Overview of **Experimental Studies** on **Inter-ELM** Pedestal localized **Fluctuations** and **Challenges** for their **Modeling**

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with contributions of

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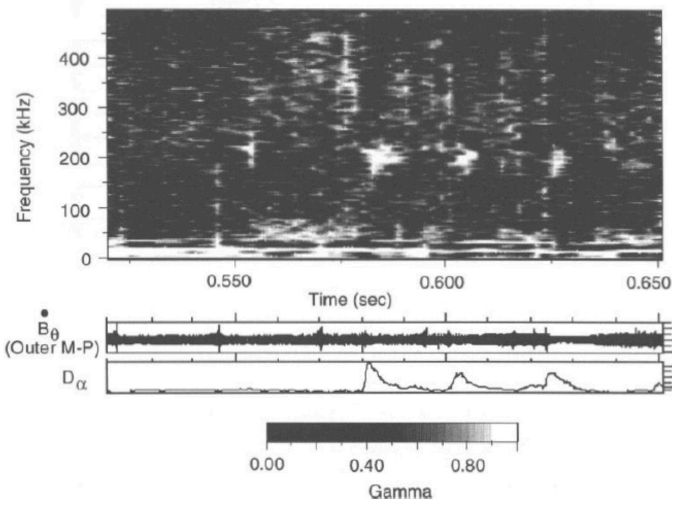
NSTX-U / Magnetic Fusion Science meeting, Princeton, Dec. 03, 2018

Long effort to characterize pedestal instabilities…

PBX-M



[S. M. Kaye et al., PPCF 1994]

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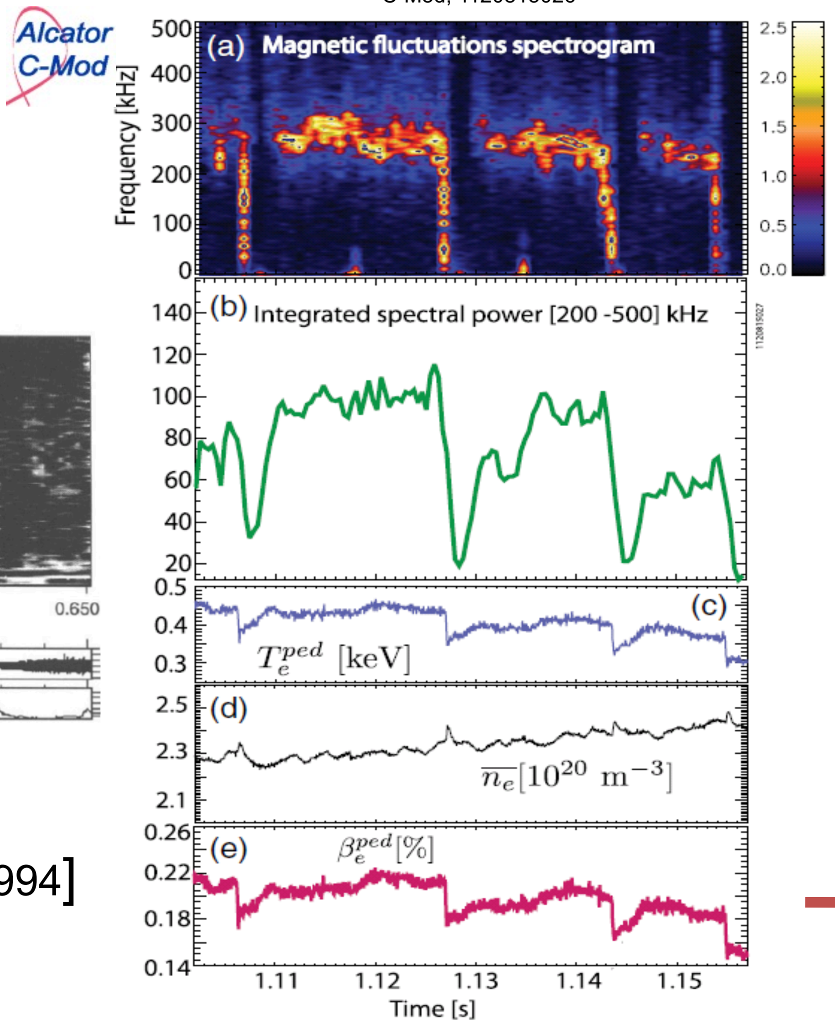
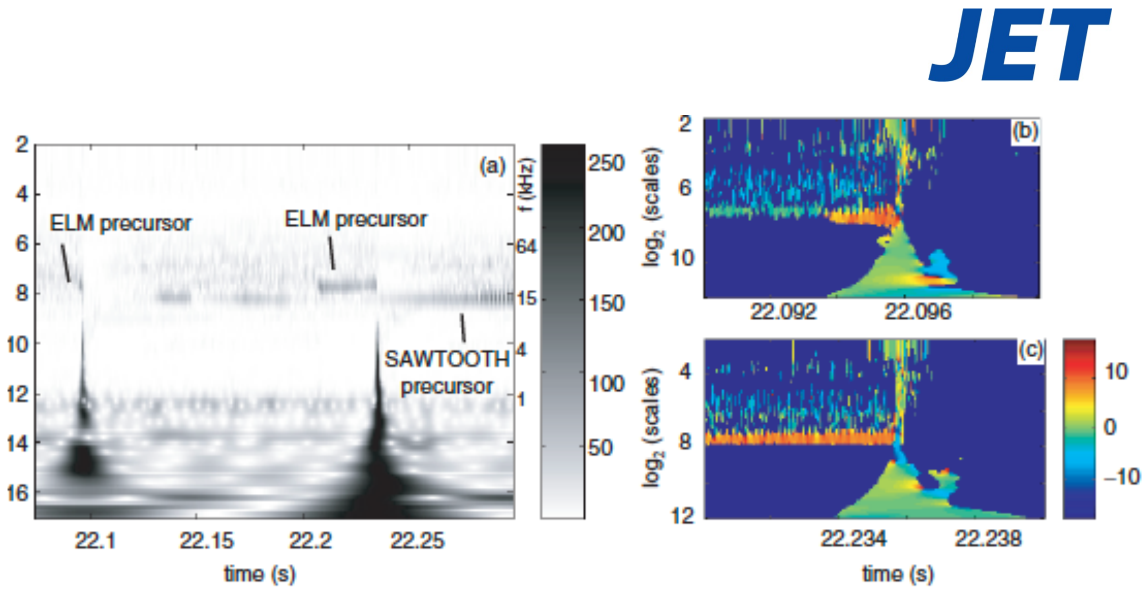


[A. Diallo, et al., PRL 2014]

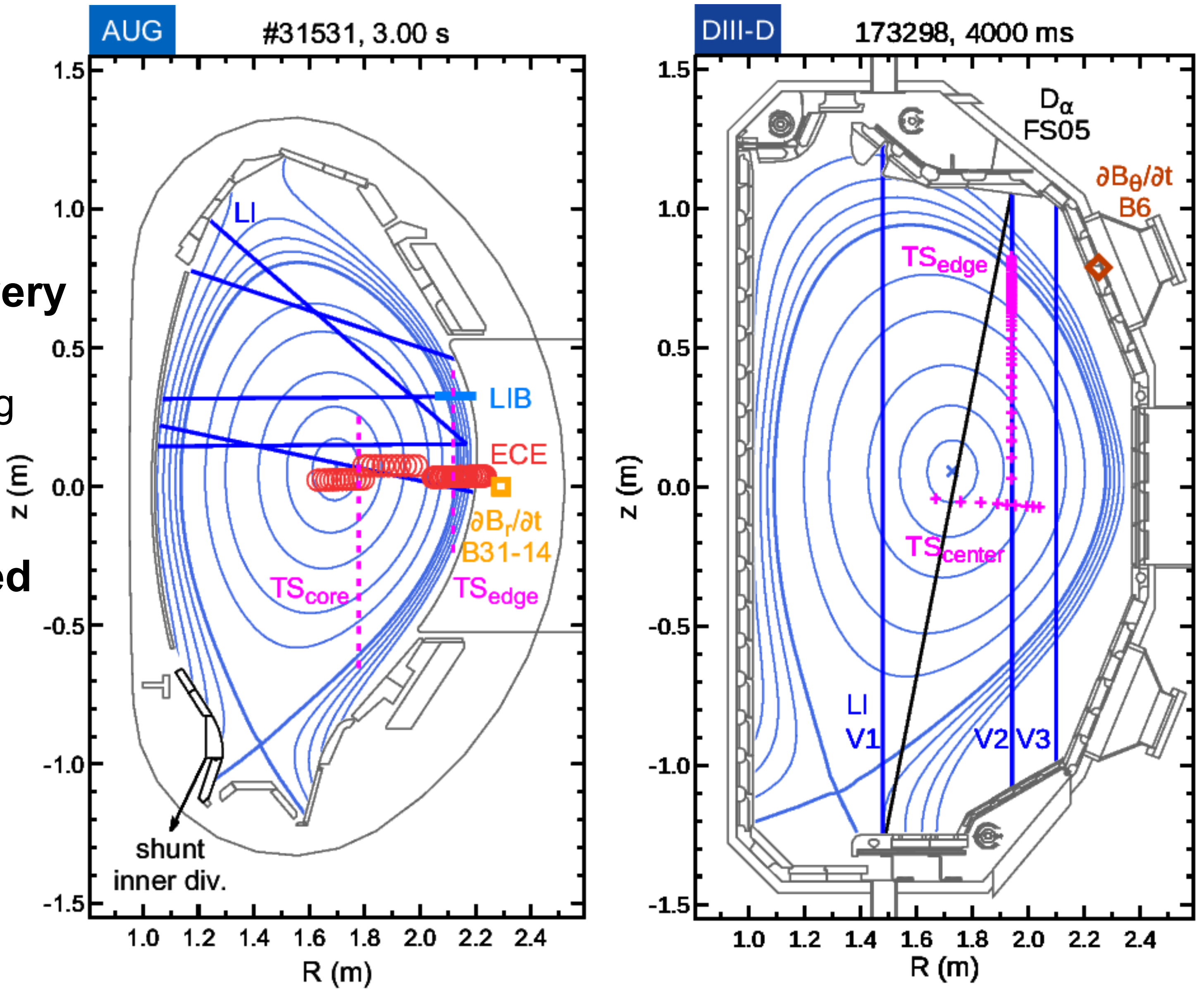


[F. M. Poli et al., PPCF 2008]

→ Now is the time to achieve fundamental understanding of them using sophisticated modelling

Challenge - Diagnosing the pedestal

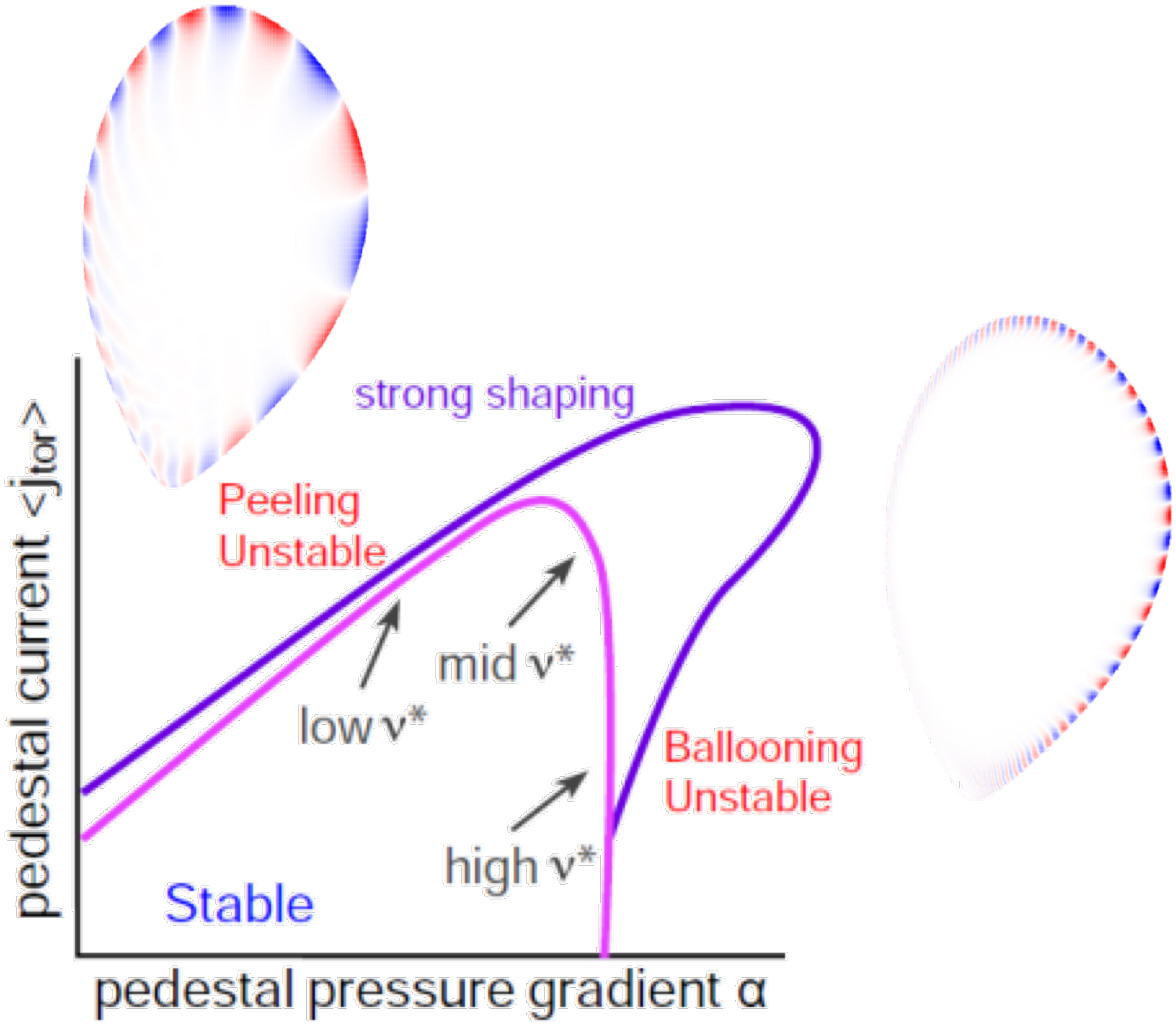
- **Profiles & fluctuations required for good interpretation**
- **Uncertainties are associated with every measurement**
  - Awareness necessary when interpreting
- **Understand and to consider the fundamental limitations of the utilized diagnostics**
  - Some examples:
    - ➢ ECE: shine through
    - ➢ BES: radial widening of emission profile
    - ➢ CER: assumption of equilibrium temperature



Theory - pedestal stability

- **Peeling-ballooning P-B theory:**
  - Peeling Mode
    - ➢ Current driven instability
  - Ballooning Mode
    - ➢ Pressure driven instability

- **P-B gives a 'hard' limit for the edge pressure**

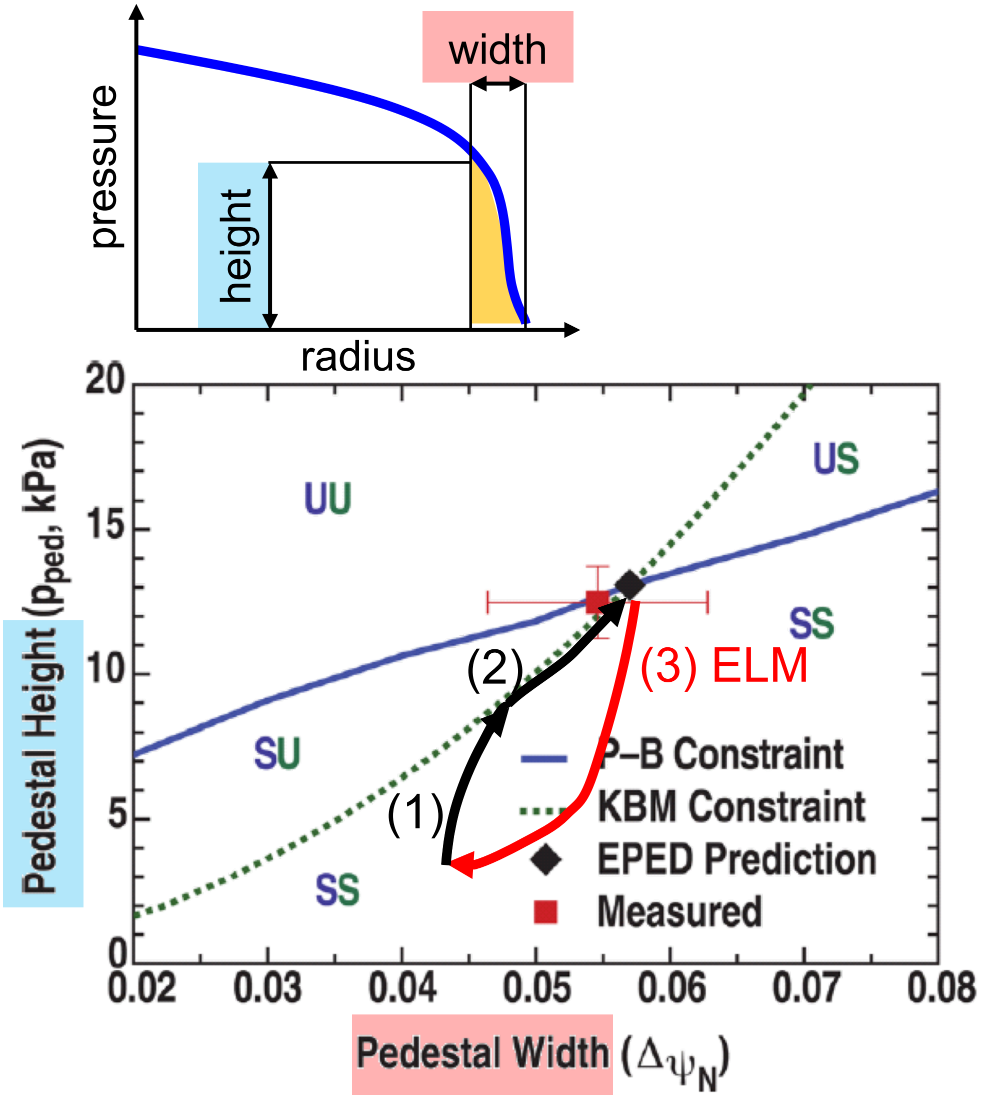


[P. B. Snyder et al., POP 2009]

Theory - pedestal evolution

- **Model for ELM cycle**
  (1) Pedestal height and width increase till kinetic ballooning mode (KBM) boundary ('soft limit') is reached
  (2) Pedestal gradient is clamped and height and width evolve along the KBM limit
  (3) ELM crash when P-B ('hard') limit is reached

- **Limitation of pedestal evolution ('soft limit') observed in several experiments**
  [A. Burckhart et al., PPCF 2010]
  [D. Dickinson et al., PRL 2012]
  [A. Diallo et al., PRL 2014]



[P. B. Snyder et al., POP 2012]

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Drive and suppression of pedestal instabilities

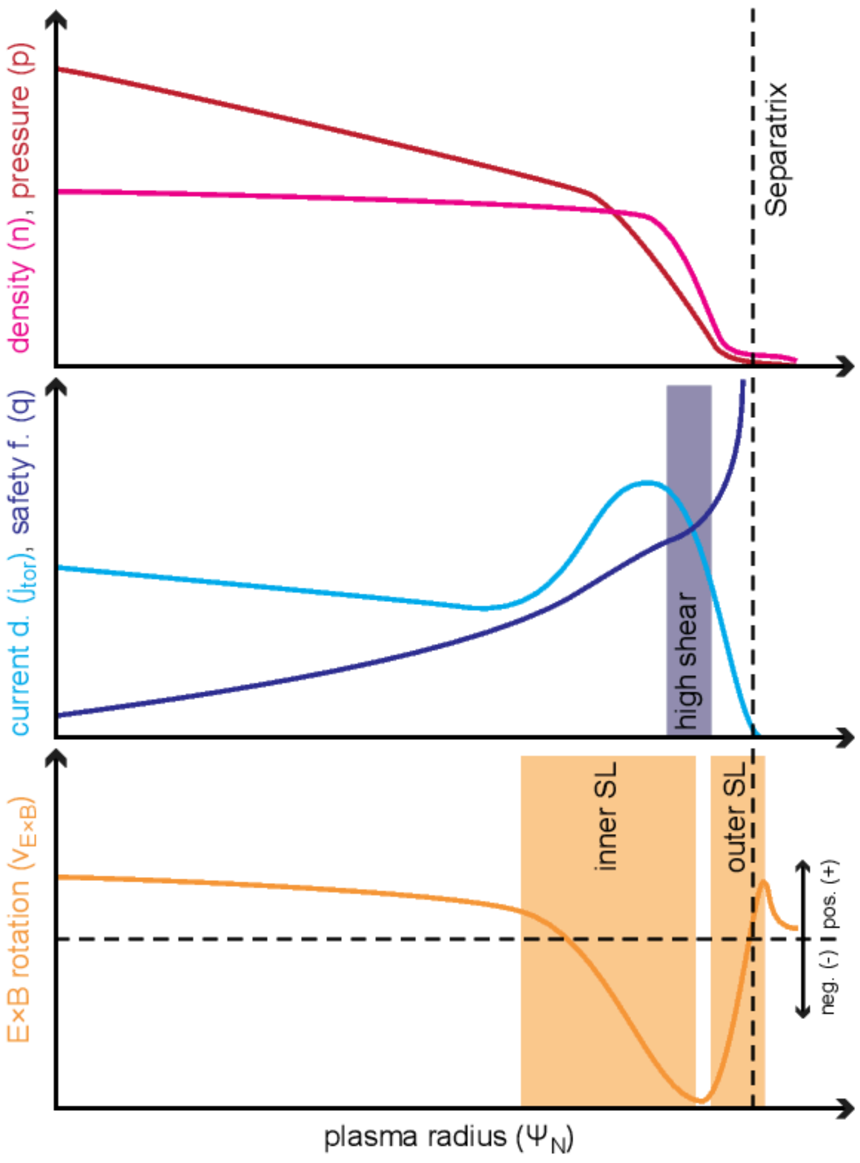
- **Pressure gradient (∇p)**
  - Typically drives ballooning-type instabilities
    - ➢ ∇p linked to density (n) and temperature
- **Edge current density (j_{tor})**
  - Main contribution is bootstrap current (j_{BS})

$$j_{BS} \propto \sqrt{\varepsilon}\, {}^{\nabla p}\!/_{\beta_\vartheta}$$

    - ➢ Order: ∇n ~ 0.5, ∇Te ~ 0.15 and ∇Ti ~ 0.1
  - Modifies the safety factor profile (q)
    - ➢ Region of high magnetic shear
- **E×B rotation ($v_{E\times B}$)**
  - Radial electric field (Er)

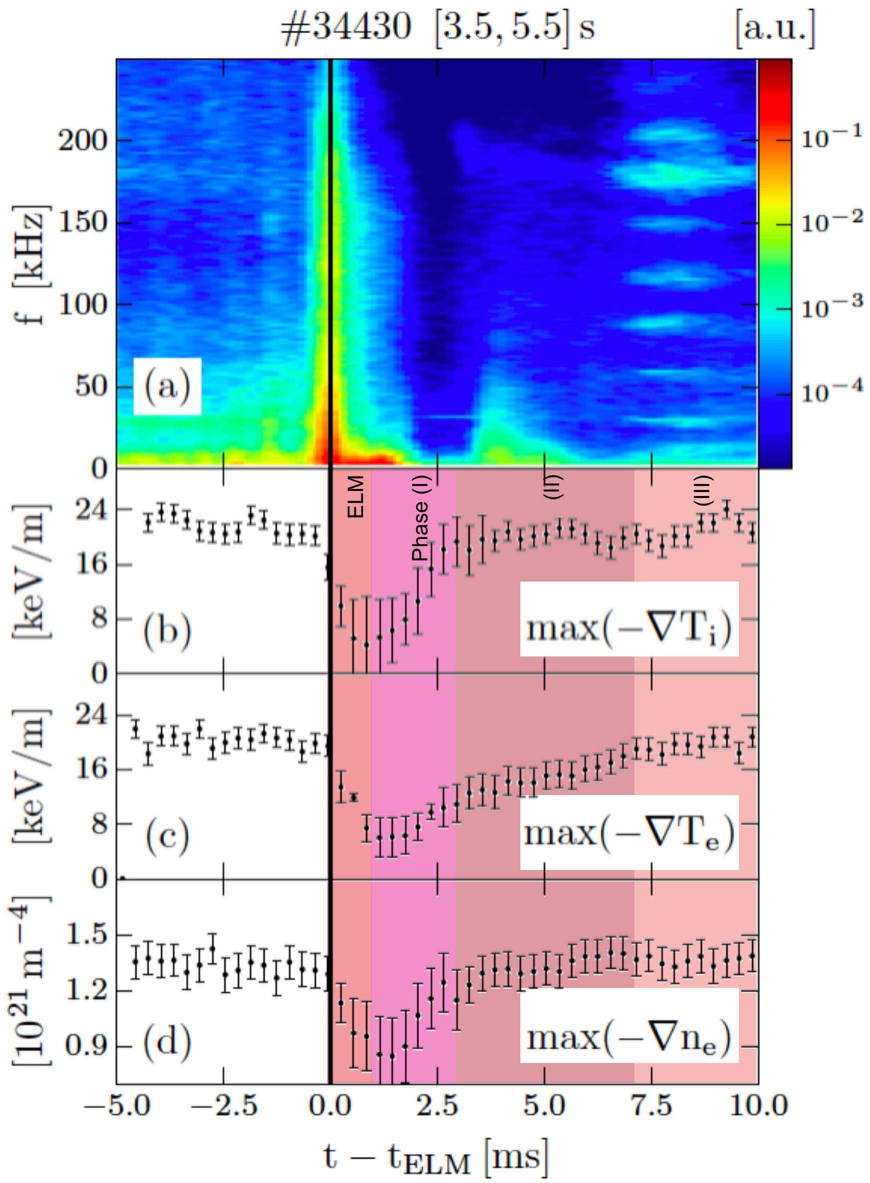
$$E_r = {}^{\nabla p_\alpha}\!/_{Z_\alpha e n_\alpha} - v_{\Theta,\alpha} B_\phi + v_{\phi,\alpha} B_\Theta$$

    - ➢ Sheared flows suppress instabilities



Distinct pedestal recovery phases & fluctuations

- **Phase (I):**
  - Electron density (n_e) gradient and ion Temperature (T_i) gradient
    - ➢ Fluctuations absent!
- **Phase (II):**
  - Electron temperature (T_e) gradient
    - ➢ Medium frequency range fluctuations
- **Phase (III):**
  - Gradient saturation
    - ➢ High frequency fluctuations
    - ➢ Low frequency fluctuations and precursor modes



[M. Cavedon et al., PPCF 2017, PSI 2018 & JNM submitted]

Abstract picture of the pedestal evolution

- **Phase (I):**
  - Electron density (n_e) gradient and ion Temperature (T_i) gradient
    - ➢ Fluctuations absent!
- **Phase (II):**
  - Electron temperature (T_e) gradient
    - ➢ Medium frequency range fluctuations
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  - Gradient saturation
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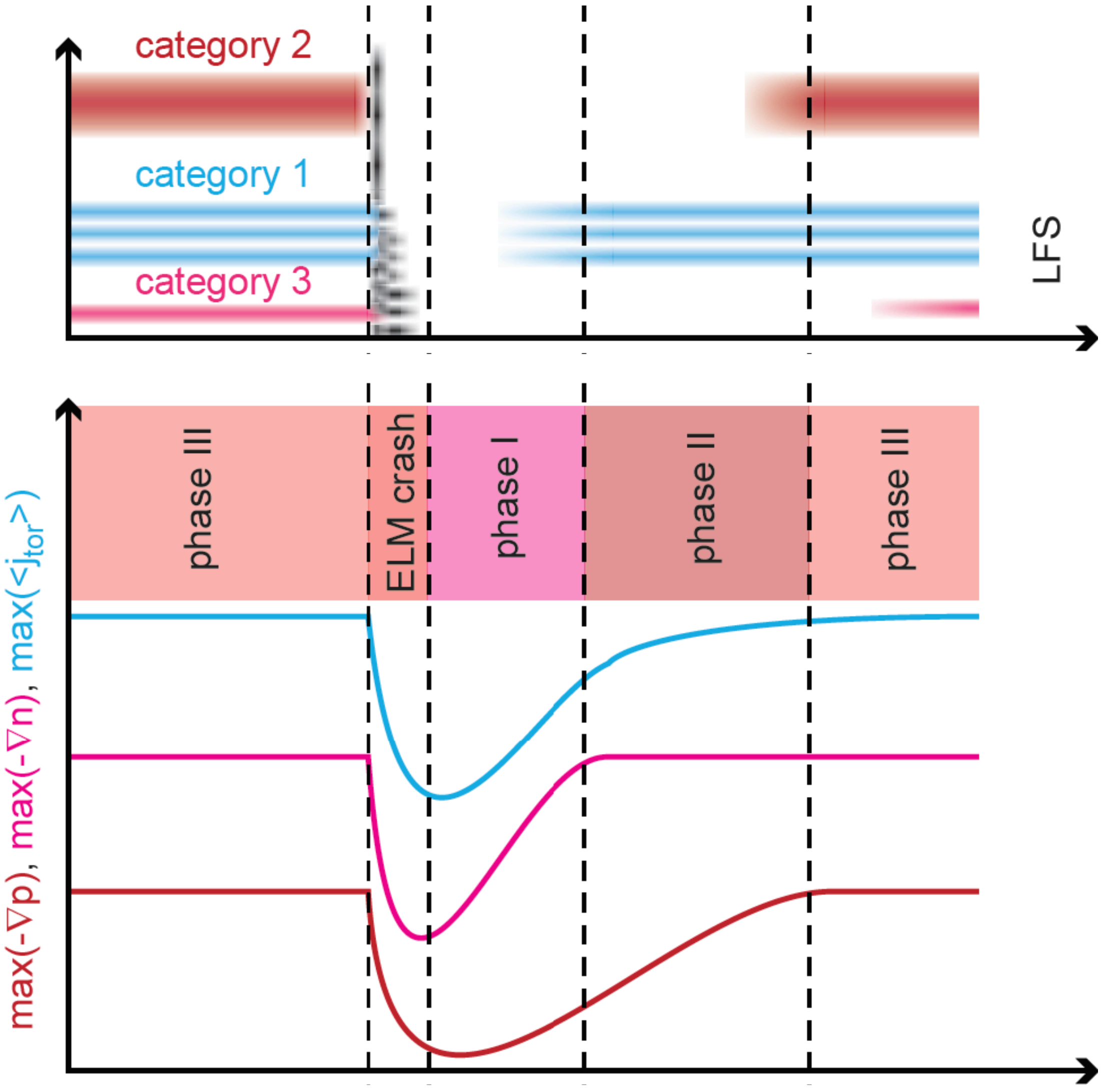
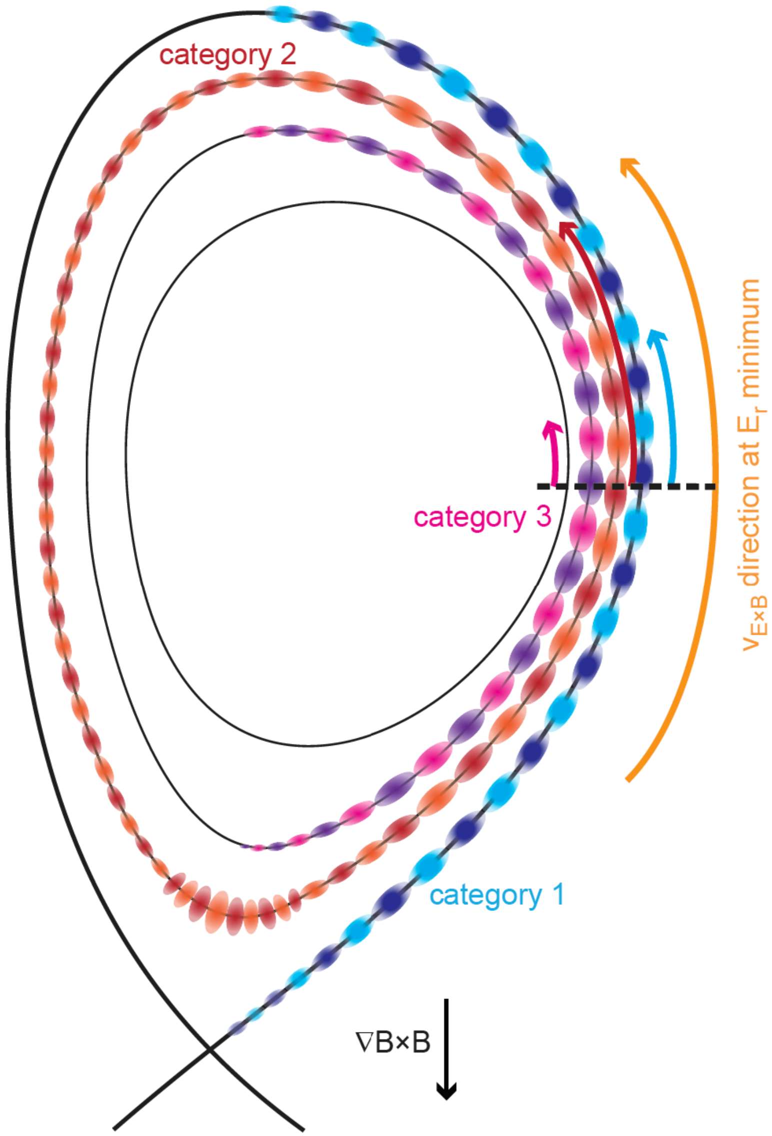


Three instability categories – An Overview

- **Category 1**
  - Separatrix localized
    - ➢ Appears at medium frequency range (30 kHz to 150 kHz)
    - ➢ Onset after pedestal recovery phase I
    - ➢ 'Ballooned' mode structure

- **Category 2**
  - Localized towards the $E_{r,min}$
    - ➢ Appear at high frequency range (> 200 kHz)
    - ➢ onset connected to T_e pedestal evolution (after recovery phase II)
    - ➢ HFS magnetic response

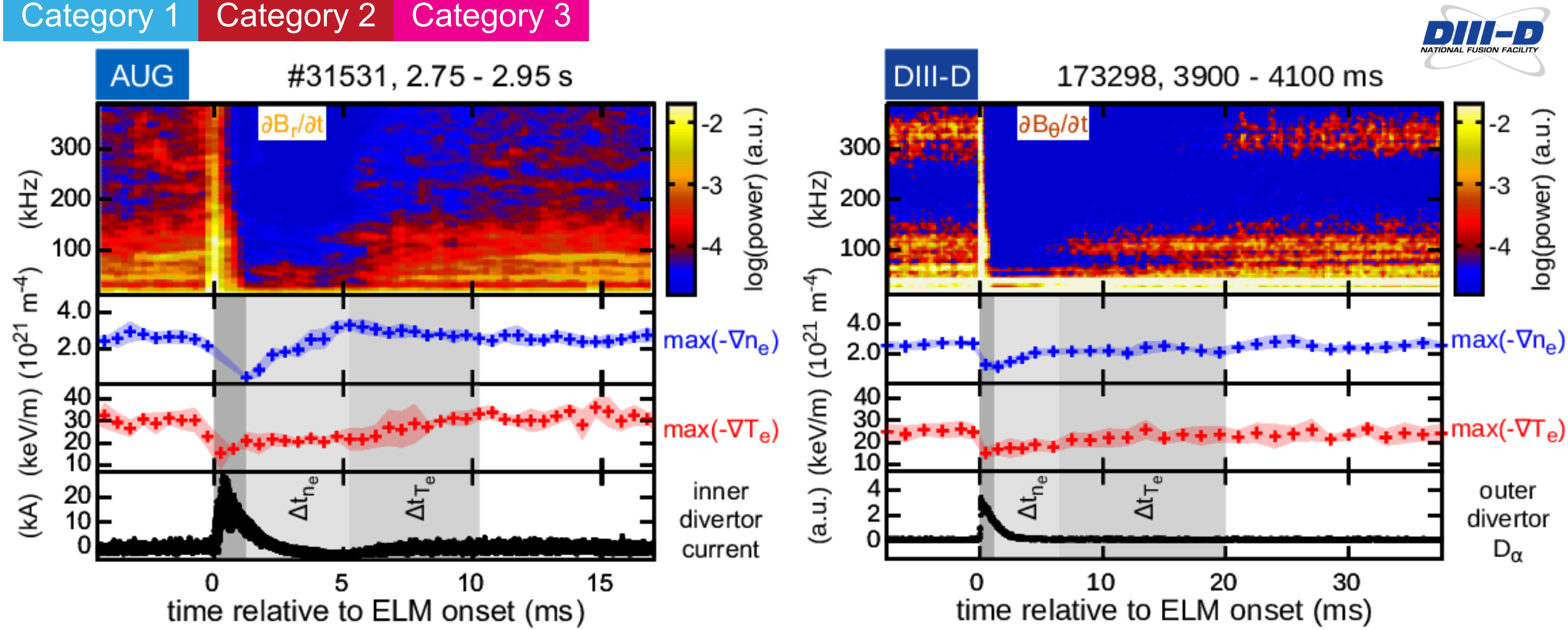
- **Category 3**
  - Localized at the pedestal top
    - ➢ Appear at low frequency range (< 30 kHz)



[F. M. Laggner et al., PSI 2018 & JNM submitted]

Saturated instabilities – Present for tens of ms

Category 1 | Category 2 | Category 3



→ Coupling has to occur to get into saturated states

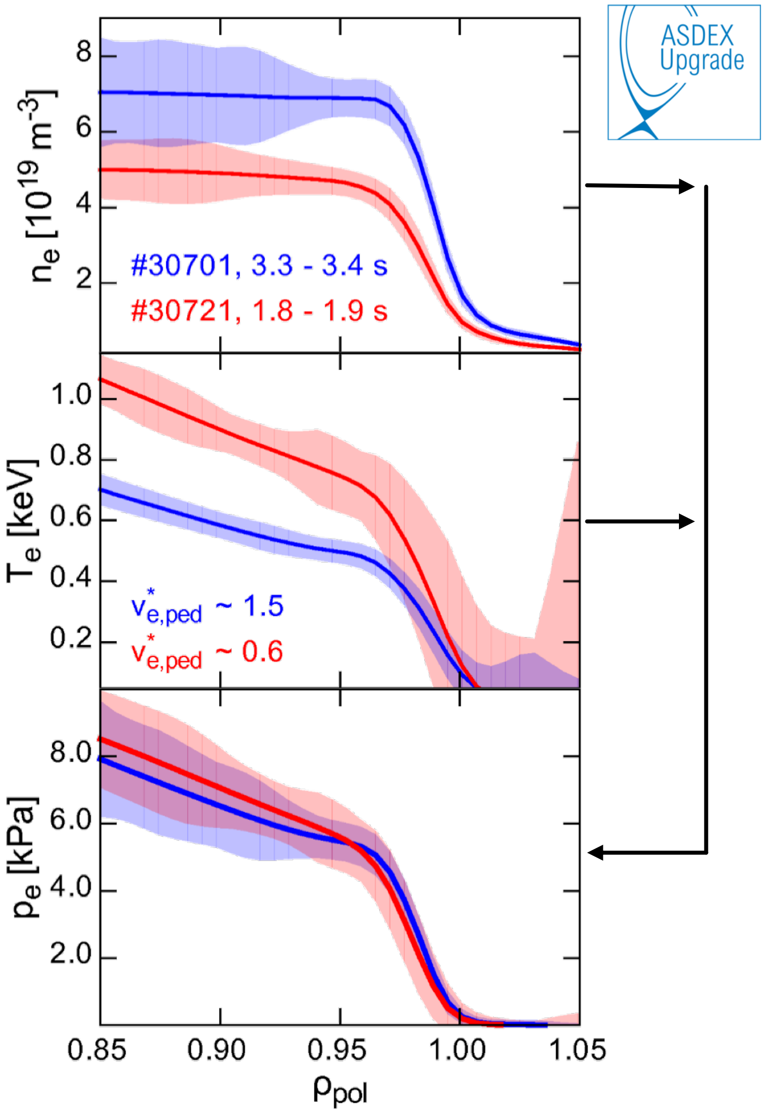
[F. M. Laggner et al., IAEA FEC 2018]

Test: Collsionality dependence – pressure match

- **High (#30701) and low (#30721) pedestal top electron collisionality $\nu^*_{e,ped}$**

- **Motivation for comparison:**
  - Pressure (gradient) driven instabilities should not change their behaviour

- **In both discharges gradients are clamped before the ELM onset ('soft limit')**



Sequence of pedestal recovery phases remains

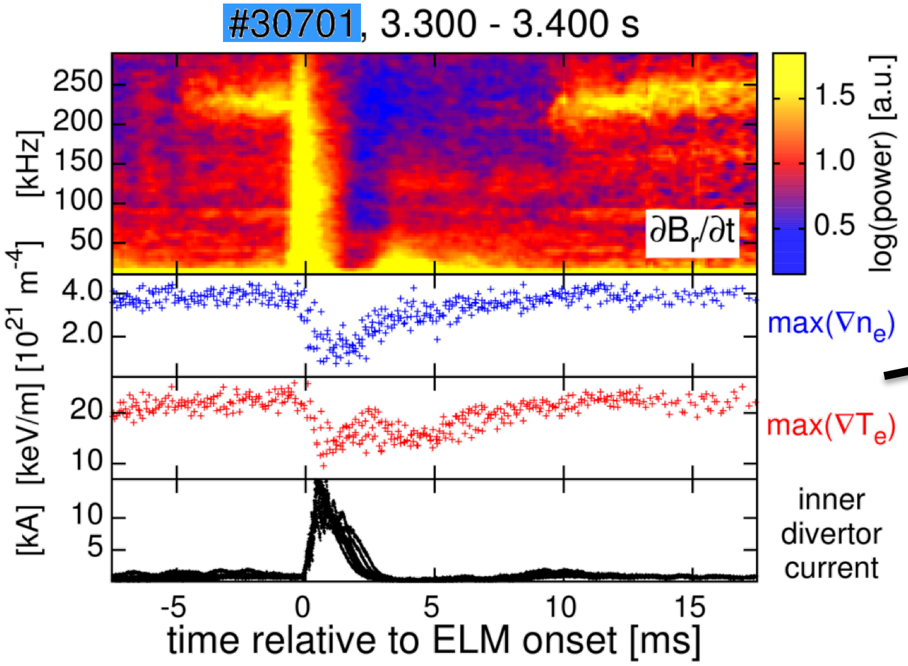
Category 2

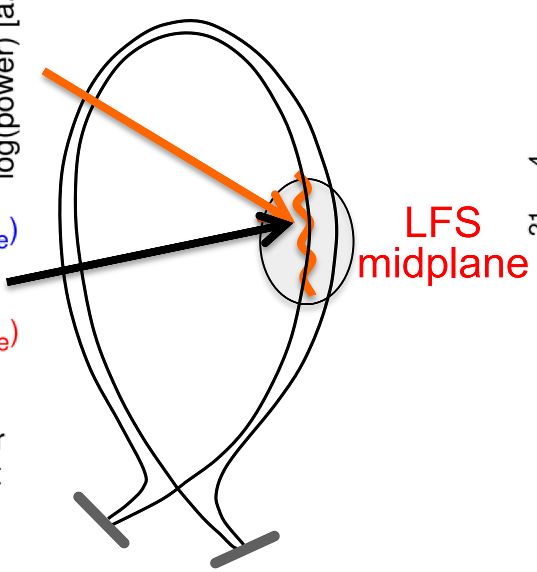
- **First $n_{e,ped}$ recovery, then $T_{e,ped}$**
- High frequency fluctuations start afterwards

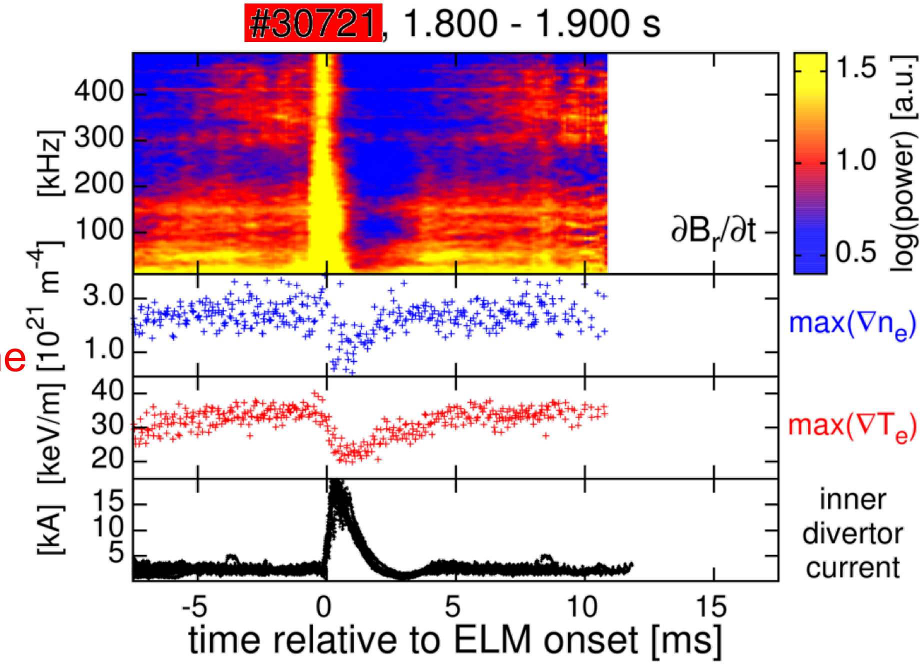
- $\max(\nabla n_e)$ and $\max(\nabla T_e)$ clamped when high frequency fluctuations
- Detected fluctuation frequency differs in both cases

High $\nu^*_{e,ped}$ (#30701) case

Low $\nu^*_{e,ped}$ (#30721) case







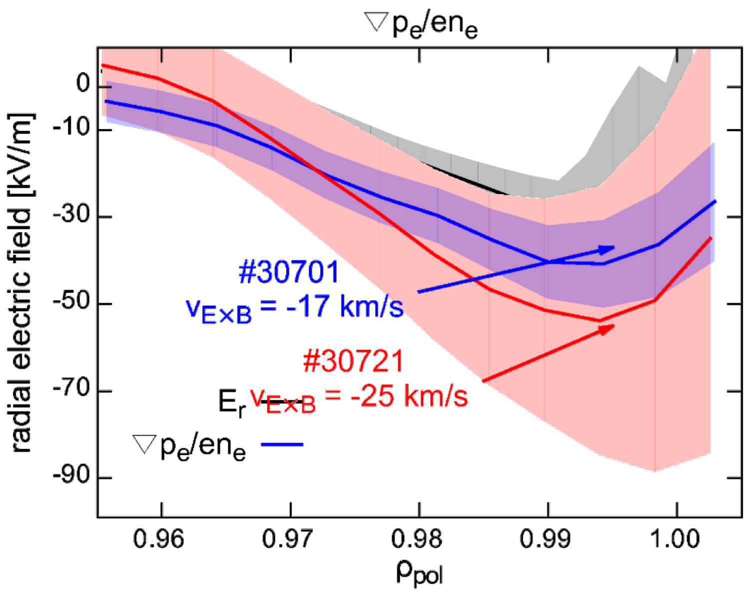
→ What determines the detected fluctuation frequency?

Plasma rotation adds to frequency in lab frame

- H-mode → strong E×B background velocity at the edge
- ASDEX Upgrade: **E_r is well described by estimation $\nabla p_i/en_i$** in the steep gradient region

  [E. Viezzer et al., NF 2014]

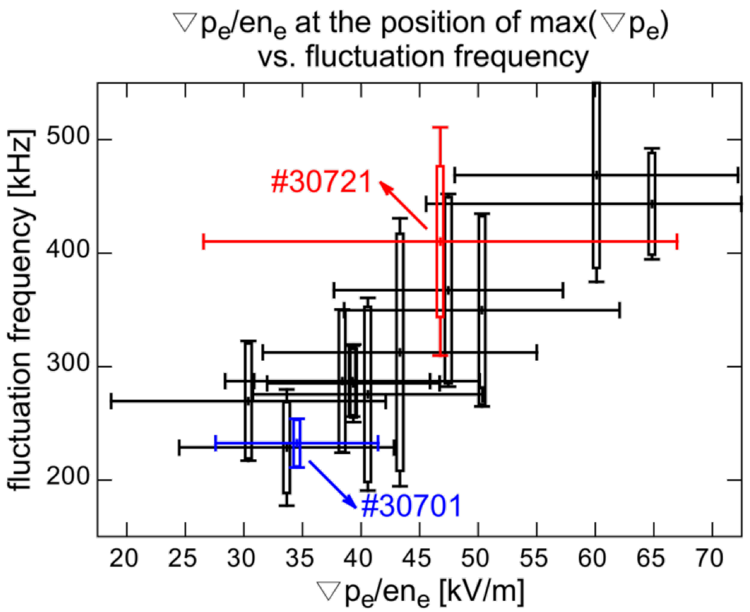
- E_r and $\nabla p_e/en_e$ agree within their errors in the analyzed cases



Lab frame frequency depends E×B rotation

Category 2

- 11 discharge intervals:
  - Constant I_p and B_t
  - Selected to span wide range of $\nabla p_e/en_e$
  - Clear magnetic fluctuations
    - ➢ Onset correlated to $T_{e,ped}$ recovery



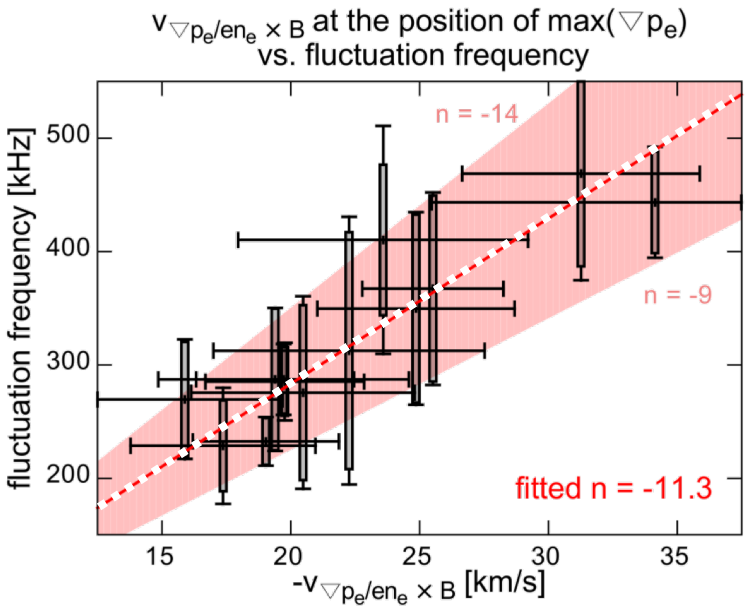
- Detected fluctuation frequency increases with $\nabla p_e/en_e$ at position of max(∇p_e)

→ Mode is located in the steep gradient region

Toroidal mode structure of n ~ 11

Category 2

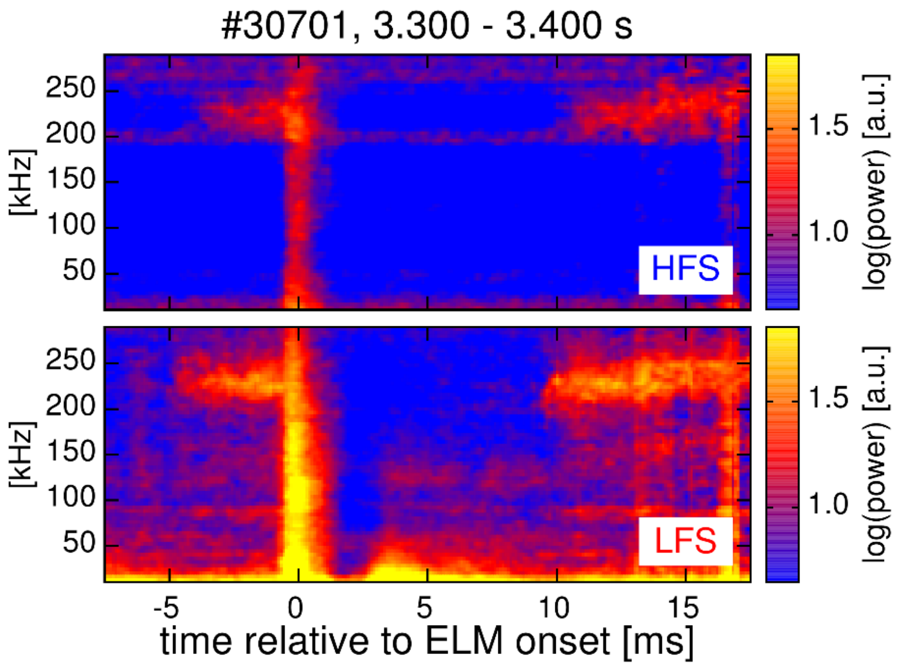
- Fit of n using the discharge intervals with different $\nabla p_e/en_e$
- Fit of toroidal mode number:
  - $n \sim U_{tor} \cdot f_{magn} / (v_{\nabla p_e/en_e} \cdot q \cdot U_{tor}/U_{pol} + v_{tor})$
- Fitted **n ~ -11**
  - In agreement with n numbers determined from magnetic pickup coils

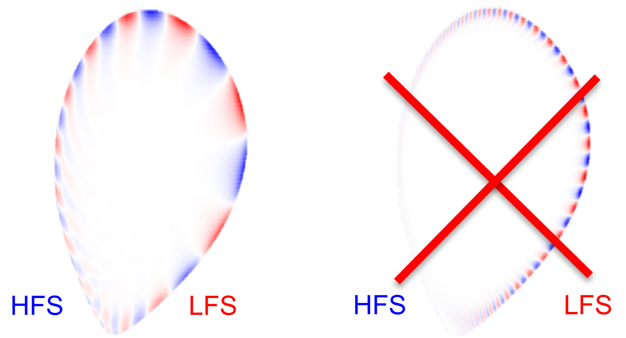


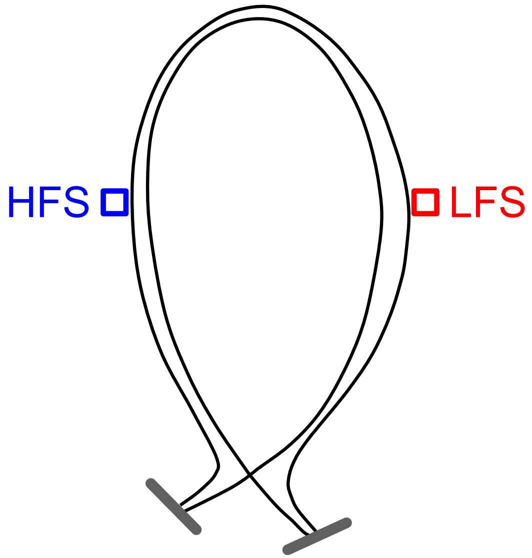
HFS signature suggests peeling like mode structure

Category 2

- Fluctuation **signature visible on the HFS**
  - Similar onset as on the LFS
  - Same frequencies as on LFS





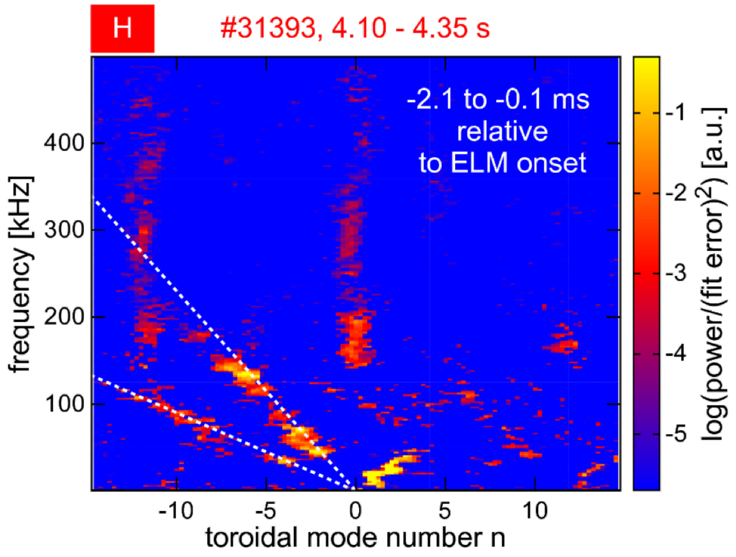


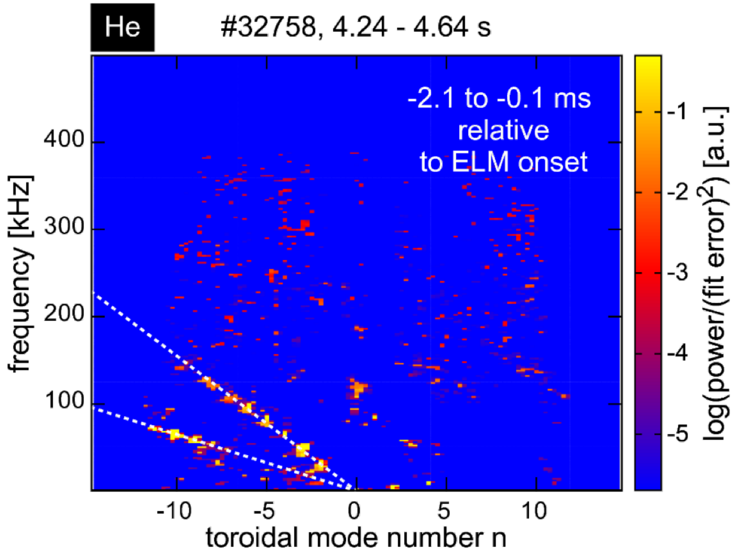
[F. M. Laggner et al., PPCF 2016]

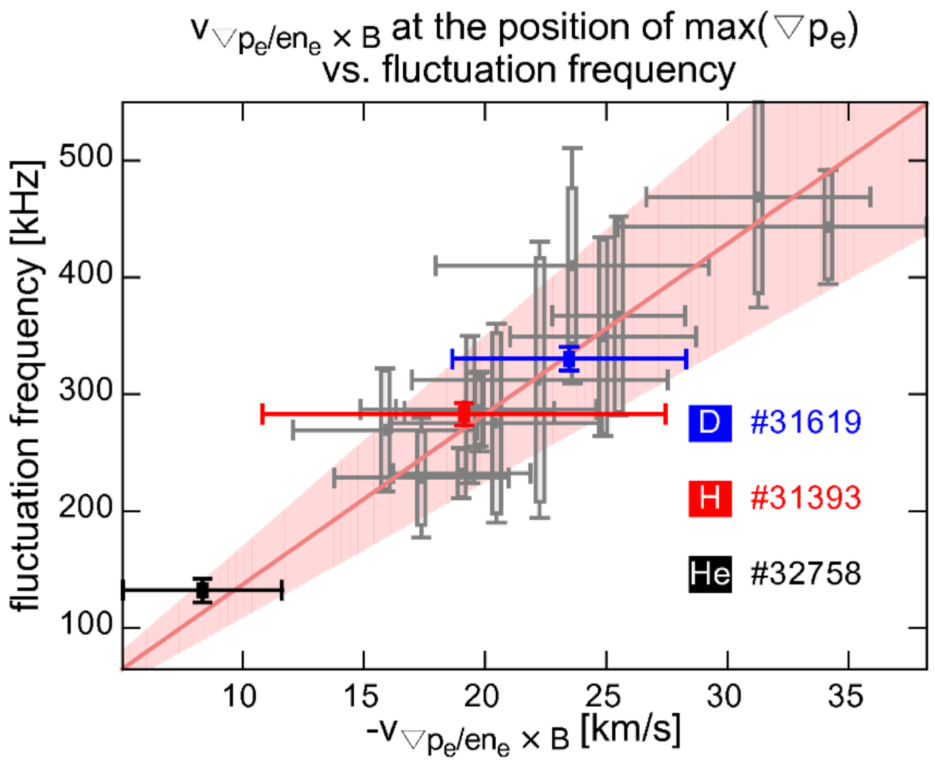
Test: Main ion dependence – D, H and He plasmas

Category 2

- **Mode propagation with the background E×B velocity**
  - Toroidal mode structure with n ~ -11 in all investigated cases
- **Comparison of D, H and He plasmas**
  - Similar sequence of pedestal recovery phases
    - ➢ Dominant mechanisms in the pedestal recovery are not changed by a change of the main ion species



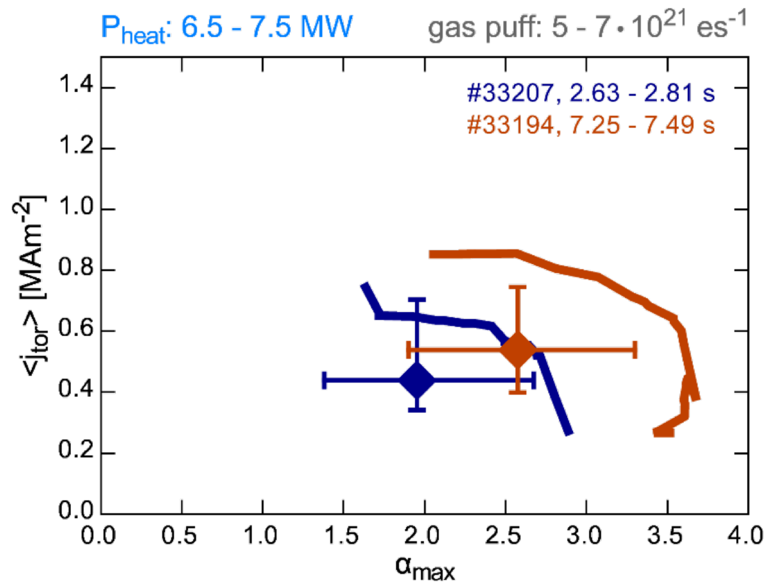




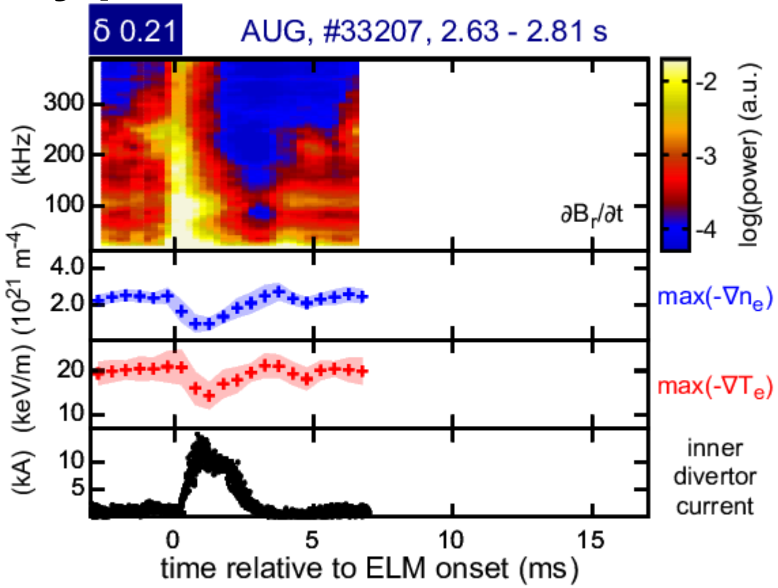
[F. M. Laggner et al., APS invited 2016 & POP 2017]

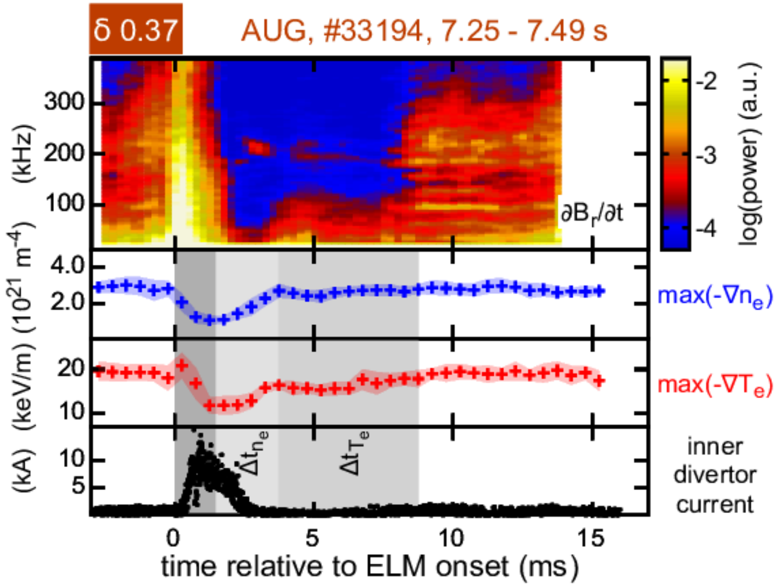
Test: Shape dependence – Triangularity variation

Category 1 Category 2



- **ELM frequency (f_{ELM}) and PB boundary affected**
  - Reduction of f_{ELM}
    - ➢ Pedestal recovery phases extended at high triangularity
  - Extension of PB stable area
- **BUT: Sequence of pedestal recovery phases remains**
  - Fluctuation onsets stay correlated





[F. M. Laggner et al., IAEA FEC 2018]

Test: Safety factor dependence – I_p variation

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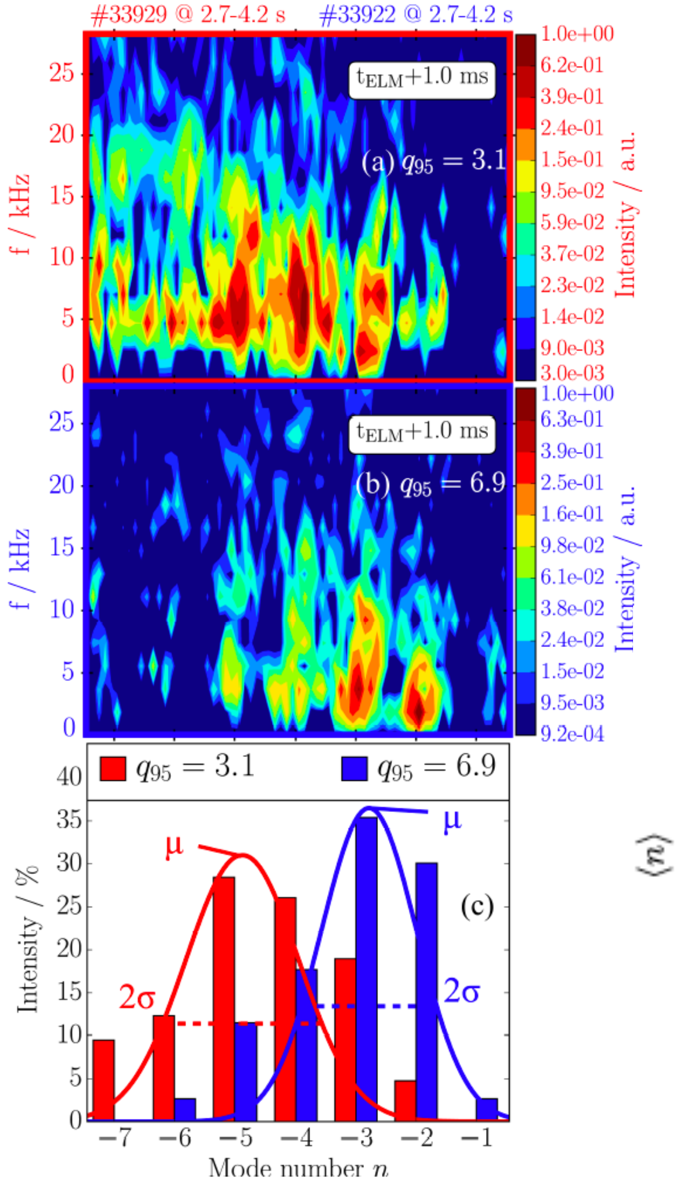
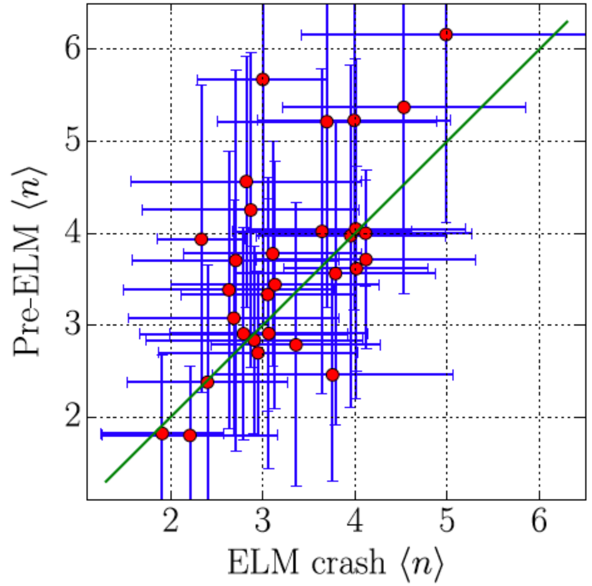
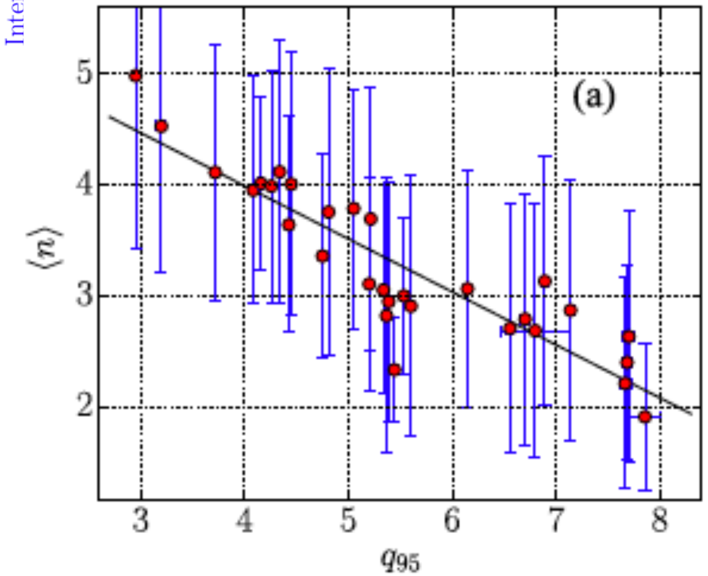
Category 1

- **Study focused on the structure of the ELM crash**
- **BUT: pre-ELM and ELM structure are correlated**
- **Average toroidal mode number <n> decreases with increasing q_{95}**
  - ➢ Poloidal structure conserved





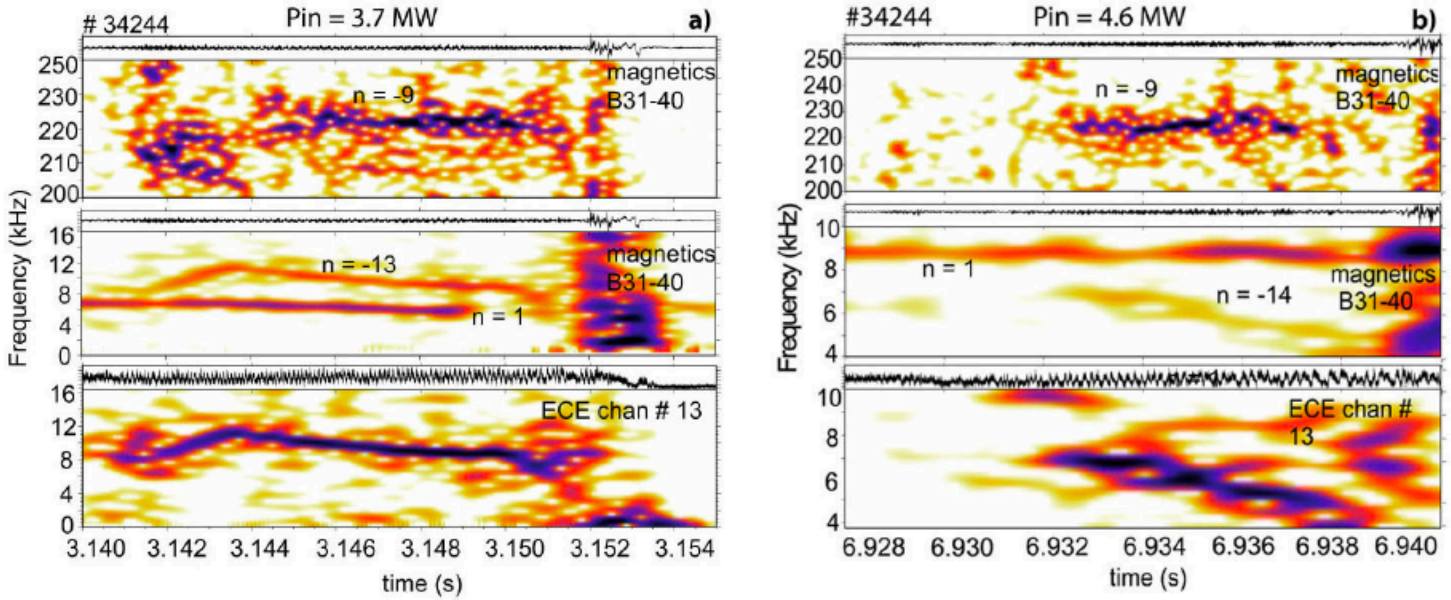


[A. F. Mink, et al., PPCF 2018]

Category III localized at the pedestal top

Category 3 Category 2

- **Analysis from ECE & magnetics**
  - Category III at low frequency in the ECE & magnetics
  - Category II visible in magnetics
- **Change Category III frequency with P_{NBI}**
  - Decrease of pedestal top rotation

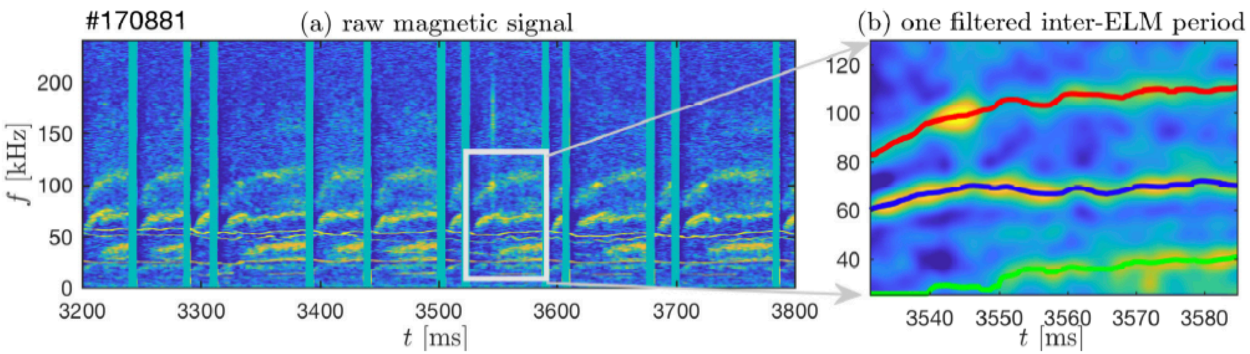


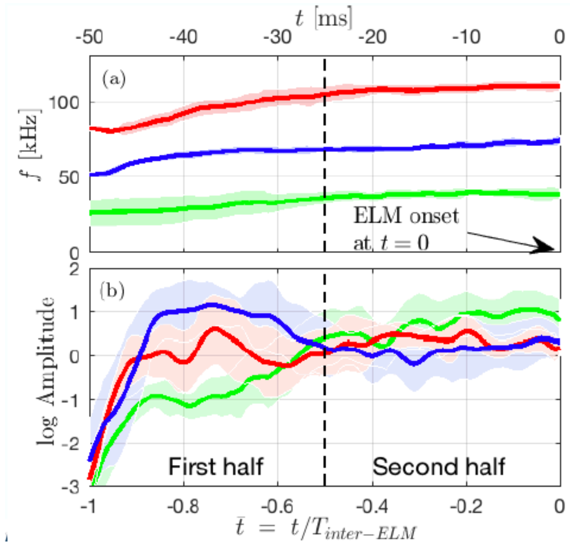
[B. Vanovac, et al., NF 2018]

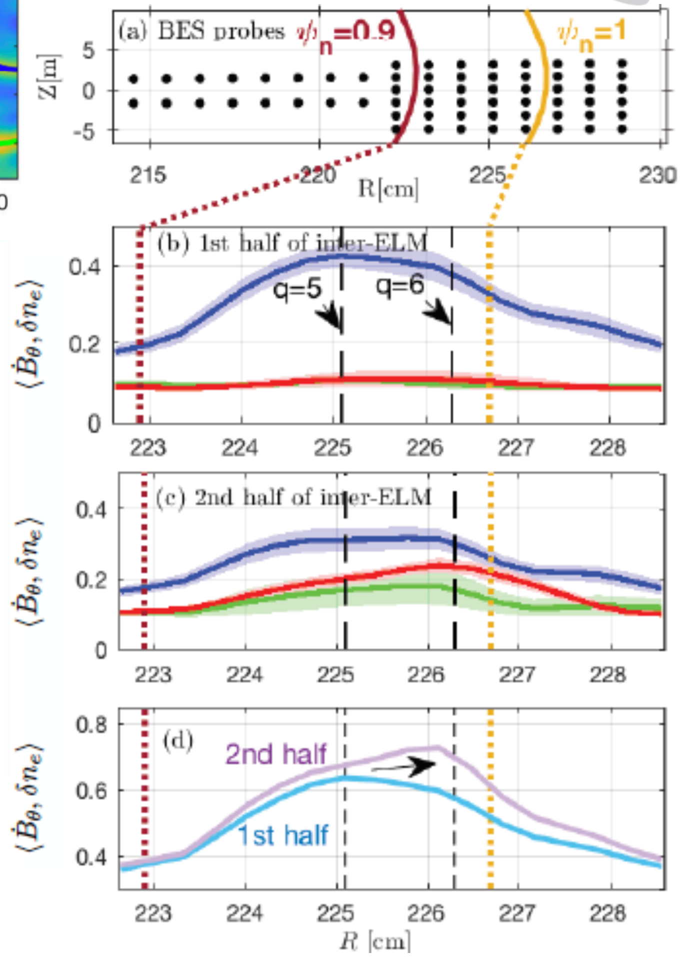
Matching condition for Category I and III

Category 1 | Category 3

- **Suggested to be related to the ELM onset**
  - Non-linear coupling of inter-ELM instabilities
- **Fluctuation band amplitudes tracked through ELM cycle**
  - Change in the spectral power of individual bands
- **Radial localization of bands using BES**
  - Category III (green) further inwards







[A. Diallo, et al., PRL 2018]

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Summary - Three instability categories

- **Category 1**
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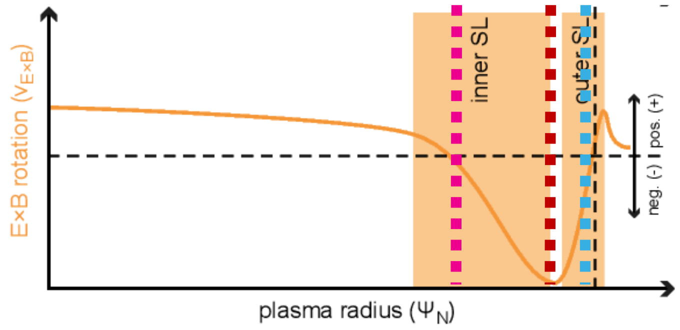
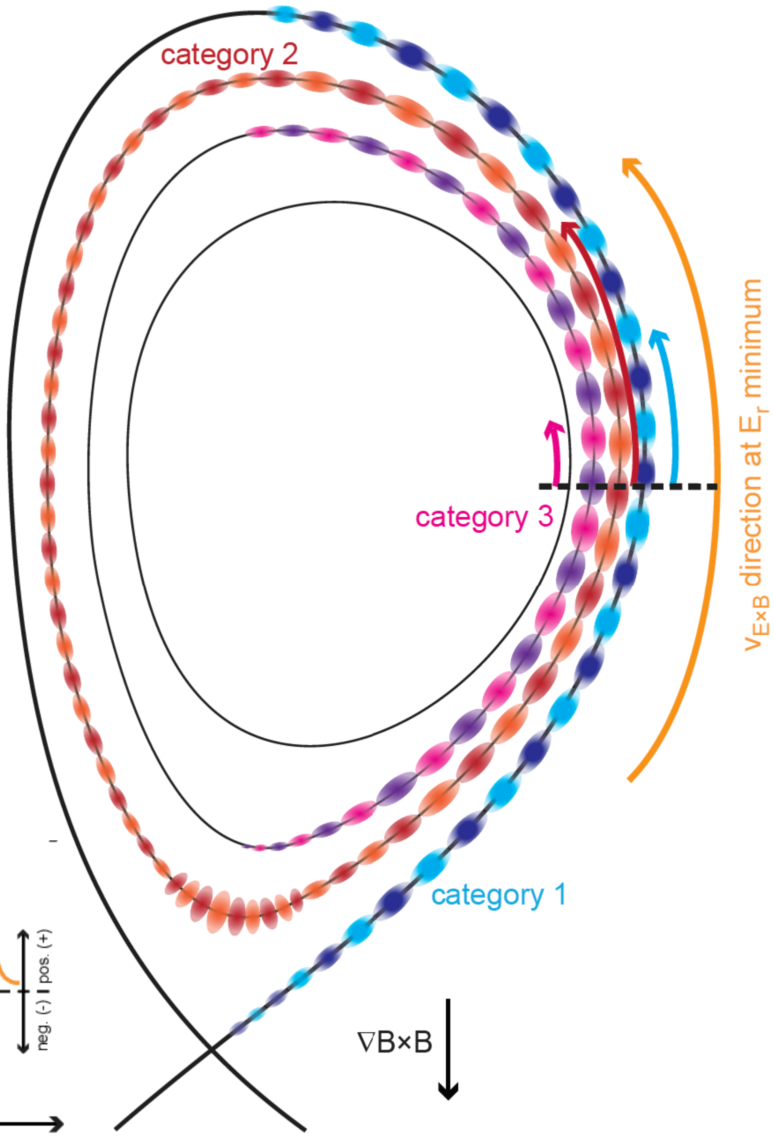
    - ➢ onset connected to T_e pedestal evolution (after recovery phase II)
    - ➢ HFS magnetic response
- **Category 3**
  - Localized at the pedestal top
    - ➢ Appear at low frequency range (< 30 kHz)
- **MODELLING CHALLANGED TO REPRODUCE ‘ROBUST’ INSTABILITIES**



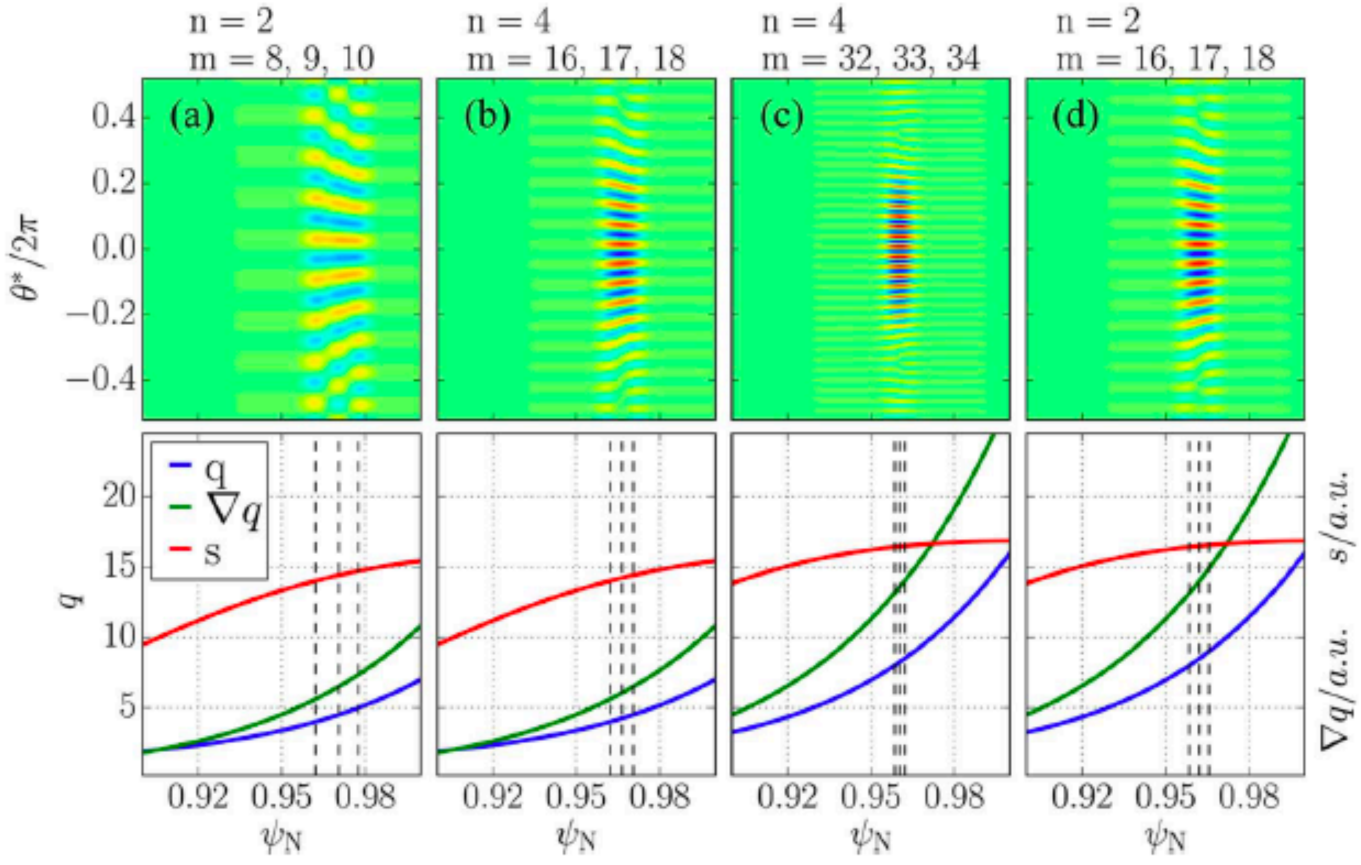


[F. M. Laggner et al., PSI 2018 & JNM submitted]

Why n changes with q_{95}

Category I

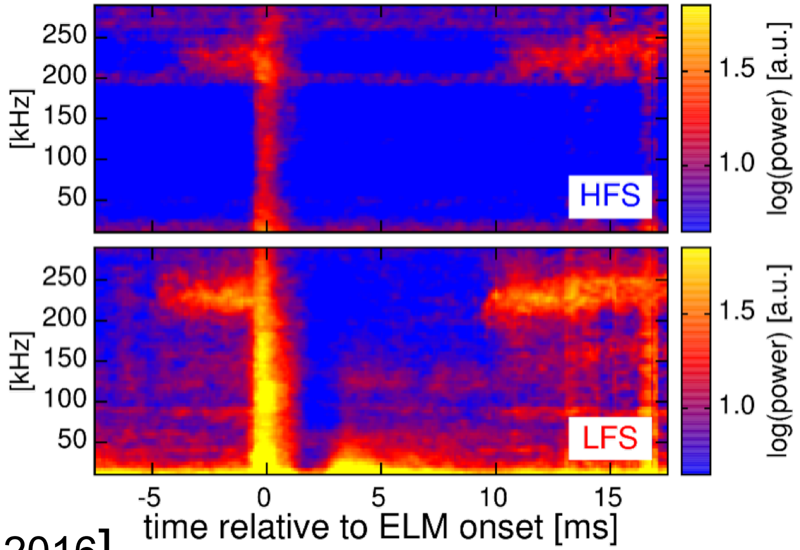
- **Minimization of n for a given distance of resonances**

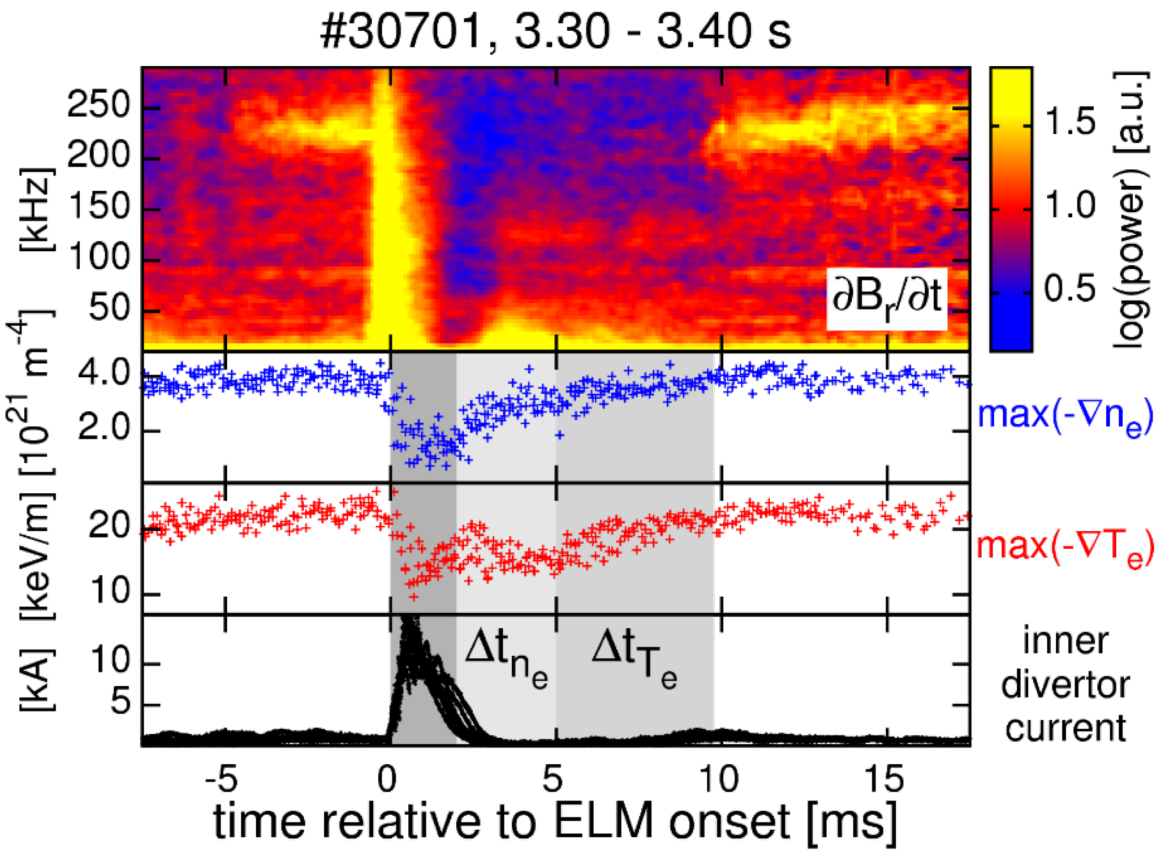


[A. F. Mink, et al., PPCF 2018]

Inter-ELM pedestal evolution in AUG

- **Distinct recovery phases of n_e and T_e profiles**
  - max($-\nabla n_e$) saturates with onset of medium frequency fluctuations
  - max($-\nabla T_e$) evolves till high frequency fluctuation onset
- **Fluctuation signature visible on the HFS**





[F. M. Laggner et al., PPCF 2016]

- Pedestal recovery phases in D and H
  1) n_e pedestal
  2) T_e pedestal

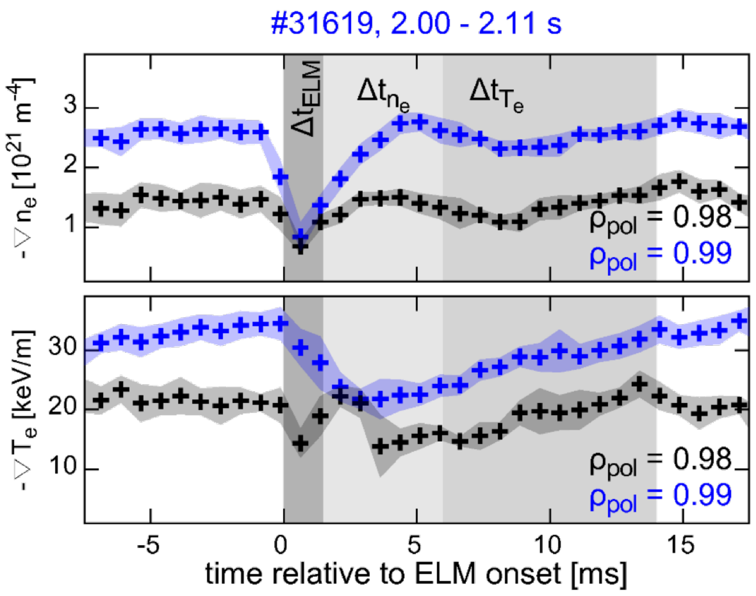
- Different timescales
  - attributed to changes in Pnet, gas puff and neutral velocity

➢ Indication for similar mechanisms acting in the pedestal recovery

D

P_{net} ~ 3.8 MW

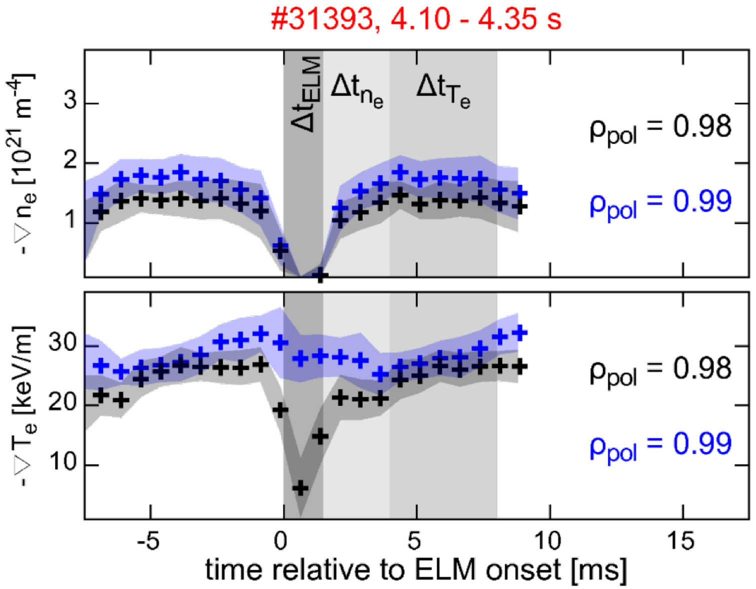
gas puff $1.5 \cdot 10^{21}$ s^{-1}



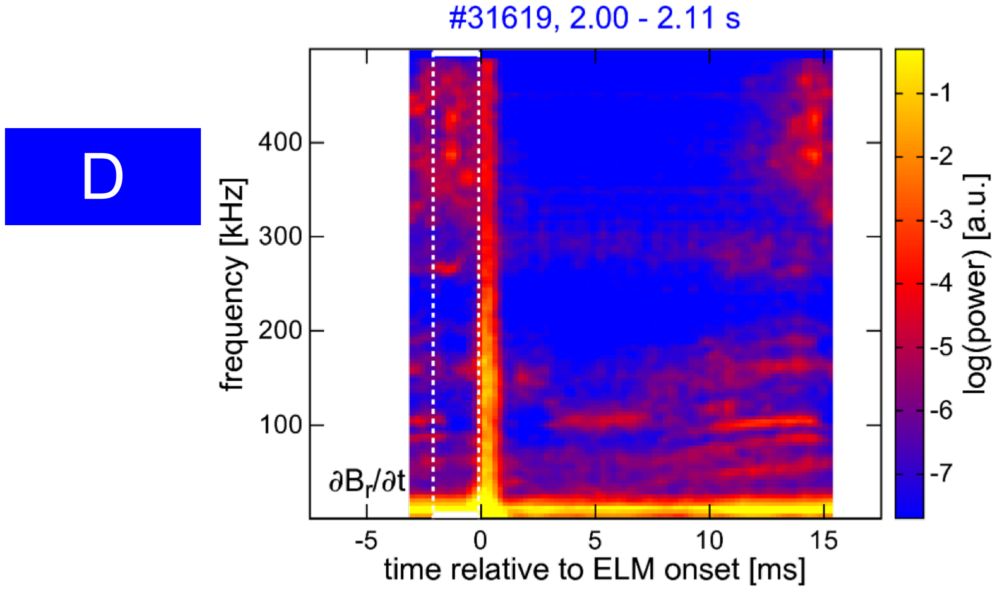
H

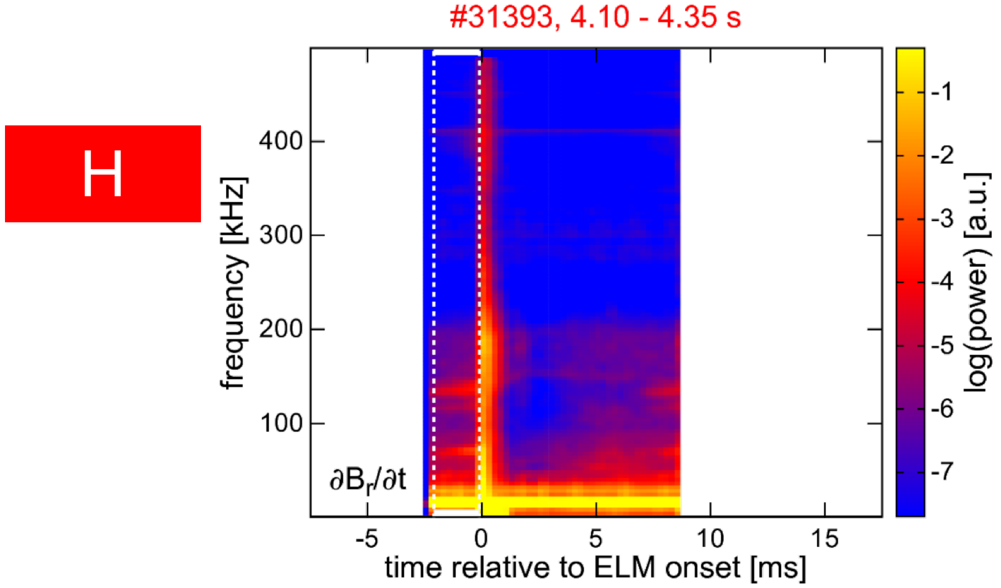
P_{net} ~ 7.3 MW

gas puff $12 \cdot 10^{21}$ s^{-1}



- ∂Br/∂t measured at the LFS midplane
  - Radial magnetic fluctuations (∂Br/∂t)
- Core modes
  - Frequency < 40 kHz
- Lower magnetic activity during Δtne
  - 40 kHz < frequency < 200 kHz
- After ΔtTe activity at high frequencies
  - Frequency > 200 kHz



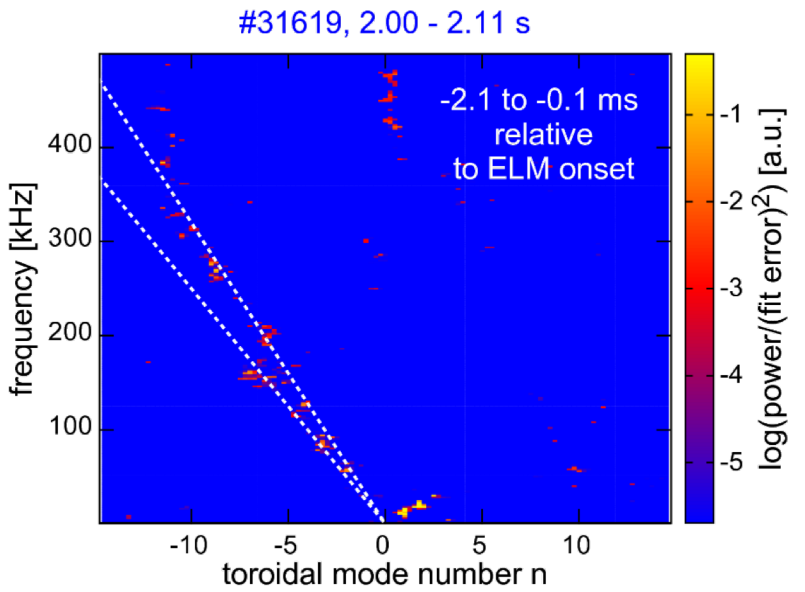


- Negative n:
  - Counter-current propagation or propagation in electron diamagnetic direction
  - Direction of the E×B background flow
    - Er at the edge approximated by ∇p/en
      [E. Viezzer et al., NF 2014]

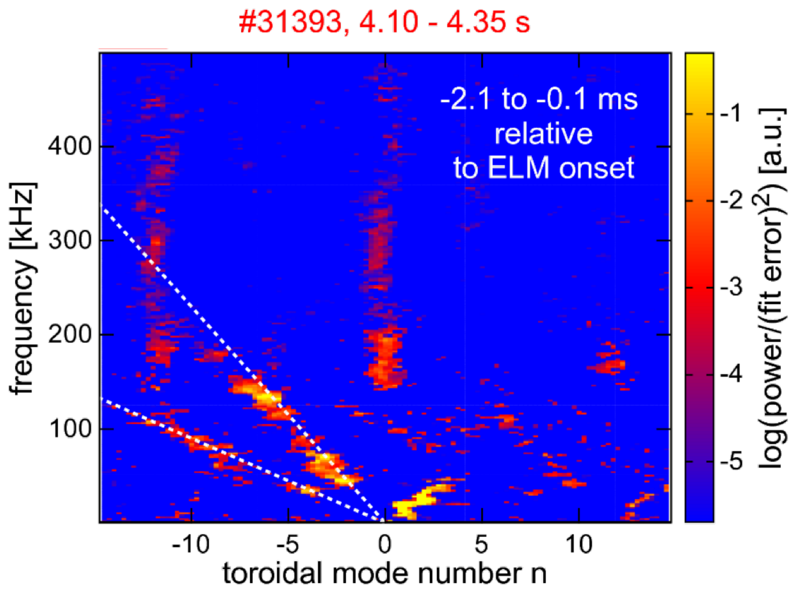
- Two mode number branches with similar n
  [F. Mink et al., accepted in PPCF]

- Slope represents different rotation velocity relative to the lab frame
  - E×B velocity affected by shallower ∇ne

D



H

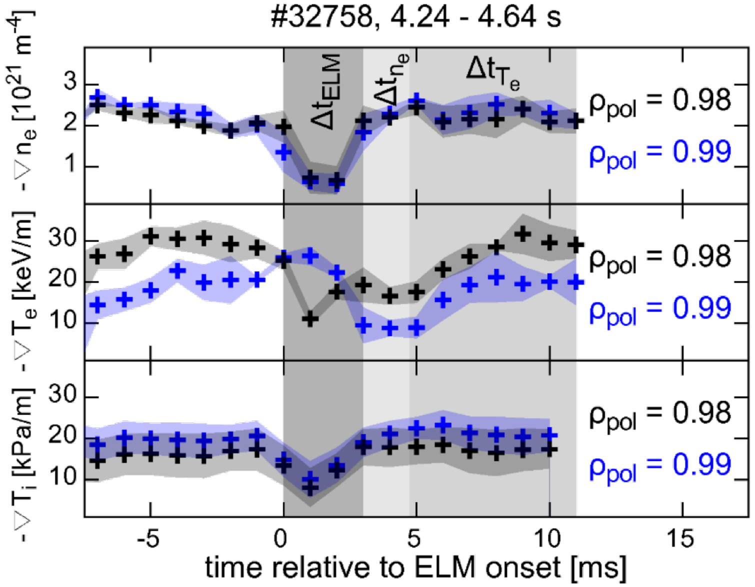


- ∇Ti recovers during Δtne
    - Established before the recovery of ∇Te

- Consistent with recent findings in D plasmas
    - Poster on Friday
        - M. Cavedon et al., Session YP10: YP10.00057

          [M. Cavedon et al., PPCF in preparation]

He



- Lower magnetic activity during Δtne
  - 40 kHz < frequency < 200 kHz

- Two mode number branches

- Slope shallower than for D and H
  - Low rotation velocity relative to the lab frame

He