ELMS ONSET TRIGGERED BY MODE COUPLING NEAR RATIONAL SURFACES IN THE PEDESTAL

by

A. Diallo[1]
J. Dominski[1], K. Barada[2], M. Knolker[1],
G.J. Kramer[1],F. Laggner[1], and G. McKee[3]

[1]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[2]Department of Physics, University of California, Los Angeles CA, USA
[3]Department of Engineering Physics, University of Wisconsin, Madison, WI, USA

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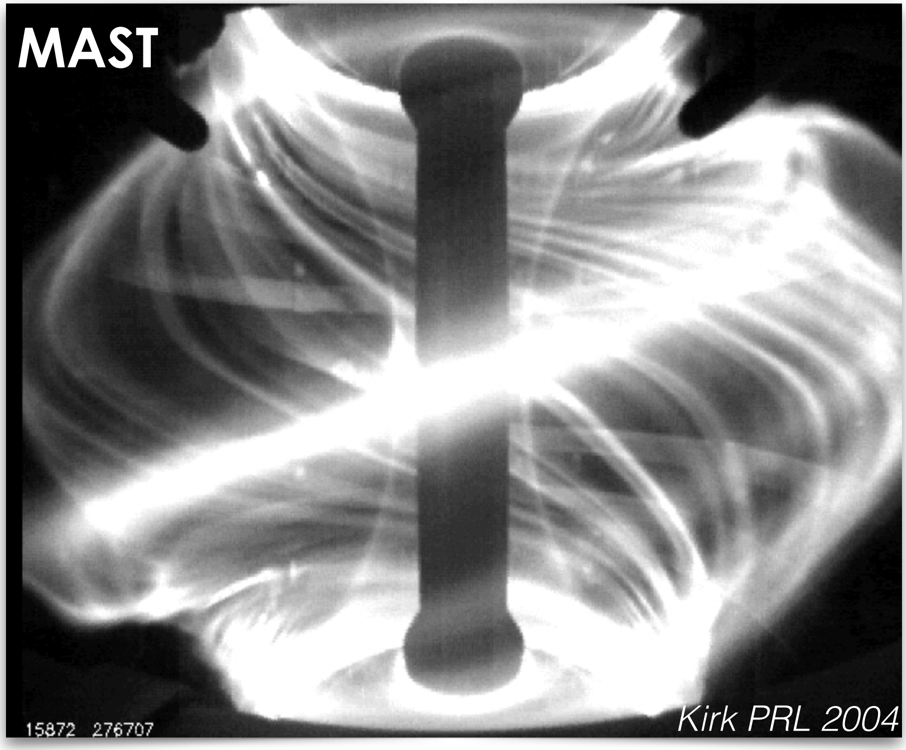
PPPL

Edge Localized Modes (ELMs) remain one of the risk for the success of ITER

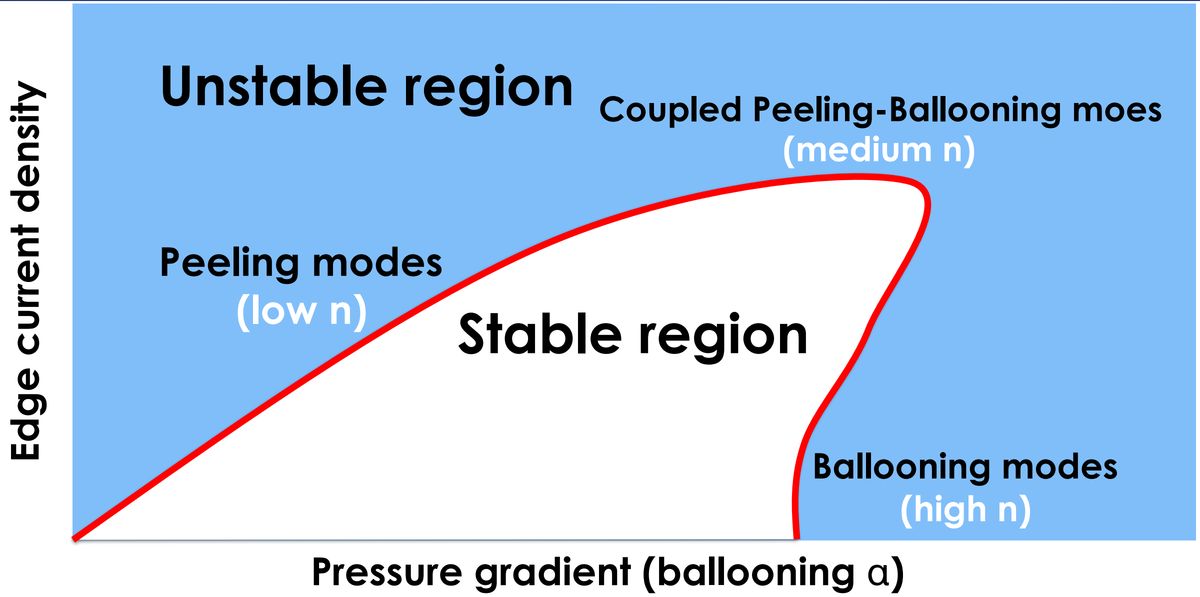
- The explosive release of energy from magnetically confined plasmas produces dramatic events called - ELMs
- ELMs have a detrimental effect on the plasma facing components.
- ELMs pose one of the most serious obstacles for steady-state operation in a future fusion device.

ELMs: filamentary structure



What triggers the ELMs?

Peeling-ballooning model is the leading physics model for the ELM onset



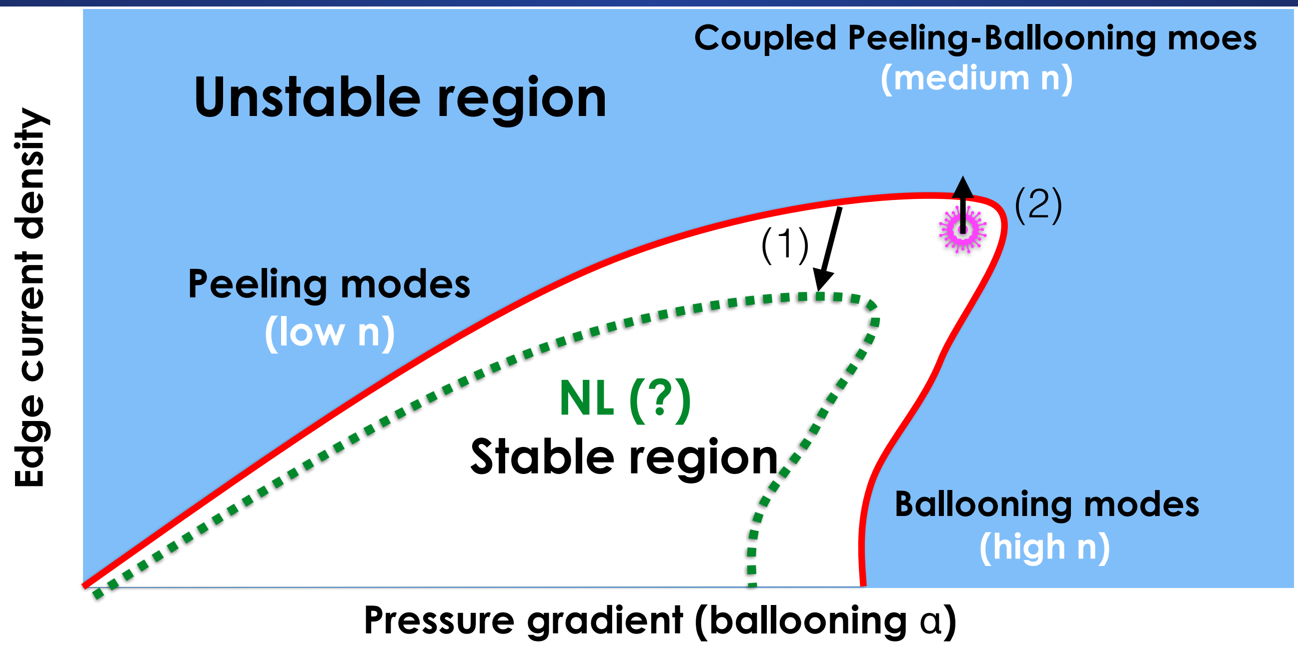
- **There is a body of literature supporting this paradigm.**

Zohm PPCF 1996
Connor, PPCF 1998
Snyder 2002
Leonard PoP 2014

- **Alternative nonlinear MHD model points to ELMs being the results of a basic detonation.**

Hurricane, PoP 1997
Cowley PPCF 2003

Is the PB model sufficient to explain the ELM onset?



- **Can nonlinear (NL) mechanisms:**

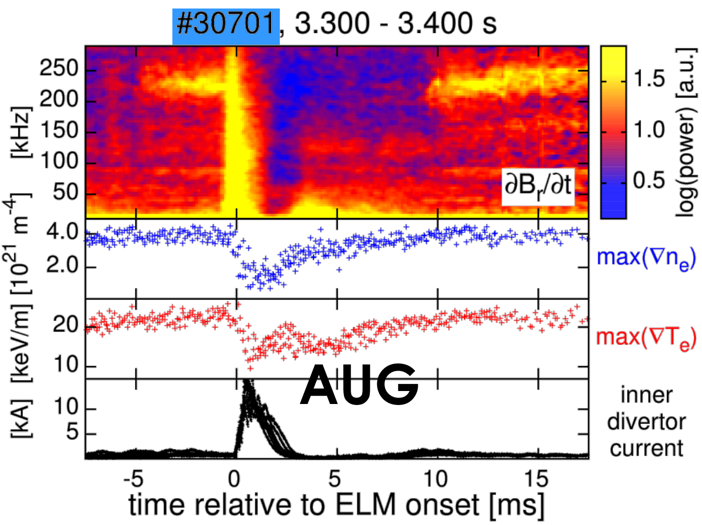
  (1) **modify** the stability boundary which could explain why the pedestal is pinned to a marginally stable region (for multiple transport time scales)?

  (2) **provide** a local modification of the current density profile in the narrow pedestal region?

SELECTED PREVIOUS RESULTS ON INTER-ELM FLUCTUATIONS WHERE THE PEDESTAL IS PINNED IN METASTABLE REGIME PRIOR TO THE ELM ONSET

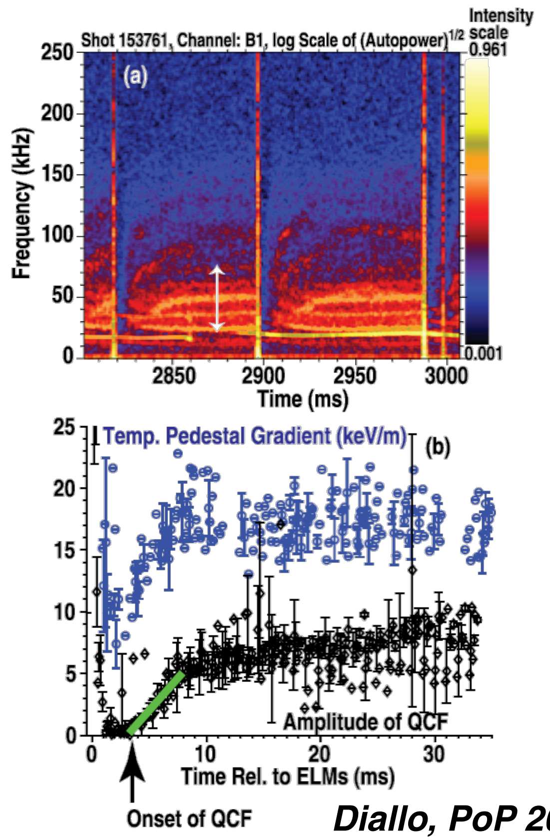
Pedestal parameters remain clamped during many transport time scale prior to the ELM onset

- **AUG, DIII-D showed that the pedestals ∇n_e and ∇ T_e are clamped before ELM onset.**
- **On C-Mod, the T_e^{ped} is clamped suggesting that its gradient is also clamped.**

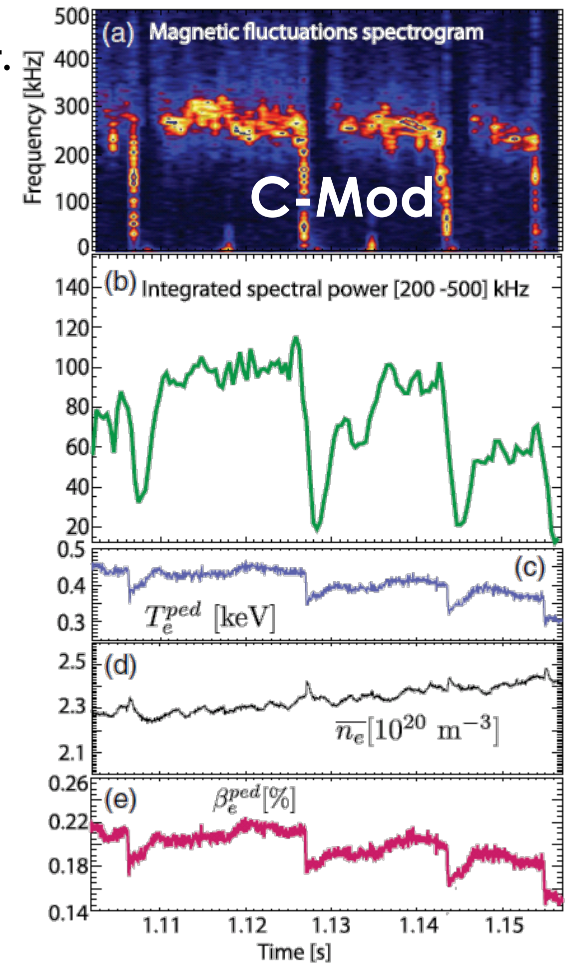


In some cases, there are no obvious changes of the pedestal width.

Burckhart, NF 2010
Laggner PPCF 2016



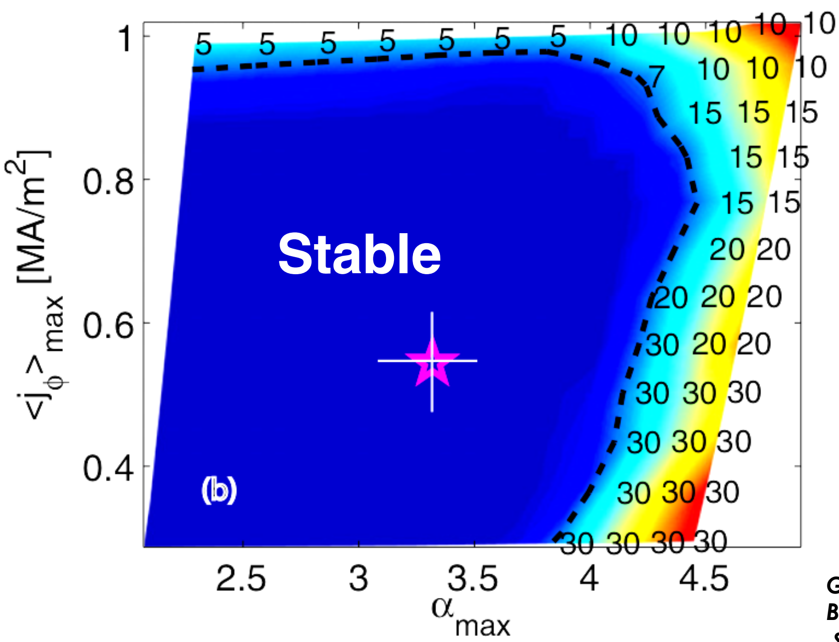
Diallo, PoP 2015



Diallo, PRL 2014

Examples of Stability Analysis - ELMs occur in "PB stable" regimes

- In JET ILW, ELMs sometimes appear to be triggered while the operation point is far away from PB limit.

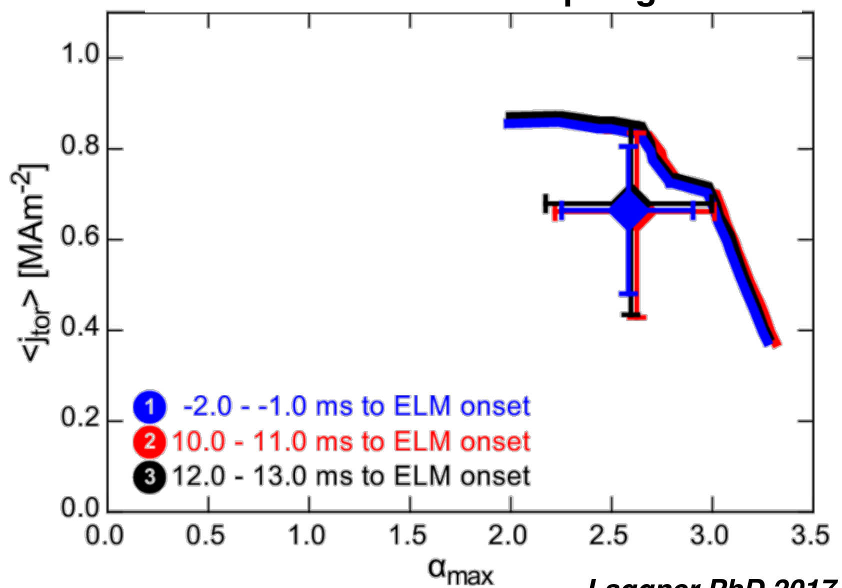


Perez von Thun EPS Invited 2018
Submitted to NF 2018

Giroud NF2013
Beurskens NF2014
SaarelmaPoP2015
Maggi NF2015
Maggi NF 2017

- In AUG, there is no evidence of the evolution of operation point or the stability point

3 phases during the inter-fluctuations & clamped gradients



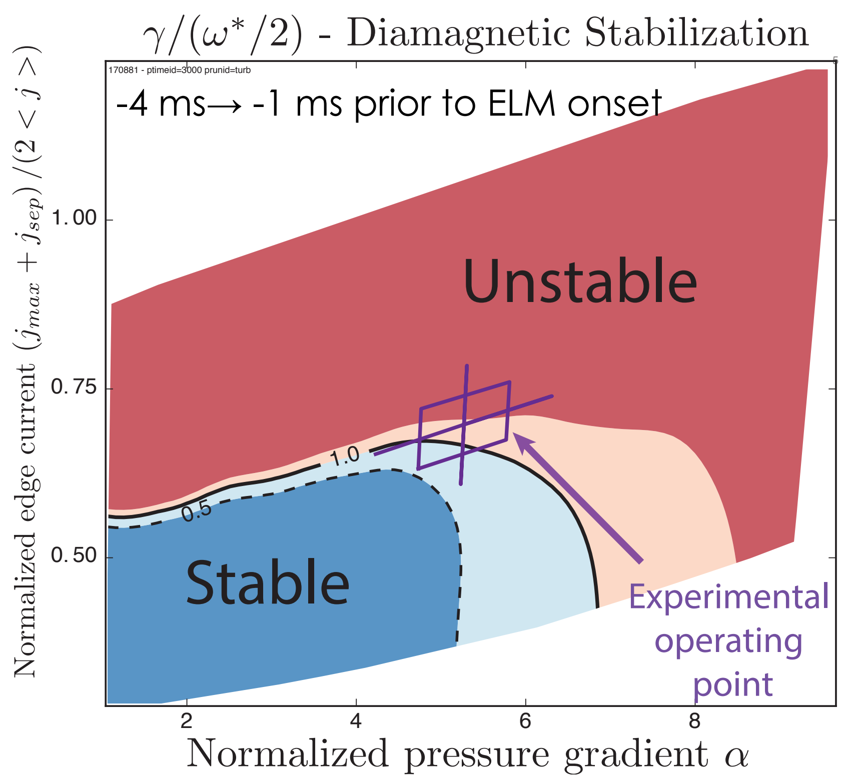
Laggner PhD 2017
Laggner EPS 2016

Pedestal parameters are pinned in a metastable regime at the PB stability boundary

- **Long before the ELM onset, the pedestal is pinned to marginal PB stability boundary.**

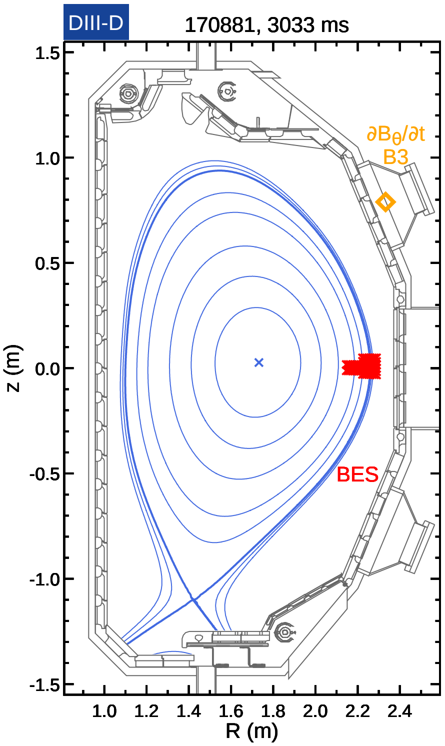
What prevents the ELM from being triggered?

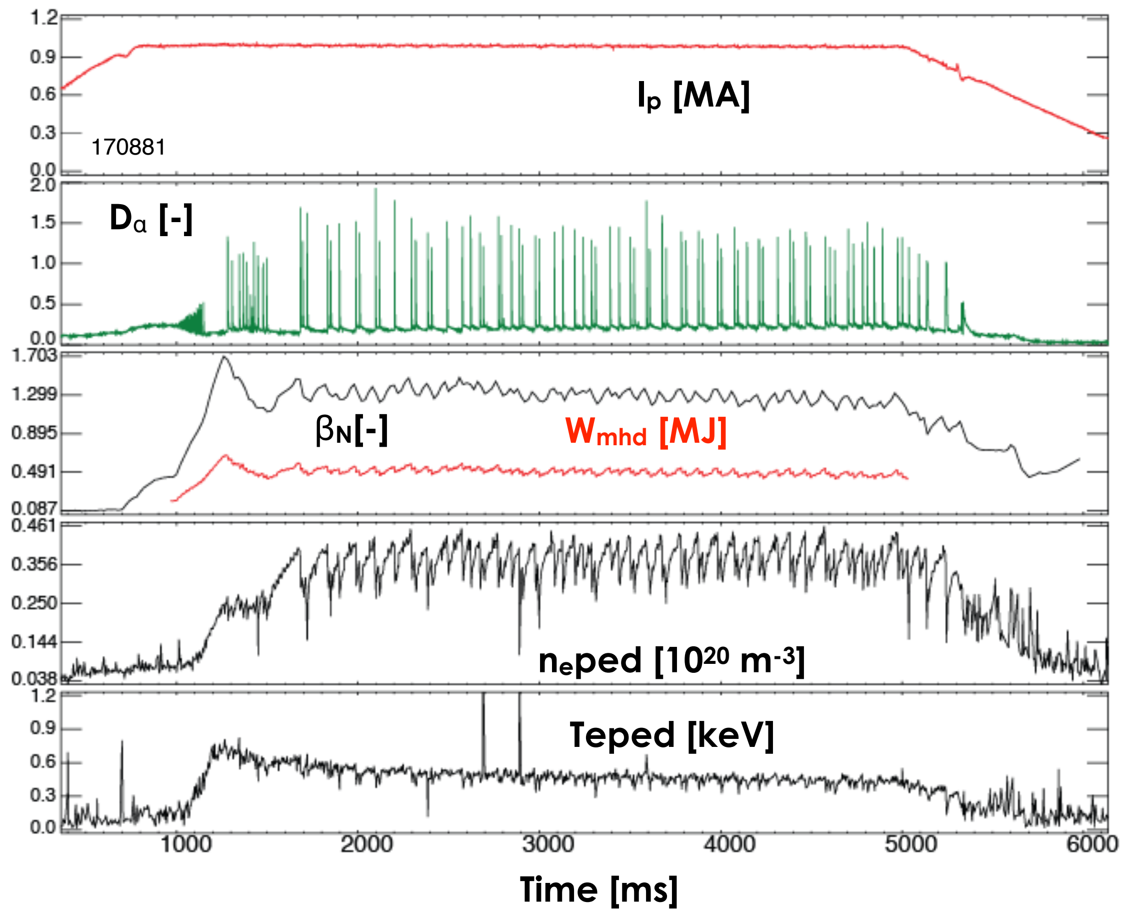
Does the PB stability *fully* capture the ELM triggering mechanism?

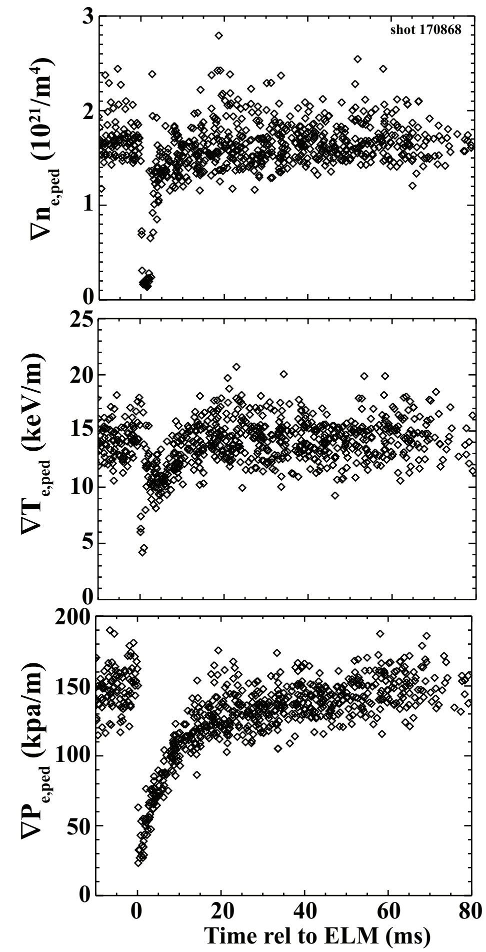


ANALYSIS (BES AND MAGNETICS) OF THE DOMINANT INTER-ELM FLUCTUATIONS DURING THE LONG INTER-ELM PERIODS

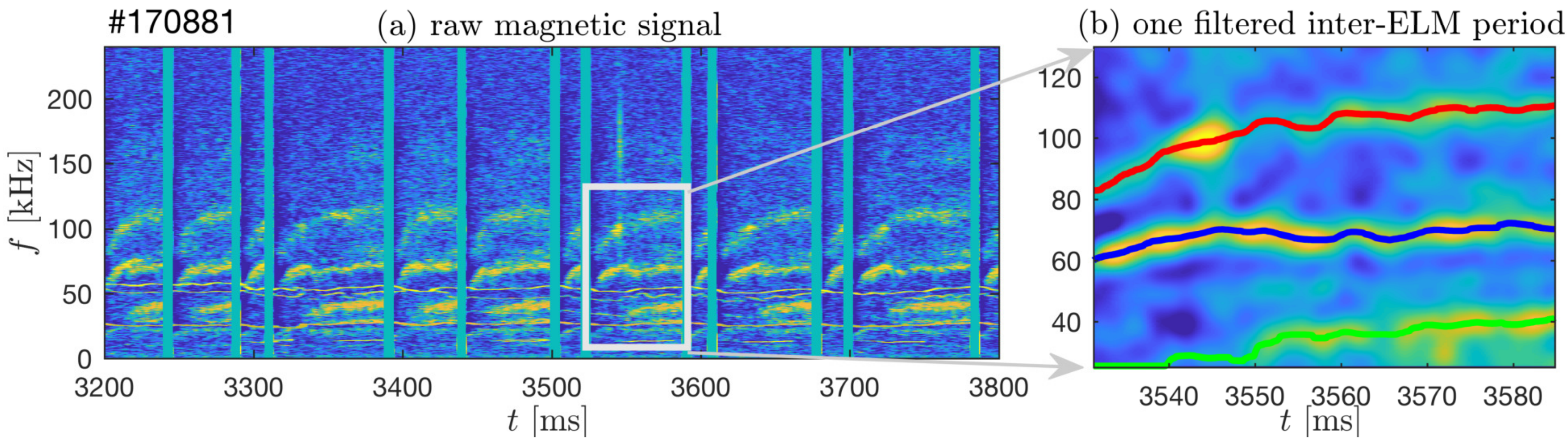
Time history of typical LSN discharges and pedestal gradient evolutions





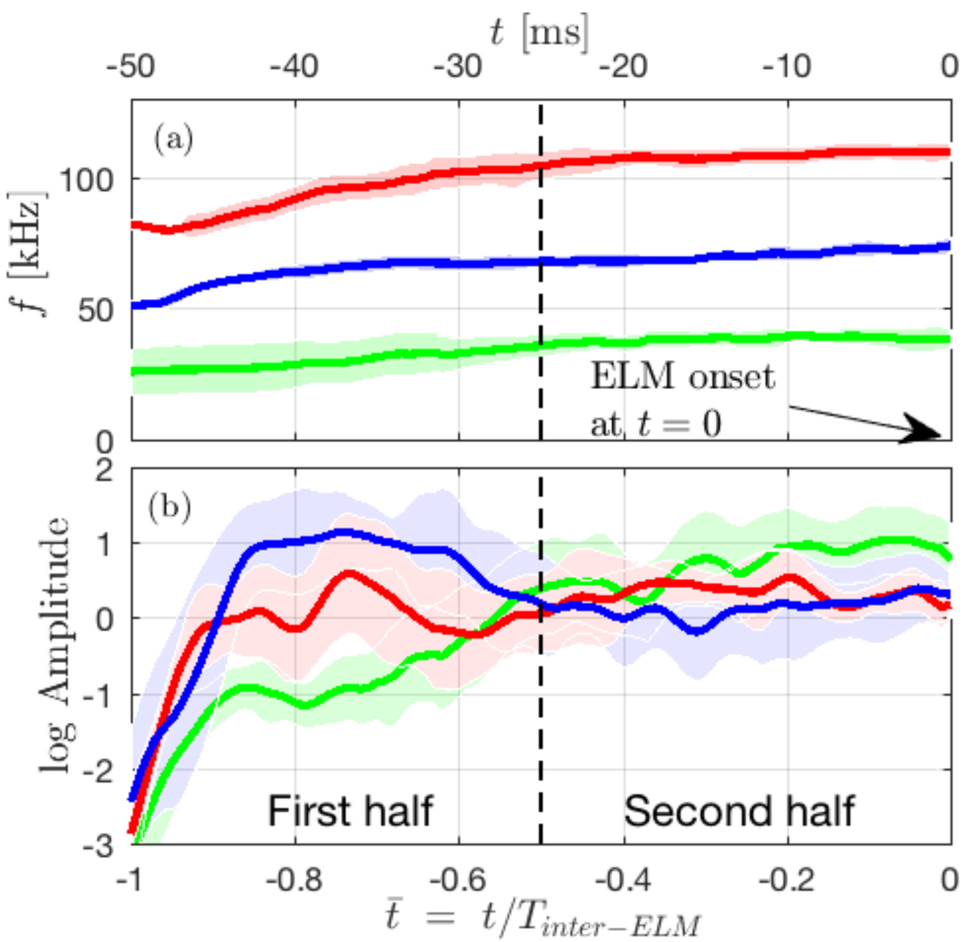


Typical inter-ELM magnetic fluctuations: identification of the dominant modes during stationary inter-ELM phase



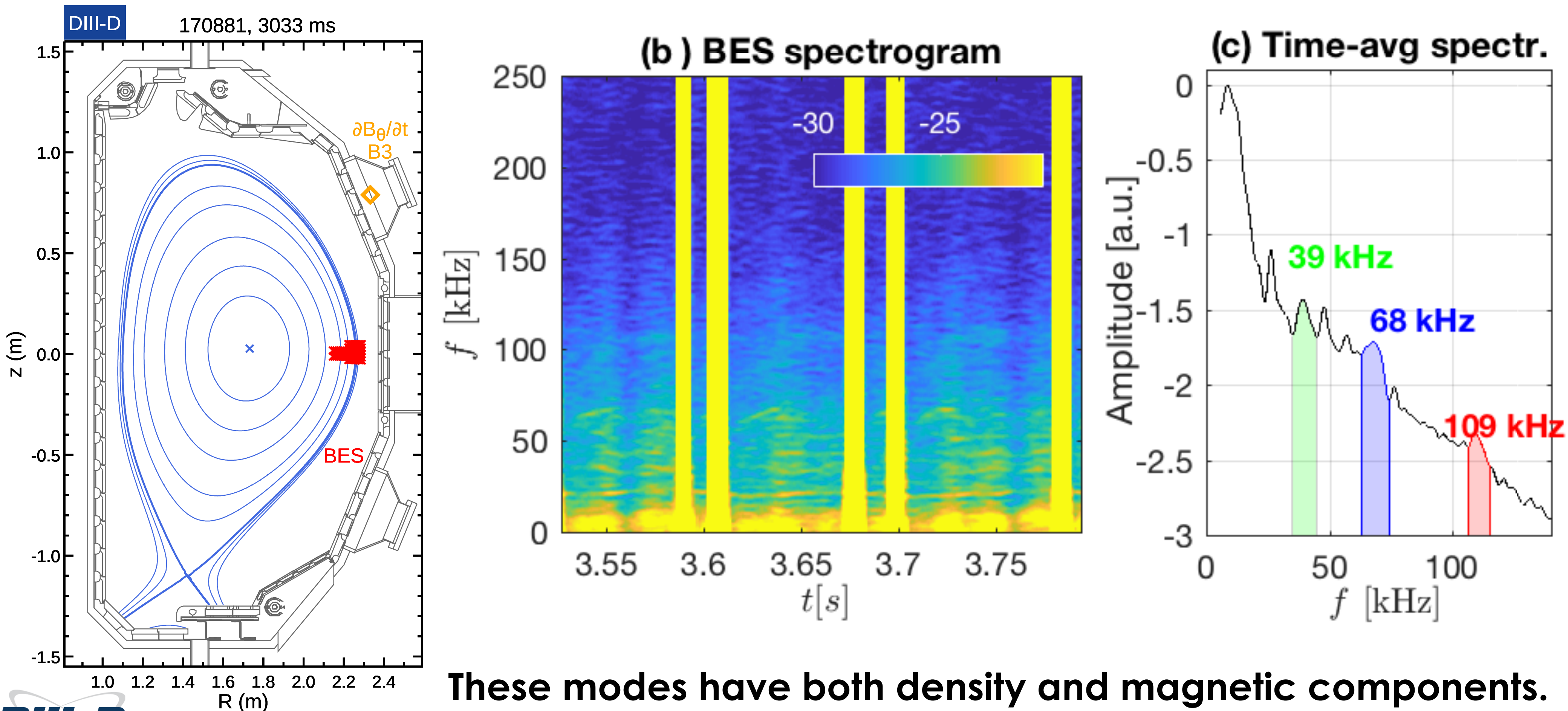
- **The noise has been filtered out and the dominant modes are tracked during each long inter-ELM periods.**
- **Short non-stationary inter-ELM phases as well as core modes are ignored from this analysis.**

Three dominant mode frequencies and amplitudes are tracked



- **We ELM-synchronized the mode frequencies and amplitudes of the magnetic signals.**
- **Statistical averages of nearly identical long inter-ELM periods.**

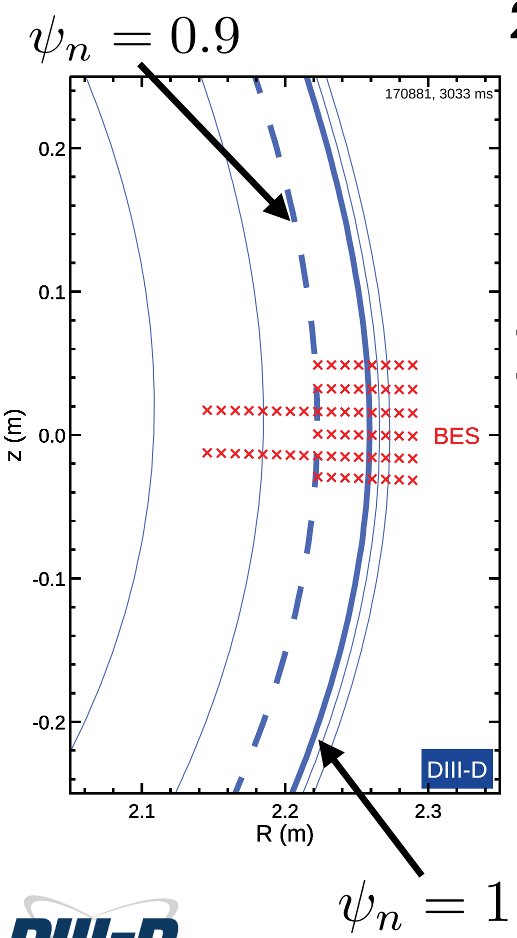
These dominant modes are also identified on the BES

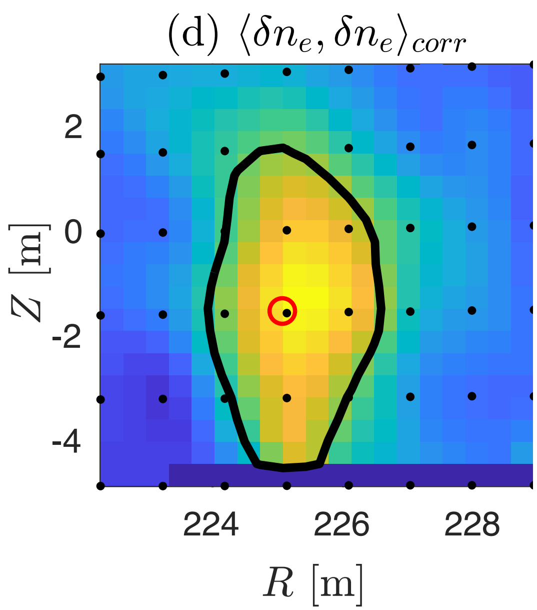


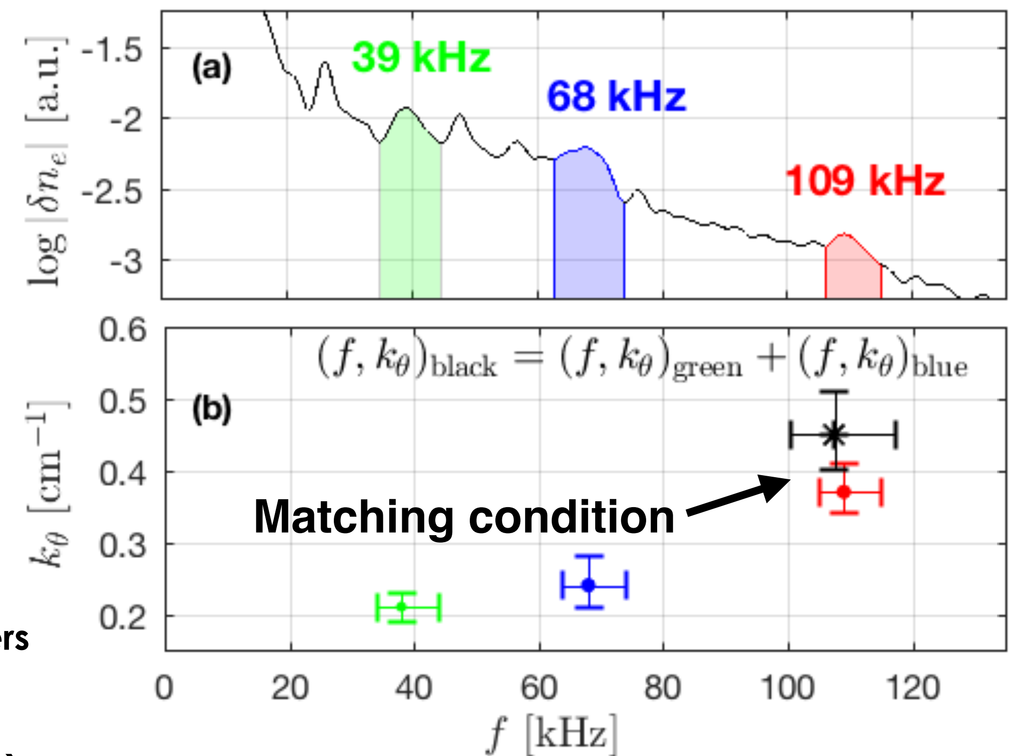
These modes have both density and magnetic components.

Determination of the modes poloidal wavelengths for each modes using BES

2-pt correlation analysis provides an estimate of the poloidal wavelength at each mode frequency.



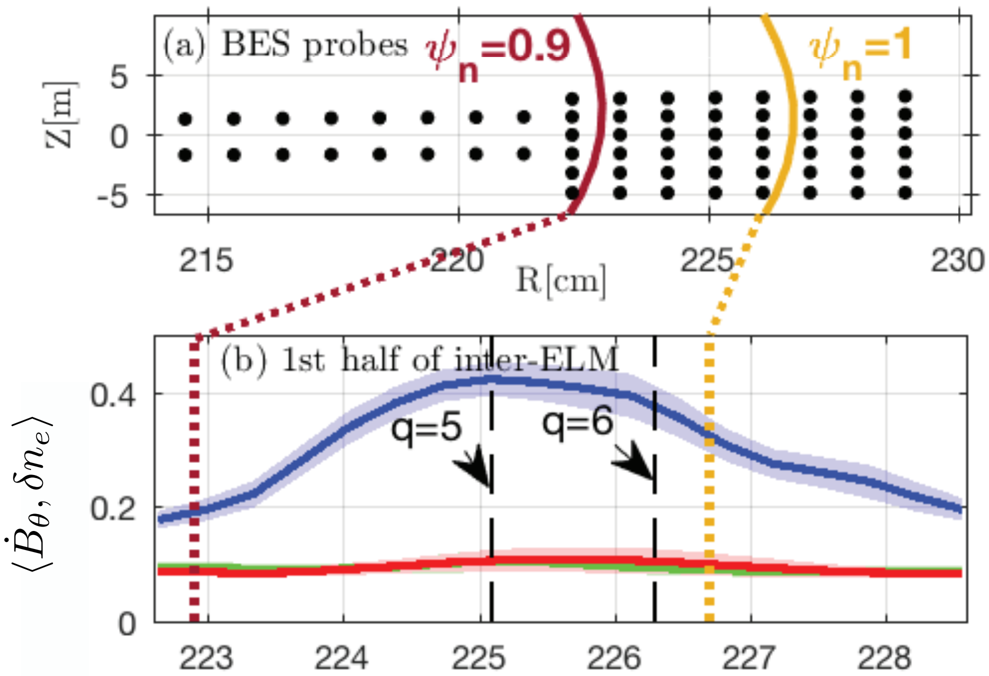


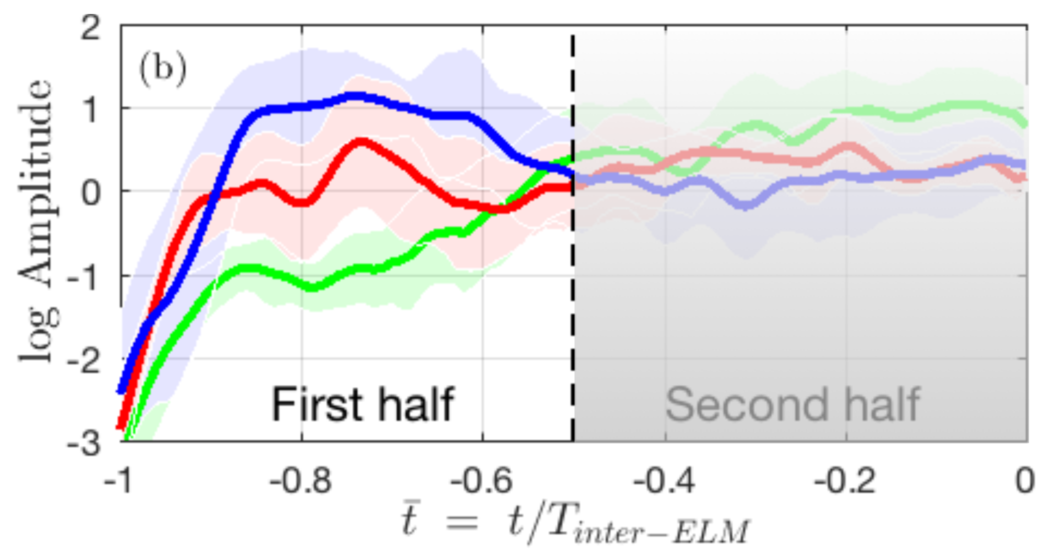


Note that these wavenumbers correspond to high m modes (need geometric correction)

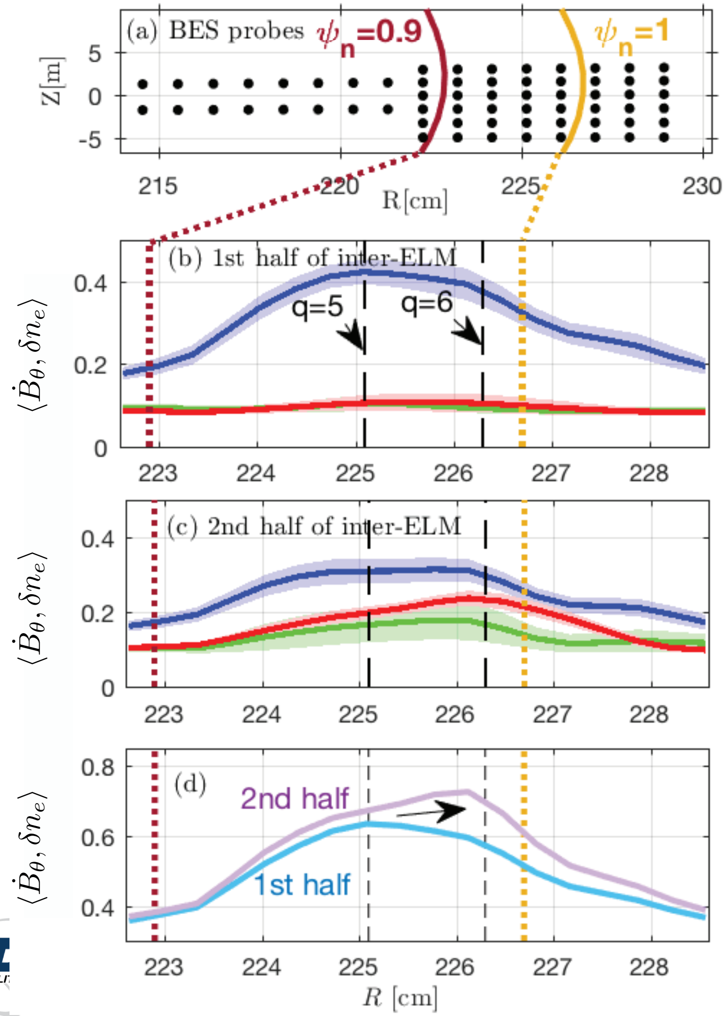
Correlation between the magnetic probes and BES provides the radial localization of each mode

This result suggests correlation between $j_{||}$ and density fluctuations.

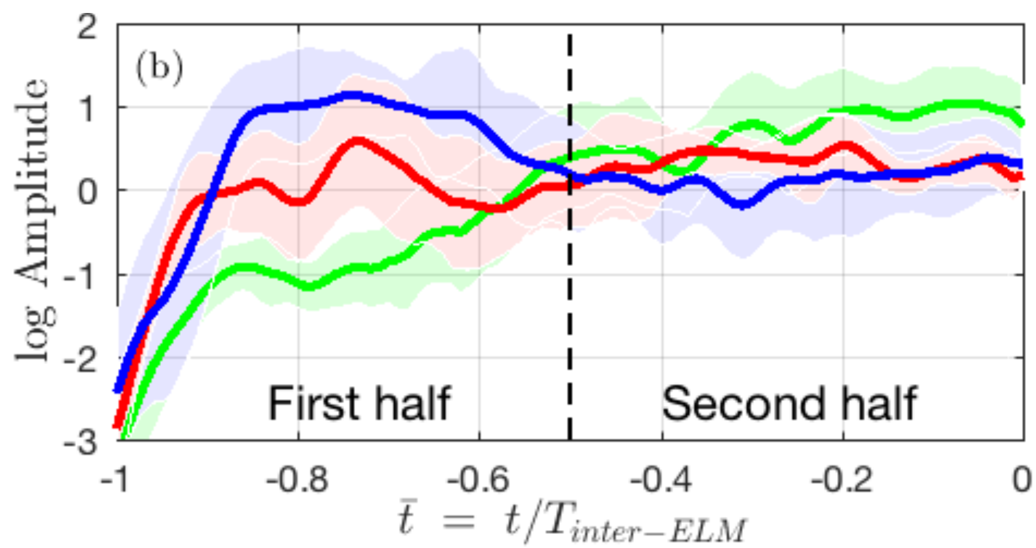




We observe an intensification of the correlation between magnetic and BES near the separatrix prior to the ELM onset



- **The red mode is excited (near q =6) as the blue mode (near q = 5) has its intensity reduced.**
  - During the phase where the gradients are pinned



OBSERVATION OF NONLINEAR DYNAMIC (THROUGH BICOHERENCE) BETWEEN THE INTER-ELM MODES

Nonlinear coupling between modes and the energy transfer can be estimated using the bicoherence

- **The three-wave interaction can be described using the Ritz model**
  Ritz, Phys. Fluids B 1989
  Kim, PoP 1996

Rate of change of the spectral power *Energy transfer term*

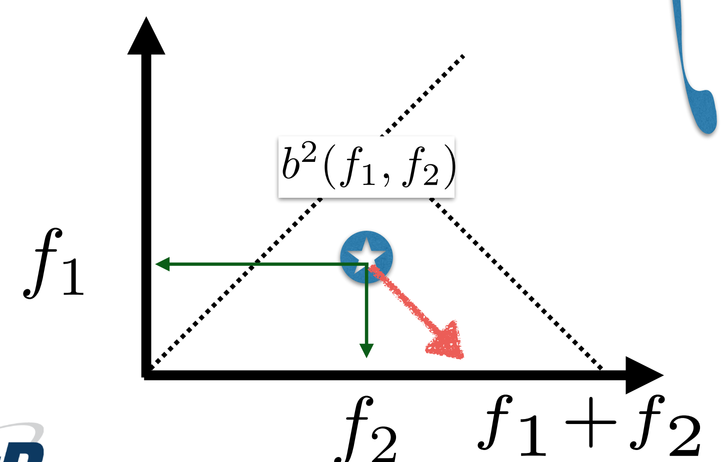
$$\frac{\partial P_f}{\partial t} \simeq 2\gamma_f P_f + \sum_{f_1,f_2} T_f(f_1,f_2)$$

- **Definition of bicoherence:**

$$b^2(f_1,f_2) = \frac{|\langle S_{f_1} S_{f_2} S^*_{f_1+f_2}\rangle|^2}{\langle |S_{f_1} S_{f_2}|^2\rangle \langle |S_{f_1+f_2}|^2\rangle}$$

$$b^2(f_1,f_2) = b^2(f_2,f_1) = b^2(f_1,-f_2)$$ **Symmetry**

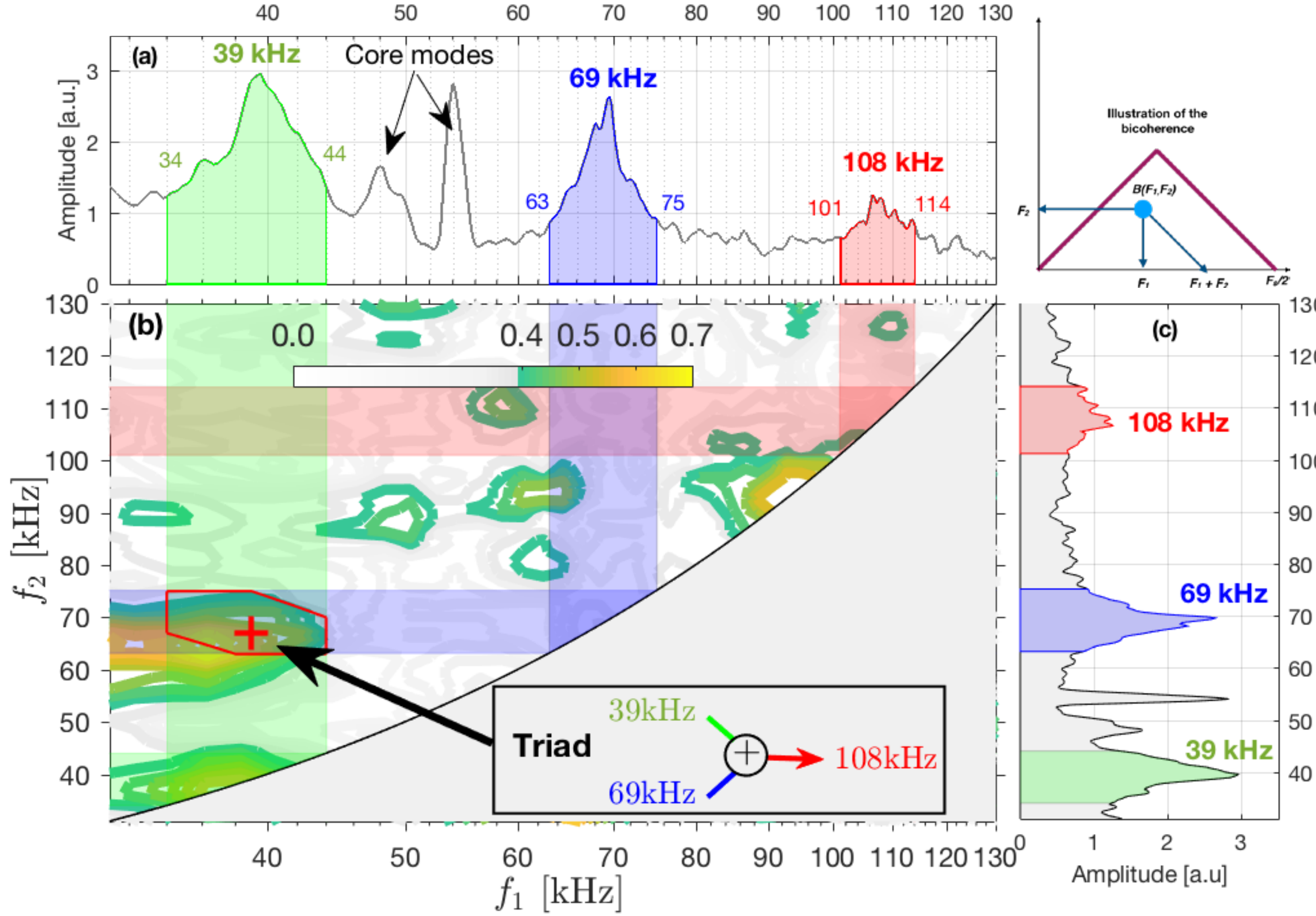
$$b^2(-f_1-f_2,f_2) = b^2(f_1,-f_1-f_2) = b^2(-f_2,f_2+f_1) = b^2(-f_1,f_2+f_1)$$



Bicoherence is a useful tool to diagnose nonlinear interactions.

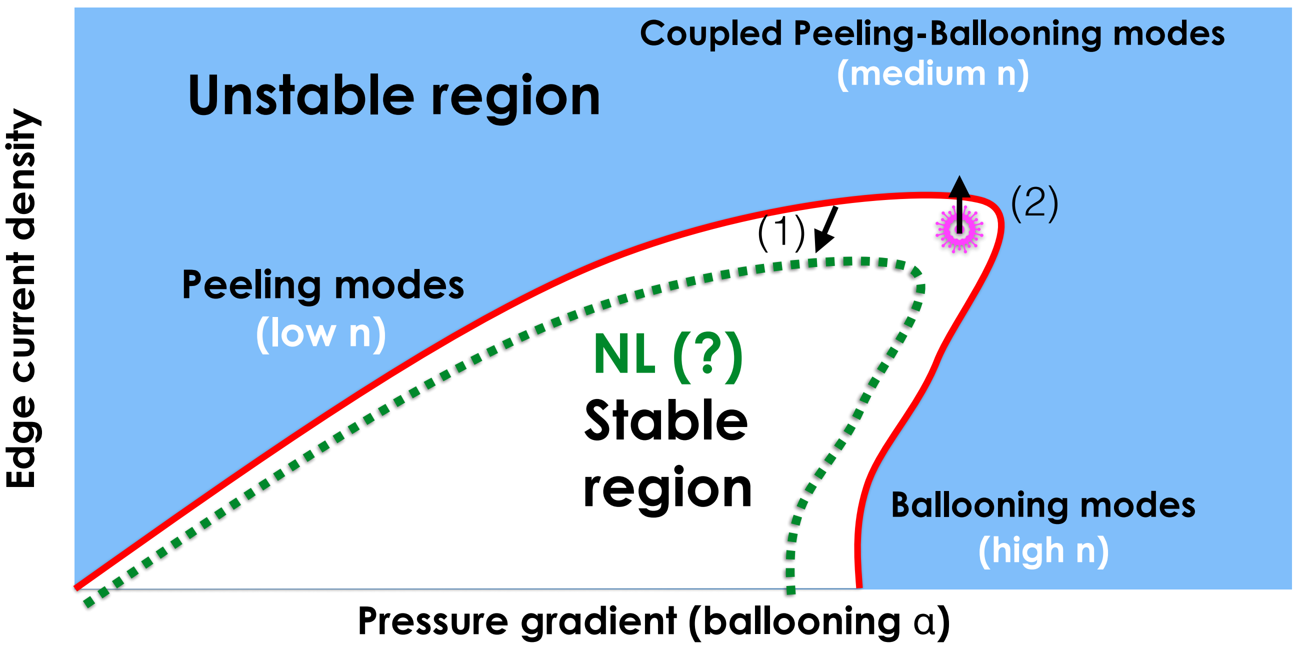
Assumption of the frozen flow hypothesis - frequency and wave number can be directly related.

Nonlinear analysis using bicoherence during the last phase of the inter-ELM period indicates coupling between pedestal modes



Why Peeling-ballooning model might not be sufficient to explain the ELM onset?

Bicoherence analysis suggests that nonlinear effects (between the dominant modes) play a role during the second inter-ELM phase when the pedestal is pinned.



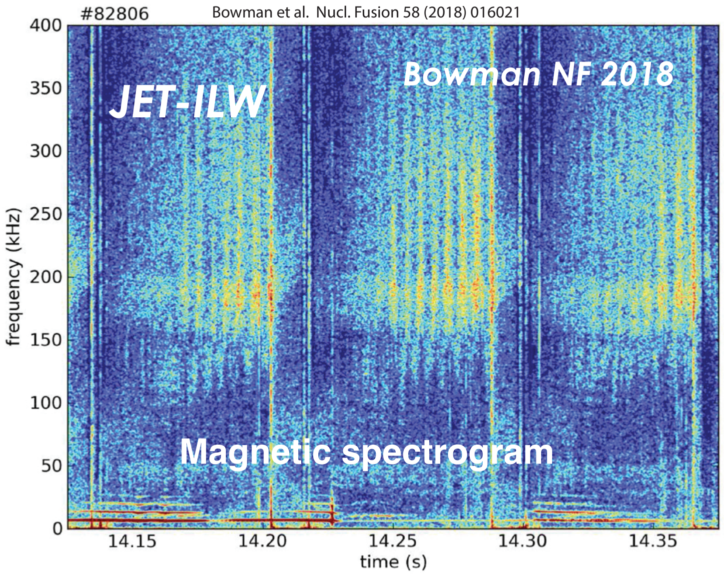
(1) **modify** the stability boundary which could explain why the pedestal is pinned to a marginally stable region (for multiple transport time scales)?

(2) **provide** a local modification of the current density profile in the narrow pedestal region?

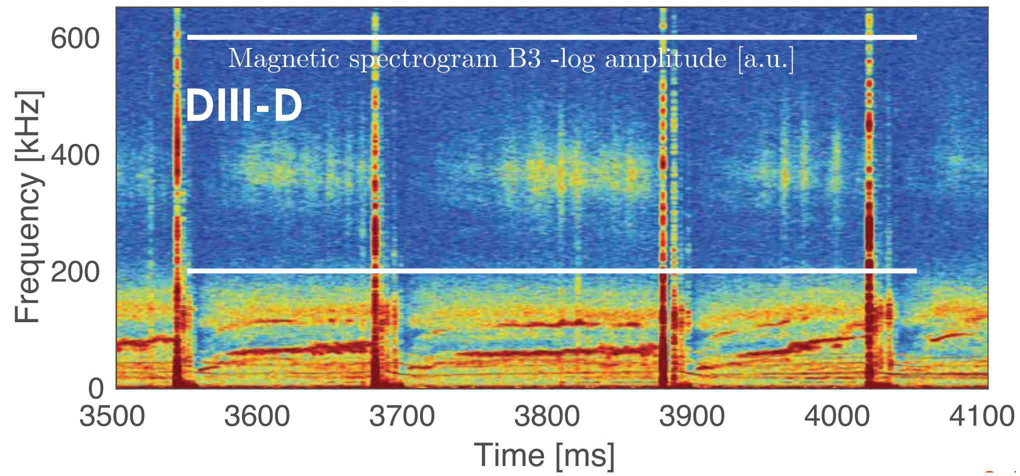
Can the local intrinsic current driven by the third mode be key player in the modification of local safety factor?

WORK IN PROGRESS: INTER-ELMS BURST EVENTS IN THE DIII-D PEDESTAL SIMILAR TO OBSERVATIONS ON JET AND AUG

Identification of inter-ELMs burst events in the DIII-D pedestal similar to observations on JET and AUG

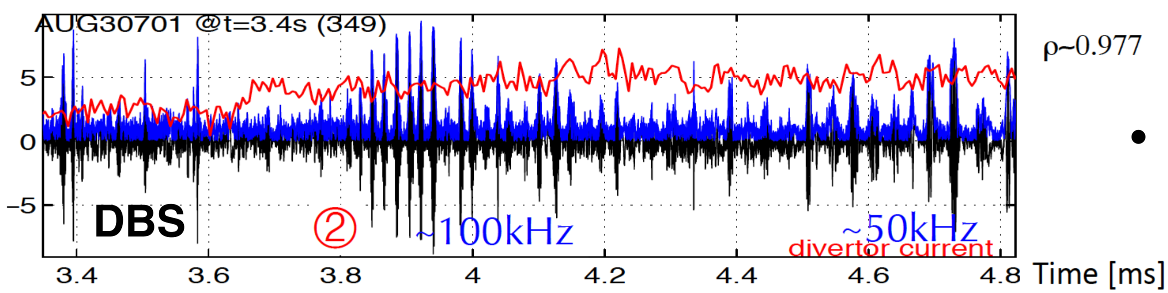


Diallo EPS 2018



② regular amplitude oscillations end of Phase II

Zoom 800 μs



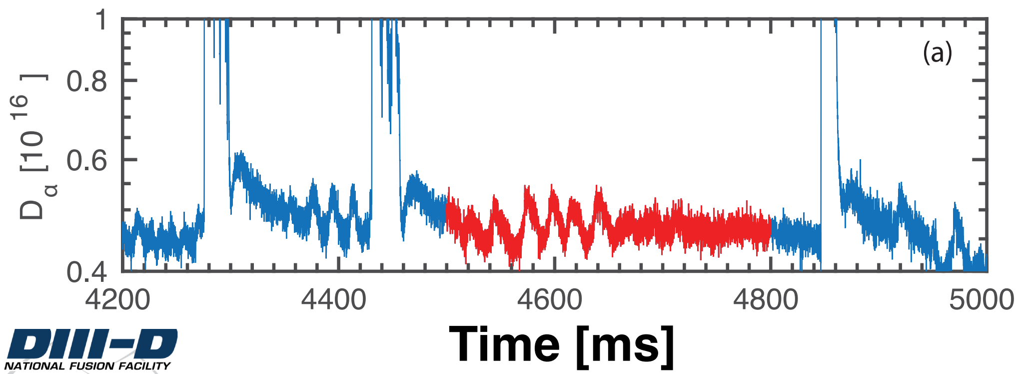
Hennequin EPS 2017

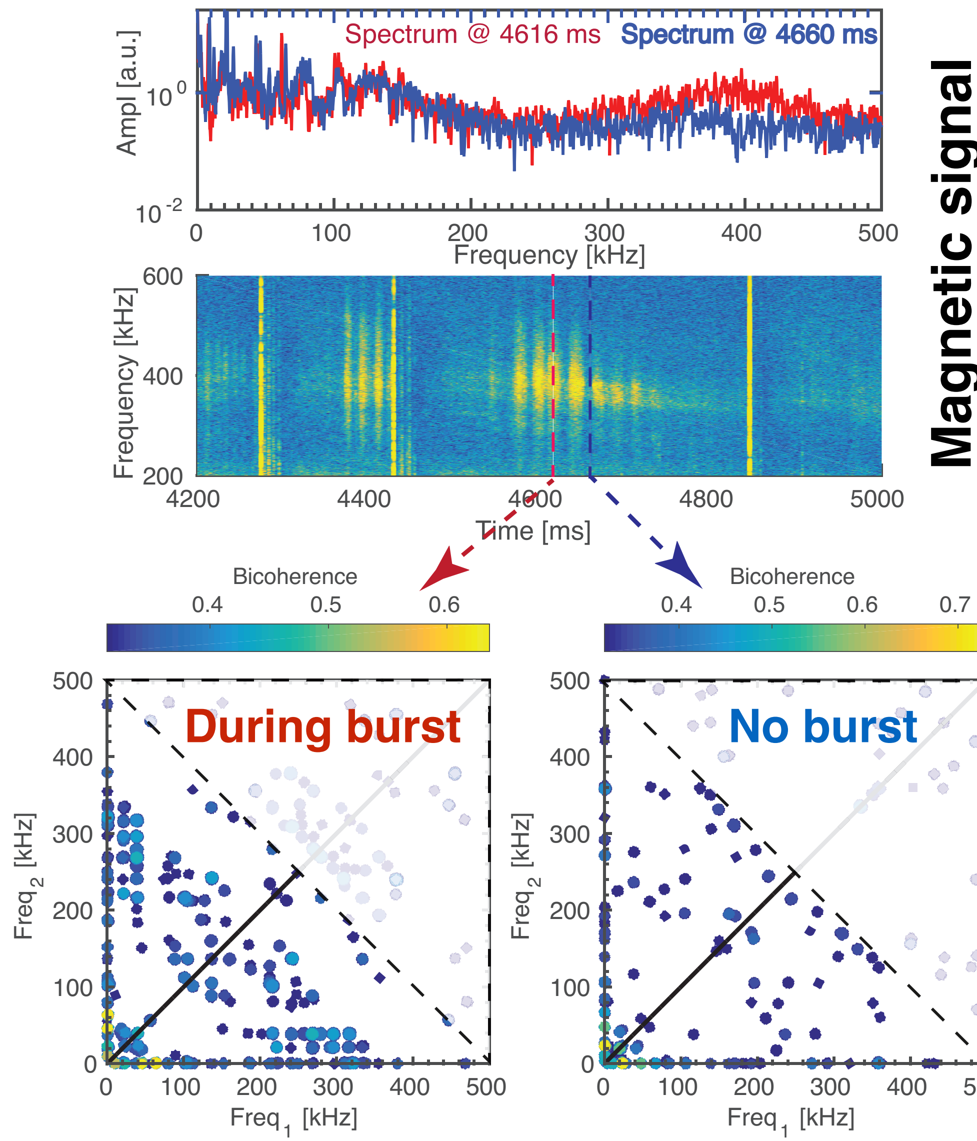
- **Train of bursts but no ELM onset.**

Are the bursts small ELMs?

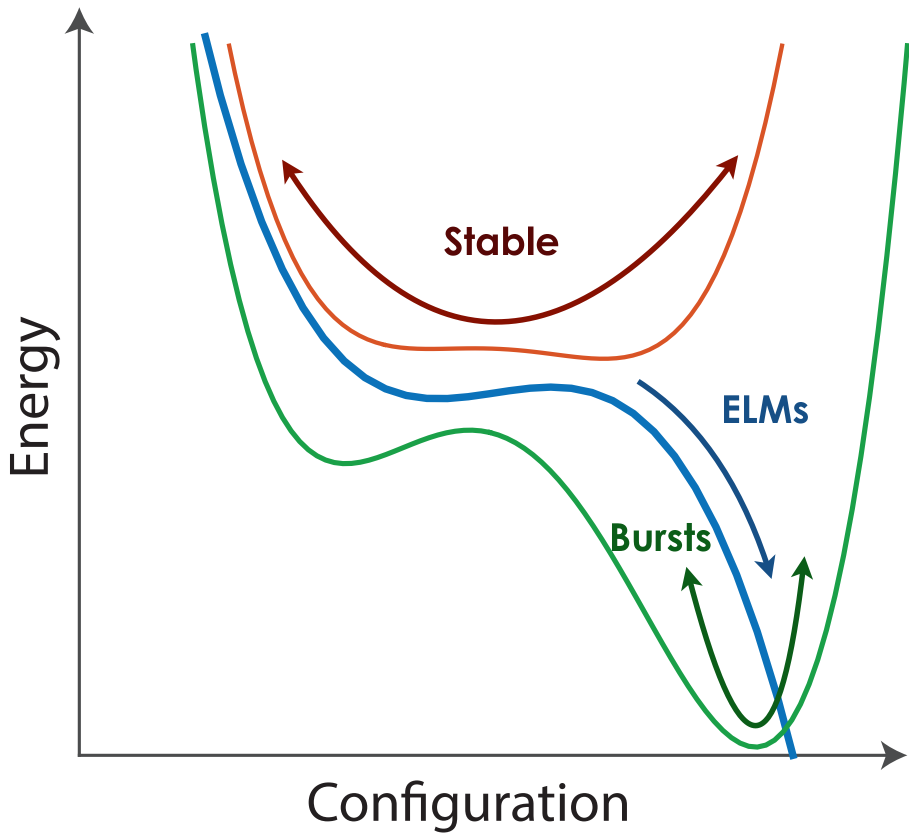
- **Bicoherence analysis suggests that the bursts are caused by sudden nonlinear coupling with saturated dominant inter-ELM modes**

- **We are investigating connections between these bursts and ELMs.**





So when does PB provide a soft limit enabling a NL mechanism to displace to a lower energy saturated states?



- **Stable linearly**
  - Unstable nonlinearly
  - Saturated state available
- **In the PB paradigm, the pedestal can be linearly stable but have nonlinear states available**

Ham PRL 2016