Effect of pedestal fluctuations on inter-ELM pedestal recovery and ELM characteristics in ECH dominated discharges in DIII-D

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Collaborators

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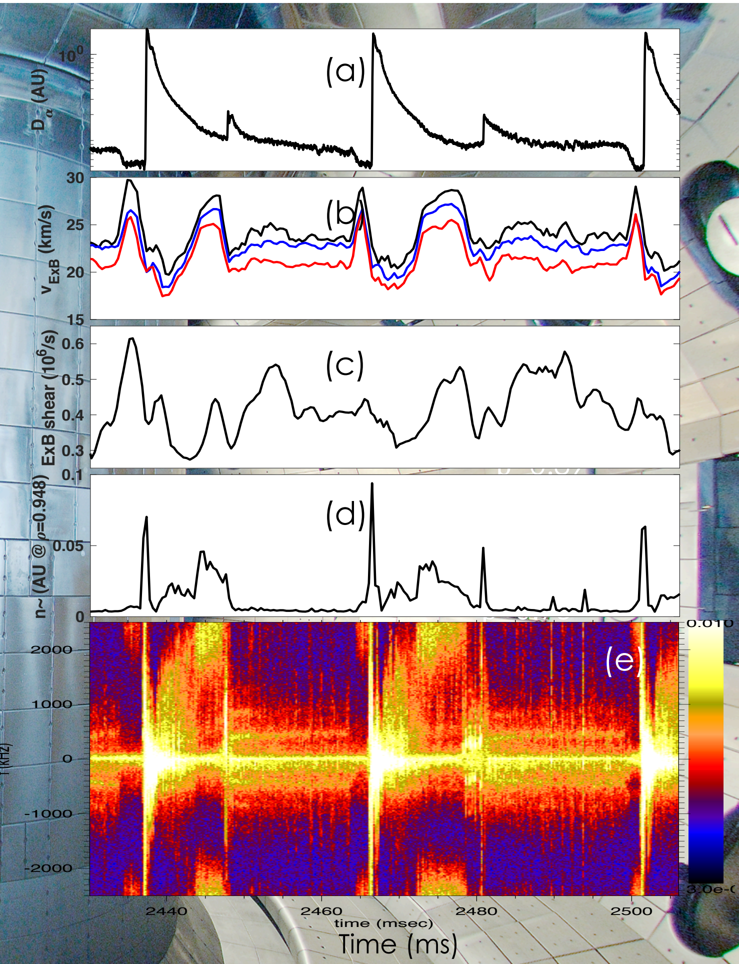

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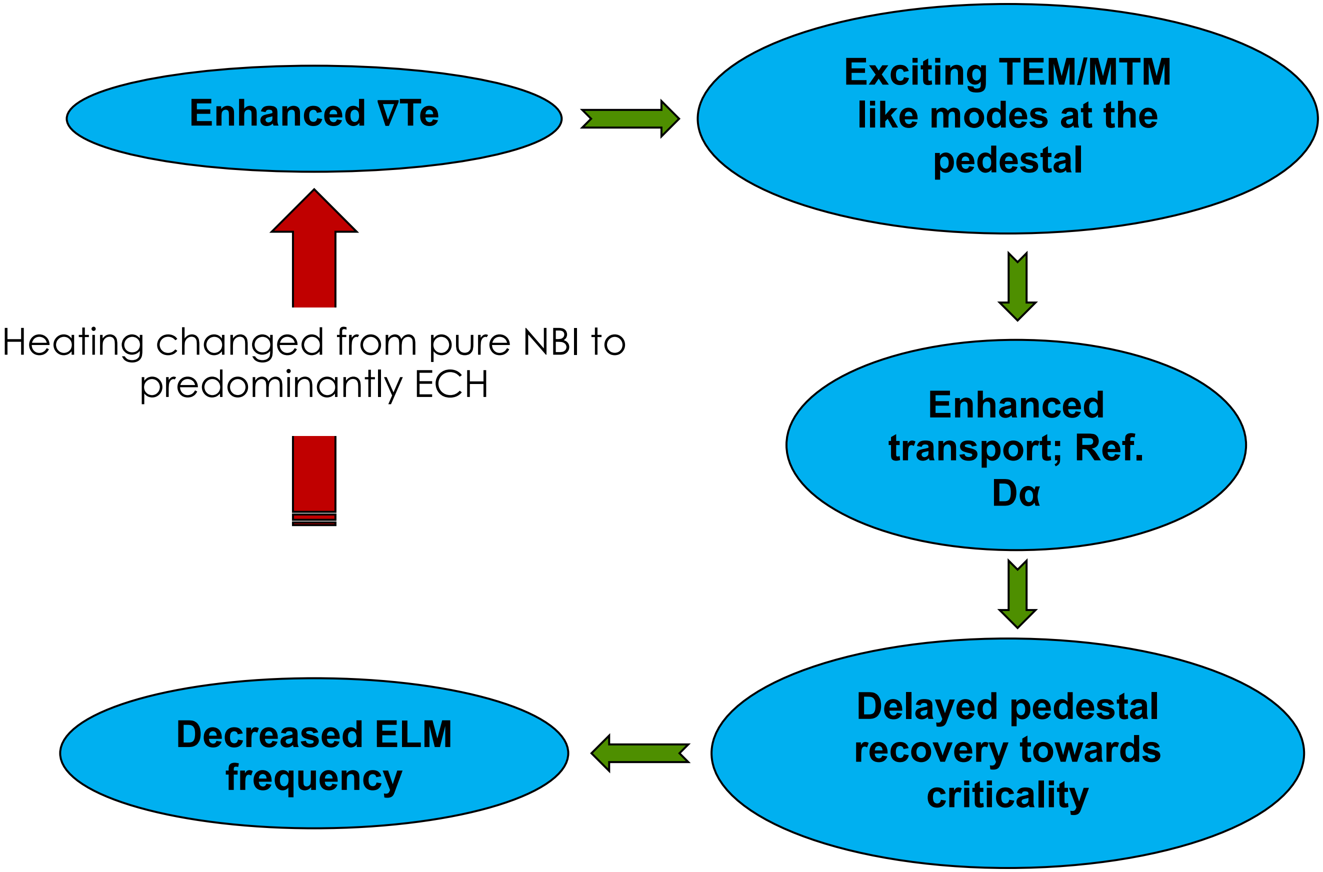
Outline

- **Working hypothesis and the main takeaway message**
- **Motivation**
- **Experimental setup**
  - Plasma parameters
  - Pedestal structure
  - MHD stability – ELITE
- **Pedestal recovery and associated turbulence in the inter-ELM phase**
  - Magnetic fluctuations – fast magnetics
  - Density fluctuations – Doppler backscattering (DBS)
- **Turbulence and transport characteristics from simulations**
  - TRANSP
  - TGLF
- **Summary**

Working hypothesis



Enhanced ∇Te

Exciting TEM/MTM like modes at the pedestal

Enhanced transport; Ref. Dα

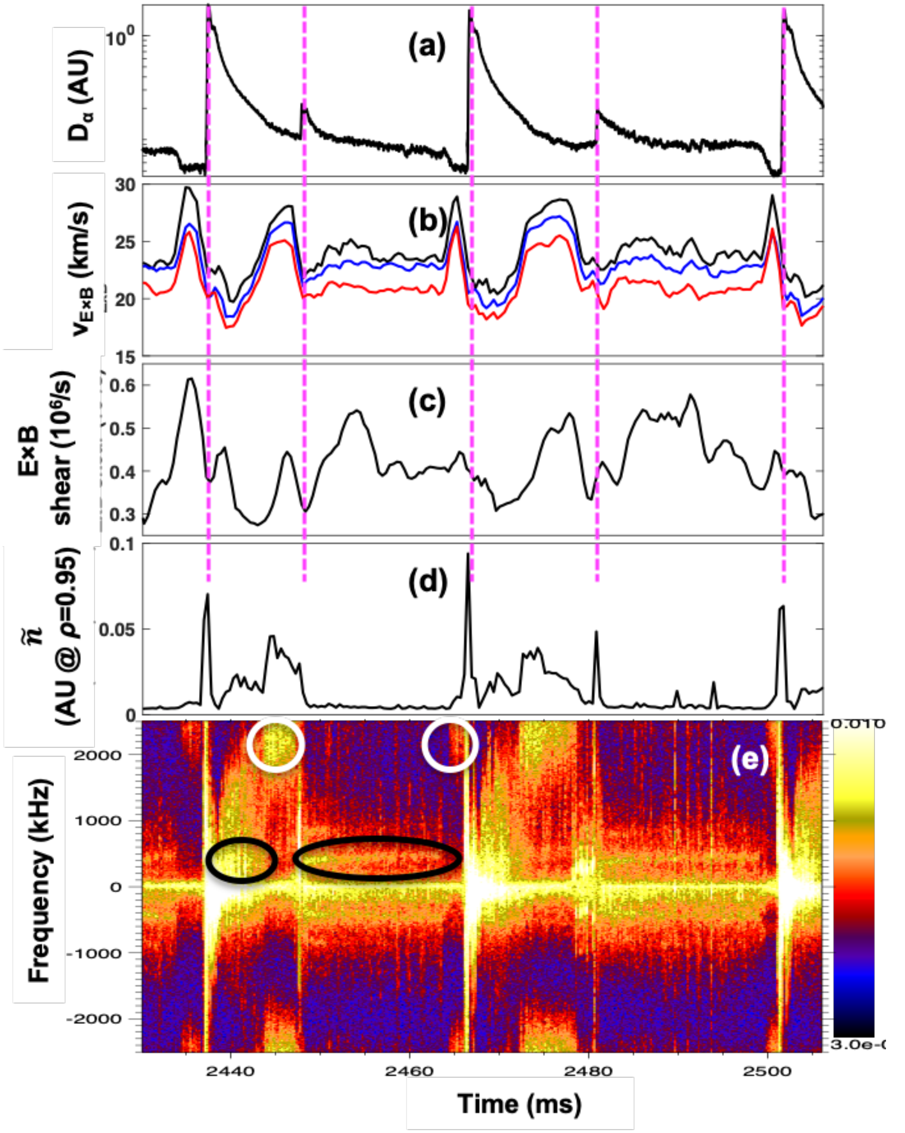
Delayed pedestal recovery towards criticality

Decreased ELM frequency

Heating changed from pure NBI to predominantly ECH

Takeaway message: Enhanced ∇T_e excites MTM and/or TEM in the pedestal

- Hence increased turbulence driven transport
- Resulting in delayed gradient recovery and thereby
- Reducing ELM frequency in ECH dominated discharges



Motivation: ELMs – the peeling ballooning instability

- **Sharp pressure gradients, and consequent large bootstrap currents at the pedestal, can destabilize peeling and ballooning modes**

- **The dominant modes are referred as coupled 'peeling–ballooning' modes and are driven by both parallel current (J_{ped}) and the pressure gradient (p'_{ped})**

- **These intermediate – n (4~40) peeling–ballooning modes impose constraints on the pedestal height**

↓

Peeling-ballooning (PB) model for ELMs

Motivation: ELMs – the peeling ballooning instability

- **ELMs can be mainly type I, II or III: we will focus on type I (giant) ELMs**
  - As per the definition of type-I ELMs:
    - *frequency of type I ELMs increases with the power input crossing the edge plasma*
    - *ELM characteristics do not depend on the power deposition location or the heating mix*

- **Several experiments have observed conditions where ELMs are not triggered even though pedestal gradients have reached critical PB gradients and continue in a long metastable state prior to an eventual onset of ELM**
  - in most cases, in the inter-ELM period, some turbulent mode appears that alters transport and hence affects pedestal recovery
  - PB model may not be sufficient to describe the inter-ELM pedestal recovery – no comprehensive understanding till today
- **Role of turbulence and interplay of turbulence and gradient recovery after ELMs leading towards the next ELM is quite crucial**

Motivation: Pedestal gradient recovery has strong impact on ELM characteristics

- **Modifying the pedestal gradient recovery in the inter-ELM phase can lead to very different ELM characters – both amplitude and frequency wise**
  - Pedestal recovery can be influenced greatly by tweaking the underlying turbulence and transport
  - Turbulence and transport in the inter-ELM regime can be modified by changing several factors like ∇T_e, T_e/T_i ratio and collisionality

- **Adding ECH can modify the pedestal ∇T_e as well as lower collisionality**

- **Here we focus on the pedestal density, temperature and pressure recovery in the pure NBI and ECH dominated discharges**
  - Along with the associated fluctuations

This poster: in a nutshell

- **ELM frequency reduced by 40% when heating is changed from pure NBI to predominantly ECH in DIII-D**
  - At similar or even a bit higher total injected power
- **The question is: why does the ELM frequency change so drastically?**
  - While the major plasma parameters, like I_p, shape, q_{95}, remain similar
- **Excitation of quasi-coherent modes and turbulence driven transport play a vital role in the inter-ELM pedestal recovery**
- **What are the implications for ITER and beyond?**
  - Emphasize importance of turbulence driven transport in determining ELM behavior and to propose electron heating as a tool to modify ELM frequency through the modification of ∇T_e in the pedestal for ITER and beyond
  - Also, self-sustained ignition in ITER is envisaged through thermal electron heating by α-particles and better insight of pedestal behavior with electron heating is essential
  - Provide important inputs for optimizing the codes for predicting pedestal behaviour
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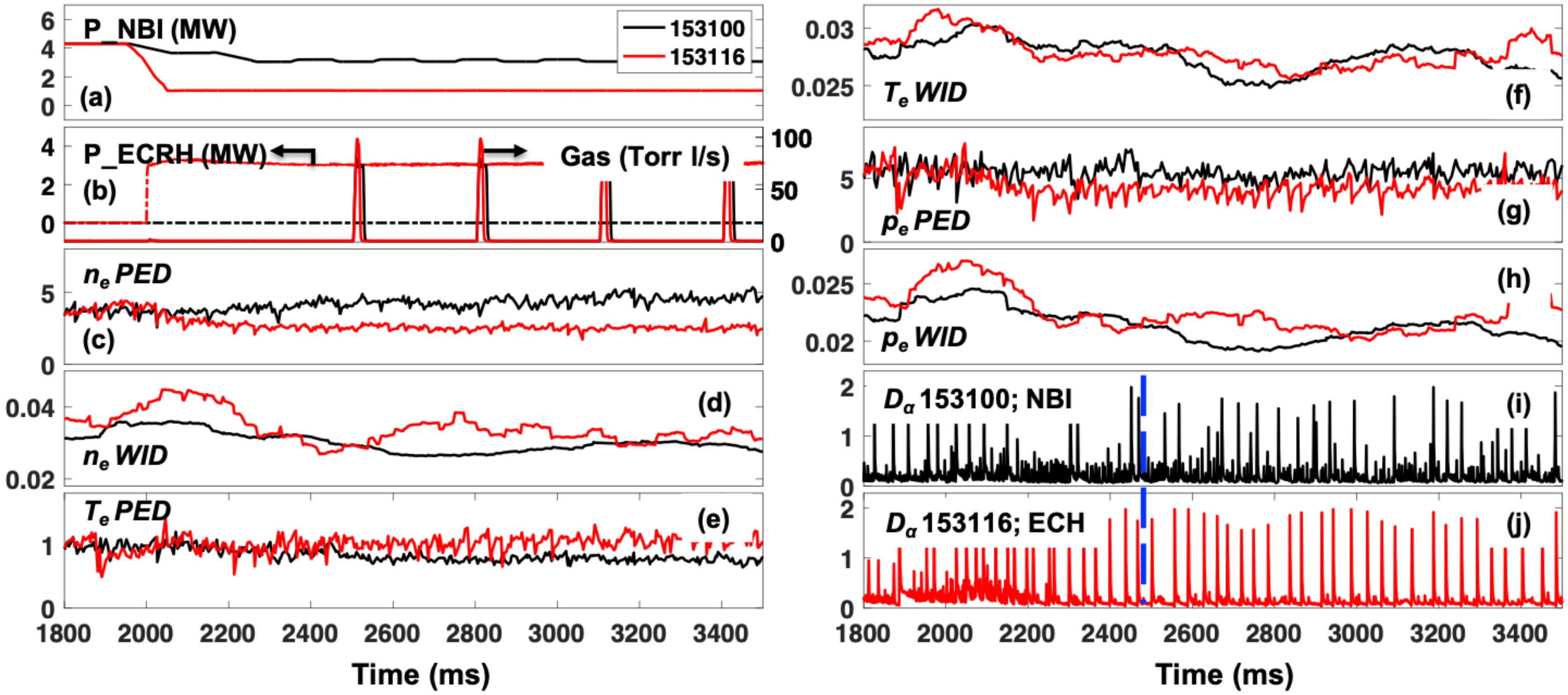
ELM dynamics: 40% reduction in ELM frequency in ECH dominated shots as compared to pure NBI

- **LSN discharge; ECH deposition at ρ = 0.2; balanced torque; P_{tot} 3~4 MW**
- **Much higher ELM frequency (f_{ELM} ~ 46 Hz) in pure NBI shot (#153100); P_{inj} is 3 MW**
- **More regularly spaced, lower frequency ELMs (f_{ELM} ~ 27 Hz) in ECH shot (#153116); Higher total power ~4MW**



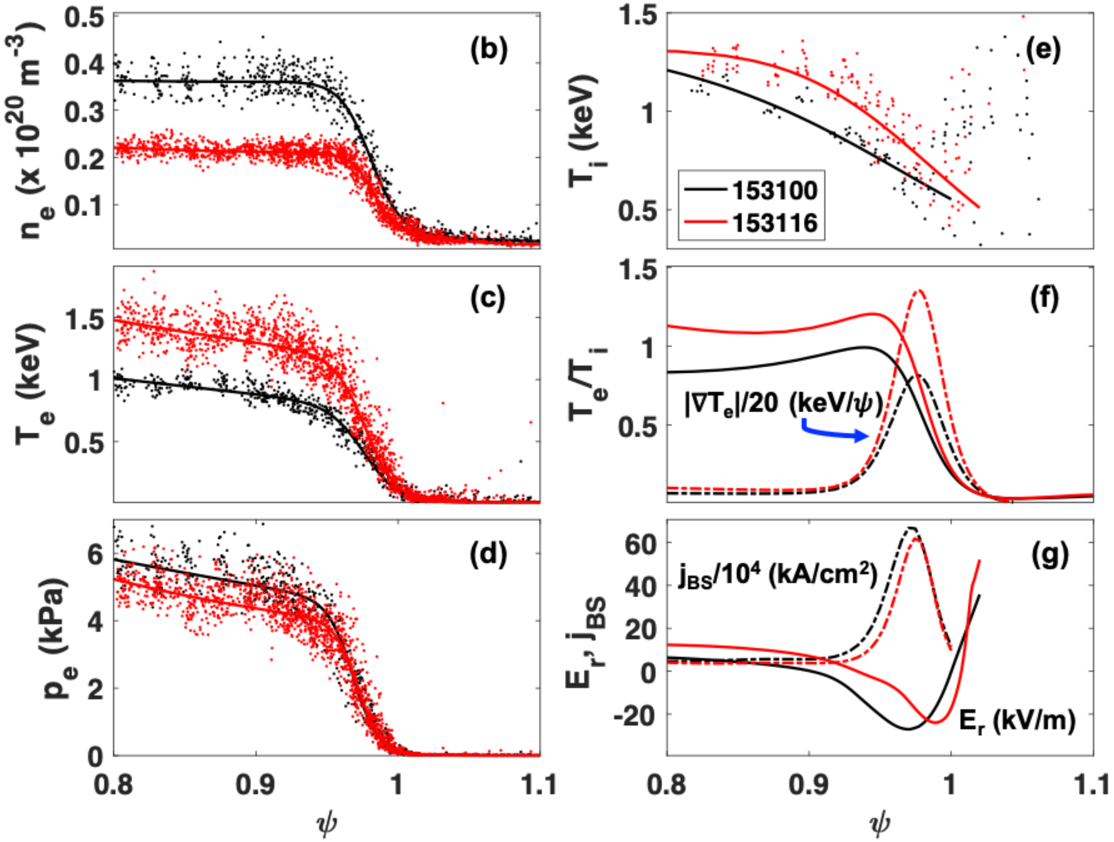
Lower f_{ELM} with higher input power: does not agree with type-I ELM definition

Average pedestal profiles: ELM synced; 70-99% of ELM cycle

- In ECH shot: majority of NBI is replaced by ECH
- n_e pedestal lower, T_e pedestal higher in ECH; p_e pedestal slightly lower In ECH shot
- T_i is comparable at pedestal for both shots
- Absolute ∇T_e higher for the ECH shot as compared to NBI shot at *steep gradient*
- Some variation in the E_r well; Bootstrap current fraction similar

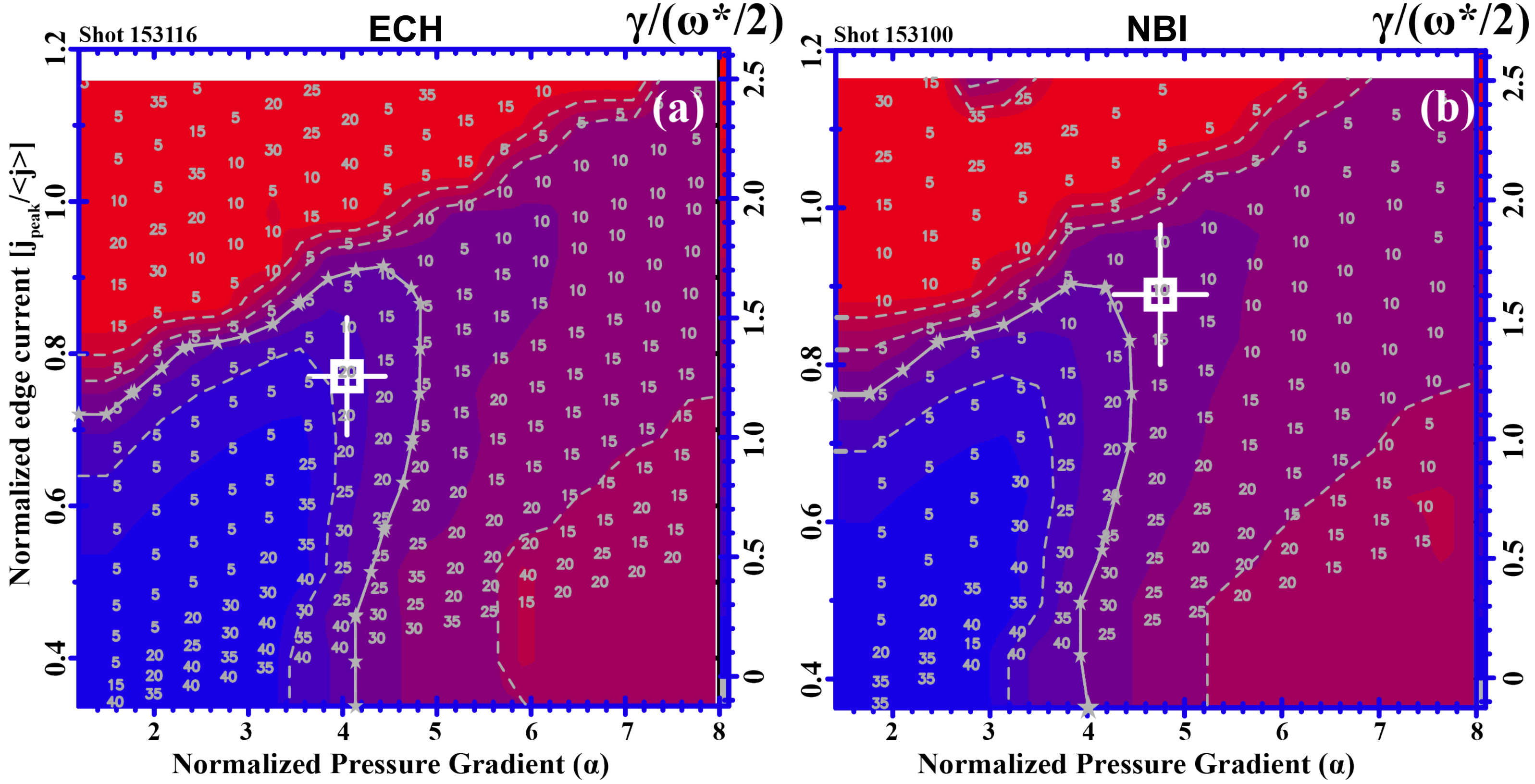
Black: NBI

Red: ECH

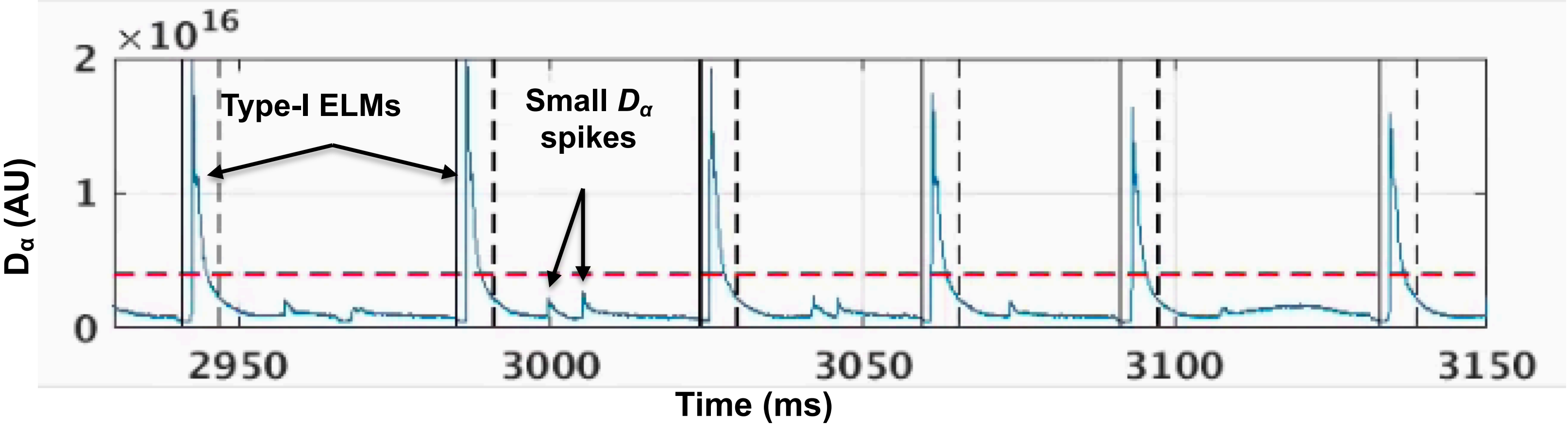


Both NBI and ECH dominated shots are similar on the stability diagram

- Both the ECH and NBI shots are close to the Peeling Ballooning inflection point (nose); ECH shot is inside the peeling-ballooning boundary while the NBI shot it just outside
- In terms of normalized edge current and normalized pressure gradient both shots are similar



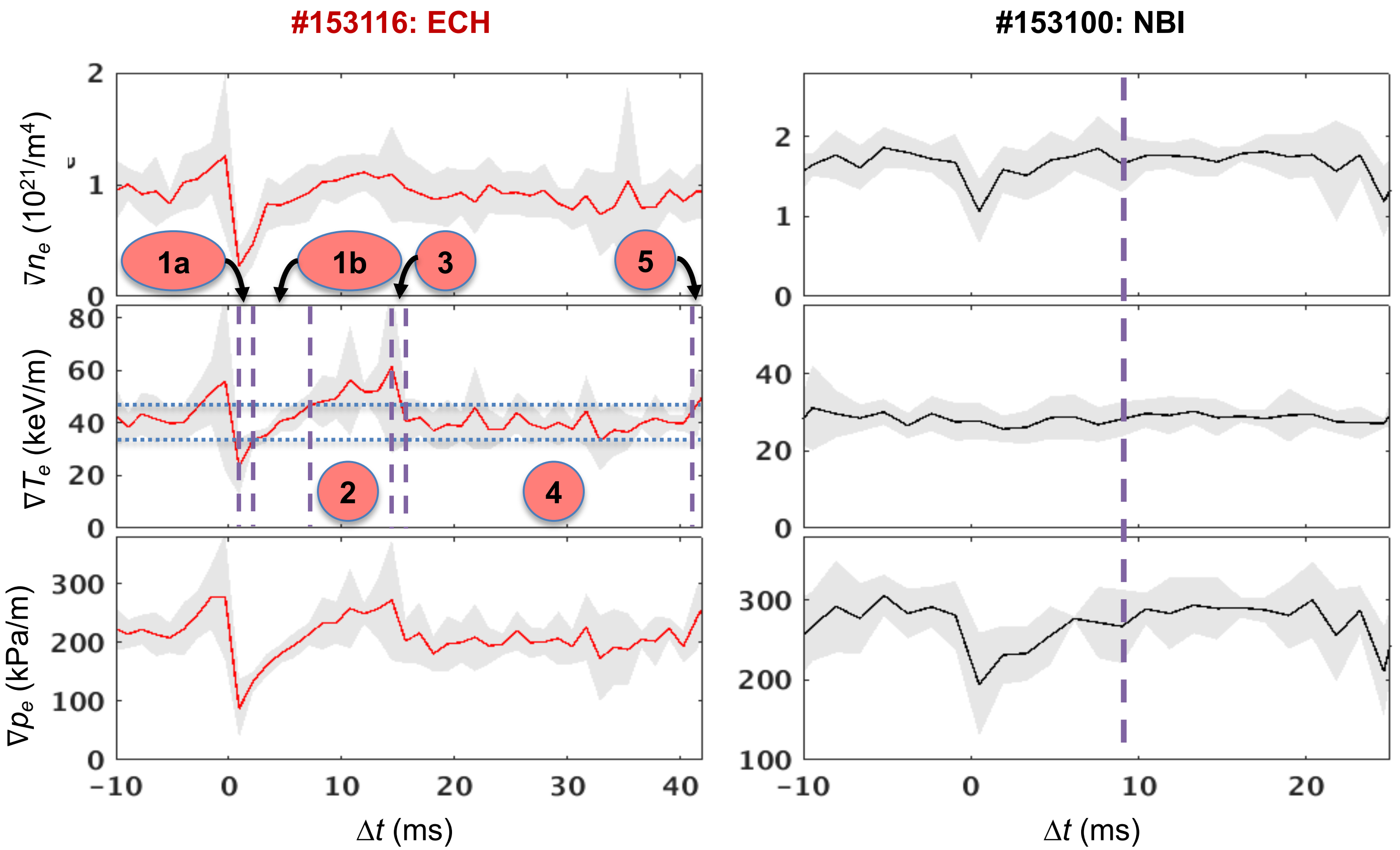
ELM synchronized analysis of Thomson Scattering data – ELM at $\Delta t = 0$



- Example of the ECH shot where ELMs are detected above the threshold – red broken horizontal line
- Each large type –I ELM crash is followed by one or two small spikes in Dα

Pedestal recovery following ELMs: Gradients recover much faster in NBI shots

- Pedestal decay with ELMs is smaller in NBI case compared to ECH case
- Initial recovery of gradients similar in NBI and ECH shots
- Sharp drop in gradients for the ECH shot at ~13 ms: due to the small D_α spike(s)



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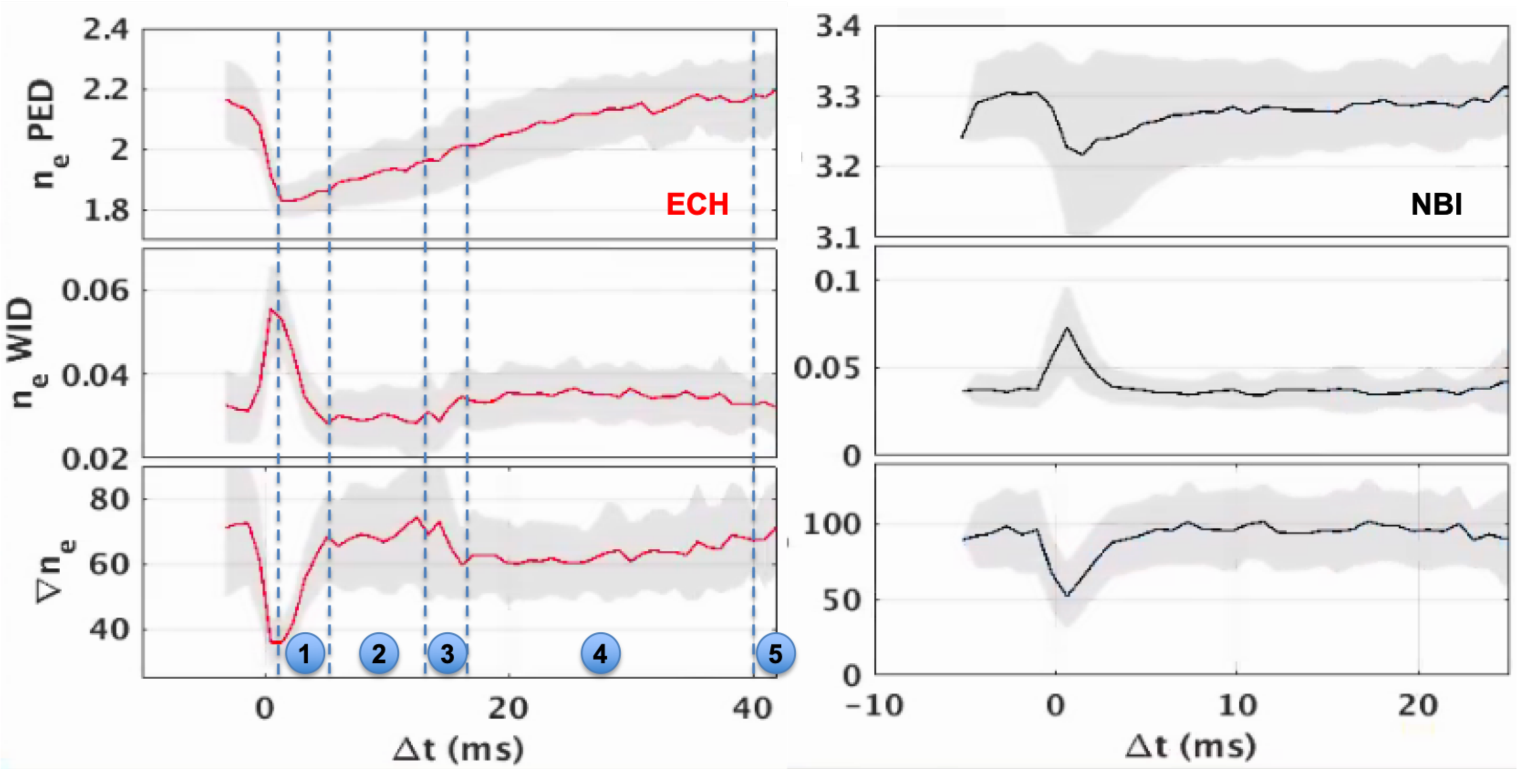
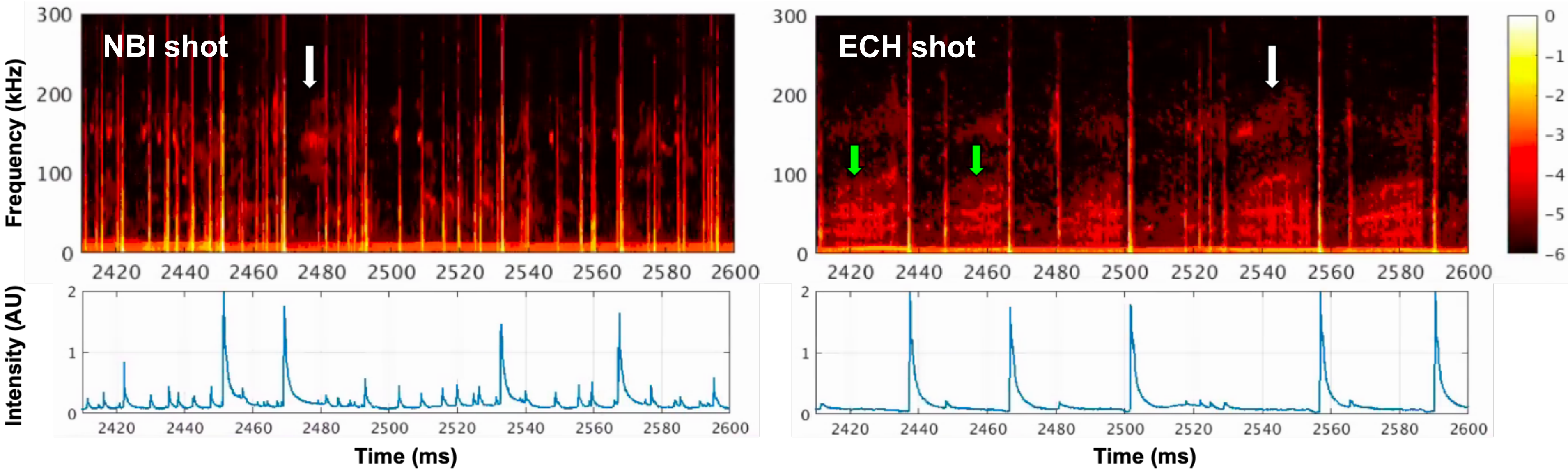
Pedestal recovery following ELMs: Gradients recover much faster in NBI shots

- Closer look at ∇n_e from profile reflectometry – data with high time resolution
- Steady recovery of both n_e^{PED} and ∇n_e in NBI shot
- Several phases in ∇n_e recovery in ECH shot, mainly due to n_e pedestal width recovery; n_e pedestal height increases rather monotonically



Distinct low frequency magnetic modes (in $\dot{B}_\theta$) in the inter-ELM period for the ECH shot

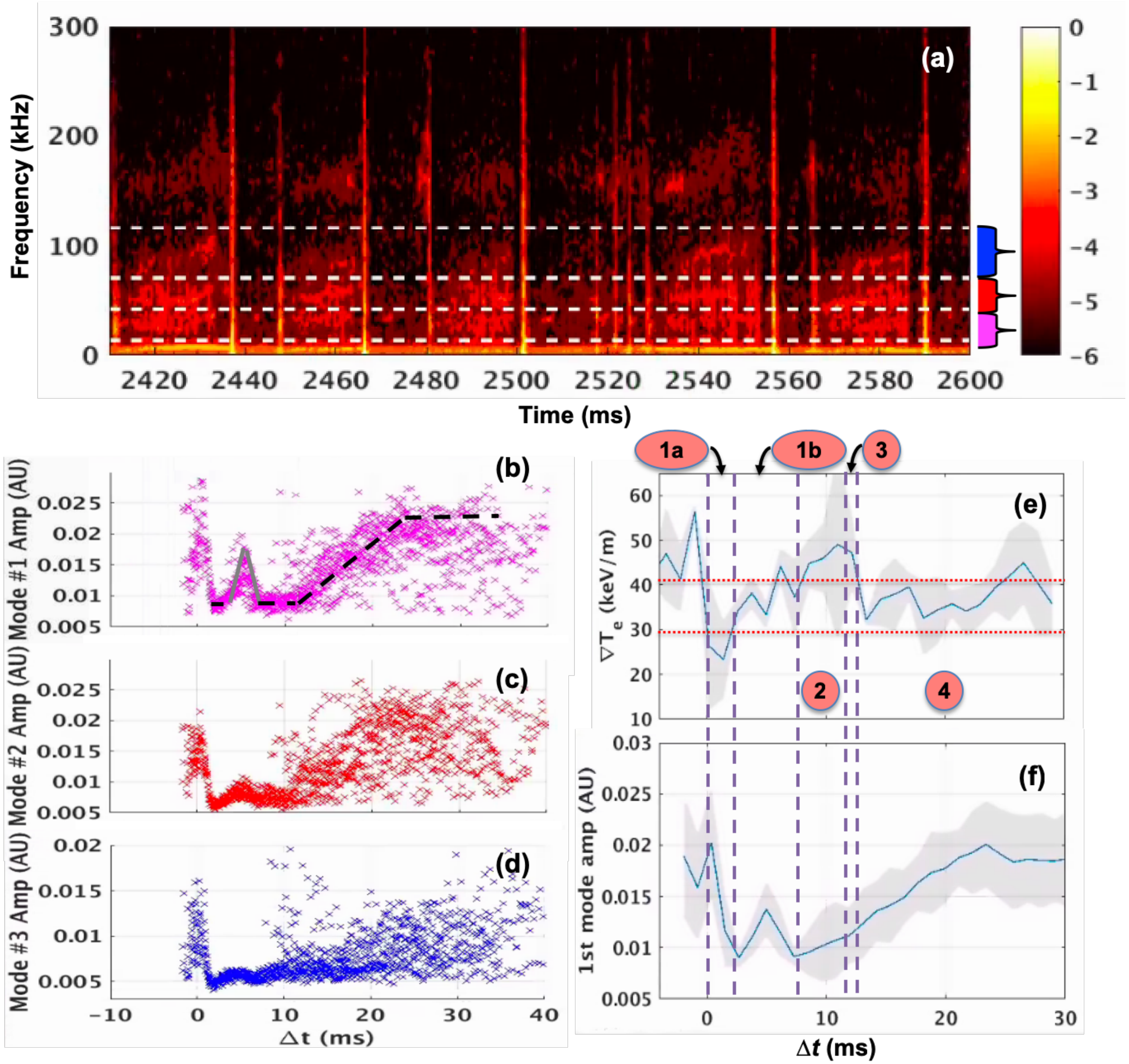
- 2 MHz acquisition in fast-magnetics
- ~150 kHz mode prior to each ELM is present in both cases (white arrows)
- Low frequency quasi-coherent modes (13~116 kHz) present in the ECH case (green arrows), prior to major ELMs



Evolution of magnetic modes in the inter-ELM period of the ECH shot is correlated with ∇T_e recovery

- **Mode amplitude evolution shows steady growth after ~12 ms**
- **Note: a small growth bump at ~5 ms: related to ∇T_e evolution**

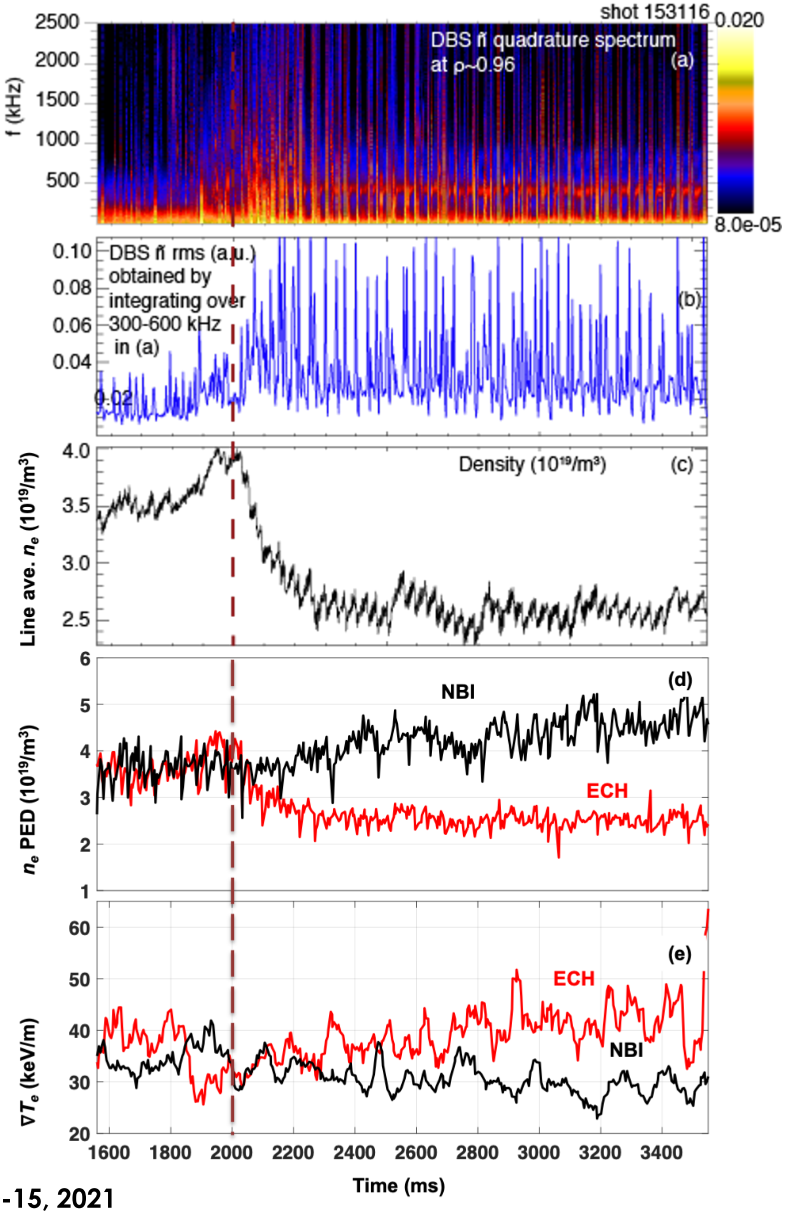
- **Two possibilities:**
  - Seems ∇T_e needs to reach a certain threshold to trigger the growth of the magnetic modes
  - Modes seems to grow only within a narrow-bounded value of the gradients



DBS – 400 kHz mode grows with ECH injection and density pump-out

- Distinct mode at 400 kHz; at ρ=0.95 and $k_\theta\rho_s$ ~0.9 (TEM-scale)
- Mode amplitude increases following ECH at 2000 ms
- Shows correspondence with density pump-out & increased ∇T_e due to ECH at 2000 ms

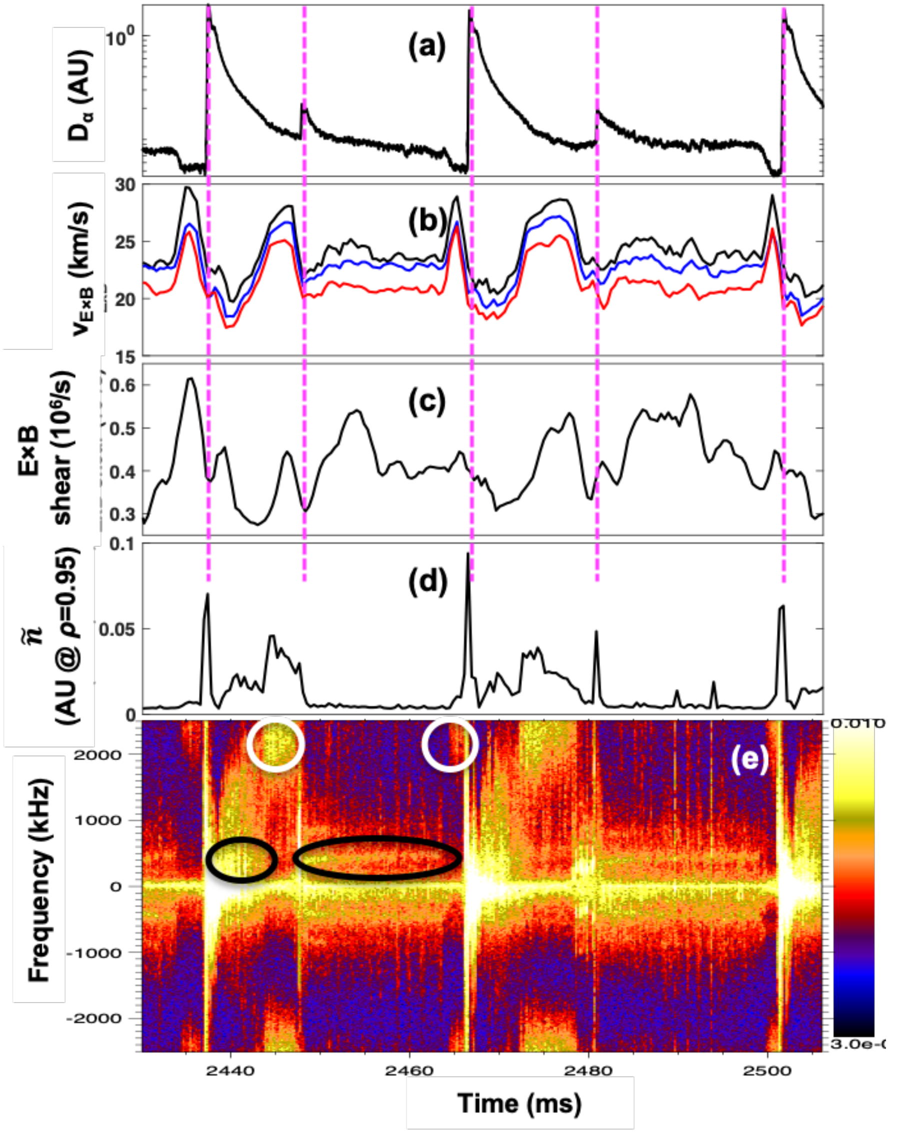
- This mode is localized at the steep gradient region of the pedestal
  - With ECH, chord-averaged density decreases leading to inward movement of higher frequency DBS channels. But lower frequency channels don't move
  - Lower frequency channels see an increase in mode amplitude whereas higher frequency channels don't see these modes following ECH injection



DBS spectra: Evolution of the two modes is correlated with the large ELMs and small D_α spikes

- Fig. (e): DBS Frequency spectrogram at $\rho = 0.95$
  - Following an ELM crash: mutually exclusive occurrence of a quasi-coherent mode at ~400 kHz and a high frequency mode at ~2 MHz

- Modes' evolution well correlated with the ELMs and the small D_α spikes
- v_{ExB} increase well correlated with the growth of ~2 MHz mode

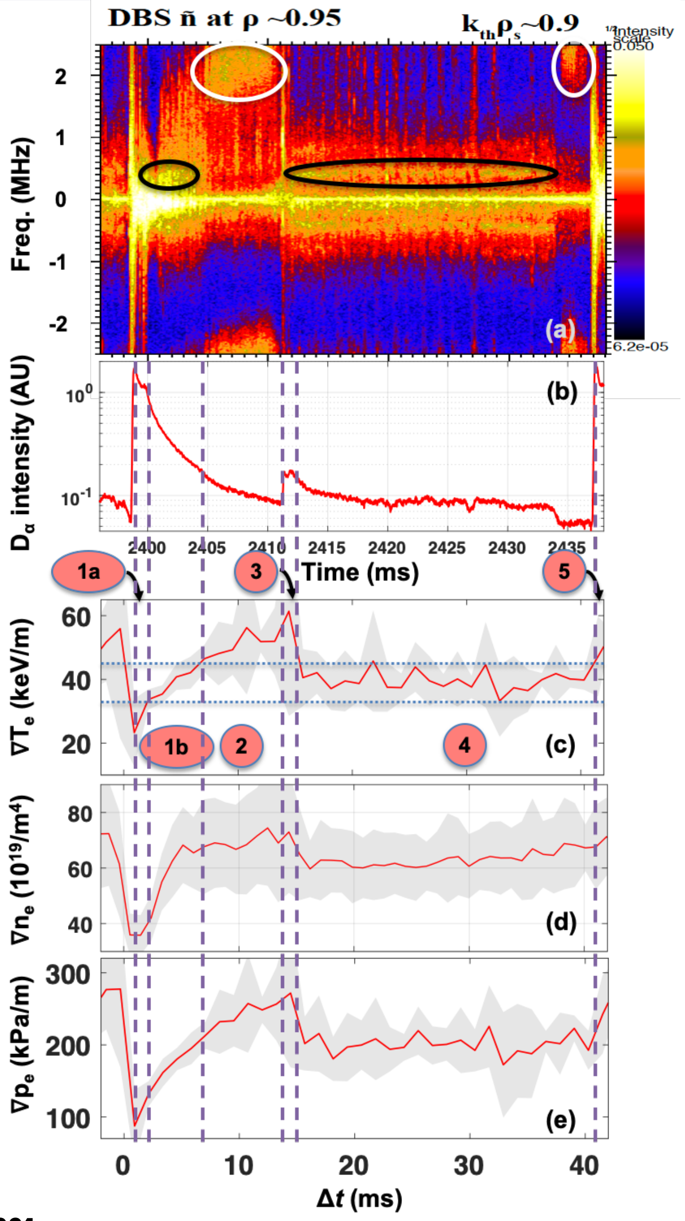


DBS spectra: Growth of the modes is correlated with pedestal gradients’ recovery

- Mode at ~400 kHz survives only when the gradients are within two horizontal red broken bounds

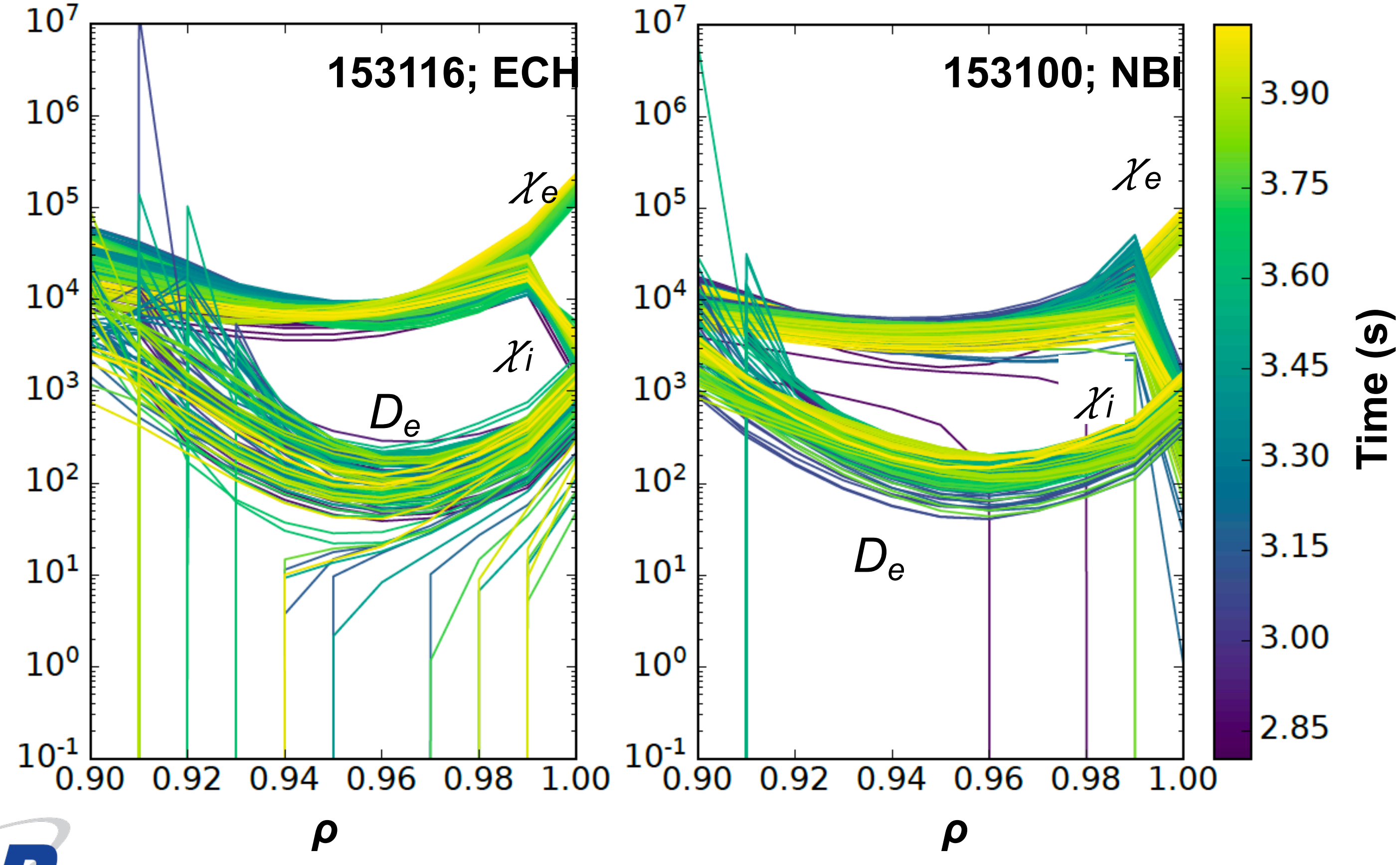
- Gradients relax slightly due to small D_α spike in phase #3

- Gradients are again within bounds in phase #4 and ~400 kHz mode appears



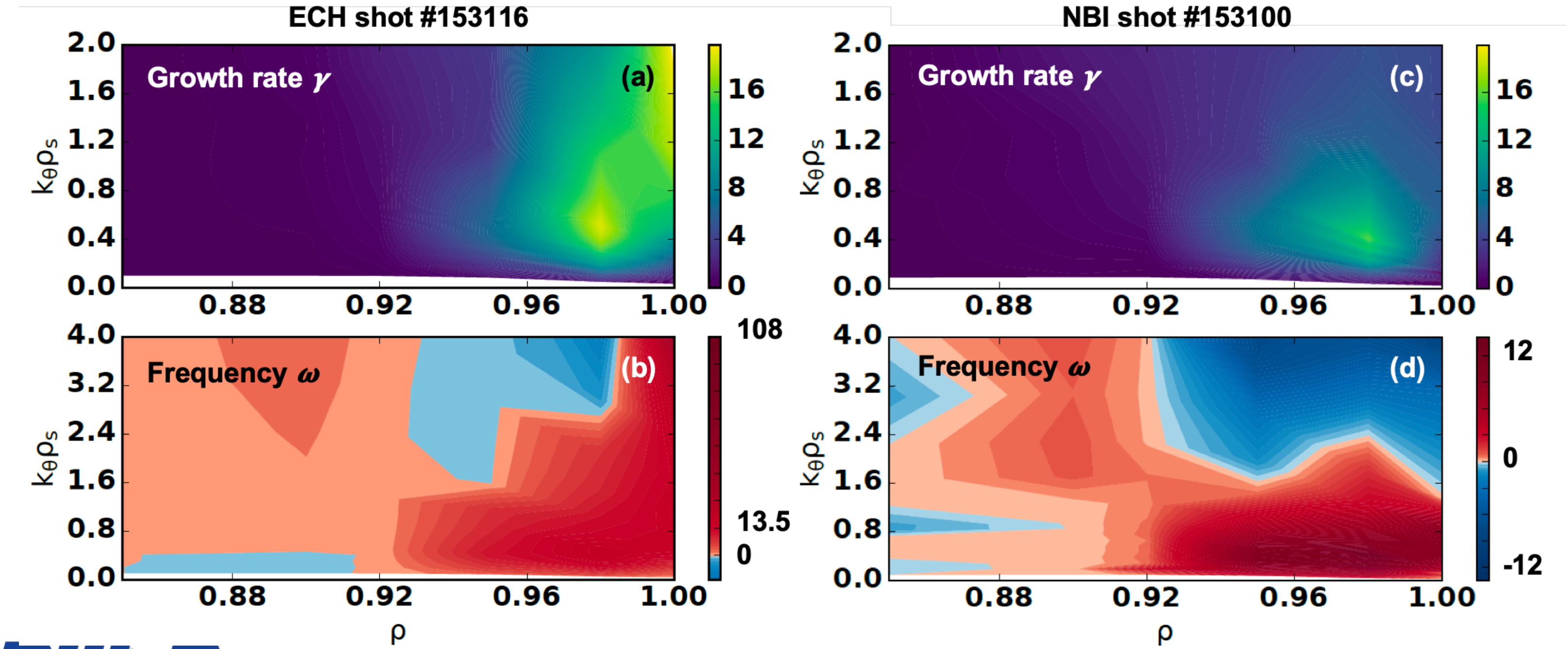
Transport coefficients (TRANSP) indicates that MTM/ETG/TEM are likely candidates

- $D_e << \chi_e$ (Fingerprints: M. Kotschenreuther et al., Nucl. Fusion 59, 096001 (2019))
  - Most likely candidate is MTM or ETG in this regime
- From pedestal top till steep gradient (ρ=0.98), $D_e << (\chi_i + \chi_e)$ & $\chi_i \sim \chi_e$ – TEM also possible



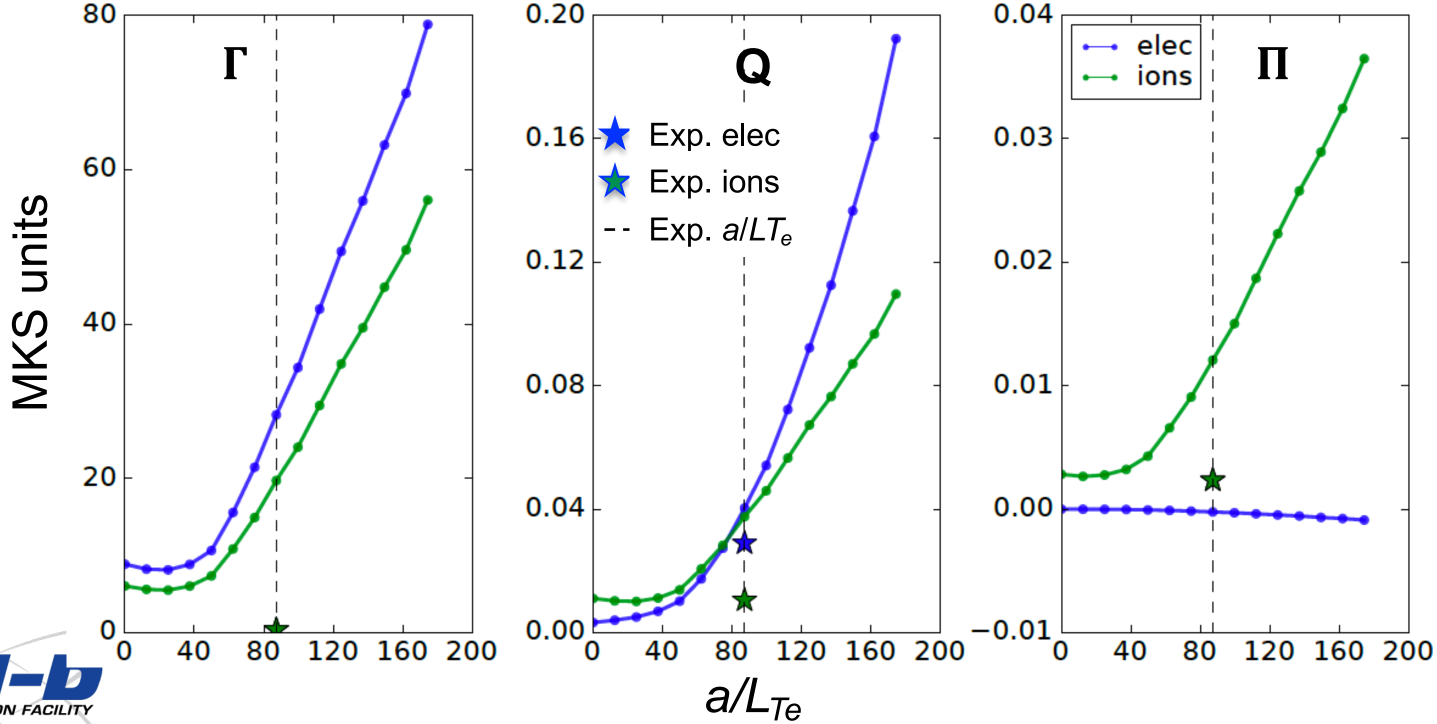
TGLF simulations predict that frequencies are in the electron direction at ion scale

- **Linear gyrofluid simulations performed with TGLF from ρ = 0.8 ~1.0**
  - For most dominant mode, growth rate peaks at ρ = 0.98, steep gradient region; Growth rate is much higher for ECH dominated discharge
  - Frequency is positive and hence, in the electron direction for $k_y \rho_s < 1$
  - Observed fluctuations in magnetics could be MTM as MTM is ion-scale, electron temperature gradient driven and frequencies in electron direction



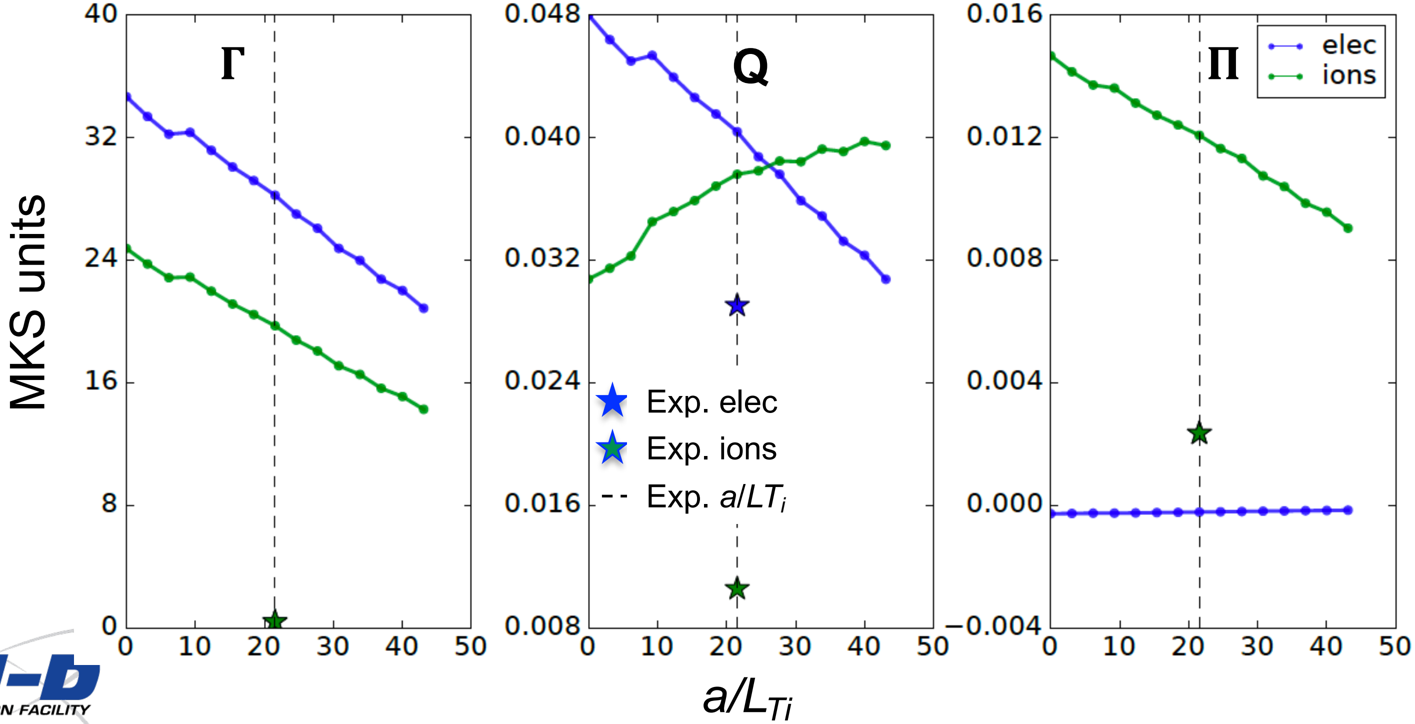
ECH discharge: (a/L_{Te}) scan in TGLF at $\rho = 0.98$ (steep gradient region) indicates ∇T_e driven turbulence

- **Both electron and ion energy and particle fluxes increase with a/L_{Te}**
  - electron and ion density profiles expected to flatten with increase in ∇T_e
- **This observation either rules out ETG or demands co-existence with other modes responsible for the particle flux**
  - ETG mostly electrostatic, rather small scale ($k_\theta \rho_s \approx 10$) and not trivial to access experimentally with diagnostics like DBS
- **Large increase in the ion momentum flux - toroidal rotation profile expected to flatten with increase in ∇T_e**



ECH discharge: (a/L_{Ti}) scan in TGLF at $\rho = 0.98$ indicates plasma is ITG stable at this radius

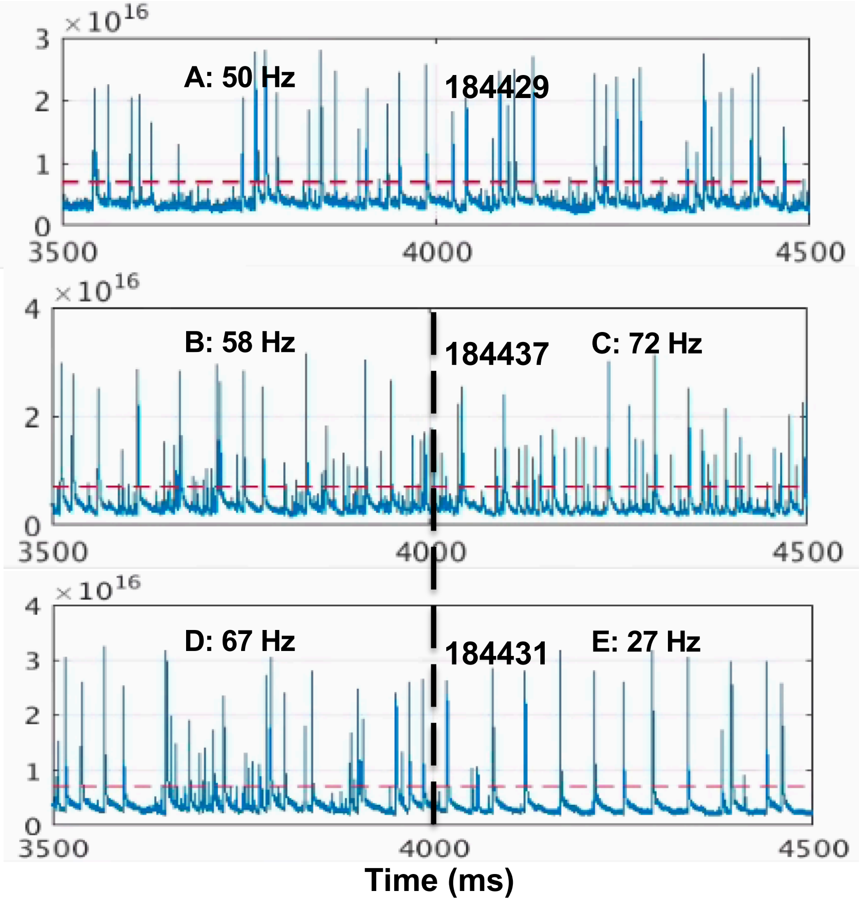
- **Increasing a/L_{Ti} will decrease both the ion and electron particle transport, thus steepening the density profiles**
- **Will have negligible effect on energy and momentum fluxes**
  - indicates that the plasma is ITG stable at this radius as the electron and ion thermal transport is not increasing with increase in a/L_{Ti}
- **Turbulent transport is mostly dominated by ∇T_e driven fluctuations.**
  - Hence, the increased turbulence observed in the ECH dominated discharge is most likely of the MTM and/or TEM nature



Variation of heating mix (NBI vs ECH) and ECH deposition location affects ELM frequency

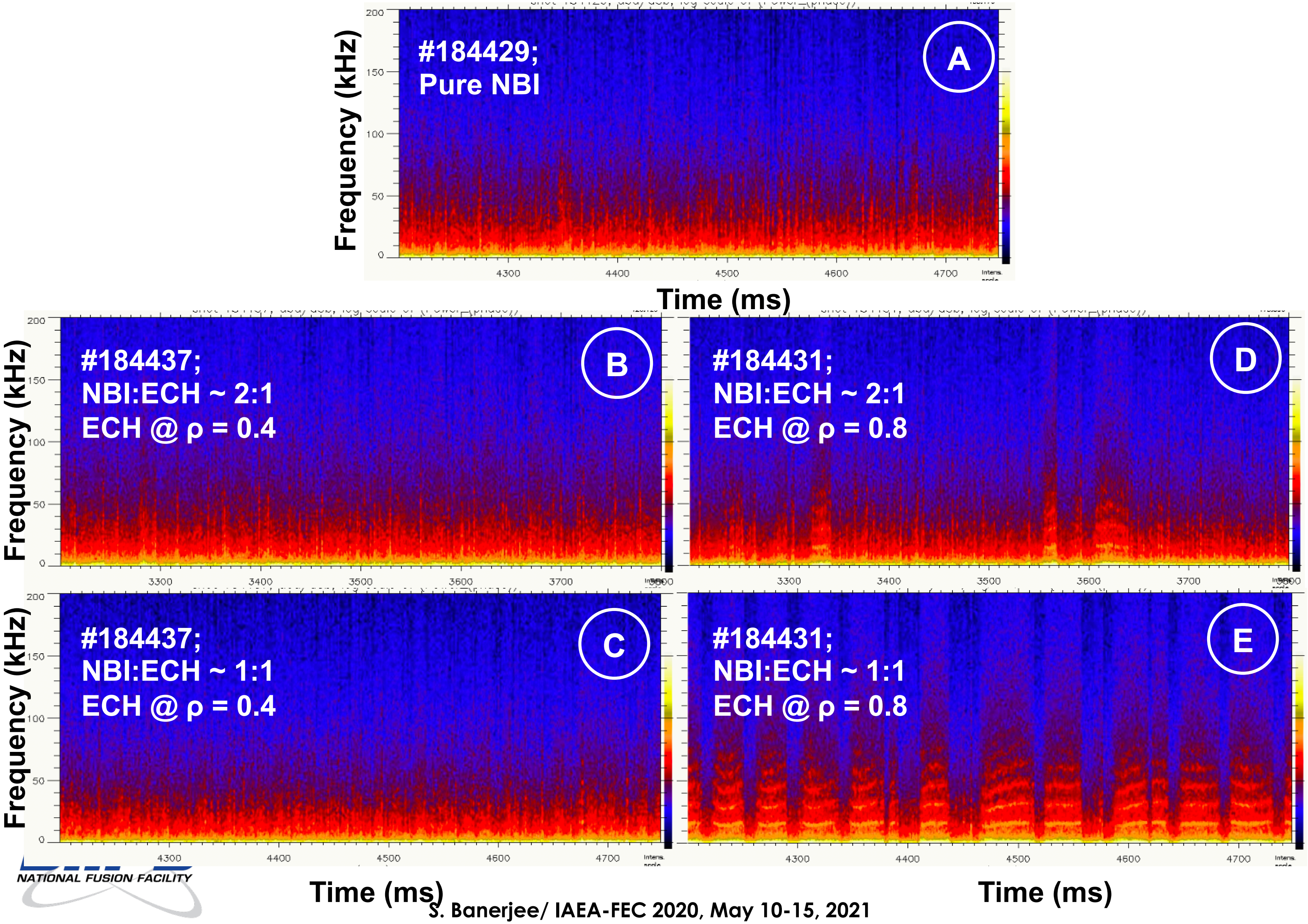
- **Shots compared have total input power ~3 MW and ~net zero torque injected**

- **A: Shot #184429 is a pure NBI shot (balanced)**
- **For core ECH injection ($\rho = 0.4$), ELM frequency increases with increase of ECH to NBI ratio**
  - **B**: 3-4s ($P_{ECH}/P_{NBI} \sim 0.5$)
  - **C**: 4-5.5s ($P_{ECH}/P_{NBI} \sim 0.9$)
- **For edge ECH injection ($\rho = 0.8$), ELM frequency decreases with increase of ECH to NBI ratio**
  - **D**: 3-4s ($P_{ECH}/P_{NBI} \sim 0.5$)
  - **E**: 4-5.5s ($P_{ECH}/P_{NBI} \sim 0.9$)



- ELM frequency increased by ~40%, compared to the pure NBI discharge, when 1:1 heating mix ratio (NBI:ECH) is applied with the ECH at $\rho = 0.4$.
- On the other hand, the ELM frequency reduced by ~50% when 1:1 heating mix ratio is applied with the ECH deposition at $\rho = 0.8$

Quasi-coherent modes observed in DBS phase spectrogram for cases D (occasionally) & E (regularly)



Summary – I

- **Type I ELM frequency decreases by 40% in ECH (at $\rho = 0.2$) dominated plasmas compared to pure NBI**
  - May be a mixed ELM regime in the ECH shot
- **Fast-magnetics show distinct MTM-like modes in inter-ELM period**
  - ∇T_e needs to be within a narrow-bounded value for growth of these modes
- **DBS shows growth of 400 kHz TEM-like quasi-coherent mode and high frequency ~2 MHz broadband turbulence in the inter-ELM period**
  - Well correlated with the pedestal ∇T_e evolution
  - 400 kHz coherent mode also appears within narrow bounded value of gradients
    - *May be responsible for enhanced transport and holding gradients lower for the ELMs to occur, for a longer period of time*
- **Transport coefficients suggest MTM and/or TEM are the most likely candidates for observed fluctuations in the ECH shot**
- **Linear eigenmode analysis corroborates this inference**
  - Frequency of most dominant mode peaks at ion-scale in the steep gradient region
  - Propagates in electron direction
- **Enhanced ∇T_e excites MTM and/or TEM and hence increased turbulence driven transport – resulting in delayed gradient recovery and thereby reducing ELM frequency in ECH dominated discharges**