The I-phase and its relation to other phenomena at AUG

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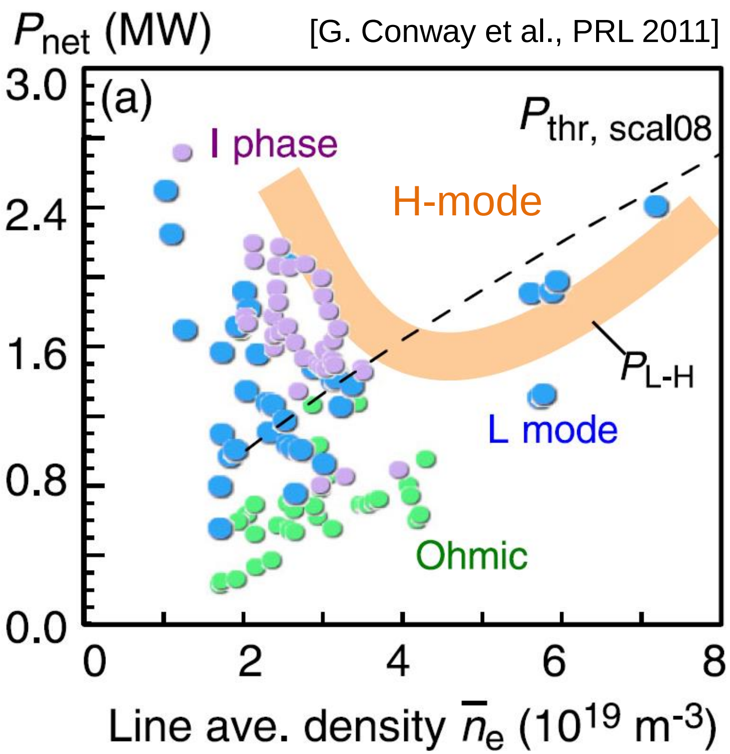
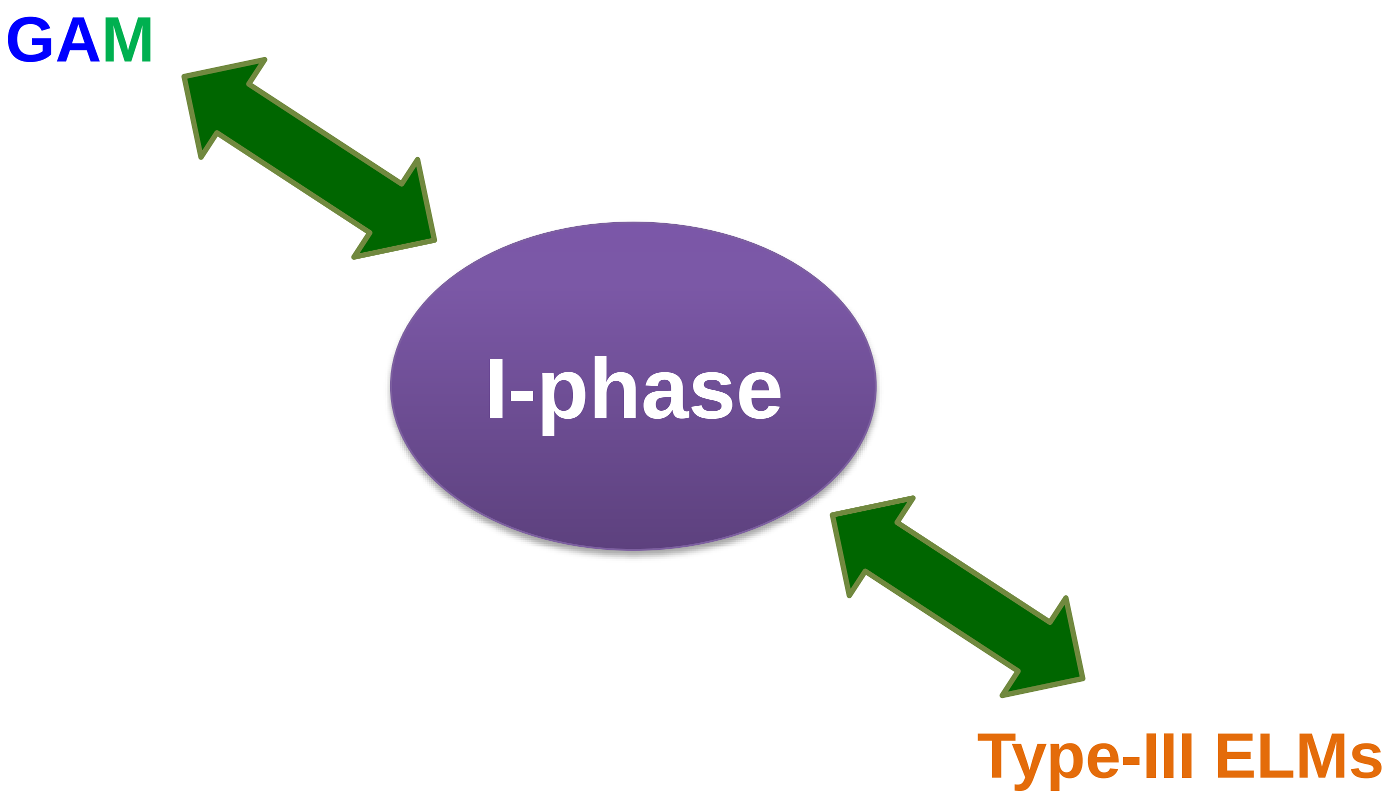
E. Wolfrum, U. Stroth, H. Zohm, and the ASDEX Upgrade Team

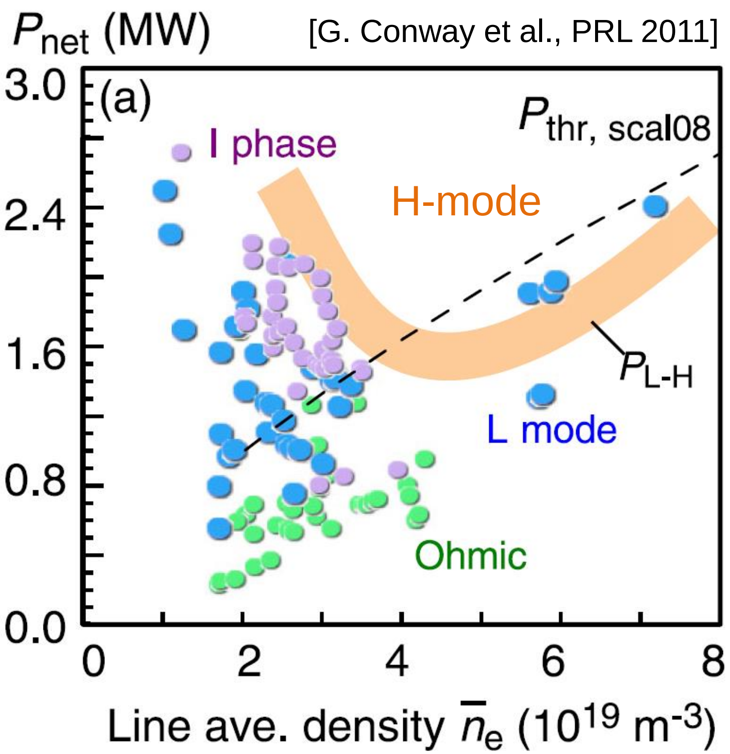
Motivation



P_{net} (MW)
[G. Conway et al., PRL 2011]
(a)
I phase
$P_{thr, scal08}$
H-mode
$P_{L\text{-}H}$
L mode
Ohmic
3.0
2.4
1.6
0.8
0.0
0
2
4
6
8
Line ave. density $\bar{n}_e$ (10^{19} m^{-3})



GAM
I-phase
Type-III ELMs



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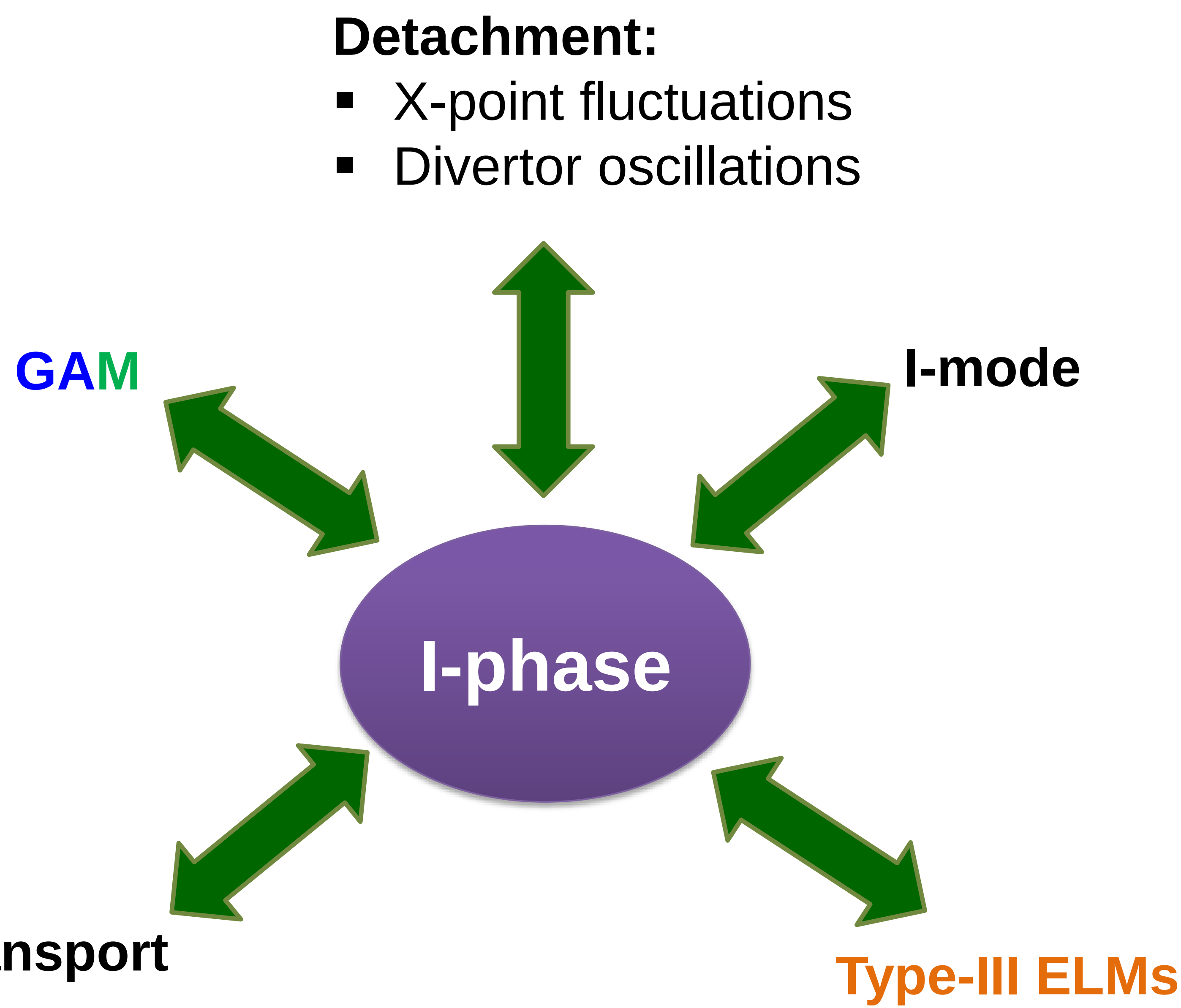


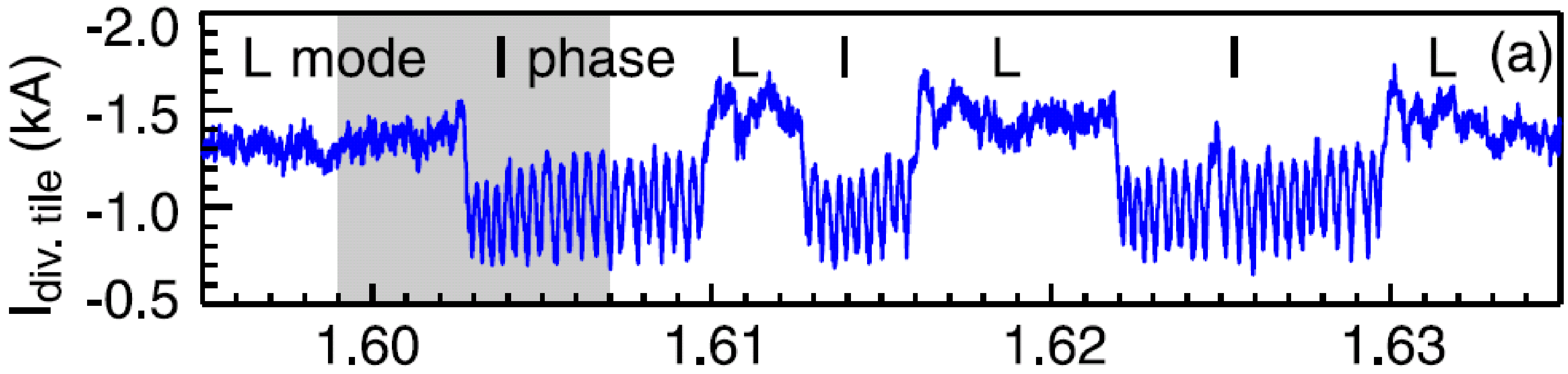
Detachment:
- X-point fluctuations
- Divertor oscillations
GAM
I-mode
I-phase
SOL-transport
Type-III ELMs

Outline

- The I-phase at low density: coexistence with GAM
- I-phase and its appearance in the SOL
- I-phase and divertor detachment
- I-phase vs. type-III ELMs
- I-phase vs. I-mode
- Summary and discussion

The I-phase at low density

[Conway et al., PRL 2011]



Definition of I-phase (Conway 2011):

- Turbulence pulsating at around 2–4 kHz
- L-I transition sharp, I-H transition soft
- pulsing extends across the plasma edge into SOL
- Occurs at low densities (< 5 10^{19} m^{-3})

The I-phase at low density

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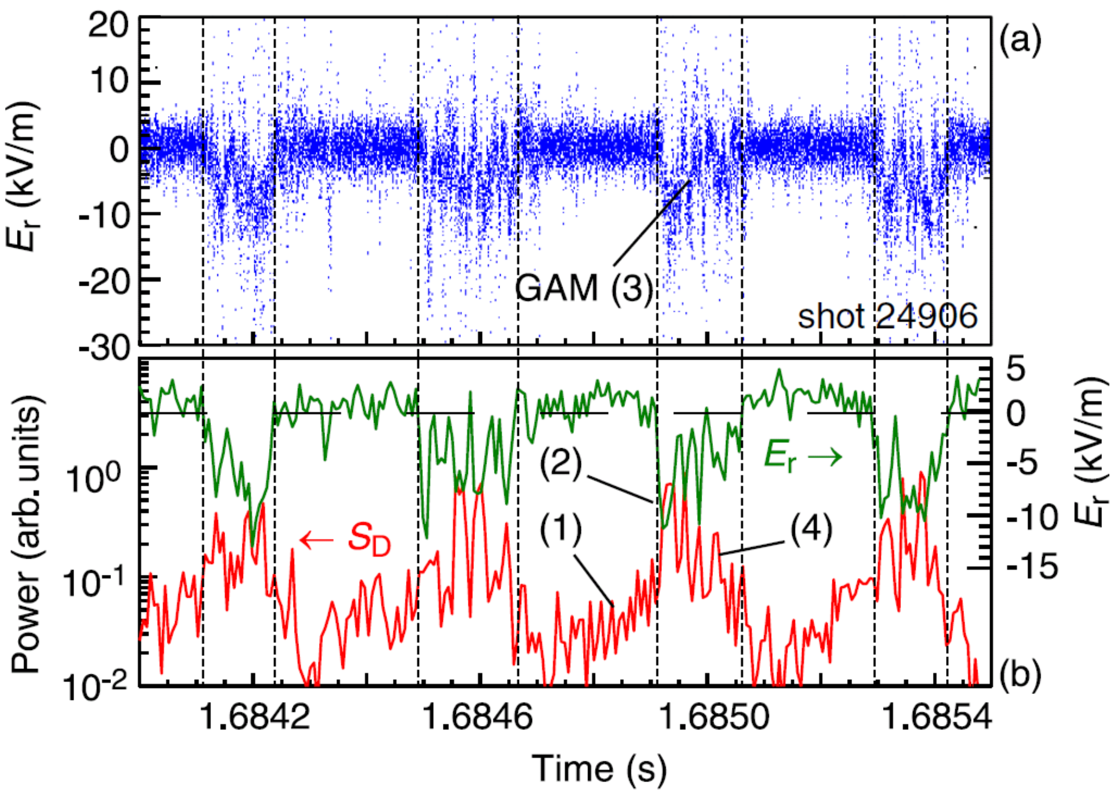

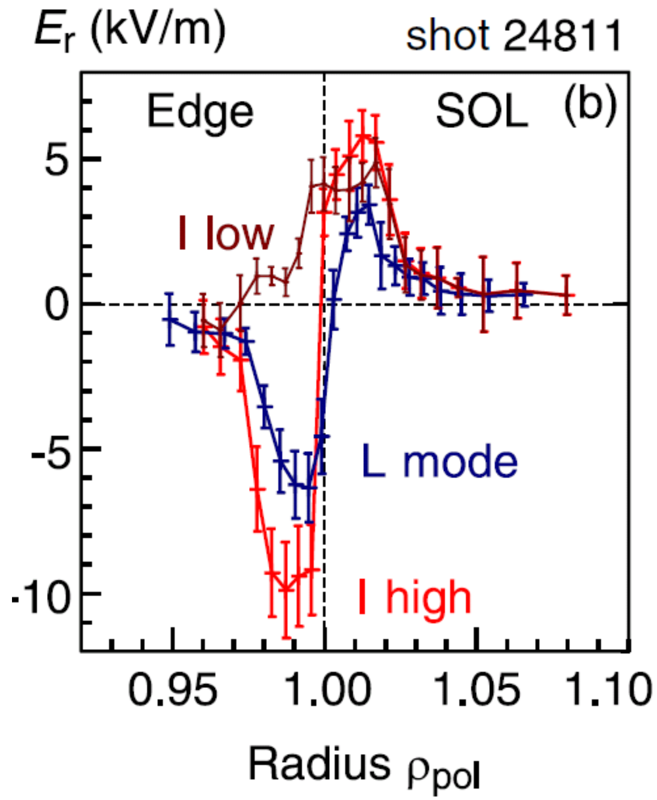

Definition of I-phase (Conway 2011):

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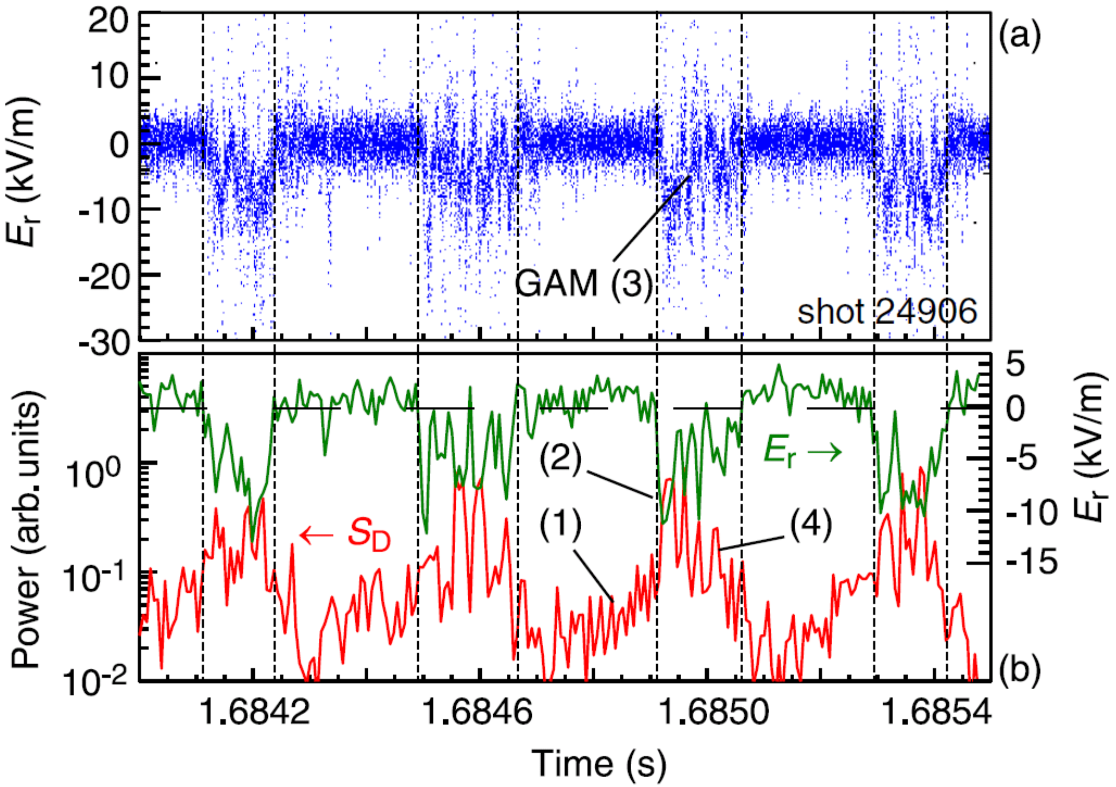

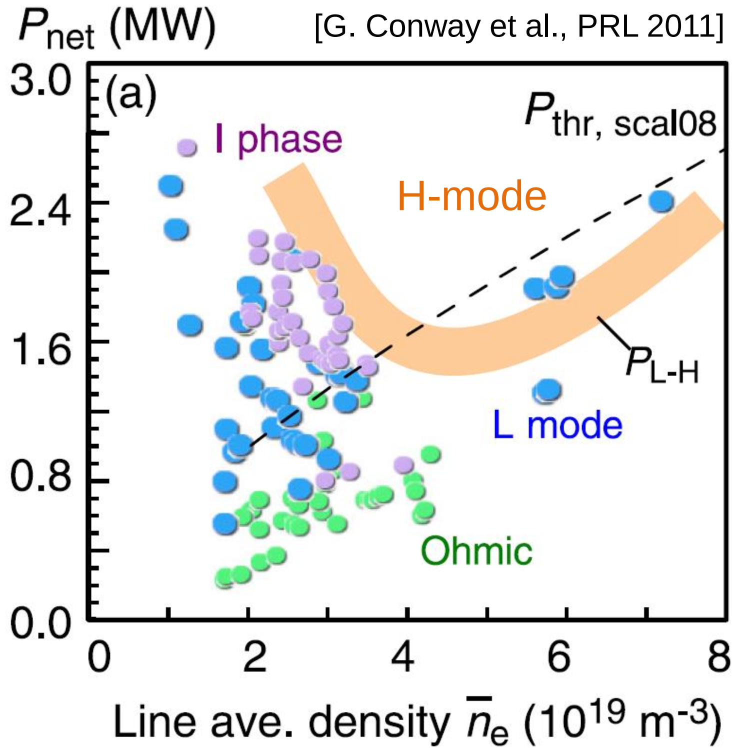

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Possible role of I-phase in LH transition (low density)

Turbulence suppression by shear:

- Turbulence correlation rate:

$$\tau_c^{-1}$$

- Mean flow shearing rate:

$$\tau_M^{-1} = \Delta u_\perp / L_r$$

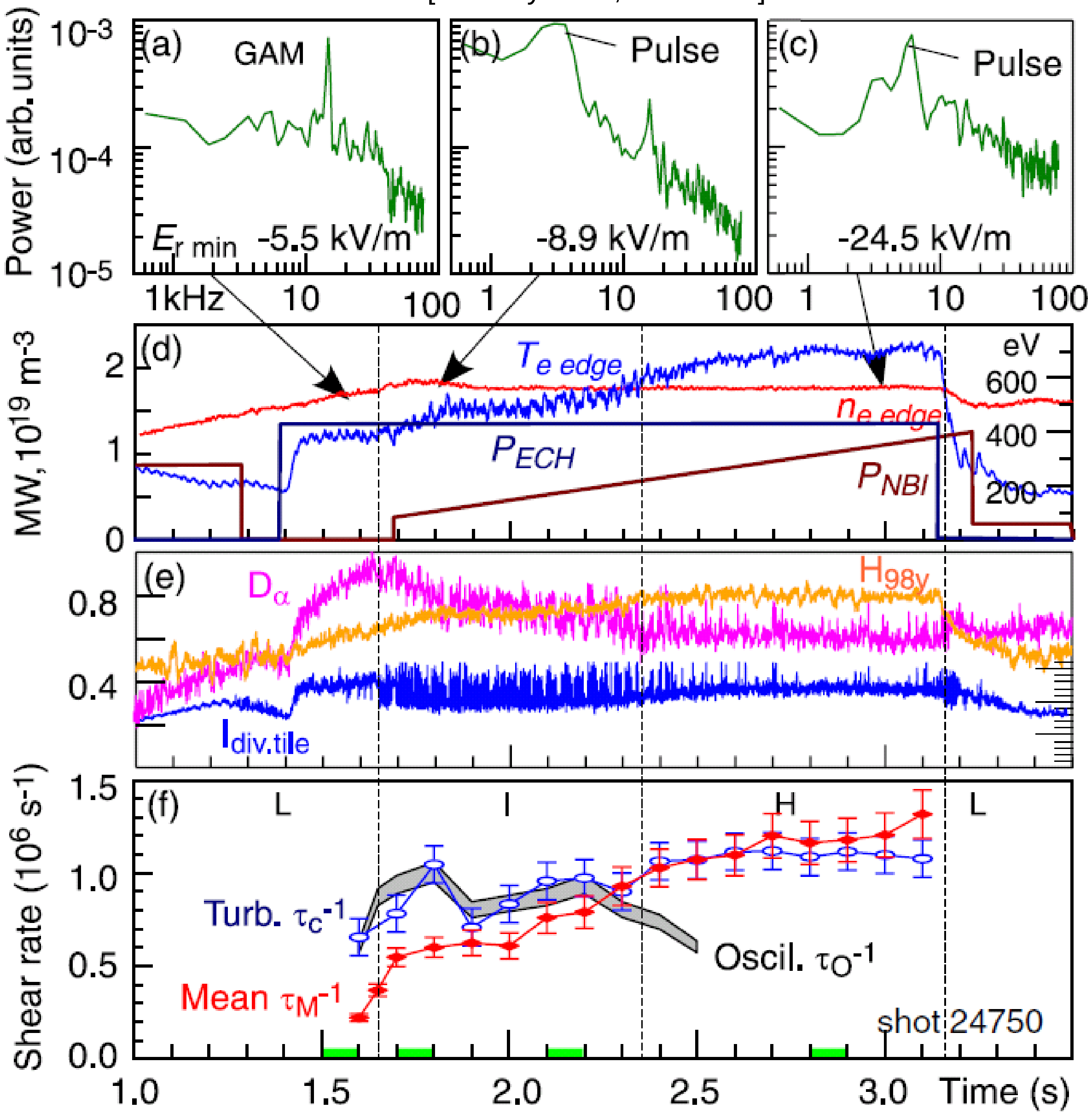
- Oscillatory flow shearing rate:

$$\tau_o^{-1} = \sigma_{u\perp} / L_r$$

Distinction by turbulence suppressor:

- I-phase: oscillatory flow
- H-mode: mean flow

[Conway et al., PRL 2011]

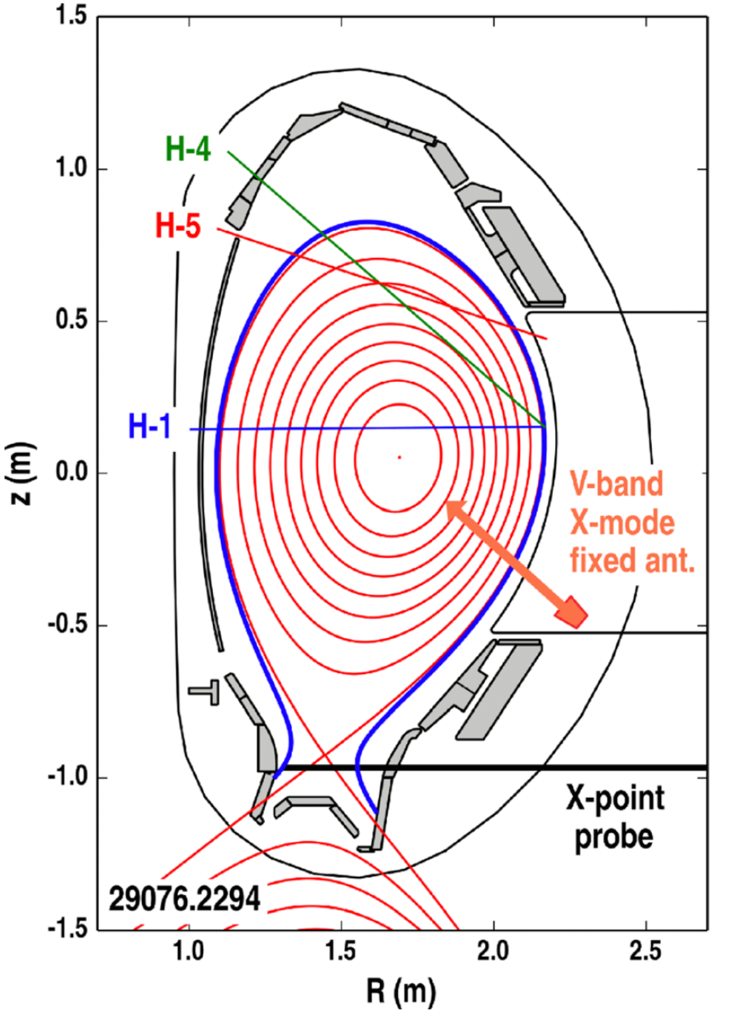


The I-phase and its appearance in the SOL

Measurements with the X-point probe (Müller 2014):

- 2 I_{sat}-pins (Mach probe), 1 pin for characteristics
- Reciprocates horizontally 2-5 cm below the X-point
- Covers LFS, private flux region and HFS

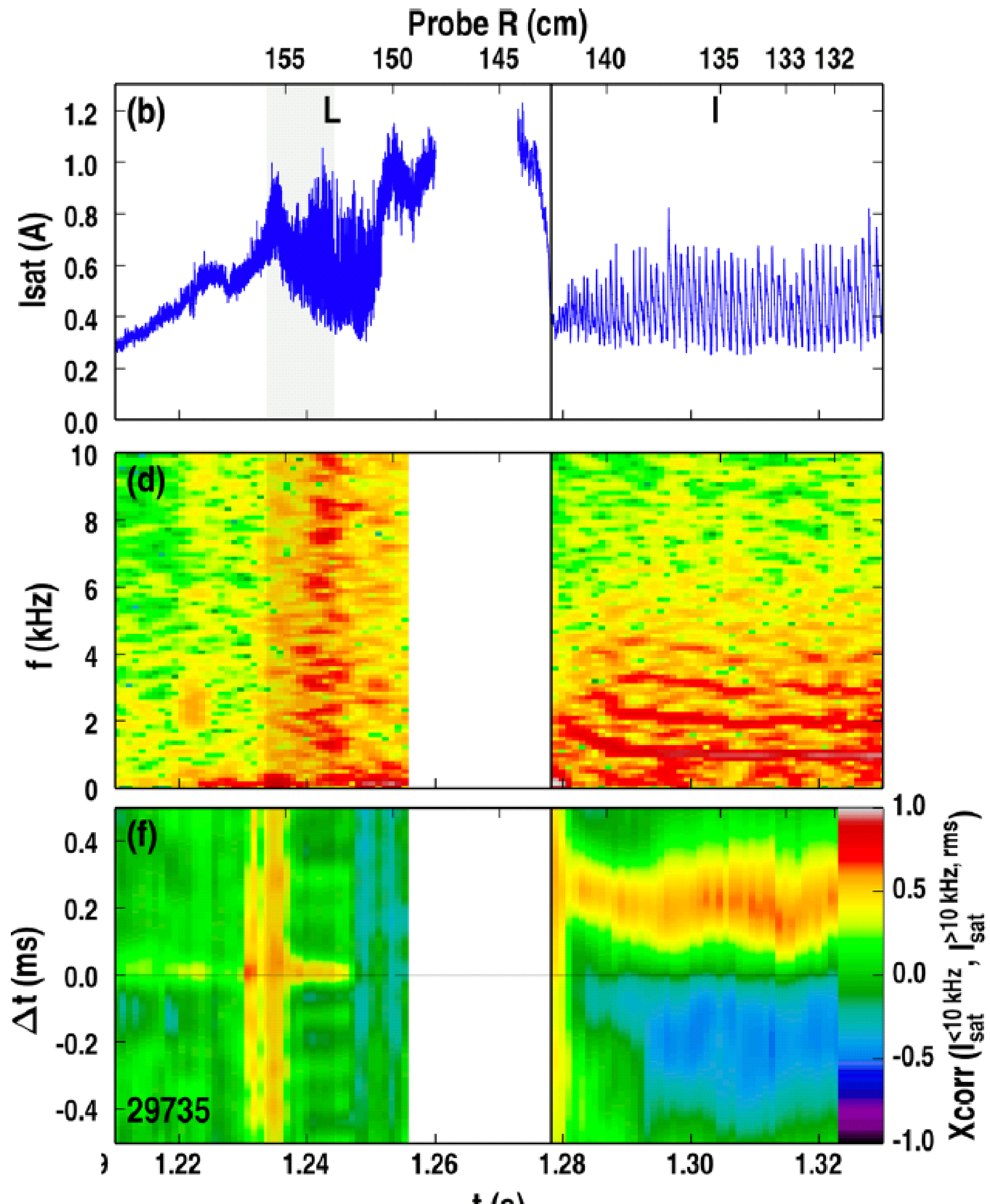
[M. Tsalas et al., J. Nucl. Mater. (2005)]



The I-phase and its appearance in the SOL

Observations (Müller 2014):

- Oscillations in parallel Mach-number (X-point probe)
- Higher harmonics in I_{sat}-signal
- Nice limit cycle between low-f (anti-ZF) and high-f (turb.): type J (ccw)
- Pulsation sometimes absent (non-linear phenomenon)



[Mueller et al., PoP 2014]

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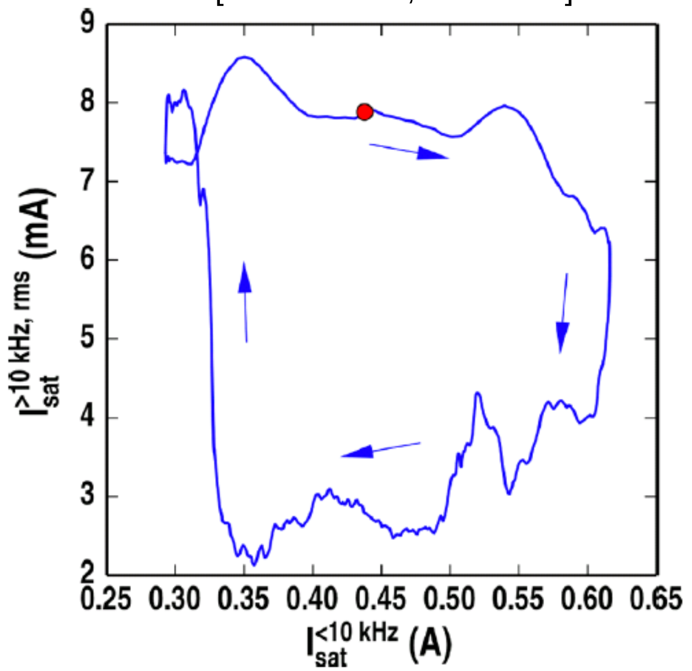
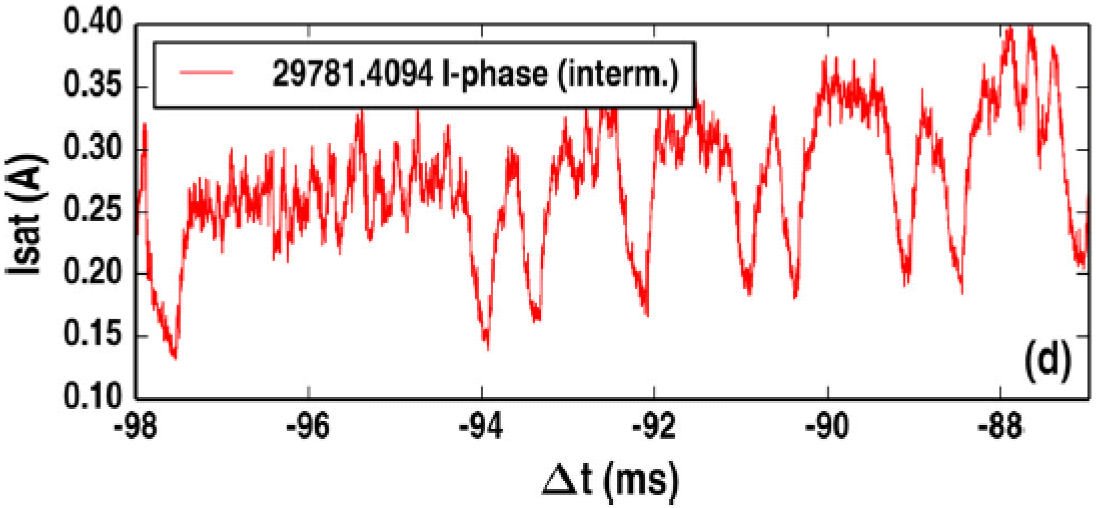
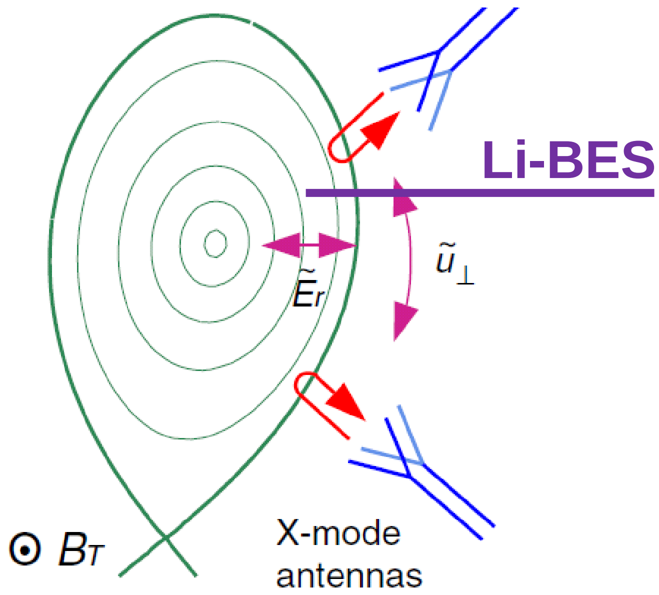
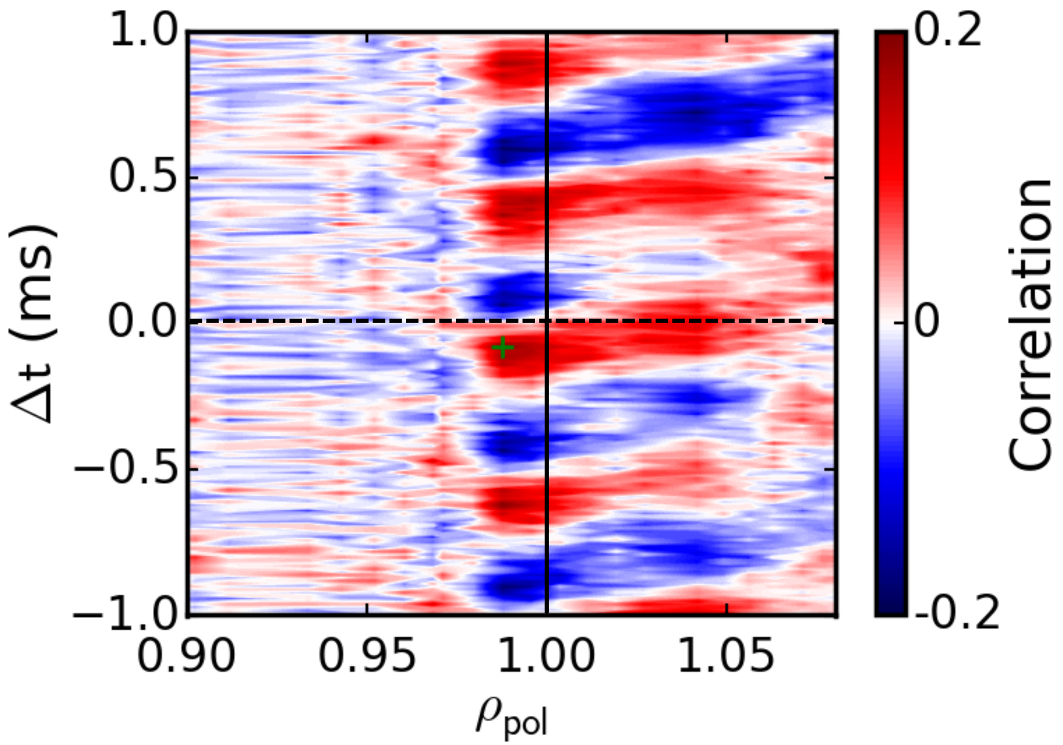




Correlation of Doppler reflectometer with edge density profiles (Li-BES):

- Pulsation in density signal strongest slightly inside the separatrix
- Propagation of pulse to the outside (200-500 m/s)
- Density gradient crashes during I-phase (see M. Cavedon: E_r profile modulated)

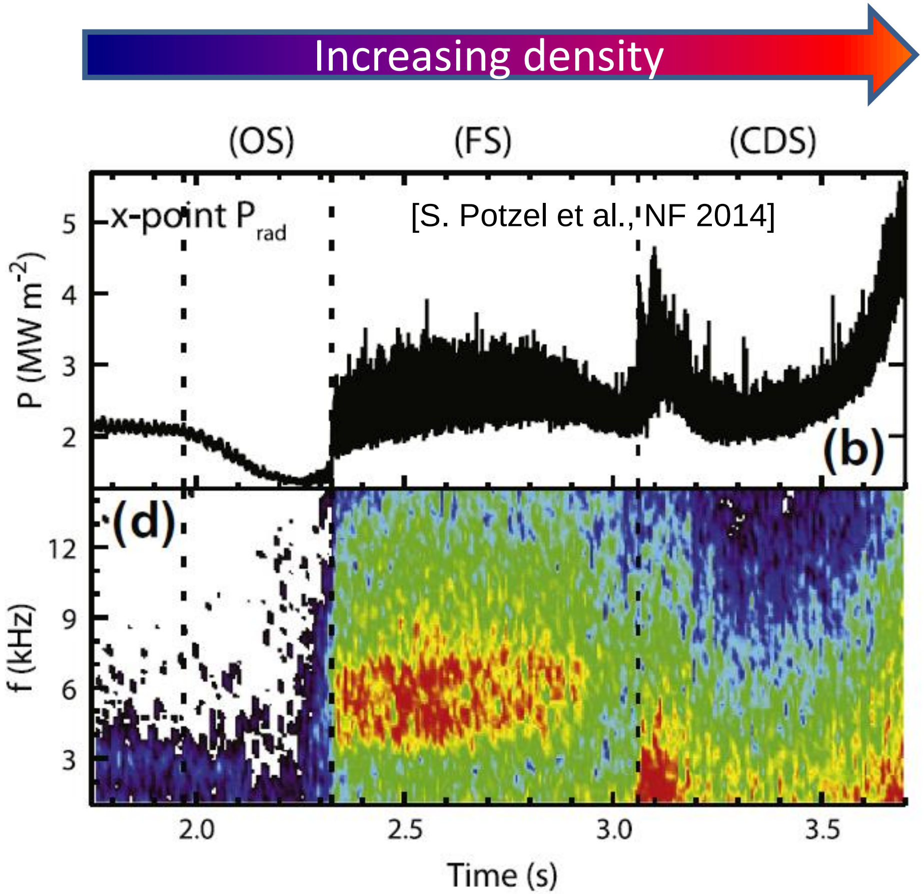


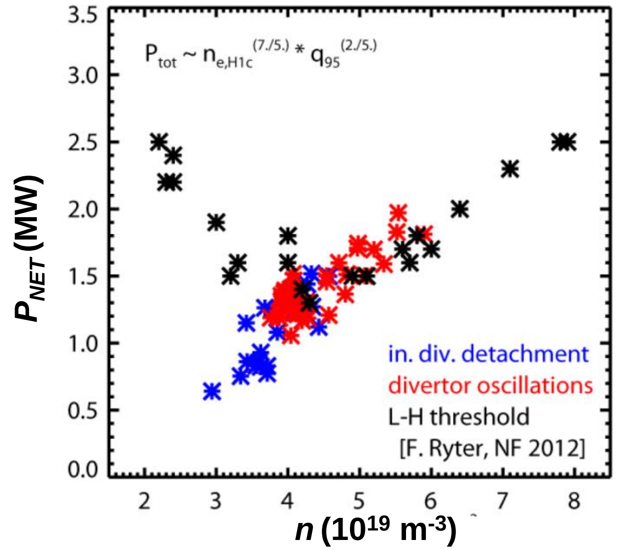


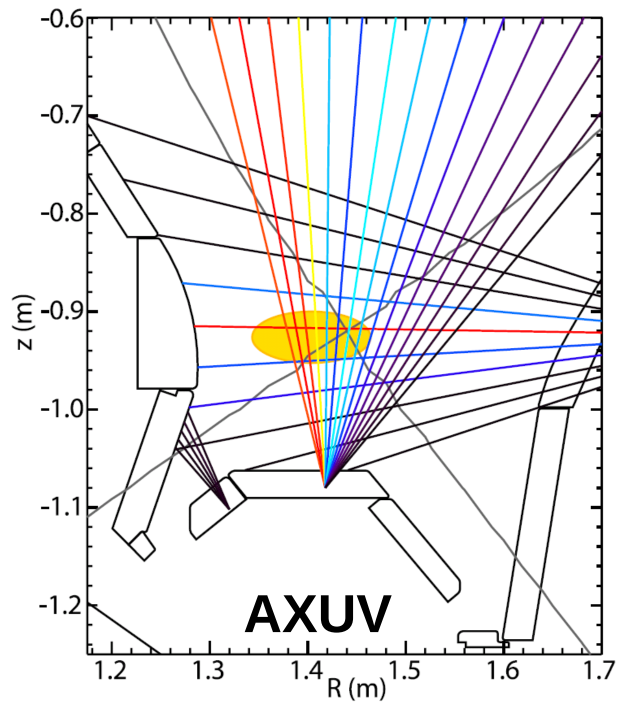
I-phase and detachment

Classification of detachment during density ramps:

- Low density: attached
- Onset of detachment (OS)
- Fluctuating state (FS)
- Complete detachment (CDS)



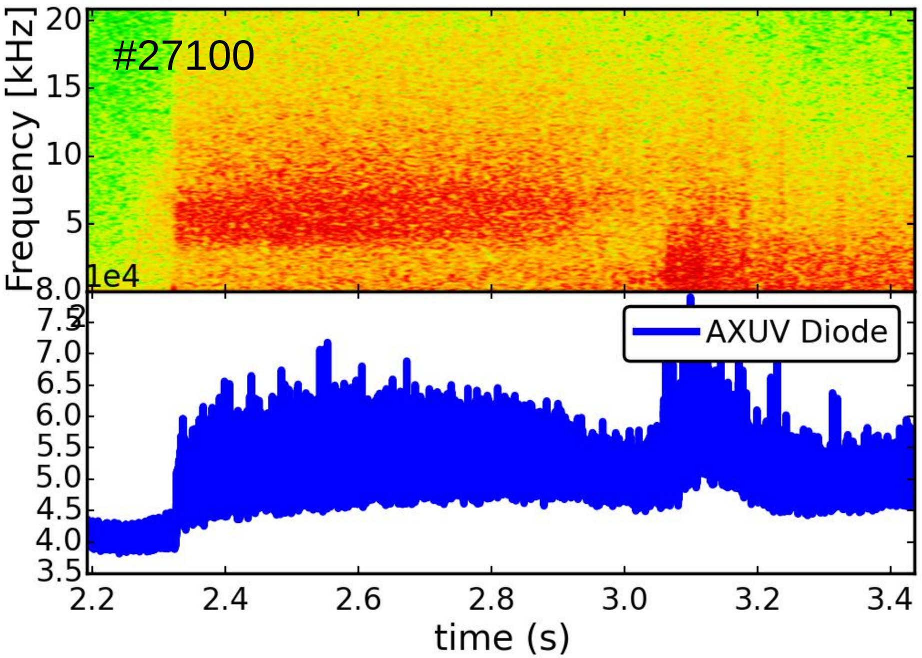




I-phase vs. X-point fluctuations: not the same

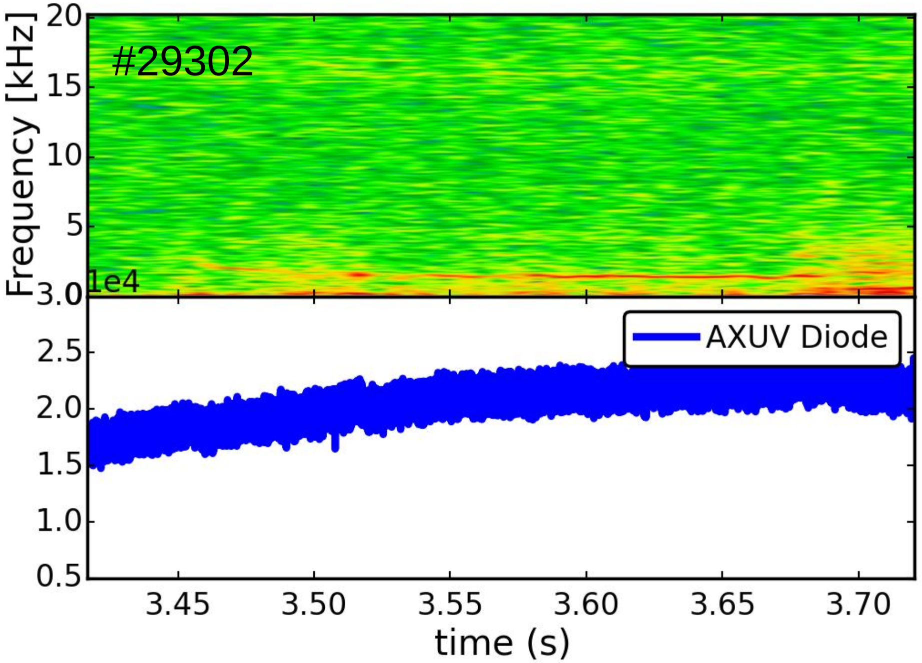
X-point fluctuations:

- Visible in AXUV diode
- Sudden onset
- Broad peak around 5.5 kHz
- Appears when inner divertor is already detached



I-phase:

- Visible in AXUV diode
- Sudden onset
- Localized peak around 2 kHz
- Appears close to LH threshold



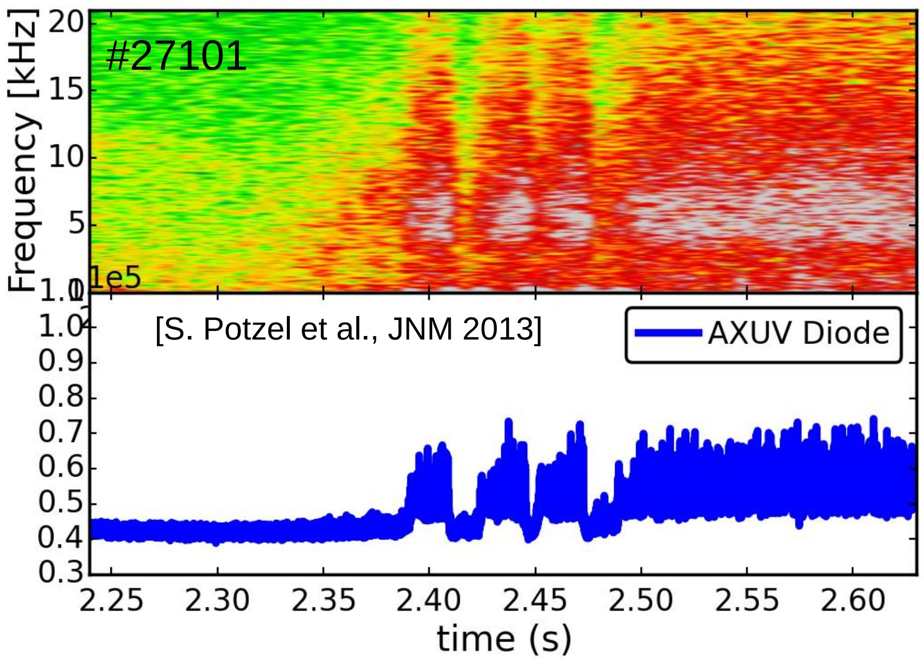
I-phase vs. divertor oscillations: not the same

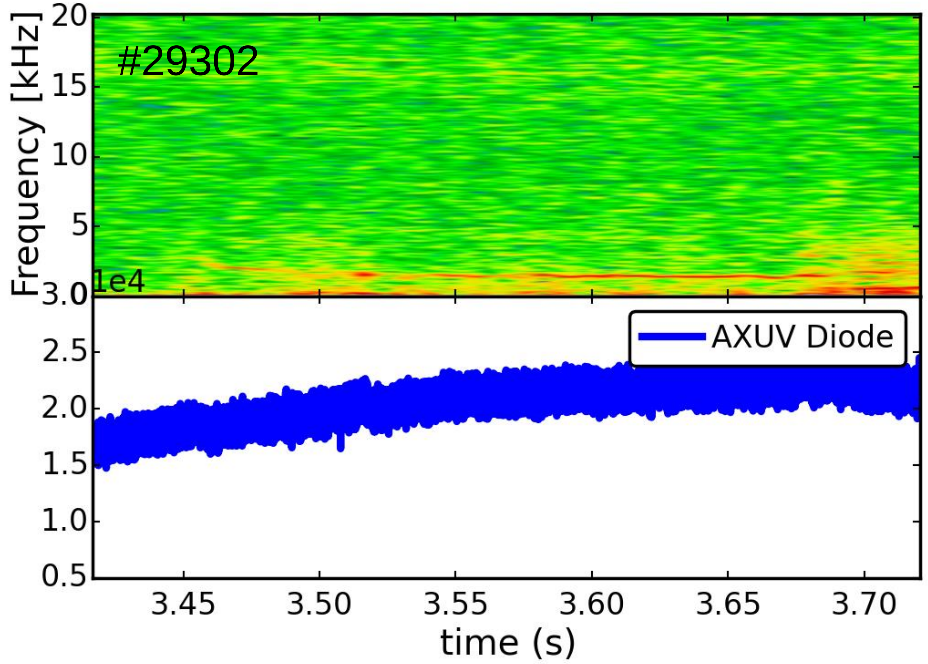
Divertor oscillations:

- Visible in AXUV diode
- Jumps between 2 states
- One state is fluctuation state
- Frequency *f* ~ 50-200 Hz

I-phase:

- Visible in AXUV diode
- Sudden onset
- Localized peak around 2 kHz
- Appears close to LH threshold

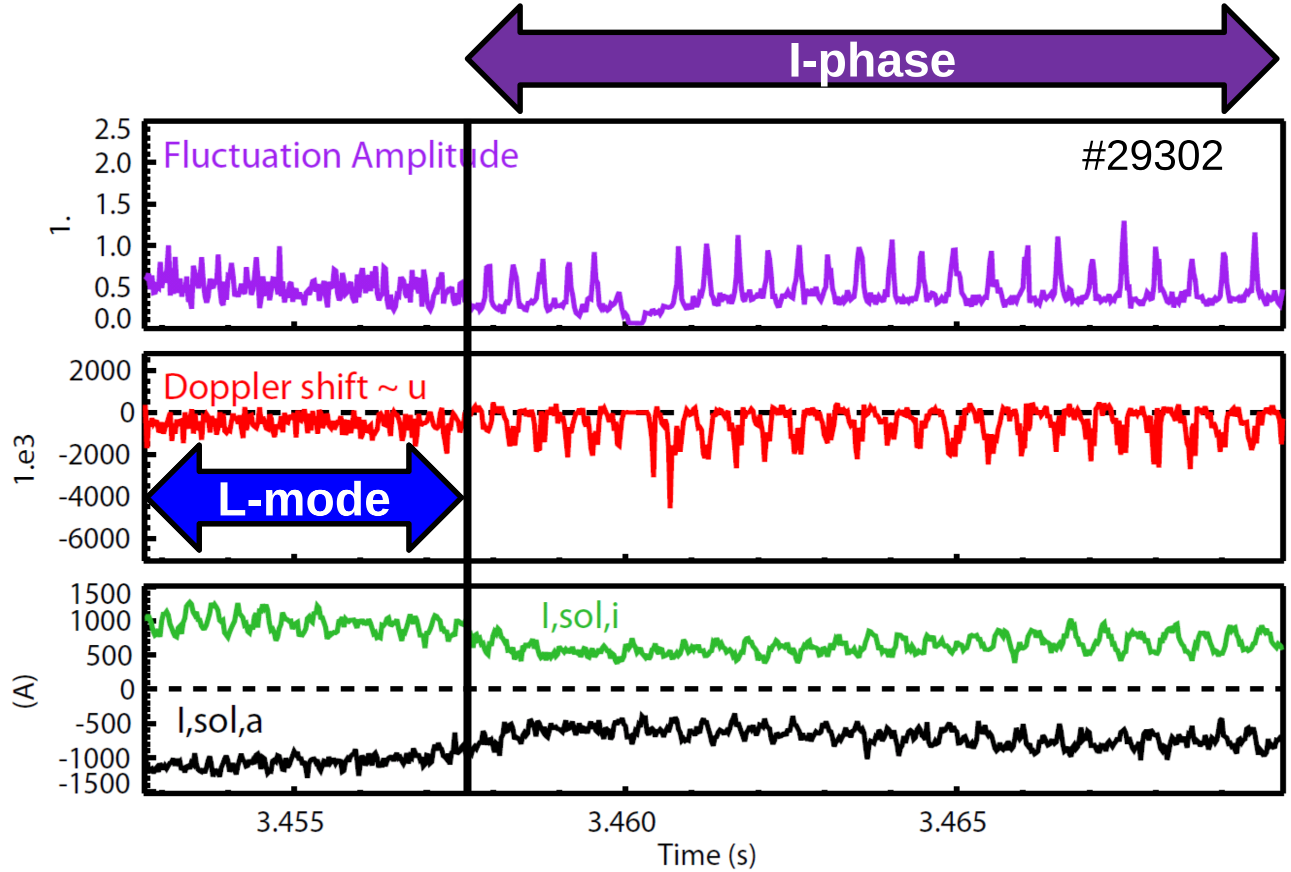




A typical I-phase at medium density

The L-I transition at medium density:

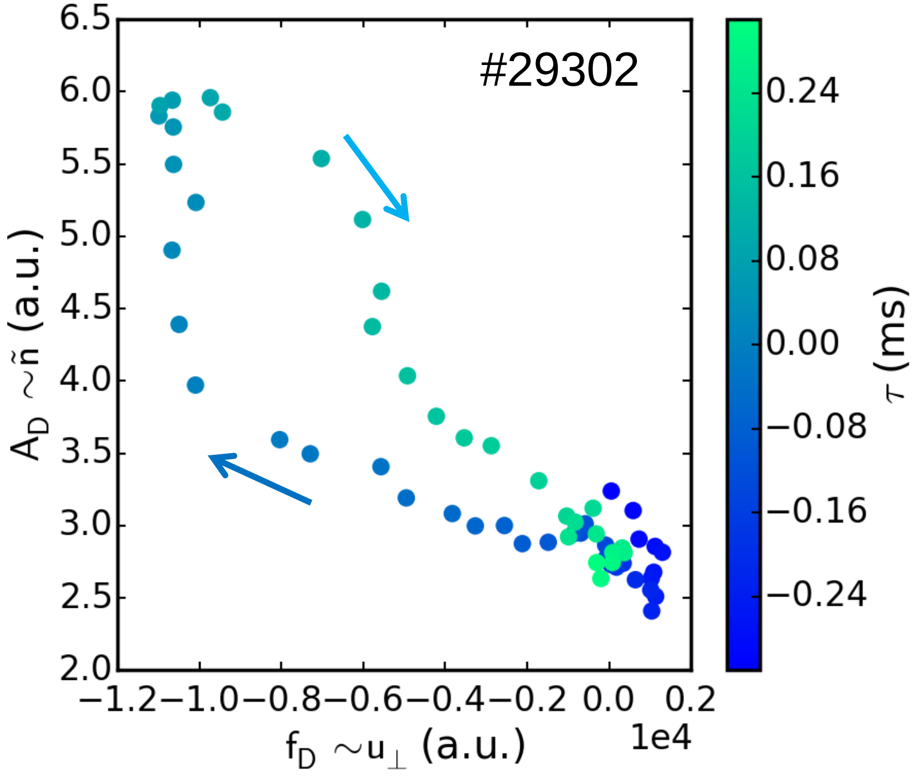
- Drop of divertor current
- Oscillation in poloidal velocity and fluctuation



A typical I-phase at medium density

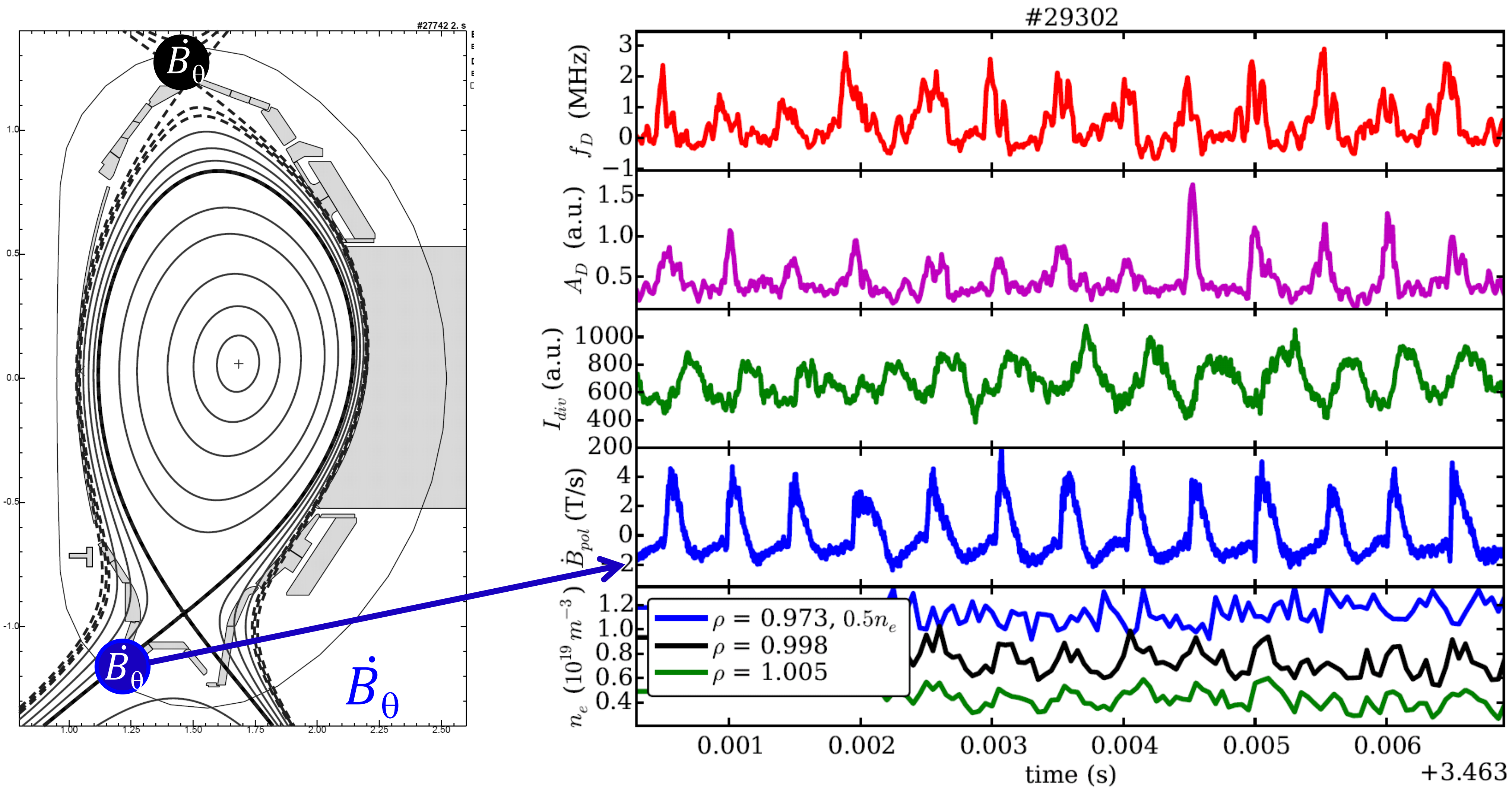
The L-I transition at medium density:

- Drop of divertor current
- Oscillation in poloidal velocity and fluctuation
- Clockwise limit-cycle in phase space
- Zonal flow-turbulence interaction?



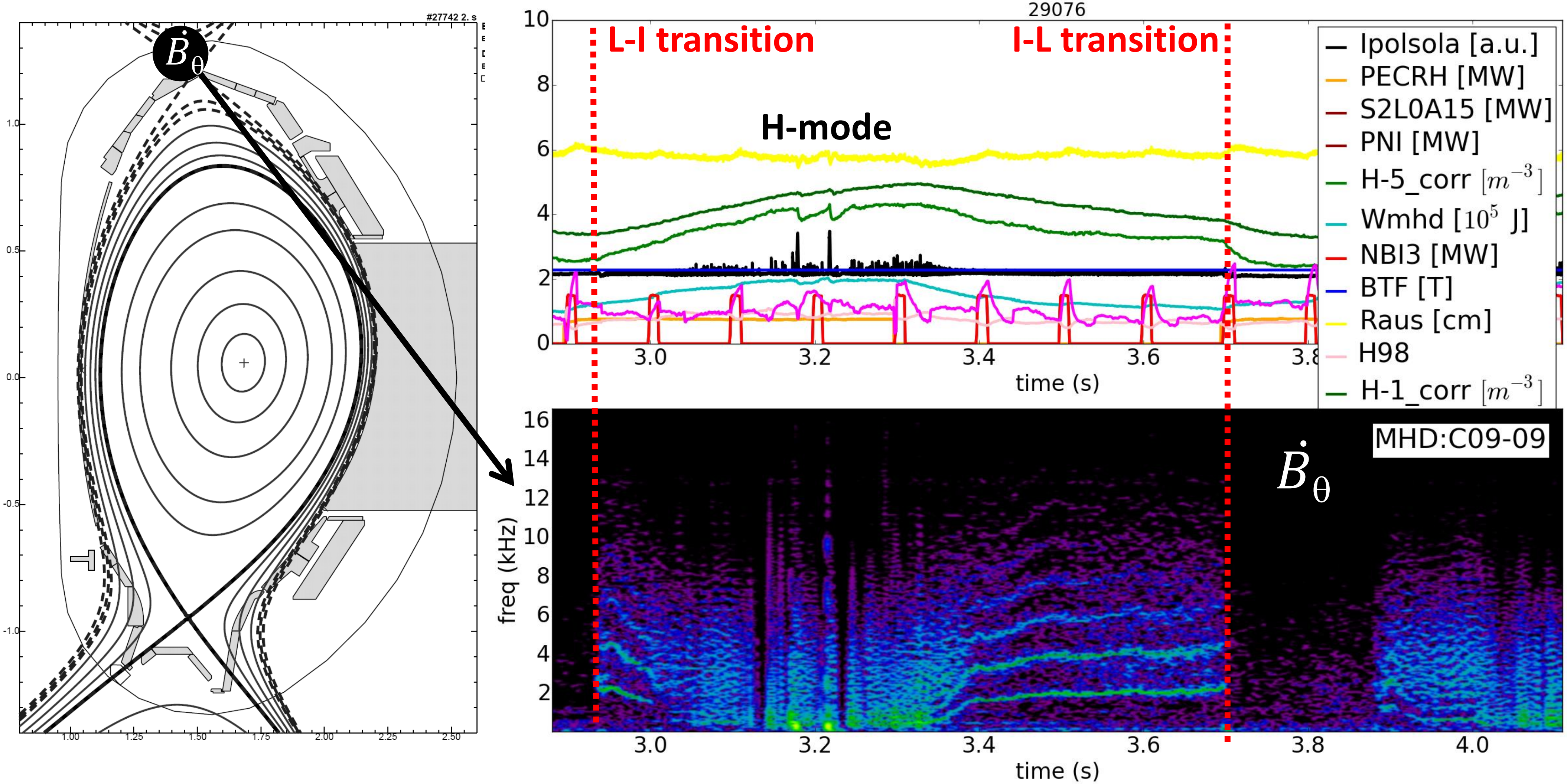
A typical I-phase at medium density

Magnetic signal is strongly correlated with Doppler:



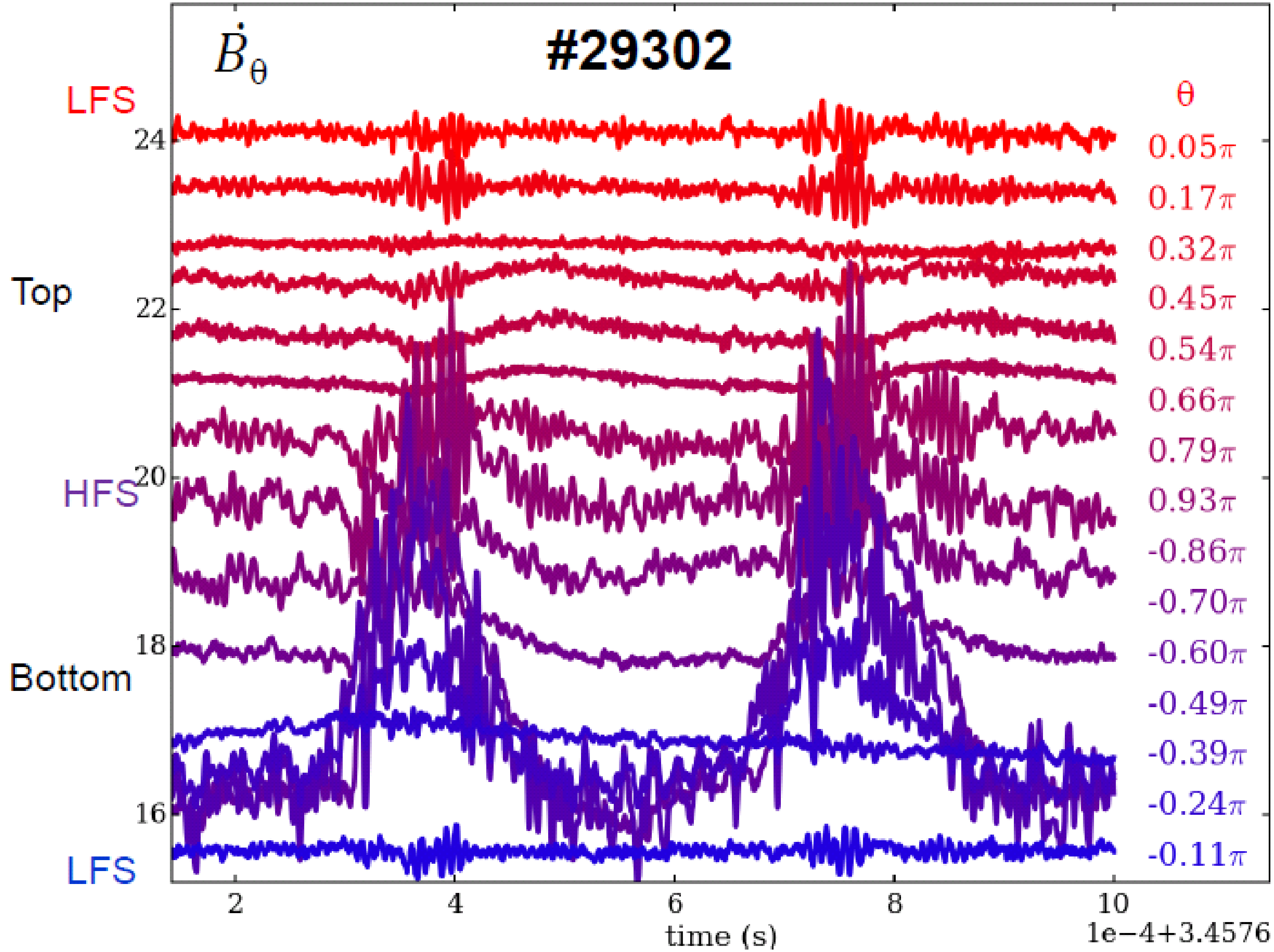
A typical I-phase at medium density

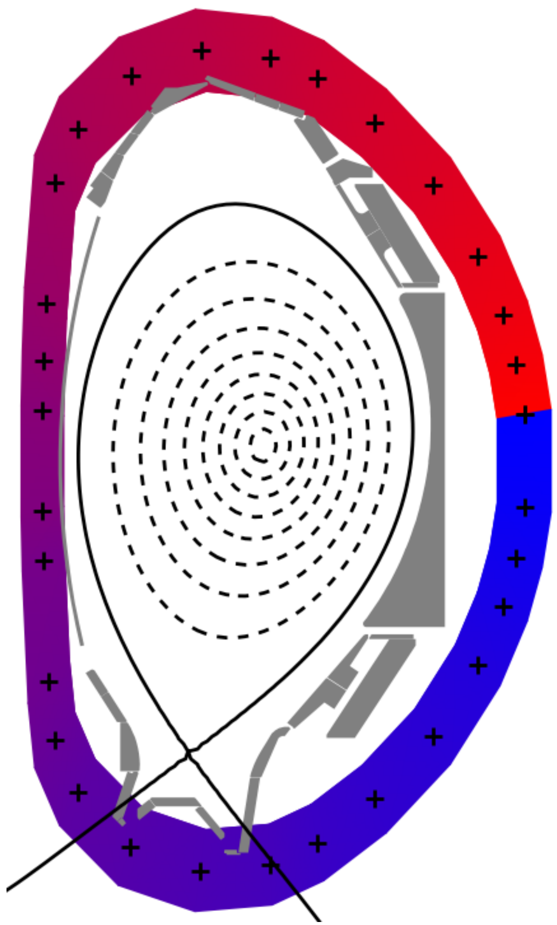
Magnetics signal shows harmonics in spectrogram:



The magnetic structure of the I-phase

Magnetic pulse propagates from X-point along HFS to top:

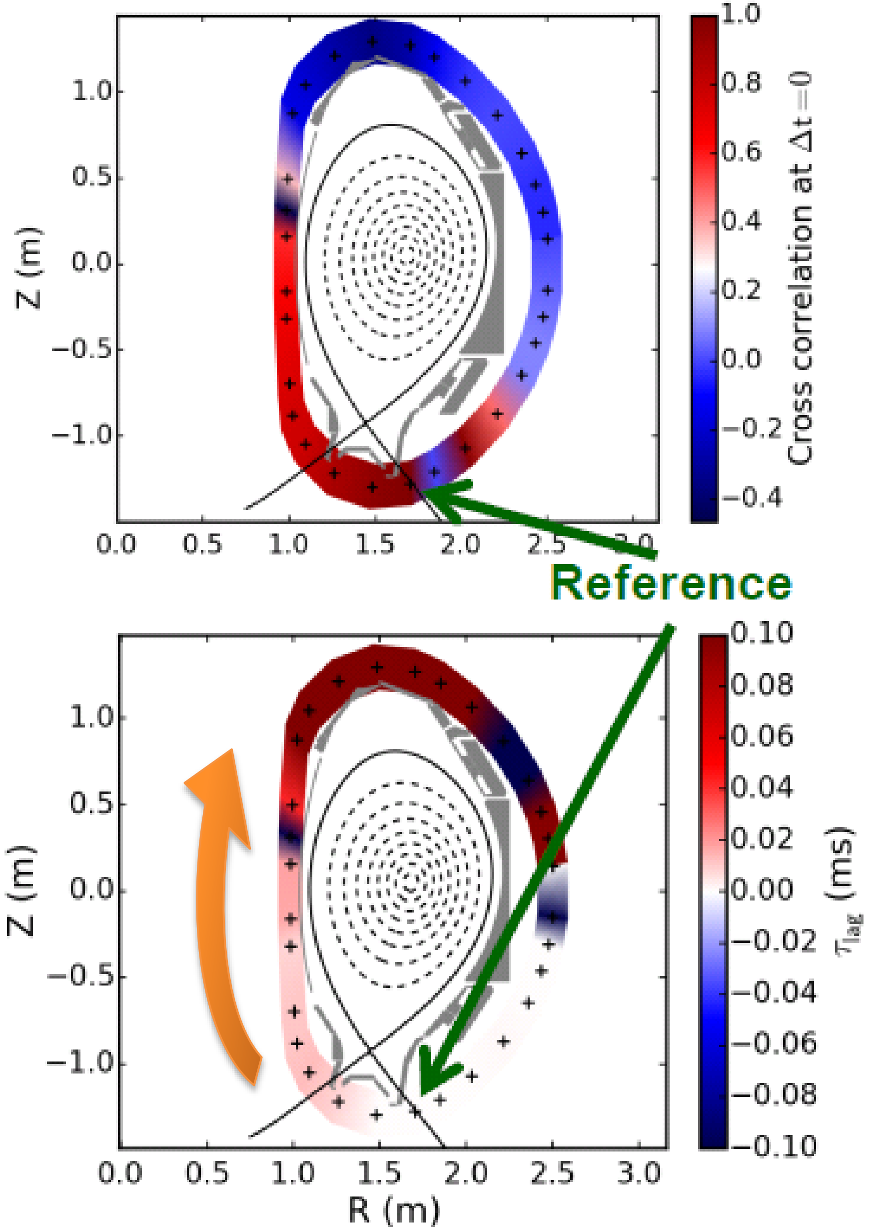




The magnetic structure of the I-phase

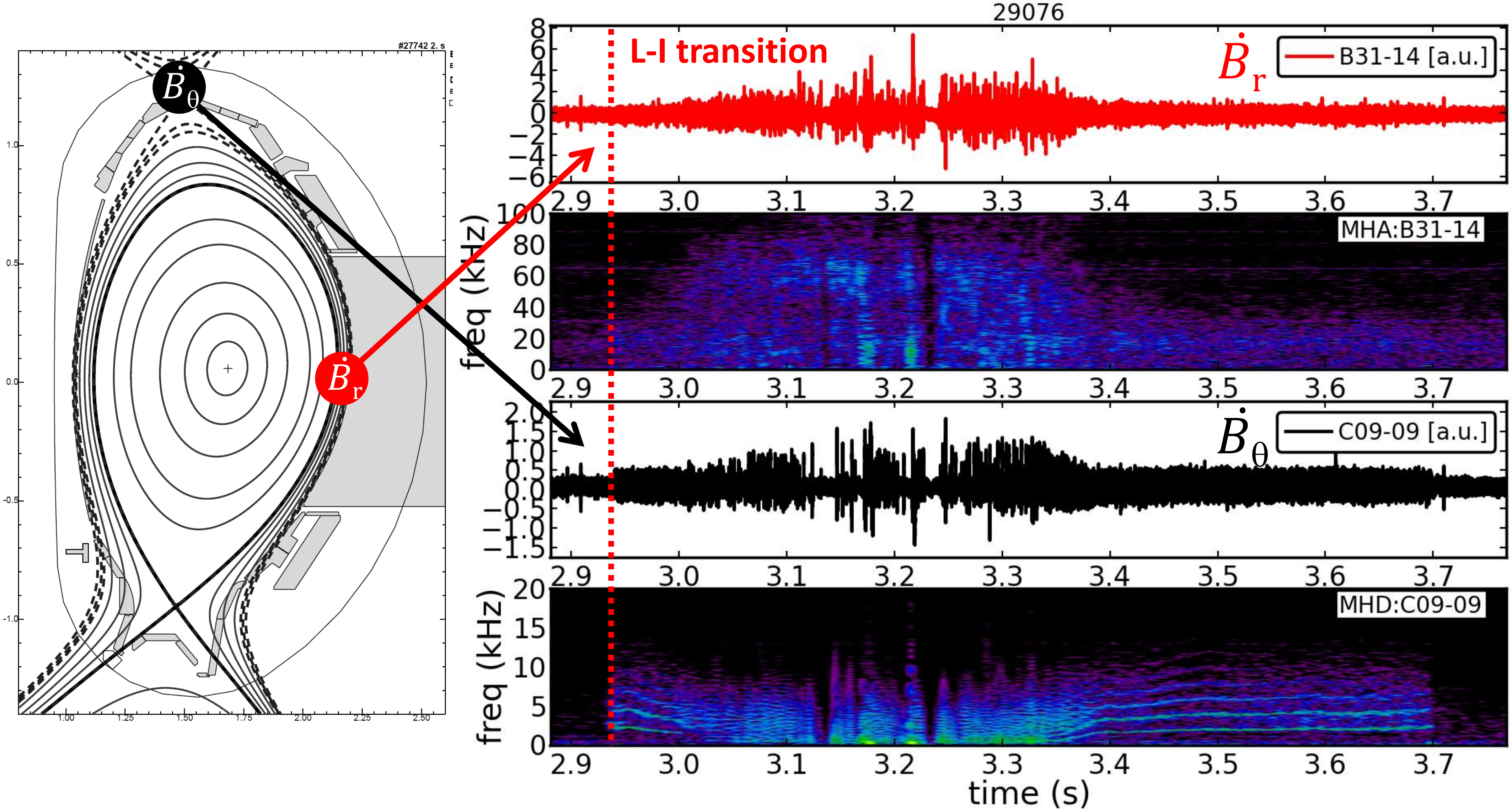
Correlation analysis reveals:

- *m=1* mode structure at $\Delta t = 0$



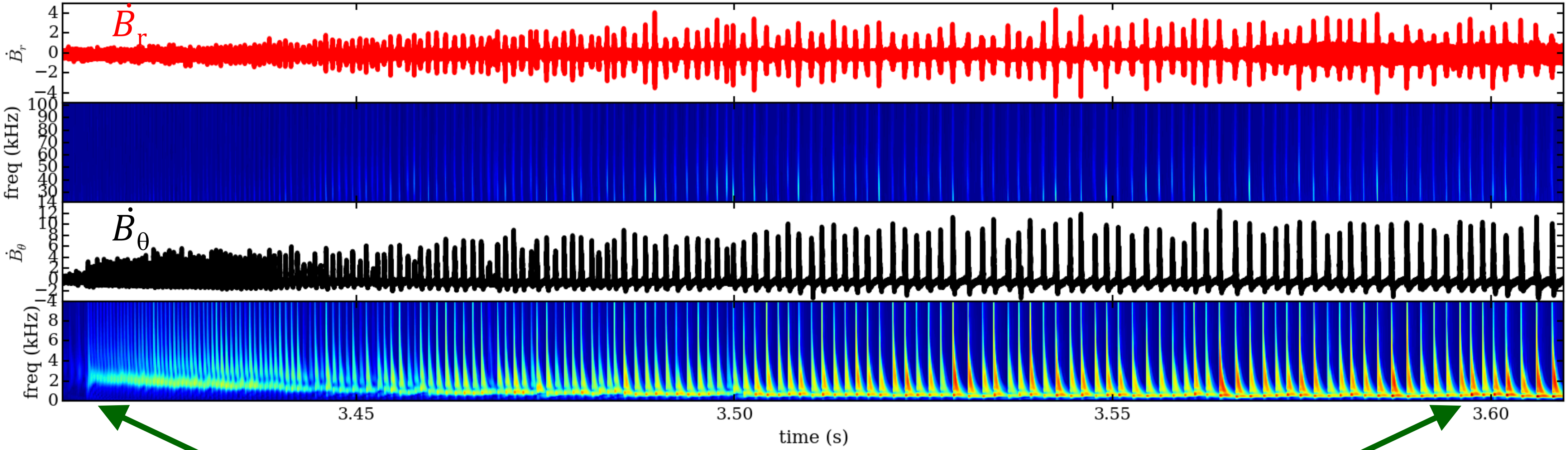
- Propagation velocity ~20 km/s in ion diamagnetic direction
- Dynamics reverses in USN configuration

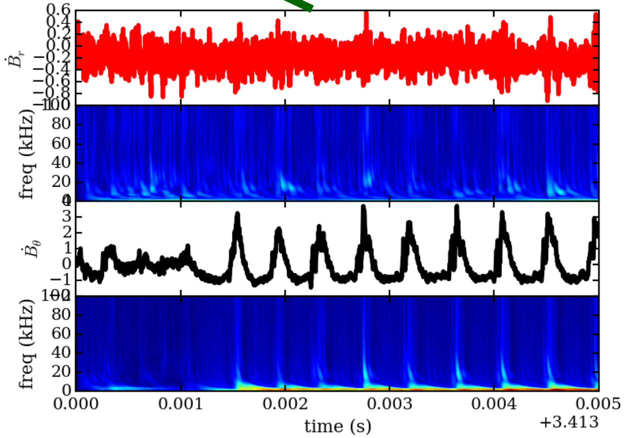
Magnetics signal shows higher harmonics in $\dot{B}_\theta$ but not in $\dot{B}_r$:

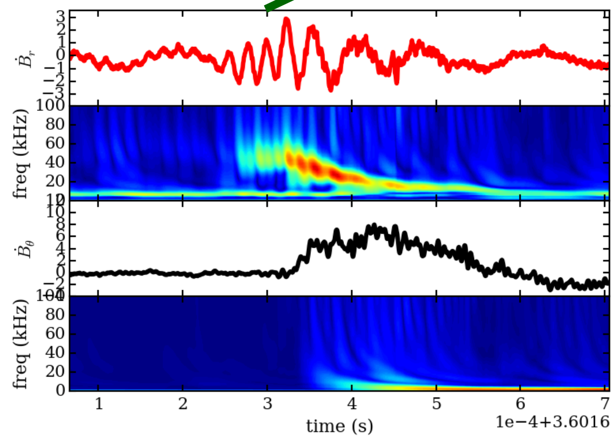


The magnetic structure of the I-phase

Smooth transition to spiky and intermittent phase: precursors in $\dot{B}_r$!







I-phase vs. Type-III ELM

Definitions:

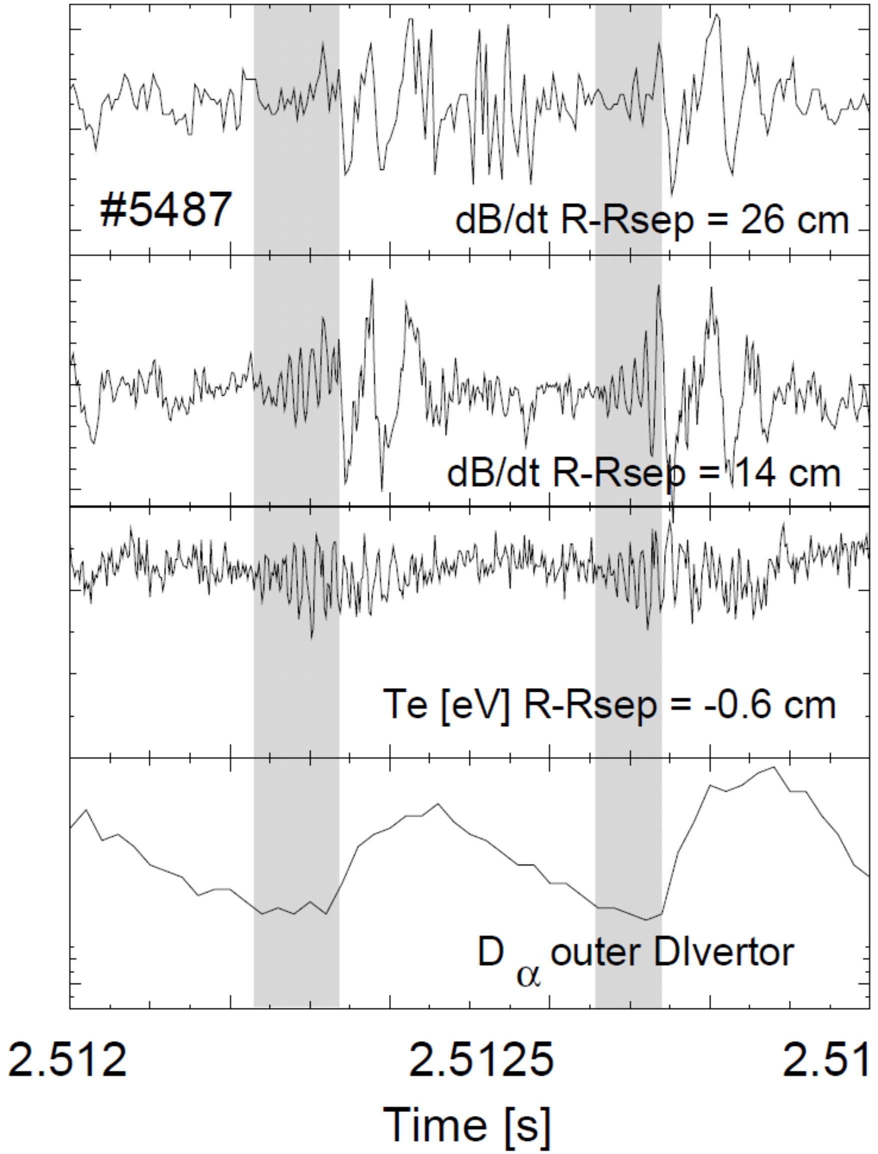
I-phase (Conway 2011):

- Turbulence pulsating at around 2–4 kHz
- L-I transition sharp, I-H transition soft
- pulsing extends across the plasma edge into SOL

Type-III ELM (Zohm 1996):

- Coherent magnetic precursor (f= 50-100 kHz)
- Mode numbers of precursor n=5-10, m=10-15
- ELM frequency decreases with heating power

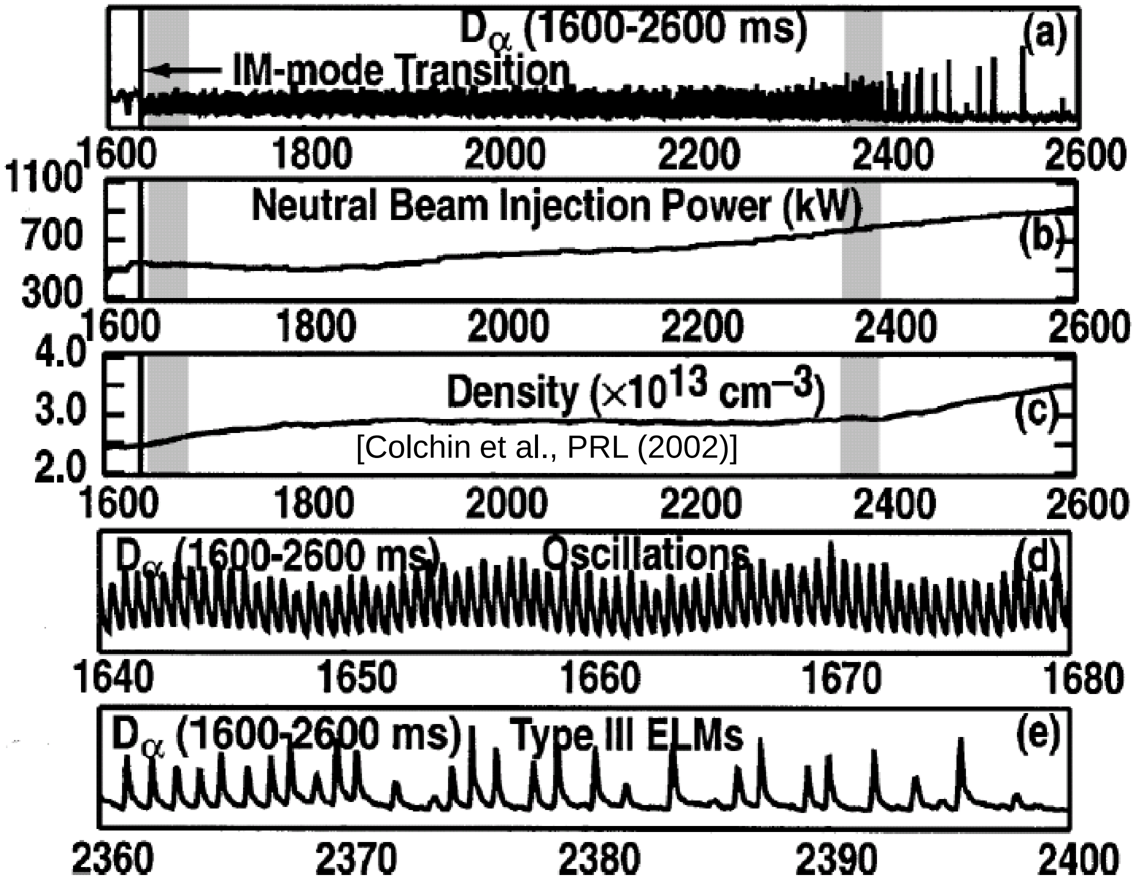
[H. Zohm et al., PPCF 1996]



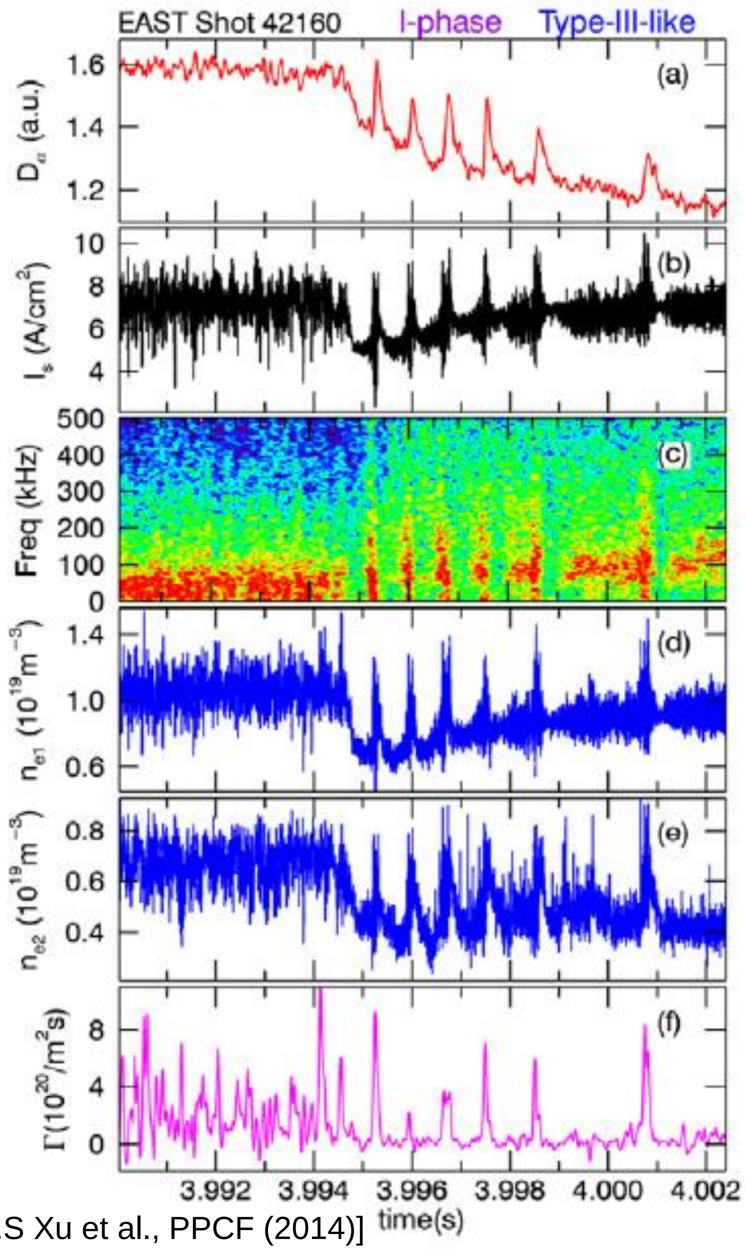
I-phase vs. Type-III ELM

Smooth transition from LCO to Type-III ELM:

- IM-mode in DIII-D (Colchin et al., PRL, 2002)
- I-phase at EAST (G.S. Xu/N. Yan, PPCF, 2014)
- M-mode at JET (E. Solano, EPS, 2013)



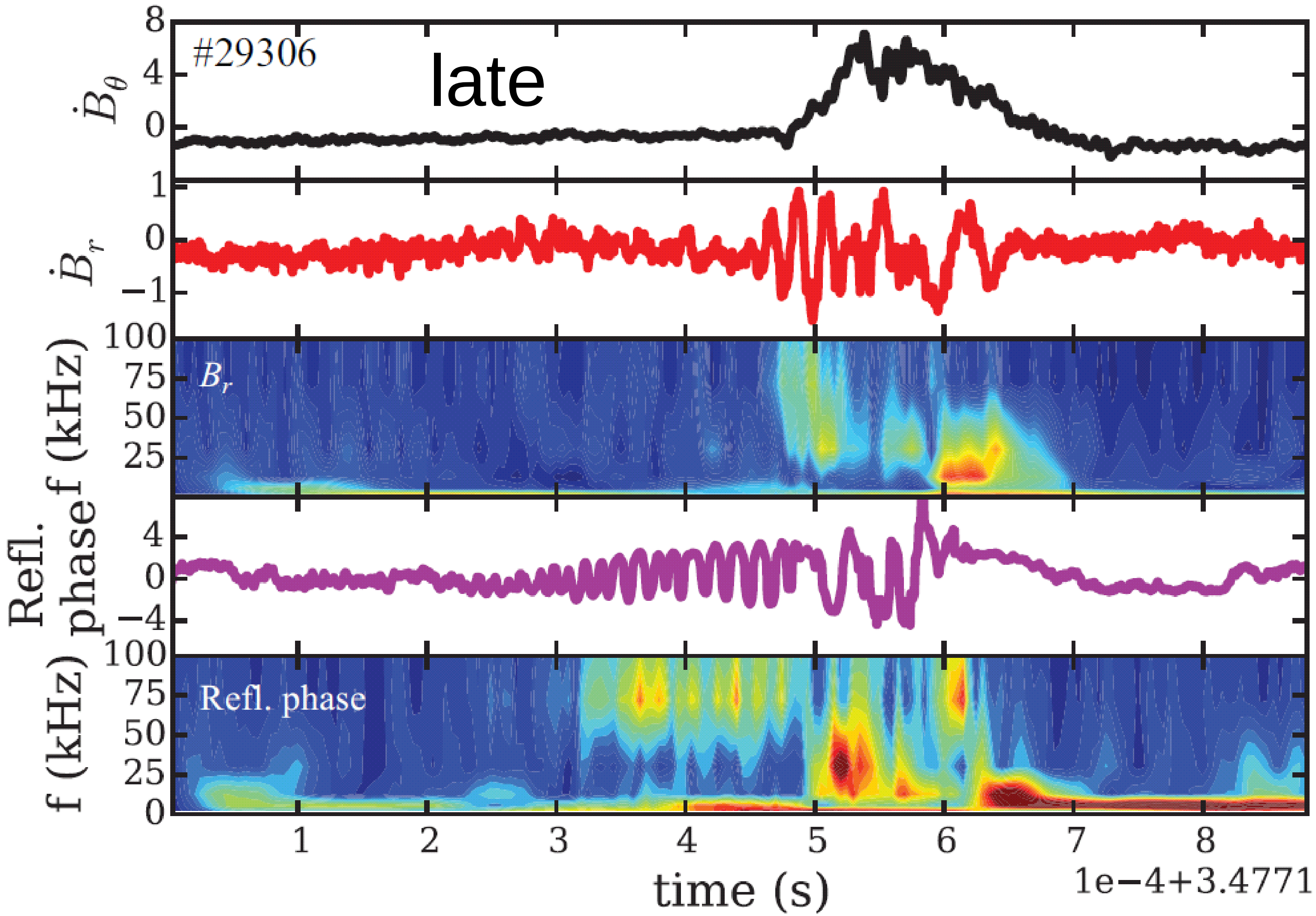
[Colchin et al., PRL (2002)]



[G.S Xu et al., PPCF (2014)]

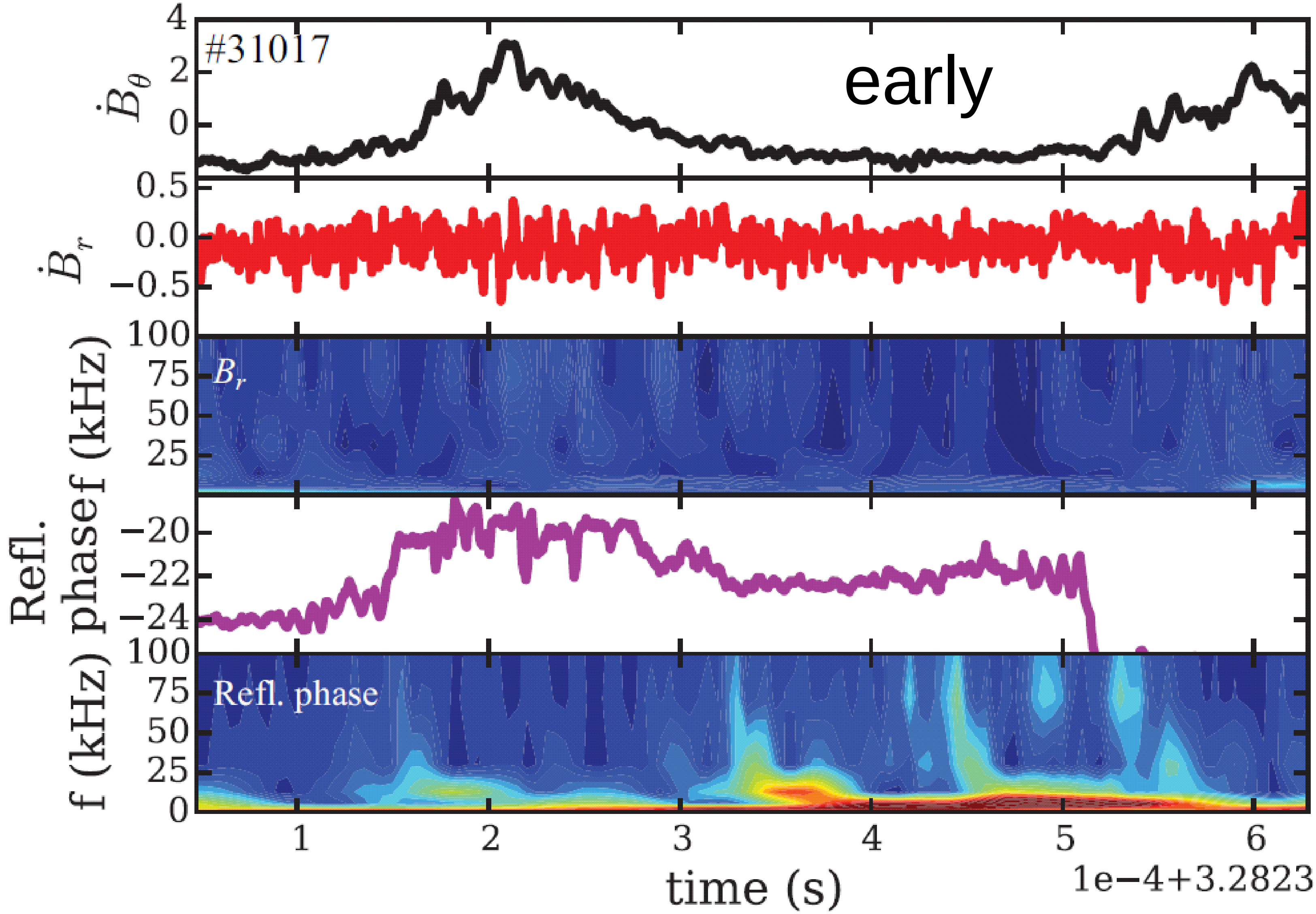
I-phase vs. Type-III ELM

Precursor properties measured with standard reflectometry in late I-phase:



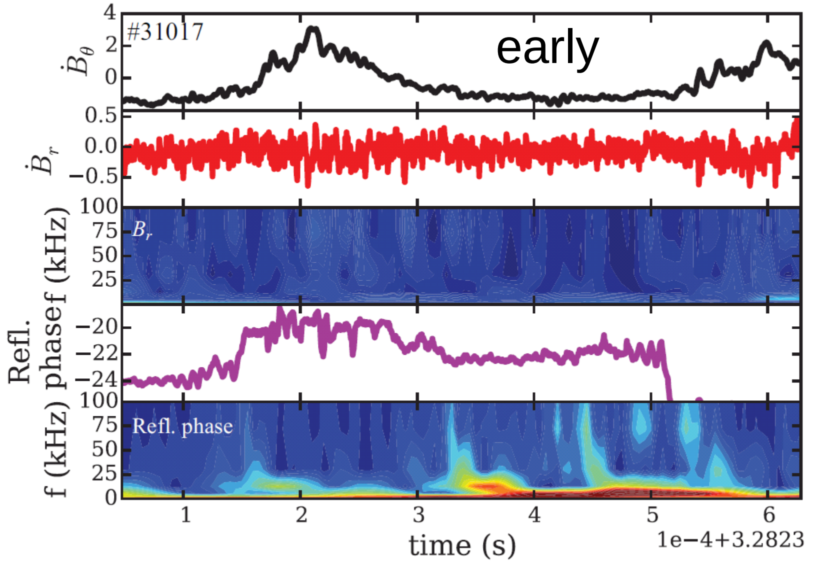
I-phase vs. Type-III ELM

Precursor properties measured with standard reflectometry in early I-phase:

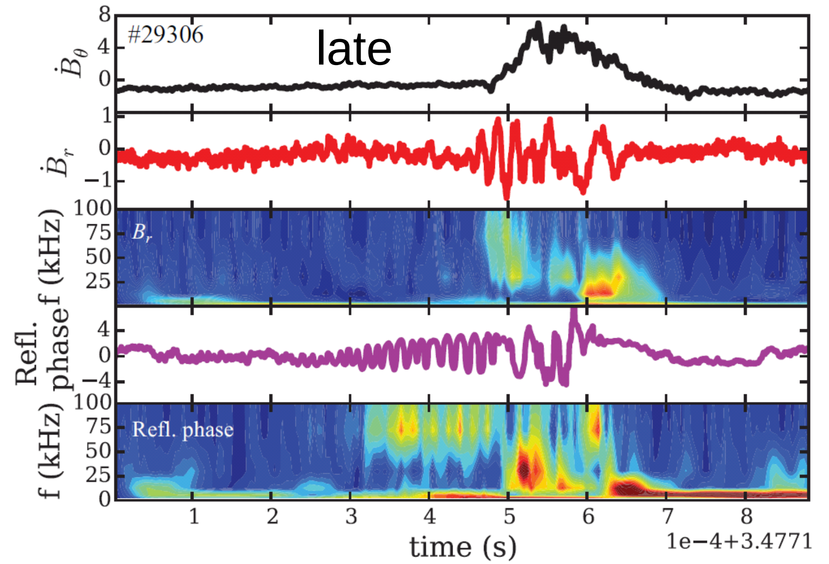


Precursor properties measured with standard reflectometry:

- Small amplitudes in early I-phase
- Located close to separatrix



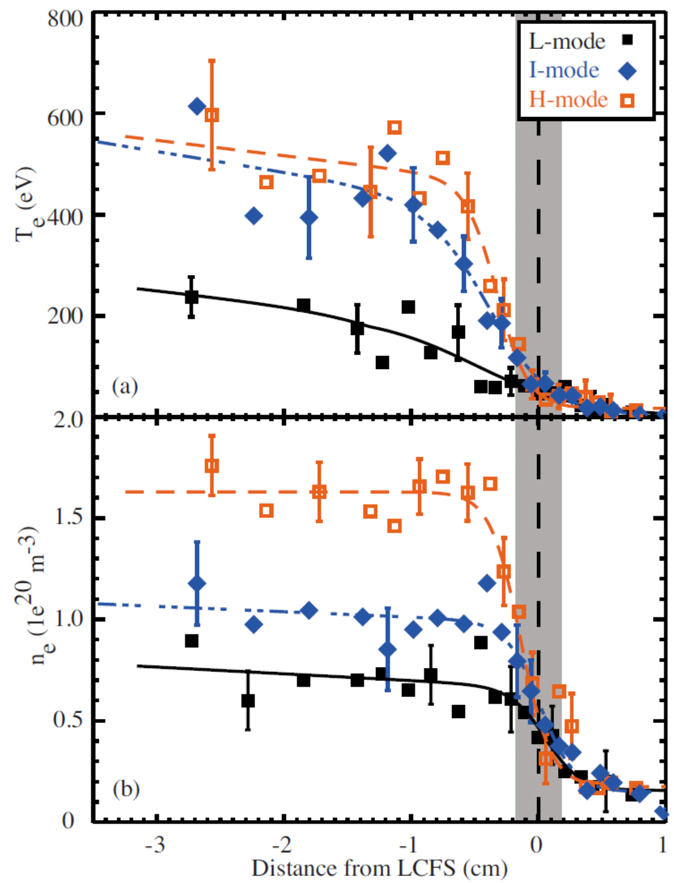
- Large amplitudes in late I-phase
- Already visible in reflectometer signal before it appears in $\dot{B}_r$



➡ **Early and late phase qualitatively identical**

I-phase vs. I-mode

[R. McDermott et al., PoP (2009)]



Definition of I-mode:

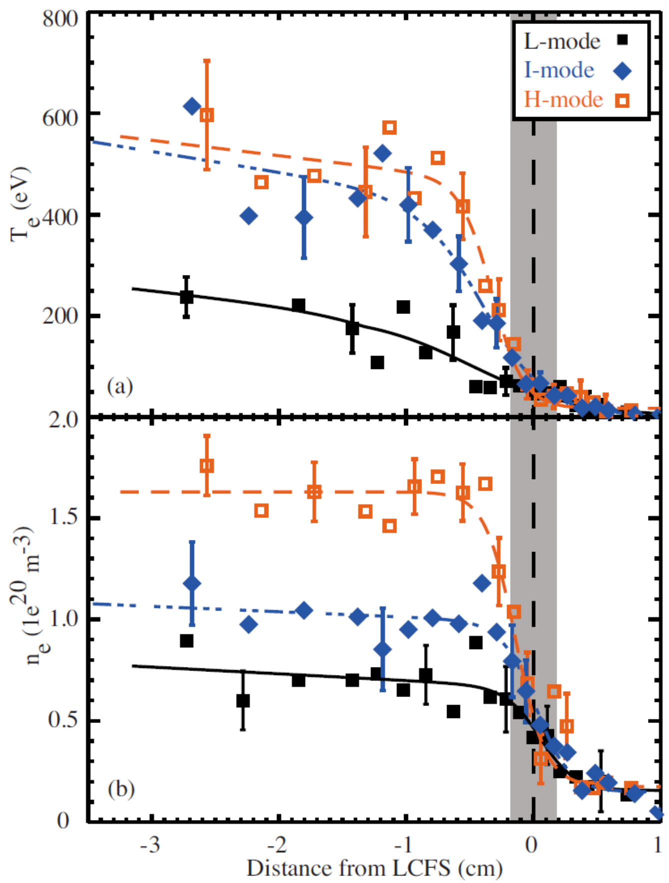
- Improved heat confinement (like H-mode), low particle confinement (like L-mode)
- Appears **only** in unfavourable B x grad B configurations
- **no oscillations**

Definition of I-phase (Conway 2011):

- Turbulence **pulsating** at around 2–4 kHz
- L-I transition sharp, I-H transition soft
- pulsing extends across the plasma edge into
- Occurs at low densities (< 5 10^{19} m^{-3})
- Does **not** occur in unfavourable B x grad B configurations

I-phase vs. I-mode

[R. McDermott et al., PoP (2009)]



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- Appears **only** in unfavourable B x grad B configurations
- **no oscillations (but spikes, GAM and WCM!)**

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- Turbulence **pulsating** at around 2–4 kHz
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- pulsing extends across the plasma edge into
- Occurs at low densities (< 5 10^{19} m^{-3})
- Does **not (clearly)** occur in unfavourable B x grad B configurations

Summary and open questions

The I-phase at AUG:

- Coexist with GAMs at low densities
- Is strongest slightly inside the separatrix and density response propagates outwards
- Exhibits strong magnetic activities (poloidal propagation, *m=1* structure, precursors)

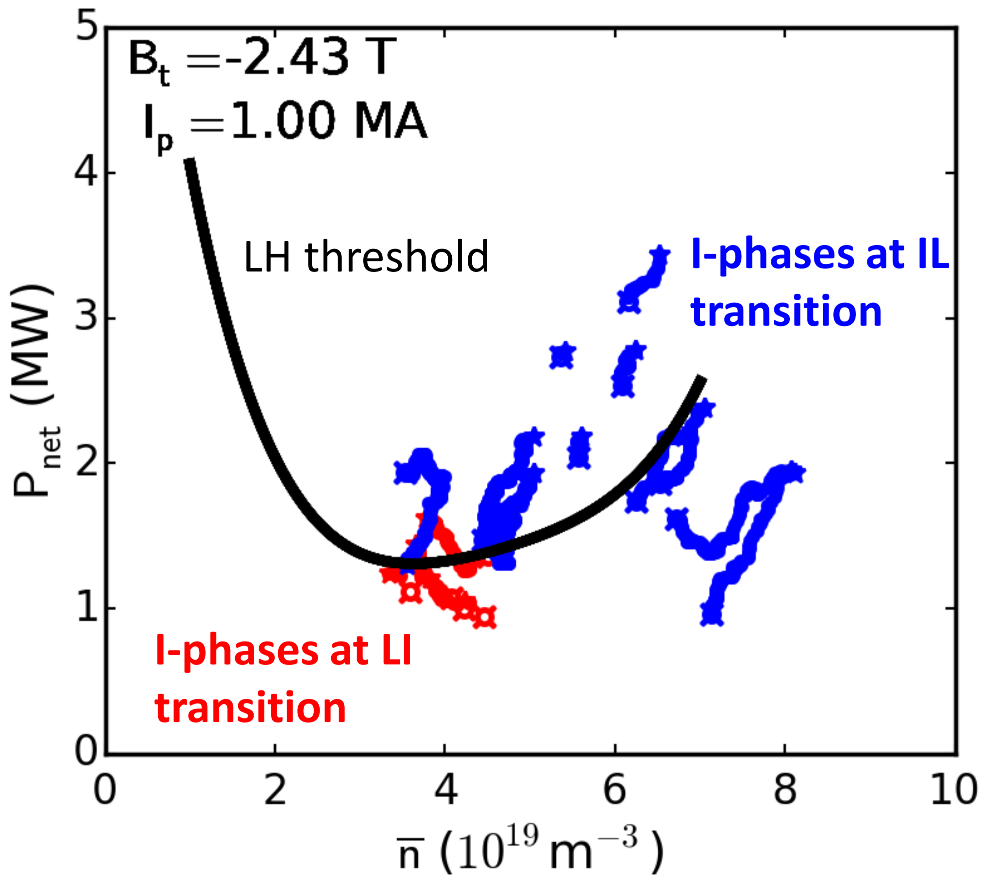
I-phase and type-III ELMs show similarities:

- Appear close to L-H transitions
- Frequency decreases with larger pedestal pressure/heating
- Exhibit precursors with frequencies of about 50-100 kHz

➡ Are type-III ELMs and I-phase the same? IM-mode = I-phase = M-mode?

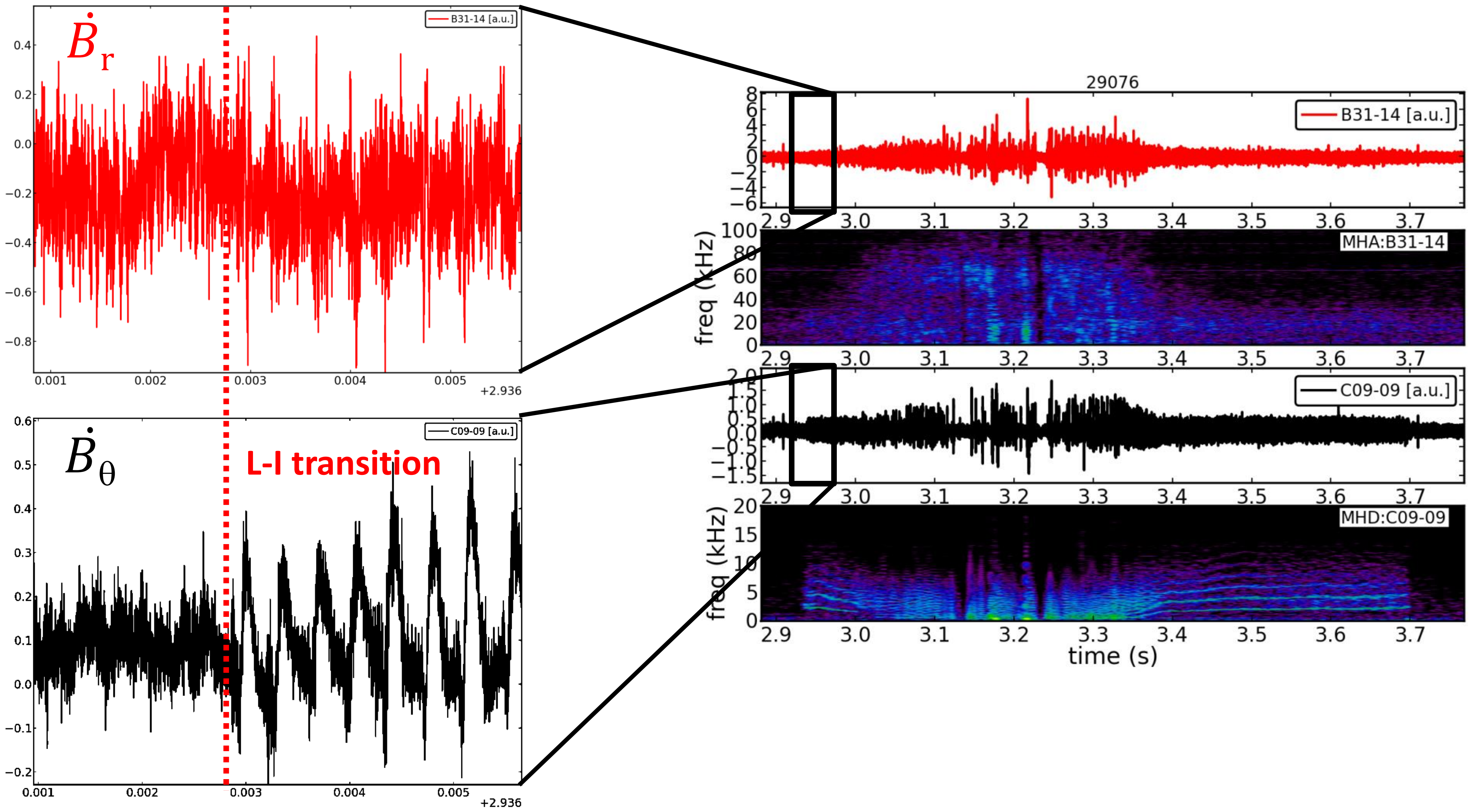
I-phase in the power density plane:

- I-phases at LI and IL look very similar
- LI transition close to LH threshold
- High density range not accessible at LI transition
- Density at IL transition much higher

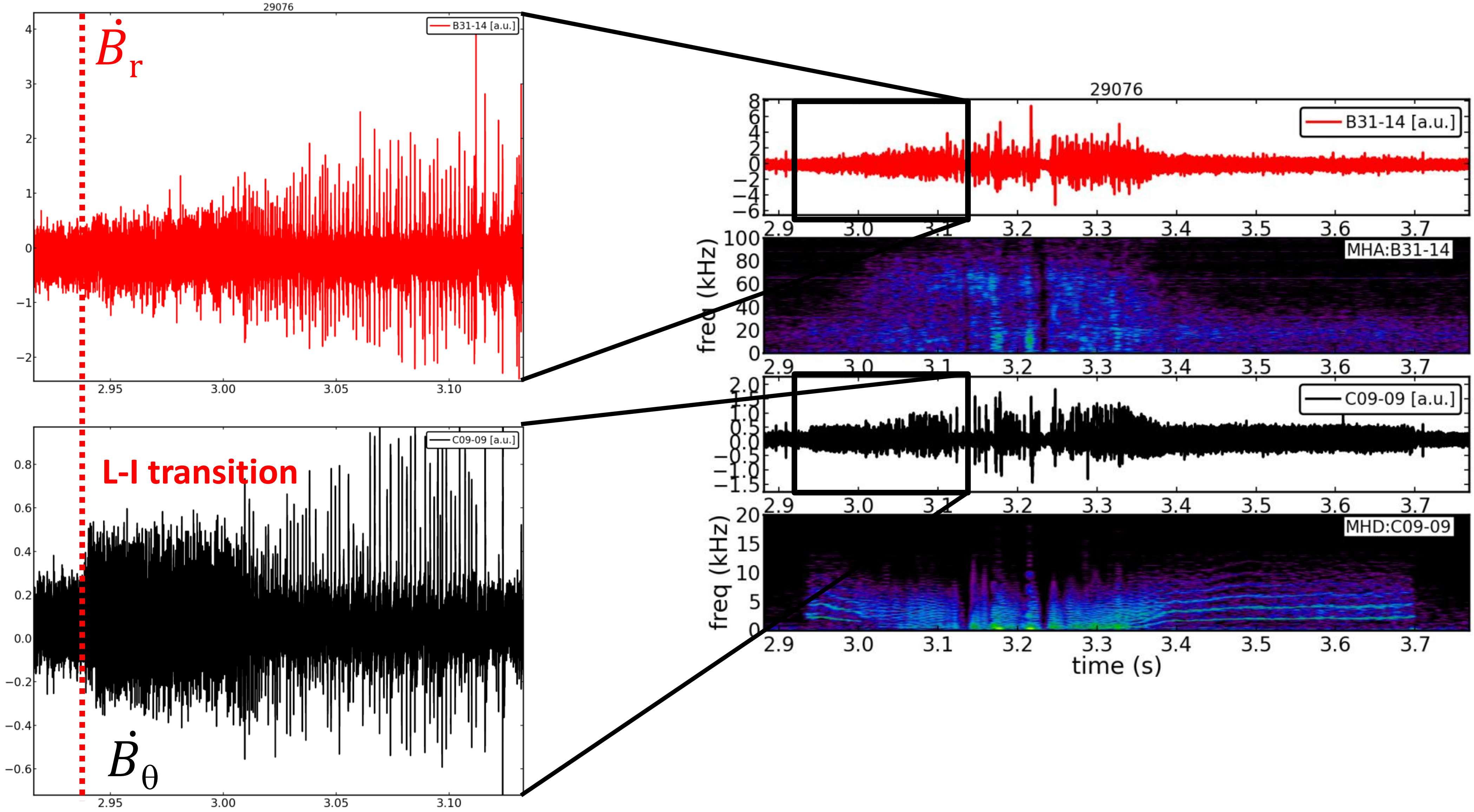


I-phase vs. Type-III ELM

Magnetics in I-phase: No precursor at the beginning

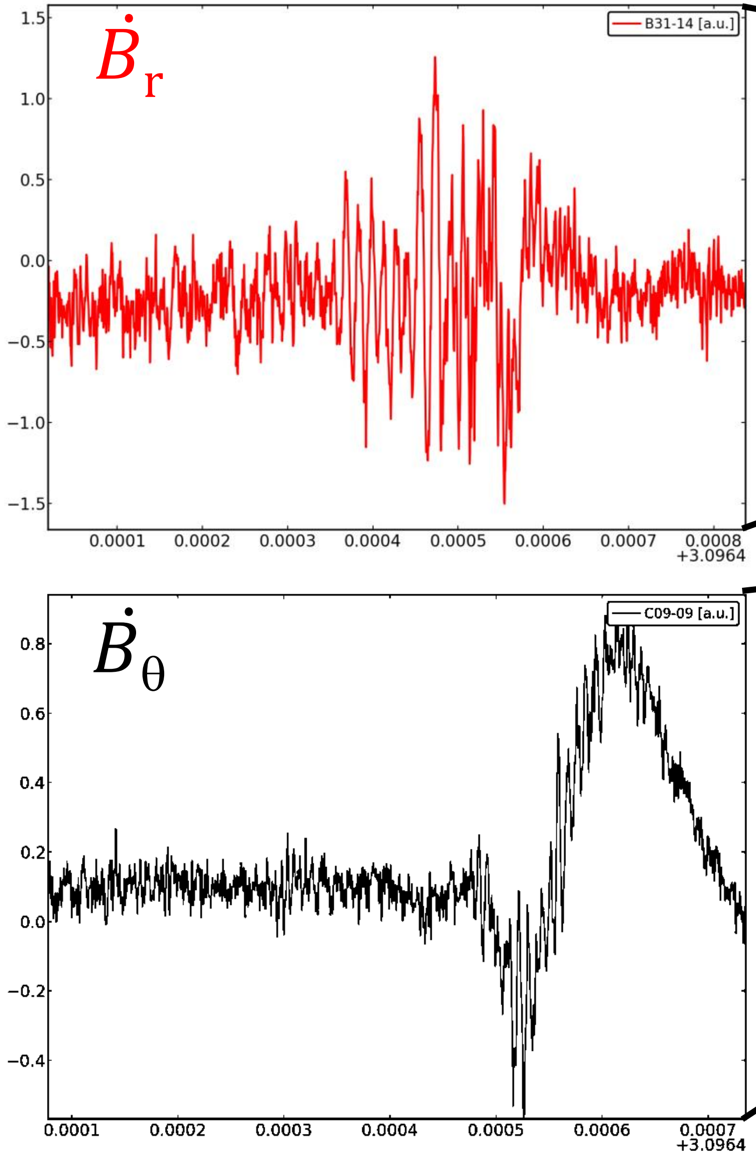


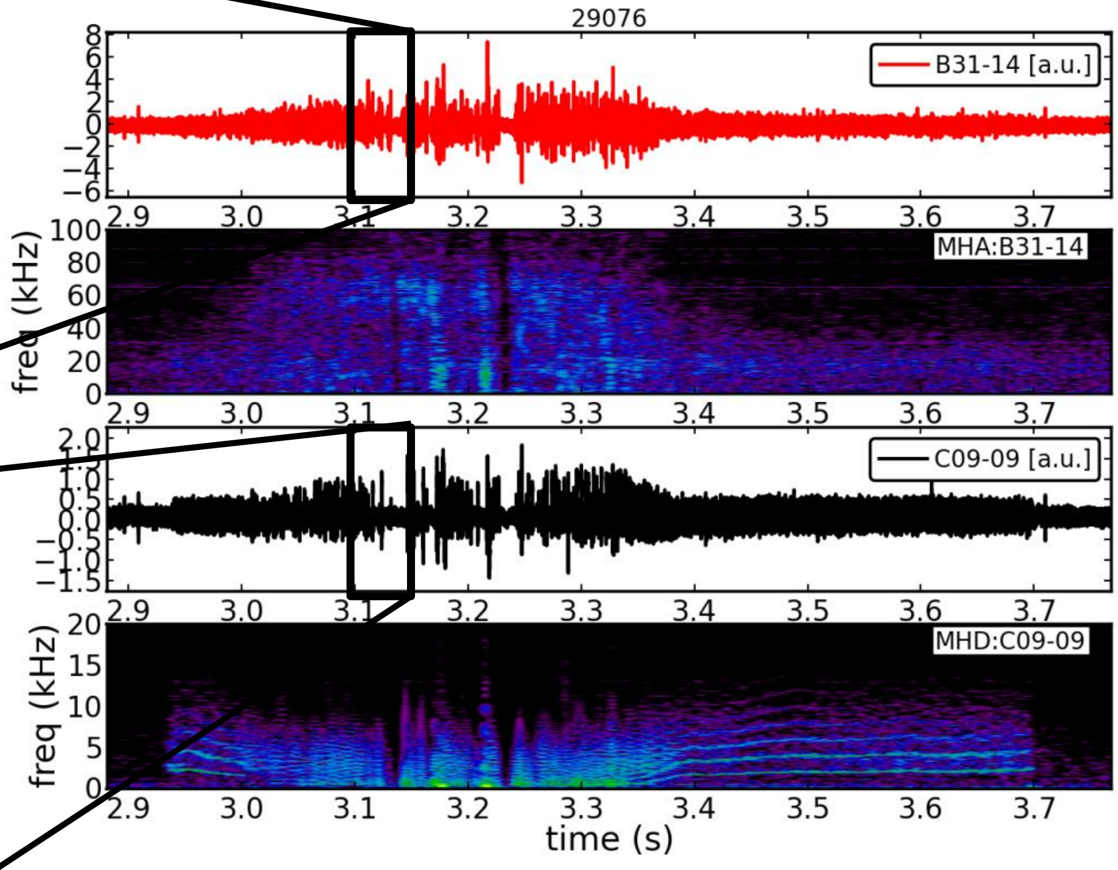
Magnetics in I-phase: Smooth transition to larger spikes



I-phase vs. Type-III ELM

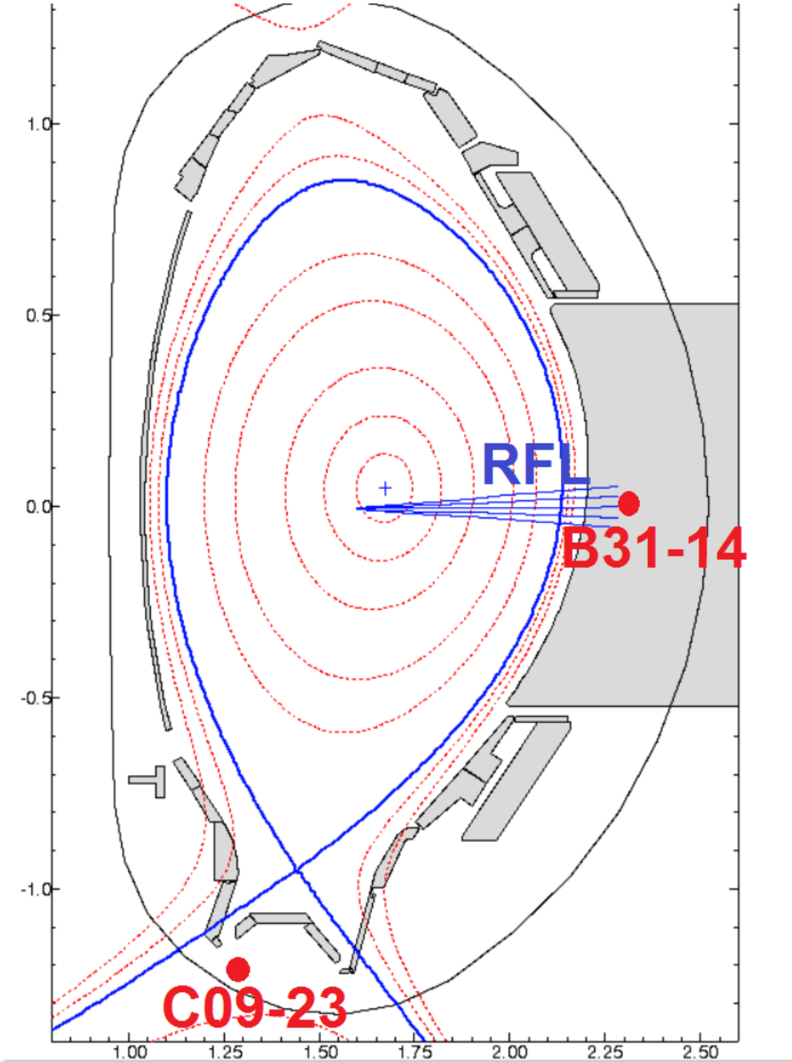
Magnetics in I-phase: Clear precursor later

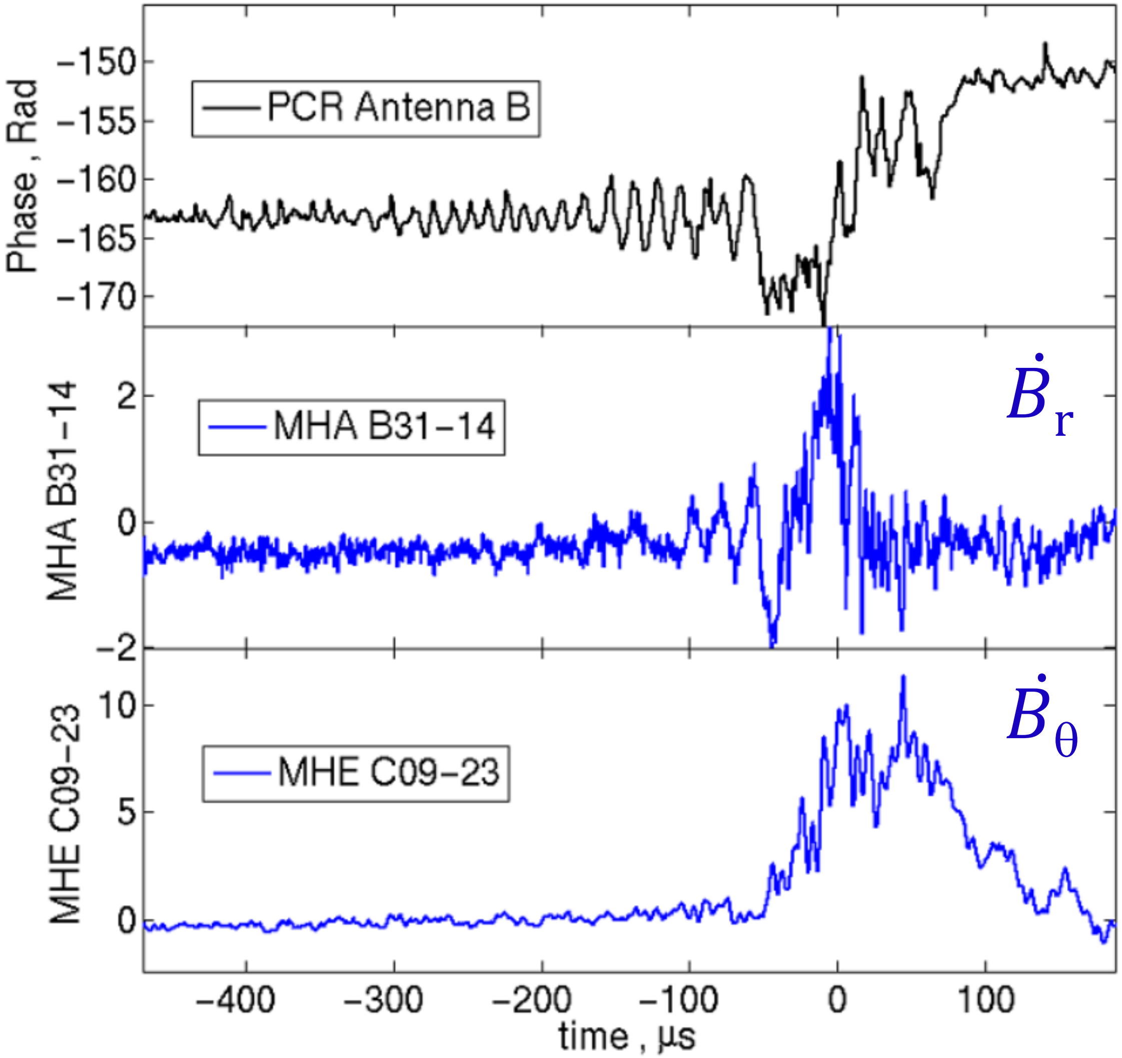




I-phase pulsation = Type-III ELM?

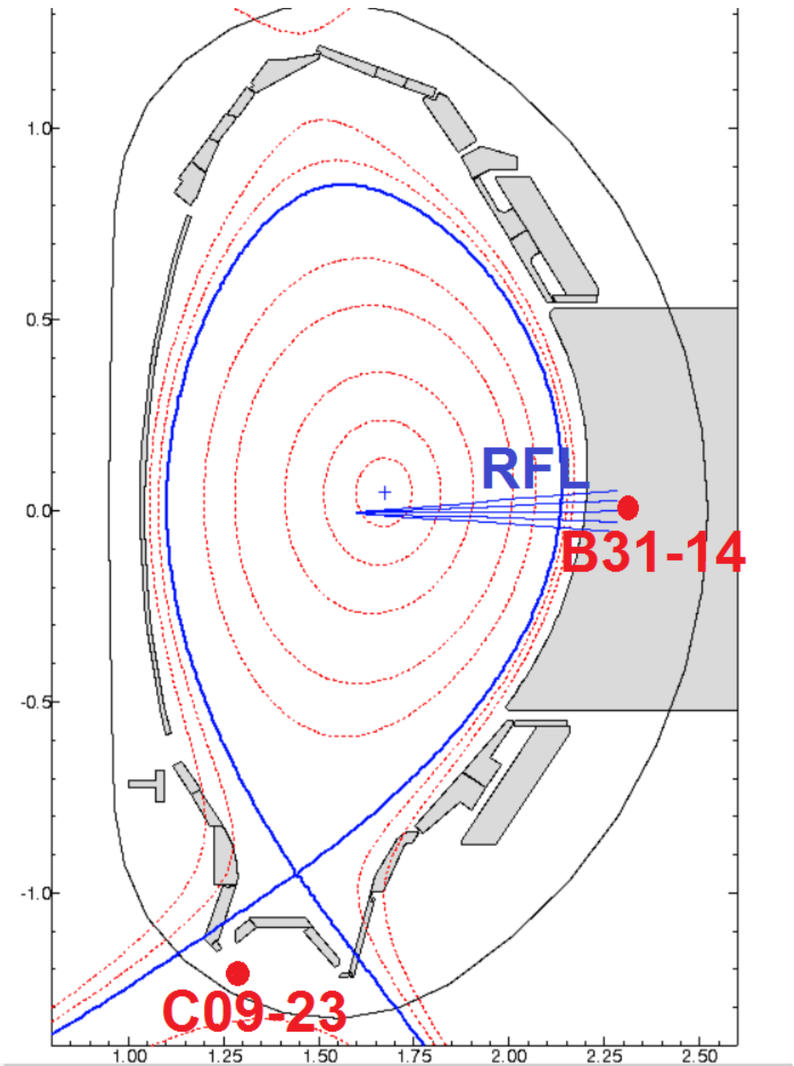
Precursors in poloidal correlation reflectometry (#31165):

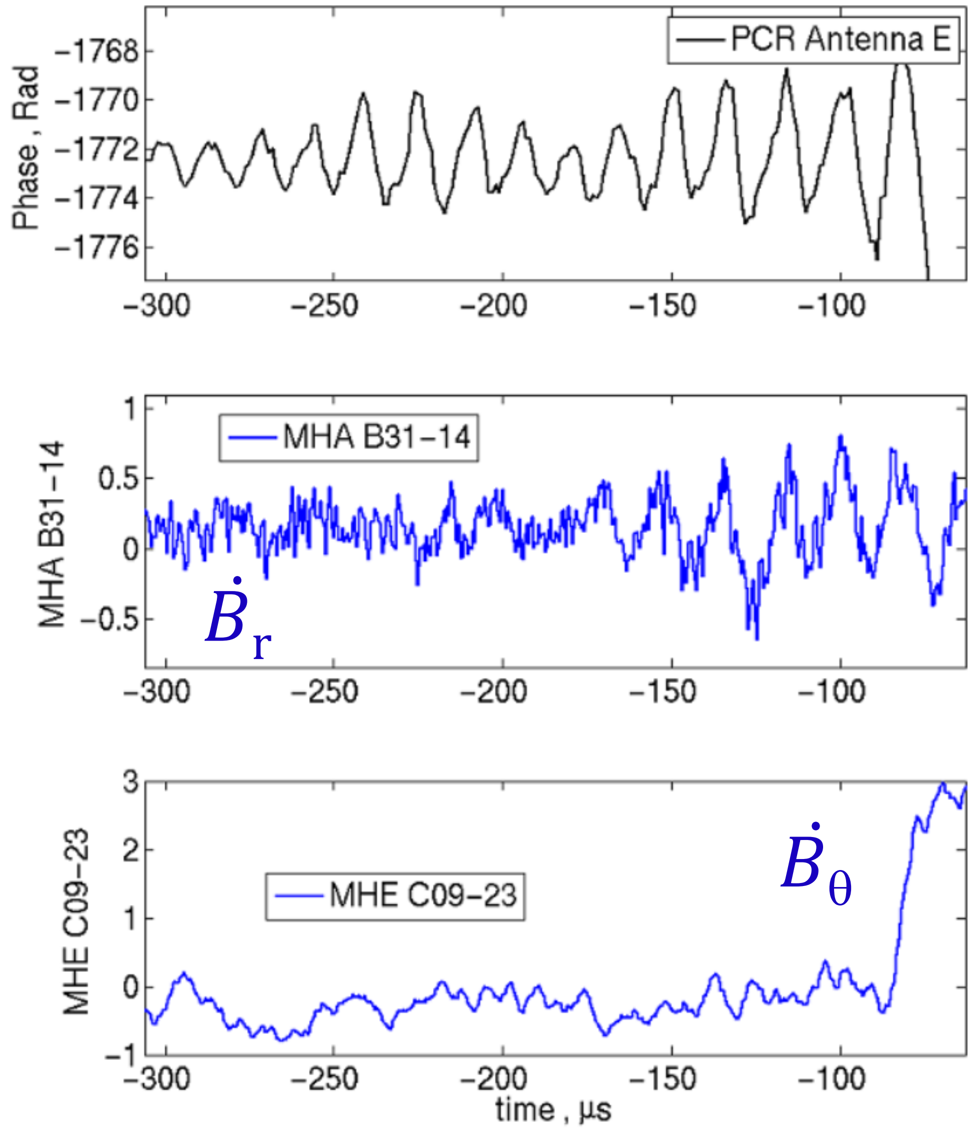




I-phase vs. Type-III ELM

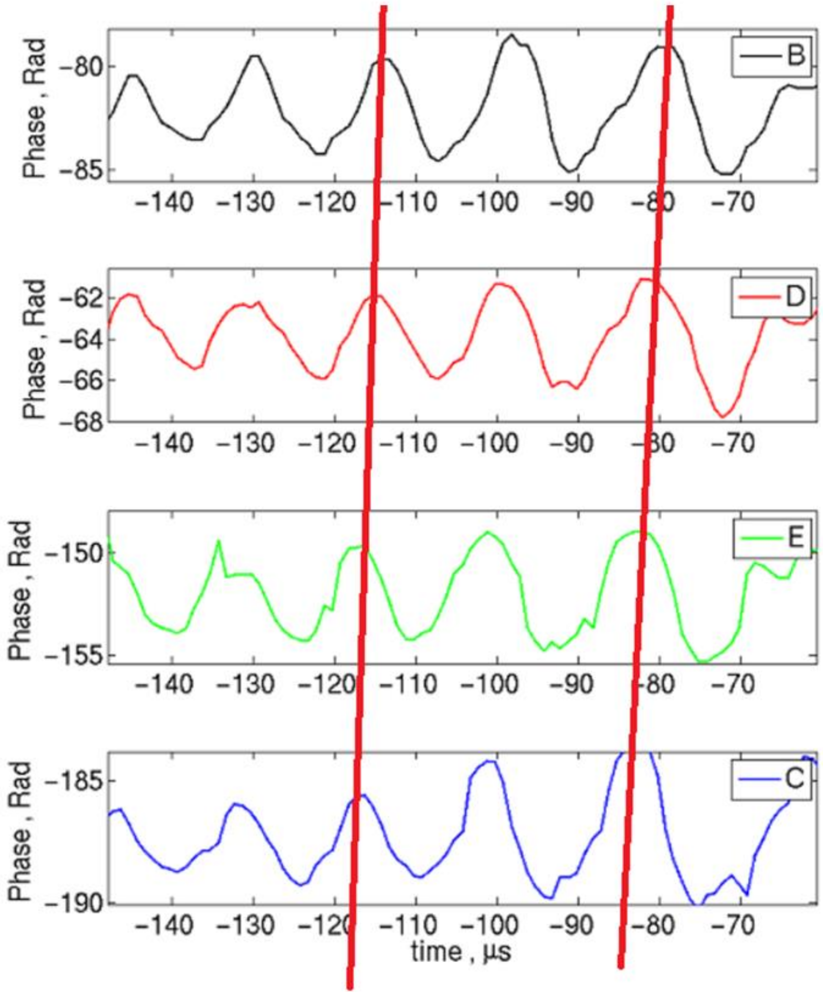
Precursors in poloidal correlation reflectometry (#31165):



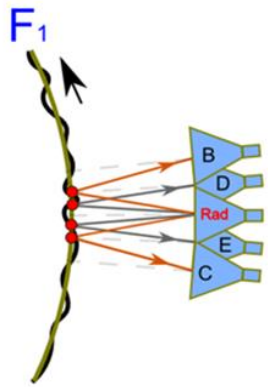


I-phase vs. Type-III ELM

Precursor properties measured with poloidal correlation reflectometry:

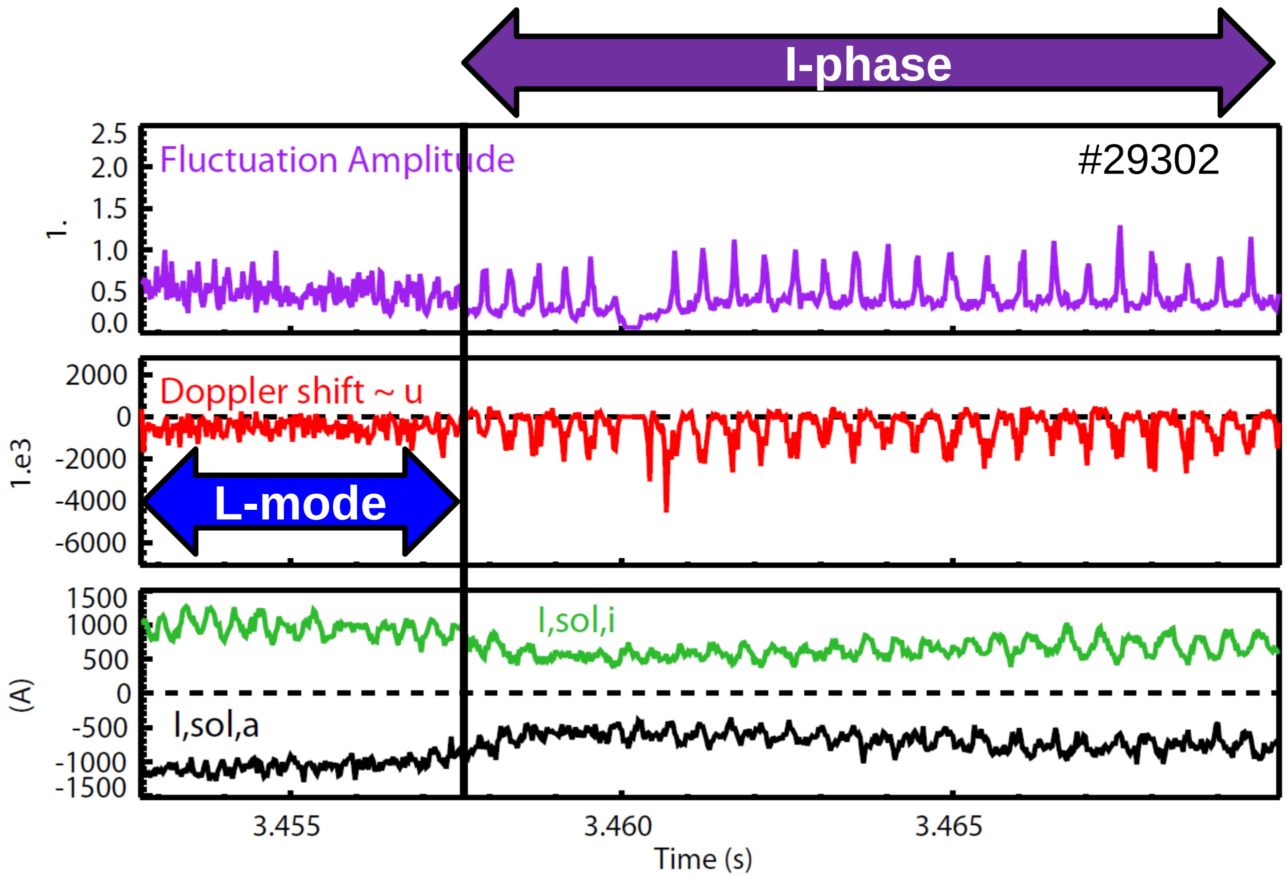


f **= 55 kHz**
v **= 12 km/s (e-diam.)**
k **= 0.28 cm^{-1}**



[D. Prisiazhniuk]

Summary: I-phase



Definition of I-phase (Conway 2011):

- Turbulence pulsating at around 2–4 kHz
- L-I transition sharp, I-H transition soft
- pulsing extends across the plasma edge into SOL ($\rho = 0.96\text{-}1.02$)
- Occurs at low densities ($< 5\ 10^{19}\ m^{-3}$)

General discussion

Open questions:

- Are I-phase and type-III ELMs the same?
- Zonal flows active or E_r given by pressure gradient relevant?
- What is the role of the GAM?
- What is the role of blobs? Passive or active?
- Why does I-phase not clearly appear in unfavourable B x grad B drift?
- Relation to theory (Frequency scaling with β, precursors,…)?
- Is there a similarity of I-phase and type-I ELMs dynamics?
- Poloidal flow in general given by neoclassics?
- …

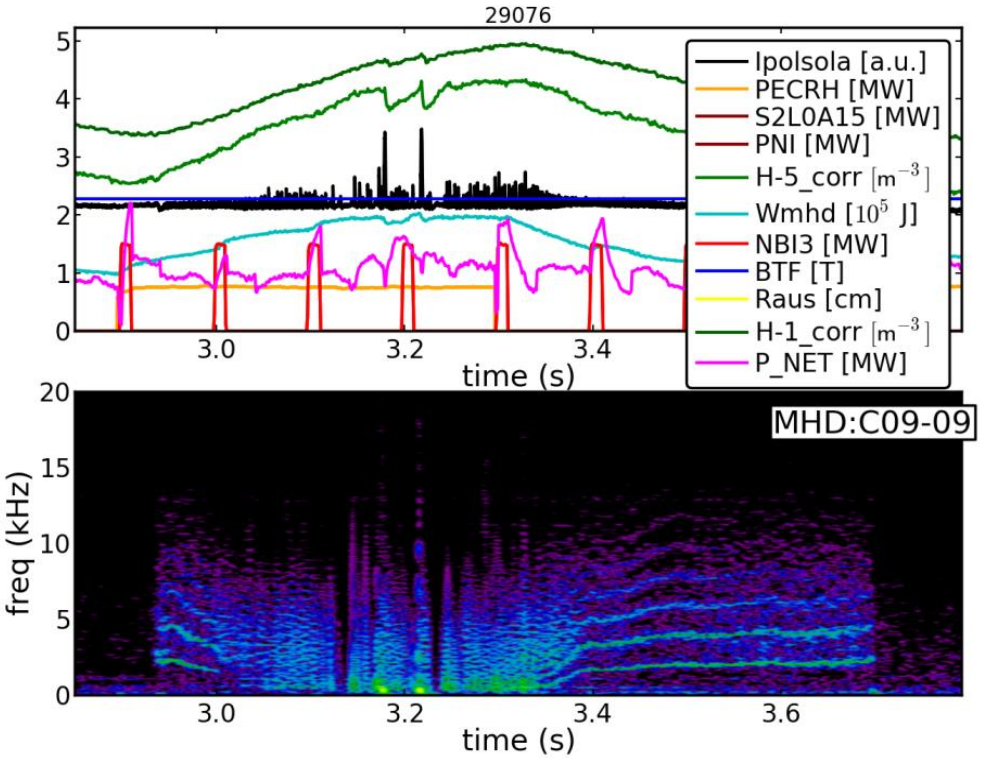
General discussion

Next steps:

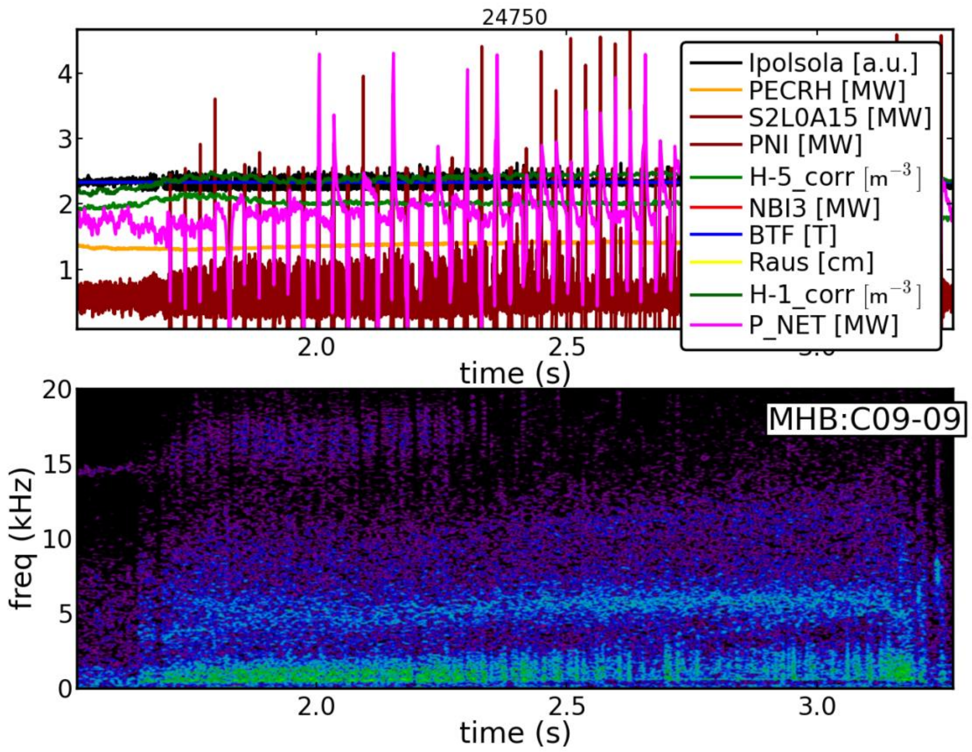
- Document the I-phase frequency (and duty cycle) dependence and comparison to theory
- Find the conditions when LCO and threshold behavior occurs
- Clarify the role of precursors
- Clarify the role of neoclassics and zonal flows/GAMs
- …

What's published about I-phase at AUG

[Mueller et al., PoP 2014]



[Conway et al., PRL 2011]



Differences between the published shots:

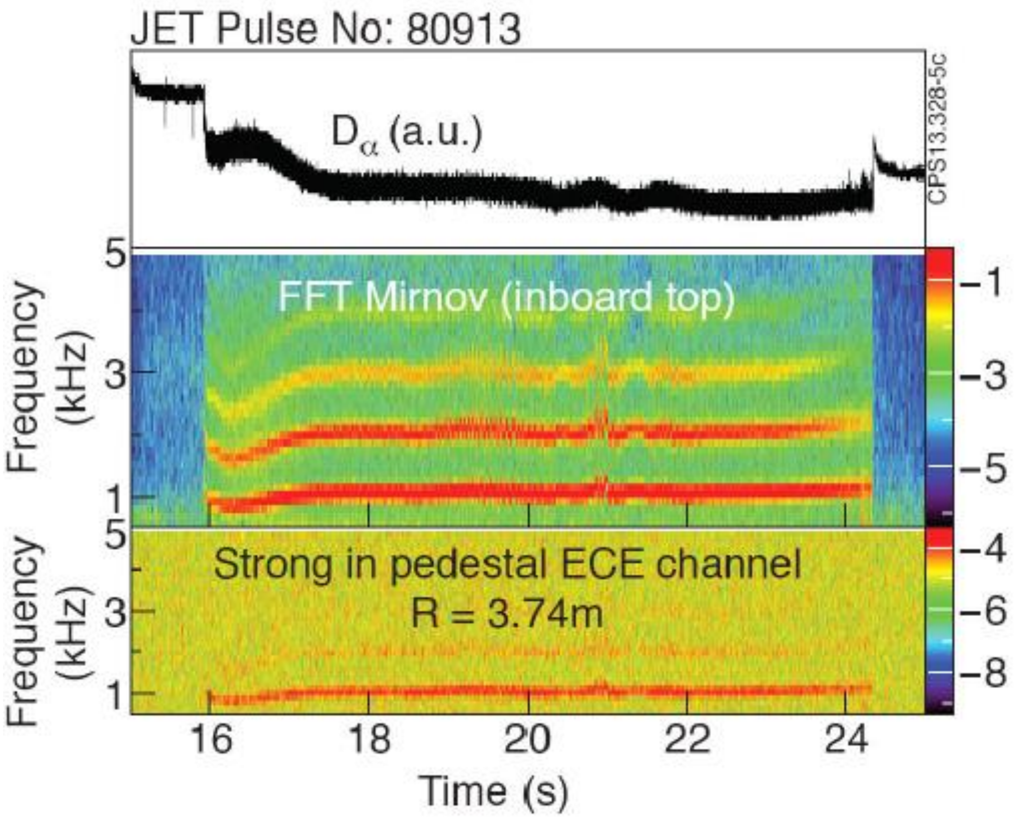
- No nice/clear H-modes (Garrard)
- Garrard: No limit cycle. Stefan: Limit cycle!
- Garrard: GAM. Stefan: No GAM?
- Magnetic signal looks different (important?)

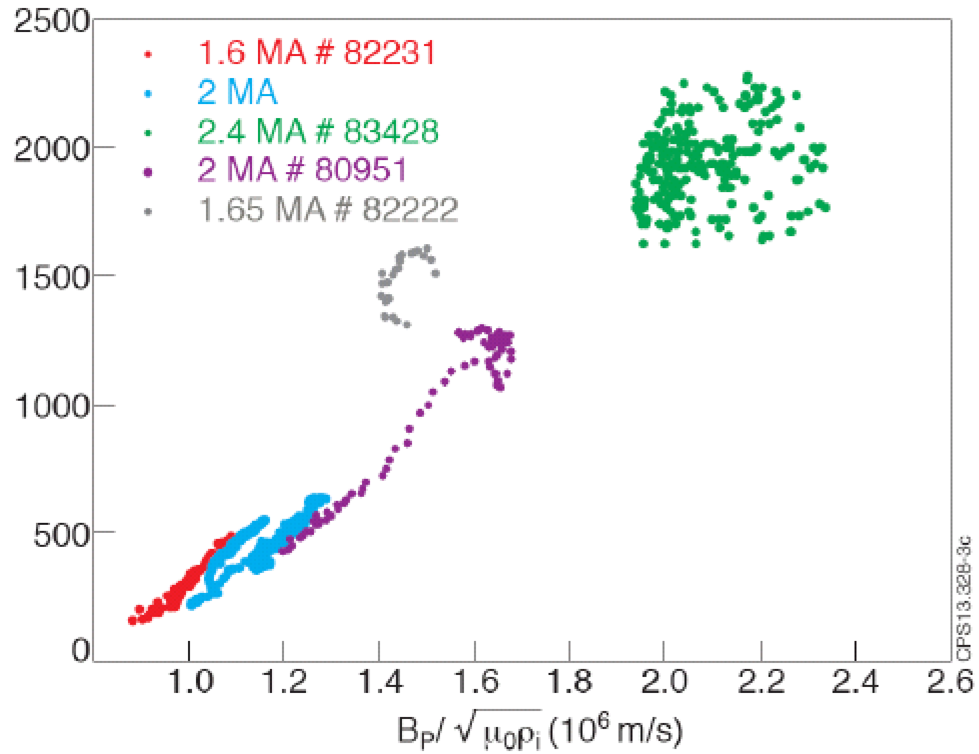
What's published from other devices

M-mode on JET (Solano, EPS 2013):

- Magnetic oscillation after LH transition (few kHz)
- m=1, n=0, up-down symmetric
- Higher harmonics in Mirnov coils
- Not electrostatic, but scaling with poloidal Alfven speed

similar to a hydrodynamic internal wave $\nu = (k_\theta^2/k)V \simeq (\lambda_r/\lambda_\theta^2)V_{Alfven,pol}$





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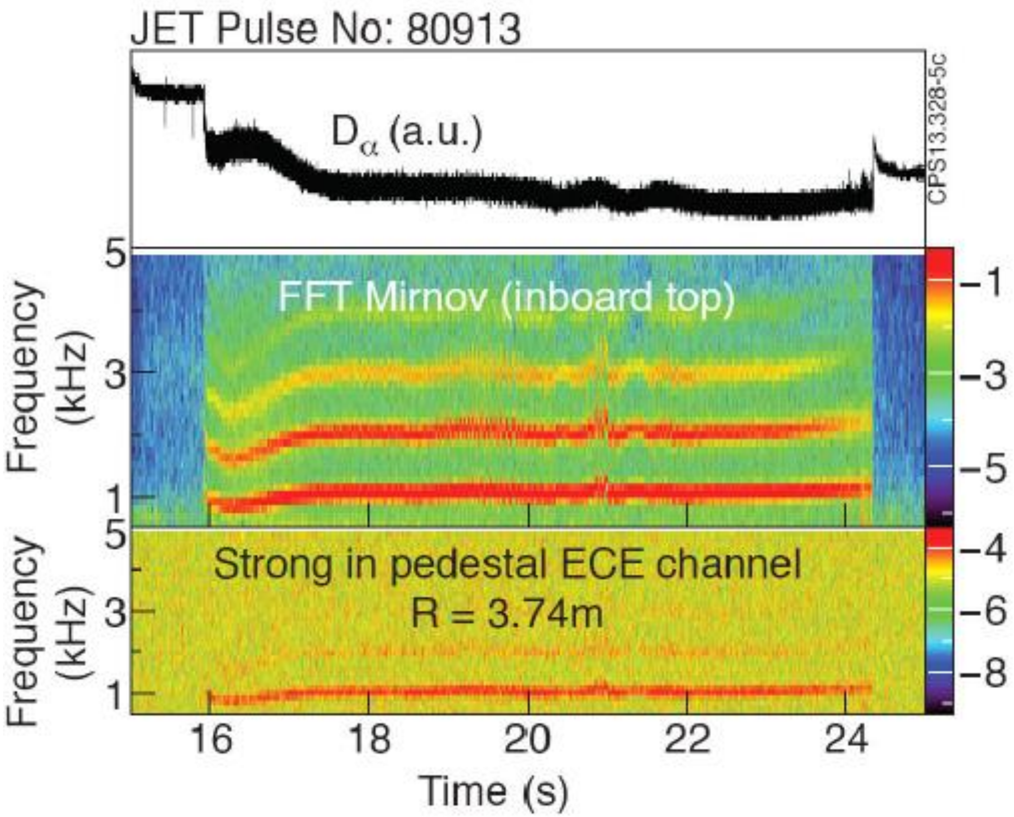
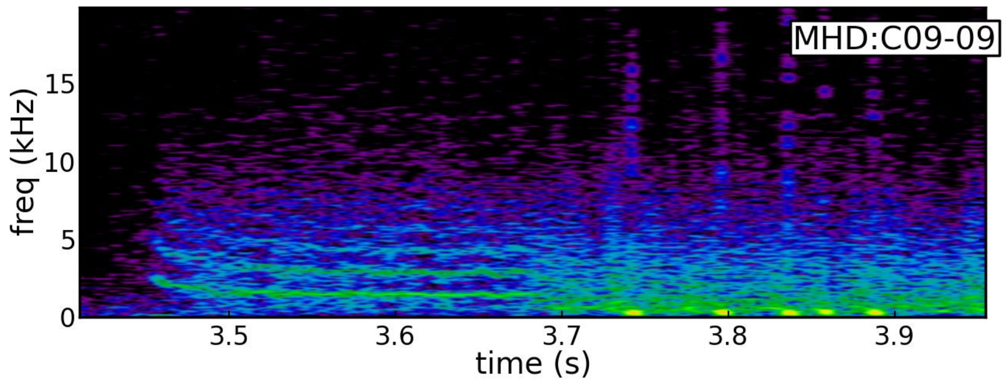


AUG



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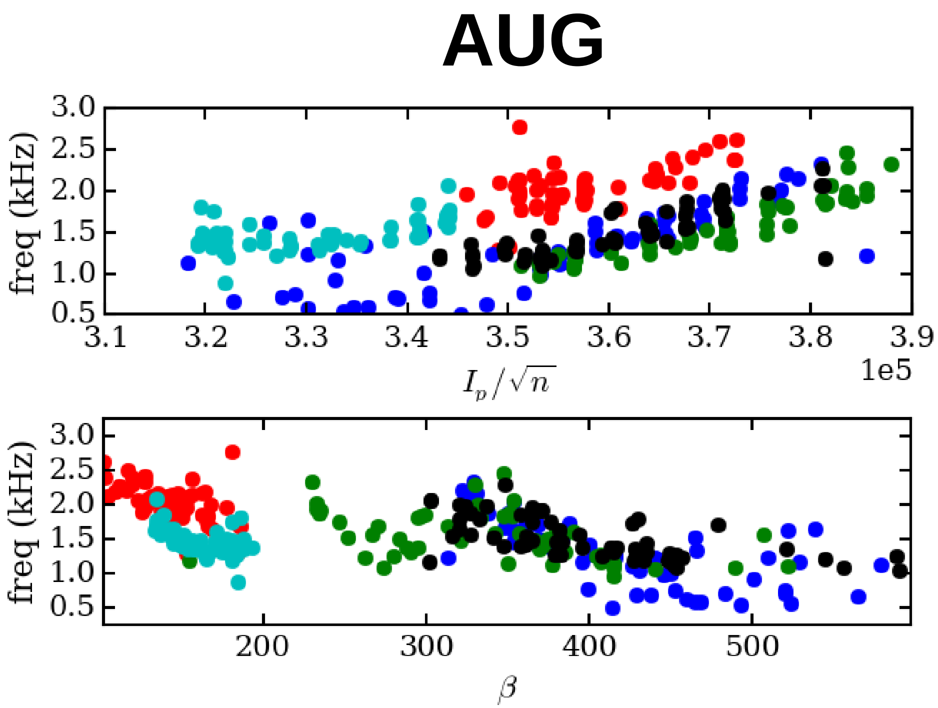

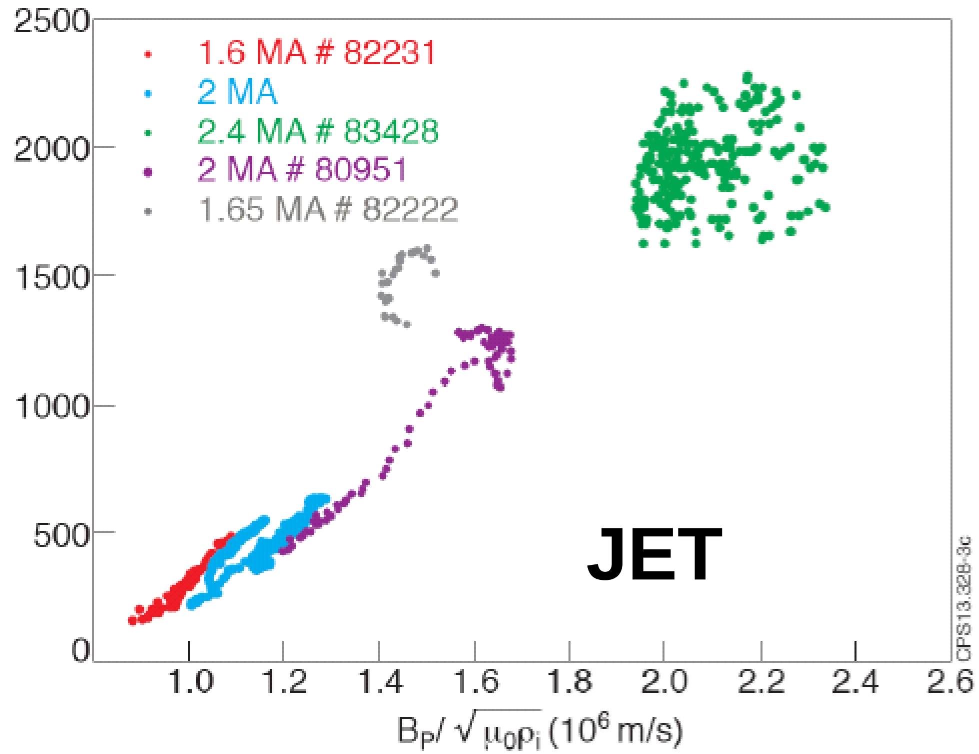

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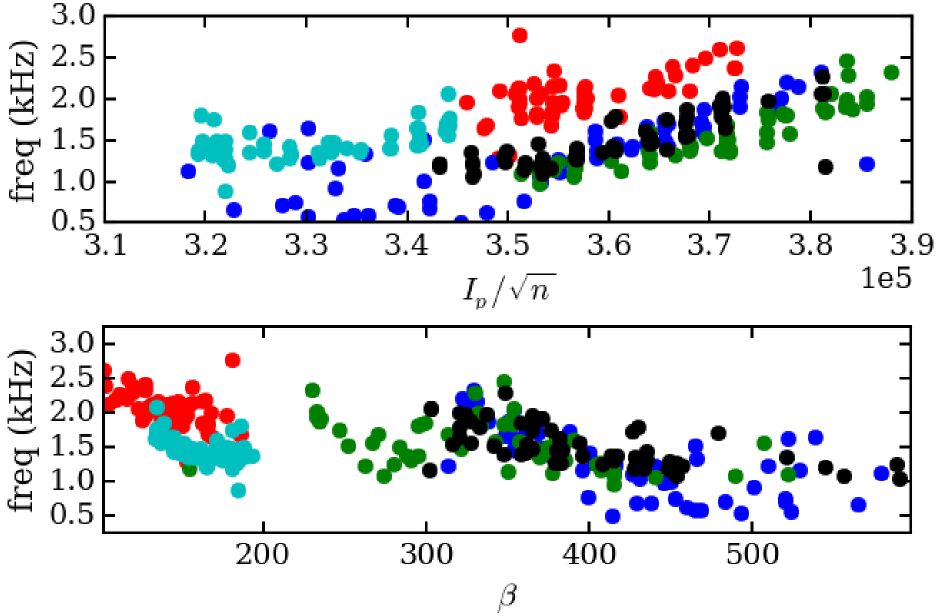
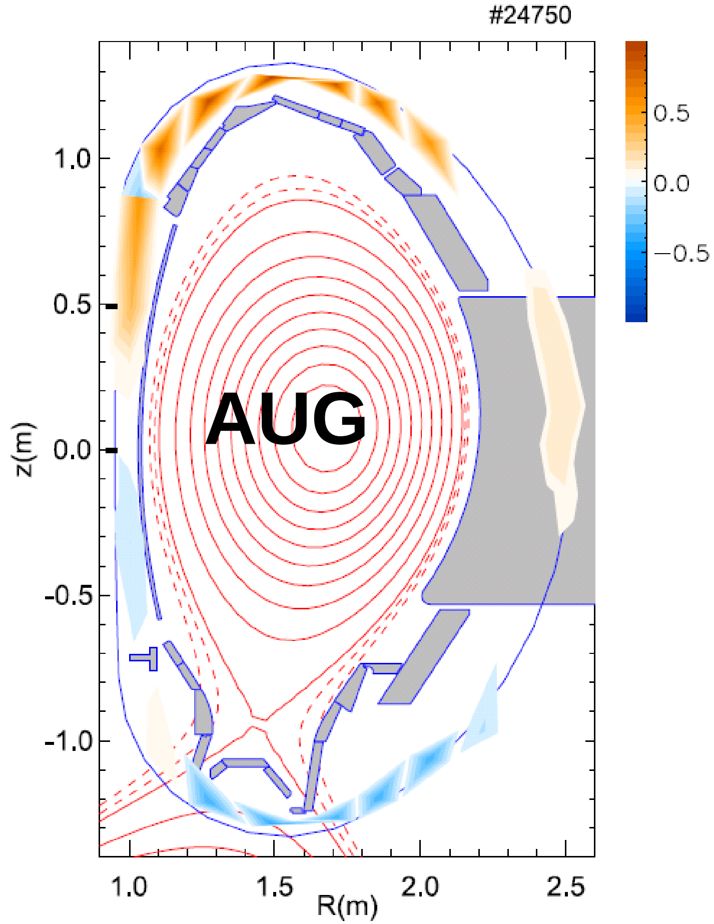
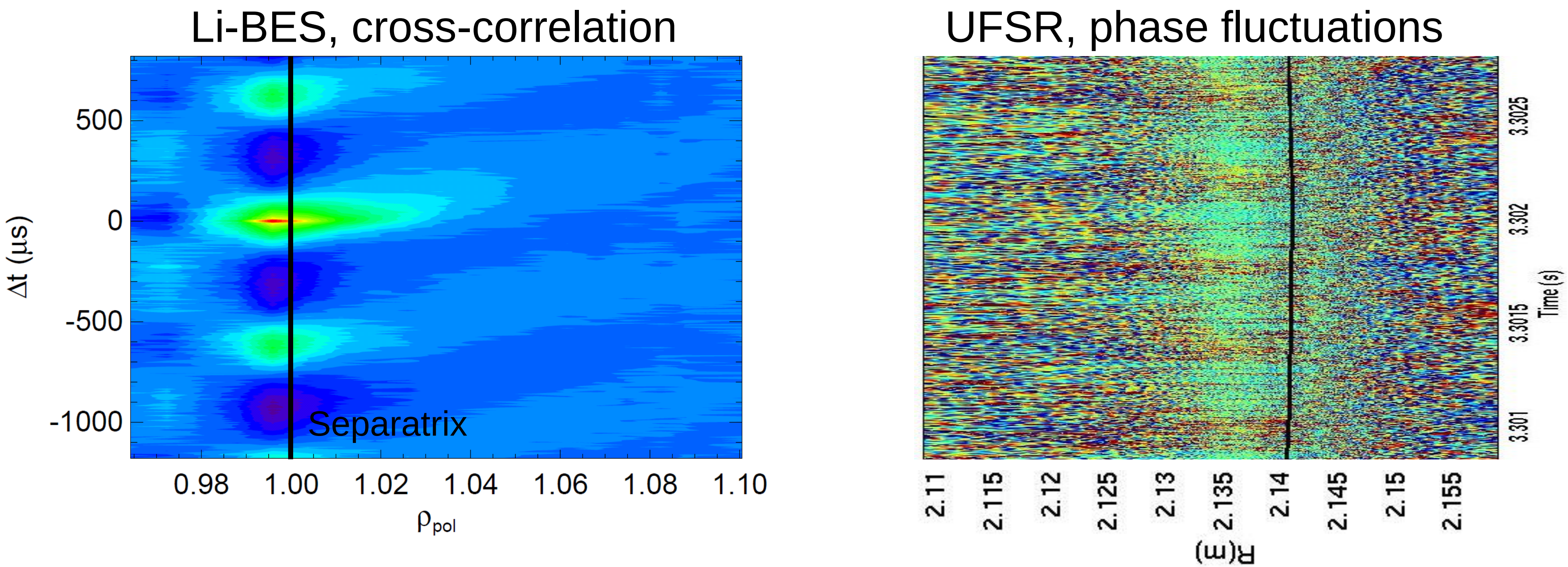




Comparison: Li-BES and Ultra Fast Sweeping Reflectometer



Density response of 2 kHz oscillations:

- **localized slightly inside the separatrix**
- **Width: ~1.5 cm**

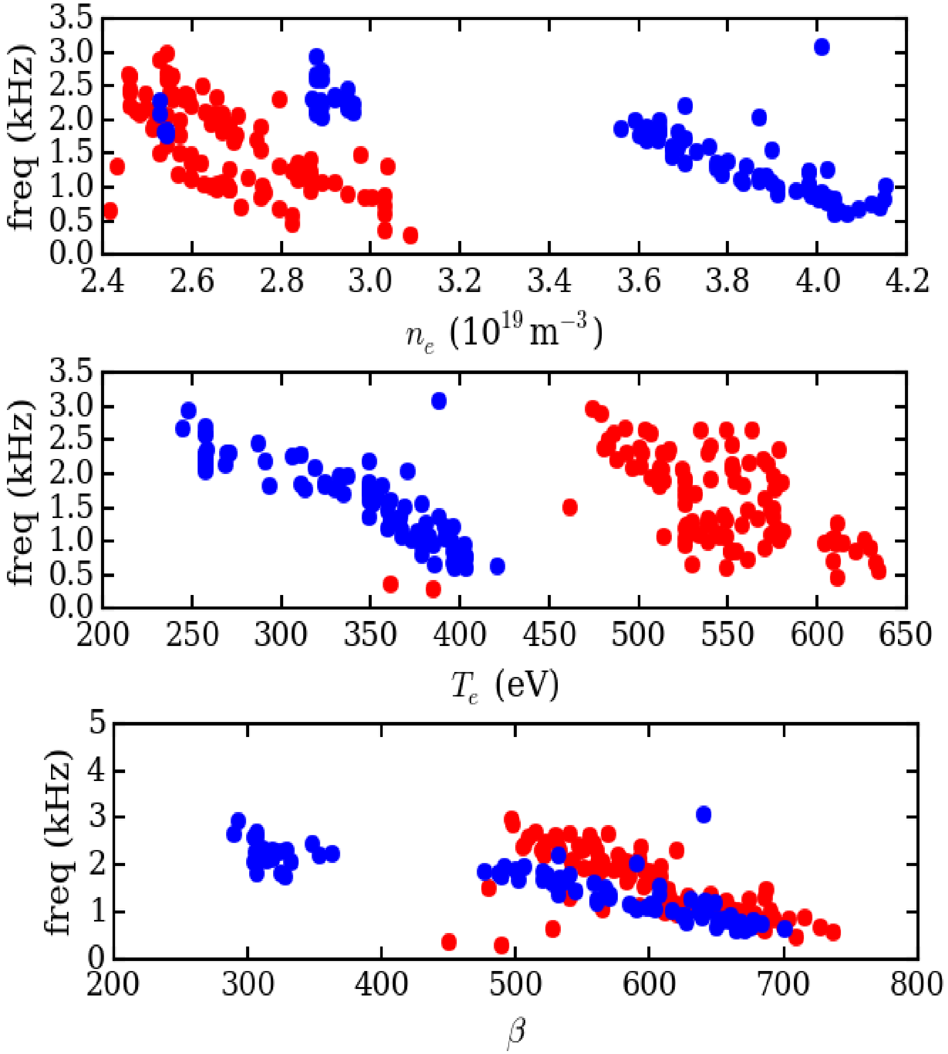
LIH vs. HIL transitions

I-phase frequency scaling:

- Frequency depends on density!
- Or on temperature?
- High density range not accessible at LI transition
- Density at IL transition much higher BUT temperature lower

➡ **Plasma pressure (β) is the same at IL and LI transition!**

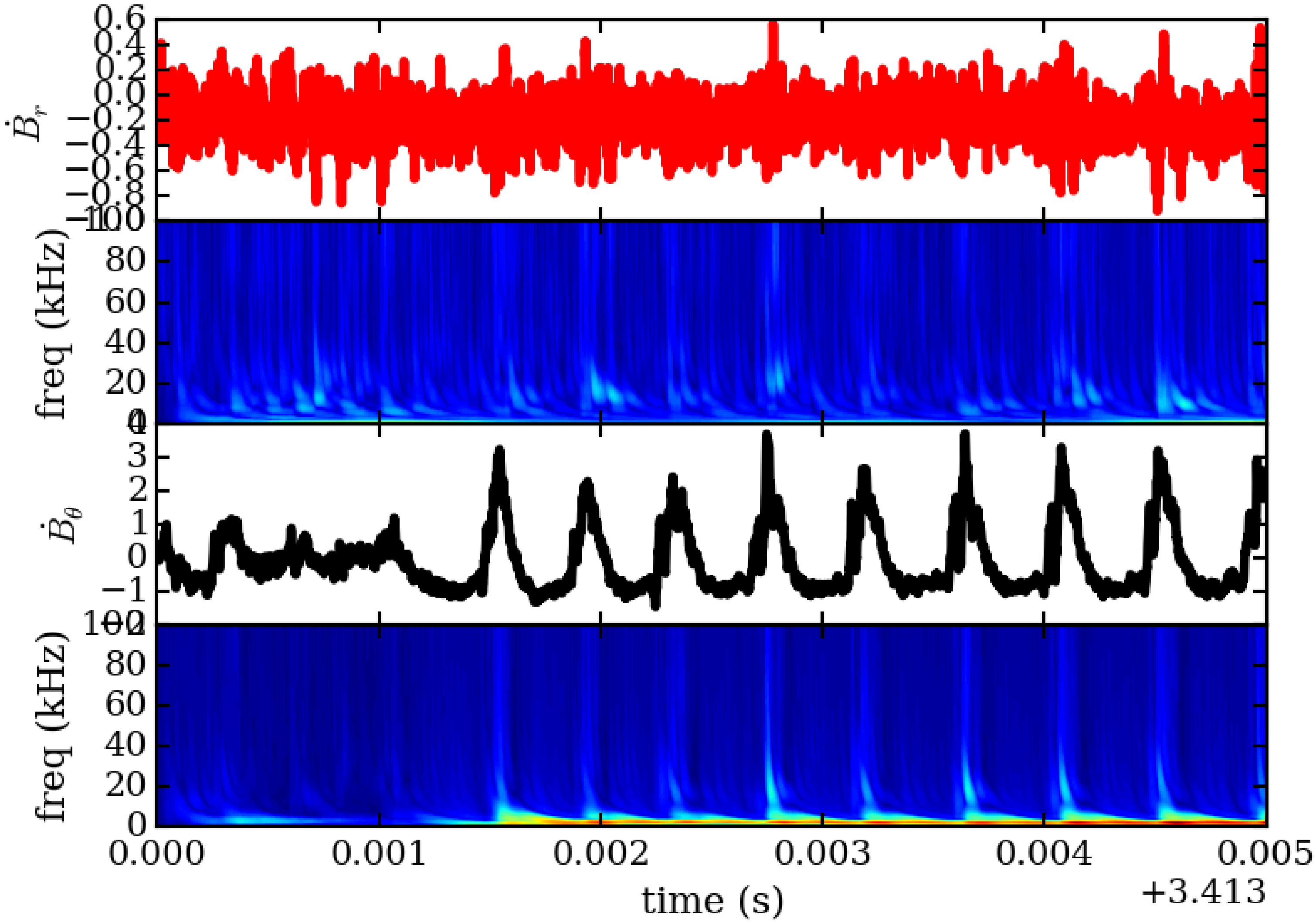
➡ **Frequency depends on β? (to be checked)**



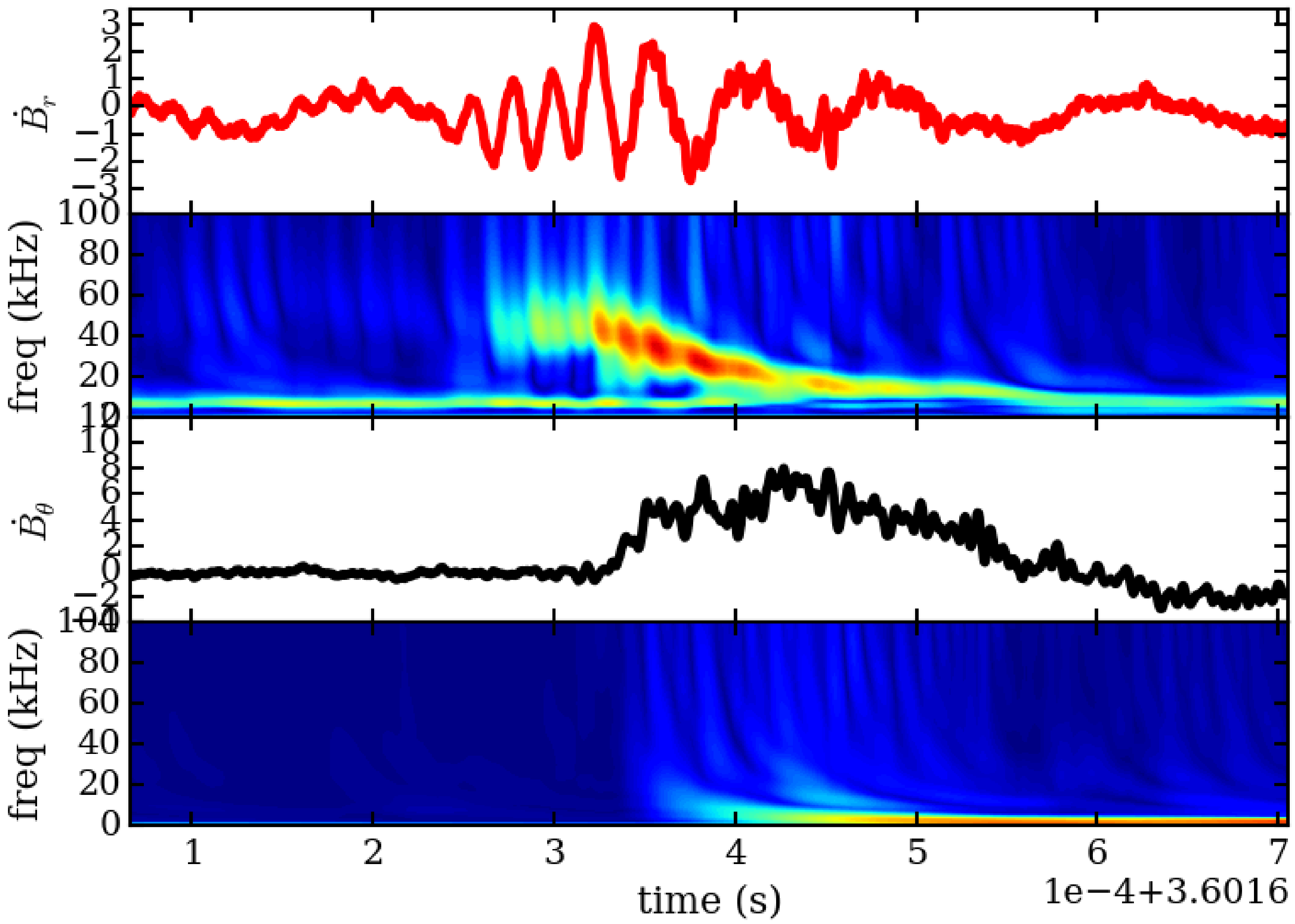
I-phases at LI transition

I-phases at IL transition

Magnetics in I-phase: No precursor in early phase



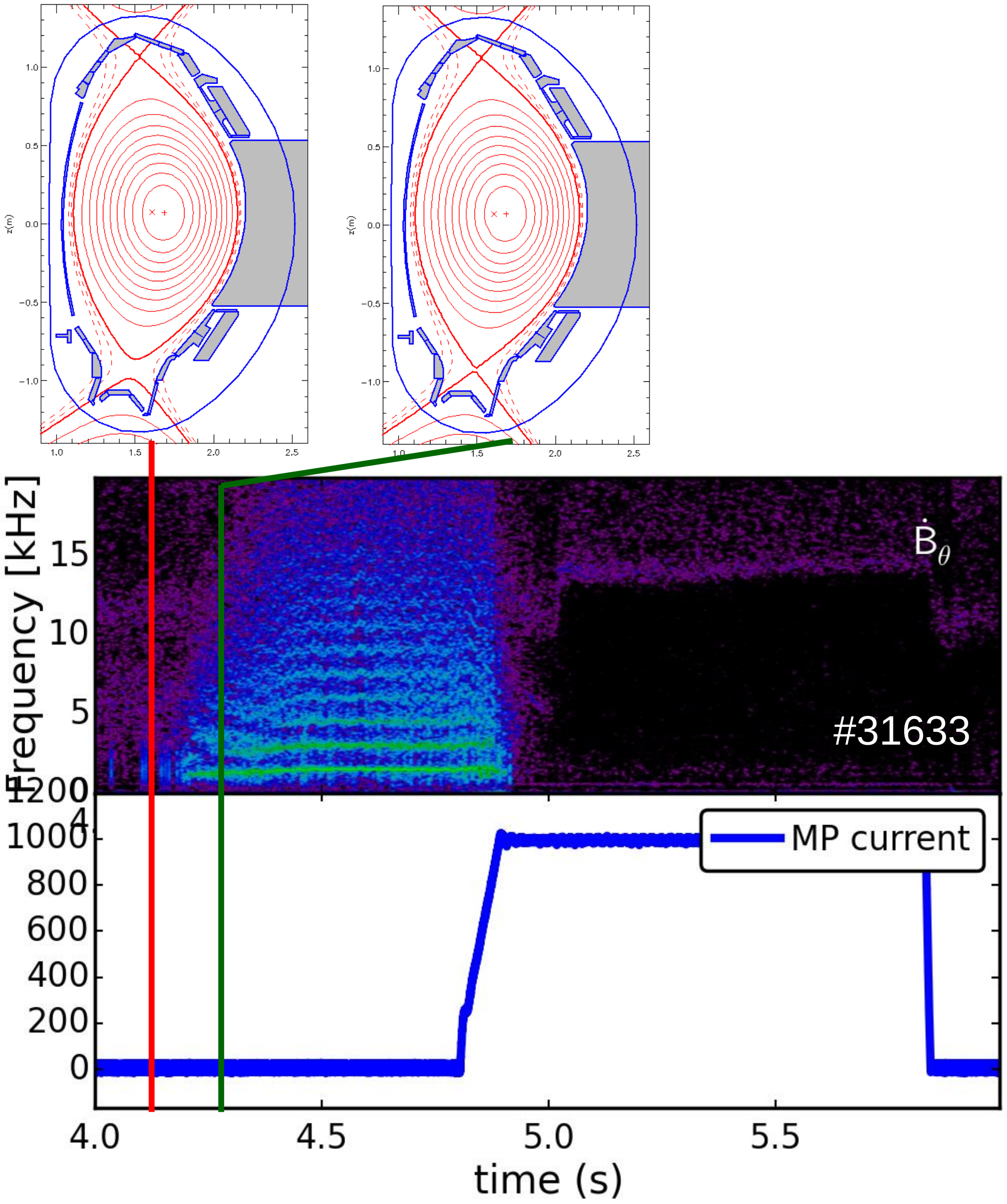
Magnetics in I-phase: Clear precursor in late phase



I-phase in different configurations

I-phase:

- No I-phase in USN
- Switched on in DN
- Switched off by MPs (density pump-out)



What's published from other devices

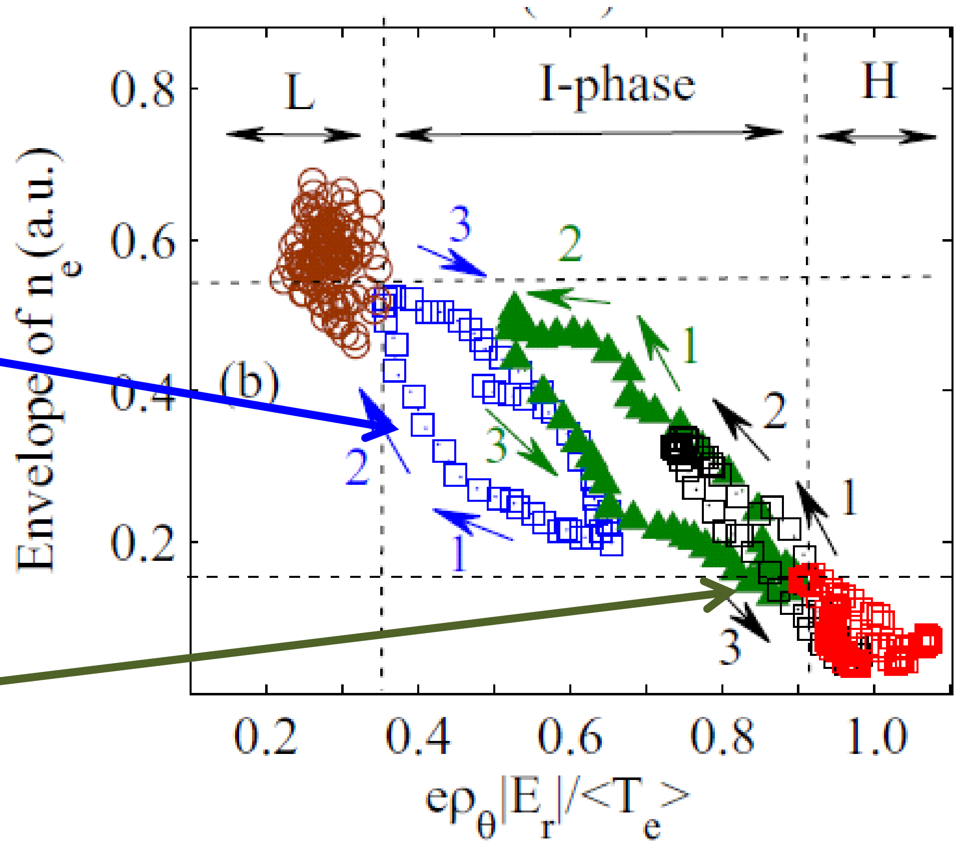
Cheng/Dong at HL-2A:

Type-Y LCO:

- **CW**
- **Close to LI threshold**
- **No IH transition**

Type-J LCO:

- **CCW**
- **Close to IH threshold**
- **Always related to LH transition**



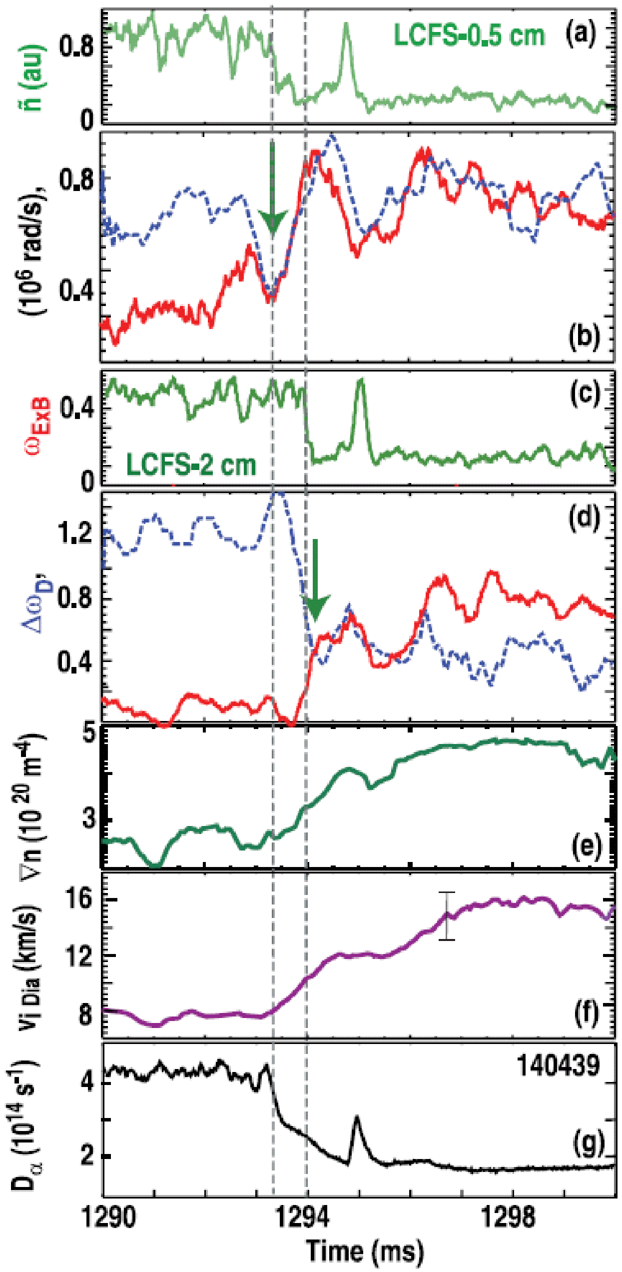
IAEA (not shown):

- **type-Y is ZF-turbulence LCO**
- **type-J is background-turbulence LCO**
- **LI transition by ZF, IH by background E_r**

What's published from other devices

Schmitz at DIII-D (NF 2014):

- Zonal flow triggers LCOs initially (90◦ between n and shear rate)
- Background shear takes over later (180◦) and sustains H-mode
- Consistent with a two predator (ZF and background shear), one-prey (turbulence) LCO model



What’s published from other devices

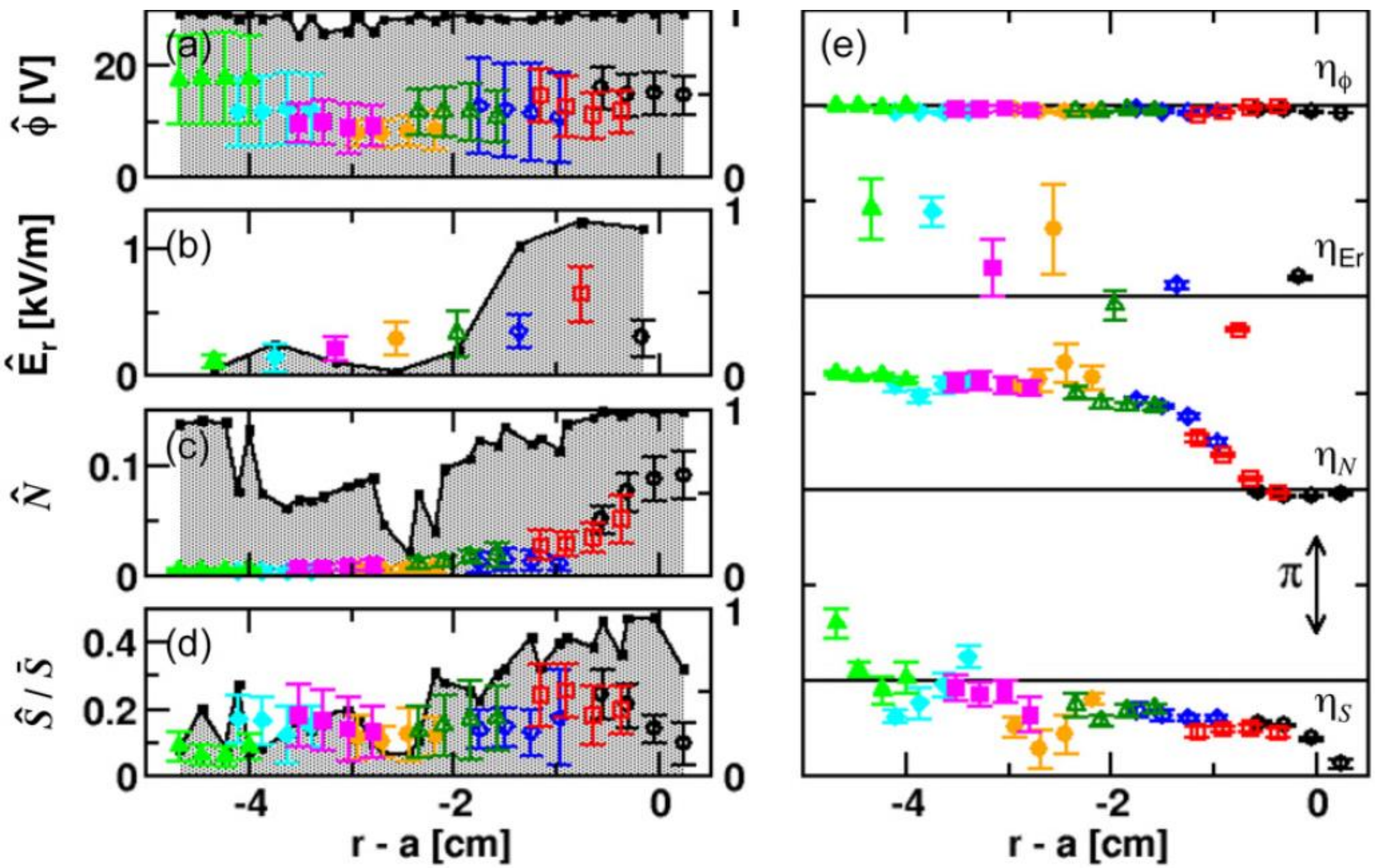
Kobayashi at JFT-2M:

Zonal flow irrelevant in LCO:

- Reynolds-stress drive too weak
- Radial wave length too long

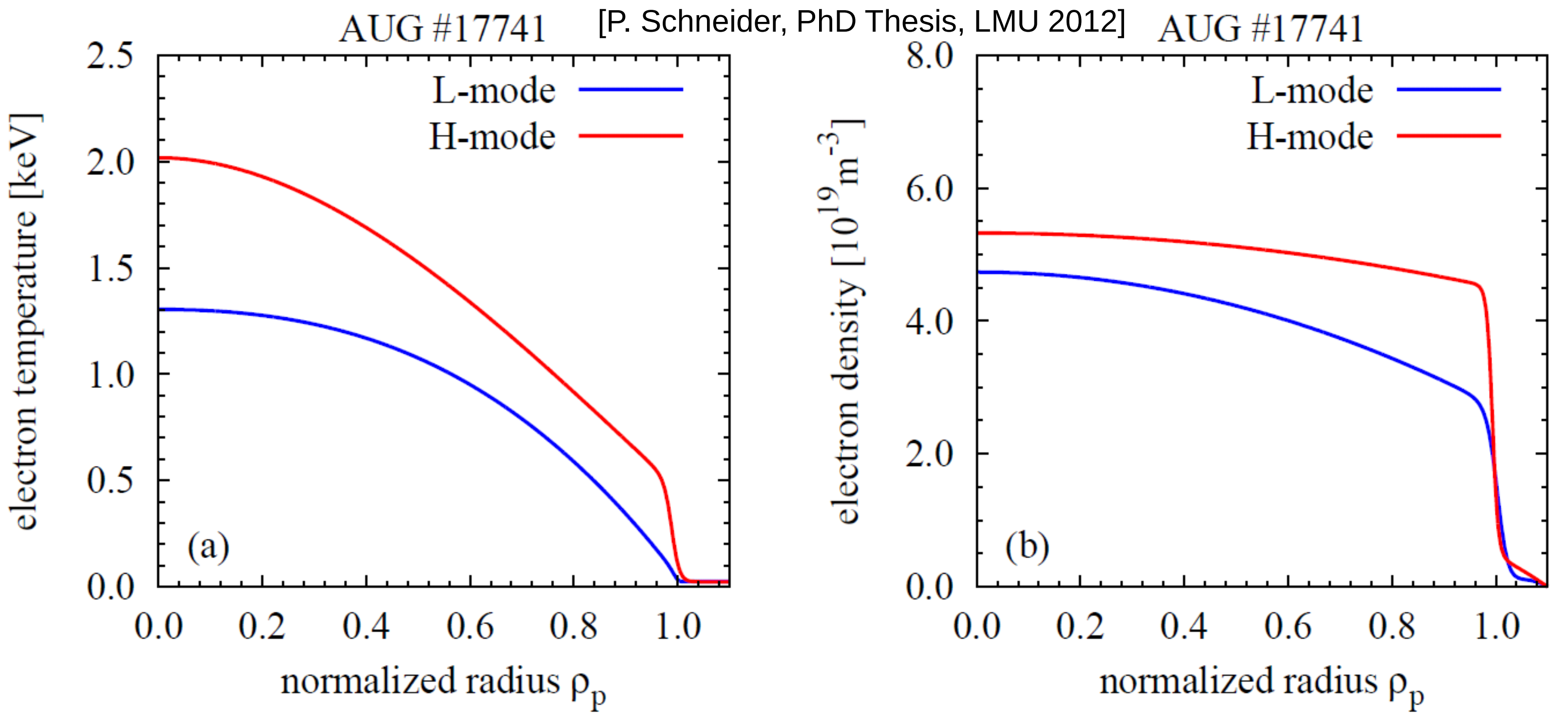
$$S = \sqrt{\langle |\tilde{\phi}|^2 + |H[\tilde{\phi}]|^2 \rangle}$$

amplitude and cross coherence with respect to $\hat{D}_\alpha$



L- and H-mode

[P. Schneider, PhD Thesis, LMU 2012]



L-mode:

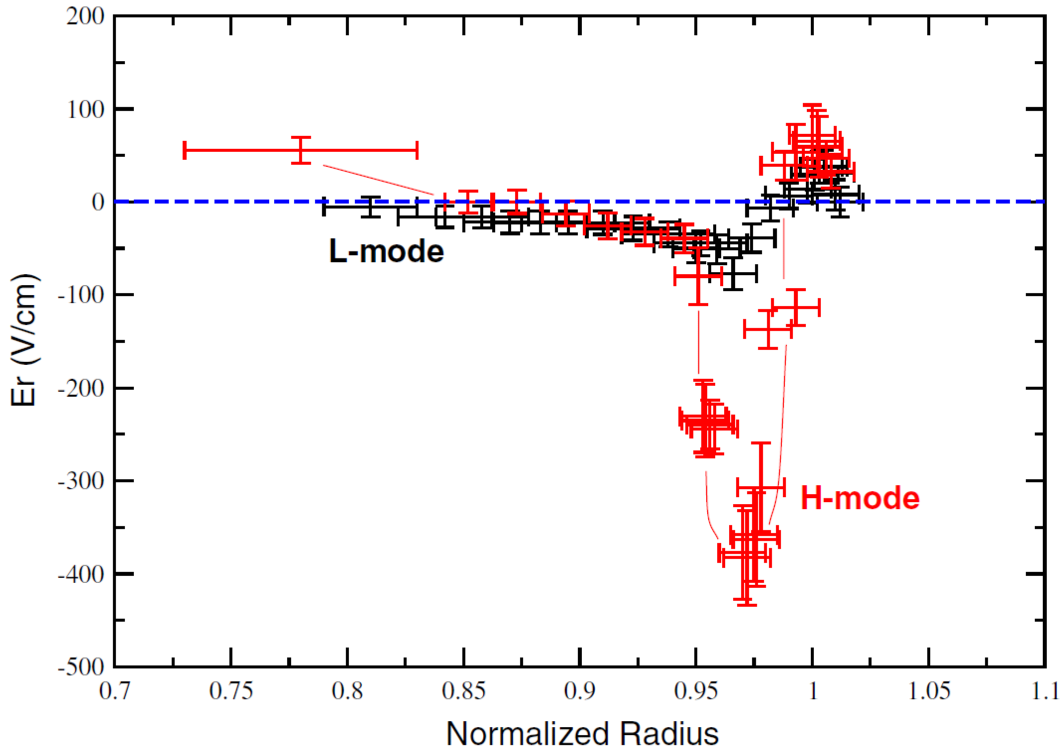
- Low confinement
- High turbulence level
- Shallow gradients

H-mode:

- High confinement
- Low turbulence level
- Steep gradients (pedestal!)
- Edge transport barrier

L- and H-mode

[J. Schirmer et al., NF (2006)]



Turbulence in H-mode "suppressed" by background flow shear:

$$u_{\perp} = -E_r/B$$

$$\Downarrow$$

$$\delta_r u_{\perp} = -\delta_r E_r/B$$

L-mode:

- Low confinement
- High turbulence level
- Shallow gradients

H-mode:

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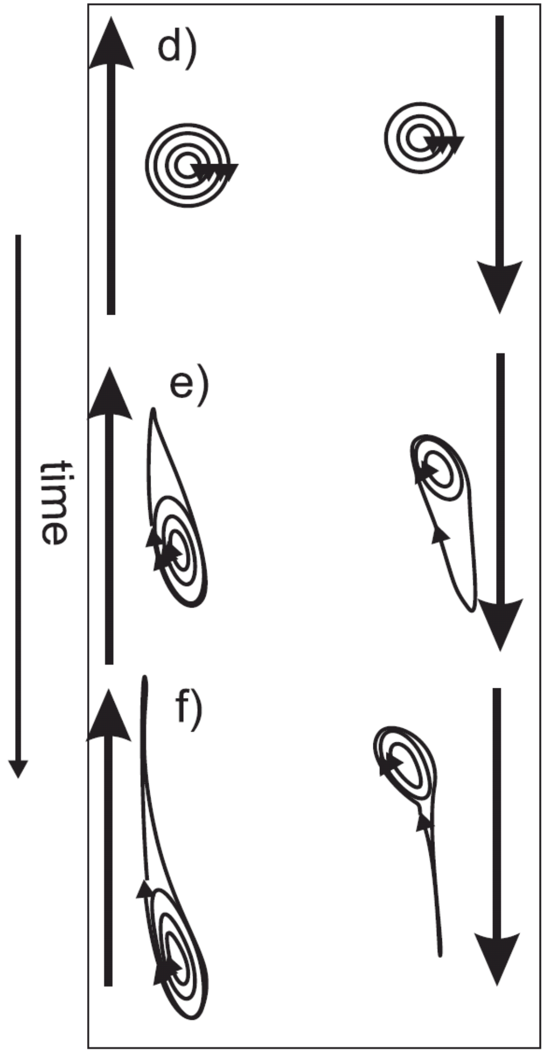
- Low turbulence level
- Steep gradients (pedestal!)
- Edge transport barrier

Turbulence “suppression” in H-mode

Turbulent eddy in a shear field:



[P. Manz et al., PRL (2009)]

Turbulence in H-mode “suppressed” by background flow shear:

$u_\perp = -E_r/B$

⬇

$\delta_r u_\perp = -\delta_r E_r/B$

⬇

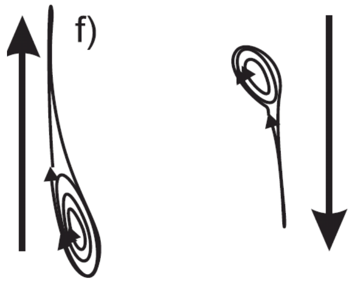
Radial size of eddy decreased by vortex thinning

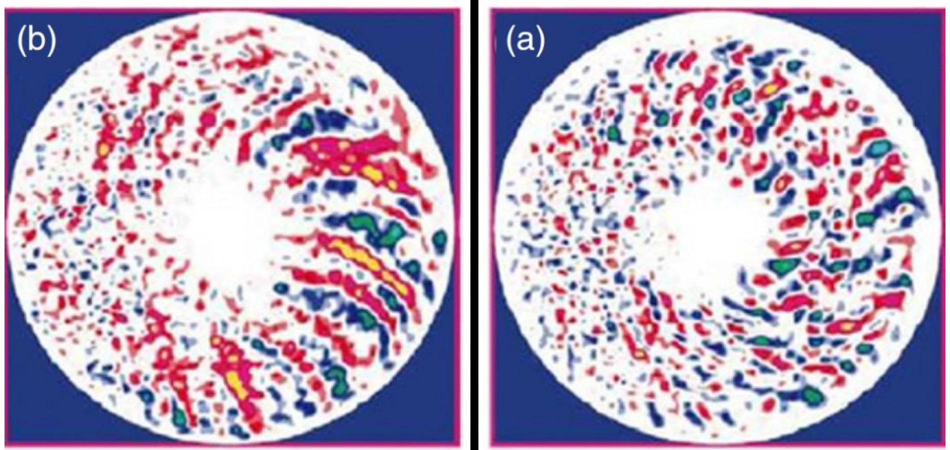
⬇

Turbulent transport reduced

Turbulence “suppression” in H-mode

Low shear: L-mode | **High shear: H-mode**





[X. Garbet et al., NF (2010)]

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$u_\perp = -E_r/B$

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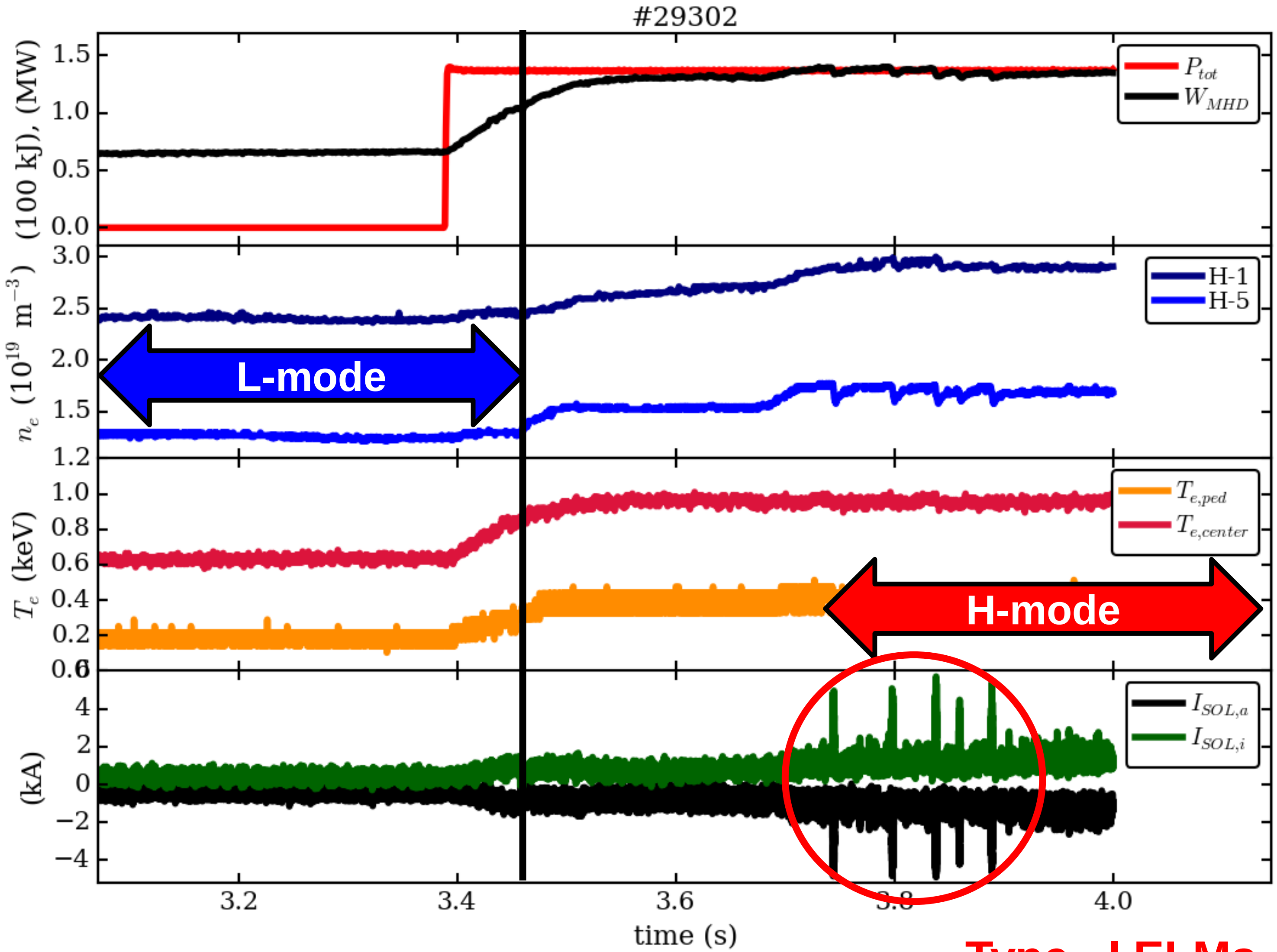
Radial size of eddy decreased by vortex thinning

Turbulent transport reduced

What happens between L- and H-mode?

Typical LH transition (low density):



Type –I ELMs

What happens between L- and H-mode?

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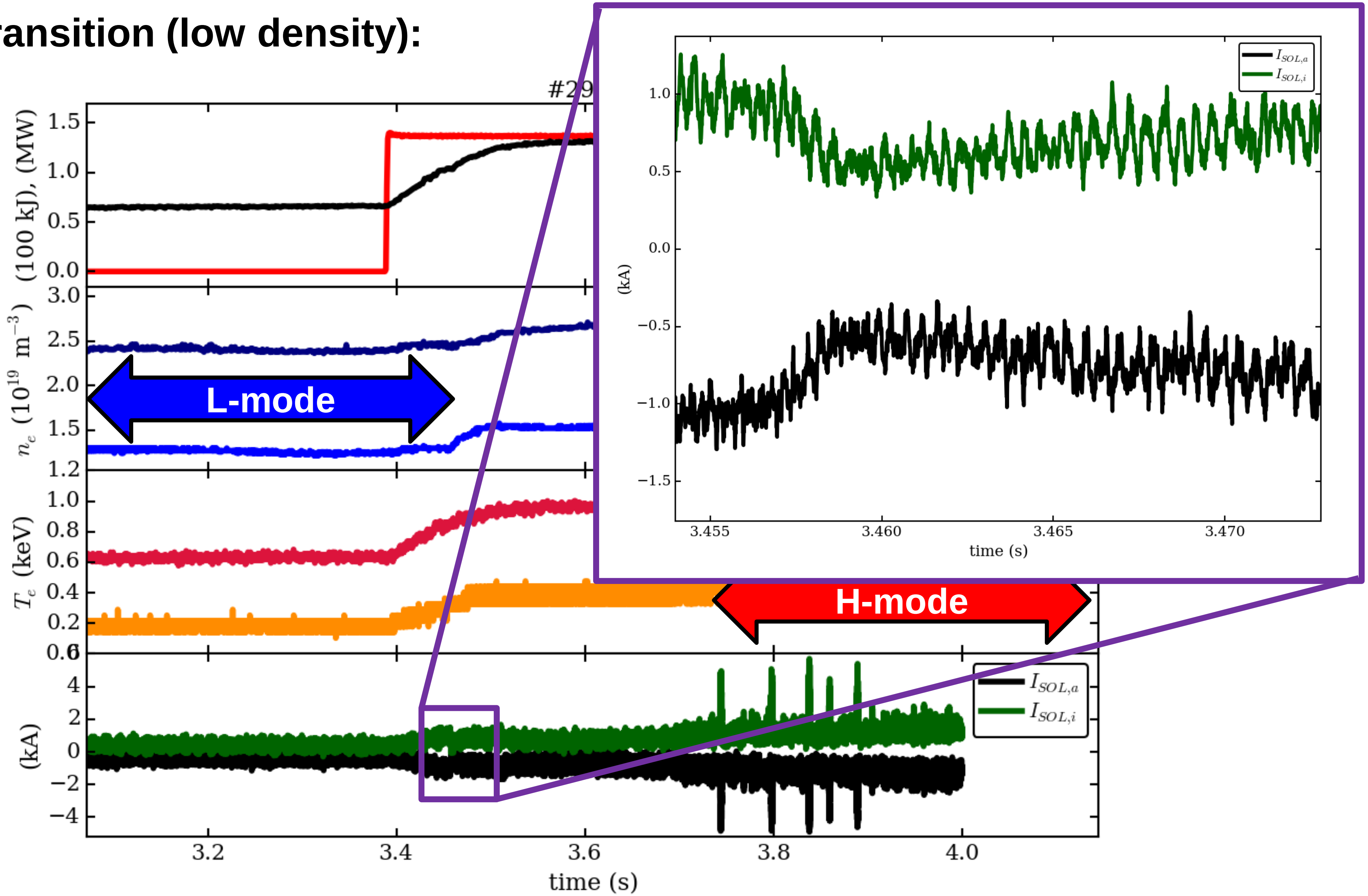
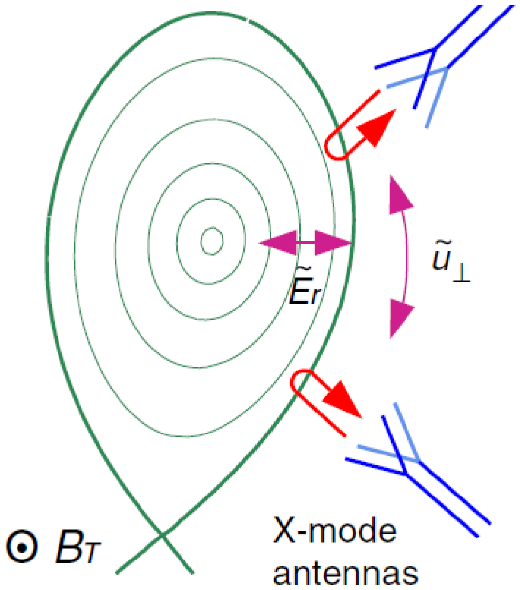


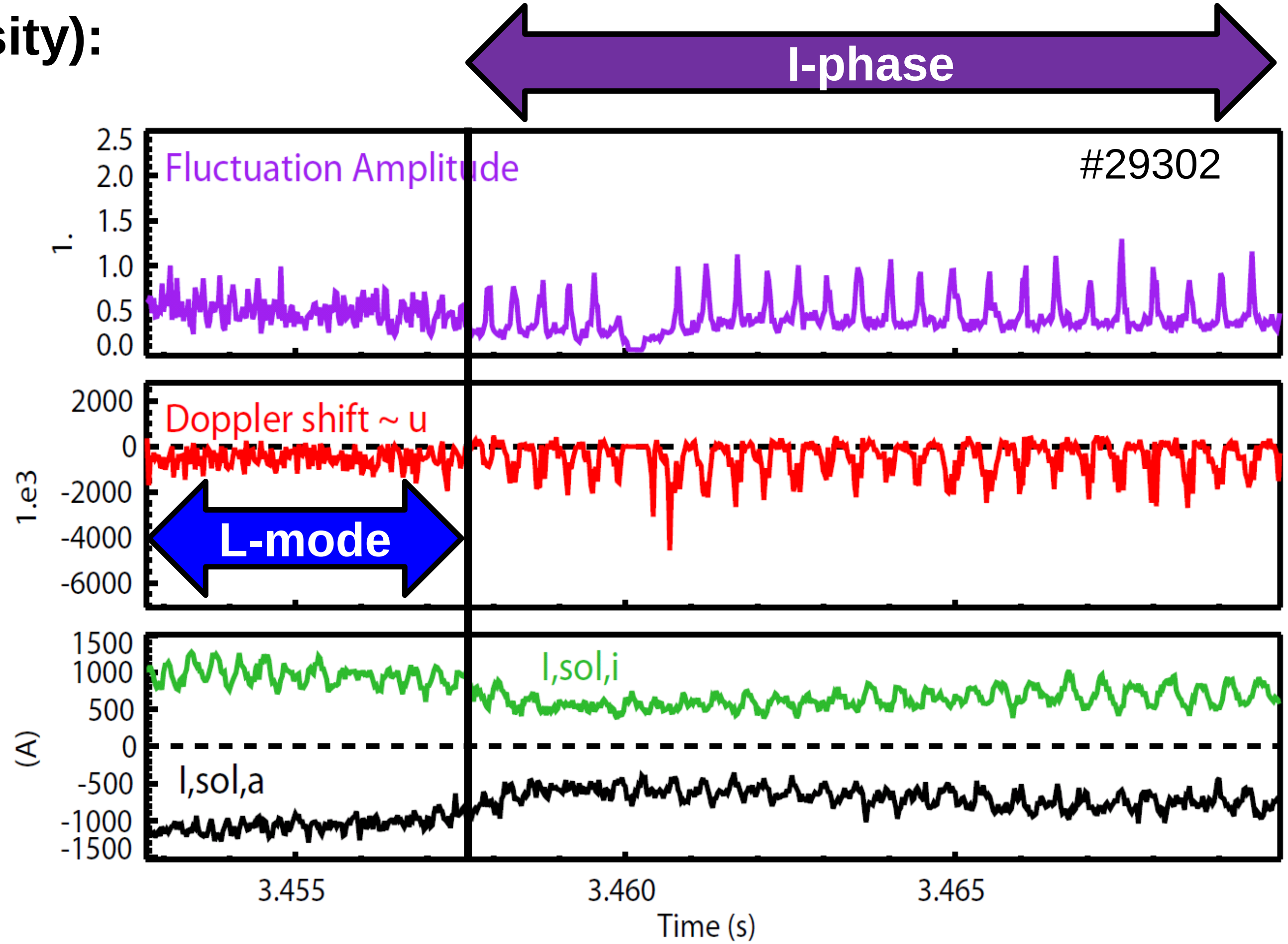
What happens between L- and H-mode?

Typical LH transition (low density):

- Doppler reflectometry



[G. Conway et al., PPCF (2005)]



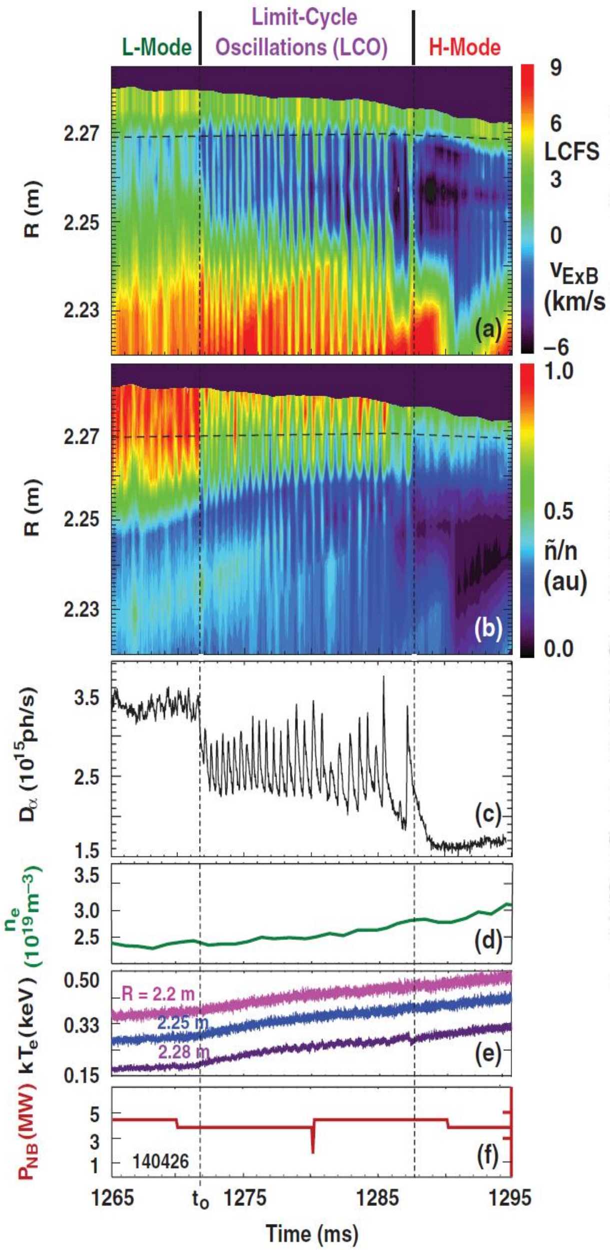
- Doppler shift: $f_D = \frac{u_\perp k_\perp}{2\pi}$

- Density fluctuation amplitude: $S(k_\perp) \propto \tilde{n}_e^2$

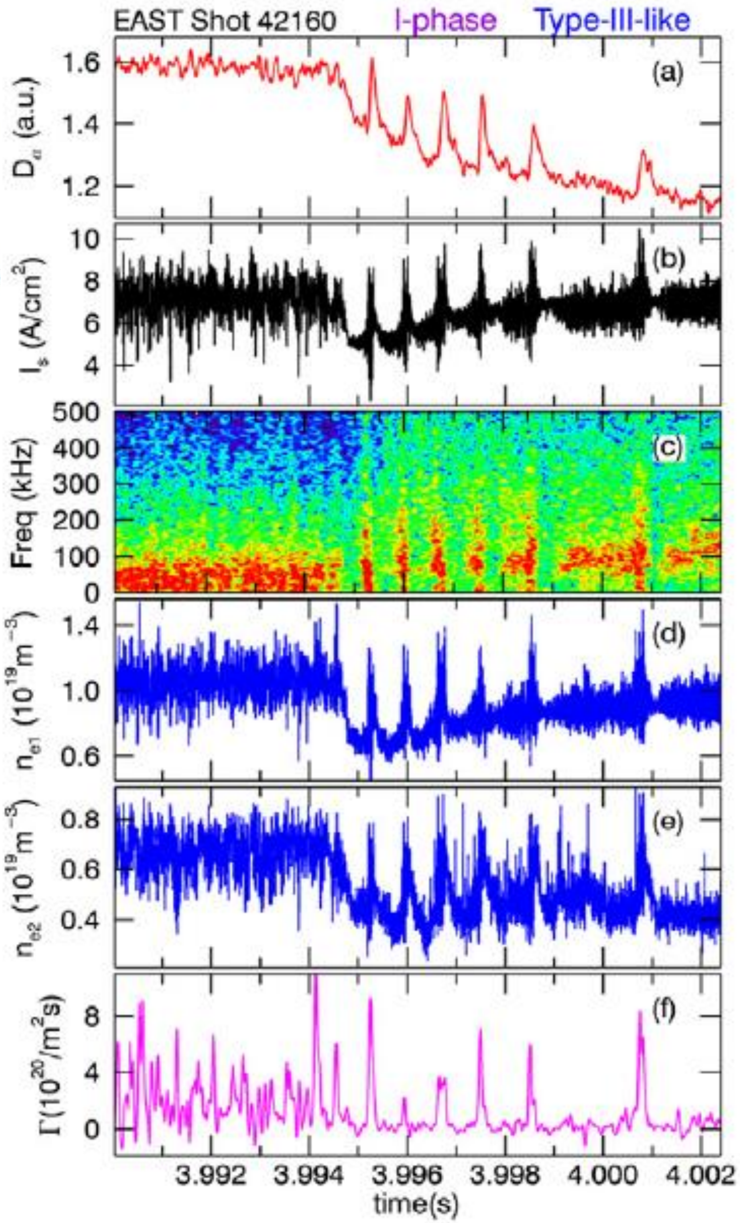
What’s published from other devices?

Other devices see basically the same:

- Limit-cycle oscillations (DIII-D, MAST, HL-2A, JFT-2M,TJ-II, NSTX,…)
- IM-mode (DIII-D)
- I-phase (EAST)
- M-mode (JET)
- Dithering (AUG)
- etc.



[L. Schmitz et al., PRL 2012]



[G. S. Xu et al., NF 2014]

Theoretical models

Aim: Description of the I-phase oscillation

Hope: Understanding of I-phase will help to understand the LH transition

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Example for a "minimal" model: [P. Diamond et al., PRL 1994]

- Turbulence increases with growth rate γ (depends on type of turbulence)

$$\partial_t \langle \tilde{n}^2 \rangle = \gamma \langle \tilde{n}^2 \rangle$$

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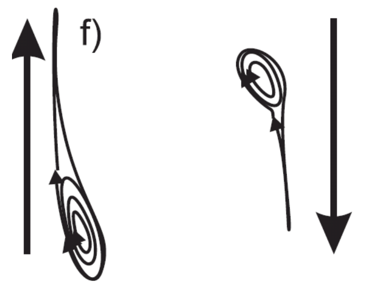
- Turbulence can drive a poloidal flow (**zonal flow**) via the **Reynold stress**

$$\partial_t \langle V_\theta \rangle = -\partial_r \langle \tilde{V}_\theta \tilde{V}_r \rangle$$

Zonal flow (also GAMs)

Reynolds stress



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$$\partial_t \langle \tilde{n}^2 \rangle = \gamma \langle \tilde{n}^2 \rangle$$

- Turbulence can drive a poloidal flow (**zonal flow**) via the **Reynold stress**
- **Viscosity** (collisions, geodesic transfer, Landau damping,…) can damp the flow

$$\underbrace{\partial_t \langle V_\theta \rangle}_{\text{Zonal flow (also GAMs)}} = -\partial_r \underbrace{\langle \tilde{V}_\theta \tilde{V}_r \rangle}_{\text{Reynolds stress}} - \underbrace{\mu \langle V_\theta \rangle}_{\text{Damping}}$$

Zonal flow (also GAMs) — **Reynolds stress** — **Damping**

A minimal I-phase model

Energetic interaction between zonal flow and turbulence:

$$\partial_t \mathcal{N} = \gamma \mathcal{N} - \alpha_1 \mathcal{N} U$$

$$\partial_t U = \alpha_2 \mathcal{N} U - \mu U$$

Two coupled equations:

- $\mathcal{N} = \langle \tilde{n}^2 \rangle$: turbulence energy
- $U = \langle \partial_r V_\theta \rangle^2$: shear flow intensity
- γ, α_1, α_2, μ are (heuristic) parameters

➡ **Lotka-Volterra type of equations**

A minimal I-phase model

Energetic interaction between zonal flow and turbulence:

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Two coupled equations:

- $\mathcal{N}$ = turbulence energy (rabbits)
- U = shear flow intensity (foxes)
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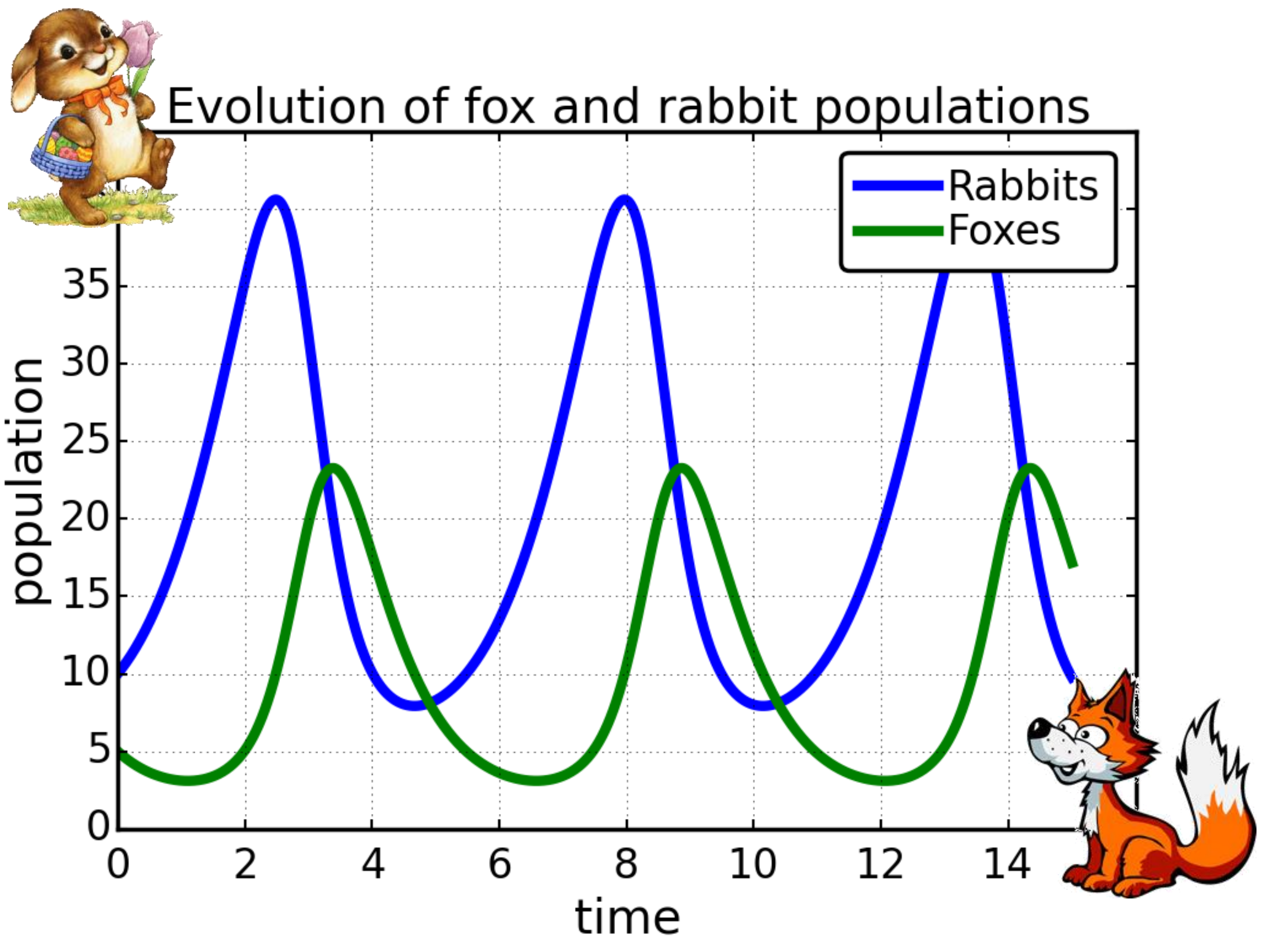
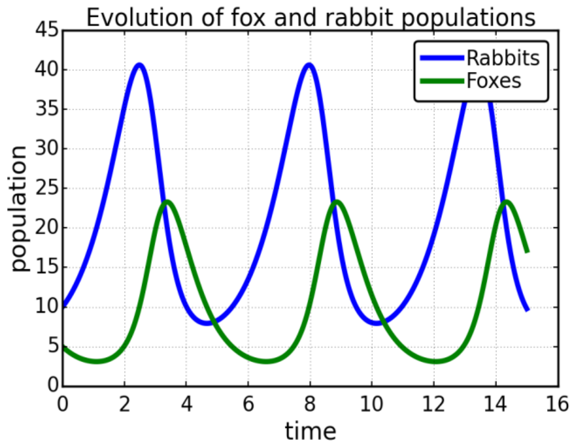


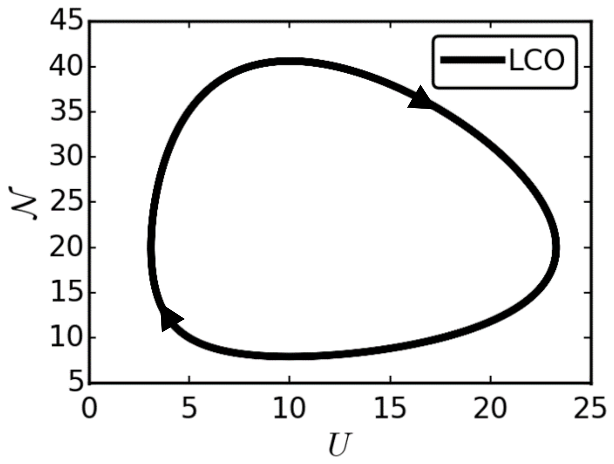
Lotka-Volterra type of equations: predator-prey oscillations

A minimal I-phase model

Solutions:

a) Limit-cycle oscillation (phase shift!)





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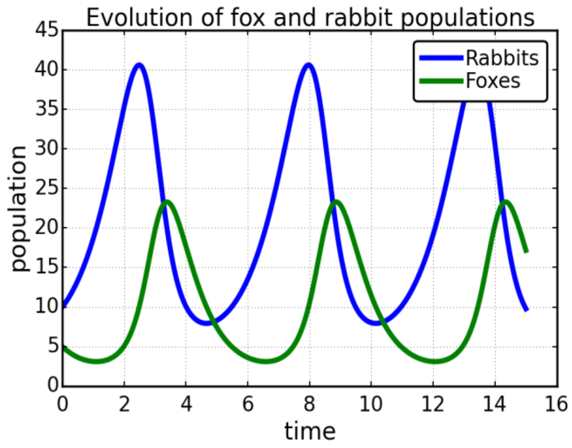
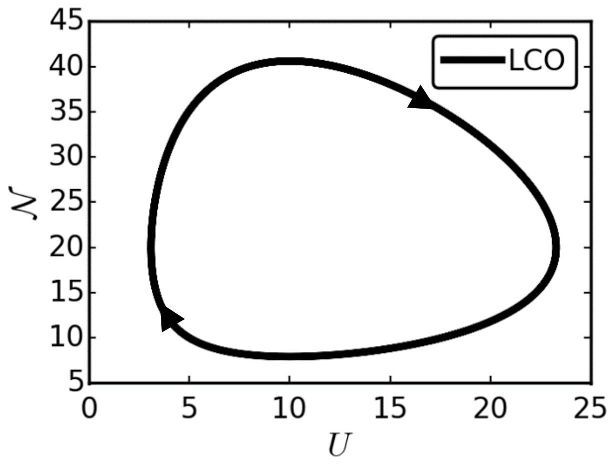
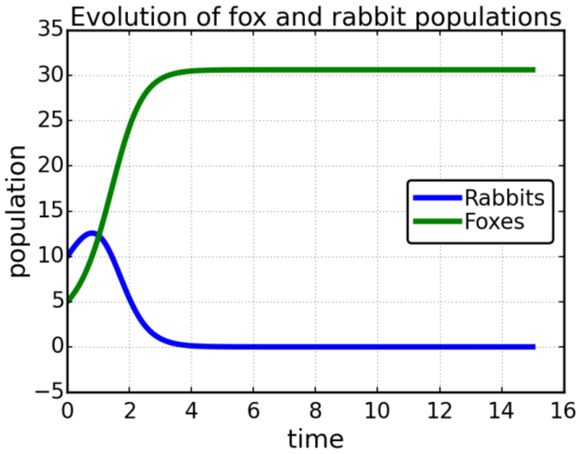
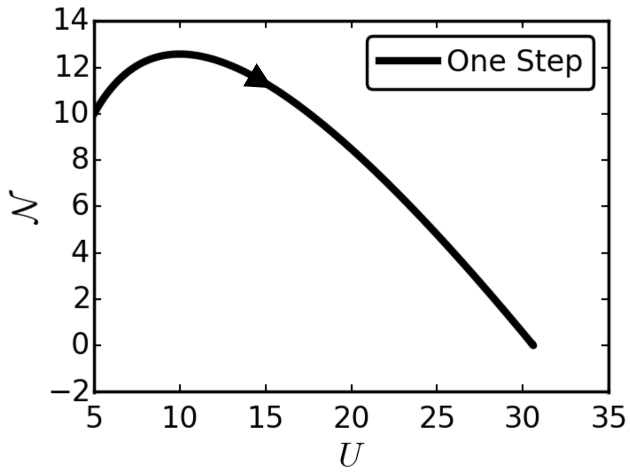




b) One step transition ($\mu = 0$):





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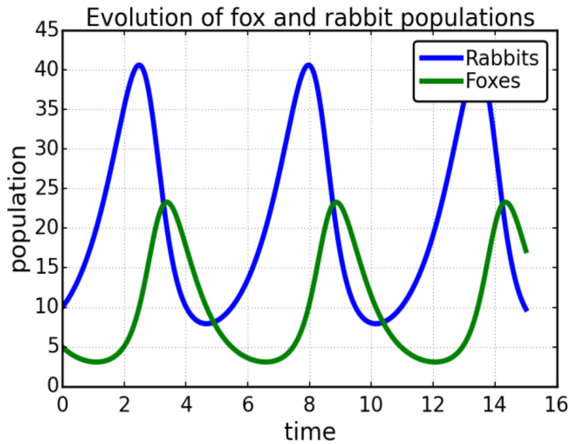

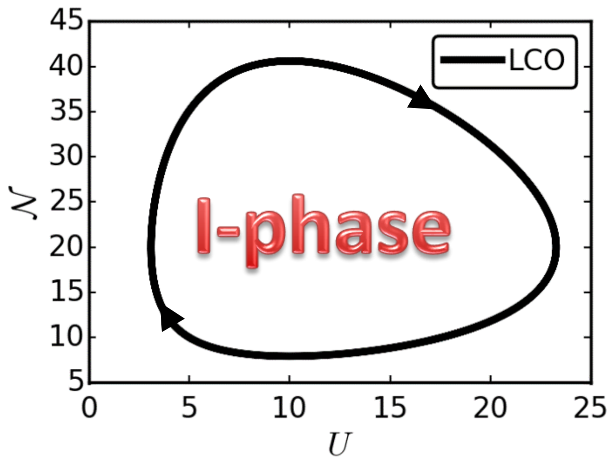

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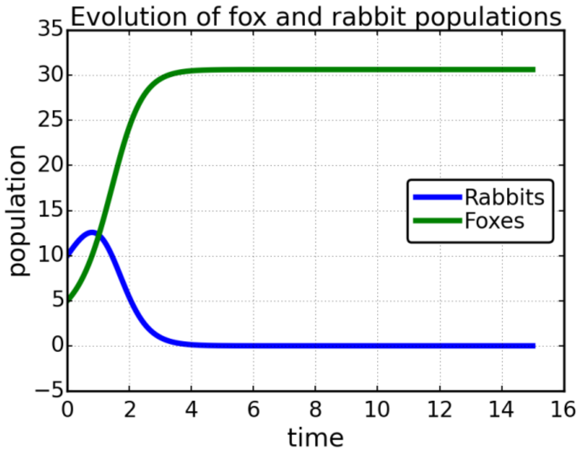
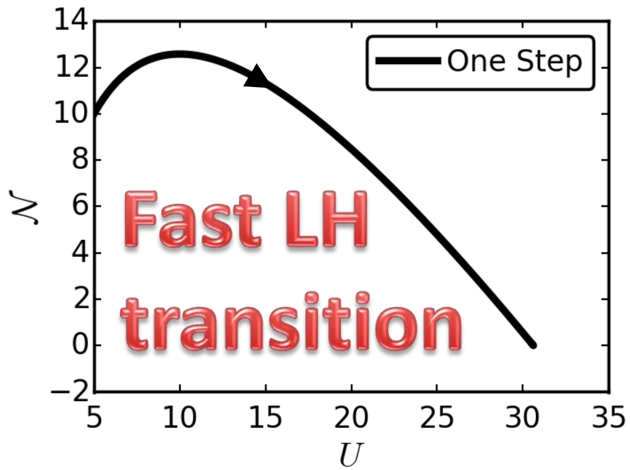
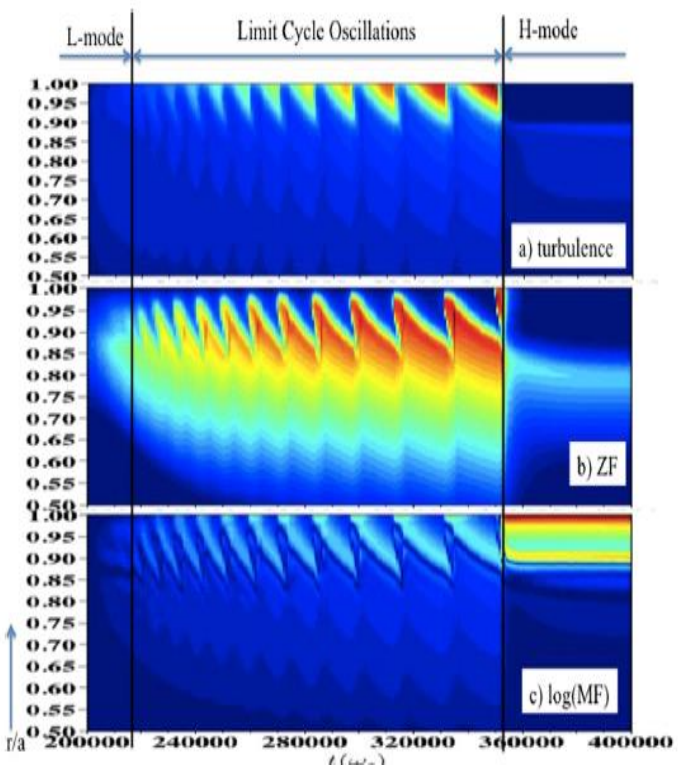




Other I-phase models

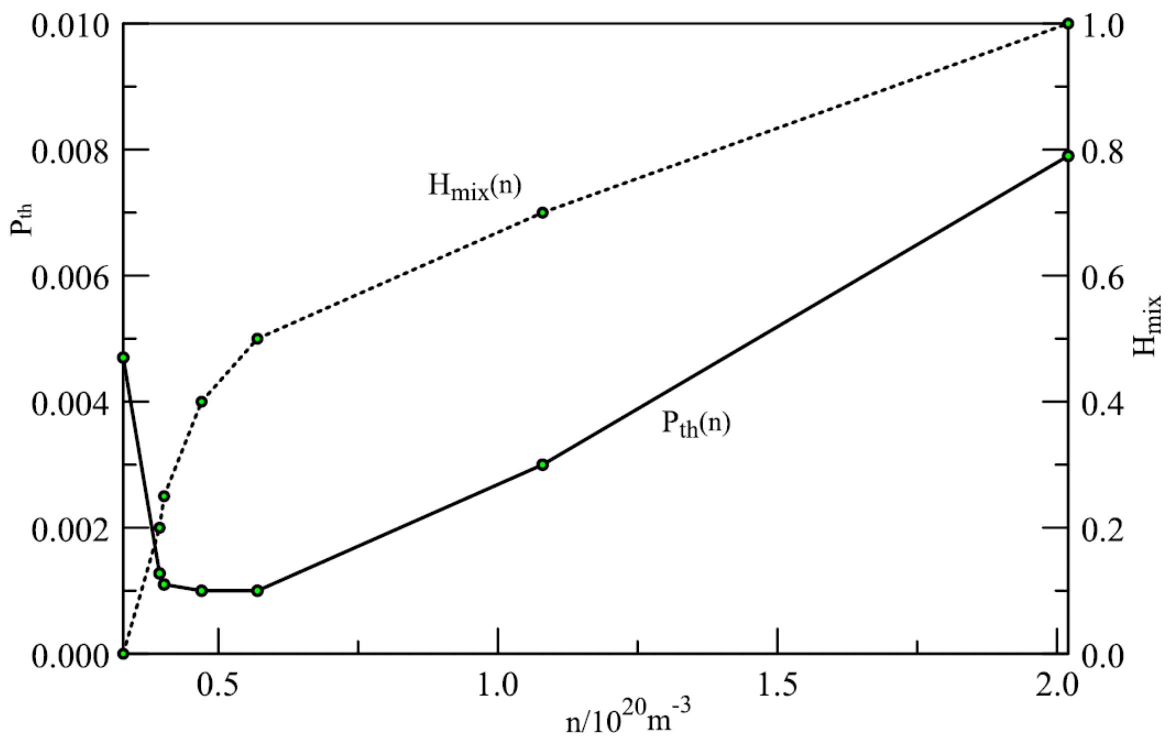
There are a lot of variations!

- Multiple predators (diamagnetic flow, zonal flow, GAMs,…) [M. Sasaki et al., NF 2012]
- Spatially dependent (full radial profile), electron/ion heating



[K. Miki et al., PoP 2012]

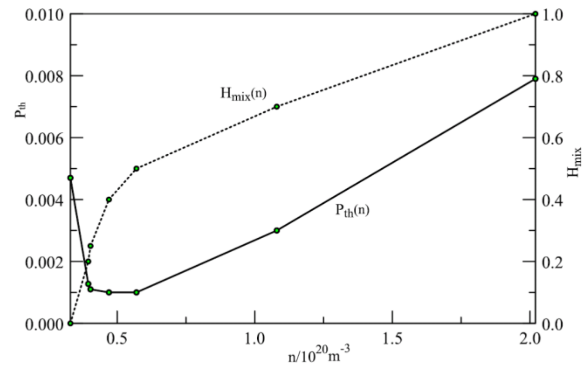
[M. Malkov et al., PoP 2015]



Other I-phase models

There are a lot of variations!

- Multiple predators (diamagnetic flow, zonal flow, GAMs,…) [M. Sasaki et al., NF 2012]
- Spatially dependent (full radial profile) [K. Miki et al., PoP 2012]
- Limit-cycle oscillations without zonal flows (type-III ELMs)
  [Itoh et al., PRL 1991]
- Bifurcation model for T_e and E_r applied to AUG data
  [H. Zohm et al., PRL 1994]



[M. Malkov et al., PoP 2015]

- Predator-prey model derived from momentum transport equations
  [G. Staebler et al., PPCF 2015]
- etc.

Problem of all of these models:

Equations contain free parameters ➡ **limited predictive capabilities**

Some works seem to confirm that zonal flows trigger the LH transition:

LH transition happens when:

$$\frac{\langle \tilde{v}_r \tilde{v}_\theta \rangle \frac{\partial \langle v_{ZF} \rangle}{\partial r}}{\gamma_{eff} \epsilon_T} > 1$$

i.e. when the energy transfer from turbulence to flow

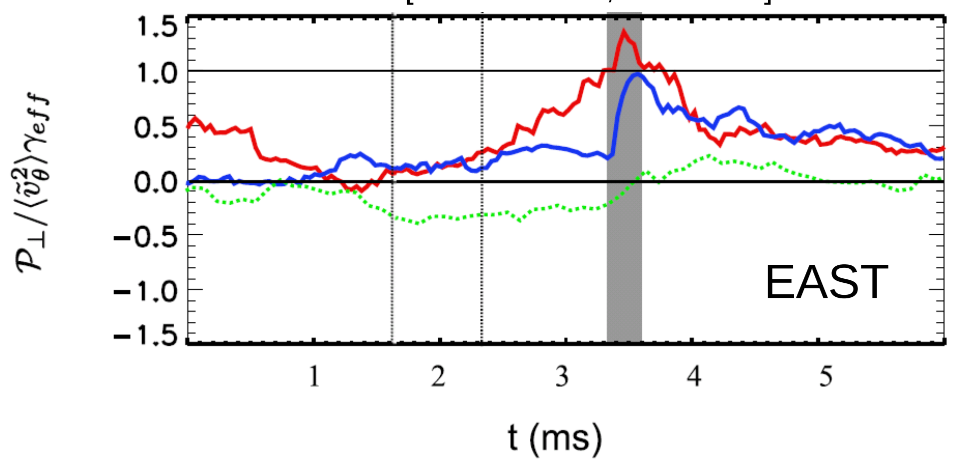
$$\mathcal{P}_\perp = \langle \tilde{v}_r \tilde{v}_\theta \rangle \frac{\partial \langle v_{ZF} \rangle}{\partial r}$$

exceeds the growth of turbulence

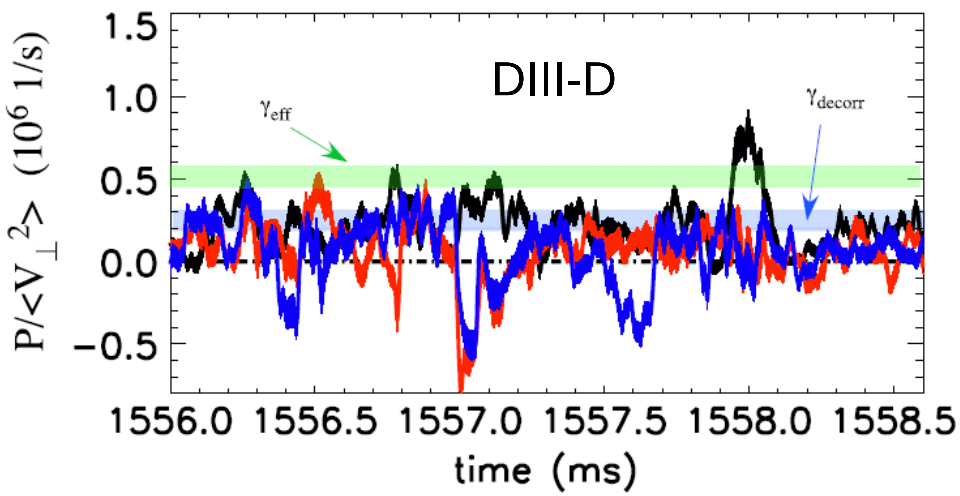
$$\gamma_{eff} \epsilon_T$$

with turbulent energy $\epsilon_T = \langle \tilde{v}^2 \rangle$.

[P. Manz et al., PoP 2012]



[Z. Yan et al., PRL 2014]

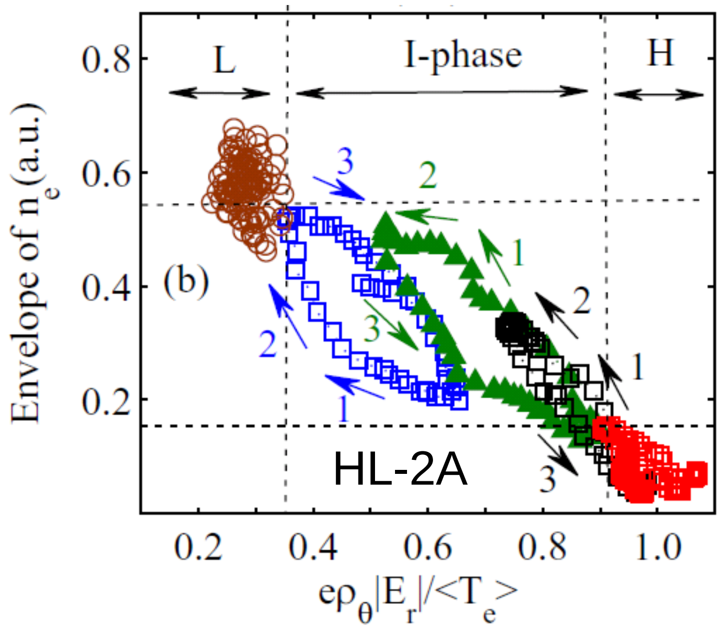


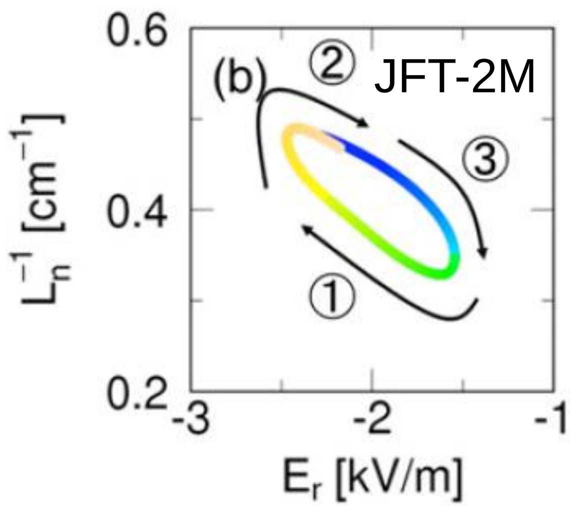
Other works don't agree with pure zonal flow models:

- Limit-cycle in wrong direction
  - Explanation: mean flow $E_r \approx \frac{\nabla p}{en}$ drives IH transition

- Reynolds stress drive too weak and radial wavenumber too large
  - Explanation: mean flow involved in I-phase oscillations

[J. Cheng et al., NF 2014]





[T. Kobayashi et al., PRL 2014]