Advances in physics and performance of the I-mode regime over an expanded operating space on Alcator C-Mod*

A. E. Hubbard,
D. Brunner, S.-G. Baek, A. Creely, I. Cziegler[1],J.W. Hughes,
B. LaBombard, Y. Lin, Z. Liu [2,3], E.S. Marmar, M.L. Reinke[4],
J.E. Rice, B. Sorbom, C. Sung[5] J.L. Terry, C. Theiler[6], J. R. Walk,
A.E. White, D.G. Whyte, S.M. Wolfe, S.J. Wukitch, X.Q. Xu[3]
and the Alcator C-Mod Team

MIT Plasma Science and Fusion Center
[1]York Plasma Institute, Univ.of York, UK, [2]ASIPP, Hefei, China,
[3]LLNL, Livermore, CA, USA, [4]ORNL, Oak Ridge ,TN, USA
[5]University of California, Los Angeles, CA, USA
[6]EPFL, Swiss Plasma Center, Lausanne, Switzerland
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Alcator C-Mod

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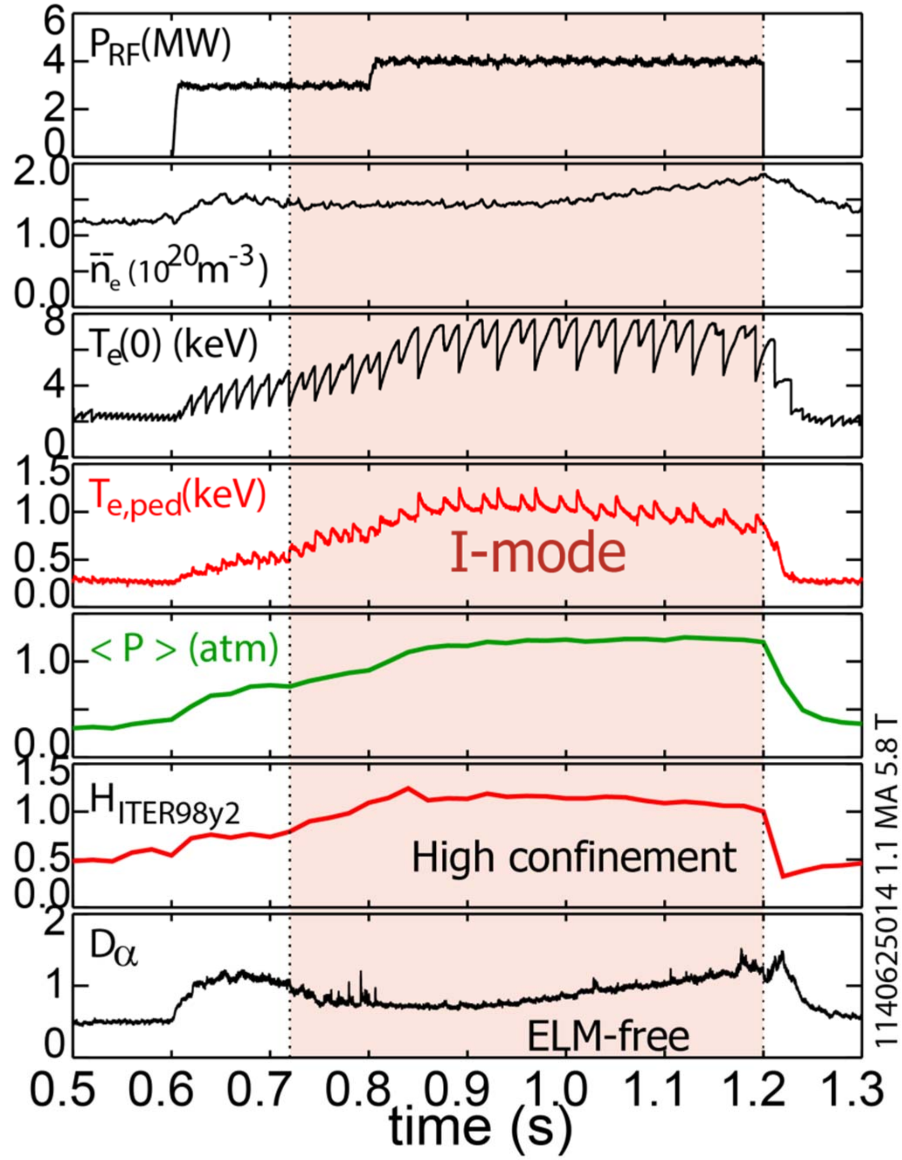
Outline

- **Key features of the I-mode regime for fusion energy.**
- **Expanded operating space on C-Mod.**
  - Magnetic field increased to 8 T.
  - Near double null configurations.
- **Particle and energy transport**
- **Pedestal physics and transitions.**
- **Extrapolation of I-mode for fusion devices**
  - Prospects, issues, and needed research.

I-mode regime combines the best features of H-mode and L-mode

Alcator C-Mod

- **Temperature pedestal and high energy confinement.**
- **L-mode density pedestal and low particle confinement.**
  - Stationary, controlled densities.
  - Avoids accumulation of high or low Z impurities and need for routine boronization.
- **ELM-free, avoiding damaging heat pulses.**
  - Pedestals are MHD stable.
- **Highly attractive features for fusion energy.** Key issues:
  - Can it be accessed in reactor conditions?
  - Will τ_E will be high enough?



1.1 MA, 5.8 T, q_{95}=3.4
LSN, upwards **B**×∇**B**

I-mode has now been achieved over very wide ranges of parameters

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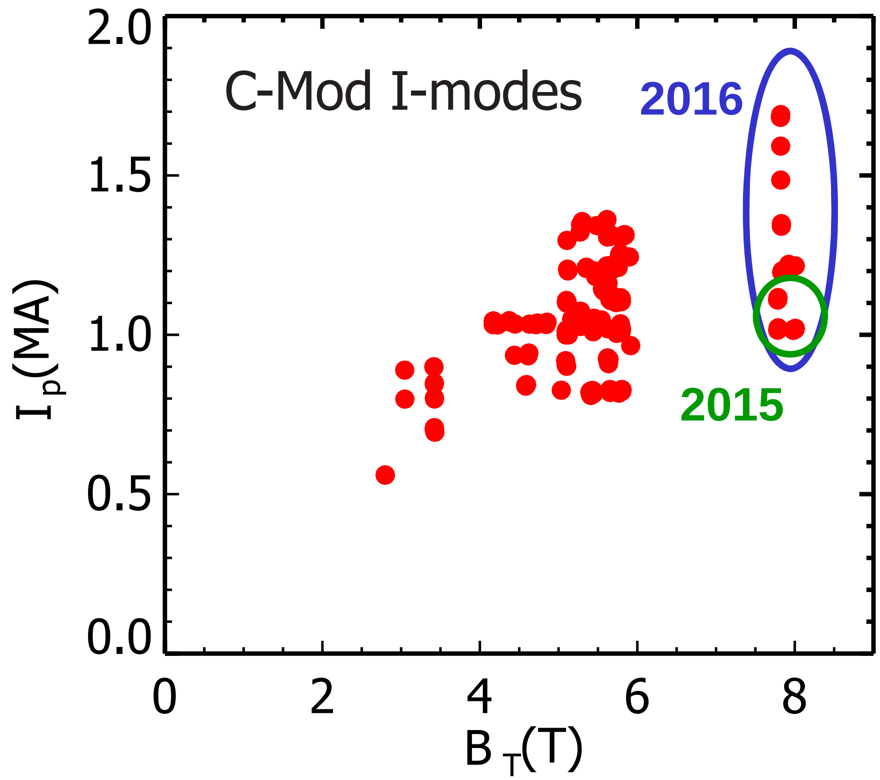
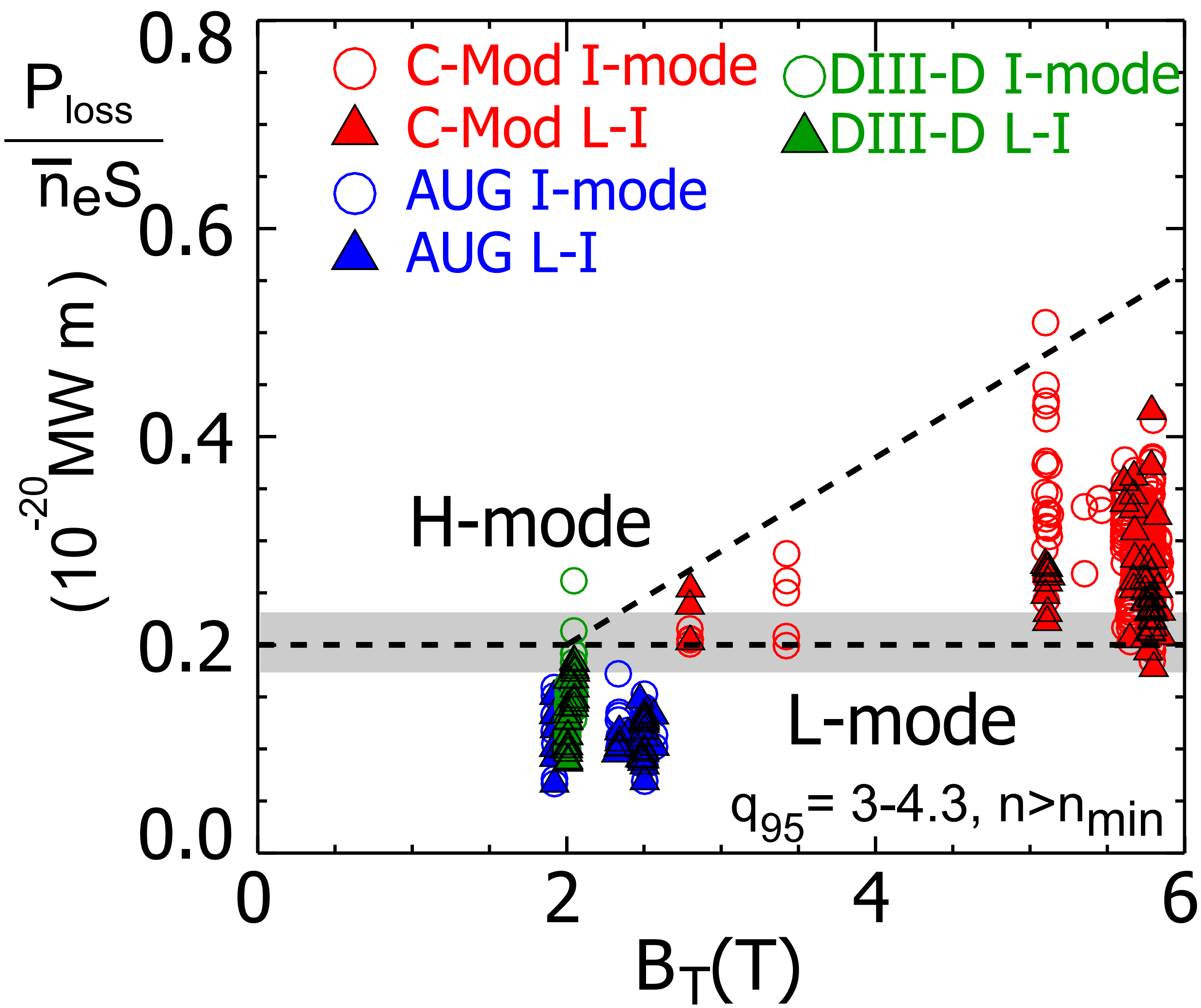
- **Multidevice studies on C-Mod, ASDEX-Upgrade, DIII-D** were reported at FEC 2014 Hubbard, Osborne, Ryter et al NF16
- **I-mode is robust over wide ranges of dimensional parameters:** I_p 0.4-1.4 MA, B_T 1.9-6 T, density 0.16-2.4x10^{20}m^{-3}, P_{loss} 1.5-4.1 MW and **dimensionless parameters**: q_{95} 2.4-5.2, ν^*_{ped} 0.17-4,
- **Heating with ICRH, NBI and/or ECH.**

- In 2015-2016, 30% of C-Mod operation has been in the configuration favouring I-mode, with ion **B**×∇**B** drift *away* from X-point. Emphasis on
  - Extending to even higher magnetic field and current (8 T, 1.7 MA).
  - Identifying and addressing key physics issues for extrapolation.



FEC 2014: weak dependence of L-I threshold, larger power range with higher B_T



- At <3 T, modest increases in power tend to give I-H transitions.
- At >5 T, can remain in I-mode to much higher powers.
  - Some discharges still have I-H transitions.

8 T I-modes confirm, extend the promising trends with B_T

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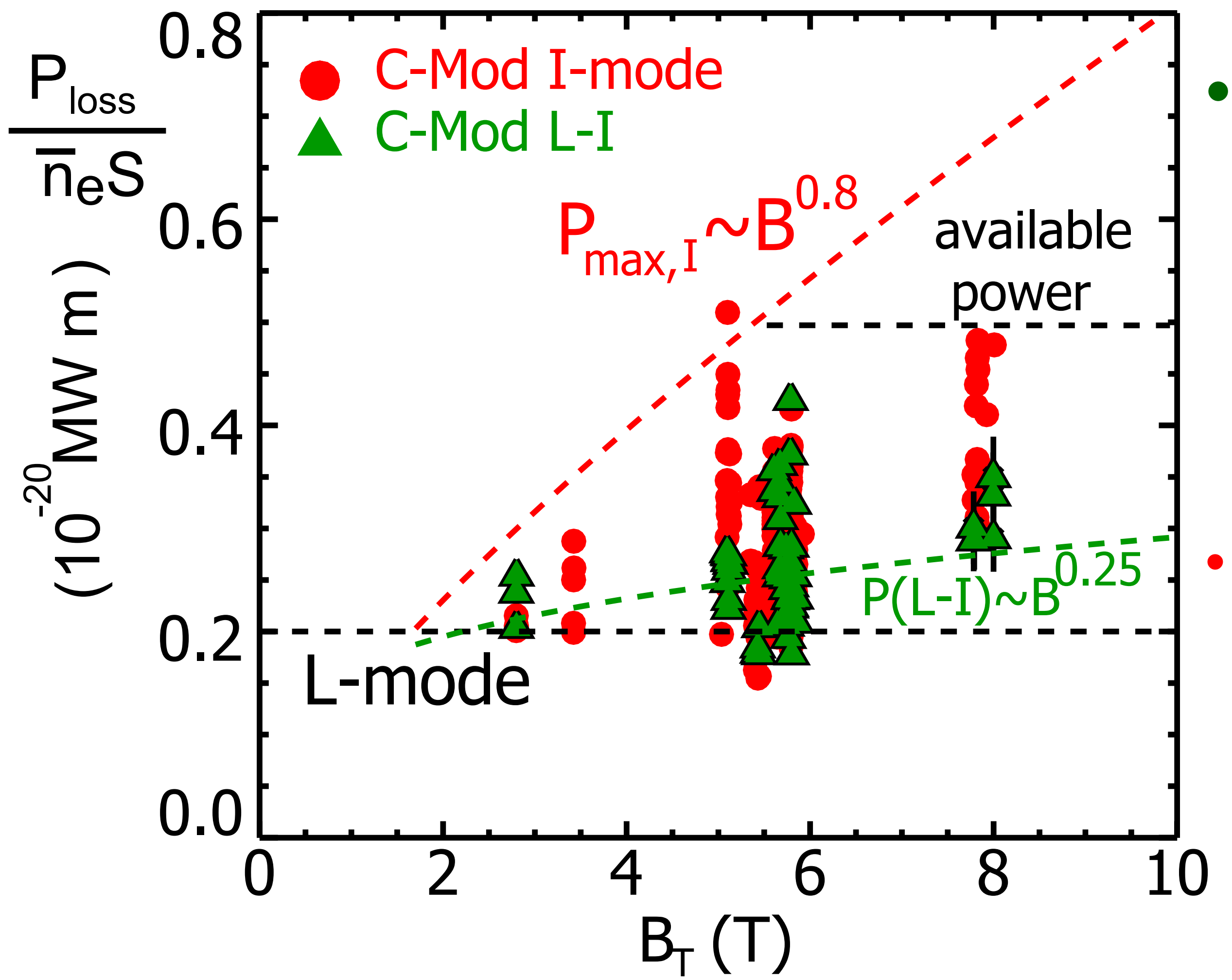
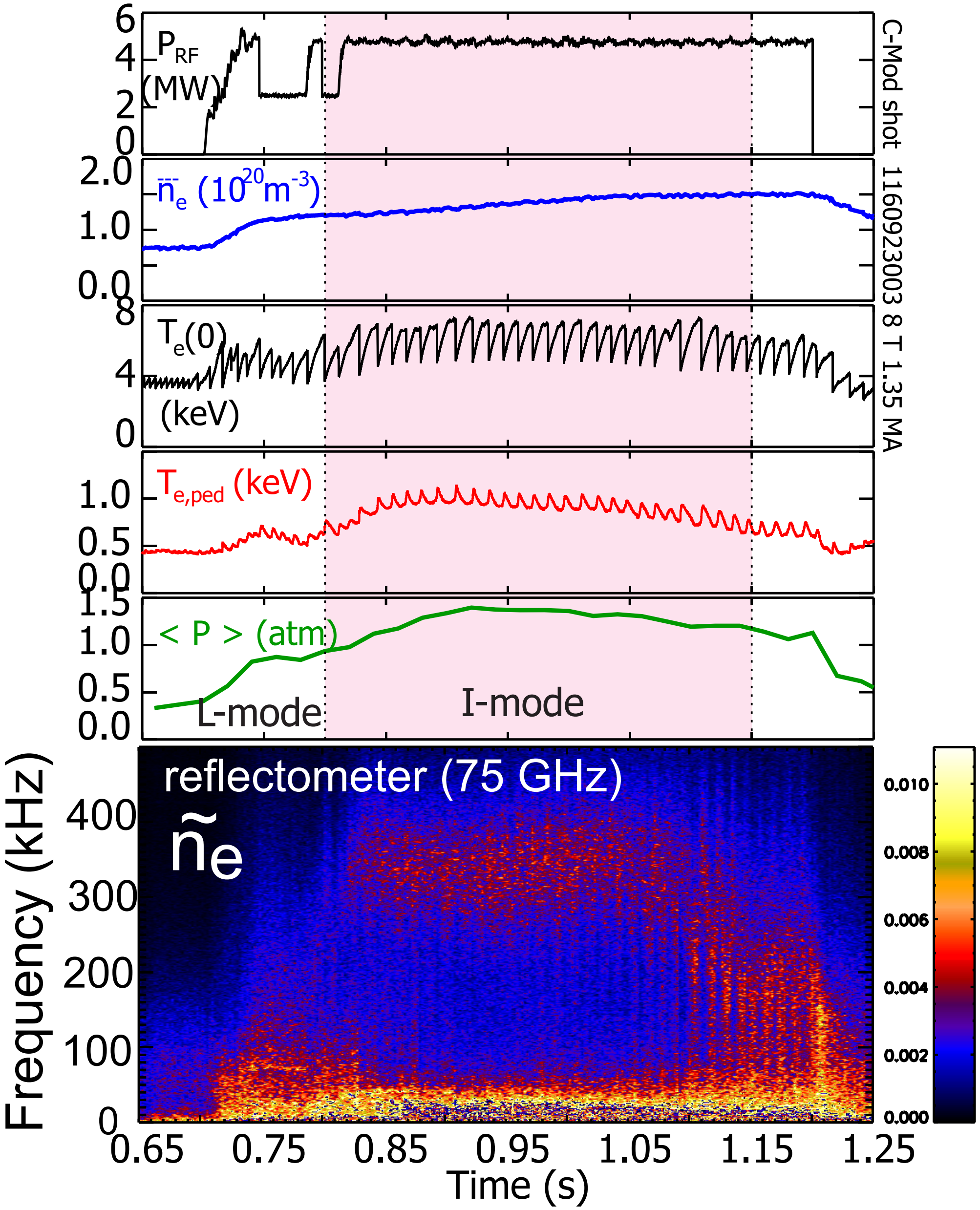


- **$P(L\text{-}I)/n_e \sim B_T^{0.25}$.**
  - At 8 T, we used $D(He^3)$ ICRH, which has lower single pass absorption than usual D(H), hence P_{loss} more uncertain.
- **NO discharges at 7.8-8 T had I-H transitions, up to 5 MW available ICRF power** ($P_{tot}/S \leq 0.63$ MW/m^2) **=>** power range is even larger than at 5-6 T.
  - Some had I-L back-transitions.

High B I-modes exhibit typical features

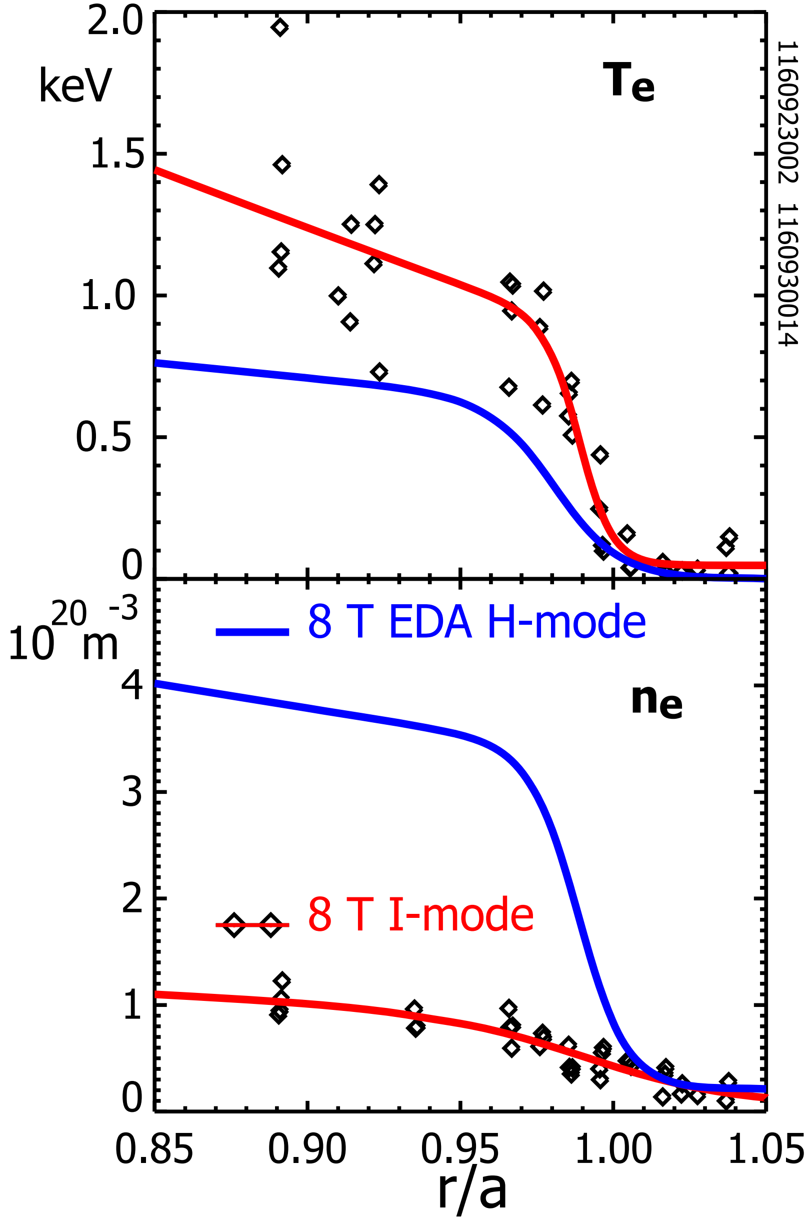


Example with 7.8 T, 1.35 MA, (q_{95}= 3.7), P_{RF}=4.7 MW:

- 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 (higher than at lower I_p and B_T).
  - Up to 450 kHz at 1.7 MA.

T_e, T_i pedestal and E_r well in 7.8 T, 1.35 MA I-mode

Alcator C-Mod



- Steep T_e gradient, 1 keV pedestal
- L-mode density profile.
  - Contrasts with EDA H-mode at similar B, I, P_{loss}.

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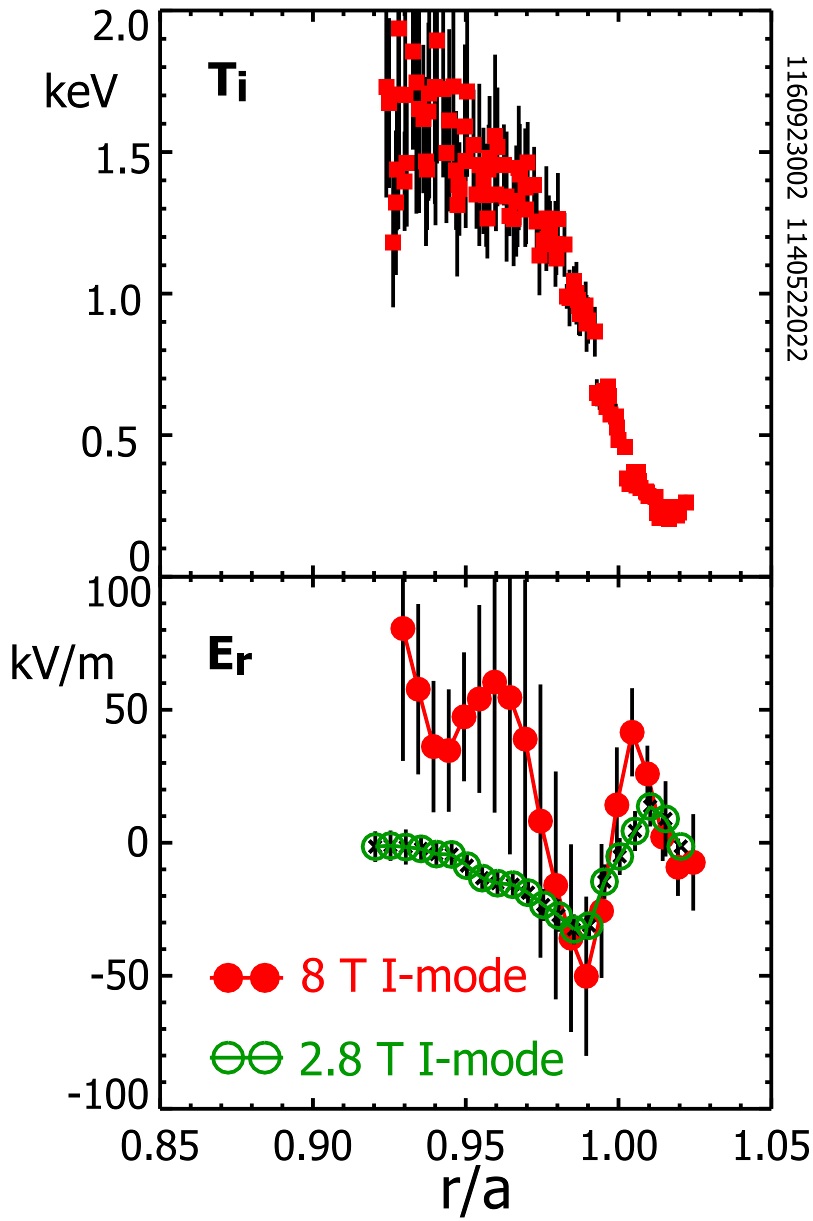
Alcator C-Mod



- Steep T_e gradient, 1 keV pedestal
- L-mode density profile.
  - Contrasts with EDA H-mode at similar B, I, P_{loss}.
- CXRS shows T_i pedestal.
- E_r well 100 kV/m depth ($E_{r,min}$ -50).
  - Much steeper than 2.8 T I-modes (at lower I_p and P_{loss}).
  - In the range of typical stationary H-modes, ~30-100 kV/m.

I-mode has also been extended to near DN configurations, sharing heat flux

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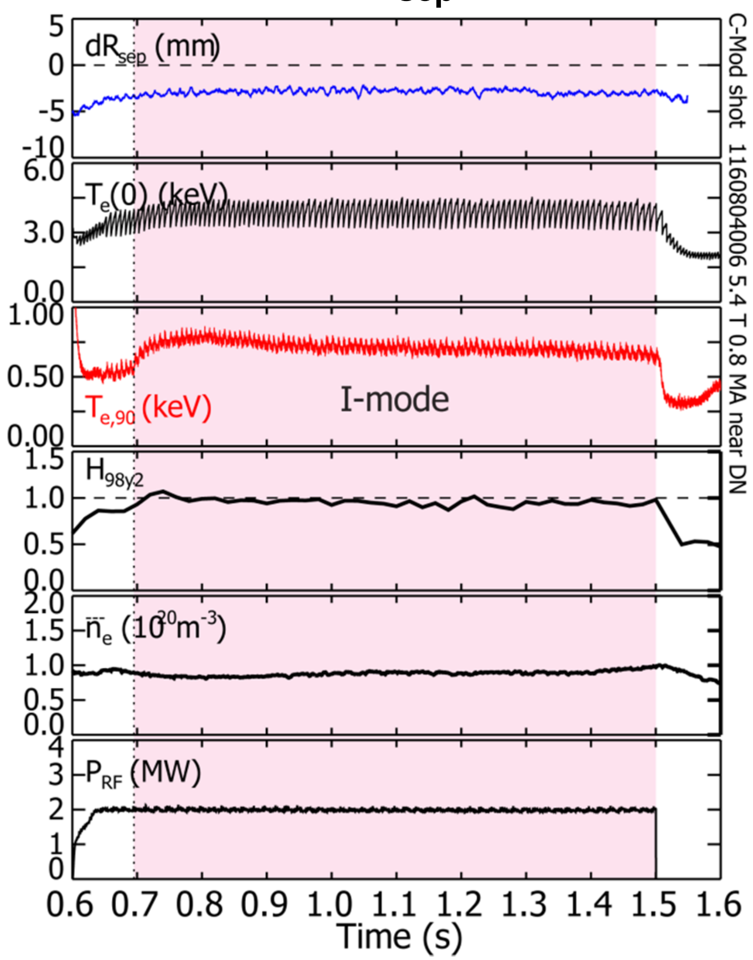
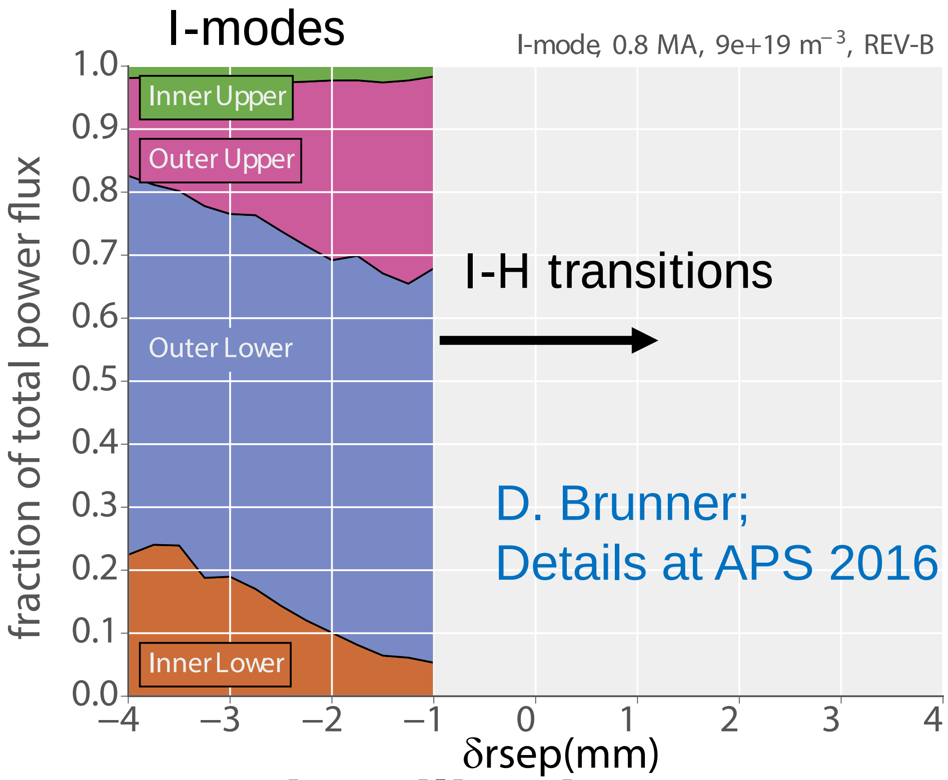
Near-DN I-mode, δr_{sep} -3 mm



- I-mode is most robust with ion **B×∇B** drift *away* from X-point.
- 2016 experiments, at 5.4 T, found I-mode could still be *accessed* with δr_{sep} as small as 3 mm.
- Can *maintain* I-mode with δr_{sep} 1-2 mm.
- DN or drift towards X-pt give I-H transitions; These H-modes are very high confinement (H_{98}>2), but transient.

I-mode has also been extended to near DN configurations, sharing heat flux



- I-mode is most robust with ion **B×∇B** drift *away* from X-point.
- 2016 experiments, at 5.4 T, found I-mode could still be *accessed* with δr_{sep} as small as 3 mm.
- Can *maintain* I-mode with δr_{sep} 1-2 mm.
- Small δr_{sep} shares power more evenly between strike points.

Power handling in reactor scenarios is still a key issue:

- Lack of ELMs in I-mode eliminates transient heat load.
  But, steady heat flux is still high, and detachment is challenging; tend to get I-L transitions first.
- Advanced divertors are likely needed for reactors in *any* regime. Simulations with X-Pt Target Divertor are very promising – see **Umansky TH/P6-32, Thurs. pm**

Particle and Energy Transport in I-mode

I-mode has L-mode τ_{imp}, $H_{98,y2}$ 0.7-1.3

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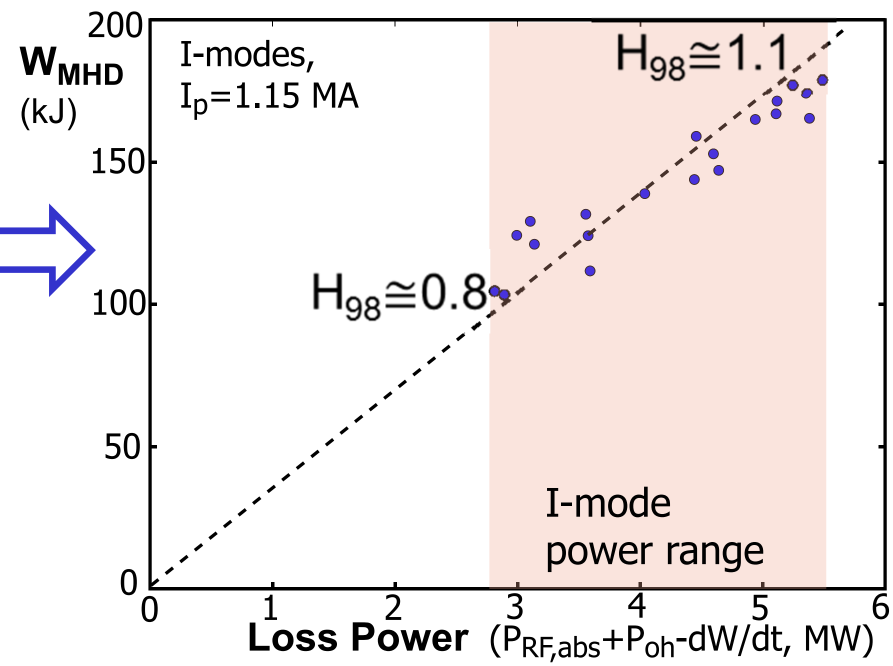
- Extensive studies with injected Ca or Mo show τ_{imp} **is at L-mode levels** (15-40 ms),10-100X lower than H-mode [Howard RSI'11. Rice NF'15]
- Range in H_{98} indicates H-mode-like confinement, but some differences in τ_E scaling. One key difference is **more favourable power scaling.**

Stored energy increases nearly linearly with power – thus H_{98} increases with power.

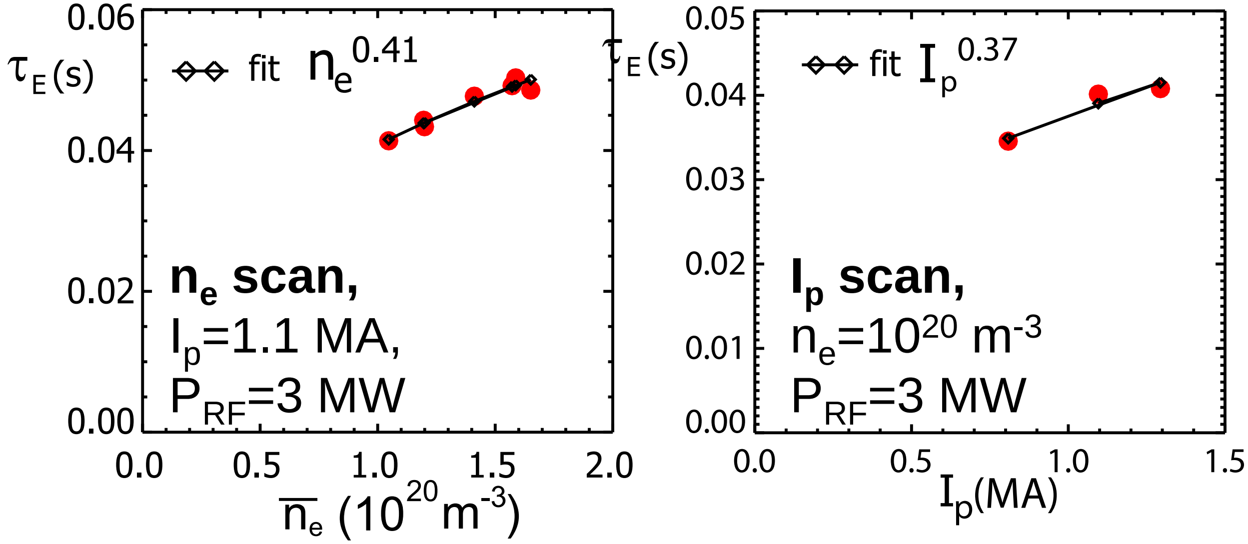


- **Prior regression on 200 I-mode slices supports this:**
  $\tau_{E,Imode} = I_p^{0.68} B_T^{0.77} n_e^{0.02} P_L^{-0.29}$
  - Contrasts with $\tau_{ITER98p} \sim P_L^{-0.7}$
- As with other empirical scalings, covariances might affect dependences, eg on I_p, B_T, n_e.

Walk, MIT Ph.D. 2014

Single-parameter scans done in 2016 for more direct assessment of τ_E trends

- Initial analysis suggests some differences, eg positive density scaling, weaker I_p scaling.

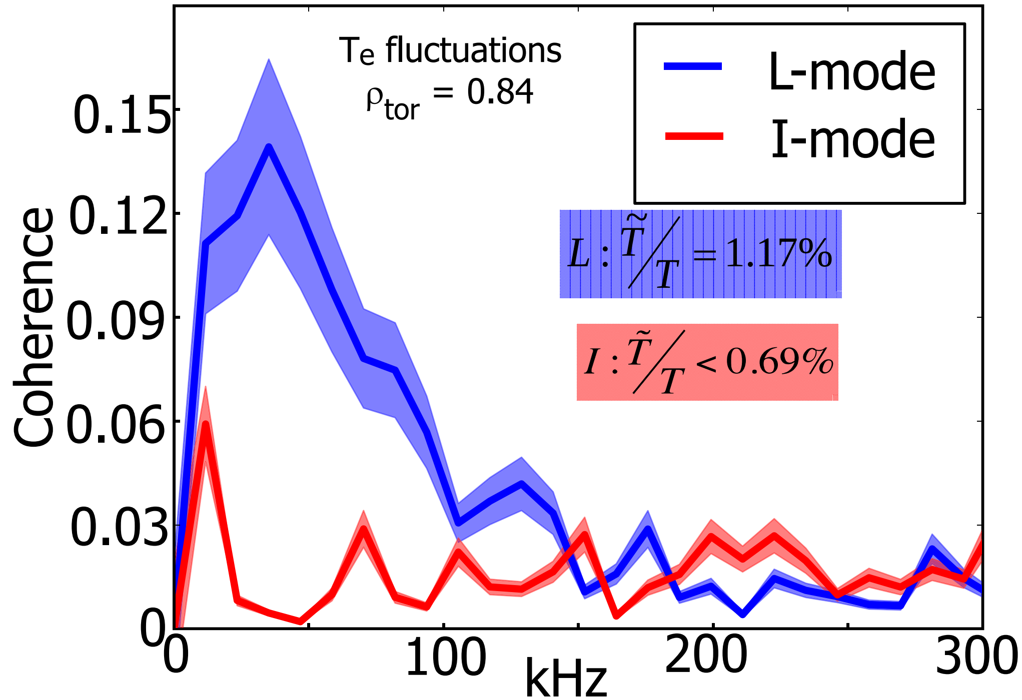


- Also did recent scans of dimensionless parameters, ρ^*, ν^*, β, keeping other parameters near const. Can be used to constrain size scaling.
  - Detailed analysis is in progress. B τ_E dependence on β is more favourable than H-mode; ν^* dependence is weak.
- Multidevice study, similar to L-mode and H-mode confinement databases, would give best scaling and extrapolation to future devices, including **direct size scaling.**
  - Include existing data from AUG, DIII-D, and results from other tokamaks as they become available. Planned ITPA activity.

Validating core transport models in I-mode regime

Comparing L, I, plasmas at 5.4 T, moderate power, find in expt:

- Strong (~2x) reduction in core χ_e.
- Low k T_e fluctuations (CECE) are reduced.



White PoP 2015
Creely NF 2016

Nonlinear GYRO simulations and measurements of $\chi_{e,inc}$ indicate:

- ExB shear suppression of the ITG is larger in I-mode vs L-mode
- ITG can account for observed low-k turbulence but not transport. =>High-k electron scale (ETG) turbulence is important.
- I-modes are more 'stiff', resembling H-mode – **hence T_{ped} is key.**

Details in APS invited, A. Creely, VI2:4 .

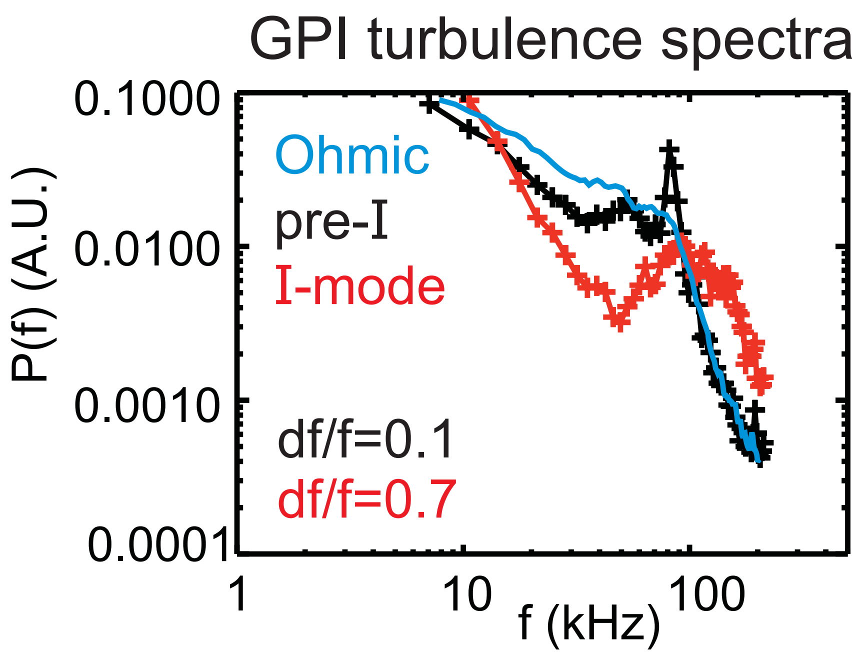
Pedestal physics and transitions.

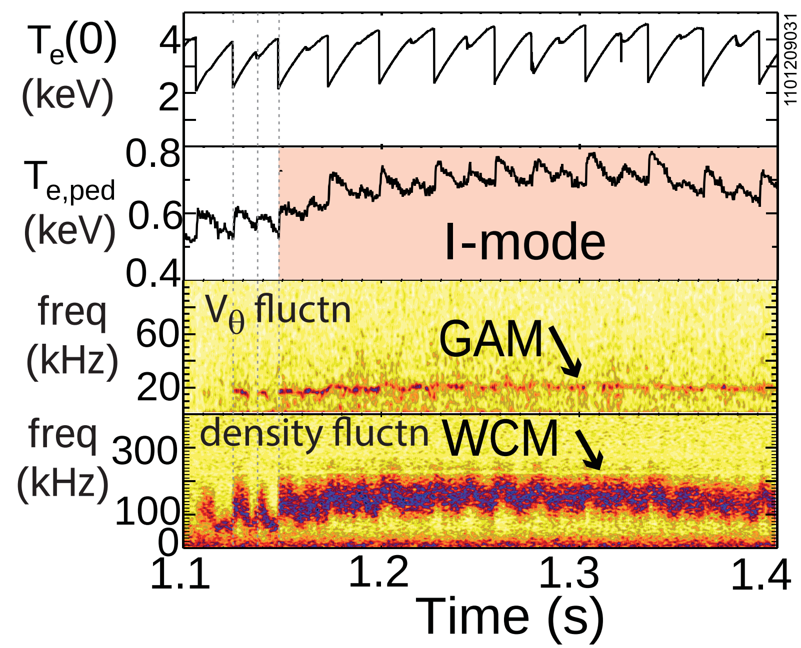
Pedestal flows and turbulence are key to L-I transitions

Several simultaneous changes occur in the pedestal region at L-I transitions:

- **Reduction in mid-freq turbulence,** correlated with χ_{eff}.
- Fluctuating flow at **GAM** frequency (10's of kHz) .
- **Weakly Coherent Mode** – broad fluctuation at few 100 kHz

Cziegler APS 2015





- Has become clear in last 2-3 years that GAM is very important in broadening WCM, and likely in I-mode access, particle and energy transport. Consistent on C-Mod (Cziegler PoP 2013), AUG (Manz NF 2015).

Manz EX/P6-32, Thurs pm

Transfer from turbulence to zonal flows is 2x lower with $B\times\nabla B$ away from X-pt, opening an I-mode power window

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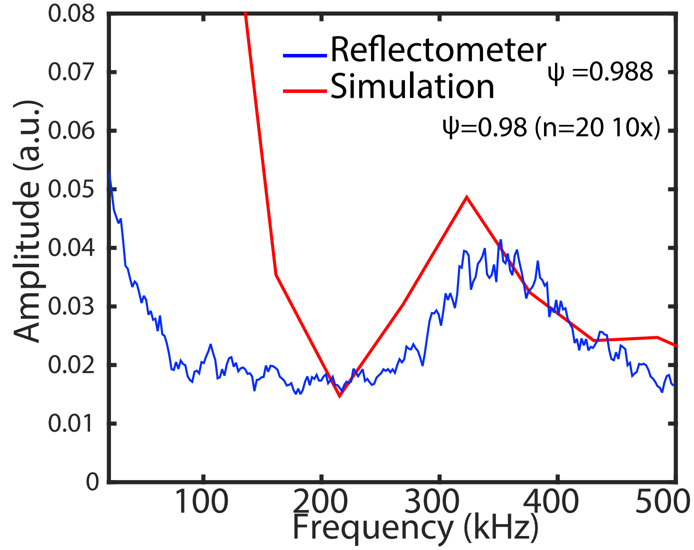
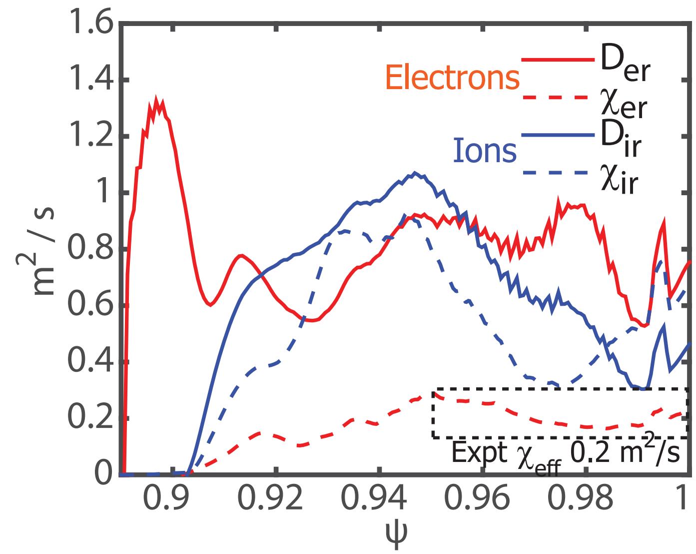
- Prior work has shown L-H transition occurs when energy transfer rate into ZF exceeds turbulent drive. [Manz PoP12, Yan PRL14, Cziegler PoP 14,NF15]
- **Transfer rate in the configuration with $B\times\nabla B$ away from X-pt ("unfavourable") is only half the rate towards X-pt ("Favourable") => higher H-mode threshold!**
- In the I-mode window, energy is also transferred to GAMs

I. Cziegler, York APS 2015, PRL in prep

Simulations of I-mode pedestal

- Simulations of a high density, 5.8 T I-mode pedestal have been carried out with BOUT++. Details in Poster TH/P2-28, Z. Liu (Tues).
- Nonlinear simulations find a mode with many features of WCM (n=20, 350 kHz, electron diamagnetic direction)
- Predicts larger particle diffusivity than thermal, consistent with the key feature of I-mode. Predicted χ_e is close to experimental $\chi_{eff.}$
- Extensions to include zonal flows and GAMs are in progress.





- Other groups are working on gyrokinetic simulations of I-mode pedestal, and of L-I transitions.

Extrapolation of I-mode for fusion devices

Key features and issues for ITER, DEMO

Alcator C-Mod

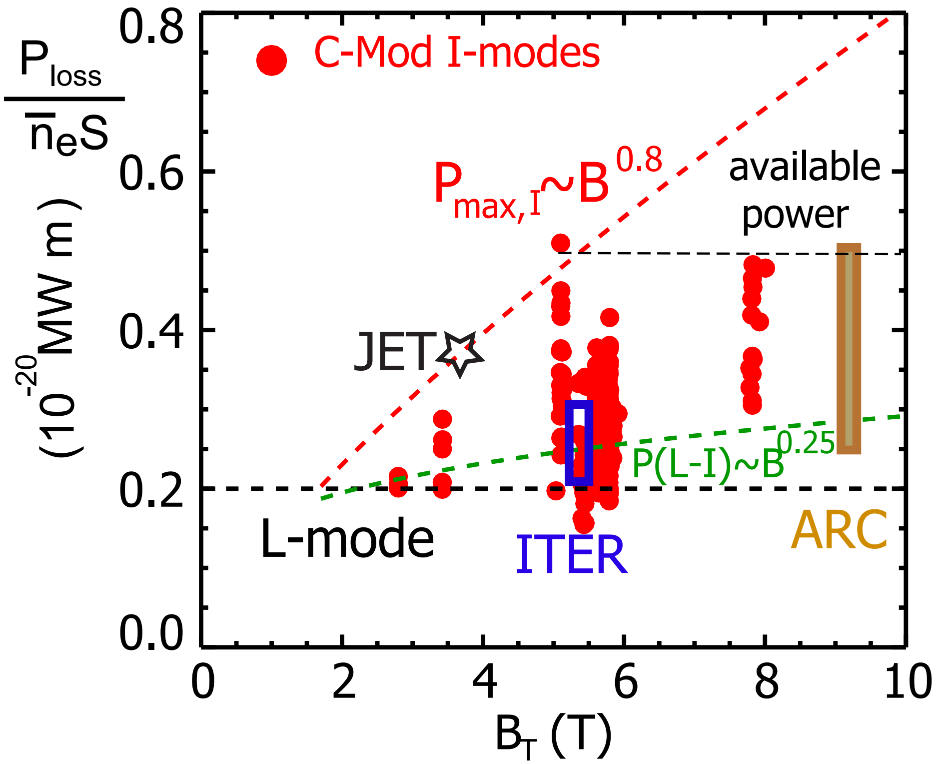
Key features:

- **Naturally ELM-free**
  - Do not need external control tools such as RMP coils or pellets.
- **L-mode particle confinement has major operational advantages compared to H-mode:**
  - High Z impurities do not accumulate. Compatible with metal PFCs (Mo on C-Mod, W on AUG).
  - Do not need (or use on C-Mod) frequent boronization, which is impractical in a reactor.
  - Performance recovers well from any injections during a discharge.
  - Density is readily controlled, not set by a particle barrier.

Key Issues:

- Can I-mode be *accessed* with P_{ext}? (L-I threshold)
- Can it be *maintained*, once fusion power increases? (I-H threshold, density range)

Expanded power range with B_T is positive for ITER, high B DEMOs



For information on **ARC**, see Dennis Whyte **FIP/P7-6**, Friday am

Scaling C-Mod P/n_e by surface area, predict **for ITER**:

- $P(L\text{-}I) \sim 70$ MW at $5\times10^{19} m^{-3}$.
  - NBI with rev I_p is biggest issue.
- If accessed, should be able to maintain to full P_{fus} at higher n_e.

For ARC (B_T=9.2 T, R=3.3 m):

- $P(L\text{-}I) \sim 46$ MW at $5\times10^{19} m^{-3}$
- Could maintain to full P_{fus} (525 MW) at $n_e \sim 1.3\times10^{20}$ m^{-3}.
  - I-mode profiles were used for steady state scenarios [Sorbom FED 2015].

- **Multi-device scalings of thresholds, density range as well as τ_E are needed for more confident extrapolation.** Experiments at larger size (JET, JT60-SA) will be extremely valuable.

Progress in both operating space and physics of I-mode on C-Mod

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- **I-mode regime, with high energy confinement, low particle confinement, no ELMs, has now been achieved over very wide parameter ranges.** (B_T 2.8-8 T, I_p 0.55-1.7 MA, 1.5-5 MW).
  - Weak dependence of L-I threshold on B_T.
  - Upper power range increases with B_T; at 8 T *no* I-H transitions are observed up to P_{tot}/S= 0.63 MW/m^2)
  - I-modes extended to near DN configuration for better flux sharing.
- **GAM and weakly coherent mode in pedestal are key to I-mode physics, thermal transport barrier.**
  - Simulations are beginning to predict these features, as well as core transport.
  - Transfer rate from turbulence to zonal flows varies with magnetic drift direction, explaining L-H dependence and opening up I-mode window.
- **Experiments on other tokamaks are now critical to continue research on this promising regime for fusion, and provide a firm basis for extrapolation to future fusion devices.**