ELM Suppression by Real-Time Boron Powder Injection in W divertor on in EAST

IAEA-CN-1167

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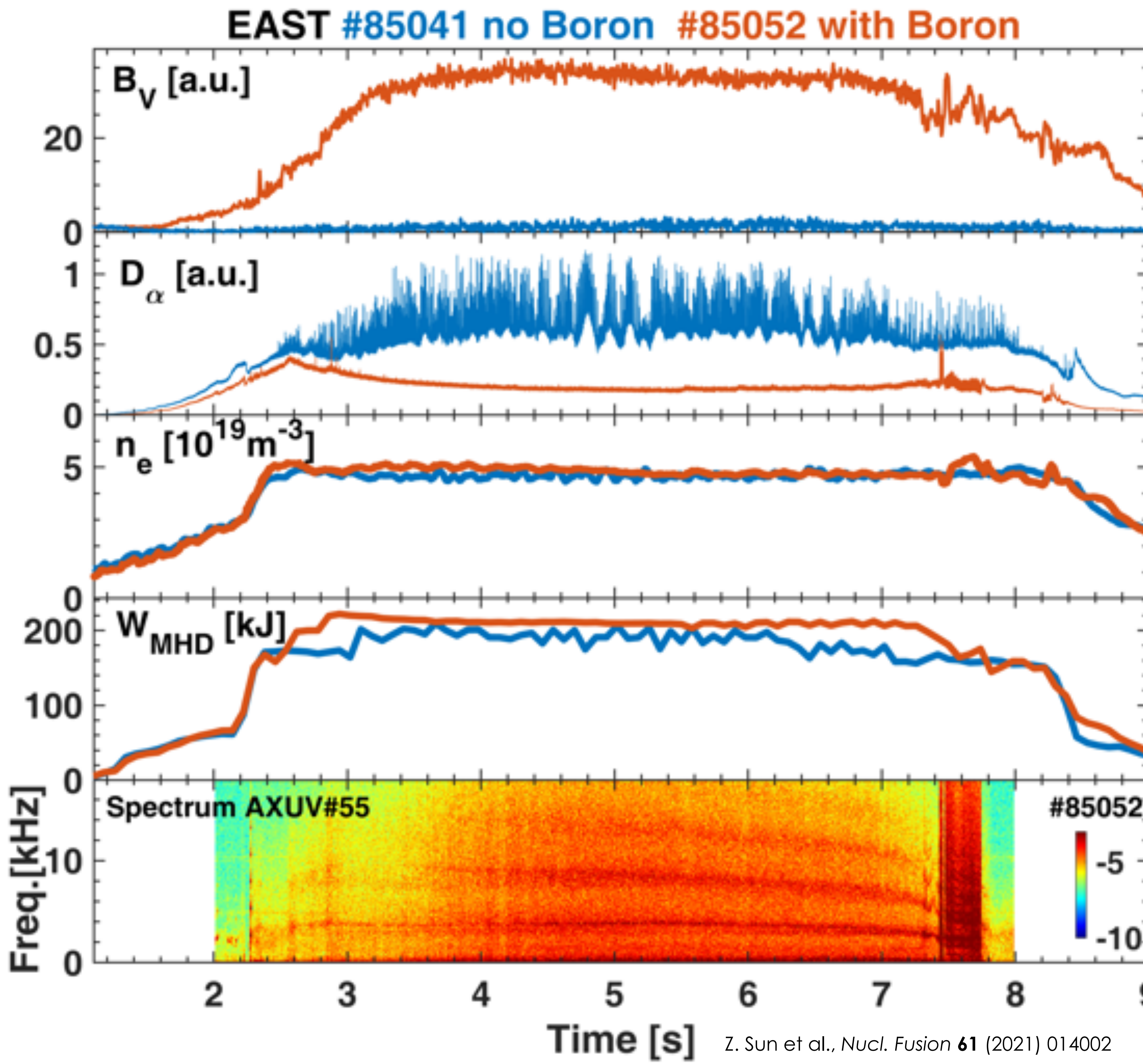
28th IAEA Fusion Energy Conference (FEC 2020) - Virtual Event
10–15 May 2021

Boron injection led to ELM suppression

I_p = 0.5 MA, B_t = 2.5 T, P_{heat}~ 6 MW, USN, grad-B drift ↑, toward X-point
Type-I ELMs, $H_{98(y,2)}$ ~ 1



- **Suppression of ELMs with con[stant] stored energy and density**
- **Clear drop in D_α baseline**
- **Harmonic mode onset and saturation**

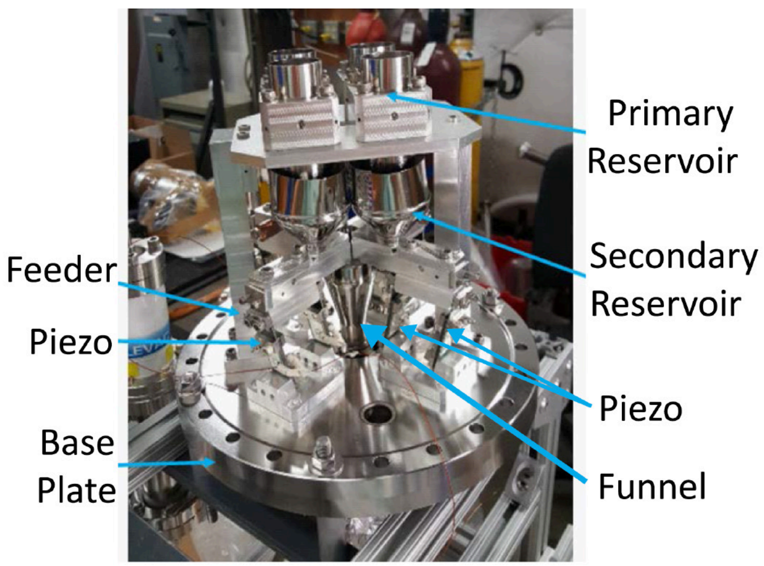
Z. Sun et al., *Nucl. Fusion* **61** (2021) 014002

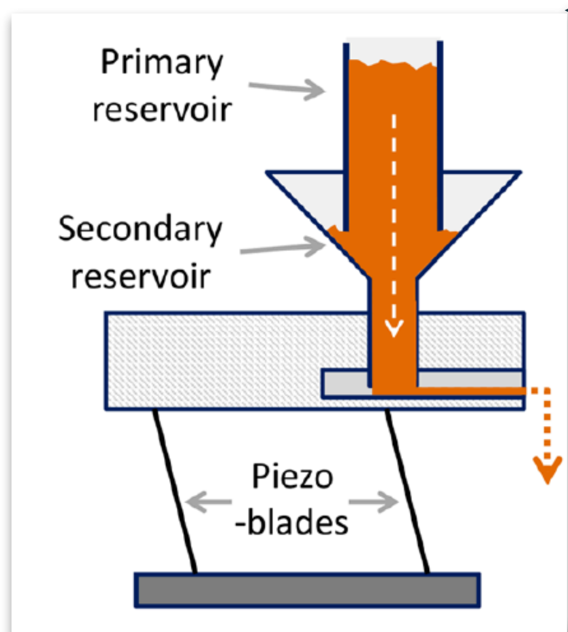
Real-time impurity powder injection used for ELM control, wall conditioning and power exhaust

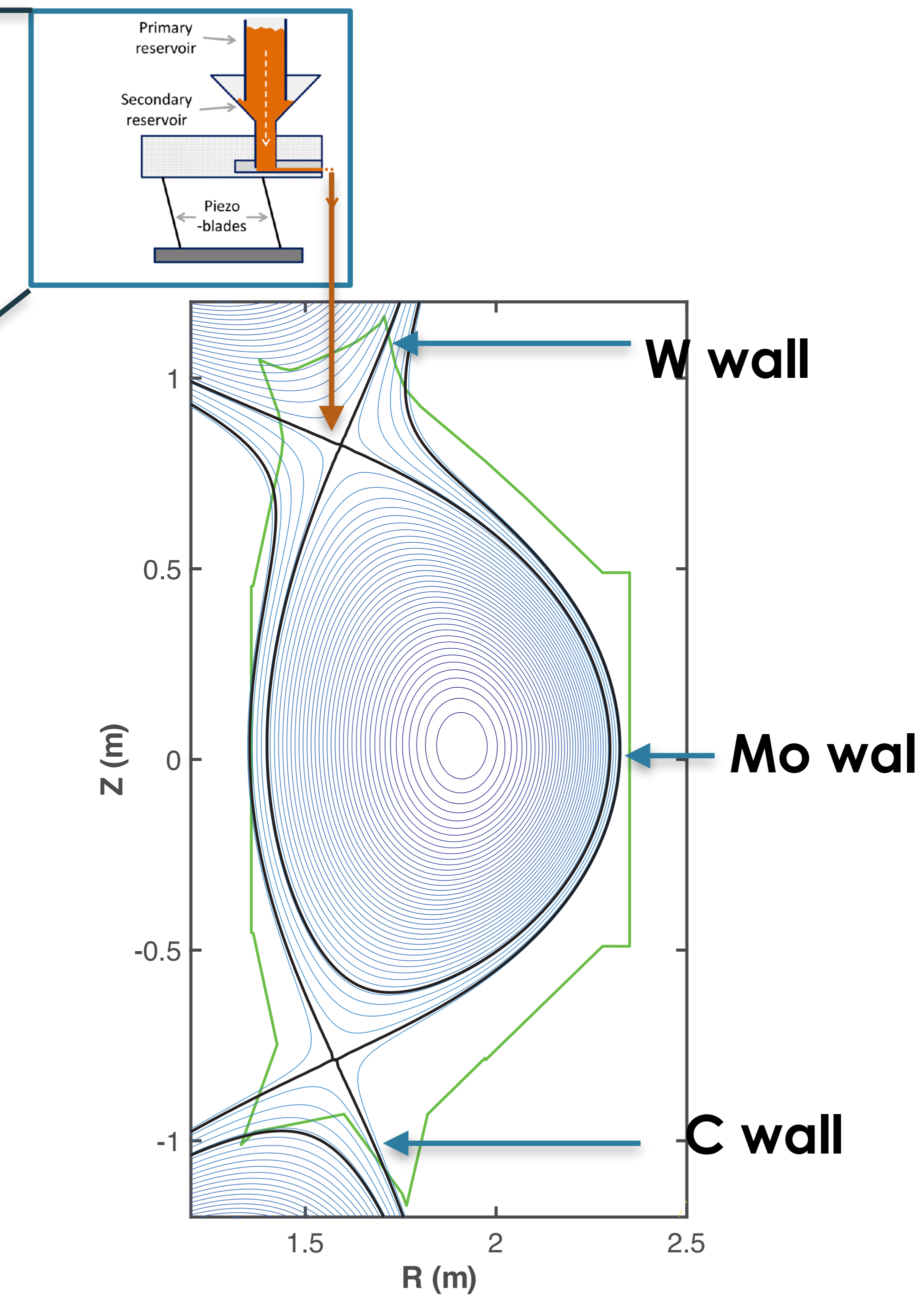
- **ELM control**
  - alter edge stability toward ELM-stable or small ELM regimes
    - EAST, KSTAR
- **Wall conditioning**
  - continuously alter wall coatings for improved PMI and core performance
    - EAST, AUG, DIII-D, LHD, W7-X & WEST
- **Power exhaust**
  - enhance divertor and boundary power dissipation to heat flux control
    - EAST, AUG, DIII-D

This talk will focus of ELM suppression in EAST

Impurity Powder Dropper (IPD) on EAST







- **IPD has been used to provide real-time conditioning**
- **IPD has four reservoirs and enables the injection of multiple materials**
- **On EAST, IPD drops material in the upper X-point**

A. Nagy et al., *RSI* **89** (2018) 10K121

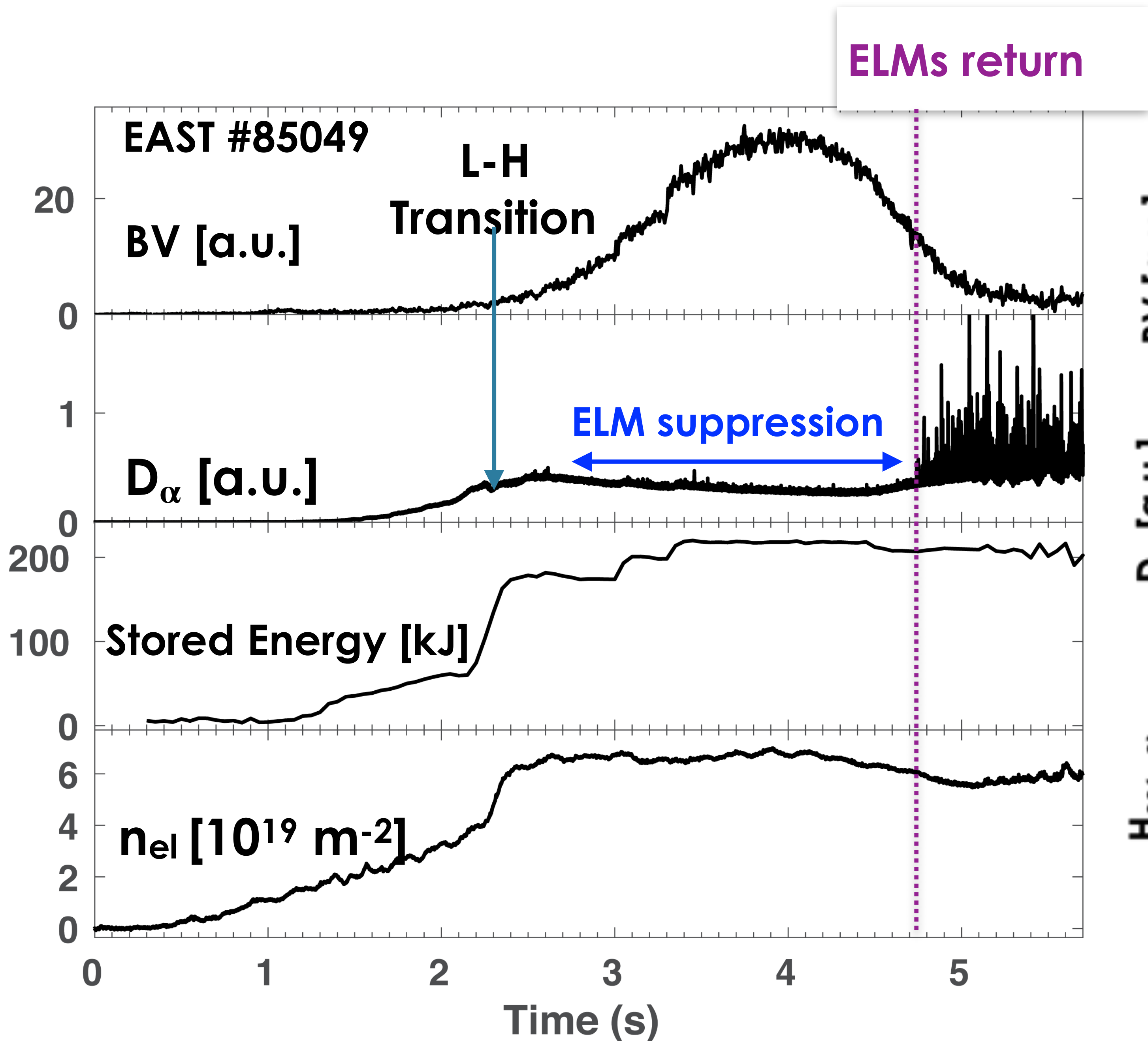
ELM suppression with B powder injection: Regimes and key characteristics

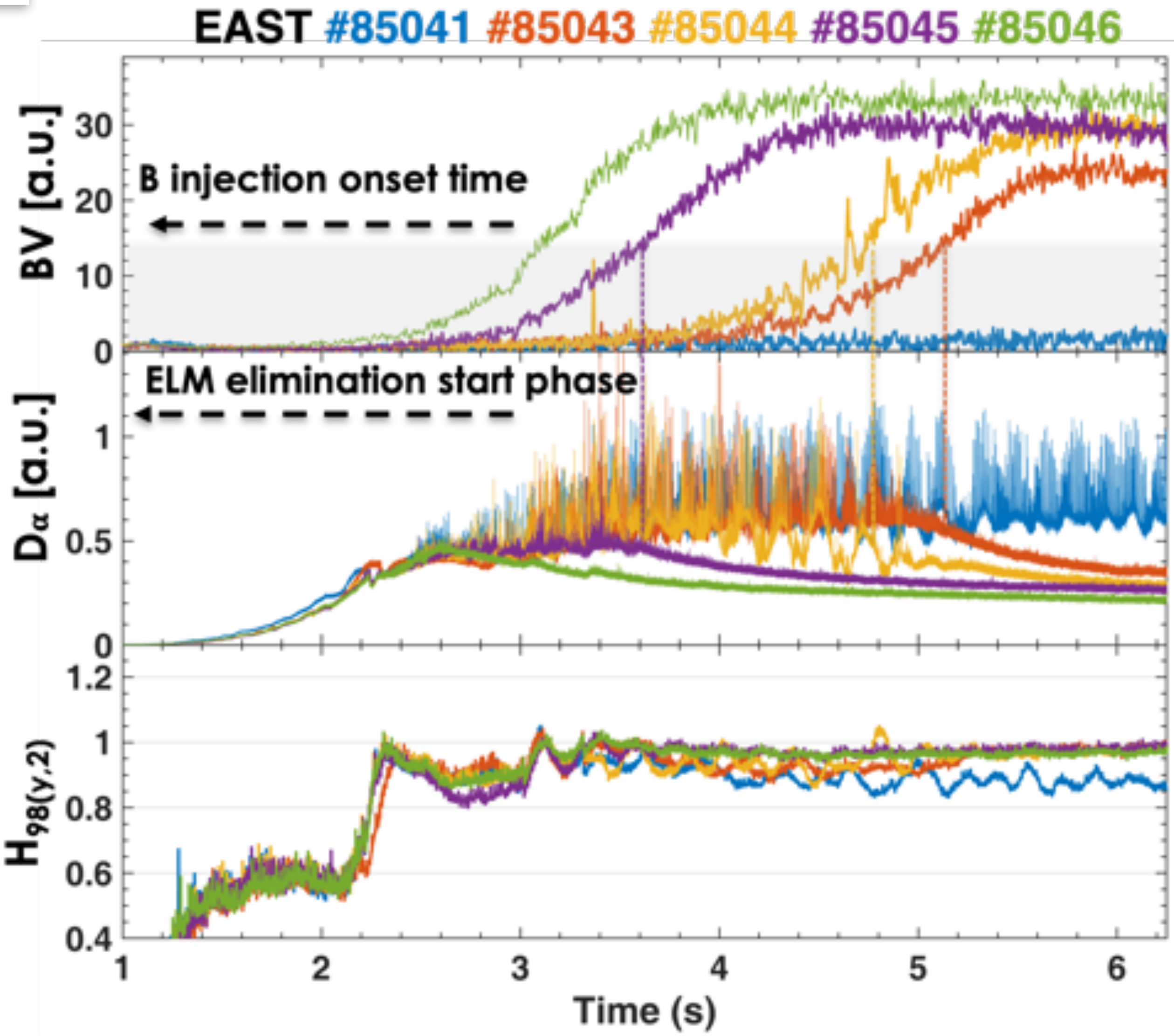
- **Wide range of operation conditions**
  - RF-only & RF + NBI heating: 2.8 MW – 7.5 MW
  - q_{95} between 4.4 and 7.2 (typical 0.5 MA, 2.5 T)
  - Density range: 0.25 – 0.85 n_{GW}
  - With D or He majority
  - Both directions of grad-B drift

- **Suppression occurs when a threshold in B injection rate is crossed**
  - increased with heating power R. Maingi et al., *IAEA FEC 2021*

- **Onset and saturation of mode**
  - Multiple harmonics ~ 2-5 kHz fundamental
  - Localized near separatrix and drives particle transport

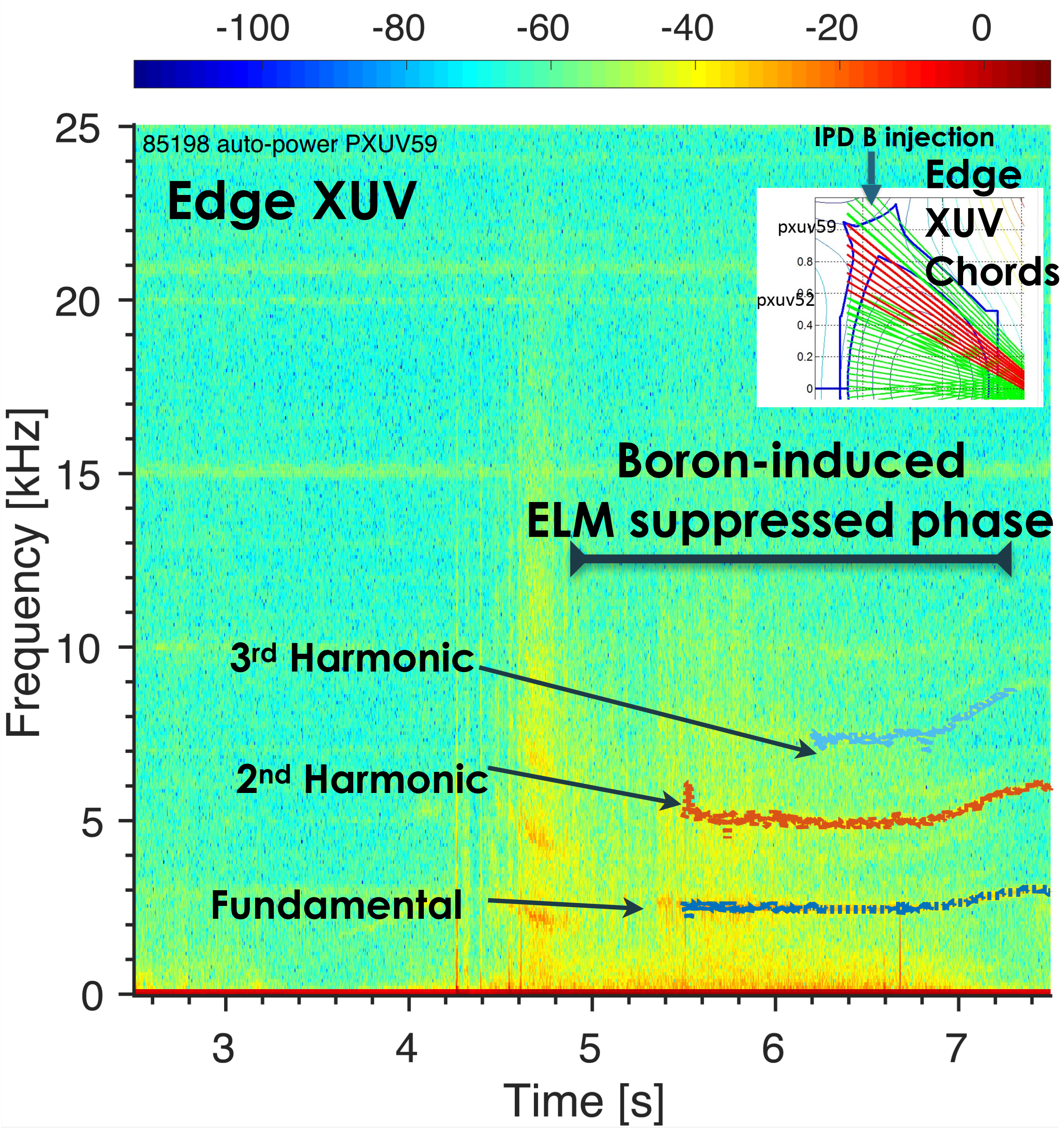
ELMs suppression correlates with boron injection



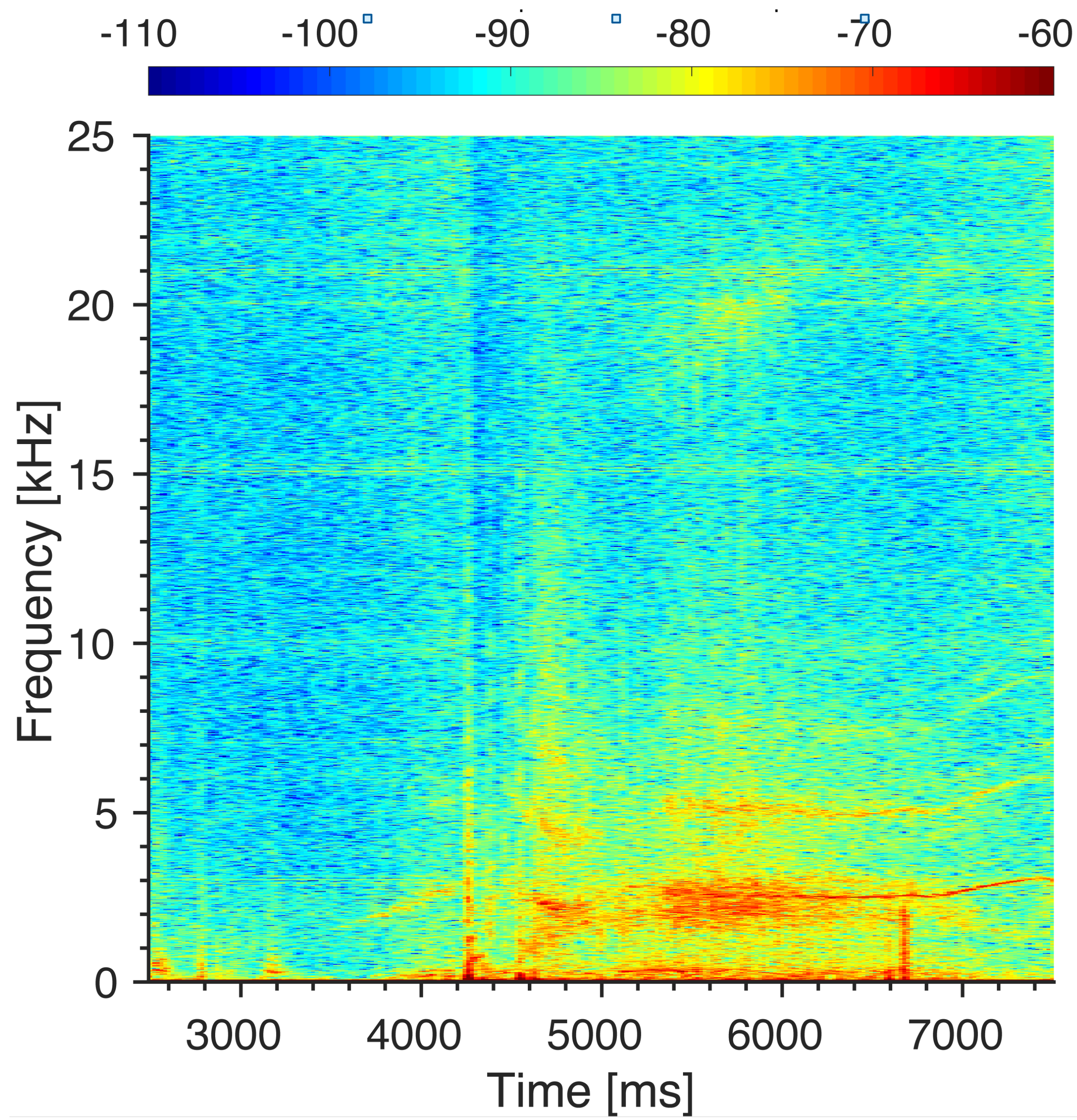


Identification of coherent fluctuations with harmonics in both magnetic and impurity radiations (XUV) spectra

XUV signal is proportional to $n_e \times n_z \times f(T_e)$



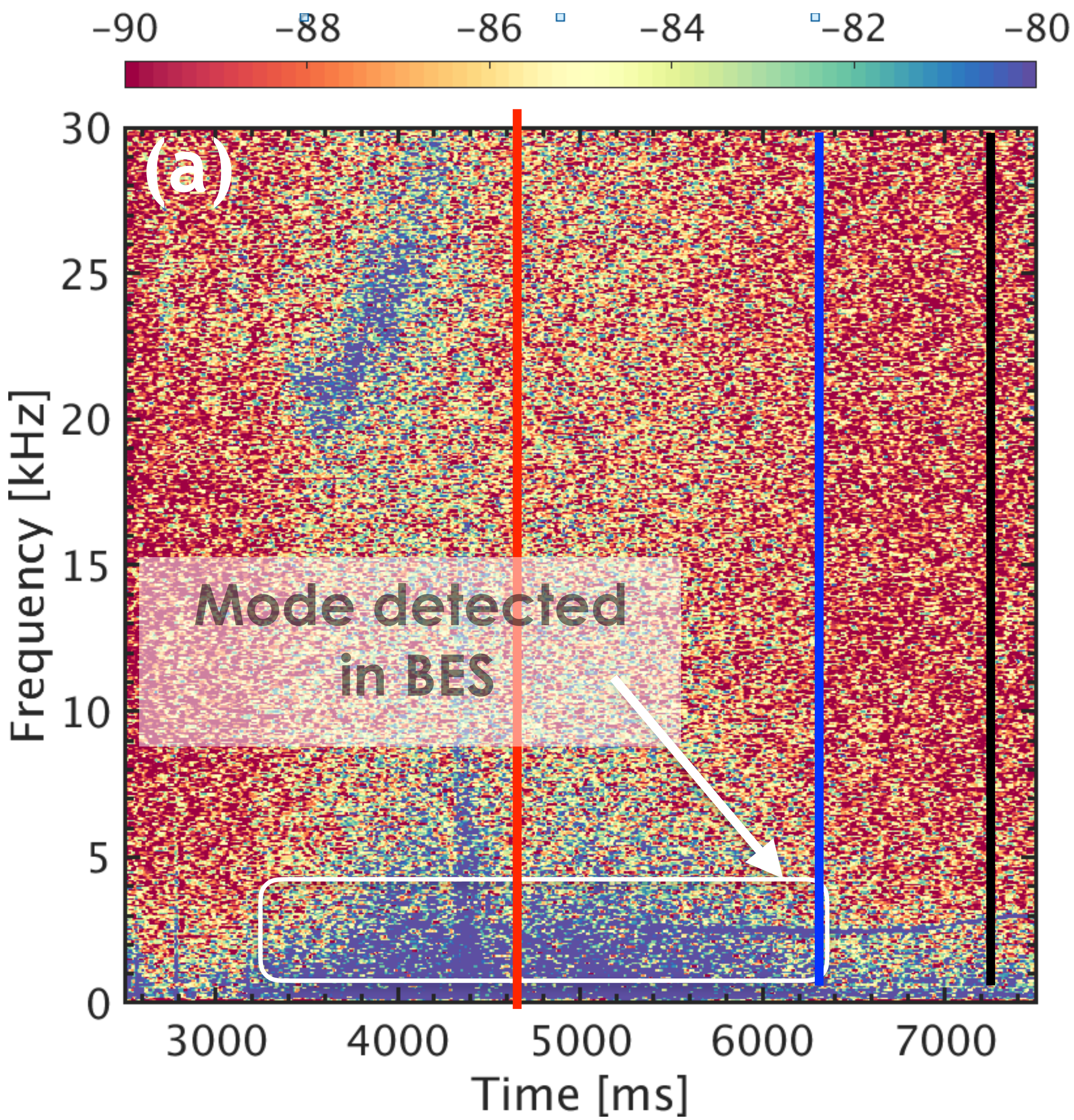
Cross-power magnetic and edge XUV signals

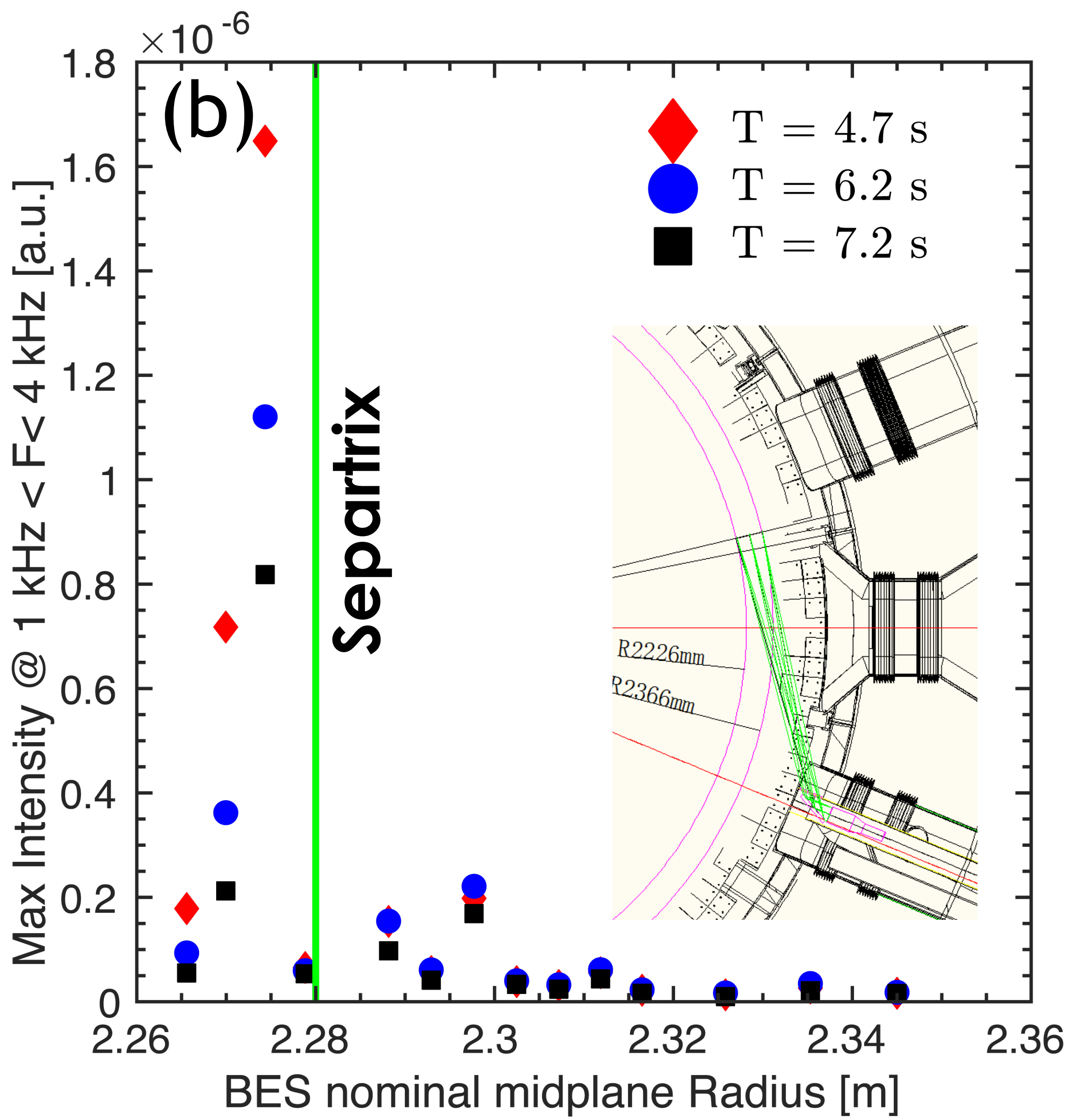


Mode appears to be localized near the seperatrix

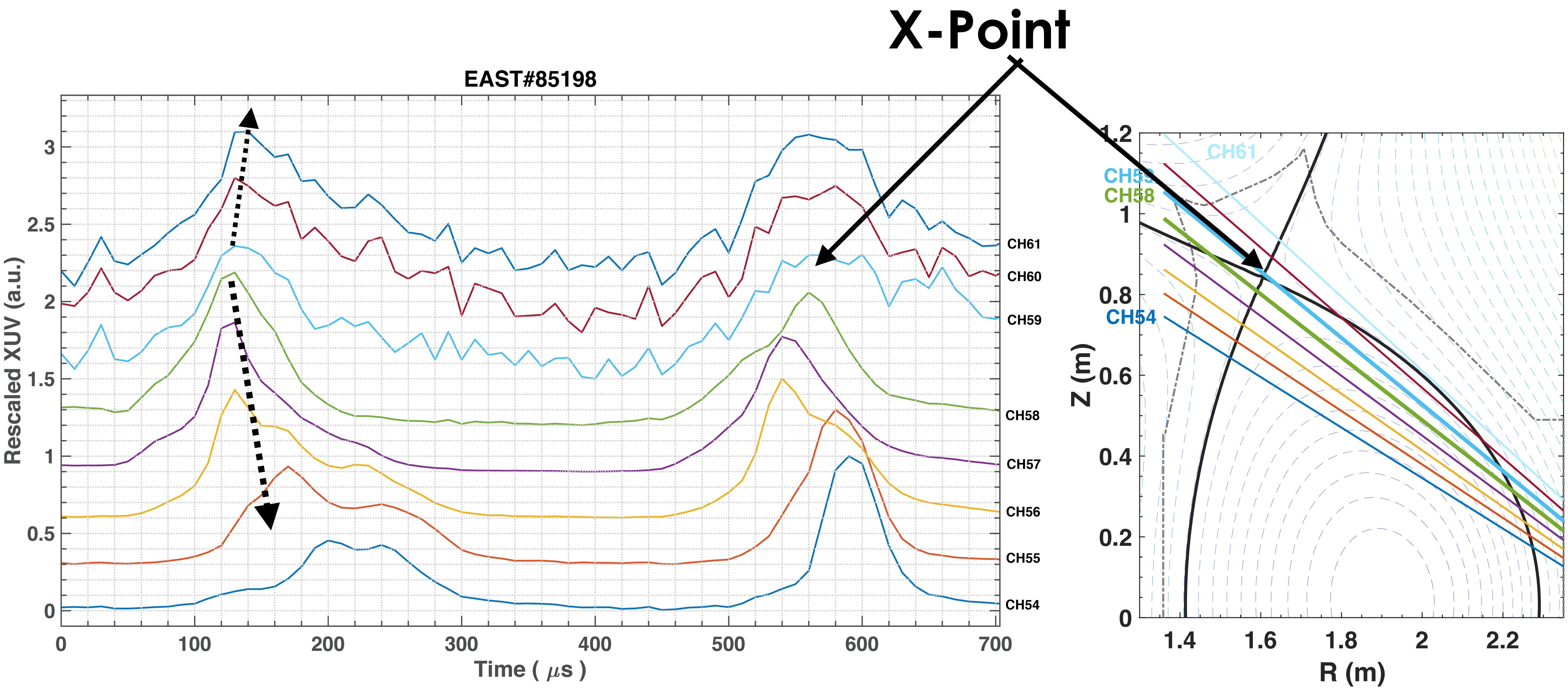
Using midplane D_α emission (BES system with D_α filters)

Radial Profile of mode amplitude



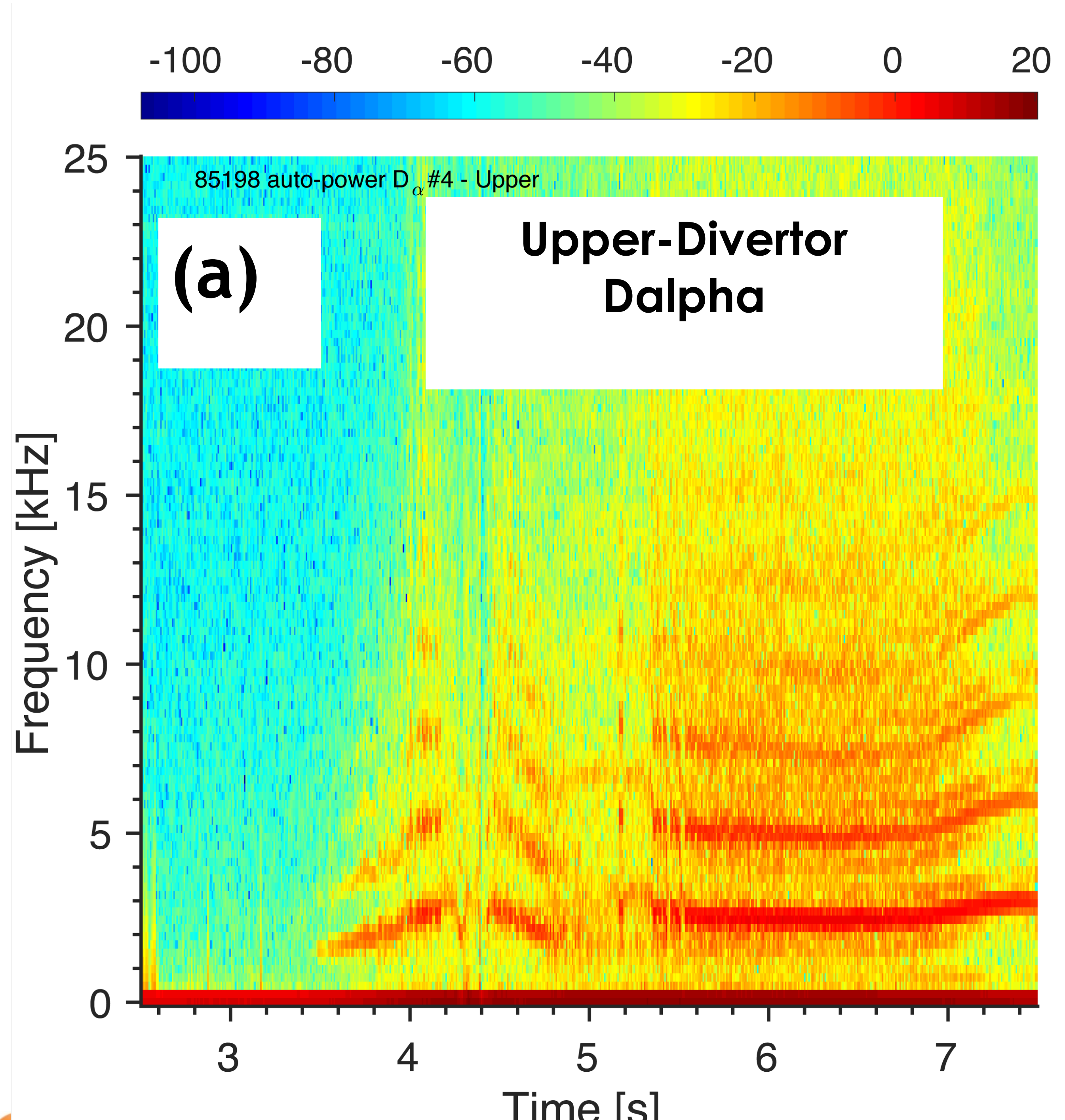


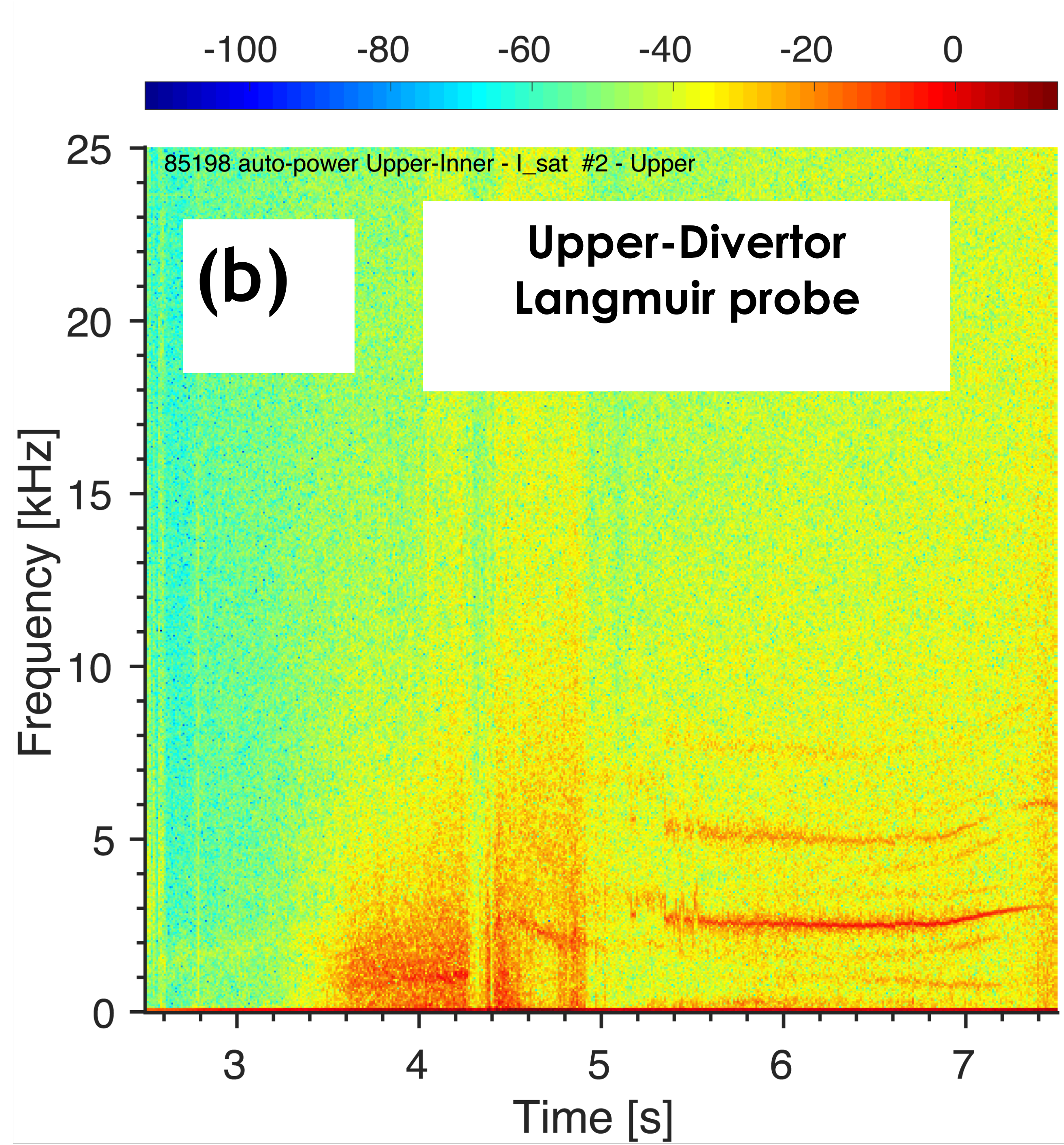
Mode propagates poloidally away from the X-point



Boron-induced mode affects the particle transport

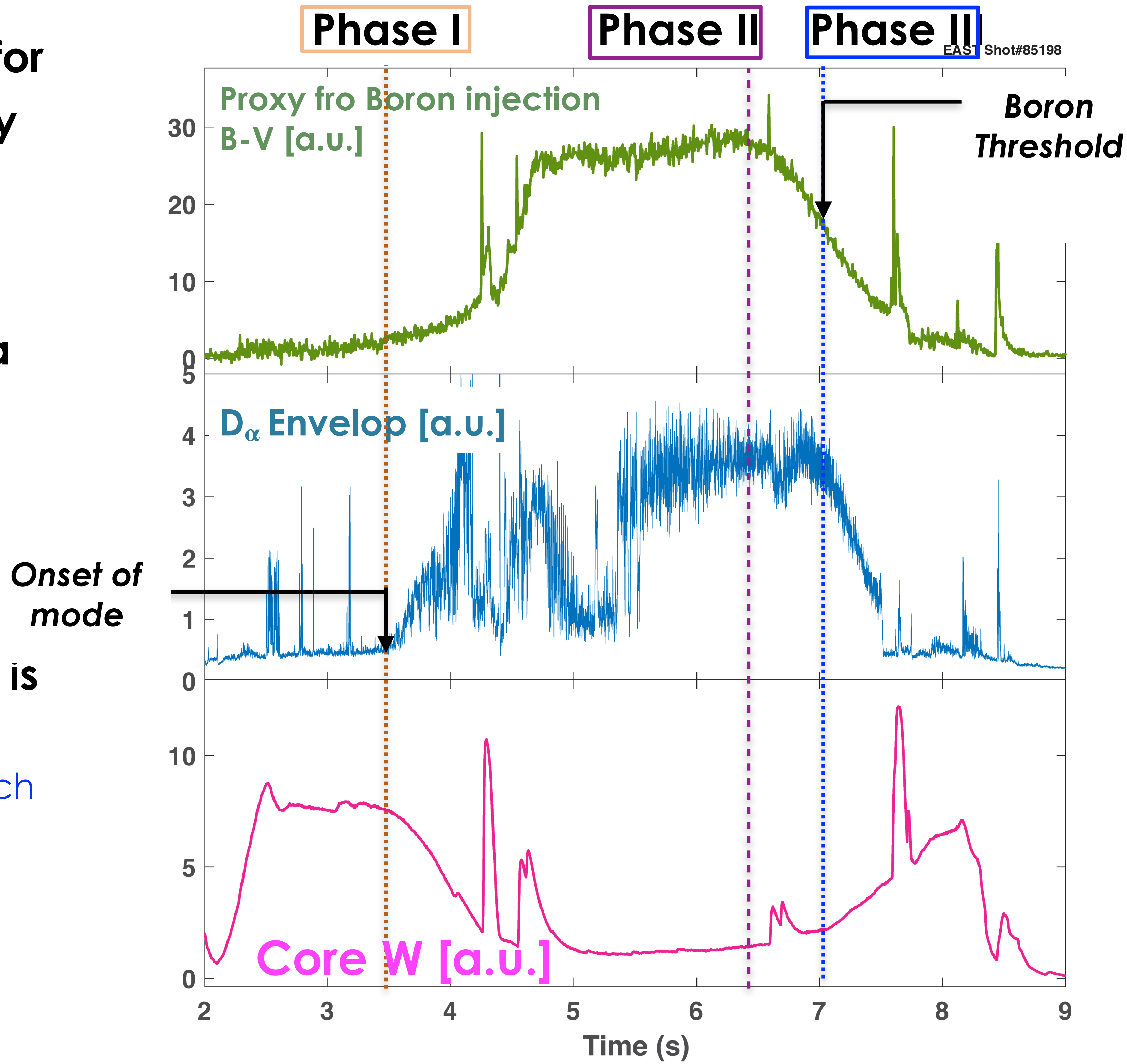
- Modes are also observed in the divertor using D_α and Langmuir probes
- Observation of the modes in I_{sat} suggests particle transport





Identification of three phases during the Boron injection

- **We use the rms of D_α as proxy for the amplitude of low frequency modes**
- **<u>Phase I:</u> Onset of mode amplitude when B-V reaches a threshold**
  - Mode appears to decrease the core W impurity accumulation
- **<u>Phase II</u>: Mode amplitude is constant when boron injection is interrupted**
  - Existence of a threshold after which mode decreases
- **<u>Phase III:</u> Mode amplitude decreases at the same rate as the boron emission**



Origin of this mode?

- Ablated Boron in X-point produces density perturbation akin of a density accumulation

- Density perturbation propagates poloidally away from the X-point

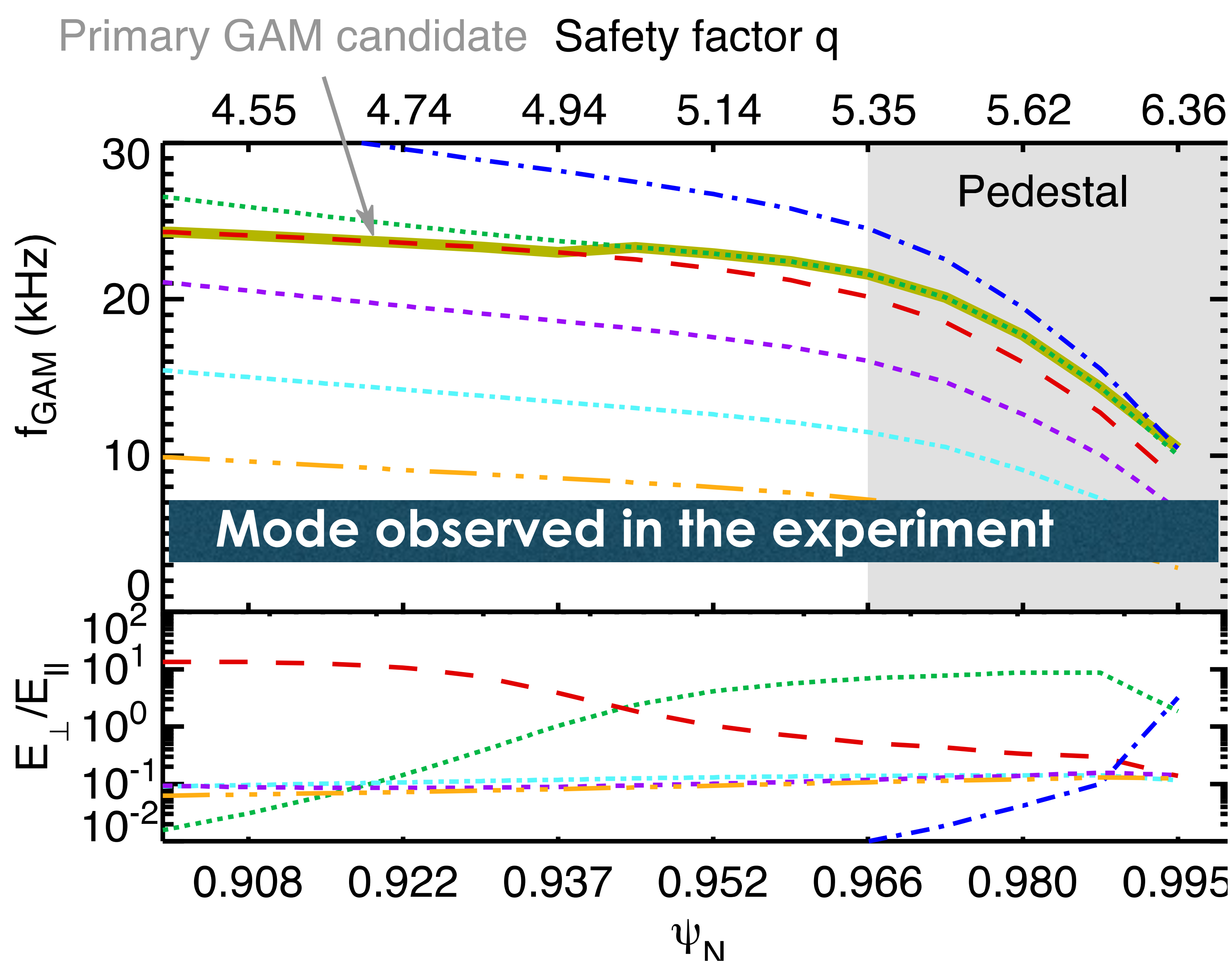
- Hypothesis: This perturbation couples to GAM

- Step-wise approach:
  - Investigate whether the experimentally observed low-frequency modes can be GAMs
    - simple two-fluid approach to establish basic plausibility
    - Extend analysis using a high-fidelity gyrokinetic code XGC
  - Simple 2D toy model to assess the impurity-induced GAM driving mechanism
    - Can we explain the multiple harmonics?

Spectrum of geodesic acoustic mode and ion sound wave (ISW) frequencies

- **Two-fluid calculation in the limit $k_r \rightarrow 0$**

- **Ratios of perpendicular (ExB flow) to parallel kinetic energy of the eigenmode, i.e., GAM vs. ISW character**



Model Assumptions

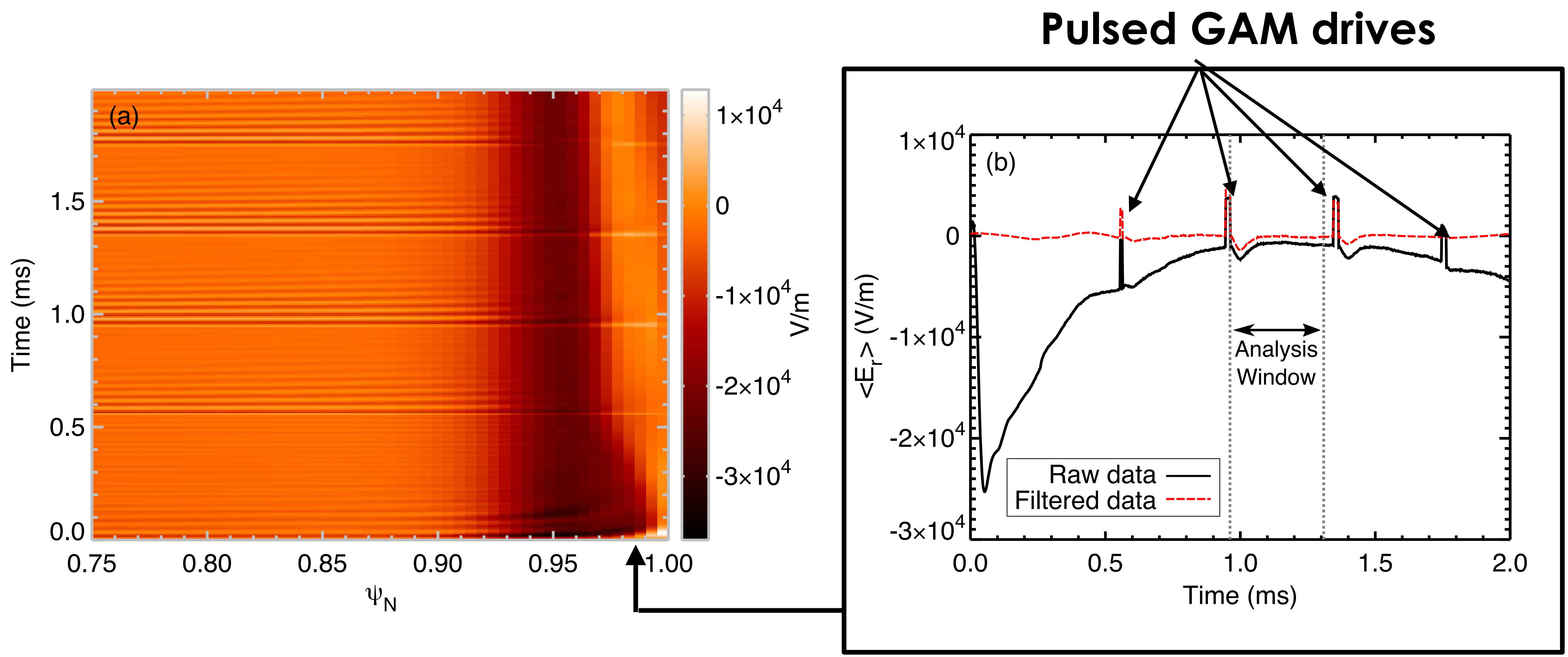
- **Simulation performed with XGC**
  - Total-f code
  - Realistic geometry including scrape-off layer
  - Here: axisymmetric electric field → turbulence excluded

- **We assume excitation of GAMs with the powder dropper depends on the position of the dropper rather than the type impurity used**
  - only two species, deuterium ions and electrons are included

- **No ablation model was included - we assumed that density perturbations due the ablation is translated to E_r variations**

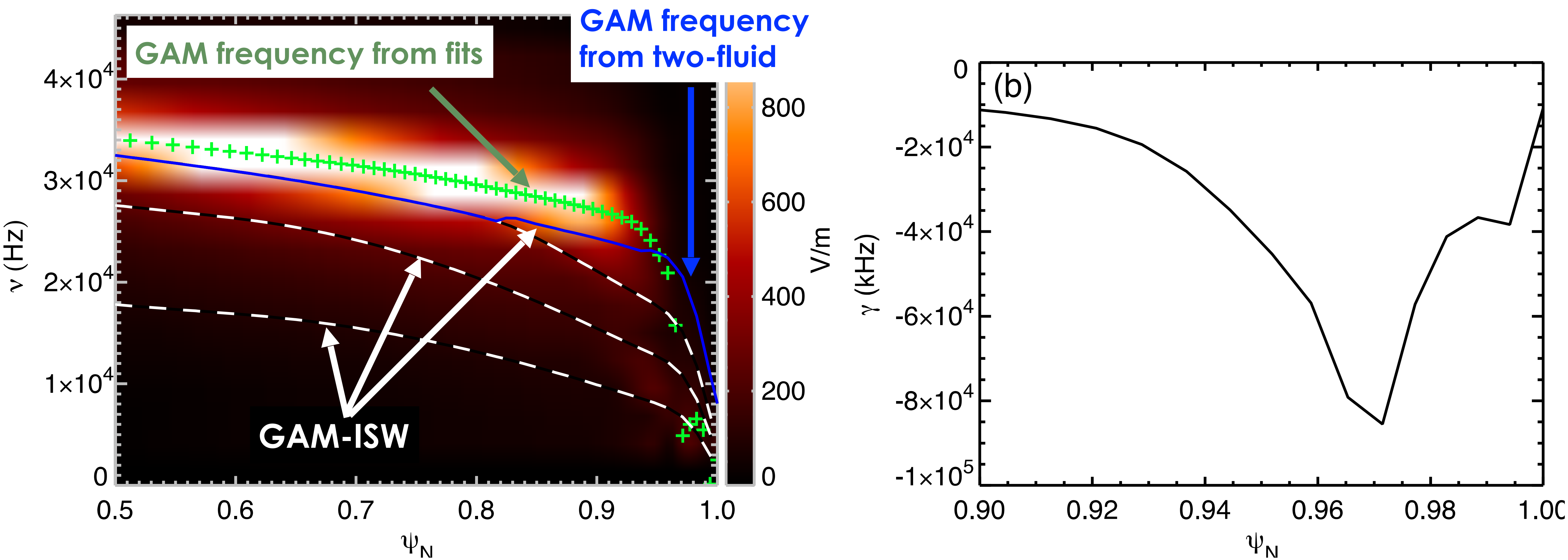
GAMs are excited by adding a bias voltage to the self-consistent flux-surface averaged (zonal) electrostatic potential instead of a pressure perturbation

- **Applied Er kicks to drive the GAMs**
- **Extracted the flux-surface averaged radial electric field <Er>**
- **Slow <Er> temporal evolution due to neoclassical transport is removed for further analysis**



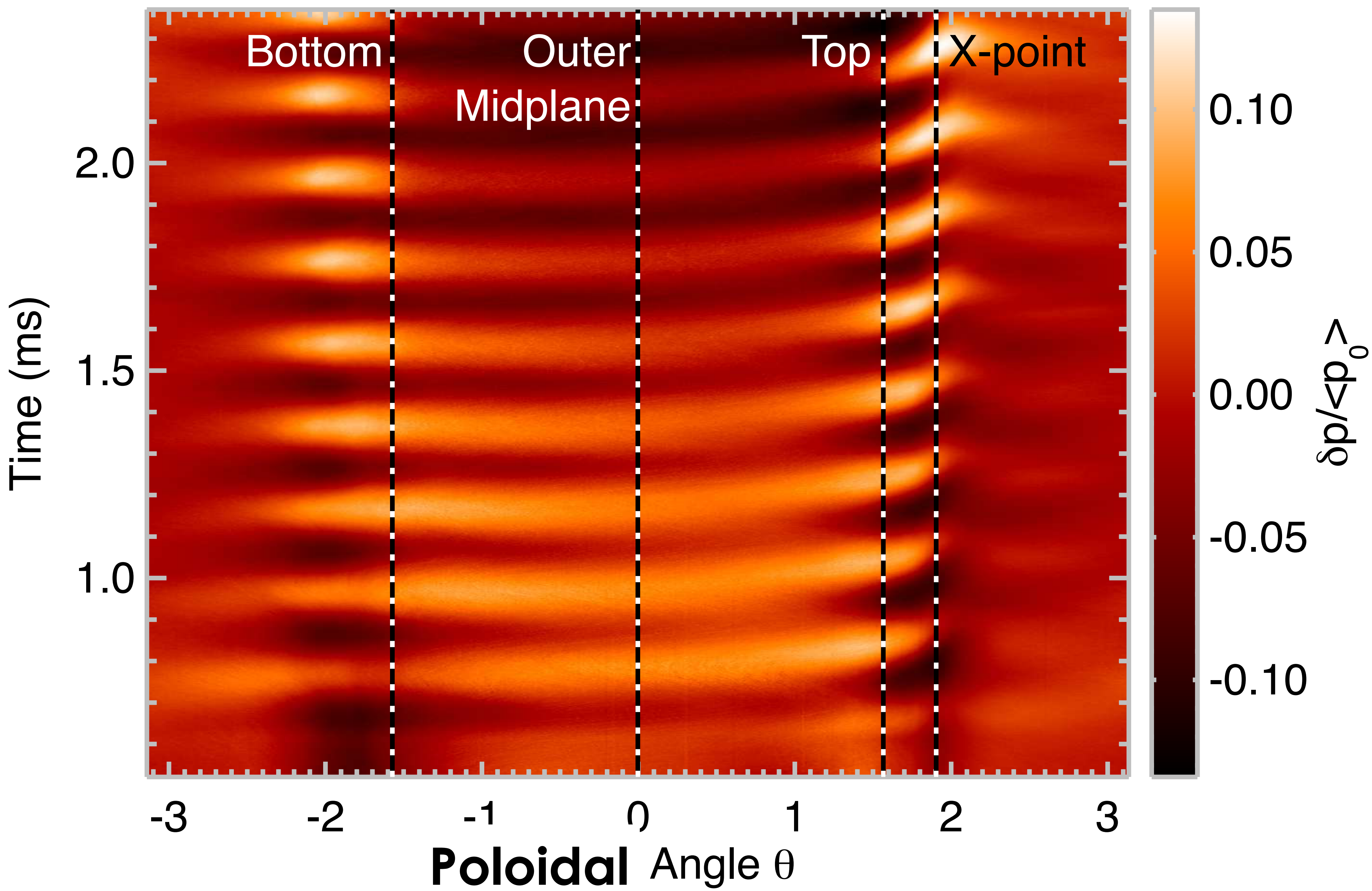
Consistency between the radial electric field and the GAM-ISW spectra

- For each flux-surface ψ, we fit an exponentially damped sinusoidal oscillation to the (Er)(ψ) data



- **Observed damping is most likely due to (collisionless) Landau damping in steep pedestal gradient** (finite-k_r effect, e.g. Xu et al., Nuclear Fusion 2009)
  - The high gradient of the GAM frequency in the pedestal leads to fast increasing radial wavenumbers k_r

Poloidal structure of a GAM mode generated with continuous drive at 5 kHz peaks very close to the X-point



Can density perturbation induced by the powder dropper generate an n=1 mode, which could nonlinearly couple to a n=0 mode?

- **Pathways that could enable such mechanism**
  - through the velocity space distribution of the injected particles
    - which is different from the neoclassical equilibrium distribution and leads to excess radial transport
  - **through direct coupling to the m=1 pressure perturbation of the GAM**
- **Focus on the possibility of direct coupling:**
  - Can a continuous particle source produce an oscillation?
  - Can such oscillation couple to an axisymmetric mode?

Simple 2D model produces n=1 oscillation with harmonics from localized continuous source

- Evolve density in toy model representing toroidal rotation, diffusion along field lines, and a localized particle source
- **y and z represent the poloidal and toroidal direction**
- Periodic boundary conditions

diffusion of the density injected by the source along the magnetic field lines

$$\frac{\partial n(y,z,t)}{\partial t} = v_z \frac{\partial n}{\partial z} + D\frac{\partial^2 n}{\partial y^2} + \gamma S$$

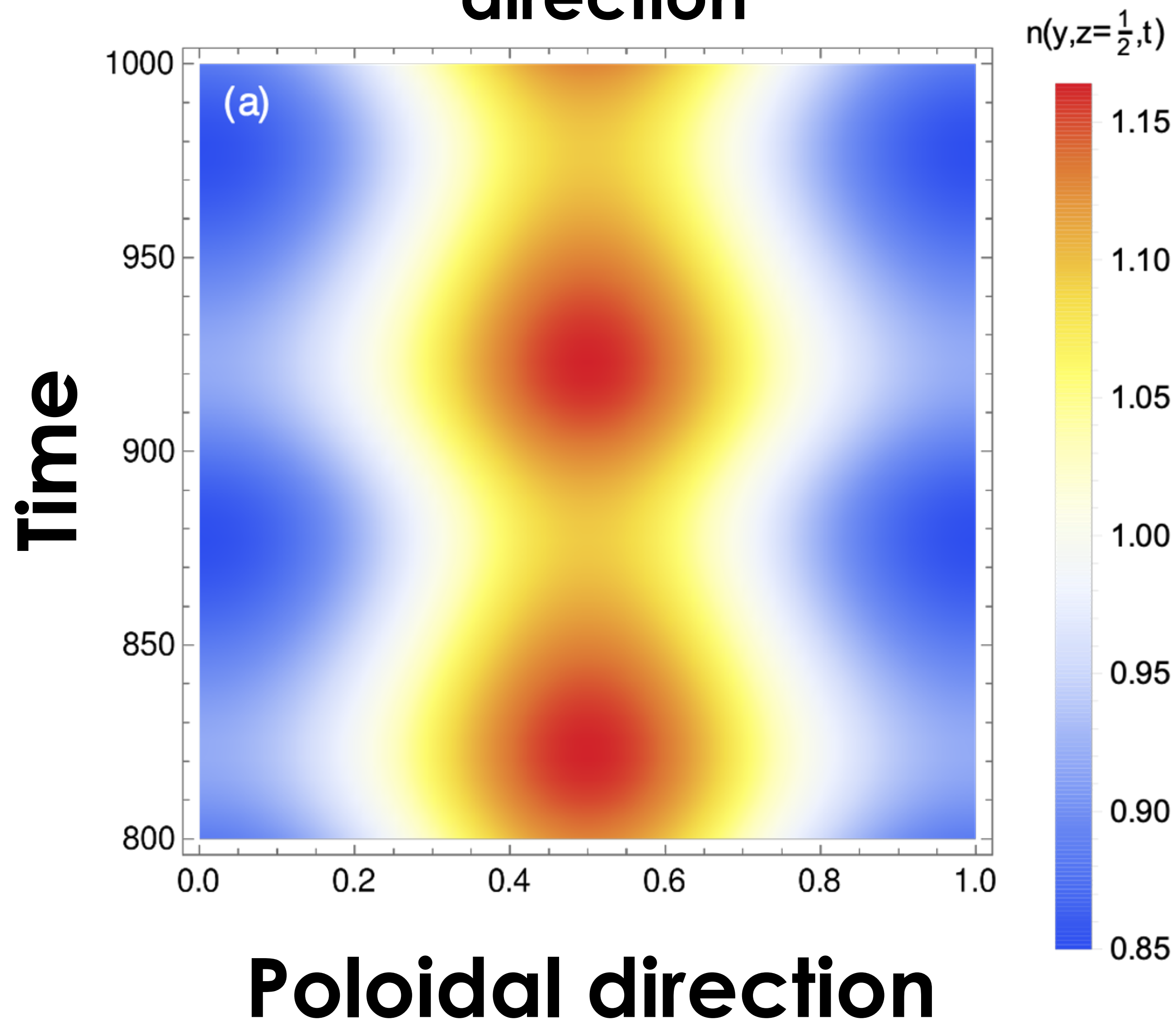
divergence of the (rigid body) toroidal flow

particle source

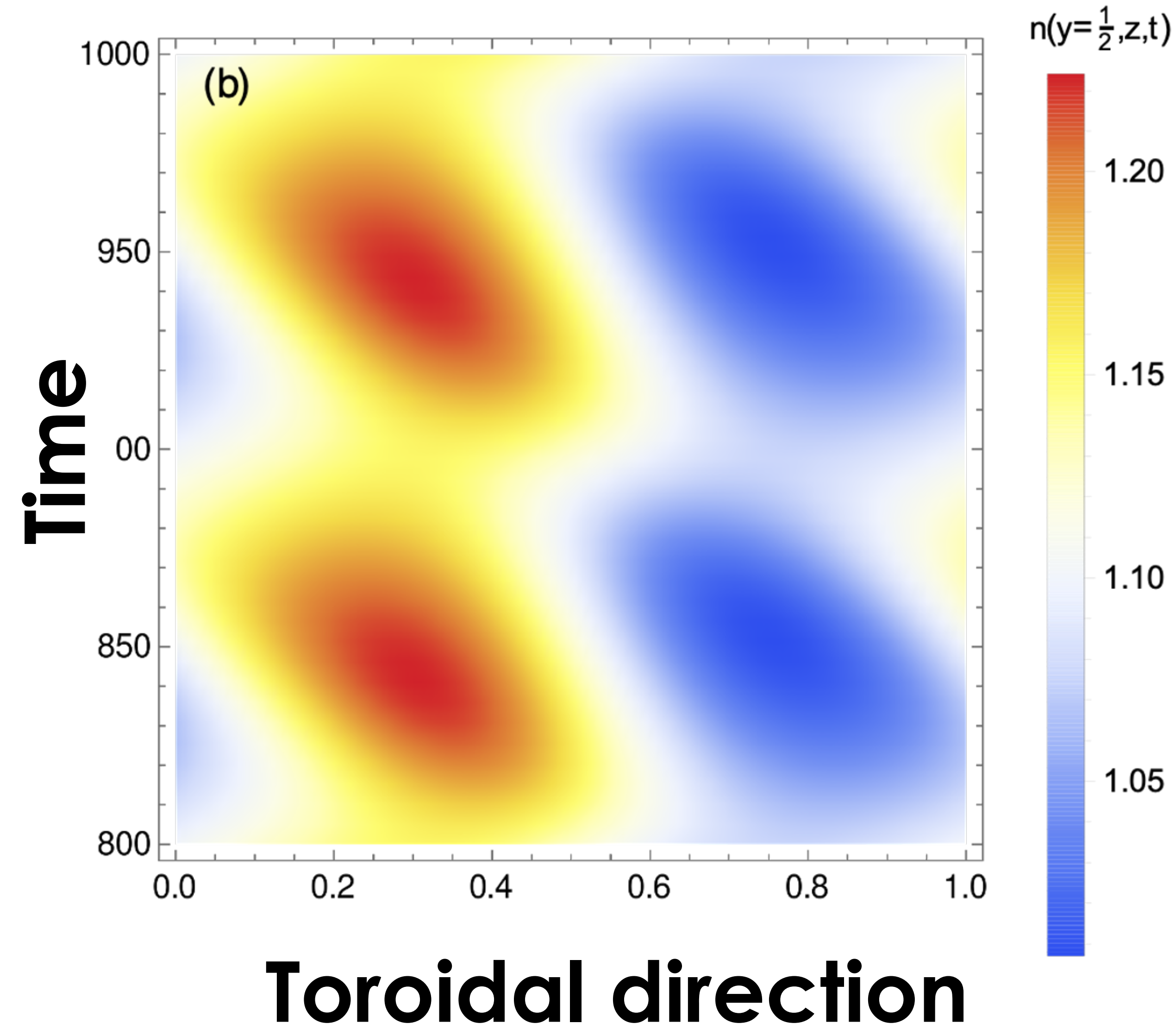
$$S(y,z) = \frac{1}{N}\exp\left[\left(\frac{y-1/2}{\sigma}\right)^2 + \left(\frac{z-1/2}{\sigma}\right)\right] - 1$$

Principal mode at toroidal rotation frequency with harmonics due to source localization

Roughly Gaussian cross section in poloidal direction



n=1 mode at toroidal rotation frequency



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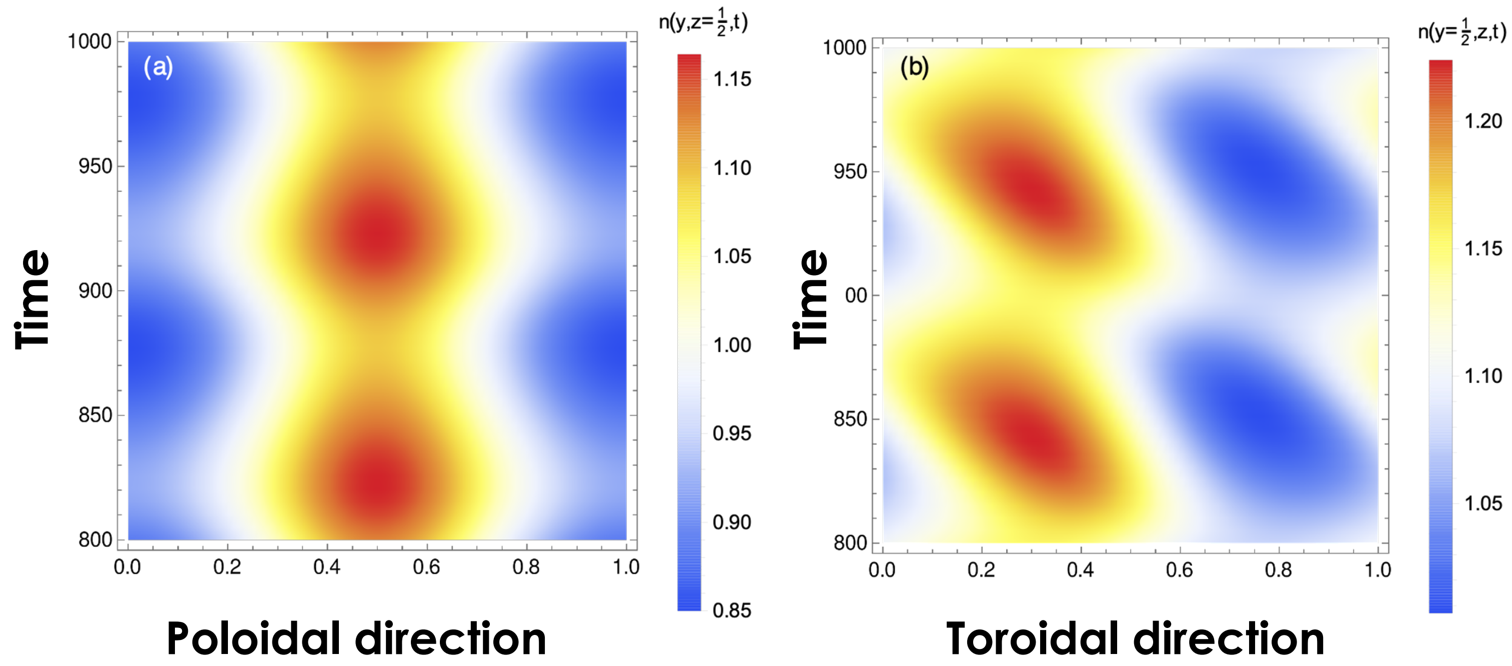
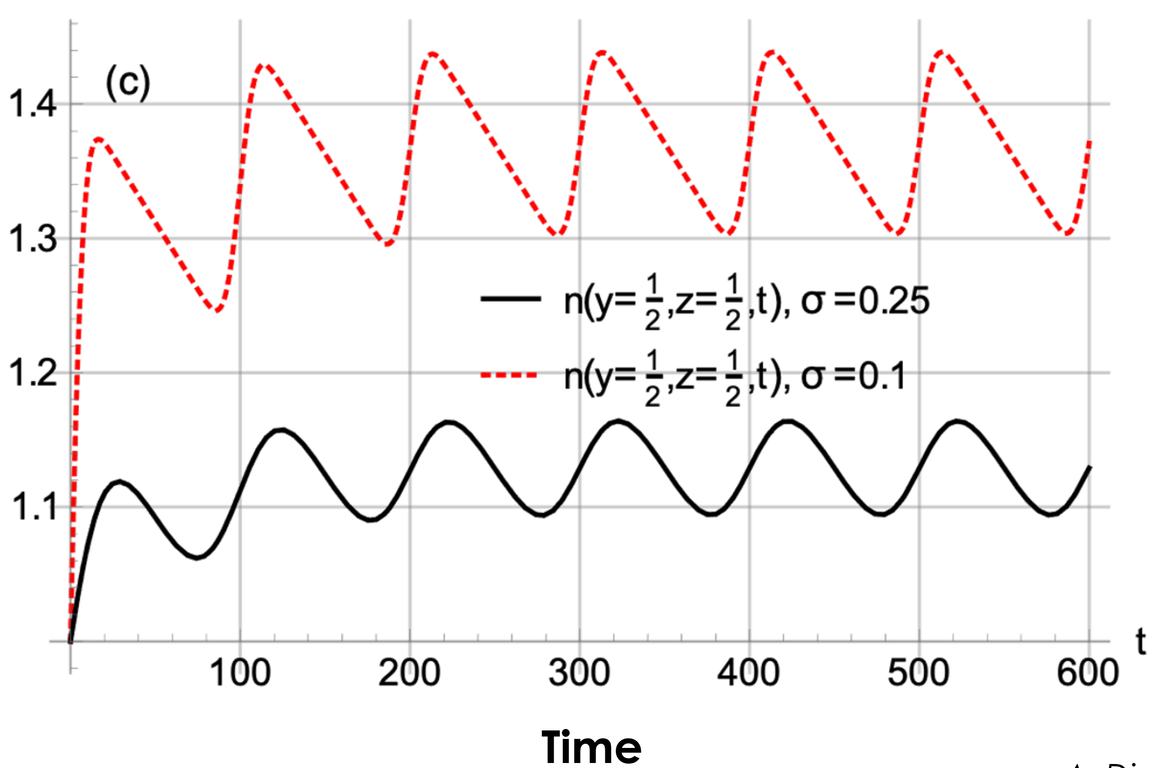
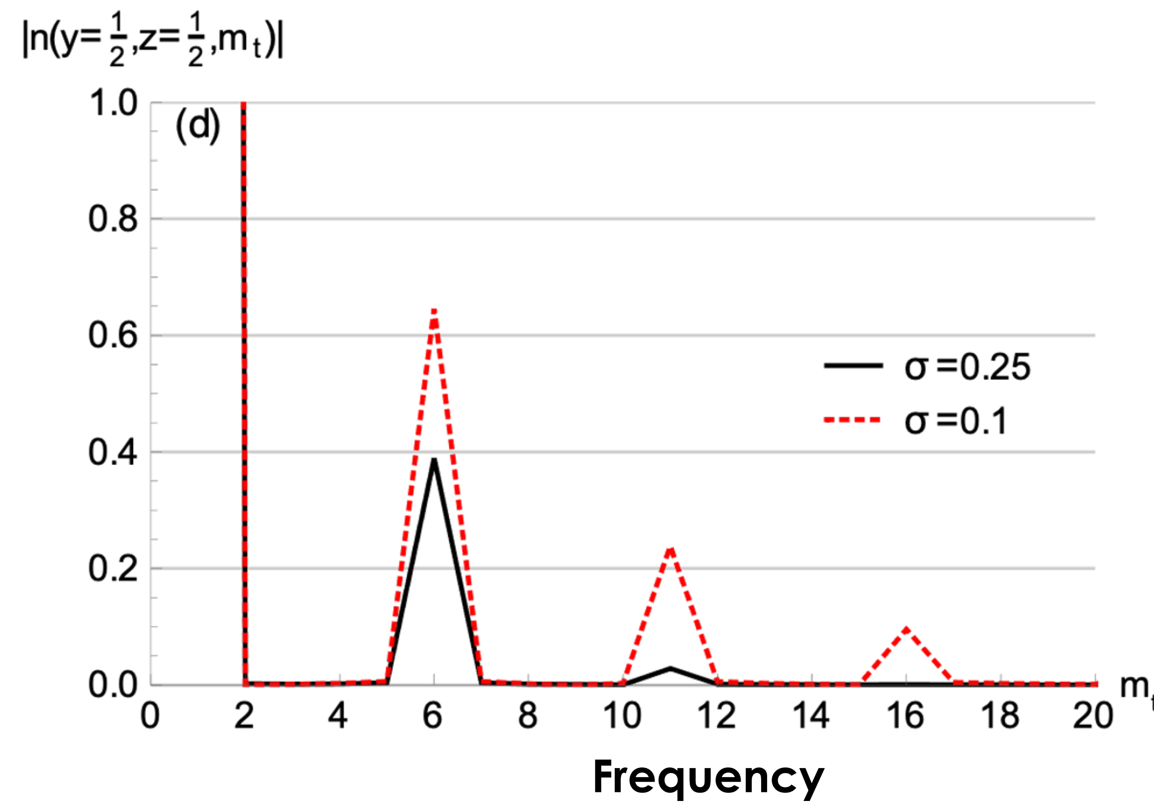


More localized source produces higher harmonics



Harmonics in temporal Fourier spectrum



Summary

- **Initial modeling of the boron powder induced of edge mode using neoclassical XGCa**
- **Results:**
  - ☑ Observed frequencies in the pedestal are consistent with GAM
  - ☑ Continuous injection of powder can lead to multiple harmonics modes as observed ion experiments
    - Localized and narrow powder drops lead to multiple harmonics
    - Broad source lead to one mode consistent with CD4 experiments
  - ○ While the n=1 mode can be excited using continuous powder injection, coupling to n=0 is unclear
    - Presumably due to the simplified geometry - might need his fidelity simulation in realistic geometry
- **Future work: extension of simulation coupling boron ablation and turbulence in XGC**

Magnetic spectrogram suggests multiple modes

- **Multiple mode are observe during Boron-induced ELM suppressed phase**
- **ELM suppressed phase exhibit both low and high frequency modes**
- **Dynamics of the frequencies appear to show multiple dependencies with density?**