e S=const would scale to P_{thresh}~ 70 MW for ITER at $n_e=5x10^{19} m^{-3}$. Weaker scaling with S would reduce P_{thresh}.
- I-H threshold power: Upper power range increases with B_T. C-Mod results at 5.3 T indicate ITER could maintain I-mode to P_{loss}=350 MW at 10^{20} m^{-3}, above the expected heating and alpha power.

Key issues and future work

- **Density and pressure range:** To date I-mode has been achieved at moderate β and n/n_G.
  - All pedestals seem well below stability limits, with headroom. *Is β just set by heating or transition power? How can we increase?*
  - C-Mod experiments show density can be increased at higher power. *What is the limit in density and can it be robustly maintained?*
- **Confinement and threshold scalings.** I-mode has clear differences to H-mode scalings, including weak power degradation of τ_E, I_p dependence of P(L-I), and B_T dependence of P(I-H) . *New multimachine scalings are needed for confident extrapolation.*
  - Experiments are planned soon on EAST and KSTAR.
  - Experiments on JET, with larger size and intermediate B_T, would be particularly valuable.
- **Access with favourable vs unfavourable drift.** Reversing B_T (usually along with I_p) poses operational issues in devices using NBI, including ITER. *Examples exist with favourable drift, should be explored further.*

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- *The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.*