I-mode and H-mode plasmas at high magnetic field and pressure on Alcator C-Mod

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Outline

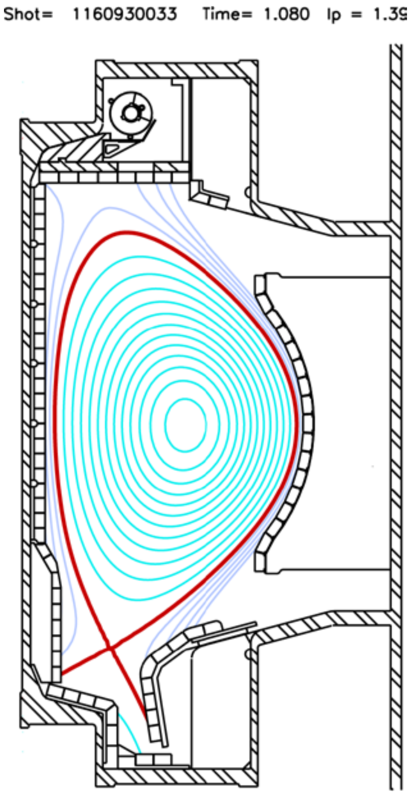
- **Overview of Alcator C-Mod and its main confinement regimes.** *Why high B and pressure?*

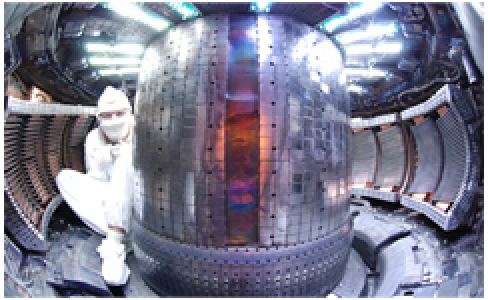
- **Extension of regimes to highest field and pressure.**
  - EDA H-mode.
  - ELMy H-mode, ‘Super-H’ exploration.
  - I-mode.

- **Highlights of pedestal and transition physics.**

- **Implications for future fusion devices**
  - Extrapolations, open issues, and needed research to resolve them.

Alcator C-Mod Tokamak:
Compact, high B, high power density





- R=0.68 m
- **a=0.21 m**

} V ~0.9 m³, S ~7.4 m²

- **B ≤ 8.1 T** (LN2 cooled Cu magnets)
- **I_p ≤ 2.0 MA**

- **Shaped, diverted (similar to ITER).**
- **Divertor, all PFCs high Z metal.**
  — Mostly Mo, from day 1, some W tests.

All RF heating (no torque or core fueling)

- ICRH: 50-80 MHz, ≤ 6 MW
- LHCD: 4.6 GHz, ≤ 1.2 MW

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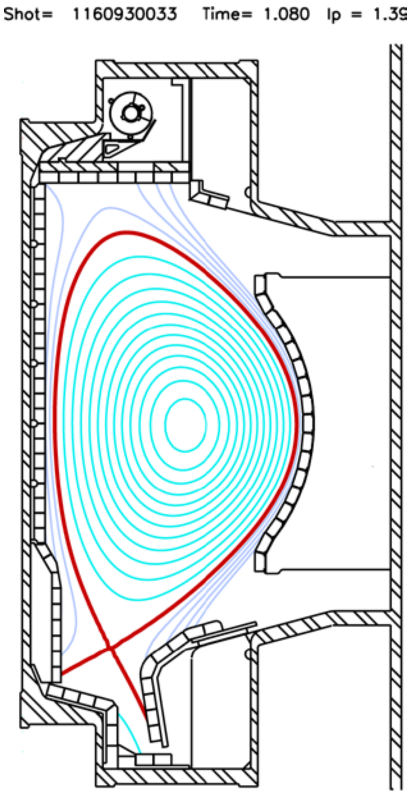

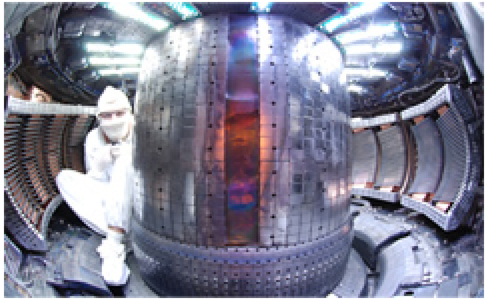

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- **B ≤ 8.1 T** (LN2 cooled Cu magnets)
- **I_p ≤ 2.0 MA**

→ Density limit $n_{G=}I_p/\pi a^2$ ≤1.4x**10^{21}**m^{-3} (Max $\bar{n}_e$>5x10^{20} m^{-3}, $n_{e,0}$ >10^{21}m^{-3})

All RF heating (no torque or core fueling)

- ICRH: 50-80 MHz, ≤ 6 MW
- LHCD: 4.6 GHz, ≤ 1.2 MW

→ P/V ≤ 7.4 MW/m^3, P/S ≤0.94MW/m^2, PB/R≤ 73 MW-T/m

→ Divertor $q_{//}$ ≤ 3 GW/m^2 (λ_q<0.5 mm)

Confinement physics strongly favors **high B** to produce fusion capable devices at **smaller size**

Alcator C-Mod

Lawson criterion: $n\,T\,\tau_E = \mathbf{p}\,\boldsymbol{\tau_E}$ sets fusion gain $Q=P_{fus}/P_{ext}$.

Power density

$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^{\,2}\epsilon^2}{q_*^2} RB^4$$

At fixed power density, aspect ratio ε

$$p\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

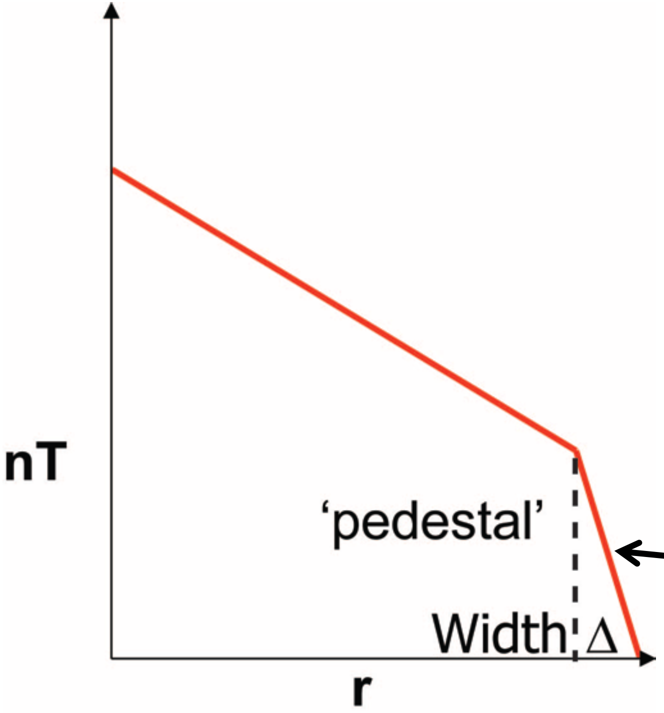
Options for fusion devices:

1. **Increase H, β_N, decrease q_{95}.** Optimize confinement, at stability limits.
2. **Increase R.** Increases cost. $V \propto R^3$
3. **Increase B.** Allows smaller R, away from operational limits.

Alcator program has emphasized the **high field approach**, especially as new High T Superconductor magnets make higher B steady state reactors feasible.

- *How high can field B, pressure be increased in practice?*
- *Do physics, trends from lower B tokamaks hold, or are there surprises?*

Physical models indicate pedestal, core pressure should increase with B_T, I_p.



If pedestal gradient is limited by high-n ballooning modes:

$\nabla p(max) \;\alpha\; I_p^2$

(or ~ B_T^2 at fixed safety factor q_{95})

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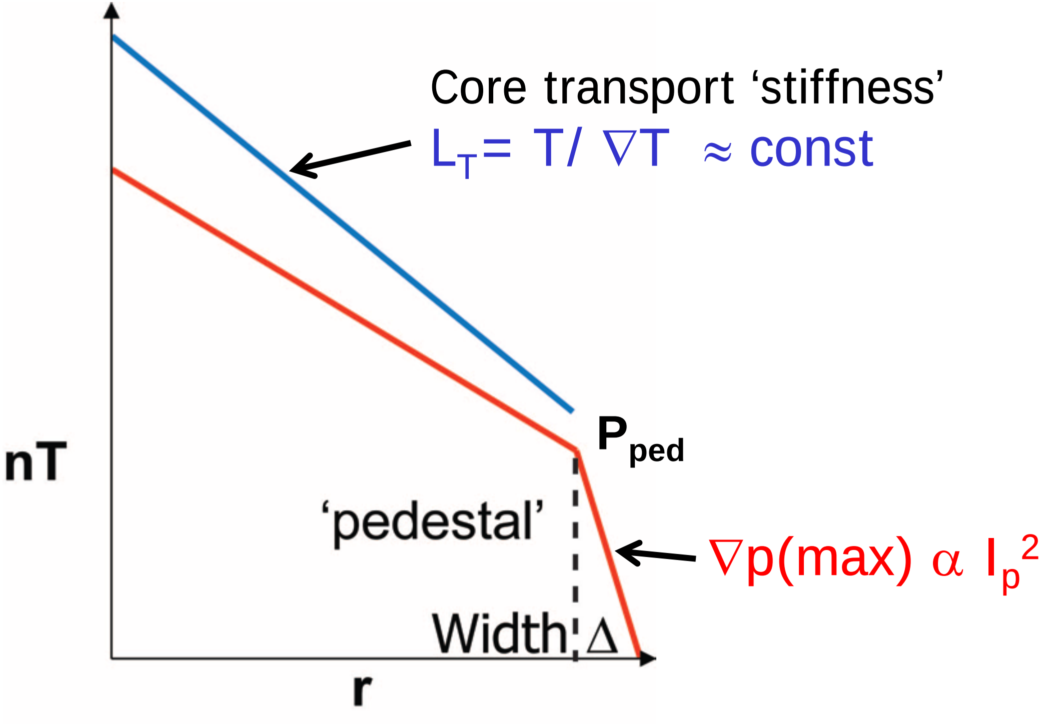
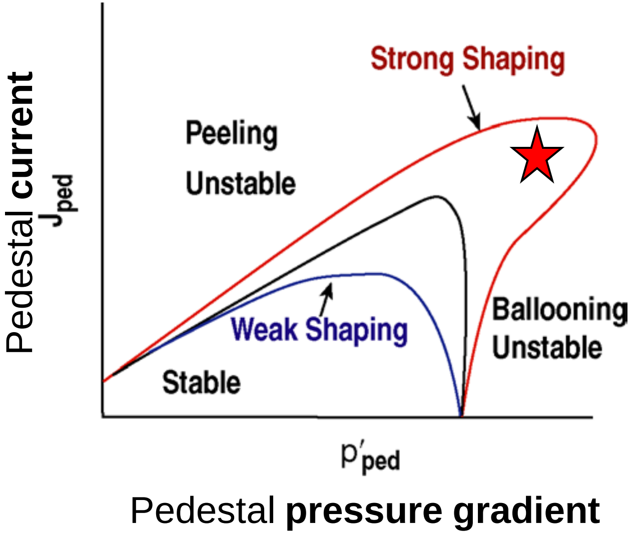


- **Stiffness of core T profiles is widely observed** in tokamaks, including all C-Mod regimes. Greenwald NF'97.
  - Now well understood, and predicted by GK models
    eg N. Howard I1:10

- Implies a **minimum <u>Pedestal</u> pressure, p_{ped}** is needed for fusion.

Physical models indicate pedestal pressure should increase with B_T, I_p.

- *Pedestal limit is not quite that simple.*
  Set by coupled peeling-ballooning modes.



- **If p-b limit is violated, typically get Edge Localized Modes (ELMs)** which release bursts of pedestal energy.
- Would be a big problem in a fusion device with high p_{ped}.
- Ideally want to operate in a stable region, just below limits.

Physical models indicate pedestal pressure should increase with B_T, I_p.

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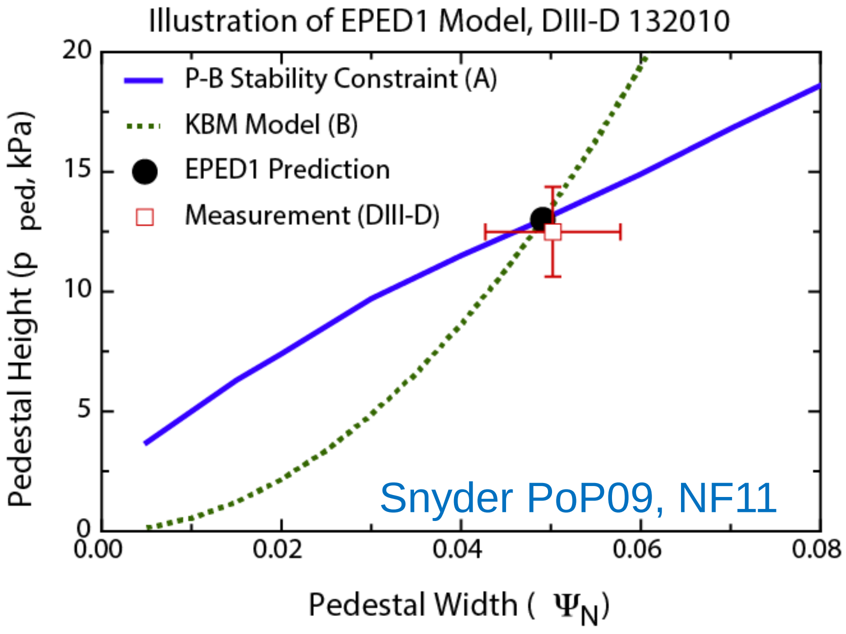
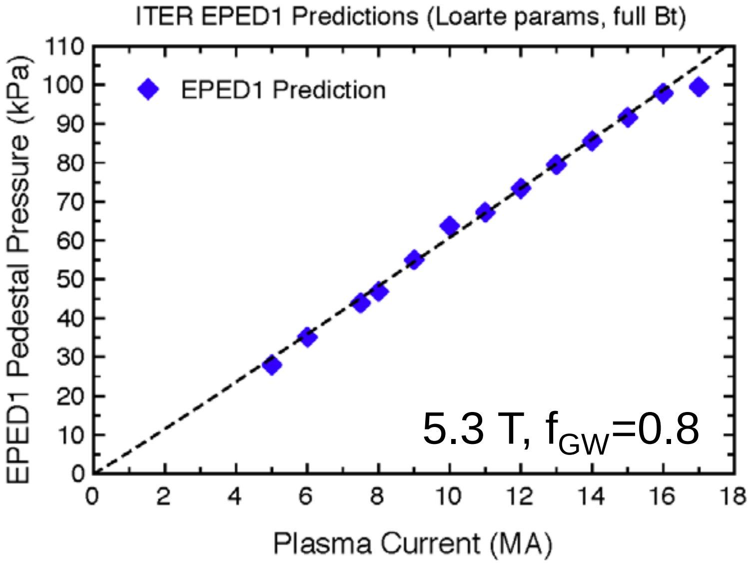
  Set by coupled peeling-ballooning modes.
- EPED model combines P-B and KBM constraints to predict height and width



Physical models indicate pedestal pressure should increase with B_T, I_p.

- *Pedestal limit is not quite that simple. Set by coupled peeling-ballooning modes.*
- EPED model combines P-B and KBM constraints to predict height and width.
- It typically still predicts that pedestal height scales approximately as

$$p_{ped} \propto B_T B_{pol} \propto B_T I_p$$



➢ Should operate at highest B_T, I_p.

- C-Mod can match ITER's B_T, B_{pol}. *Can it reach ITER's predicted pedestal pressure at 15 MA? (90 kPa)*

Snyder, PEP ITPA 2012

C-Mod has explored several high energy confinement regimes

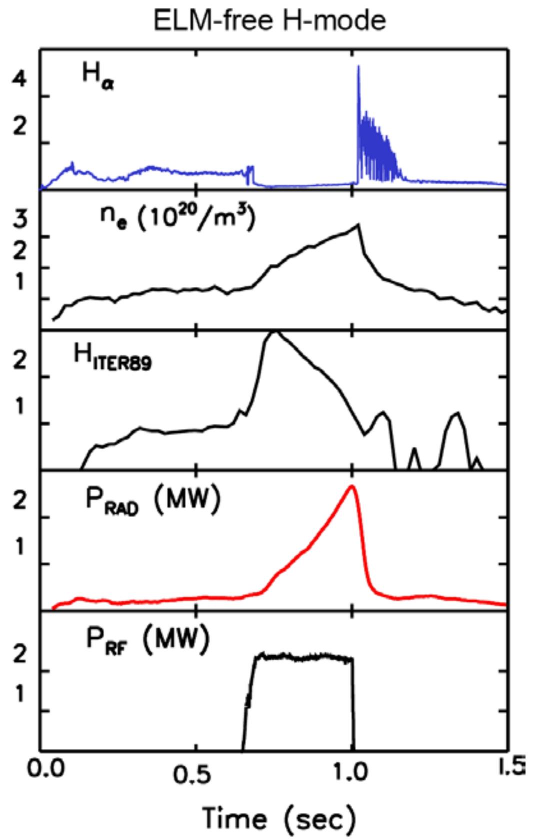
Regime	ELMs?	Stationary?
ELM-free H-mode	NO	NO ☹
ELMy H-mode	YES ☹	YES
Enhanced D_α (EDA) H-mode	NO	YES
I-mode	NO	YES

Will illustrate each of these regimes with examples at C-Mod's most typical operating field, B_T~5.4 T.

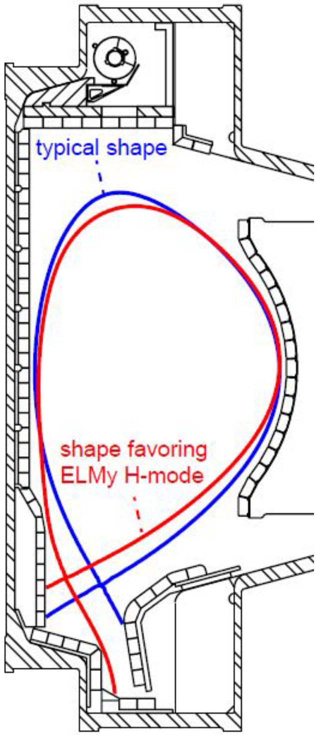
- C-Mod is the only diverted tokamak able to explore these high confinement regimes at full ITER field.
- The most efficient ICRH scenario, D(H), can be used in this B range for f~80 MHz.

ELM-free H-mode

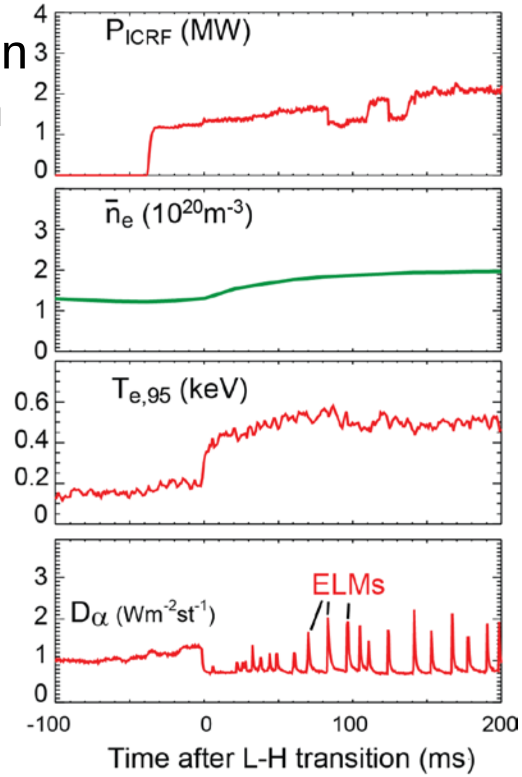
- C-Mod tends to access **ELM-free H-mode** in ITER-like shape, at lower q_{95} and density,
  - Note P/P_{th}~ 1-2, at H-mode n_e.
- This has **very high energy confinement**, but also high particle confinement.
- **Density and radiation increase**, leading to transient H-mode, radiative collapse.
- **Some edge mechanism is needed to increase particle transport, 'flush' impurities!**



ELMy H-mode

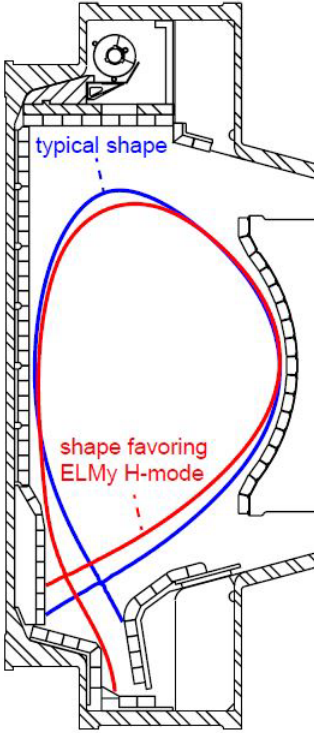


- **Type I ELMy H-mode** on C-Mod is *only* accessed in a shape with modified (reduced) pressure limits, at lower ν^*.
  - Power supply limitations restrict this shape to $I_p < 1$ MA.
  - Particle transport is provided by ELMs. →Stationary density and radiation.



Hughes NF 2013

ELMy H-mode



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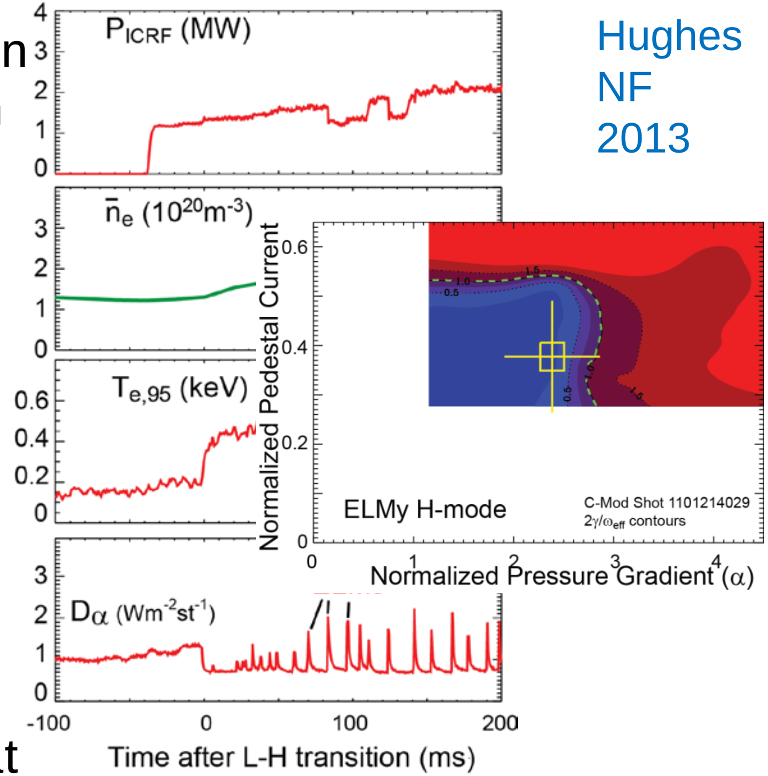
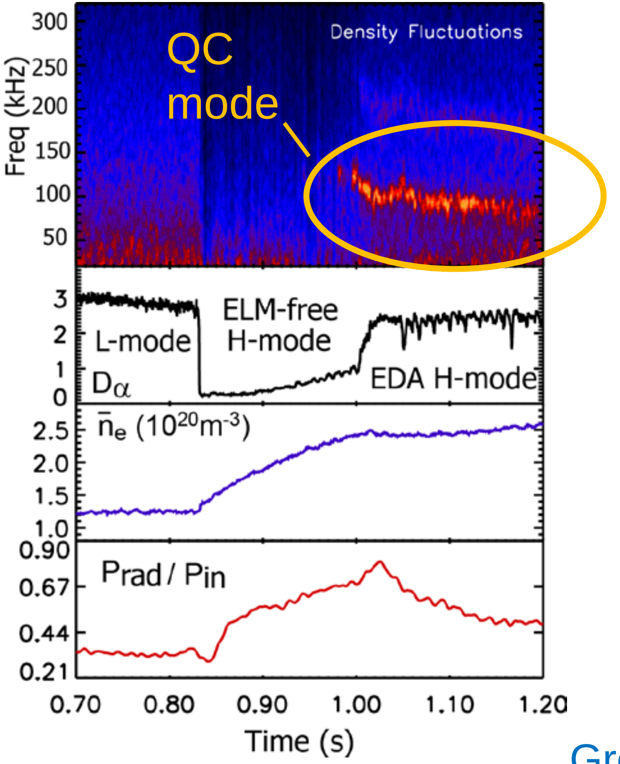
    →Stationary density and radiation.
- C-Mod validates models at unique parameters.



Hughes NF 2013

Enhanced D_α H-mode

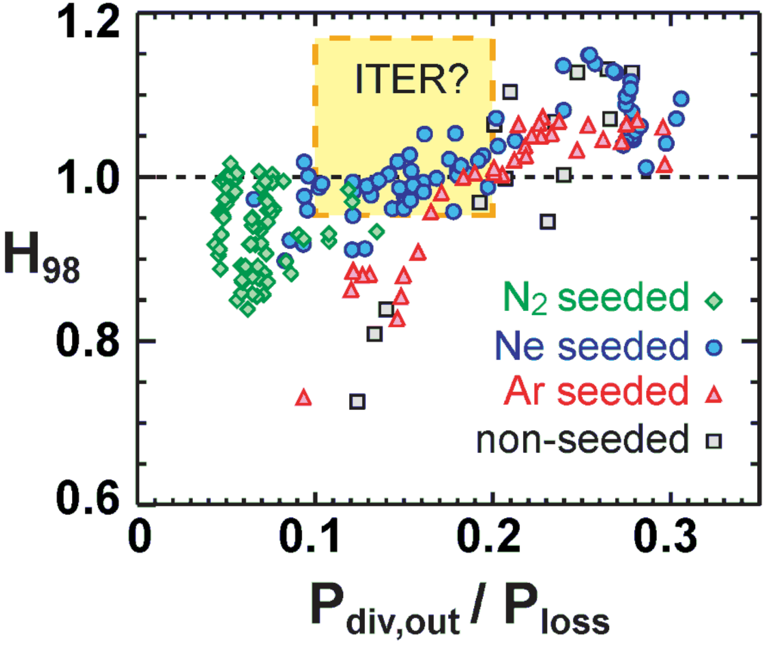
- In EDA H-mode, particle transport is increased by a **continuous fluctuation, the Quasicoherent (QC) mode.**
- Gives stationary density, impurity radiation, WITHOUT Periodic ELMs.
  - Need boronization.
- Has been routinely achieved over a wide range of C-Mod shapes, plasma parameters
  - until 2016 only up to 6.2 T.
- **Access to EDA regime is favoured by higher ν^*, higher q_{95}, ∇p**



Greenwald FST 2007

Enhanced D_α H-mode

- An advantage of the EDA regime is that seeding can readily be used to reduce divertor heat flux, while maintaining needed high confinement.
  - H98 ≥1 as long as $P_{net} \geq P_{thresh}$ (at H-mode n_e)



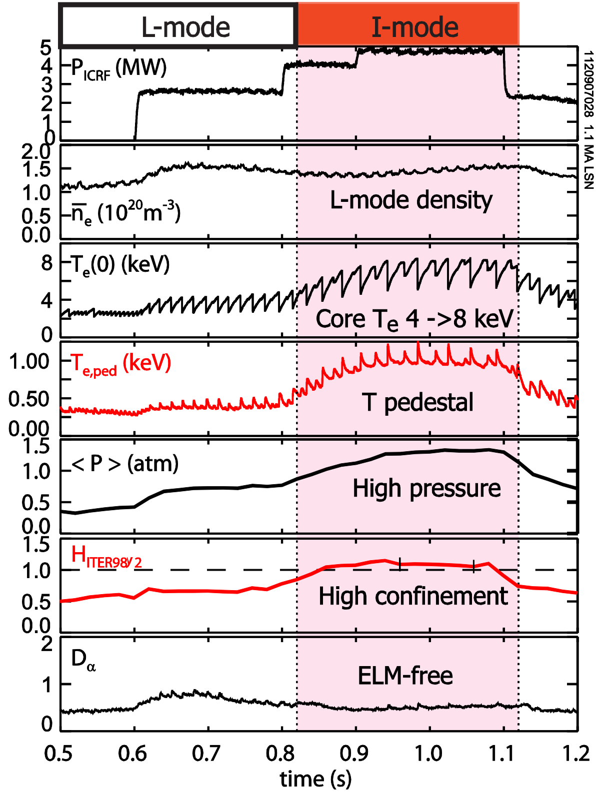
Loarte, PoP 2011,
Hughes, NF 2011

I-mode regime has a thermal barrier, without a particle barrier

Alcator C-Mod

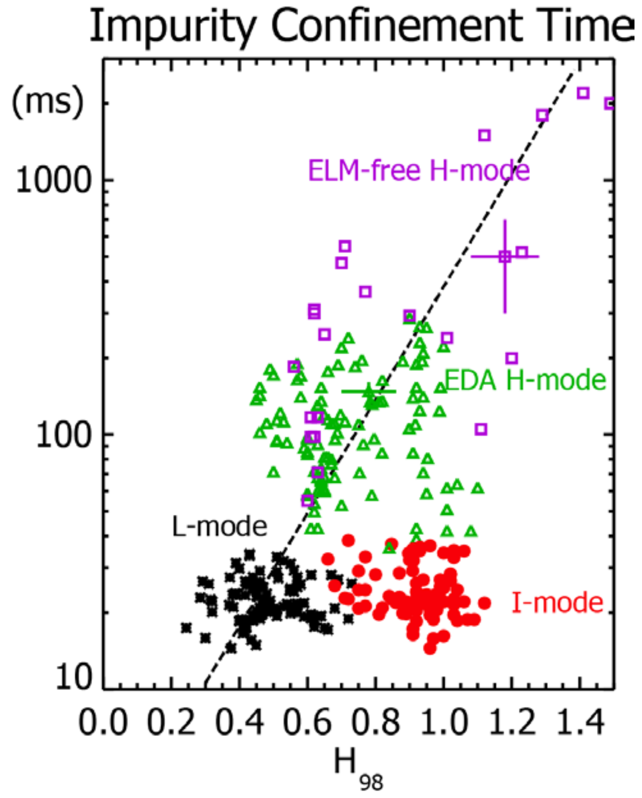
- **H-mode-like temperature pedestal and energy confinement.**
- **L-mode density pedestal and low particle confinement.**
  - Avoids impurity accumulation.
  - Unlike C-Mod H-modes, routine boronization is *not* needed.
- **ELM-free.**

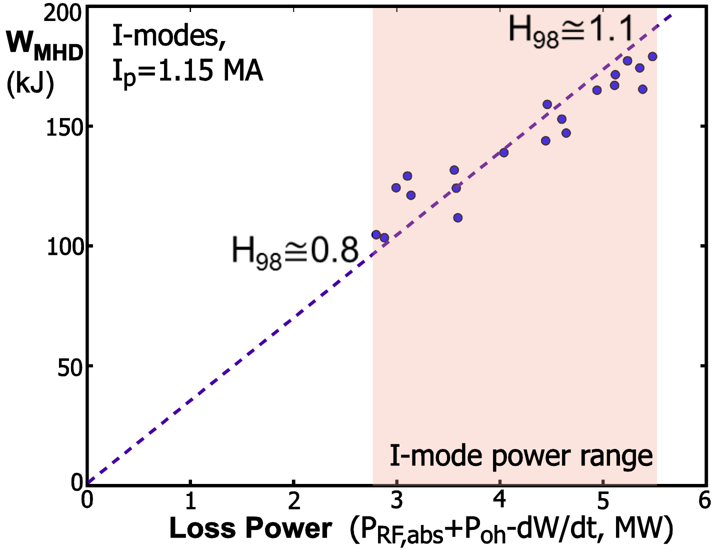
- **Accessed when ion B×∇B drift is *away* from the active X-point (which raises L-H power threshold).**
- **Accessible at low ν*, low q_{95}.**



Whyte NF 2011, Hubbard IAEA 2012

Particle and energy confinement in I-mode vs H-mode





Weaker power degradation in I-mode:

$\tau_{E,Imode} \sim P_L^{-0.3}$ vs $\tau_{ITER98p} \sim P_L^{-0.7}$

A. Hubbard, EPS 2017

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- **Extension of regimes to highest field and pressure.**
  - EDA H-mode.
  - ELMy H-mode, ‘Super-H’ exploration.
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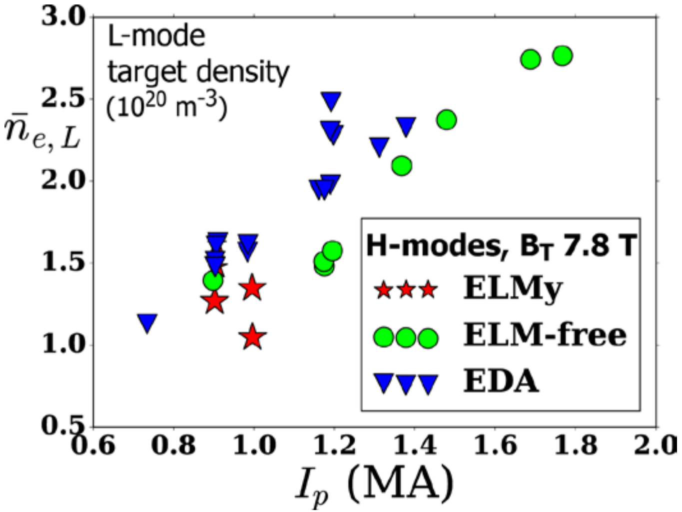
- **Highlights of pedestal and transition physics.**

- **Implications for future fusion devices**
  - Extrapolations, open issues, and needed research to resolve them.

EDA H-mode regime extended to 7.8 T

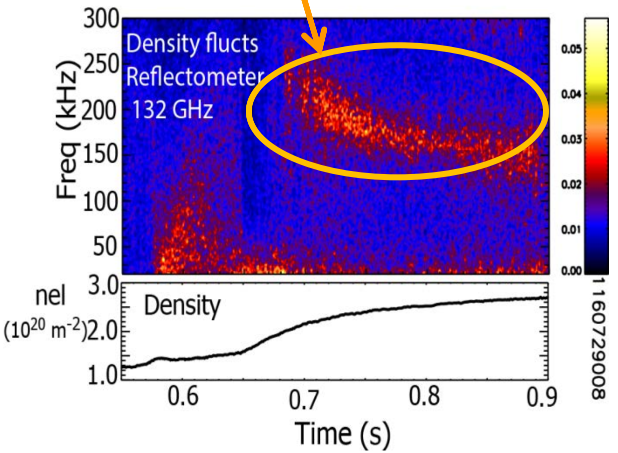
- For 80 MHz ICRH at ~ 8T, need to use D(He^3), a lower absorption scenario, hence lower effective power is available. η_{RF}~50-80%.
- Obtaining EDA H-modes was a challenge
  - L-H power threshold: $P_{th} \sim n_e^{0.7} B^{0.8} S^{0.9}$ (Martin 2008)
  - **C-Mod P_{th} at 7.8 T roughly fit ITPA scaling** (E. Tolman, TTF17)
  - To get EDA H-mode, we need a minimum L-mode target density (n/n_G > 0.25).

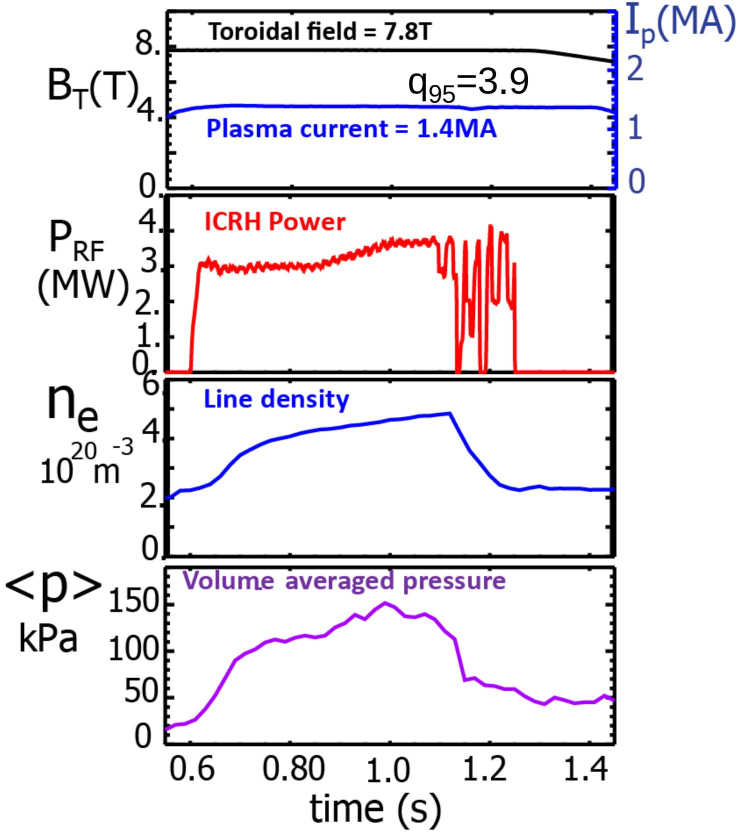
- **7.8 T EDA H-modes** accessed for I_p =0.7-1.4 MA ($q_{95} \geq 3.9$)
- **ELM-free H-modes** to 1.8 MA (q_{95}=3.1)
- **ELMy H-modes** at 0.9-1 MA.



EDA H-mode at 7.8 T, I_p =1.4 MA.

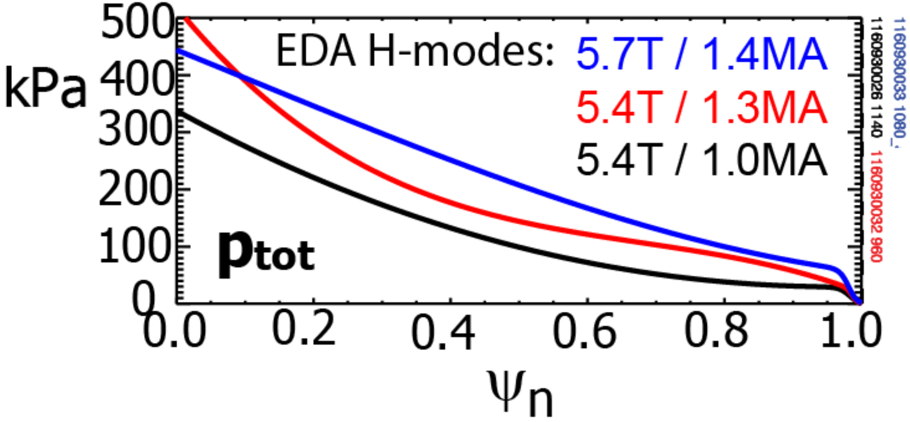
- **Reached high plasma pressures**
  - Pedestal pressure 30 kPa
  - Volume average <p> 150 kPa
  - Central pressure p_0 350 kPa.
- Usual quasicoherent mode in pedestal, at higher freq, 230- 150 kHz.

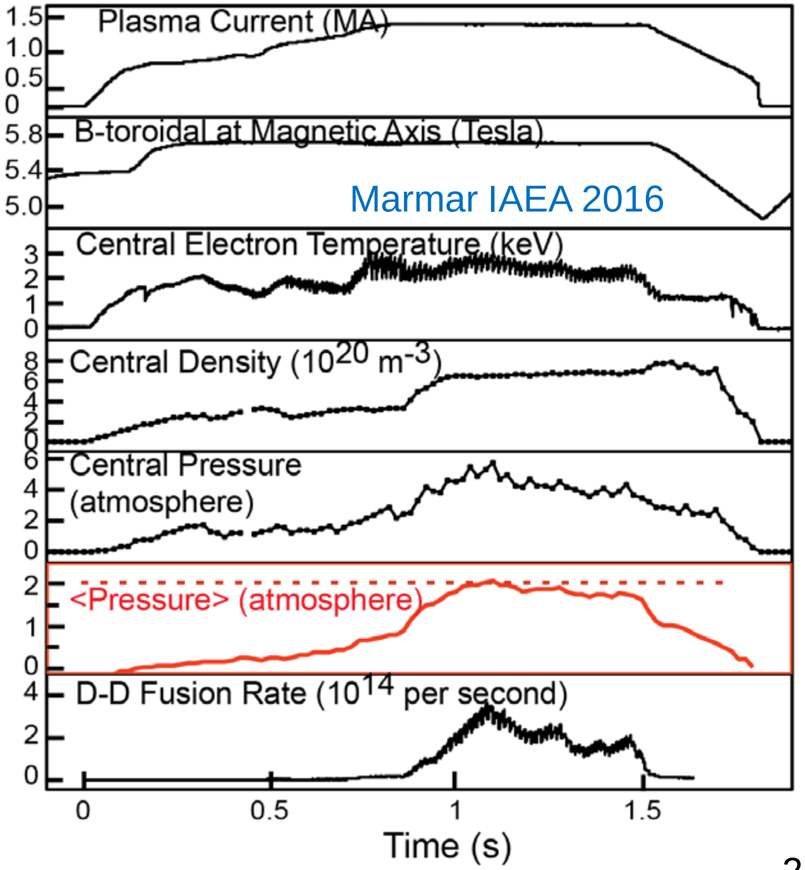




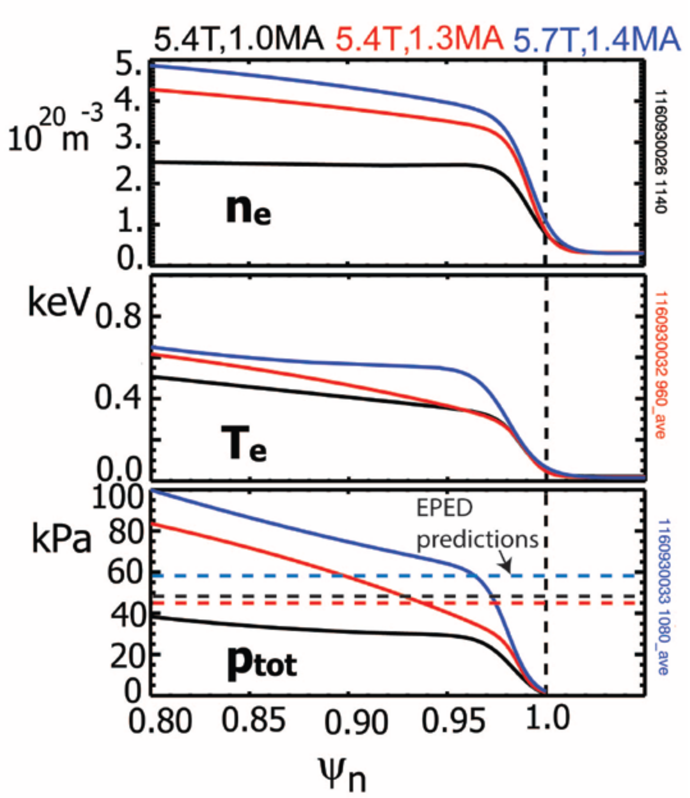
Maximum plasma pressure was obtained in EDA at 5.7 T, 1.4 MA

- At this intermediate field we could use more efficient D(H) ICRH, at r/a=0.2-0.35, still with high I_p =1.4 MA.
  - Optimized with strong fueling, N seeding.
- Achieved **world record <p> 207 kPa.**
- **No ELMs**, near stationary conditions.

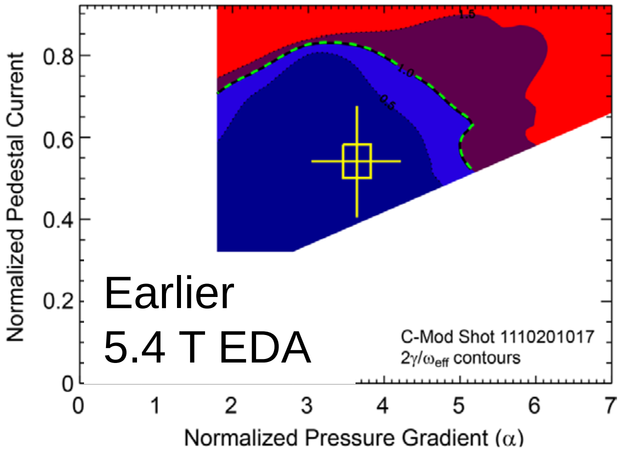




High pressure EDA H-mode pedestals are still below peeling-ballooning stability limit

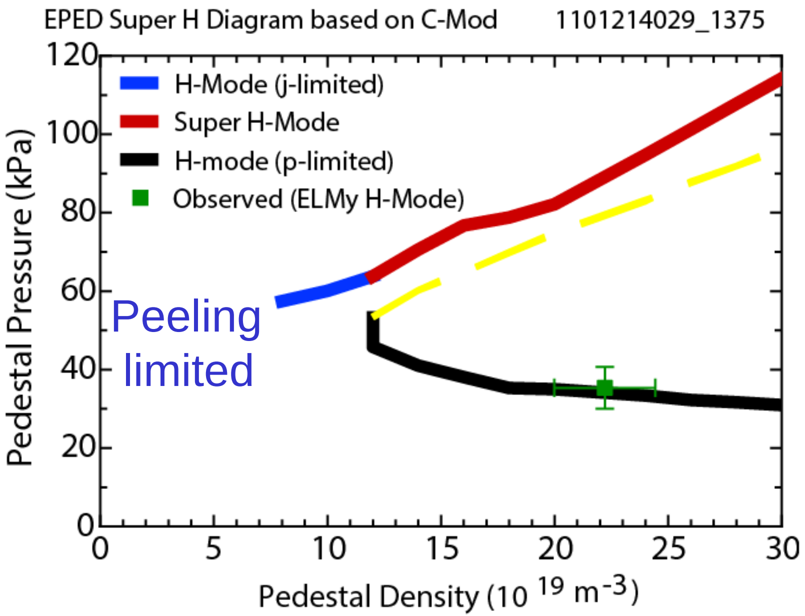


- Typical of EDA H-modes; tend to be at higher ν*, far from peeling boundary.



Could peeling limit, and even higher pressures, be reached at low ν, more like expected ITER pedestals?*

EPED predicted peeling limit, higher p_{ped} should be possible at low n_e, high T_e



- Predictions by P. Snyder, well before experiments. *How to access such low ν^* H-mode pedestals?*

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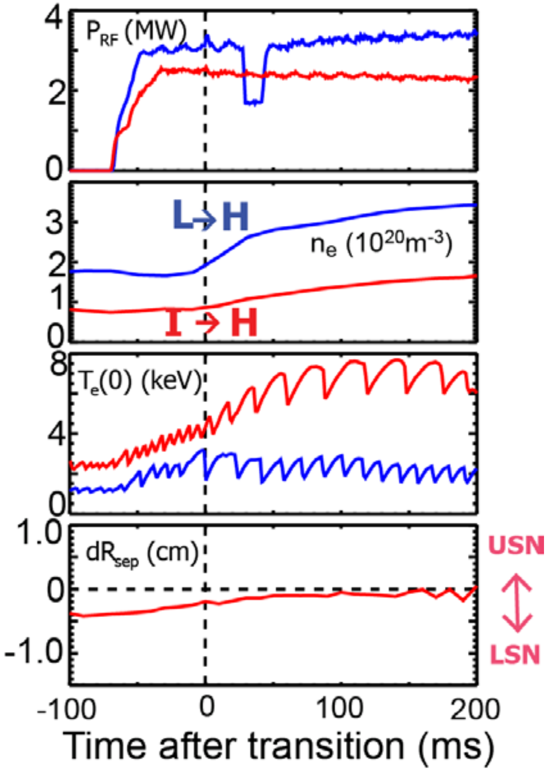
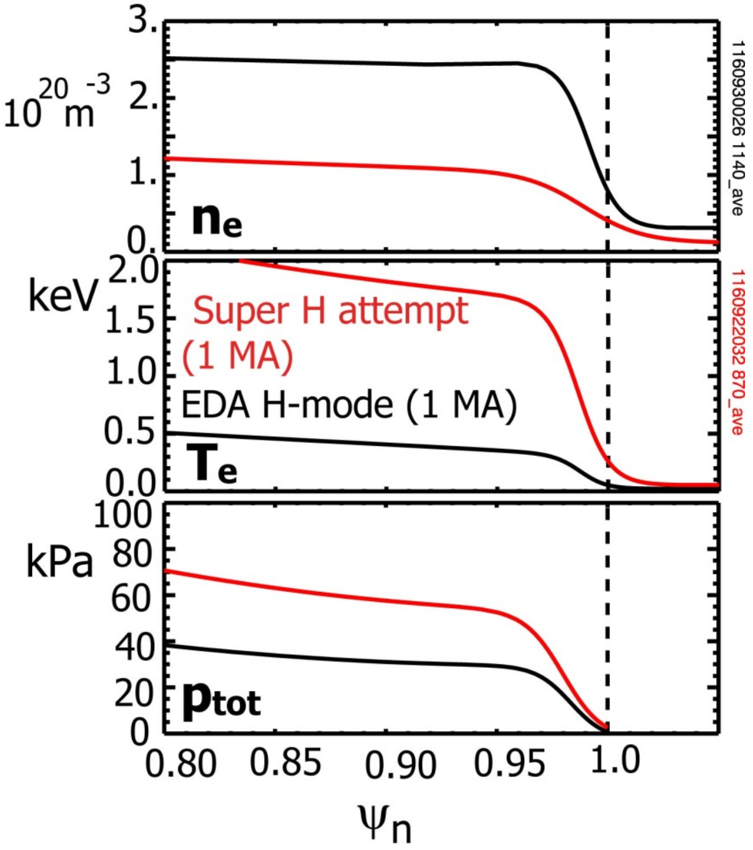


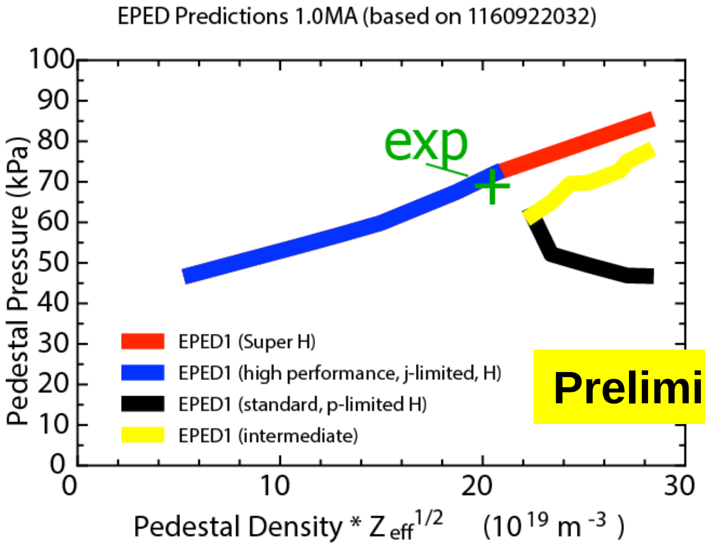
- Predictions by P. Snyder, well before experiments. *How to access such low ν* H-mode pedestals?*

1. Start with a hot I-mode, instead of a cold L-mode!
2. Shift X-point location to trigger H-mode (recall I-mode prefers drift away from X-point).
3. Modify shape to promote instabilities, vs ELM-free.

Experiments confirmed higher pressure pedestal, likely at peeling limit.

Alcator C-Mod



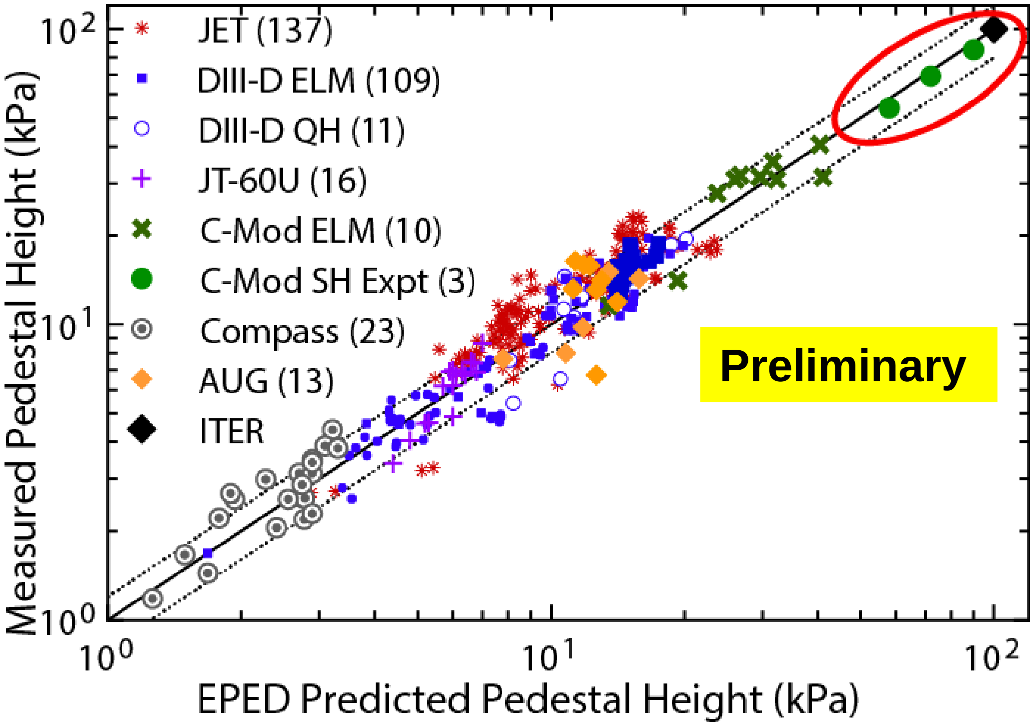


Hughes, Snyder TTF17

- Much higher T_{ped}, P_{ped} than EDA at same I_p (1 MA).
  - Pressure close to EDA at 1.4 MA.
- Then extended regime to I_p=1.4 MA, **record p_{ped} 80 kPa.**

Latest C-Mod H-modes reach 90 % of predicted ITER pressure, extend EPED validation

Alcator C-Mod



Hughes, Snyder TTF17

- Major accomplishment, for theory and joint experiments.
- Greatly increases confidence in ITER predictions.
  - Recall that in early 2000's, P_{ped} was highly uncertain, allowing big range in fusion Q.

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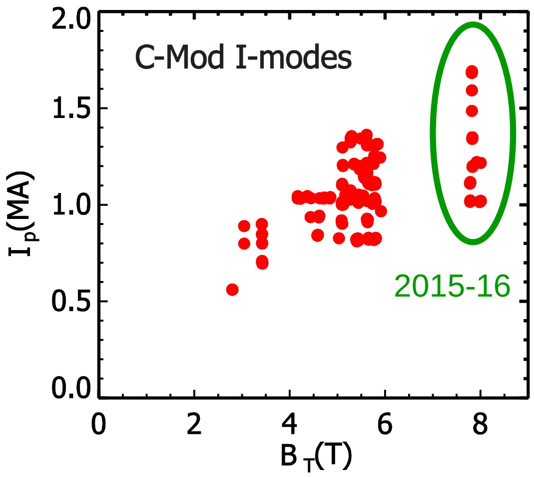
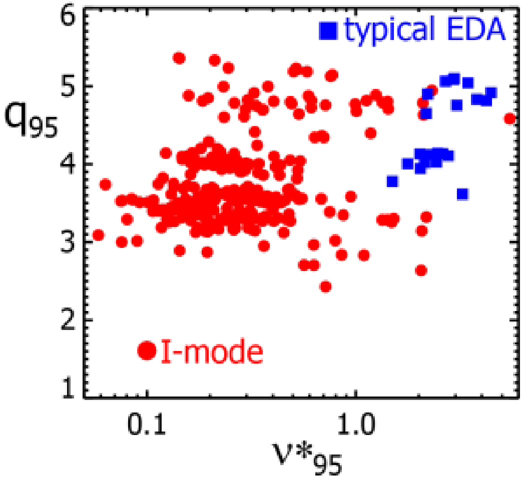
- **Highlights of pedestal and transition physics.**
- **Implications for future fusion devices**
  - Extrapolations, open issues, and needed research to resolve them.

I-mode has now been extended to a very wide range of parameters

- **Robust I-mode operation on C-Mod** :
  - B_T 2.8-**8 T**,
  - I_p 0.4-**1.7 MA**,
  - Density 0.85-**2.35 x10^{20}m^{-3}**



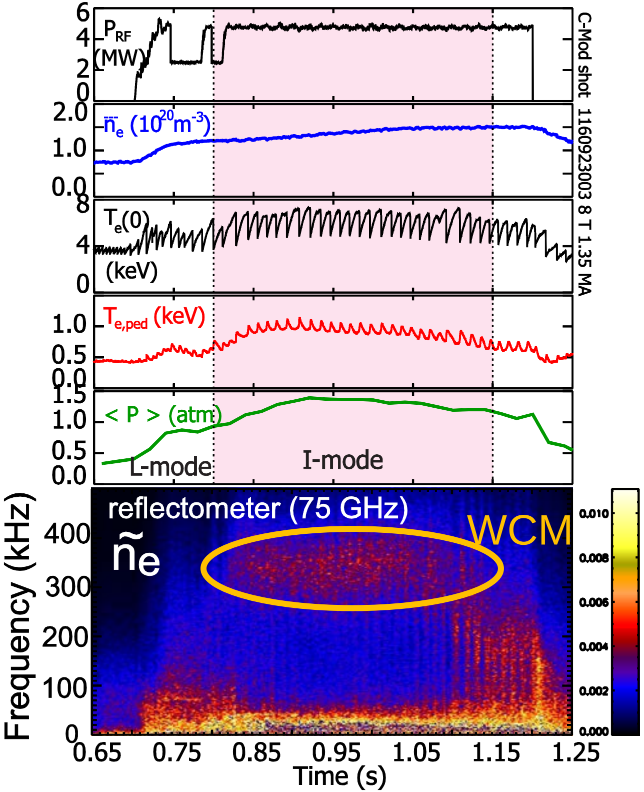


- **Has also been studied on ASDEX Upgrade and DIII-D**.
  Together, I-mode discharges have used
  - Heating with ICRH, NBI and/or ECH.
  - Mo, W and C PFCs.

- Dimensionless parameters:
  - q_{95} 2.4-5.4
  - ν^*_{95} 0.06-5.4
  - ρ^* 0.0026-0.006

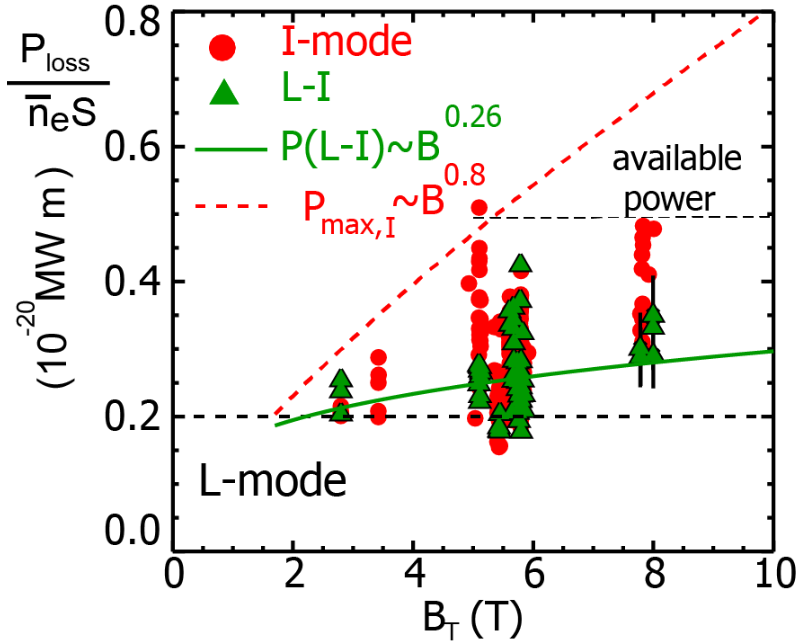
Hubbard, Ryter, Osborne NF 2016

8 T I-modes exhibit typical features



- **Example with 7.8 T, 1.35 MA, (q_{95}= 3.7), P_{RF}=4.7 MW:**
- Central T_e to 7.3 keV,
- Volume averaged <P> to 1.4 atm (0.14 MPa).
- H_{98}=1, assuming η_{RF}=80%.
- No ELMs
- Weakly Coherent Mode at 350 kHz (again higher than at lower I_p and B_T).
  - *Up to 450 kHz at 1.7 MA.*

Power range for I-mode widens with increasing magnetic field

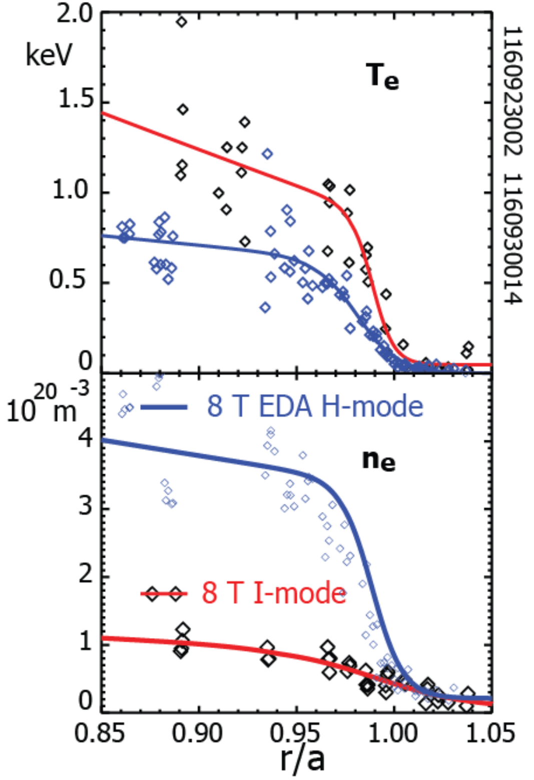


- In contrast to L-H scalings, **L-I power threshold has at most a weak dependence on B_T.**
- **$P(L\text{-}I)/n_e \sim B_T^{0.26}$.**
  - Uncertainties in P_{loss} at 8 T.
- **Maximum power for I-mode does increase with B_T.**
  - NO discharges at 7.8-8 T had I-H transitions, up to 5 MW available ICRF power ($P_{tot}/S \leq 0.63$ MW/m^2)

- **More range to stay robustly in I-mode at higher B**, avoiding H-mode.
- Consistent with experience on lower B tokamaks.

I-mode pedestals have much higher T, lower density than EDA H-mode

Alcator C-Mod



- Comparison of discharges with **7.8 T, 1.35 MA,** P_{loss} ~ 4.4 MW.
- **I-mode** has
  - Steep T_e gradient, T_{ped}~1 keV (also T_i) Low ν^*=0.15, ρ^*=0.0033
  - L-mode density profile.
- **EDA** has highest pressure, but is high ν^*.
- Pedestals in both regimes are MHD stable, **Explains lack of ELMs;** regulated by continuous fluctuations.
- Scope to increase further; **pressure at 8 T was limited only by input power.**

Outline

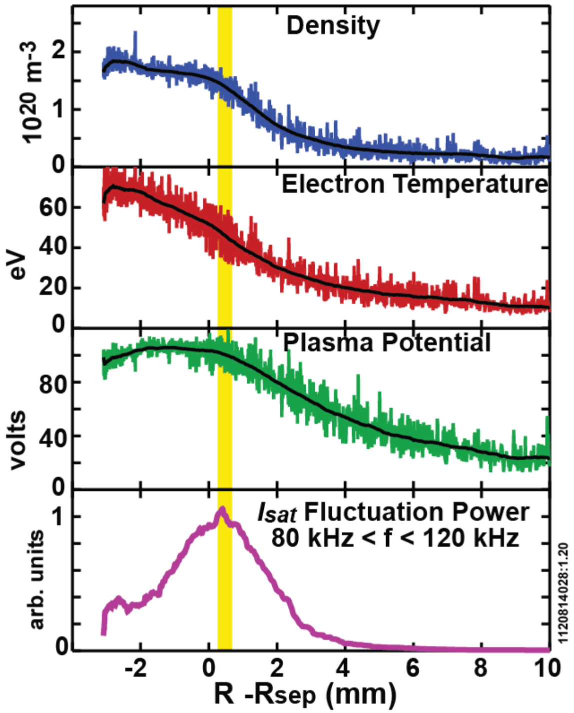
- **Overview of Alcator C-Mod and its main confinement regimes.** Why high B?
- **Extension of regimes to highest field and pressure.**
  - EDA H-mode.
  - ELMy H-mode, 'Super-H' exploration.
  - I-mode.
- **Highlights of pedestal and transition physics.**
- **Implications for future fusion devices**
  - Extrapolations, open issues, and needed research to resolve them.

Pedestal turbulence and flows are key to regimes without ELMs.

Alcator C-Mod

EDA H-mode:

- Sharp suppression of turbulence at L-H transitions, **rapid formation of both density and temperature pedestals**. Followed by appearance of QC mode.
- **New highly detailed mirror Langmuir probe measurements show that QCM:**
  - spans LCFS region with a mode width of ~ 3mm
  - drives transport directly across LCFS
  - is an **electron drift-wave with interchange drive and EM contributions**



$$\frac{\Delta n}{\langle n \rangle} \sim 30\% \quad \frac{\Delta T_e}{\langle T_e \rangle} \sim 45\% \quad \frac{\Delta \Phi}{\langle T_e \rangle} \sim 45\%$$

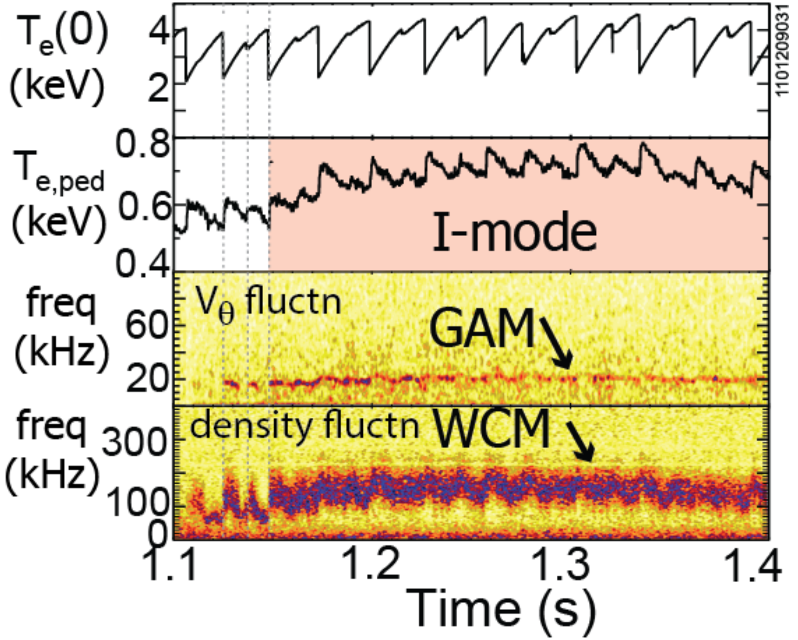
LaBombard PoP 2014

Pedestal turbulence and flows are key to regimes without ELMs.

Alcator C-Mod

I-mode:

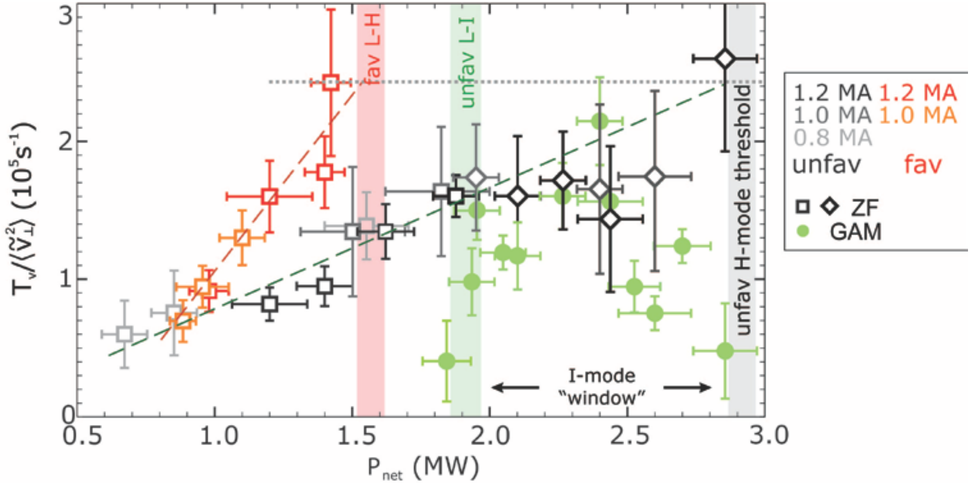
- **Reduction in mid-freq turbulence,** correlated with χ_{eff}, **formation of only a temperature pedestal**.
- **Weakly Coherent Mode** – broad fluctuation at few 100 kHz
- Fluctuating flow at **GAM** frequency (10's of kHz). Important in broadening WCM.
- Both **WCM and GAM likely drive particle transport**
- Consistent results on C-Mod (Cziegler PoP 2013) and AUG (Manz NF 2015).



For details, see Cziegler P5:175 (Friday).

Transfer from turbulence to zonal flows is 2x lower with B×∇B away from X-pt, opening an I-mode power window

- L-H transition occurs when energy transfer rate into ZF exceeds turbulent drive. [AUG Manz PoP12, DIII-D Yan PRL14, C-Mod Cziegler PoP 14,NF15]
- **Transfer rate in the configuration with B×∇B away from X-pt ("unfavourable") is only half the rate towards X-pt ("Favourable") =>higher H-mode threshold!** Opens up a power window for I-mode.



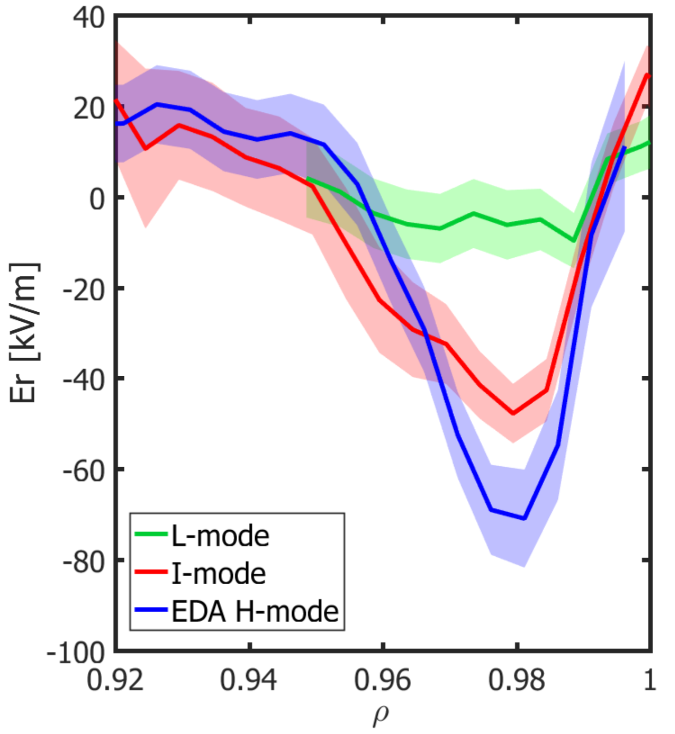
In I-mode, energy goes into both **Zonal Flows** and **GAMs**.

I. Cziegler, York
PRL 118 (2017) 105003
For details see P5:175 (Friday).

E_r wells in both H-mode and I-mode

In 5.4 T field range, **E_r follows same trends as energy confinement:**

- **L-mode** has little E_r, ~ 20 kV/m.
- **EDA H-mode**, **I-mode** both have significant E_r wells, ~ 50-100 kV/m. ⇨



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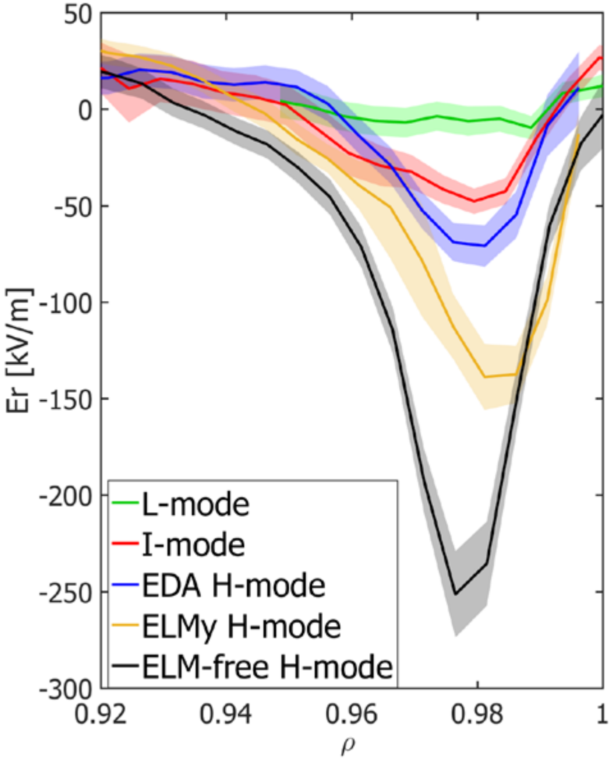
- **ELMy H-mode** ~100-150 kV/m.
- **ELM-Free H-mode** has deepest wells: in some cases 200-300 kV/m.



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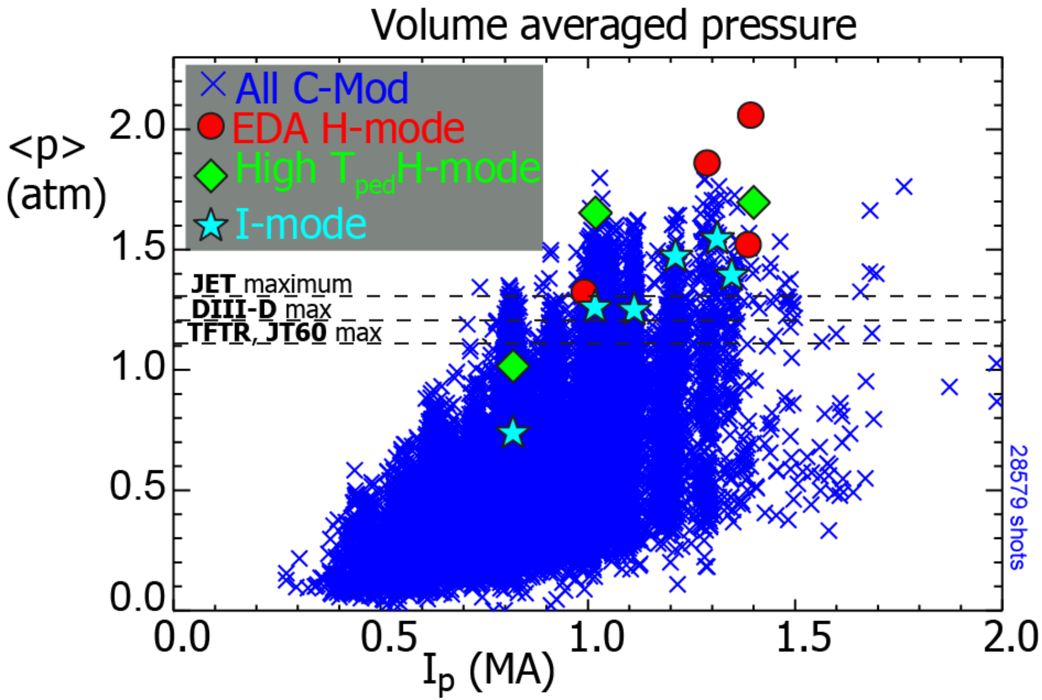
C-Mod experience confirms high pressure at high field, current, in a compact tokamak

Alcator C-Mod



- **Average pressures often exceeded those of larger, lower B, tokamaks** (R_{JET} >4 $R_{C\text{-}Mod}$).

- Similar <p>, trends for all confinement regimes (EDA H-mode, I-mode....)
- Each regime has different advantages, issues.

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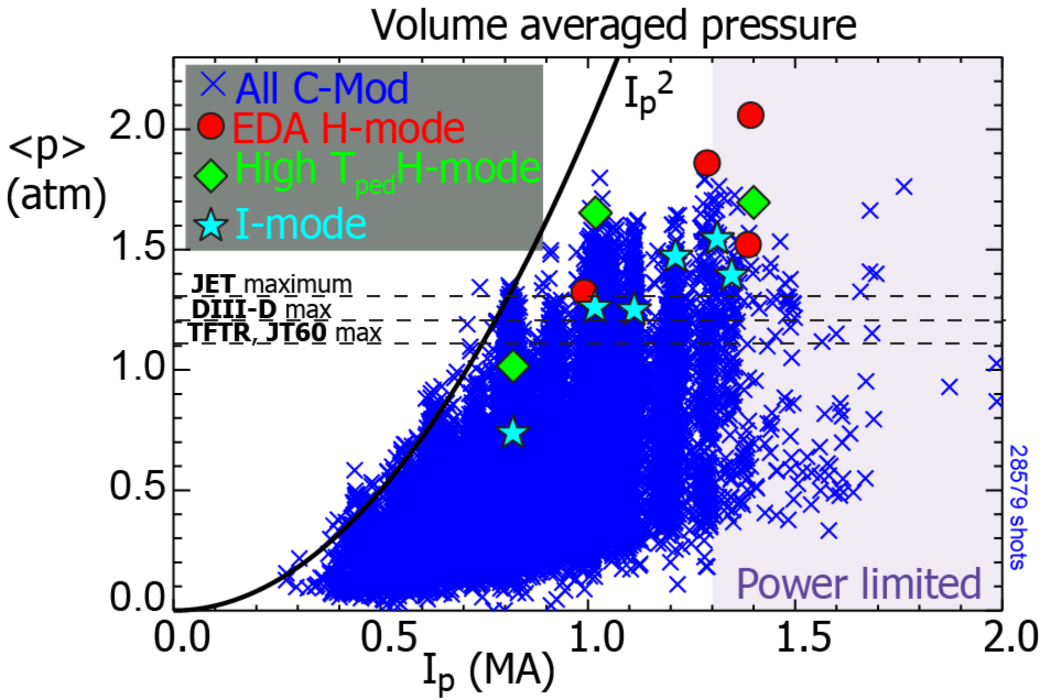


- **Average pressures often exceeded those of larger, lower B, tokamaks** (R_{JET} >4 $R_{C\text{-}Mod}$).
- **$\langle p \rangle_{max} \sim I_p^2$** to ~1 MA, but was limited by heating power at higher currents.
  - With more RF power, at 120 MHz, much higher <p> likely possible

- Similar <p>, trends for all confinement regimes (EDA H-mode, I-mode....)
- Each regime has different advantages, issues.

H-mode: Pedestals, thresholds at 5-8 T closely follow trends from lower B.

- P(L-H) follows ITPA scaling.
- EDA access possible at higher n_e, power.
- H-mode pedestal limits follow EPED predictions, to 90% of ITER $P_{ped.}$
- *No surprises!* ➡ We can confidently use prior multi-device scalings, and our present models, to project to high field DT tokamaks.

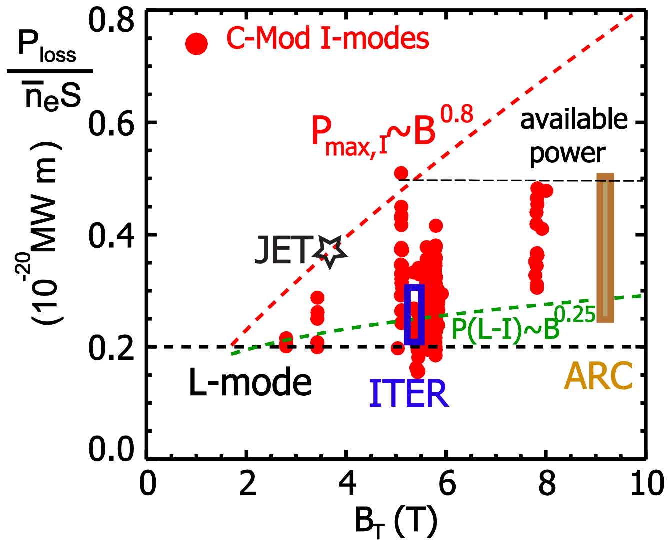
Examples: Assuming H_{98}=1, project to

- **R= 1.65 m**(~AUG, DIII-D), **B=12 T** ➡ P_{fus}=50-100 MW (**Q=2-3.6**)
- ARC*: **R=3.3 m**(~JET), **B=9.2 T, I=12 MA** ➡ P_{fus}=525 MW (**Q~13**)

*B. Sorbom, FED 100 (2015)

I-mode: Pedestals and thresholds trends with field, up to 8 T, are favourable for high B

- ***Surprise:* P(L-I) increases weakly with B_T.**
- Upper range of power increases with B_T, making I-mode regime much more robust at 5-8 T than 2-3 T.
- **Confinement remains high (H~1). No ELMs or impurity accumulation.**
- Simple projections indicate I-mode may be accessible in ITER, ARC, and could be maintained to full fusion power.



BUT: We do not yet have as much experience with I-mode.

- **Multi-device scalings of thresholds, τ_E, density range are needed for confident extrapolation.** ITPA activity, including several EU tokamaks. Experiments at larger size (JET, JT60-SA) will be especially valuable.

Some of the remaining issues and questions

Alcator C-Mod

Much work remains for understanding, and extrapolation to a fusion reactor.

For all regimes.

- How to handle high divertor heat loads?   Require advanced divertors
- Sustainment of plasma current, at high density.

H-mode:

- Can EDA H-mode still be accessed at needed high temperatures?
- How to fuel plasmas with high SOL density? Will pedestals change?

I-mode:

- Confinement scaling. *Why are particle and energy transport separated?* At what power, pressure may p_{ped}, τ_E saturate?
- Threshold scaling.   Dependence on B vs normalized parameters?
- How high in density can the regime be extended?
- Heat footprint? How can it be integrated with a detached divertor solution?

Conclusions

- **C-Mod results have demonstrated the expected strong improvement in plasma pressure at high field and current.**
  - We have developed two stationary, quiescent, high confinement regimes, **EDA H-mode and I-mode** and are making good progress on pedestal physics.
  - Each confinement regime, also ELM-free H-mode and ELMy H-mode, has been extended to B_T=8 T. Some to 1.8 MA.
  - Highest pressure of any tokamak, <p>=207 kPa, p_o=450 kPa, was achieved in EDA H-mode at 5.7 T, 1.4 MA.
  - Highest pedestal pressure, p_{ped}=80 kPa, in a low ν^* H-mode validates the EPED model to 90% of ITER prediction.
  - L-H thresholds agree with ITPA scalings to 8 T.
  - I-mode threshold trends with B are very favourable for high field tokamaks.
- **C-Mod has established a strong design basis for future high field, compact, burning tokamaks for fusion energy.**