Decoupling transport channels in tokamaks: I-mode phenomenology and physics

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With thanks for input from

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**Supported by the U.S. Dept. of Energy, Office of Fusion Energy Sciences*

21st International Stellarator-Heliotron Workshop (ISHW2017)
October 2, 2017, Kyoto, Japan

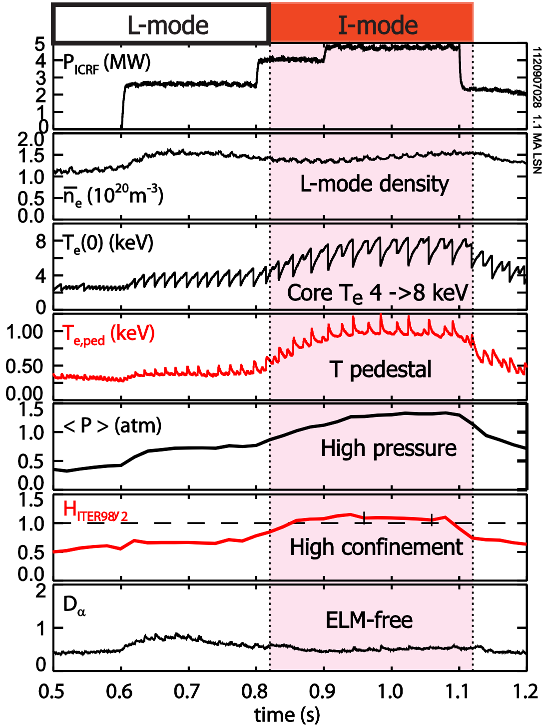
I-mode phenomenology and physics

- **What is "I-mode"?** Why of interest for fusion? How to access?
- **Evidence for separation of thermal and particle transport**
- **Phenomenology: Measurements of profiles, turbulence and flows on C-Mod and ASDEX Upgrade tokamaks**
- **Physics:** ***Possible*** **contributions to separation of transport channels** (for workshop discussion, still no definitive explanation)
- **Conclusions, questions, prospects**

I-mode is a stationary, high energy confinement regime, *without* a particle barrier

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.
- **ELM-free, avoiding damaging heat pulses.** — Pedestals are MHD stable.
- **Highly attractive combination of features for fusion energy.**

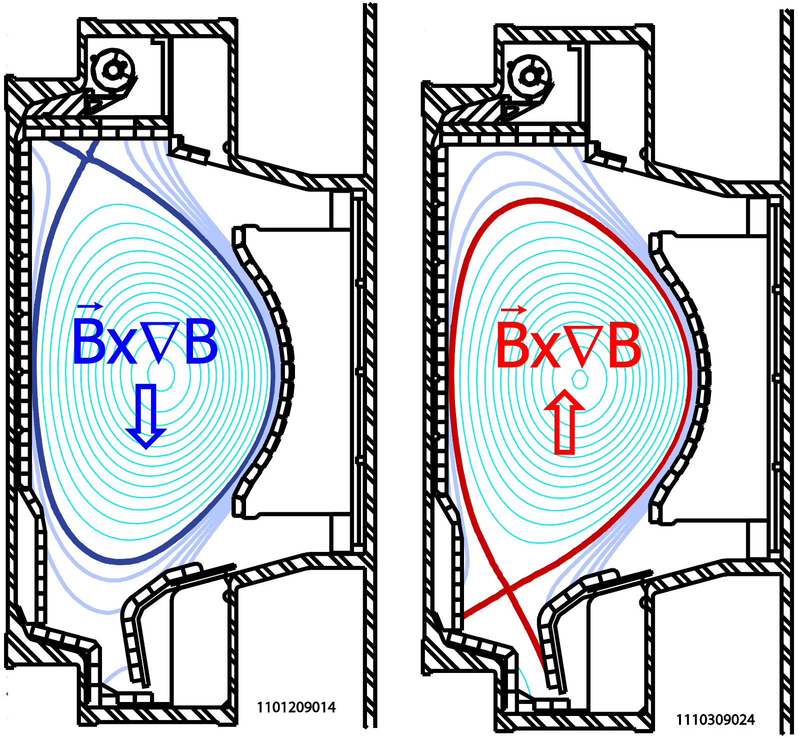


C-Mod
Hubbard
IAEA 2012

** Clarification: This is NOT the same regime as the transient Limit Cycle Oscillation phase between L and H-mode, sometimes known as "I-phase" .*

I-mode is accessed robustly on tokamaks with ion Bx∇B drift *away* from X-pt.

C-Mod

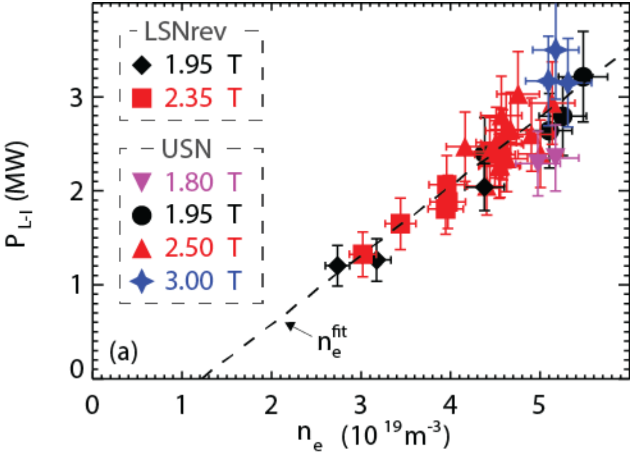


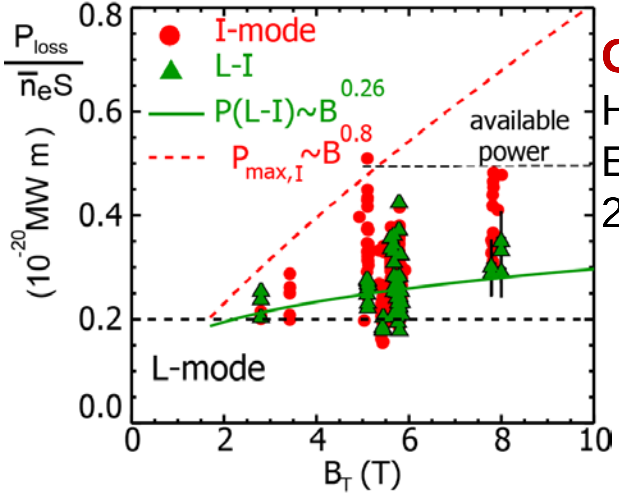
- This configuration has long (since Wagner 1982) been known to have higher L-H power threshold, hence called ‘unfavourable’.
- I-mode is accessed by slowly increasing input power, to below this higher L-H threshold (all results in this talk).
  - Some cases with “favourable” drift towards X-pt, with atypical shaping, but these are limited to low power.
- Further increases in power can sometimes lead to I-H transitions. Power range varies with device parameters.

I-mode has been accessed in several tokamaks, over wide ranges of parameters: **Robust**

- Most widely studied on **Alcator C-Mod**, **ASDEX Upgrade (AUG)** (hence focus in this talk).

AUG Happel PPCF 2017





C-Mod Hubbard EPS 2017

- Also observed on DIII-D ~2013 (Marinoni NF15), and very recently on EAST (Z. Liu H-mode workshop 2017). ITPA comparison study in Hubbard NF 2016)
- Together, I-mode discharges have used
  - Heating with ICRH, NBI, ECH and/or LH.
  - Mo, W and C PFCs.

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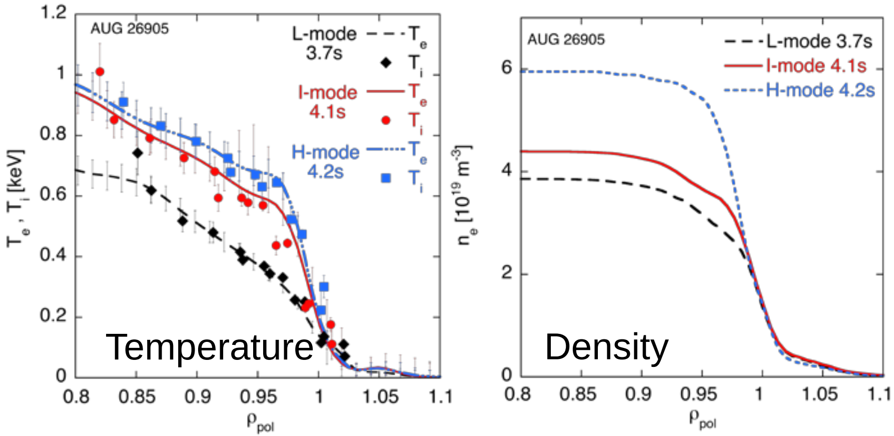
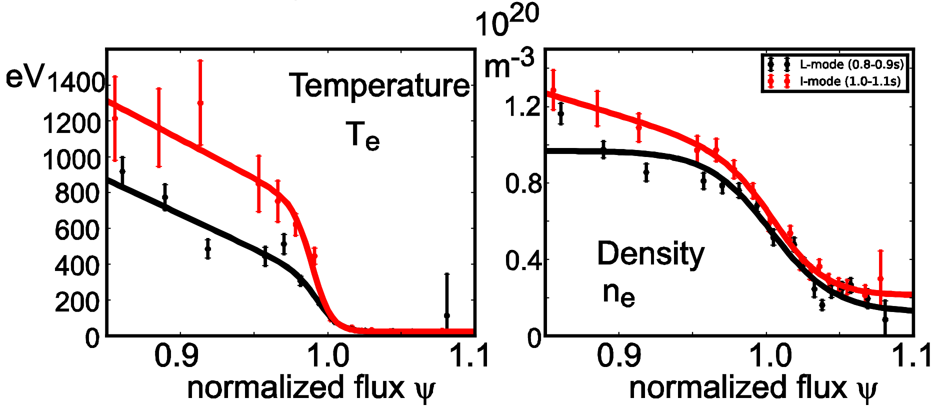
At L-I transition, pedestal develops in T_e, T_i. Density remains nearly unchanged.

- Increasing T_e, T_i, ∇T, at similar input power implies **lower thermal transport than L-mode.**
- Constant n_e, D_α imply **~same main species particle transport as L-mode.**
- More quantitative estimates (to follow) support this.



AUG
Ryter
NF 2017

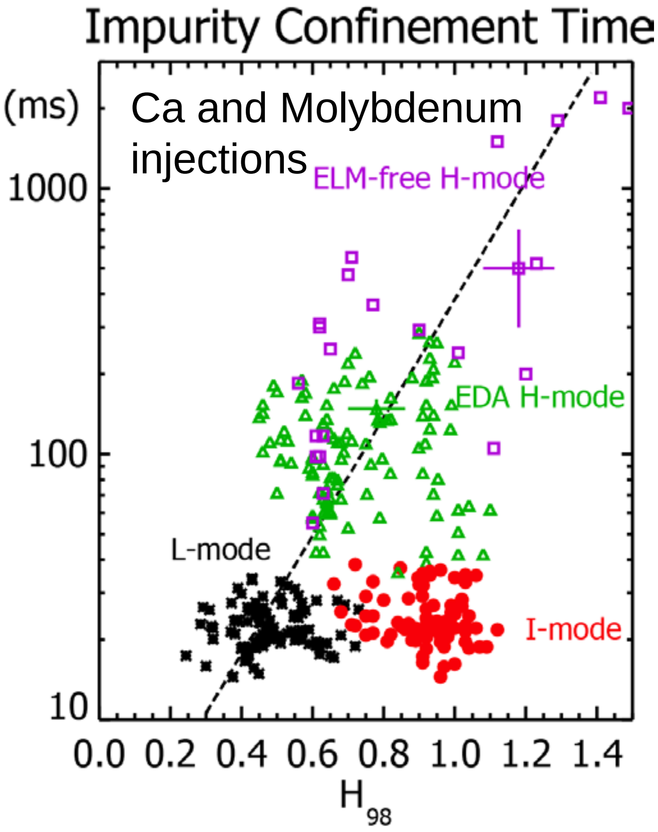


C-Mod
Hubbard
IAEA14

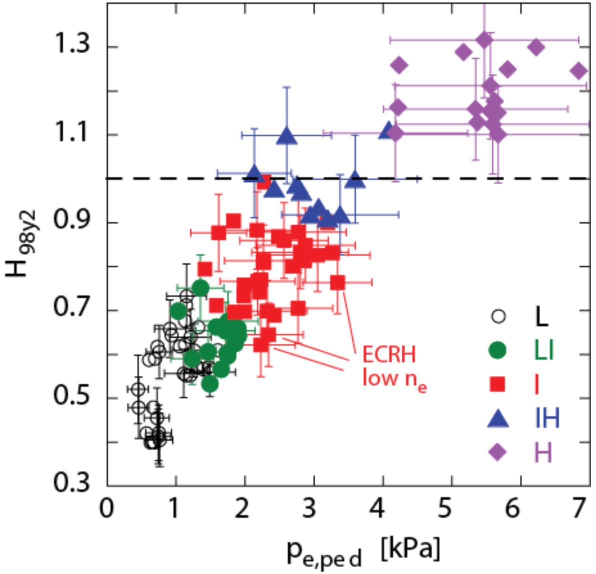
I-mode also has high global energy confinement, low global impurity confinement

C-Mod
see Rice NF 2015

(τ_I for Ca, Mo are similar)



AUG
Ryter NF 2017



- Range of $H_{98,y2}$~0.6-1.2. correlating well with pedestal (ie stiff core profiles)
- Weaker power degradation in I-mode:

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

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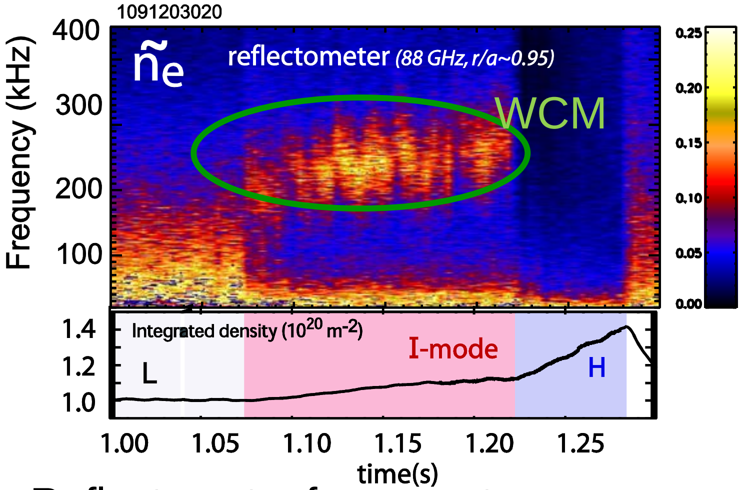
Several characteristic changes in edge fluctuations, flows at L-I, I-H transitions

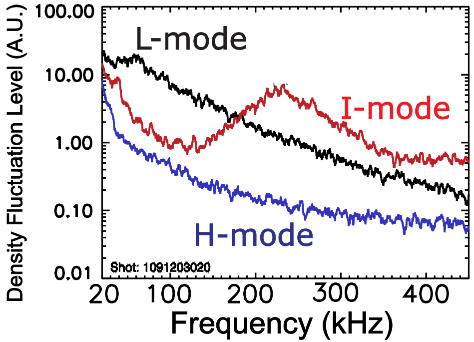
At **L-I transition**, as T pedestal forms, see

1. A DECREASE in edge broadband turbulence (n and B) in mid-f range (~60-150 kHz)
2. Usually a PEAK in turbulence at higher f "**Weakly Coherent Mode**" (~200-400 kHz on C-Mod).
3. Fluctuating flow at **GAM frequency**. (10's of kHz)

At the **I-H-mode** (particle barrier) transition, remaining turbulence drops suddenly, density and impurities rise.



Reflectometry freq spectra

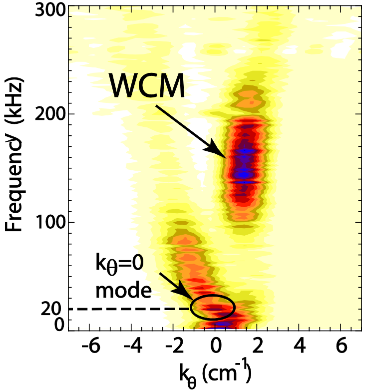


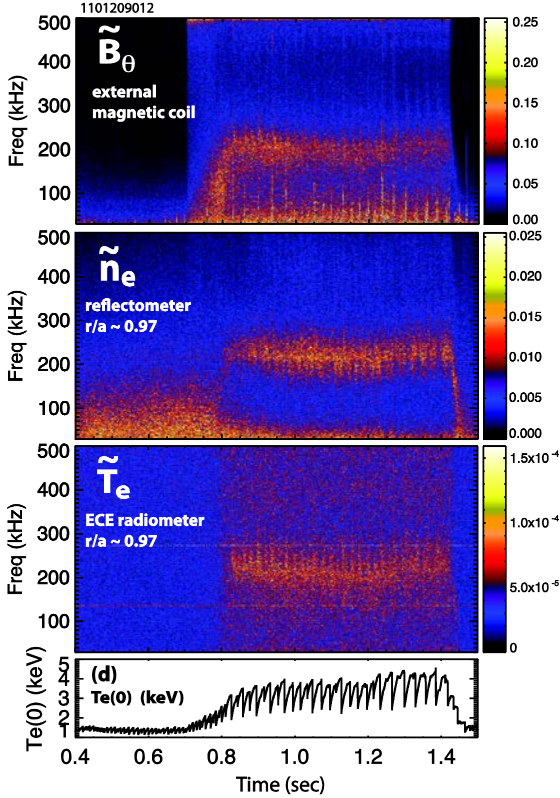
C-Mod
Hubbard
PoP 2011

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

- In most I-modes, a higher frequency turbulence feature appears, simultaneous with mid-freq reduction. On C-Mod: **$f_0 \sim 200\text{-}400$ kHz, $\Delta f/f \sim 0.3\text{-}1$**
- Fluctuations seen in **B** (magnetics), **Density** and **Electron Temperature** (ECE). **$\delta T_e/T_e$ 1-1.6% < $\delta n_e/n_e$ 6-13%.**
- All diagnostics localize WCM to the region of T pedestal. **(0.9 < r/a < 1.0)**
- **2-D Gas Puff Imaging** reveals WCM details:
  - **$k_{pol} \sim 1.5$ cm^{-1}** ($k_\perp \rho_s \sim 0.1$)
  - Propagation in **electron diamagnetic direction**

C-Mod





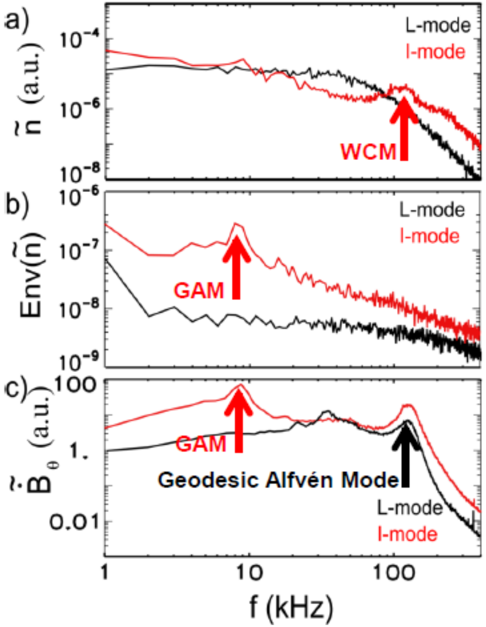
Cziegler PoP 2013, White, NF 2011

Now clear that GAM is also important, and interacts with WCM in complex ways

- Fluctuating flow v_θ at GAM frequency appears only in I-mode on C-Mod, also in L-mode on AUG. A density, $\tilde{B}$ fluctuation at similar frequency (10's of kHz) is sometimes measured.
- In both tokamaks, bispectral analysis shows GAM exchanges energy with the WCM, leading to its broad $\delta f/f$.

AUG

Manz, NF 2015

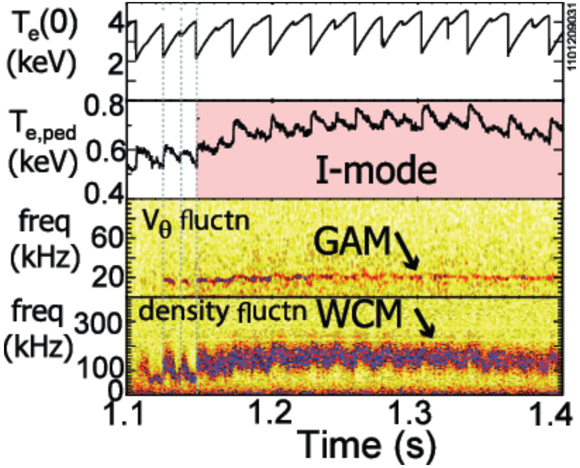


C-Mod

Cziegler

PoP

2013

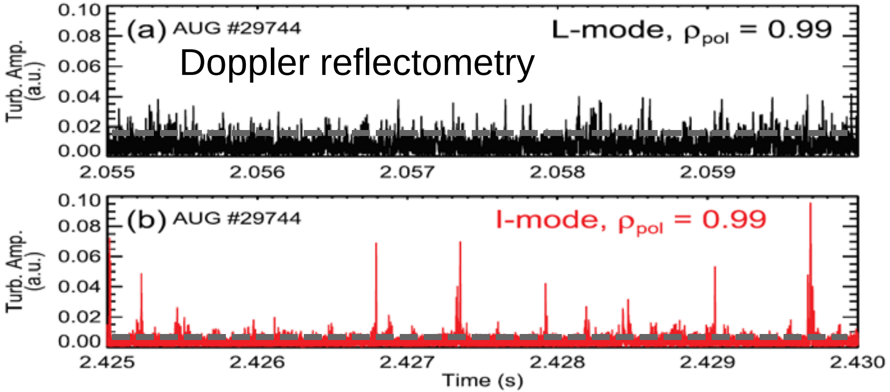


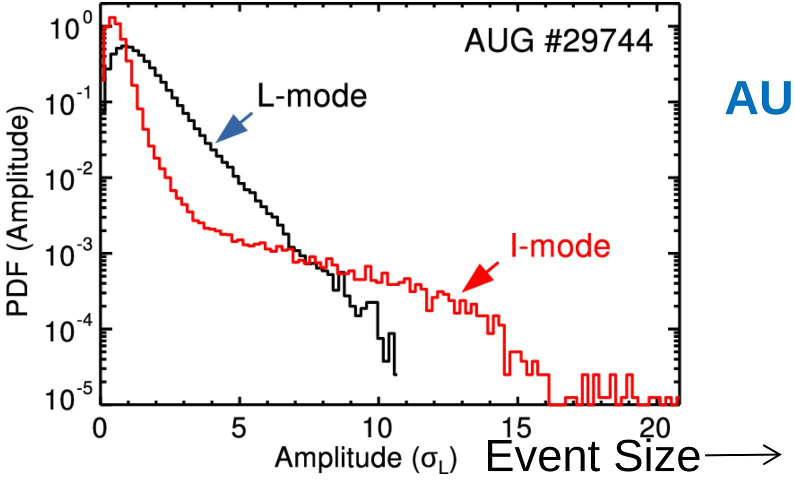
ASDEX Upgrade

Density fluctuations are strongly intermittent during I-mode

- Recent AUG measurements show I-mode has lower base-level of fluctuations than L-mode, but exhibits strong irregularly spaced ‘solitary’ bursts (*intermittency*).
- At all measured structure sizes ($k_\perp$ = 5-12 cm^{-1}): **Low fluctuation amplitudes decrease, while large fluctuation amplitudes increase (PDF broadens).** Note bursts extend to larger k than WCM ($k_\perp$ ~ 15 cm^{-1}).
- Intermittency increases with ∇T.

T. Happel *et al*, NF **56** 064004 (2016)
T. Happel *et al*, PPCF **59** 014004 (2017)
P. Manz *et al*, NF **57** 086022 (2017)



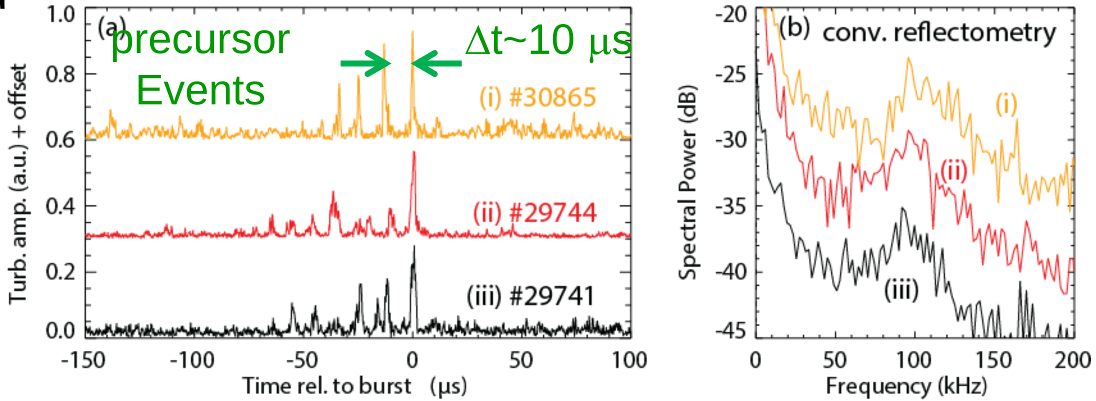


AUG

Density ‘bursts’ are connected to WCM, and to radiation at divertor.

- Intermittent events are preceded by smaller density perturbations.
- **Δt of precursor events corresponds to 1/f_{WCM}**

AUG

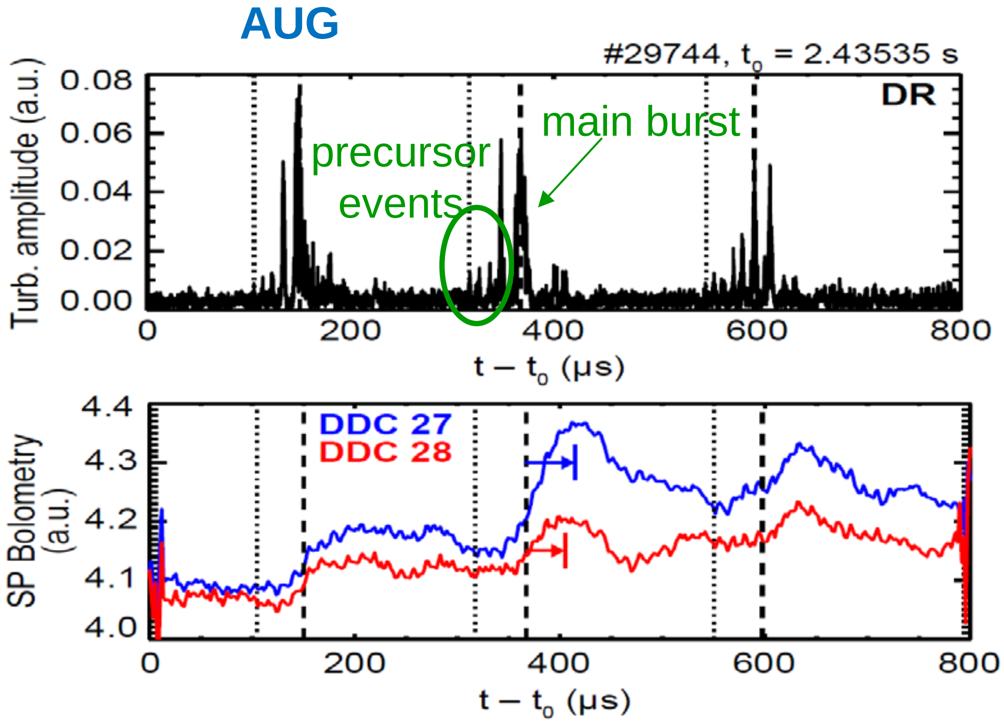


T. Happel *et al*, PPCF **59** 014004 (2017)

Density ‘bursts’ are connected to WCM, and to radiation at divertor.

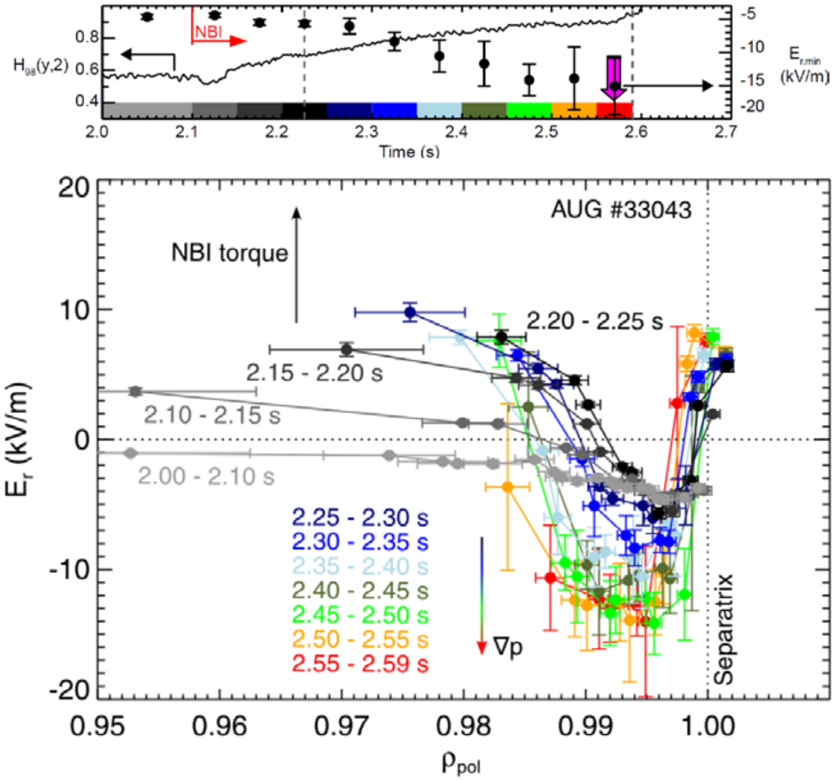
- Intermittent events are preceded by smaller density perturbations.
- **Δt of precursor events corresponds to $1/f_{\mathrm{WCM}}$**

- Bolometry signal in divertor is correlated with fluctuation amplitude, with a time delay.
  - Suggests a particle flux from inside separatrix.

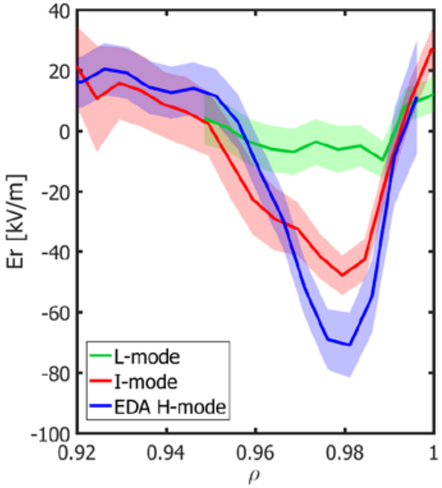


T. Happel *et al*, PPCF **59** 014004 (2017)

E_r well develops during I-modes



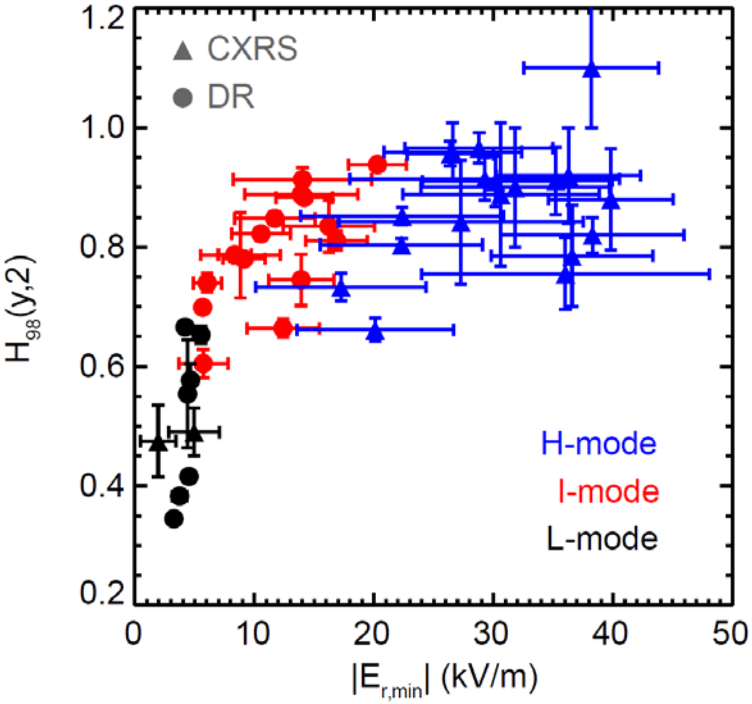
AUG
Happel
PPCF 17



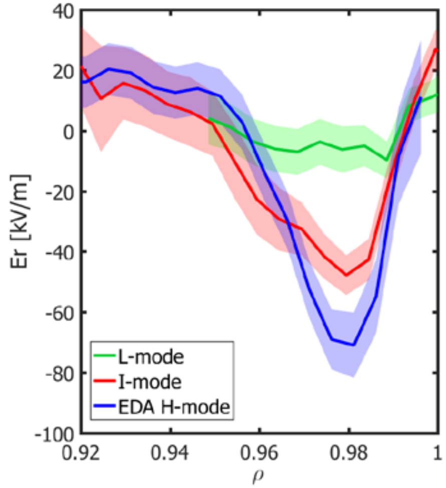
C-Mod
Hubbard
EPS17

- Builds up gradually along with T_{ped}
- ExB shear greatest in outer region.
- Steeper, deeper well than L-mode.

E_r well develops during I-modes



AUG
Happel
PPCF 17

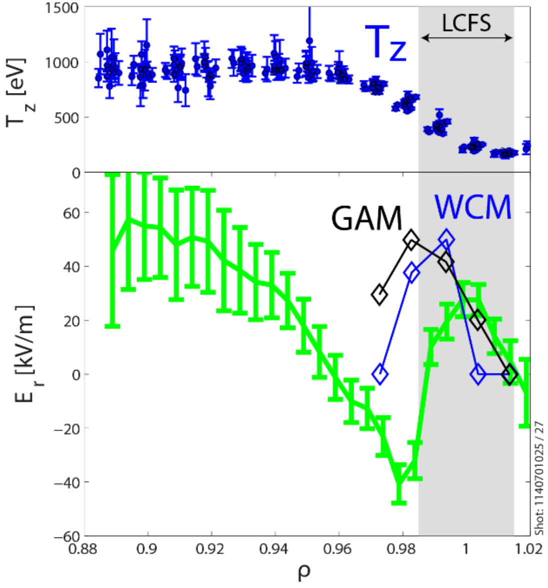


C-Mod
Hubbard
EPS17

- ExB shear greatest in outer region.
- Steeper, deeper well than L-mode.
- But, E_{rmin} less than most H-modes.

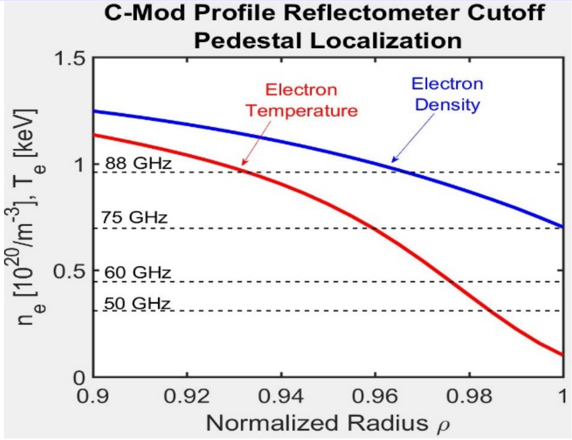
WCM and low freq GAM fluctuations are localized in the E_r well, extend to near separatrix

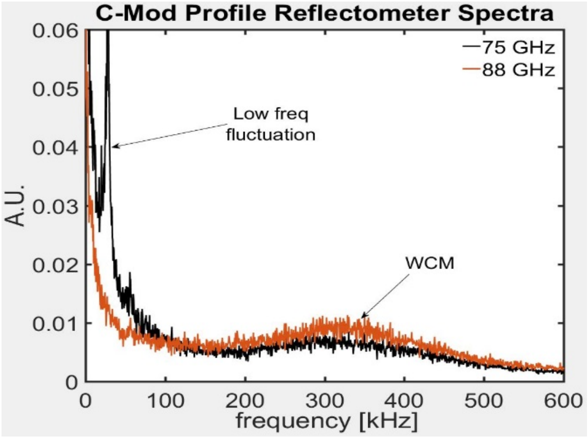
- WCM and GAM have similar radial extent.
- In E_r well, peaked in outer shear layer.
- Still detected near separatrix.



C-Mod

Cziegler
PoP 2013,
Theiler
PPCF 2017
Wilks
HMW17

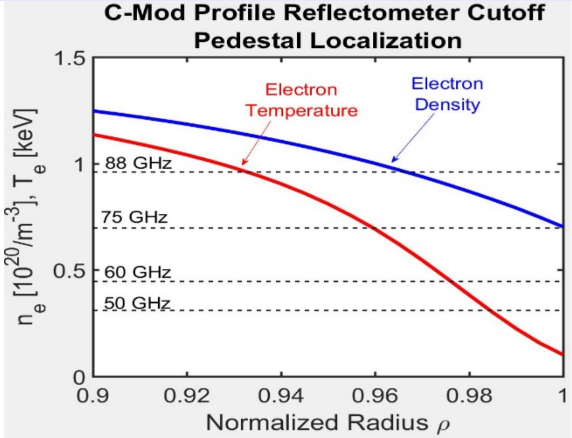


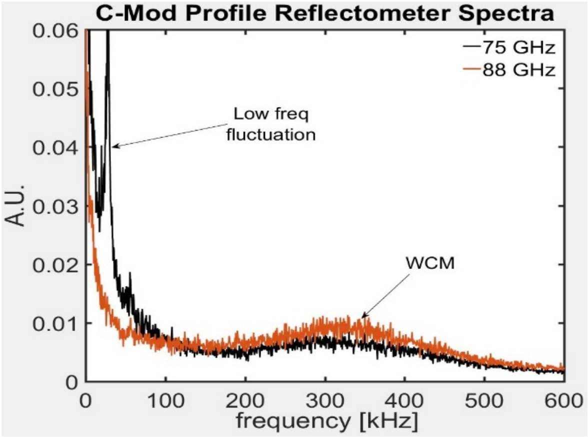


WCM and low freq GAM fluctuations are localized in the E_r well, extend to near separatrix

- WCM and GAM have similar radial extent.
- In E_r well, peaked in outer shear layer.
- Still detected near separatrix.

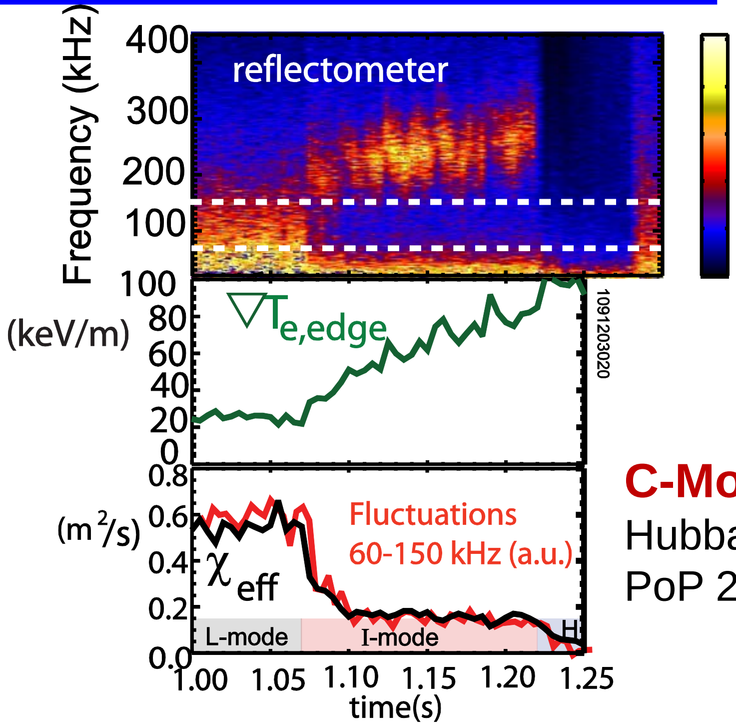
- Mode location is important since $T_{e,sep}$ is always low (~100 eV, SOL physics), while $n_{e,sep}$ can be relatively high.
- Any mode near LCFS would be expected to drive more particle than heat flux.
  (This has been measured with probes for EDA H-mode. LaBombard PoP 2014)
- Further studies of radial location and extent of turbulent features in I-mode would be valuable – and are a diagnostic challenge!





Decrease in edge thermal conductivity correlates with reduction in mid-f turbulence

- At transition from L to I-mode **edge ∇T steepens**, at near-constant P_{net} and edge $n_e \Rightarrow$ **Edge χ_{eff} is decreasing.** Edge power balance: χ_{eff} 0.6->0.2 m^2/s .
- **Edge χ_{eff} correlates well to the drop in mid-f turbulence.** (~60-150 kHz) from reflectometry
- Further, fast, drops are seen in both turbulence and χ_{eff} at I-H transitions.
- Consistent with (but does not prove) this mid-freq turbulence playing a key role in thermal transport.

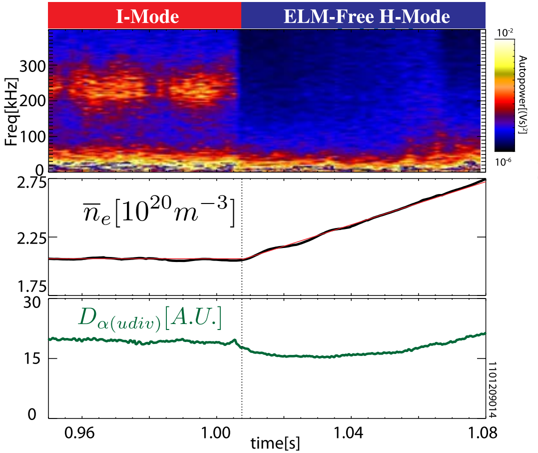


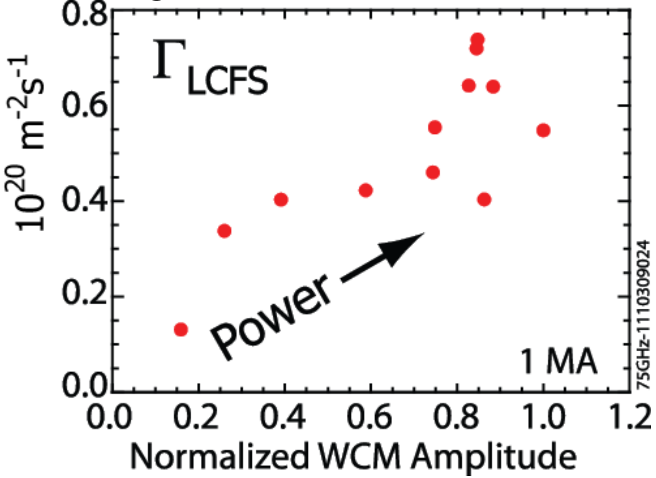
C-Mod
Hubbard
PoP 2011

Edge particle flux correlates with amplitude of Weakly Coherent Mode

C-Mod A. Dominguez, MIT Ph.D 2012.

- Relative amplitude of WCM from edge reflectometer.
- Edge particle flux Γ_{LCFS} derived from calibrated D_α imaging near the outboard midplane.





- Correlation with Γ_{LCFS} is consistent with (does not prove) the WCM playing a role in driving particle transport, perhaps helping avoid transition to H-mode.

Caveats: Γ_{LCFS} analysis was only done for a few discharges. Have not tried similar correlations for recently observed turbulence features (eg GAM, bursts)

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Physics picture(s) of I-mode

Need to explain many puzzling observations, eg.:

- **Several complex, closely related changes in turbulence and flows** (WCM, GAM and low frequency density fluctuation, intermittent n_e bursts with precursors ($\delta t \sim 1/f_{WCM}$), mid-frequency decrease.)
- **Relatively gradual decrease in thermal transport**, and development of E_r well.
- **Particle transport (electrons, impurities, likely main species) all remaining close to L-mode levels; no barrier ever develops.**
- **I-mode depends on Bx∇B direction**, which should be away from X-point; Configuration towards X-pt usually gives direct L-H transition, at lower P.
- **Weak B_T dependence of P(L-I),** vs strong for P(L-H).

Not yet an explanation for all this. Will discuss ideas, and ongoing modeling, from several colleagues. *Perspectives are my own.*

Role of E_r × B shear in decreasing turbulence, thermal transport.

- E_r well is developing in I-mode, together with temperature gradient, and correlated reduction in mid-frequency turbulence.
- Qualitatively consistent with reduction in pedestal χ due to ExB shear, as is thought to be happening in L-H transition.

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Open questions, and differences to L-H transition:

- Why does L-I transition happen so slowly, evolving over ~10-100 ms? (vs μs)
- Why not a strong positive feedback loop and sharp bifurcation as in L-H transition? Does that require a particle barrier?
  Why would E_r shear not affect the particle channel in this case??
- How do critical E_r quantities (eg ω_{ExB}, γ_E, $E_{r,min}$, $V_\perp = E_r/B$) in I-mode compare to values at L-H transition? How does magnetic configuration influence them?

Answers could help understand L-H as well as L-I, I-H physics!

Turbulence nonlinearities could explain intermittent density ‘bursts’, linked to WCM

- Recall intermittent ‘solitary’ bursts are seen at all scales, extend to higher k than WCM. And, WCM is modulated.

Possible explanation, by Happel, Manz (IPP):

- Apparently highly nonlinear turbulent interactions involving WCM, GAM, ‘bursts’ ; we could qualitatively consider **I-mode as being at the boundary between laminar and turbulent (L-mode) flow** , which is known to produce intermittency.
- 2-D drift wave equations contain nonlinearities which could give intermittent behavior:

$$\frac{\partial}{\partial t}\tilde{p}=\{\tilde{\vartheta}p\}=\{\tilde{\vartheta}\underset{\substack{\nearrow\\ \text{Turbulence drive}}}{\overline{p}}\}+\{\tilde{\vartheta}\tilde{p}\}\longleftarrow\text{Nonlinear interaction.}$$

For details, see T. Happel et al., Nucl. Fusion 56 (2016) 064004 and P. Manz et al., Nucl. Fusion 57 (2017) 086022.

Turbulence nonlinearities could explain intermittent density ‘bursts’, linked to WCM

- Several sub-terms in this nonlinear interaction (of KdV or Burgers’ type).
- A term of particular interest for I-mode is amplified by **radial temperature gradient**. Note the intermittency measured on AUG increased with pedestal ∇T.

$$\frac{\partial \tilde{T}_e}{\partial t} \sim \tilde{n}\frac{\partial \tilde{\varphi}}{\partial y}\frac{\partial \overline{T}_e}{\partial x}$$

- This gives particle and heat transport in different directions.
  Γ **is outward** and **larger**

$$\Gamma = \tilde{v}_{E\times Bx}\tilde{n} = +(k_y 1.71^2 \tilde{T_e}^2)/(\delta B)$$

Heat flux q is inward and **small**

$$q = \tilde{v}_{E\times Bx}\tilde{n}\tilde{T}_e = -\frac{1.71 k_y^2 \tilde{T}_e^3}{\delta B}$$

For details, see T. Happel et al., Nucl. Fusion 56 (2016) 064004 and P. Manz et al., Nucl. Fusion 57 (2017) 086022.

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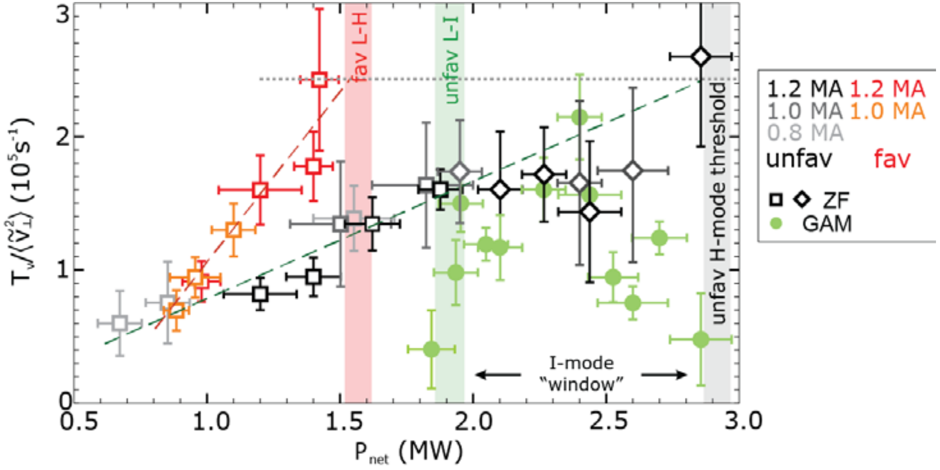
$$\frac{\partial \tilde{T}_e}{\partial t} \sim \tilde{n} \frac{\partial \tilde{\phi}}{\partial y} \frac{\partial \bar{T}_e}{\partial x}$$

- Model qualitatively fits with several observed features of I-mode. Remains to assess fluxes quantitatively. There should also be bursts in T, which are hard to measure.
- How would this model relate to E_r, and to I-mode threshold conditions?
- Why does particle transport end up just at L-mode levels?
- Why does Bx∇B drift direction matter?

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

- 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]
- **Measured 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 power threshold!**



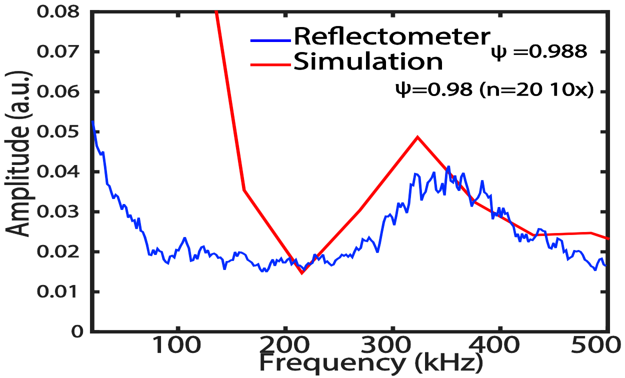
C-Mod I. Cziegler, York, PRL 118, 105003 2017

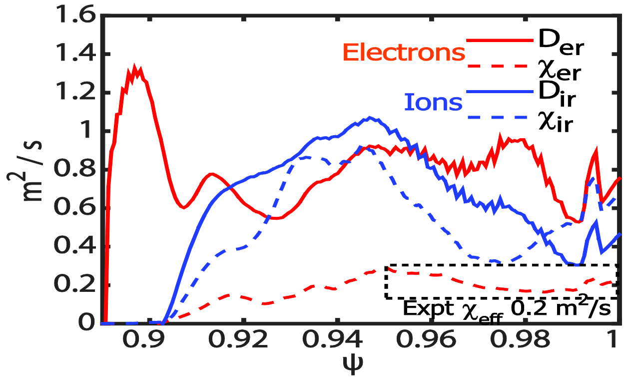
Opens a power window for I-mode.
In the I-mode, energy is transferred to GAMs as well as ZFs

Somehow, even in L-mode, nonlinear turbulence-flow interactions depend on magnetic configuration. **Why?** *Related to mean flows, SOL?*

Simulations of I-mode pedestals

- BOUT++ (6-field 2-fluid) model used to simulate a high n_e, 5.8 T C-Mod I-mode.
- Linear simulations show Drive Alfven, Resistive ballooning mode dominate.
- 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_{eff}, Γ are close to expt.





C-Mod
Z. Liu
(ASIPP)
PoP 2016.

Simulations of I-mode pedestals

- **BOUT++** (6-field 2-fluid) model used to simulate a high n_e, 5.8 T C-Mod I-mode.
- Linear simulations show Drive Alfven, Resistive ballooning mode dominate.
- 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_{eff}, Γ are close to expt.

- These initial runs set equilibrium ZF to zero, cannot capture interaction with GAM which seems important in experiment.
  - Extensions to include flows are in progress.

- Other groups are working on gyrokinetic simulations of I-mode pedestal (U. Texas), and of L-I transitions (C.S. Chang et al, PPPL).
- More such simulation work, over the evolution from L to I-mode and for a range of plasma parameters, is needed.

Neoclassical impurity transport: Predicted to be outward in I-mode pedestal.

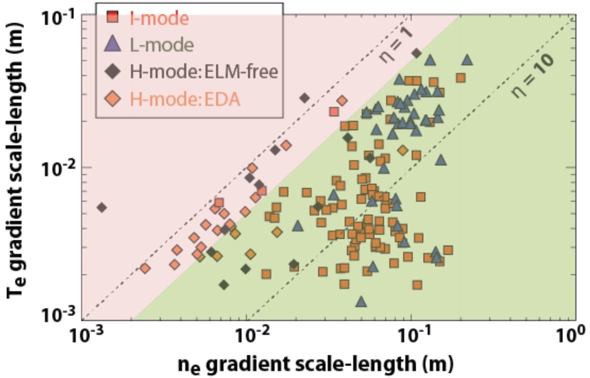
- Recent theoretical analysis of typical C-Mod I-mode, based on experimental profiles, finds **all terms in radial impurity flux are OUTWARD.**
  S. Espinosa, MIT Ph.D. 2017, submitted.
- **First term is outward if $\eta_e > 2$**
  ie $L_T < 2 L_n$, which is typical for I-modes due to steep ∇T/T, low ∇n/n. (also most L-modes; H-mode have lower $\eta_e \sim 1$).
- Other terms, depending on poloidal asymmetries and flows, are also outward.

$$\text{Radial impurity flux} \propto \overbrace{-2\epsilon^2 g}^{\text{Outward}} + \overbrace{\epsilon \frac{n_{zH} - n_{zL}}{n_{zH} + n_{zL}} (g + U)}^{\text{Outward (separatrix)}}$$

Thomson scattering: ⊖ $\propto \left(\frac{1}{2} \frac{\partial \ln T_e}{\partial \psi} - \frac{\partial \ln n_e}{\partial \psi} \right)$

Imp.dens: ⊖ $\propto \frac{n_{zH} - n_{zL}}{n_{zH} + n_{zL}}$

Pol.flow: ⊖ $\propto \frac{n_z V_z \cdot \nabla \theta}{B \cdot \nabla \theta}$



(Whyte 2010)

C-Mod
Whyte
NF 2010

A. Hubbard, ISHW2017, Kyoto

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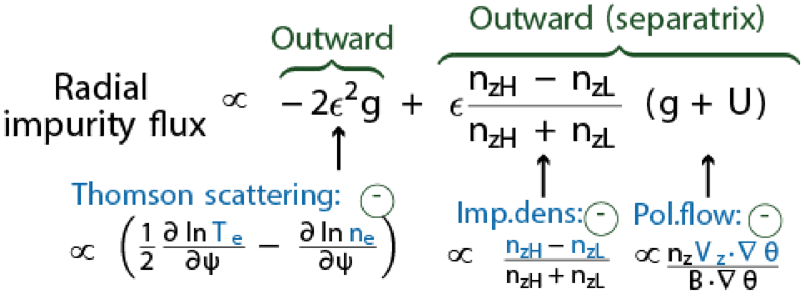

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- Total transport is sum of turbulent, neoclassical fluxes.
- Quantitative analysis of impurity, main species, and thermal neoclassical transport, and comparison to estimated turbulent fluxes, are needed.
- Outward neoclassical transport would certainly help avoid accumulation in I-mode.
- Would not explain sudden increase in density, impurities at I-H transitions, when turbulence is suppressed.
- *Why is particle transport the same in L and I-mode?*

I-mode phenomenology and physics

- What is “I-mode”? Why of interest for fusion? How to access?

- Evidence for separation of thermal and particle transport

- Phenomenology: Measurements of profiles, turbulence and flows on C-Mod and ASDEX Upgrade tokamaks

- Physics: *Possible* contributions to separation of transport channels
  (for workshop discussion, still no definitive explanation)

- **Conclusions, questions, prospects**

Summary: I-mode phenomenology and physics

- I-mode is a distinct confinement regime in which **energy confinement is improved, but all measures of particle confinement remain at L-mode levels. Also ELM-free.** This has many attractions as a fusion regime.
- Observed on multiple tokamaks, now over wide ranges of parameters.
- **Detailed measurements of pedestal profiles, turbulence, flows on C-Mod and AUG reveal complex physics** (GAM, Weakly coherent mode, intermittent bursts are all linked).
- Poses a very interesting challenge to our understanding of transport and transport barriers. Linked to longstanding differences in L-H threshold with magnetic configuration.
- Several physics ideas are emerging which might explain separation of particle and energy transport, but more work is needed to develop and test them.
  - *New ideas from the stellarator community are welcomed!*

Future prospects

- Prospects for extrapolation of I-mode to tokamak burning plasmas (presented IAEA16, EPS17 but not much in this talk) are promising, especially for high B_T devices. An ELM risk mitigation strategy for ITER, DEMO.
  - More experiments are planned on AUG, EAST, KSTAR, WEST, ST’s.
  - Need larger scale experiments for confident extrapolation. JT-60SA, with its flexible configuration, will be highly valuable.

For discussion:

- *Has a similar regime, with high thermal confinement but low particle confinement, been observed in stellarators?*
- In tokamaks, up-down magnetic configuration (X-point wrt $B\times\nabla B$ drift) clearly plays a major role in obtaining I-mode.
  How would this condition relate to non-axisymmetric configurations?

Thank you for this invitation.
I look forward to discussing during the workshop!