Advances in the understanding of the I-mode confinement regime: access, stationarity, edge/SOL transport and divertor impact

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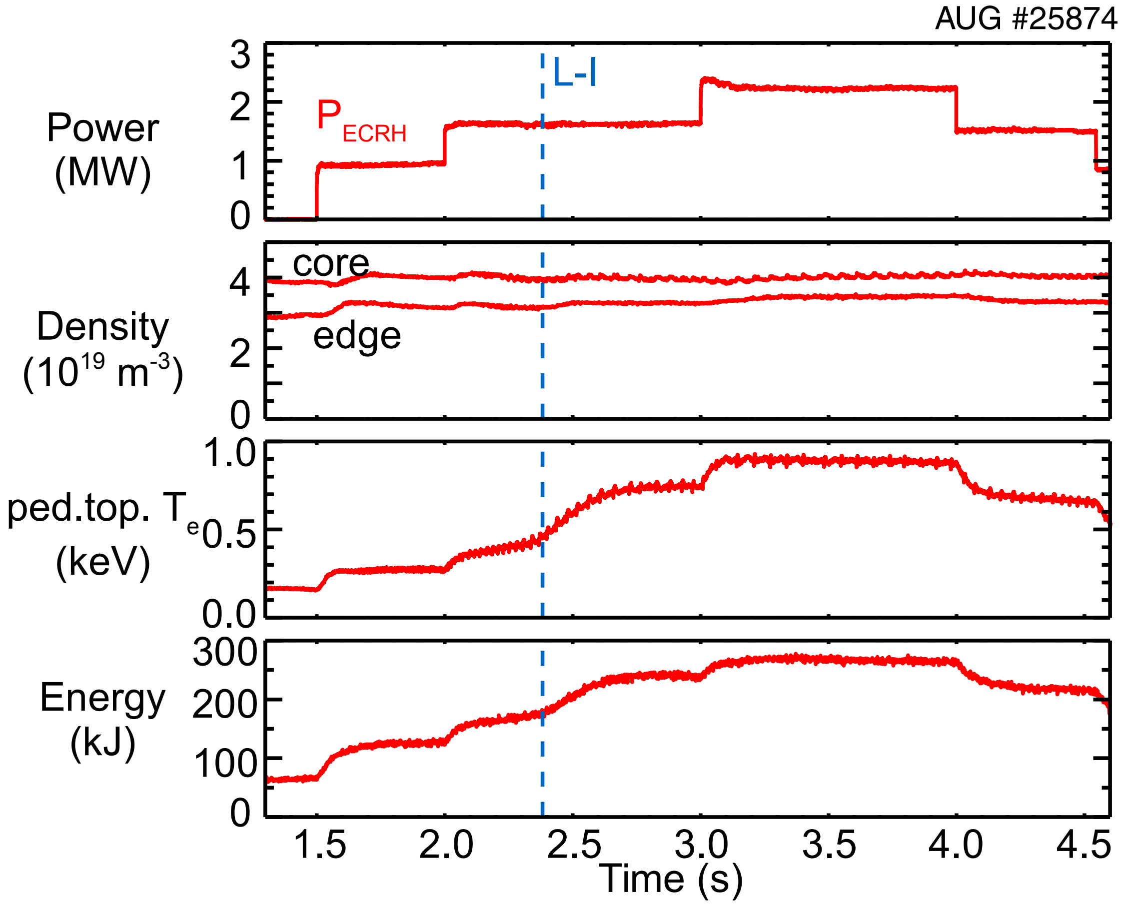
The Improved Energy Confinement Regime (I-mode)



- Obtained with unfavorable magnetic configuration ($P_{L\text{-}H}$ high).
- **Density** stays **constant**, pronounced **temperature increase.**
- No ELMs, good impurity transport properties.
- Weakly coherent mode (WCM) dominates edge turbulence spectrum.
- Is considered as a candidate regime for a future reactor.

[Ryter PPCF 1998, Whyte NF 2010]

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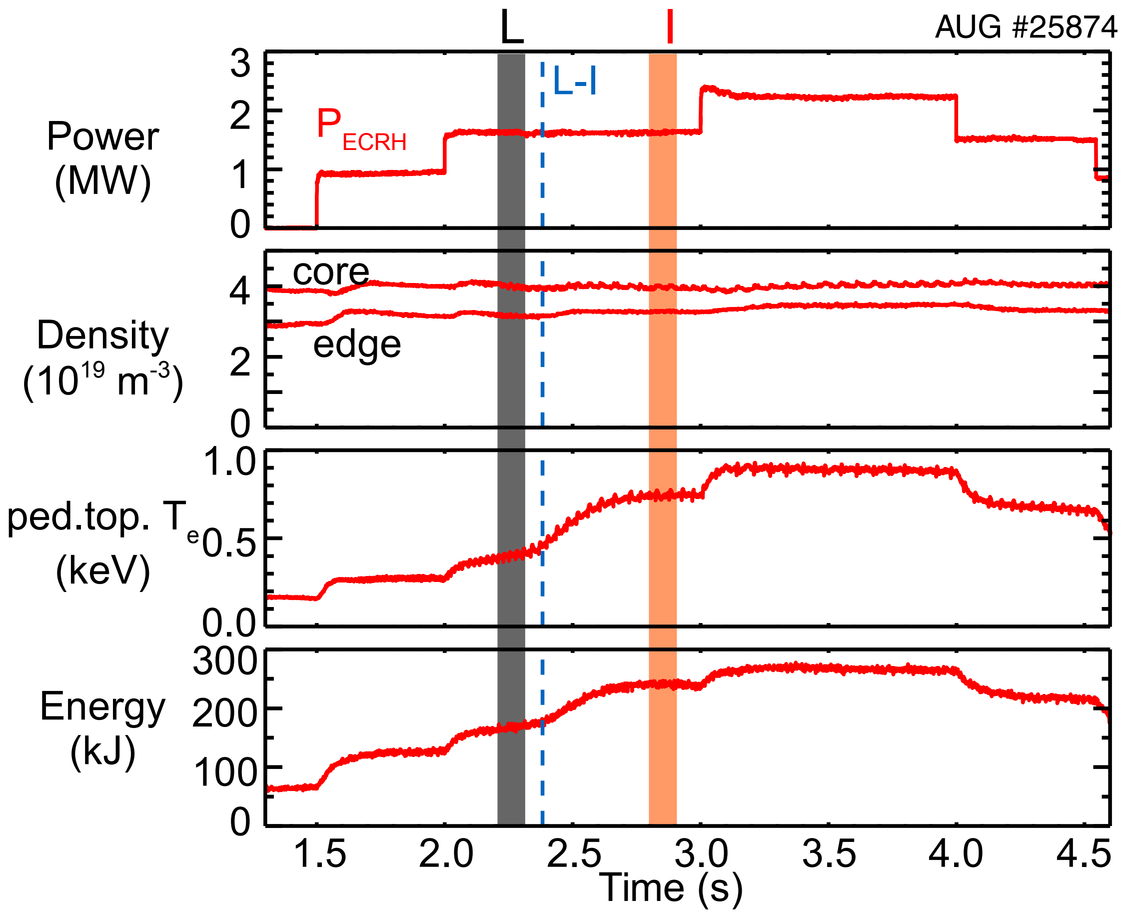
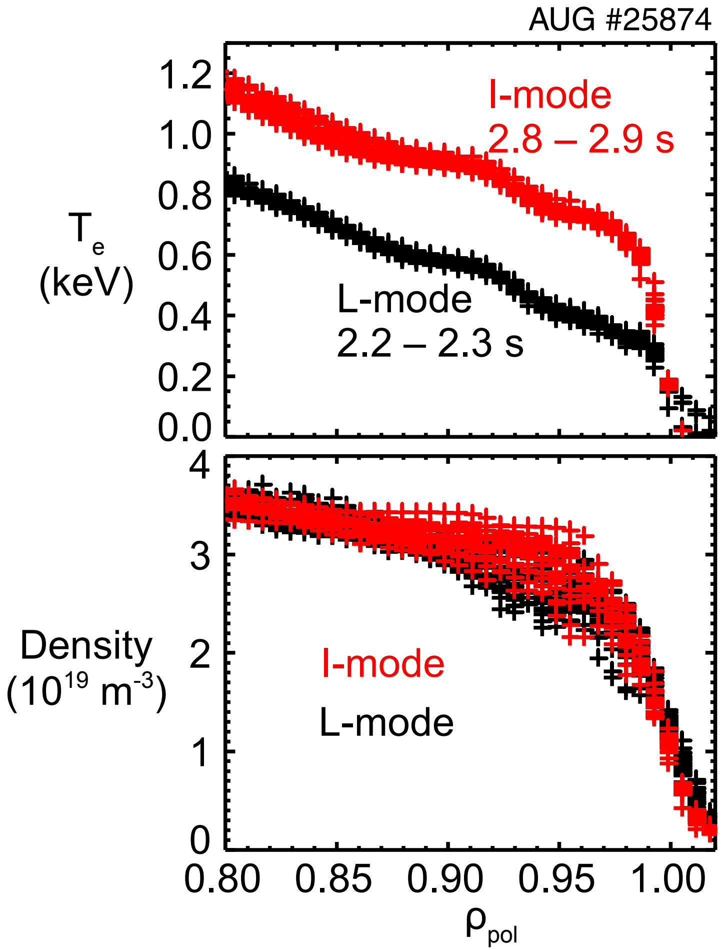




[Ryter PPCF 1998, Whyte NF 2010]

Outline

The global picture...

- I-mode Access Conditions
- Extension of Parameter Space and Robustness

The plasma edge...

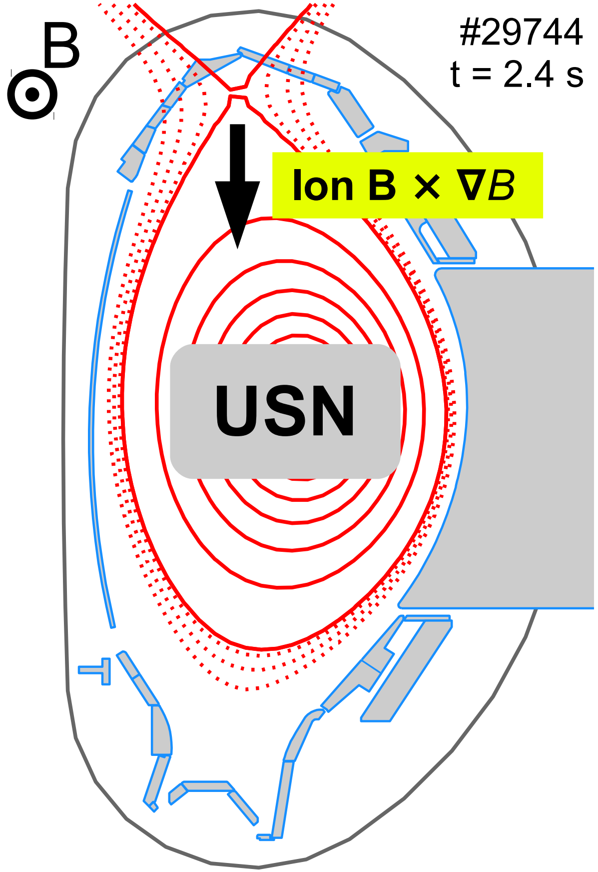
- Intermittent Density Turbulence Bursts

The divertor...

- Heat Fluxes and Fall-off Lengths
- Transient Heat Loads

Summary / Outlook

Access to I-mode by avoiding H-mode



- Ion grad B drift away from active x-point
  - Upper Single Null (**USN**)

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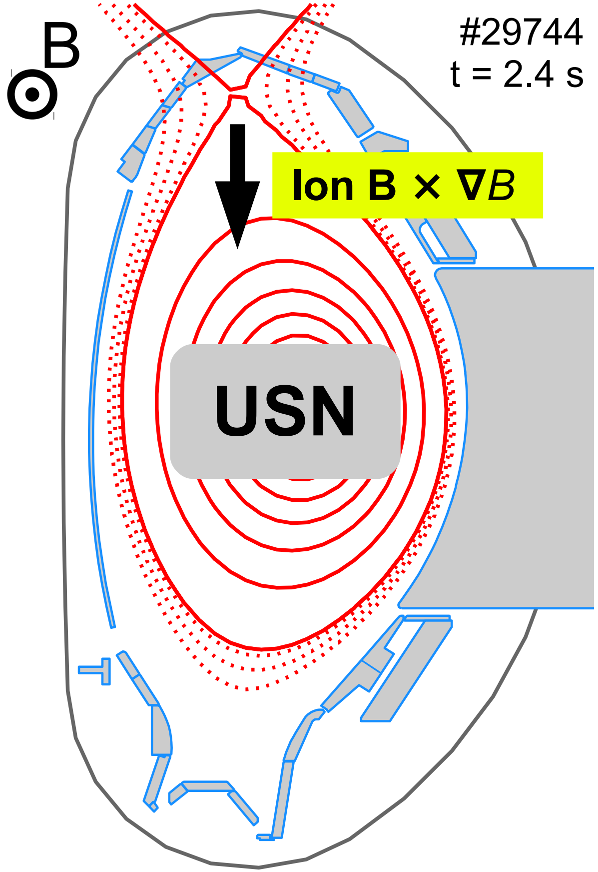
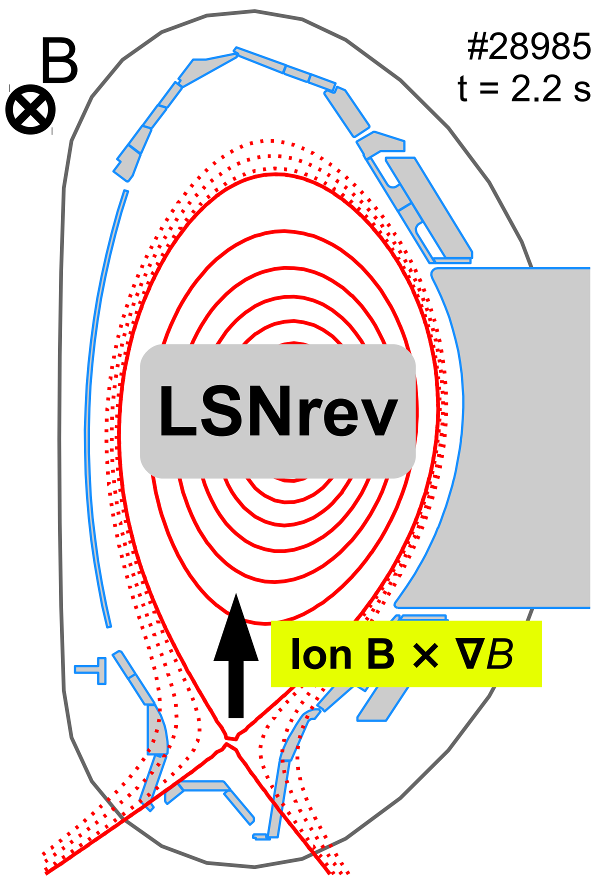


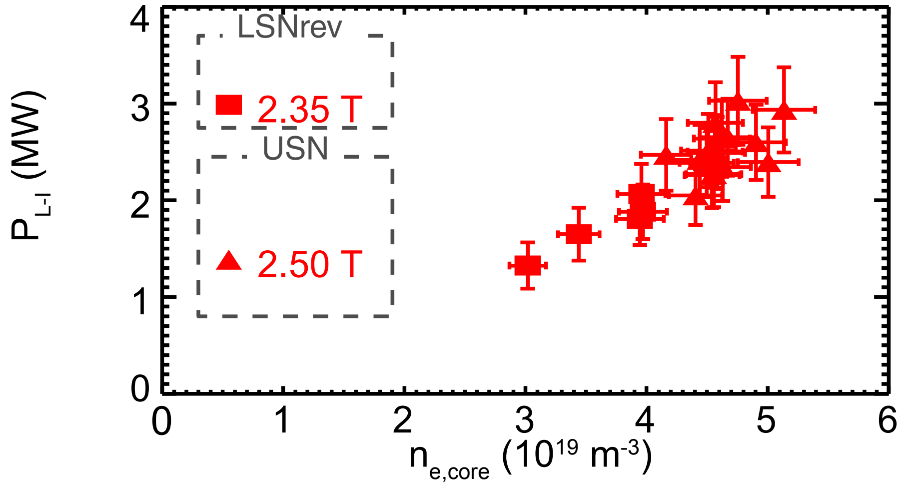


- Ion grad B drift away from active x-point
  - Upper Single Null (**USN**)
  - Lower Single Null B_t reversed (**LSNrev**)

  ⇒ **unfavorable** config.

  ($P_{L\text{-}H}$ about 2x higher than in favorable)

$P_{L\text{-}I}$ depends on density and magnetic field strength



- Offset-linear dependence on density
- Use 2.35 – 2.50 T for n_e^{fit}

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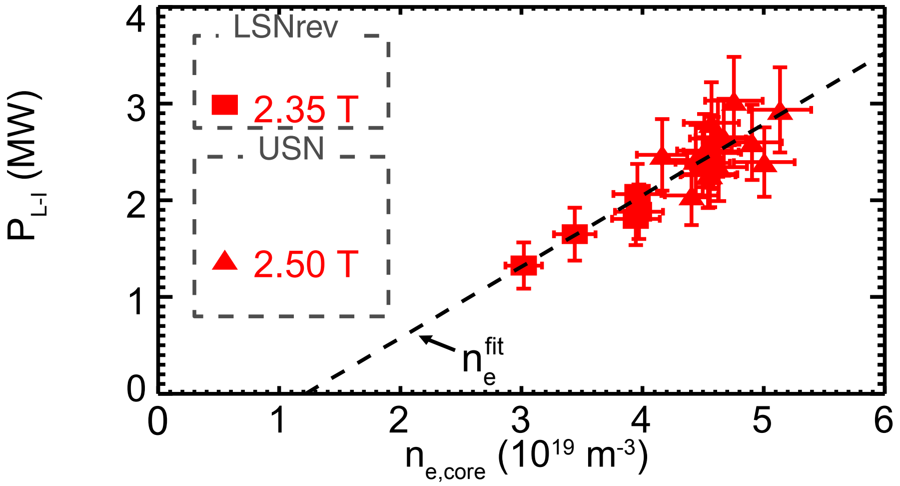

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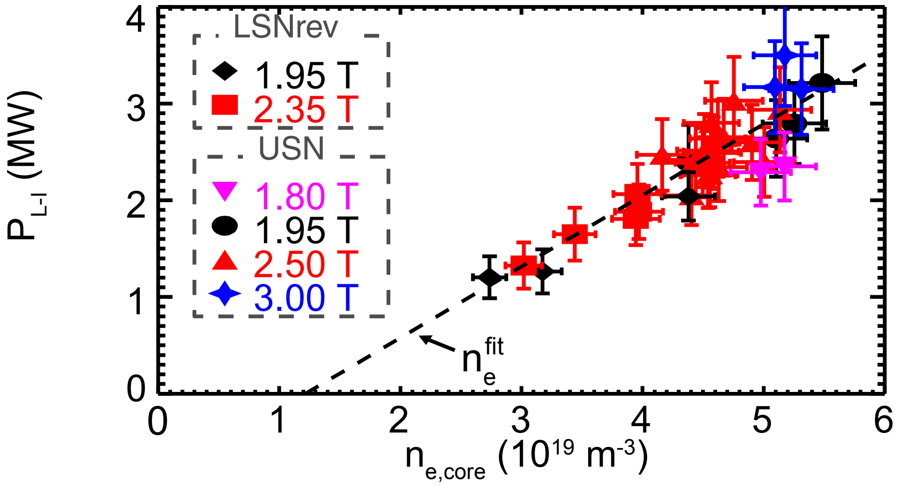

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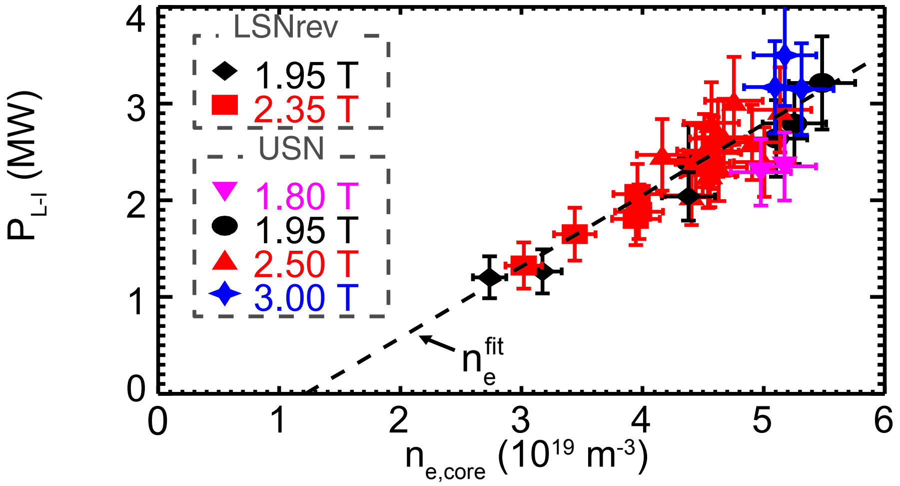
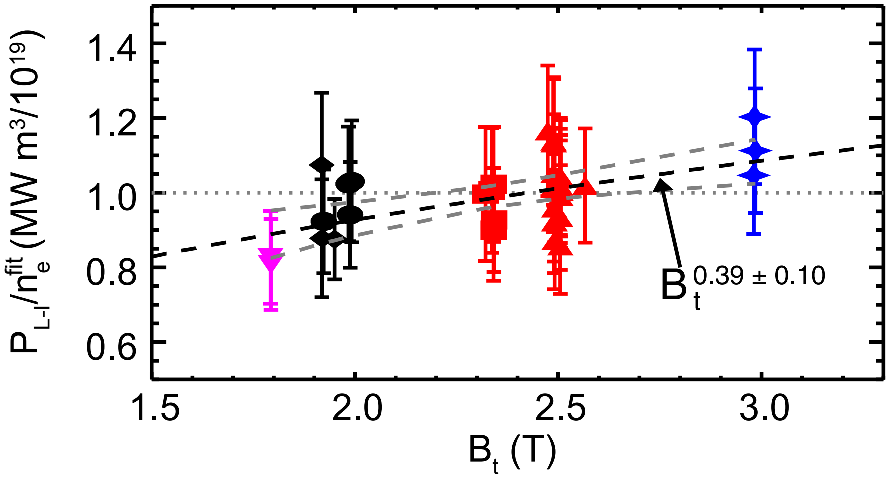
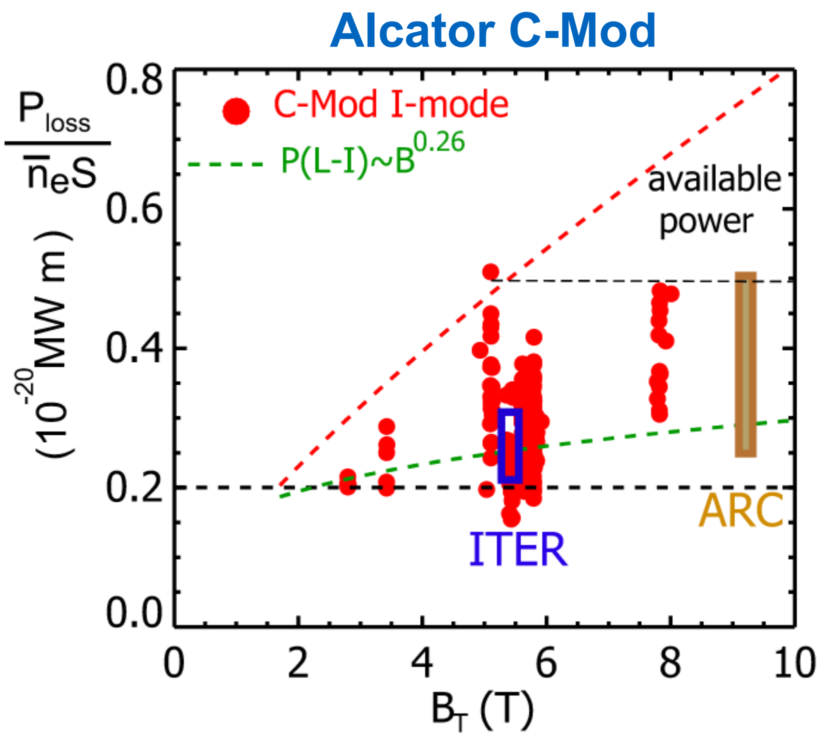
P_{L-I} depends on density and magnetic field strength





- Offset-linear dependence on density
- Use 2.35 – 2.50 T for n_e^{fit}
- Variation in magnetic field (1.8 – 3.0 T)
- P_{L-I}/n_e^{fit} reveals dependence on magnetic field strength **[Happel PPCF 2017, Hubbard NF 2017]**:
  AUG: $P_{L-I} \propto B_t^{0.39 \pm 0.10}$, C-Mod: $P_{L-I} \propto B_t^{0.26 \pm 0.03}$
- H-mode dependence stronger **[Martin JPCF 2008]**:
  $P_{L-H} \propto B_t^{0.80}$
- Could favor I-mode at strong **B**.

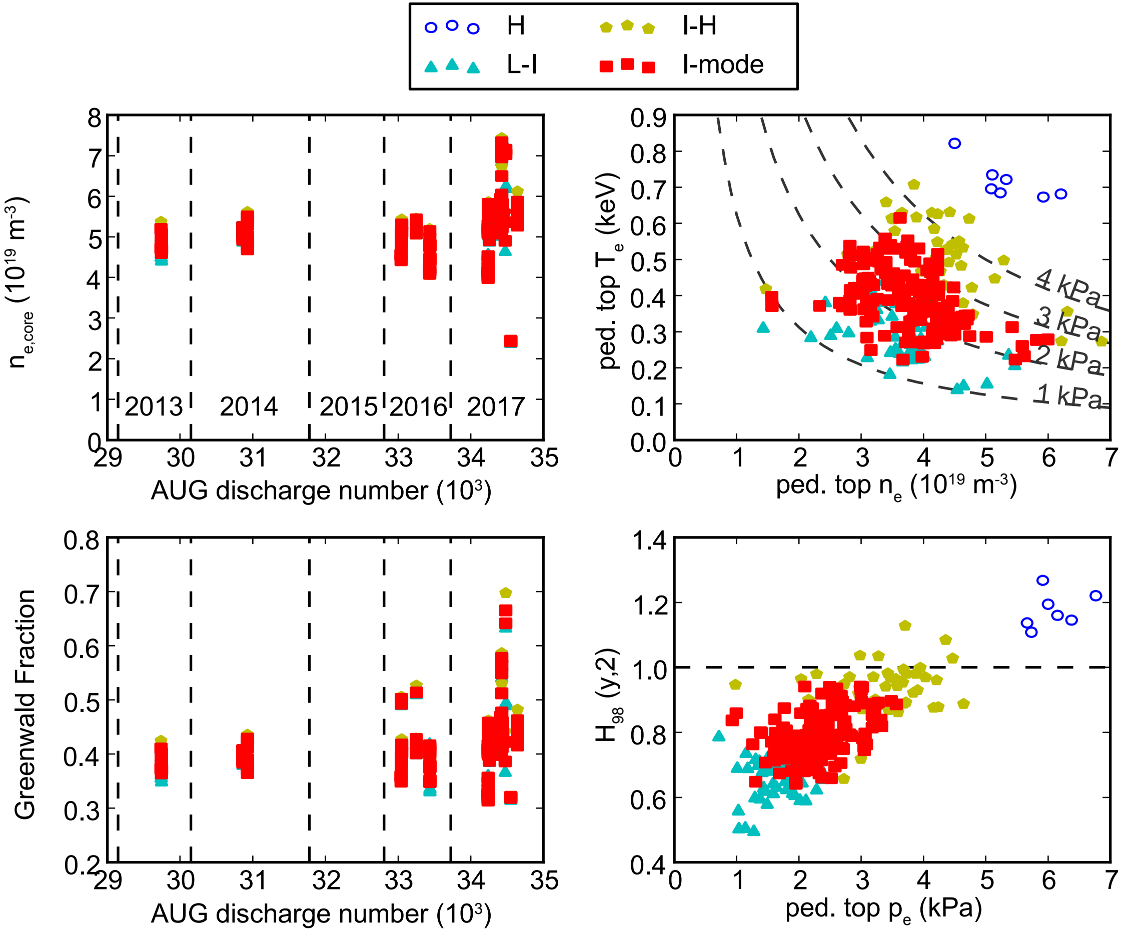
High magnetic Field Strength seems beneficial for I-mode



[Hubbard 2017 NF, Marmar OV/2-4 (Mon)]

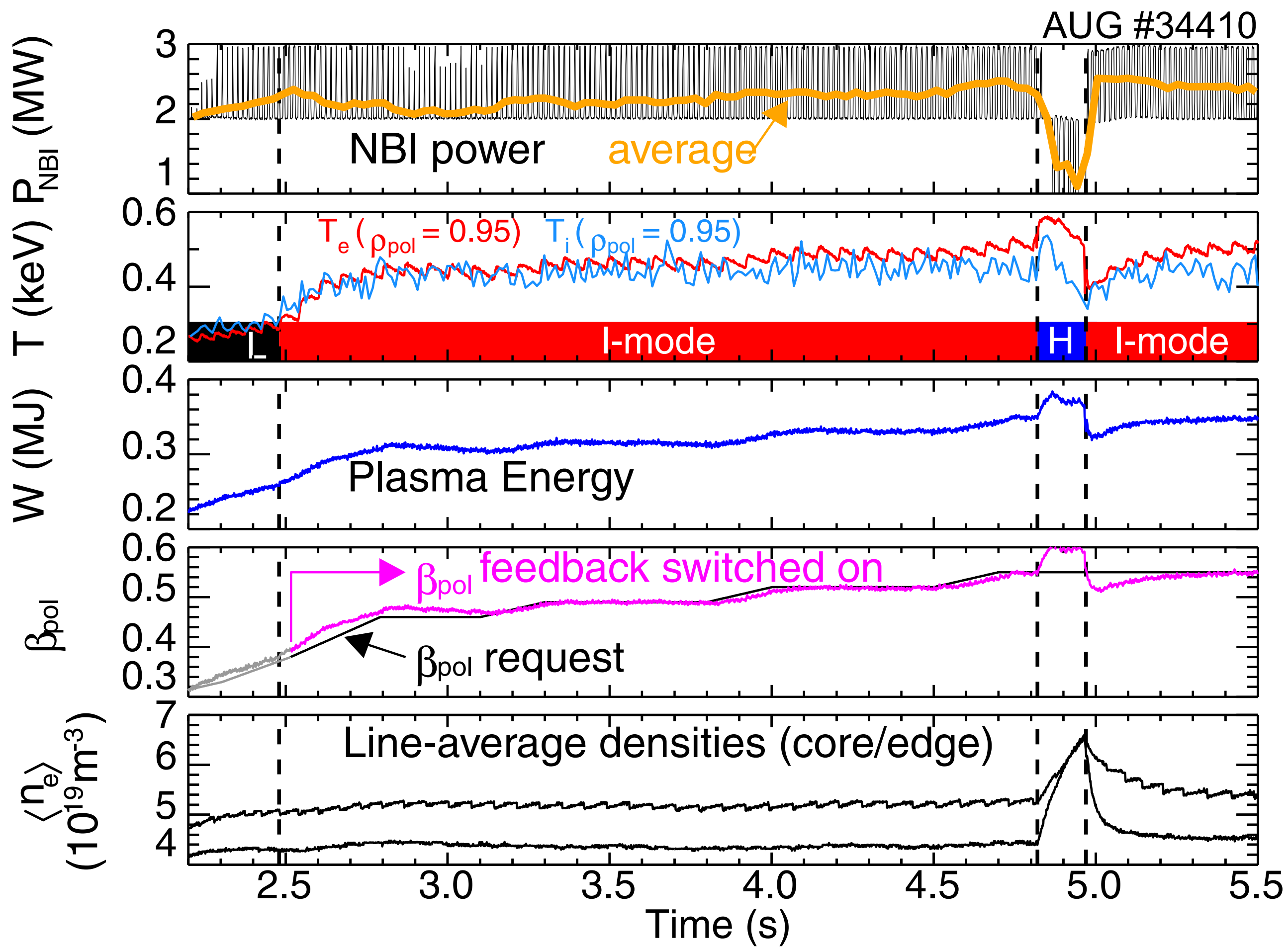
- Variation in magnetic field (2.7 – 8.0 T).
- At 8 T, no I-H transitions were achieved.
- No I-mode so far on TCV (1.45 T), but search is ongoing.
- On AUG, I-mode window smaller than on C-Mod.

Extension of Parameter Space to higher Densities



- Higher densities achieved in 2017 (absolute and GW) through gas puffing.
- Reached
  n/n_{GW} = 0.70 (transient)
  n/n_{GW} = 0.58 (stationary)
- Reached n_{sep}/n_{GW} = 0.24.
- On AUG, I-mode pedestals are within 1 – 4 kPa electron pressure.

Stationary I-modes through β feedback control



- After L-I transition, P_{NBI} reduced.
- Energy and ped. top temperature continue to rise.
- I-H transition at 4.81 s (H_{98} = 0.92)
- H-I transition at 4.97 s.
- Strong particle losses after H-I transition.

[Happel NME 2018, *submitted*]

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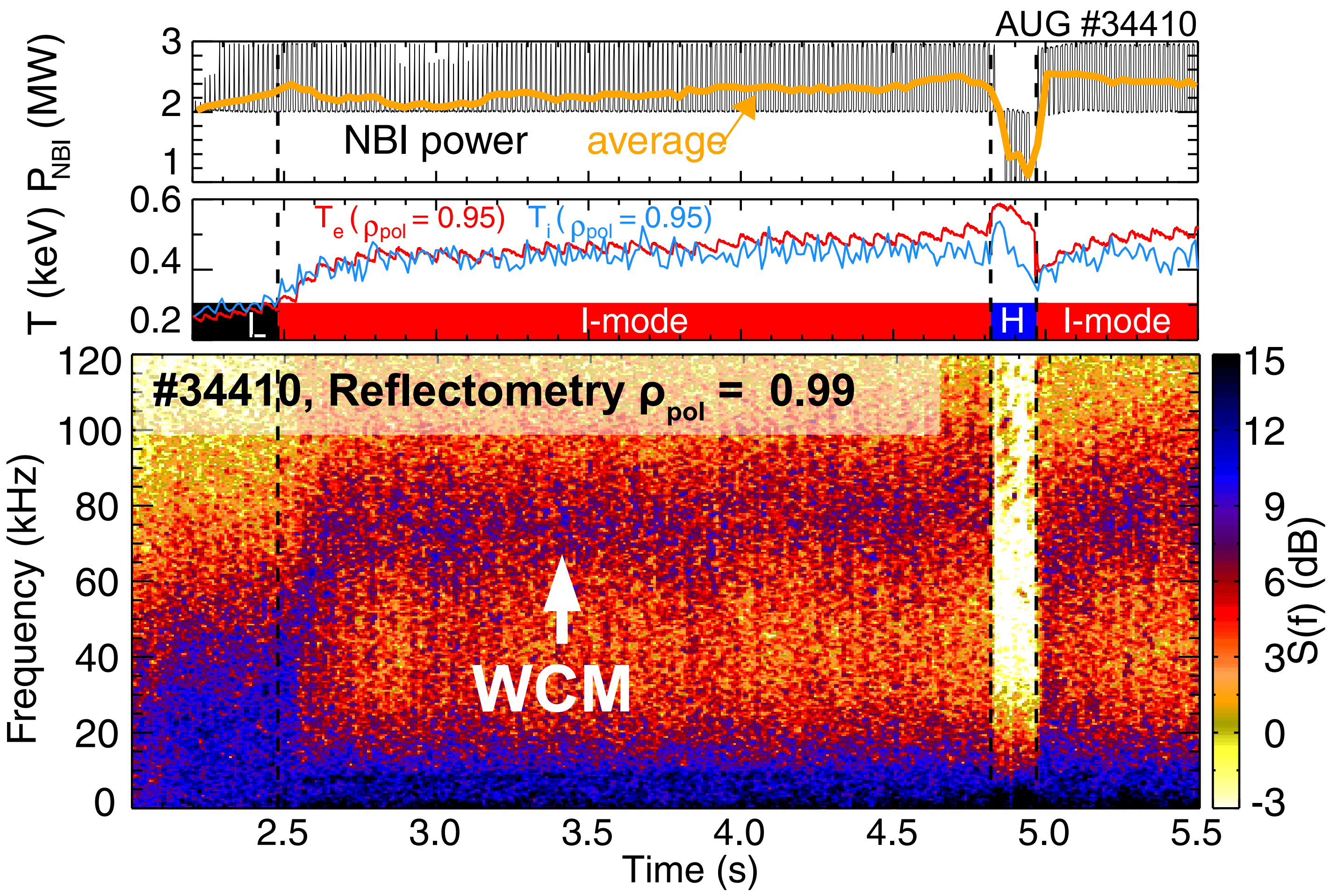

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- I-H transition at 4.81 s (H_{98} = 0.92)
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- Strong particle losses after H-I transition.
- WCM dominates edge turb. spectrum in I-mode

[Happel NME 2018, *submitted*]

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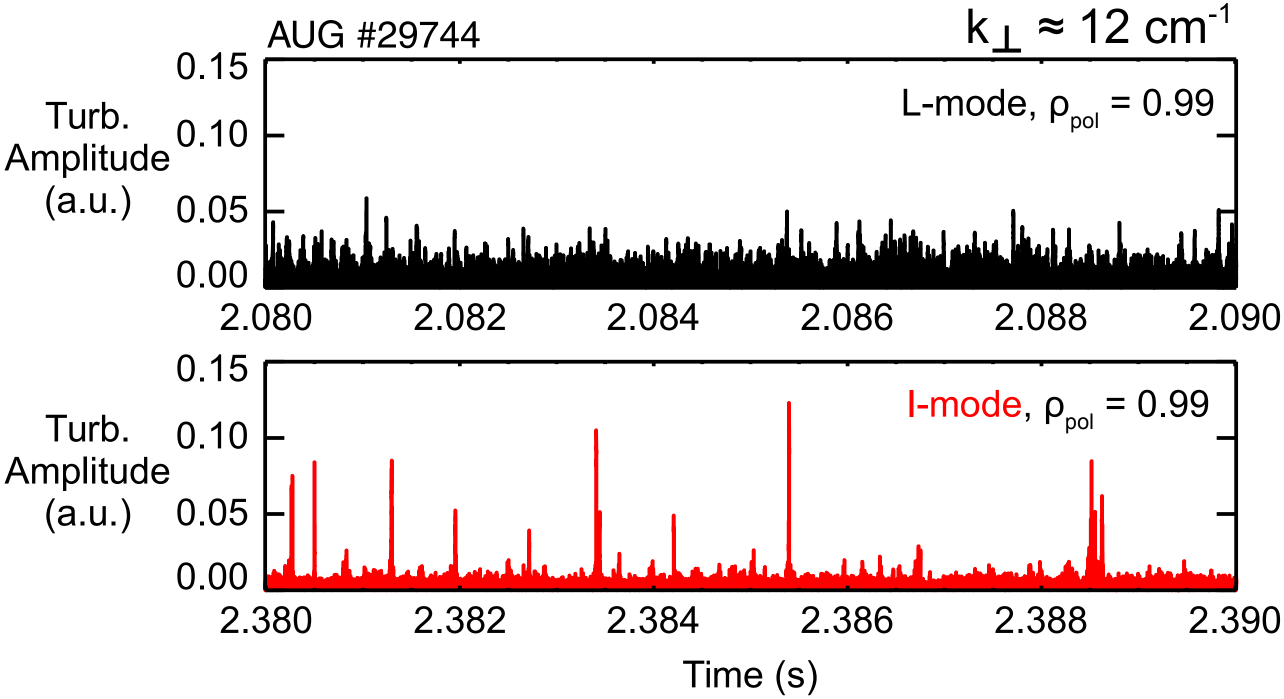
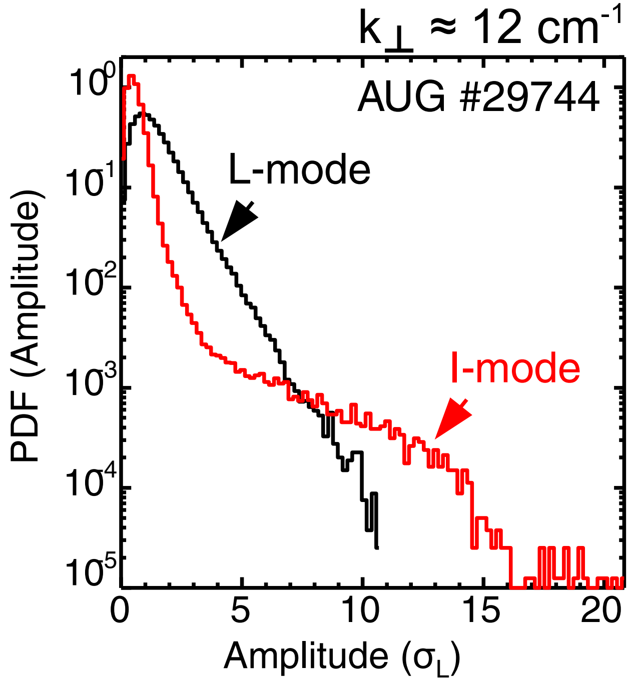
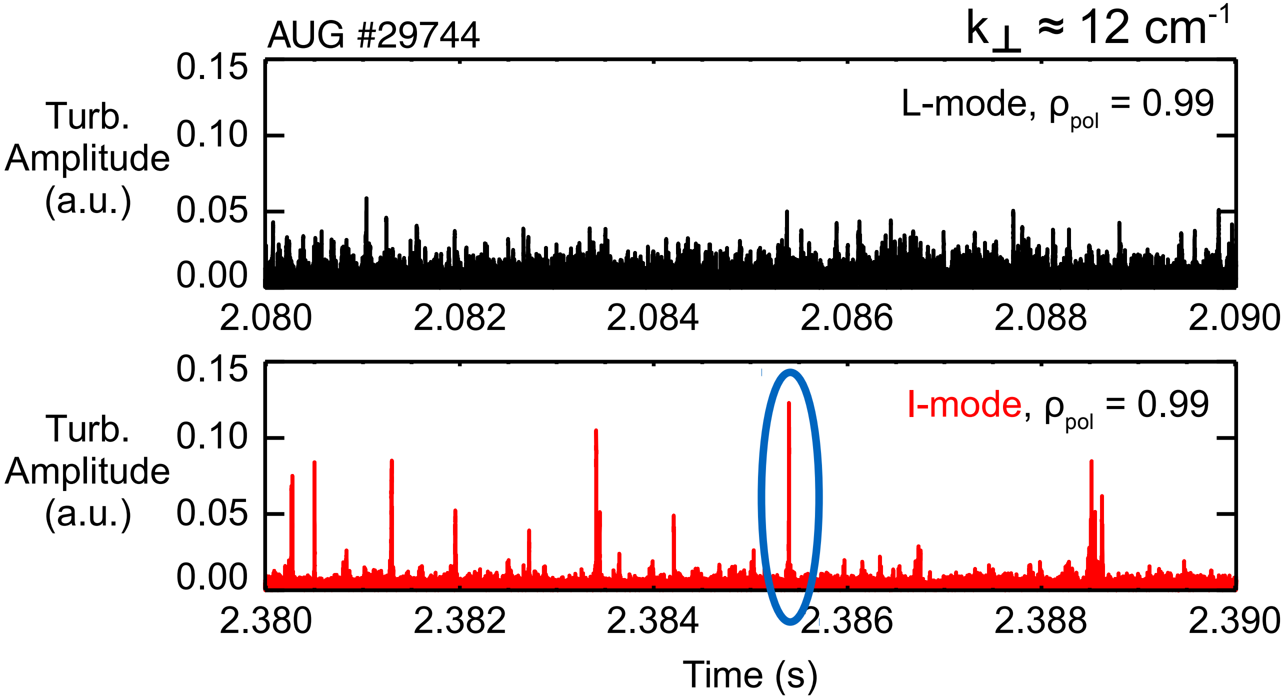
Turbulence in I-mode shows burst character

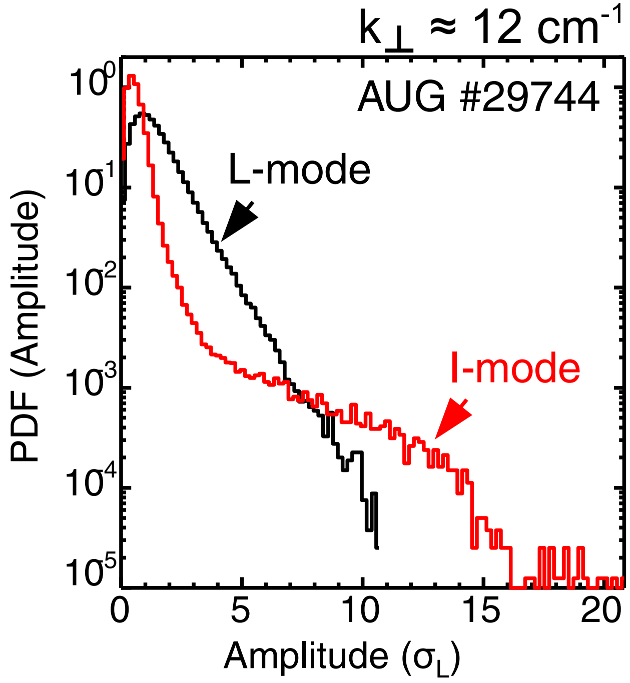




- Substantial difference between L-mode and I-mode turbulence behavior.
- I-mode PDF develops heavy tail at large amplitudes.

[Happel NF 2016, Manz NF 2017]





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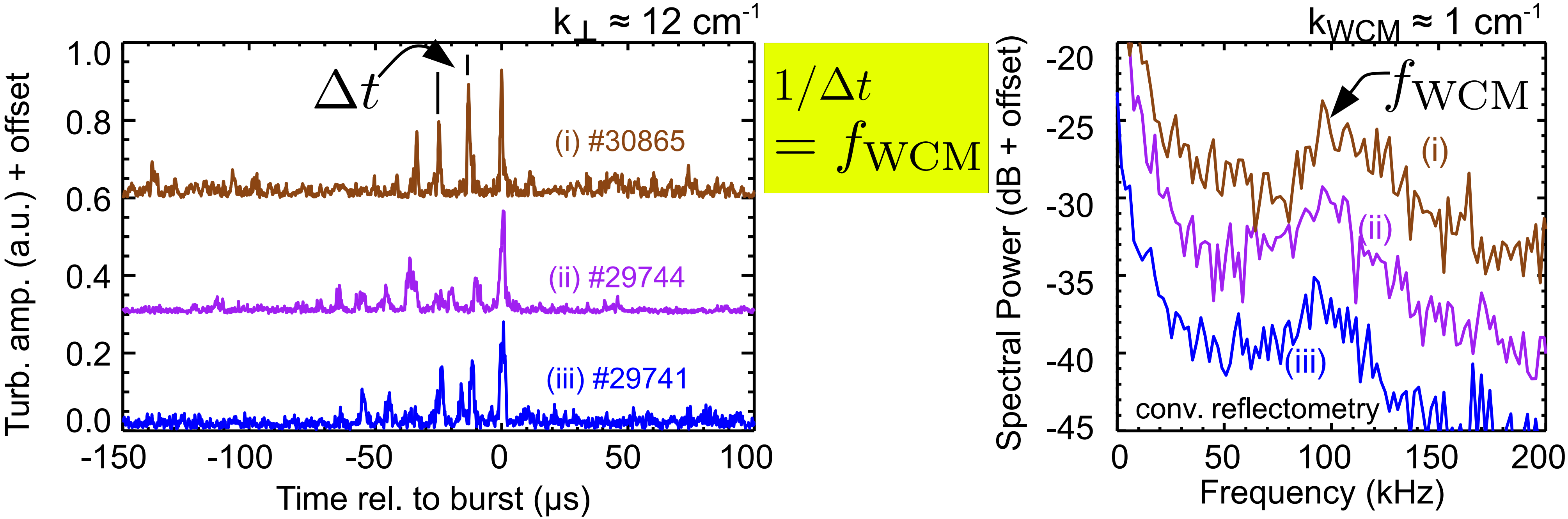
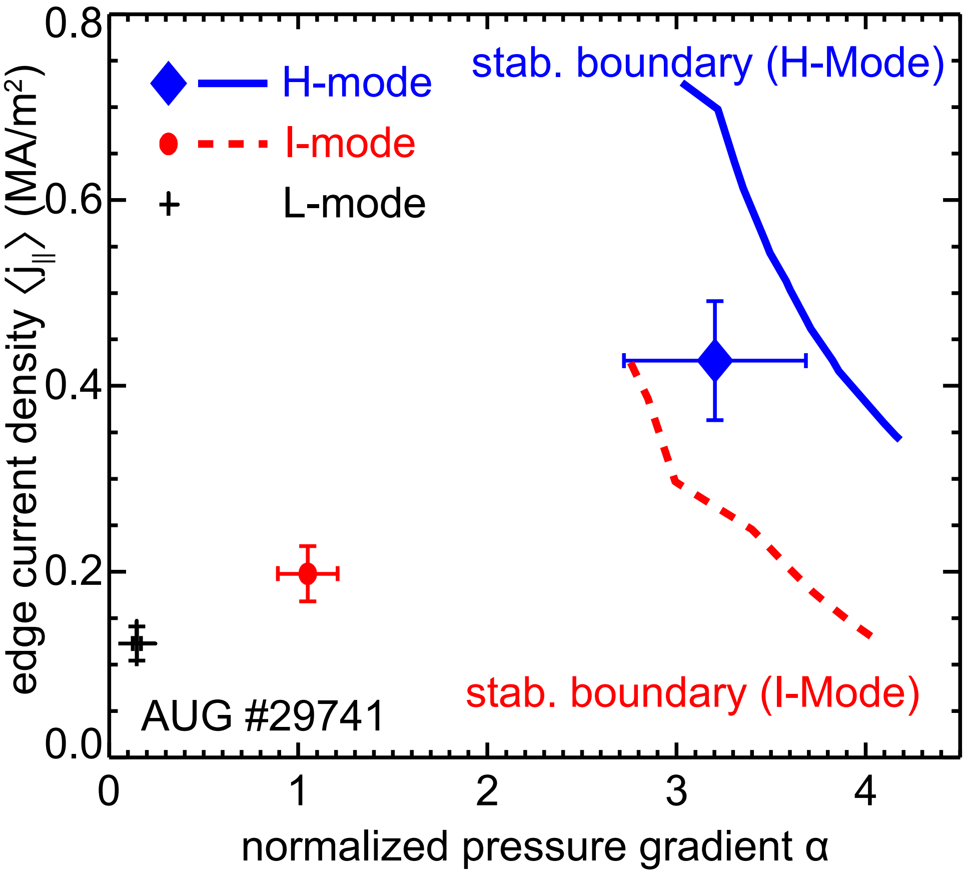
Density bursts are linked to the WCM



- **Clear link** shown between WCM and intermittent turbulence bursts.
- **Generation mechanism suggested** based on Korteweg-de-Vries nonlinearity **[Happel NF 2016, Manz NF 2017]**.
- **Link between WCM and bursts only seen in I-mode**, when WCM dominates the turbulence spectrum.

I-mode bursts are not ELMs



[Happel PPCF 2017]

- MISHKA [Mikhailovskii PPR 1997] stability analysis of L-mode, I-mode and H-mode
- H-mode close to PB-boundary, **I-mode clearly stable**
- Results agree with those from Alcator C-Mod **[Hughes NF 2013, Walk PoP 2014]**
- Not type I ELMs: PB-stable
- Not type II ELMs: plasmas not strongly shaped
- Not type III ELMs: bursts are intermittent no magnetic precursor

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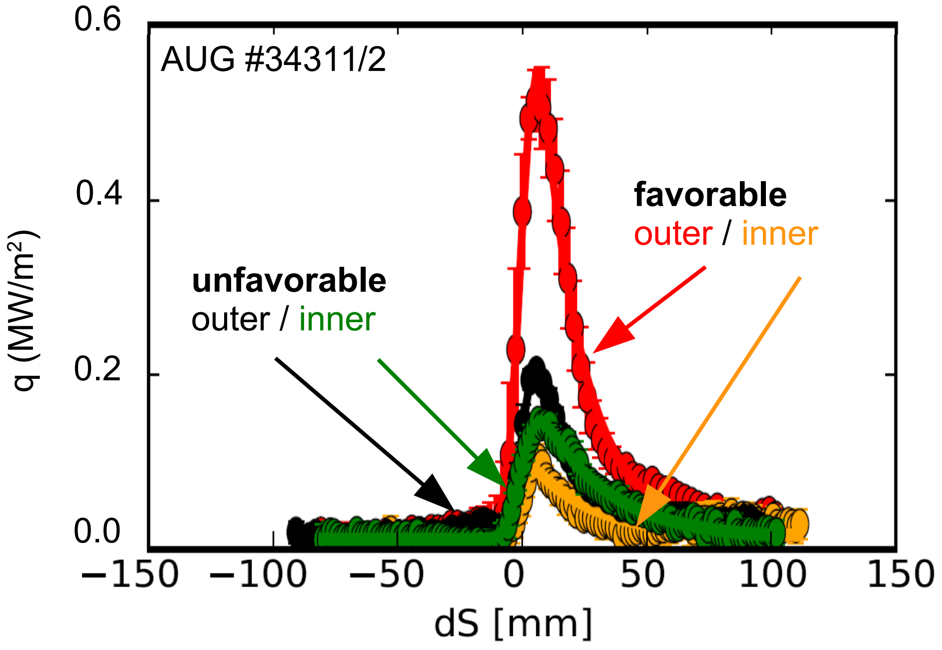
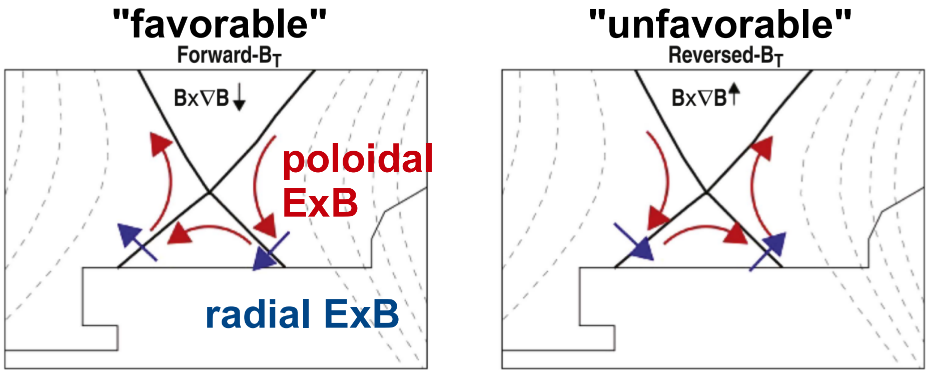
Equipartition of power loads in the divertor

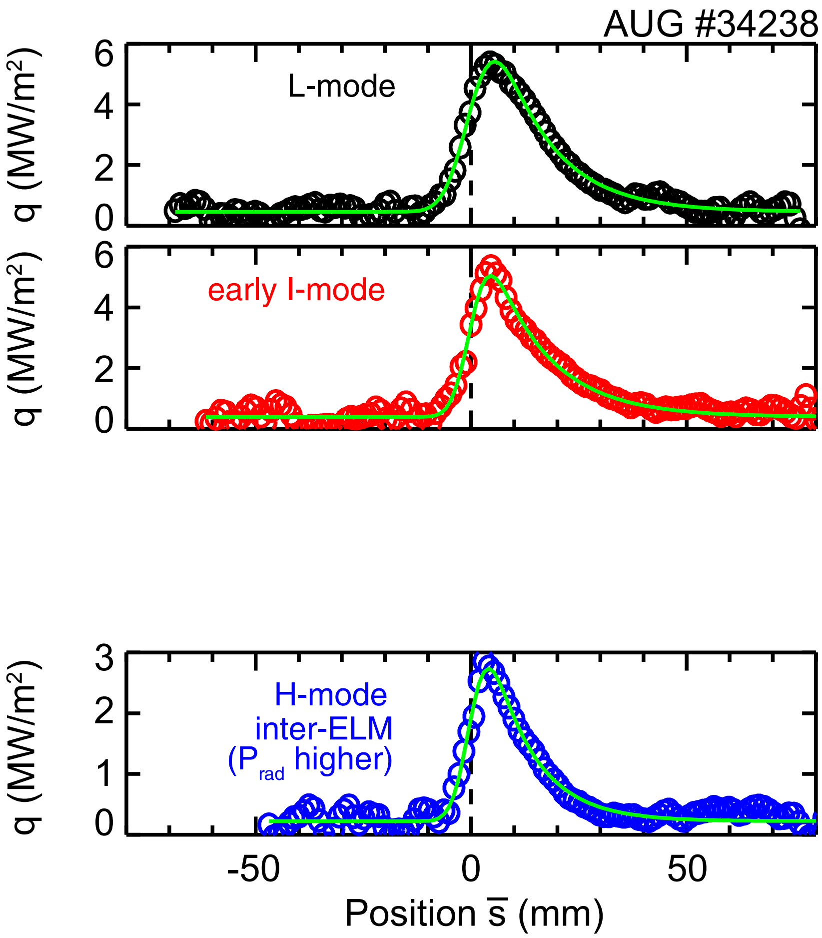




[Rognlien 1999 JNM, Leonard PPCF 2018]

- In unfavorable configuration, equipartition of divertor power loads expected.
- Due to poloidal / radial E×B drifts.
- Recent systematic investigations on AUG are consistent with expectations.
  [Paradela Perez NME 2018, *submitted*]

Divertor heat fluxes in L-mode, I-mode and H-mode



- Divertor heat flux profile inferred from infrared thermography measurements.
- H-mode inter-ELM profile narrower than L-mode profile.
- I-mode profile "in between".

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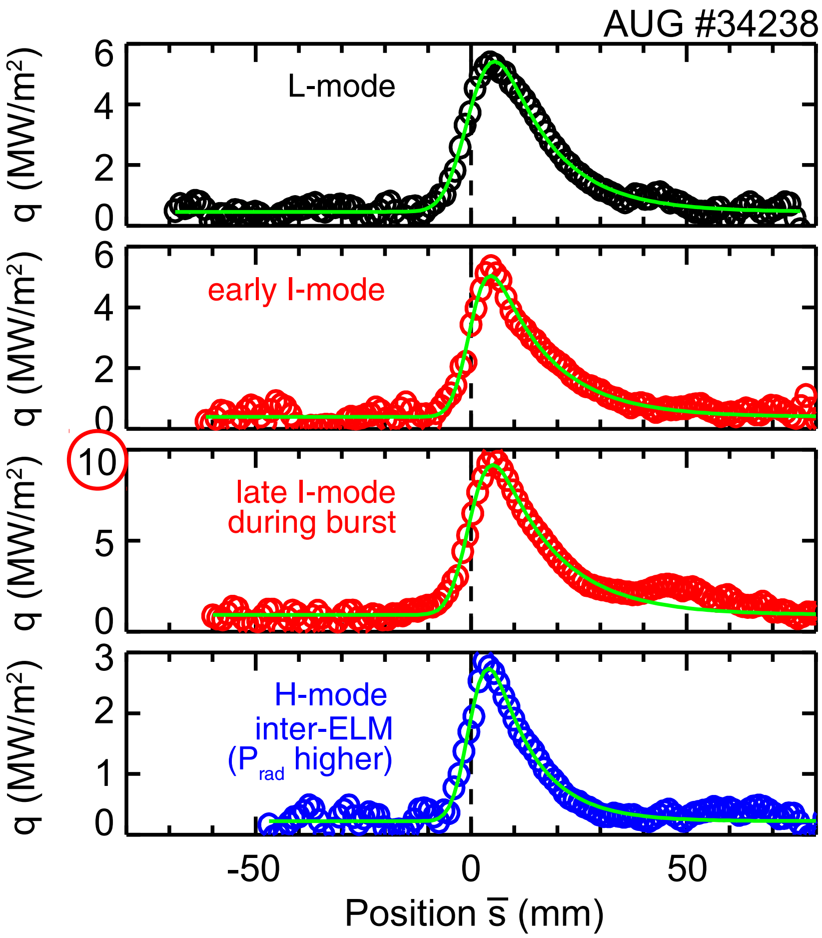
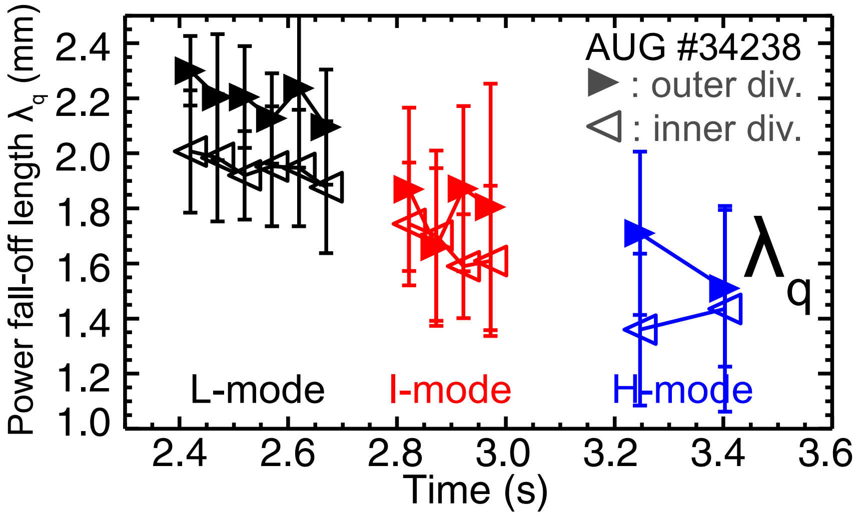


- Divertor heat flux profile inferred from infrared thermography measurements.
- H-mode inter-ELM profile narrower than L-mode profile.
- I-mode profile "in between".
- Late I-mode heat flux profiles can be of high amplitude, correspond to intermittent events.
- Fit function from **[Eich 2011 PRL, 2013 NF]**.

[Happel NME 2018, *submitted*]

Power fall-off length between L- and H-mode values



- λ_q in I-mode between those of L-mode and H-mode.
- Results consistent with C-Mod **[Terry JNM 2013, Brunner NF 2018 & Umansky EX/P6-9 (Thu)]**.

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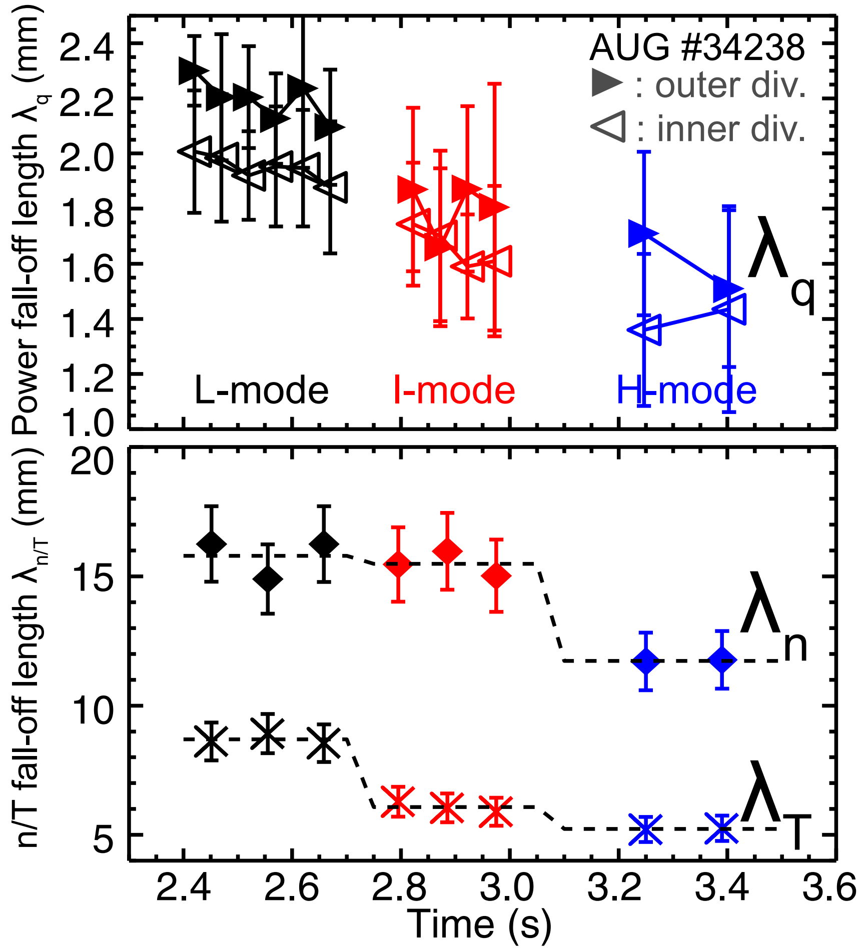
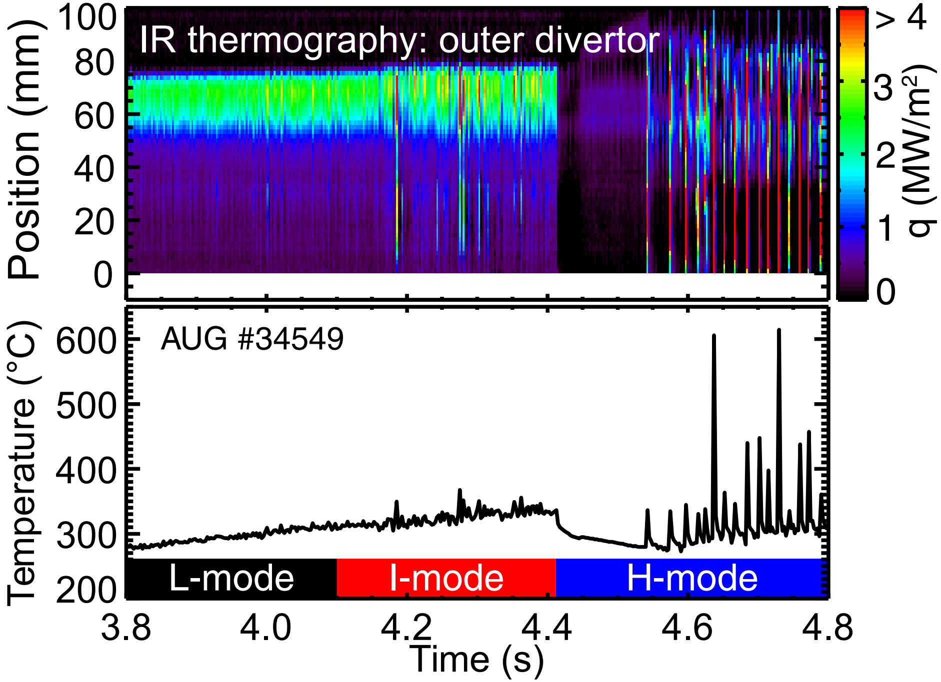


- λ_q in I-mode between those of L-mode and H-mode.
- Results consistent with C-Mod **[Terry JNM 2013, Brunner NF 2018 & Umansky EX/P6-9 (Thu)]**.
- $\lambda_q \approx 2/7\ \lambda_T \Rightarrow$ Spitzer conductivity.
- λ_n (L-mode) $\approx$ λ_n (I-mode) > λ_n (H-mode)
- λ_T (L-mode) > λ_T (I-mode) > λ_T (H-mode)
- Reminiscent of pedestal formation in temperature, but not density
  [Sun PPCF, *accepted for publication*,
  [Happel NME 2018, *submitted*].

Bursts deposit their energy during short time windows



- Temperature evolution of divertor tile affected by I-mode events and type-I ELMs.
- Temperature increase due to type-I ELMs up to 300 K.

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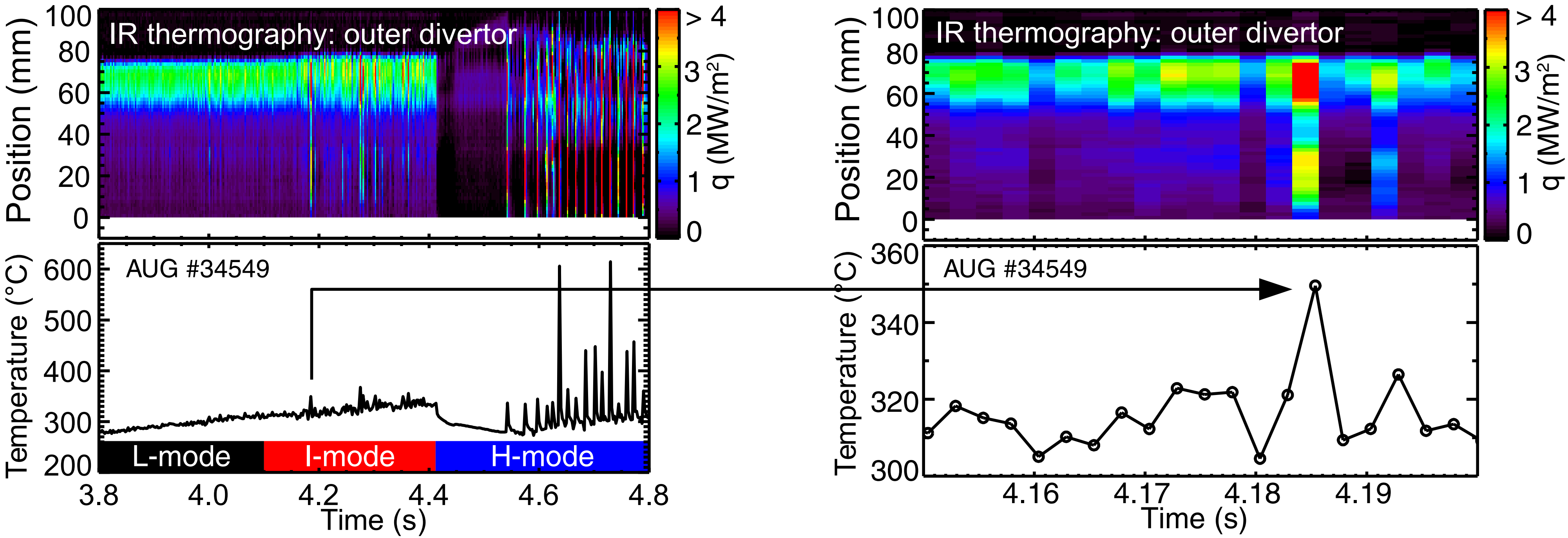

- Temperature evolution of divertor tile affected by I-mode events and type-I ELMs.
- Temperature increase due to type-I ELMs up to 300 K.
- Temperature increase due to burst at least 20 K.
- Uncertainty due to limited IR time resolution (IR: 2.5 ms [5 μs exposure] vs. burst ~ 50 μs).

Summary

- The I-mode confinement regime combines good energy confinement with L-mode like particle transport and no ELMs.
- Stationary and robust NBI heated I-modes achieved.
- Parameter space extended to higher densities (absolute and GW).
- λ_q from stationary heat loads is between those of L-mode and H-mode.
- Transient events linked to the WCM generate divertor heat loads.
- In 2019, AUG foresees experiments on I-mode detachment and pellet fuelling.