Correlation of pedestal fluctuations and inter-ELM recovery leading to reduced ELM frequency in ECH dominated discharges in DIII-D

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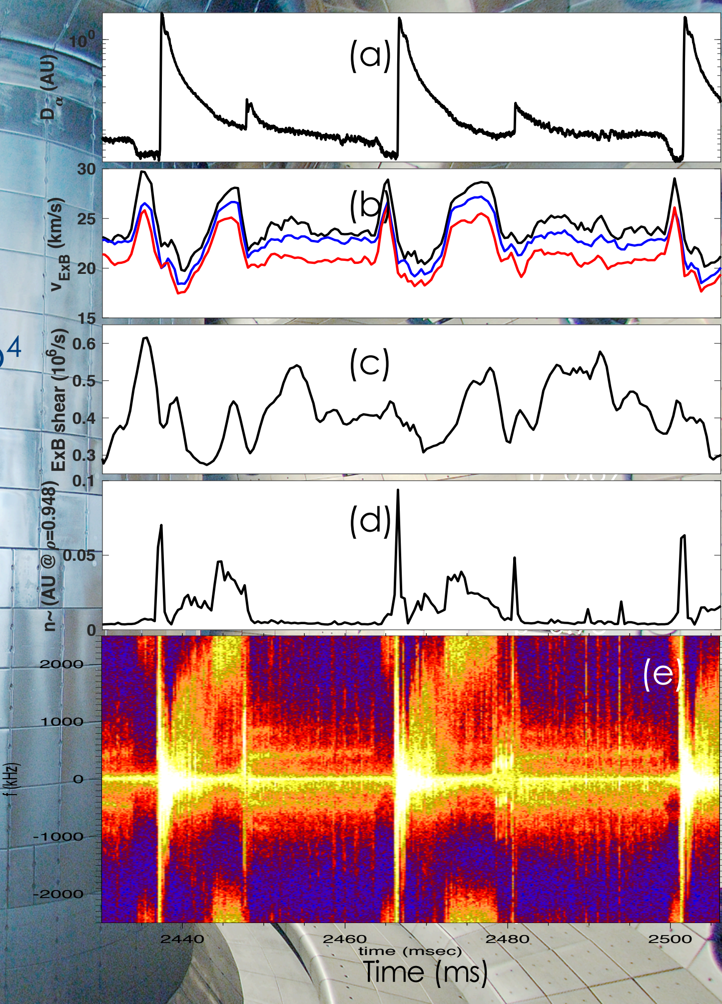

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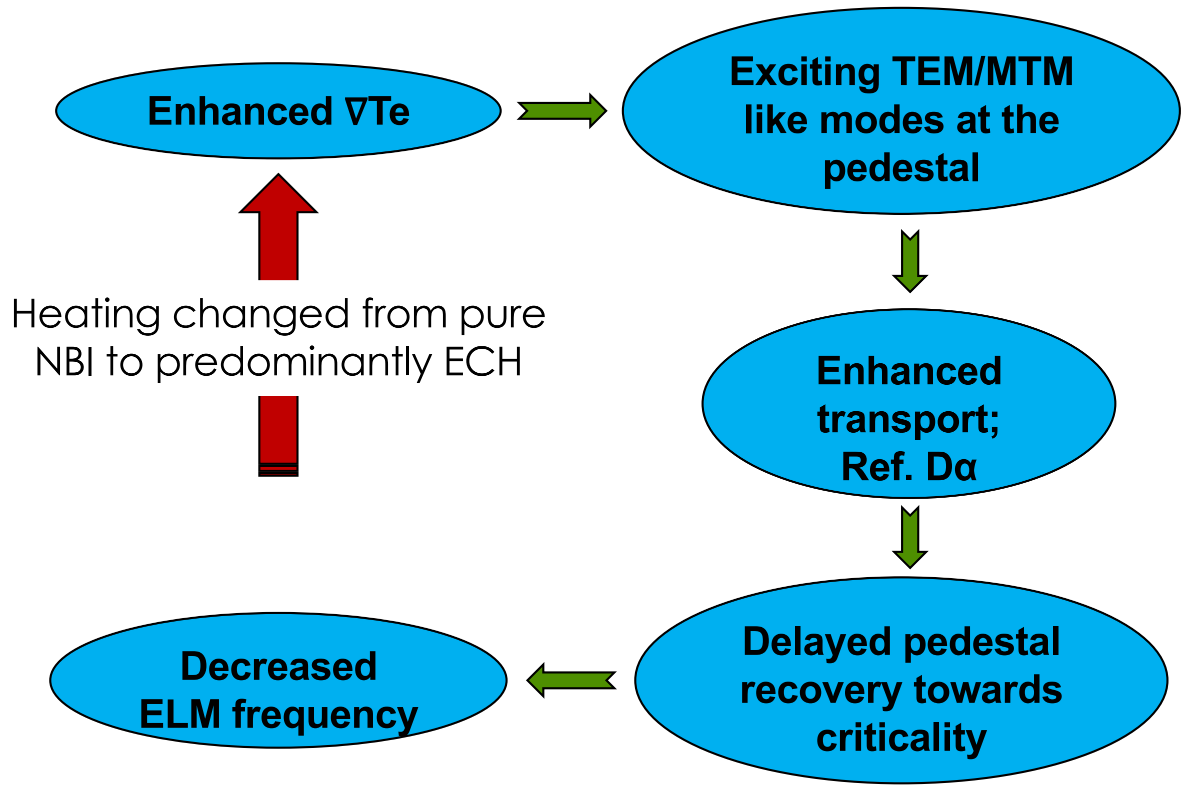
This talk: in a nutshell

- **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 role of turbulence driven transport**
- **And finally: what are the implications?**

Working hypothesis



- Better understanding of the pedestal recovery and effects of turbulence driven transport on that recovery may provide additional tools, like heating mix, for ELM control in ITER – at least prior to the burning plasma phase

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, which are functions of the pedestal width, collisionality, etc.**

↓

Peeling-ballooning (PB) model for ELMs

ELMs – the peeling ballooning instability

- **ELMs can be mainly type I, II or III: we will focus on type I (giant) 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 experimental observations 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**

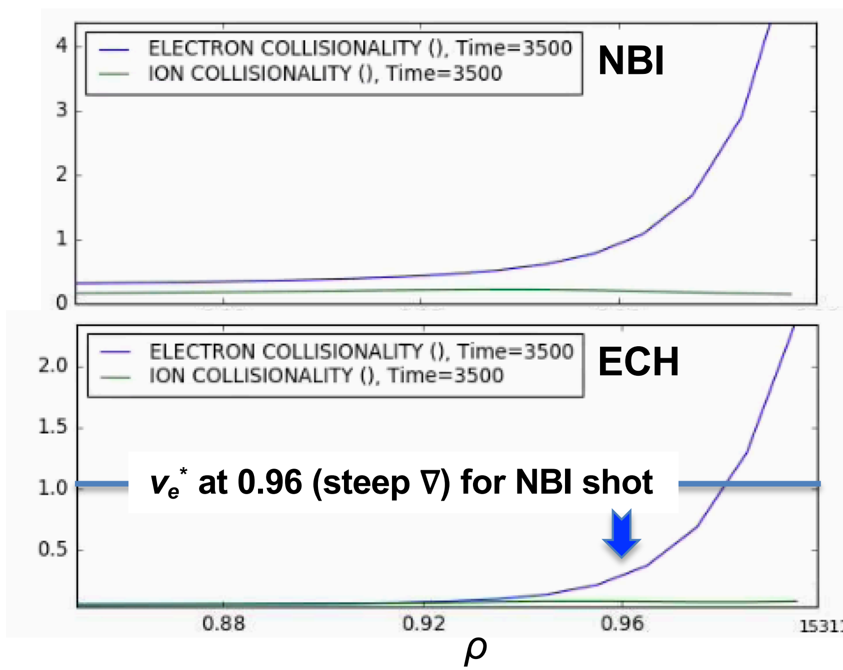
Pedestal gradient recovery has strong impact on ELM characteristics

- **Modifying the pedestal gradient recovery in the inter-ELM phase can lead to very different ELM characters – both amplitude and frequency**
  - 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 the 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**



Outline

- **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**

- S. Banerjee et al., manuscript for NF under internal review

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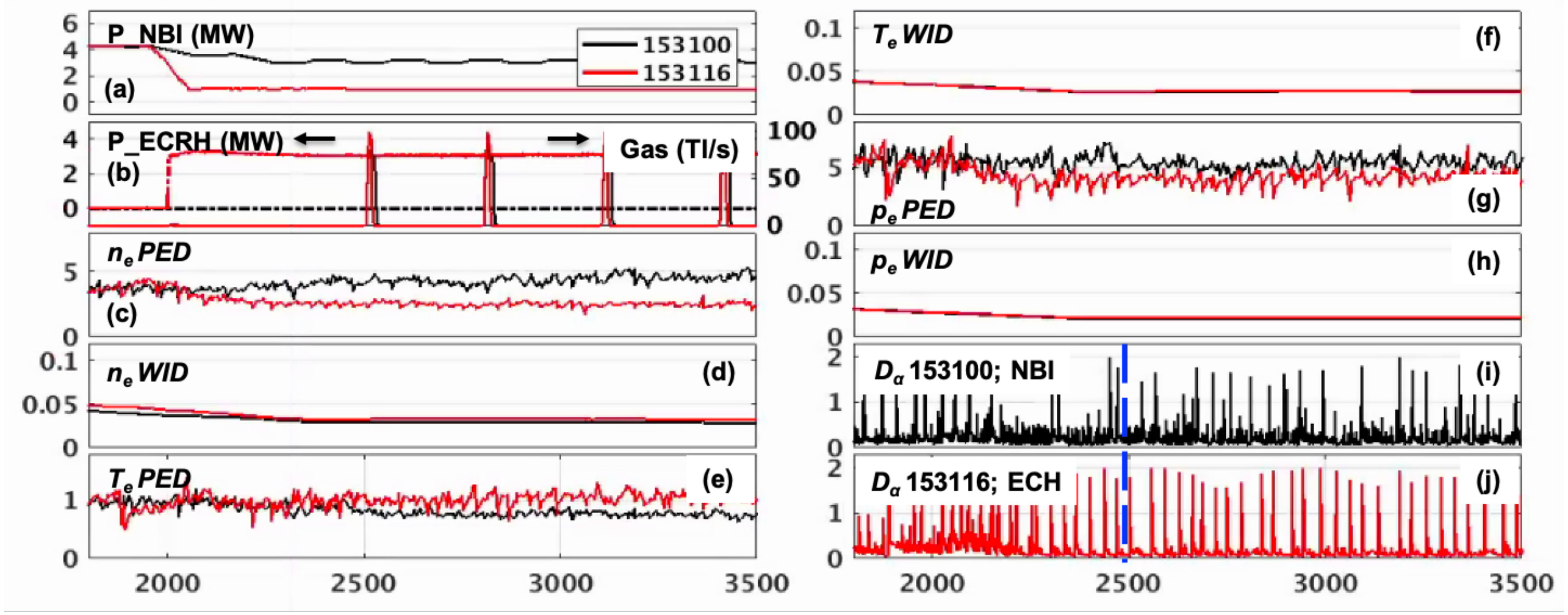
ELM dynamics: 40% reduction in ELM frequency in ECH dominated shots as compared to pure NBI

- **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)**
  - Each large ELM crash is followed by one or two small spikes in Dα
  - Higher total power ~4MW

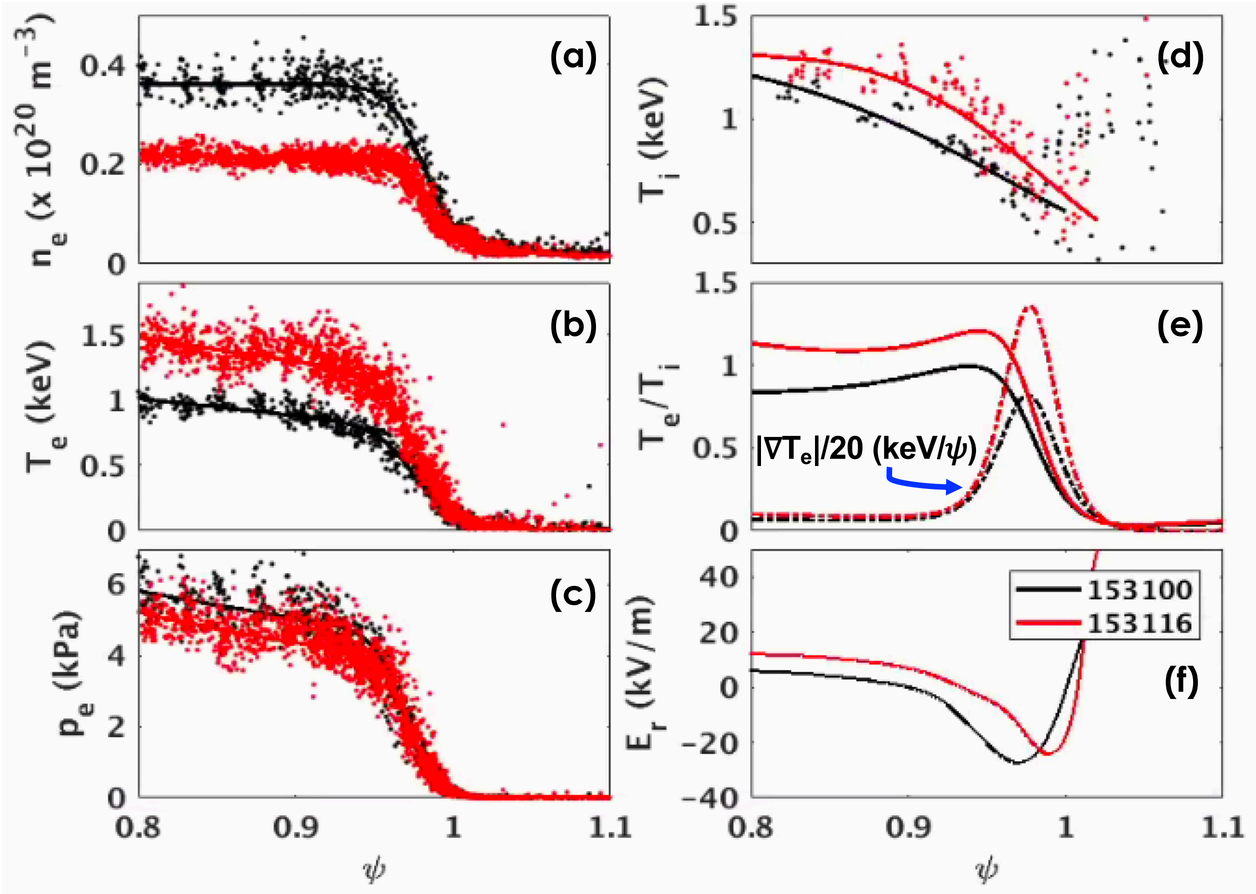


Lower f_{ELM} with higher input power: does not agree with type I ELM definition

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

- In ECH shot: majority of NBI is replaced by ECH
- NBI is in blips for CER measurements
- n_e pedestal lower, T_e pedestal higher in ECH; p_e pedestals are almost comparable
- 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

Black: NBI; Red: ECH



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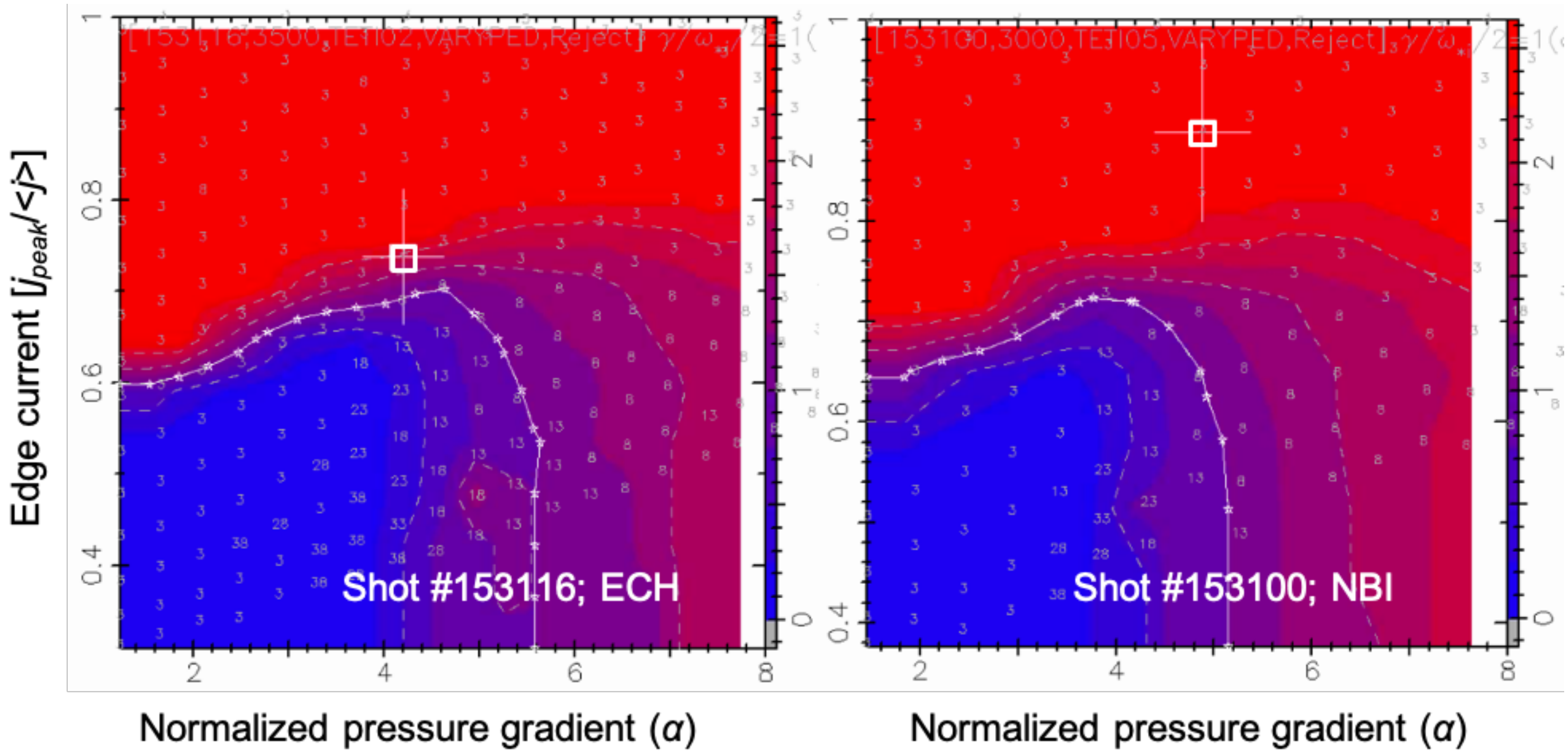
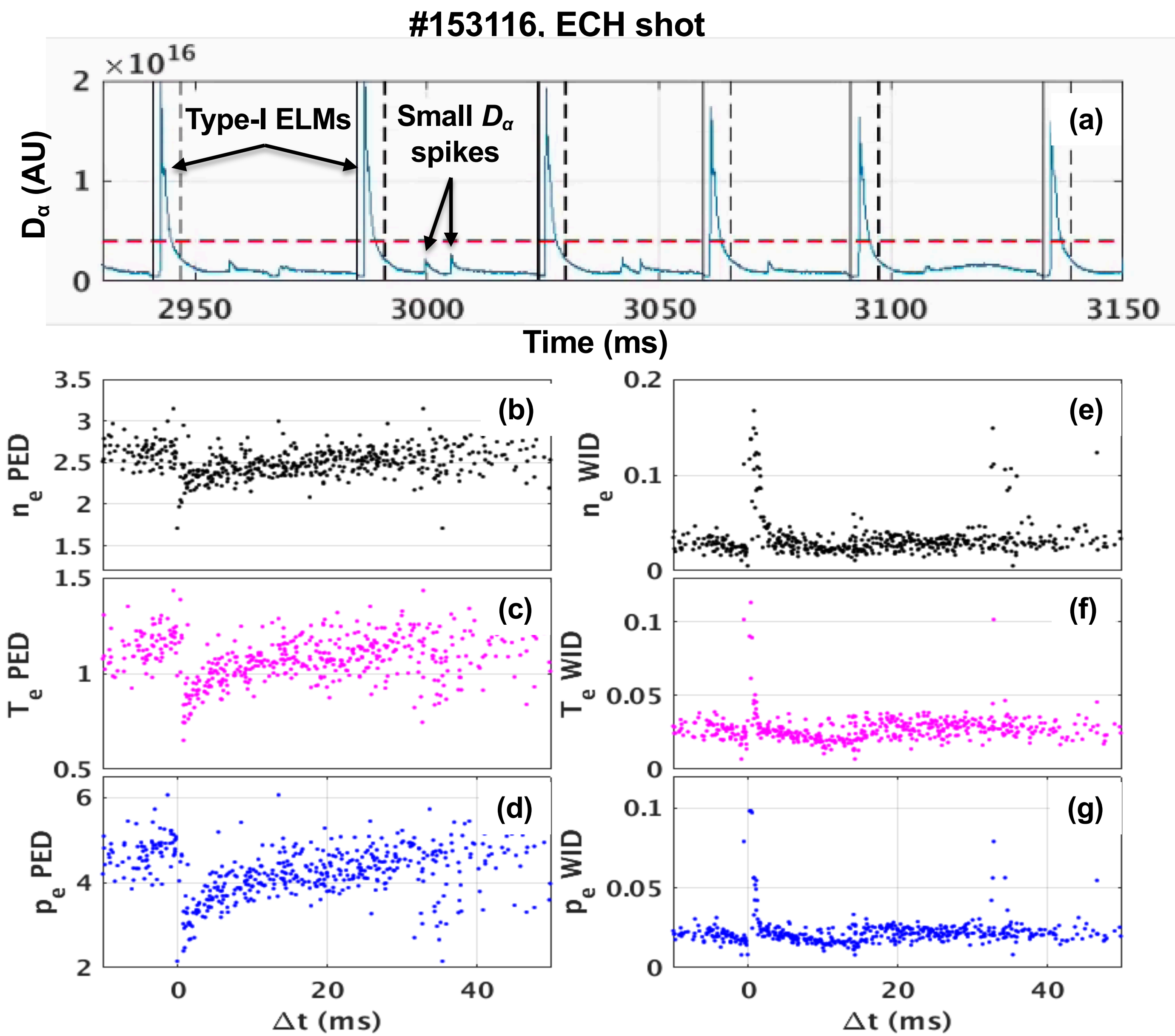
Pedestal stability

- For the ECH shot, the pedestal is close to the peeling boundary while for the NBI shot it is a bit more far away and is more towards the PB nose
- However, in both the cases, the limiting mode number is *n* ~3

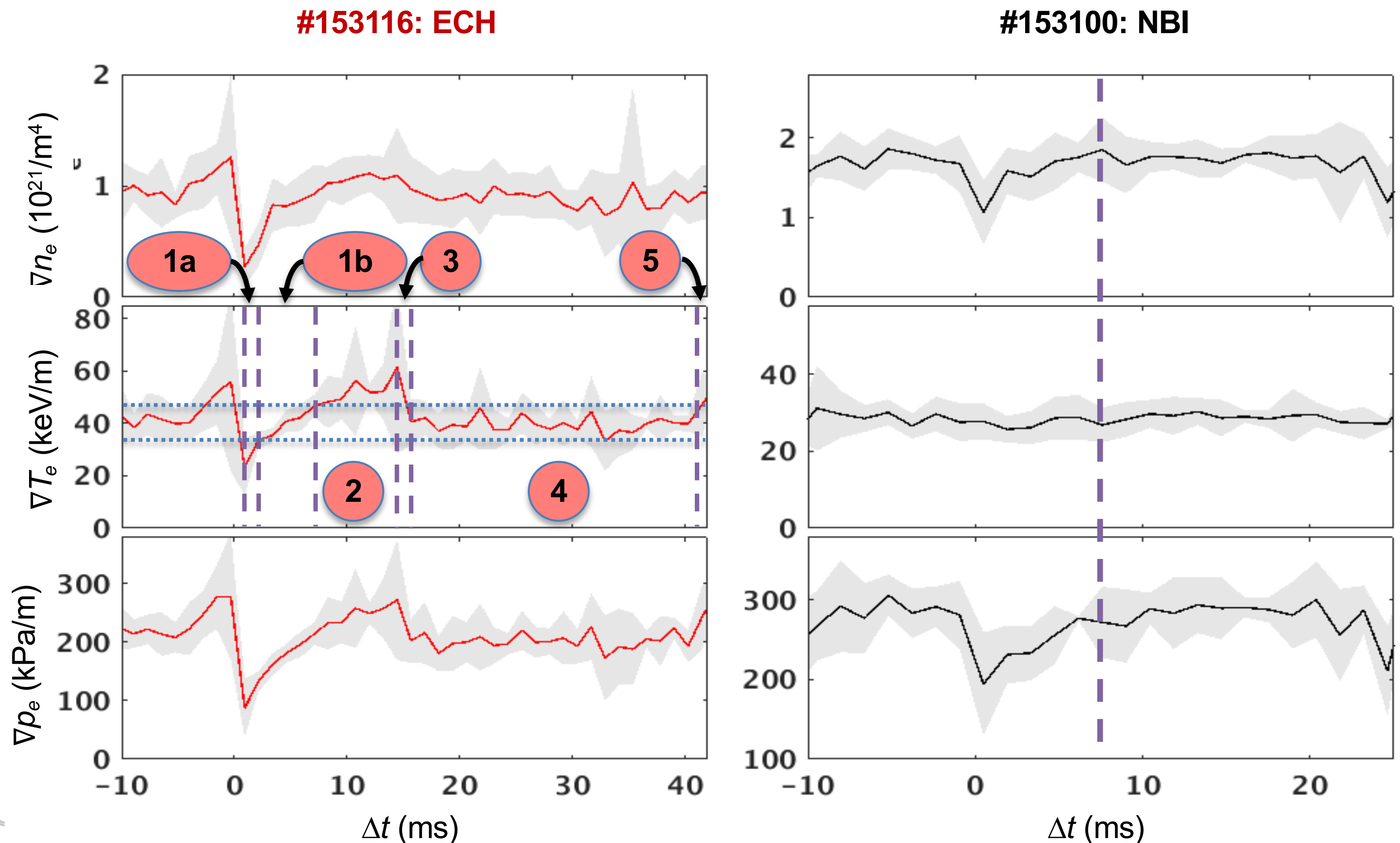


Pedestal recovery following ELMs: phase-locked analysis of Thomson Scattering data – ELM at Δt = 0



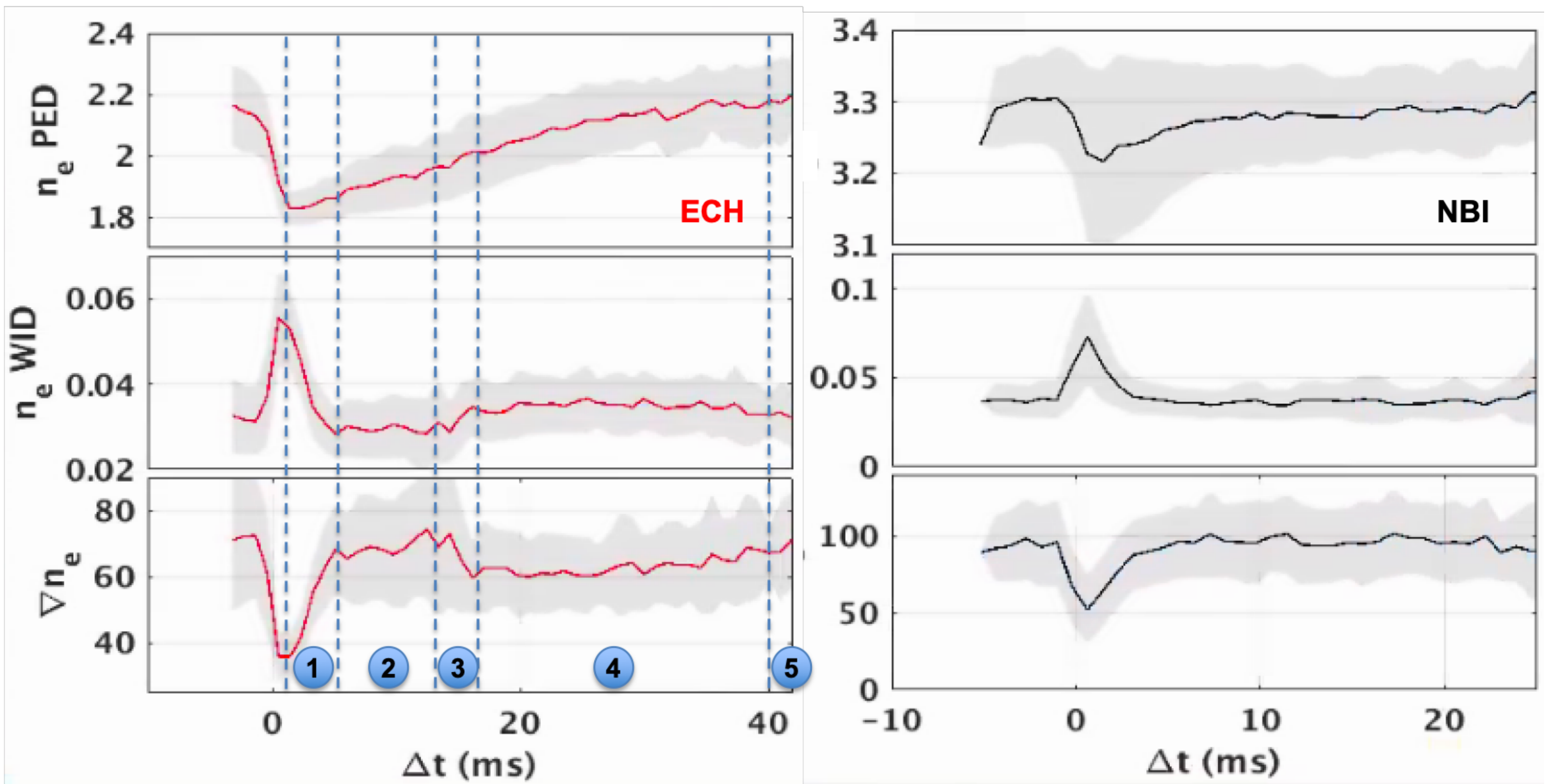
Pedestal recovery following ELMs: Gradients recover much faster in NBI shots

- 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)



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



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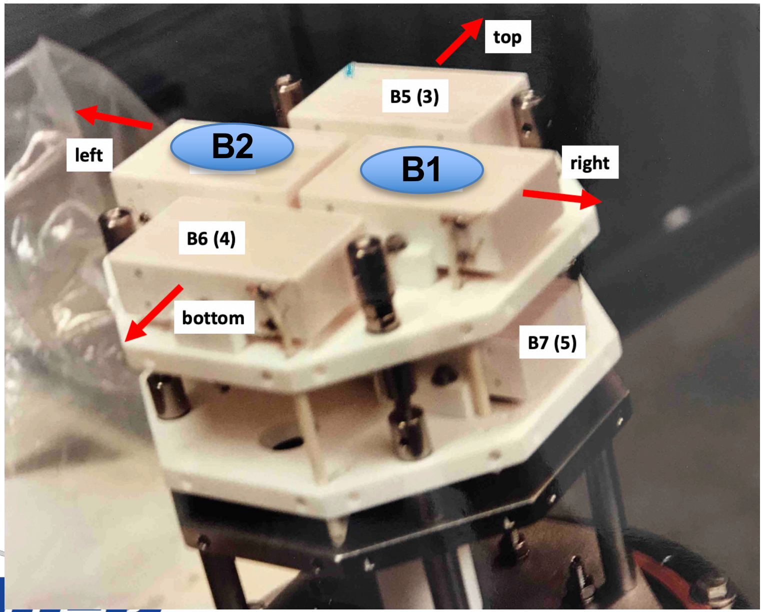
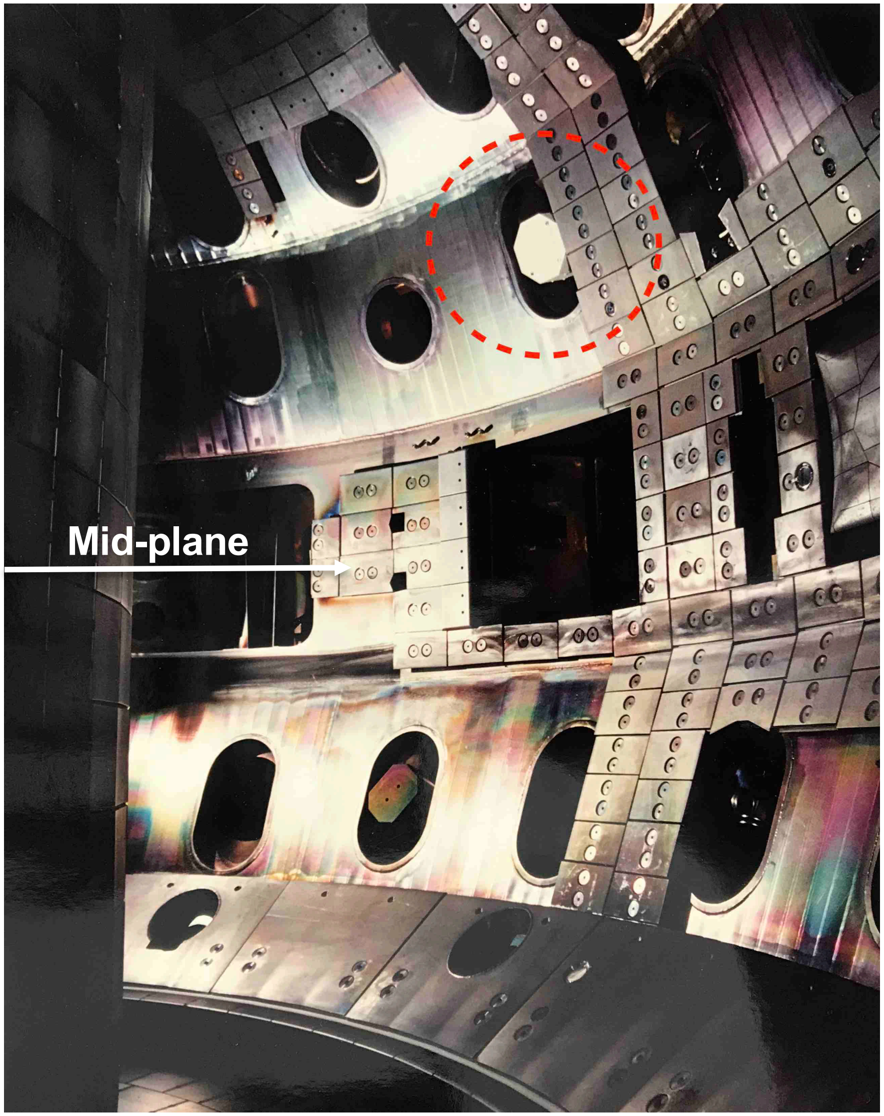
Fast magnetics on DIII-D

- Low inductance, high resonant freq. probes:
  - turns: N = 32, surface area: A = 15:625 cm^2, NA = 0.05 m^2,
  - inductance: L = 25 μH, cap: C = 210 pF
  - resonant frequency: f_{res} = 2.2 MHz
  - B1 and B2 separated toroidally by 2.2°
- Signals digitized at 2 MHz



Installed @ 135°, R + 1 port



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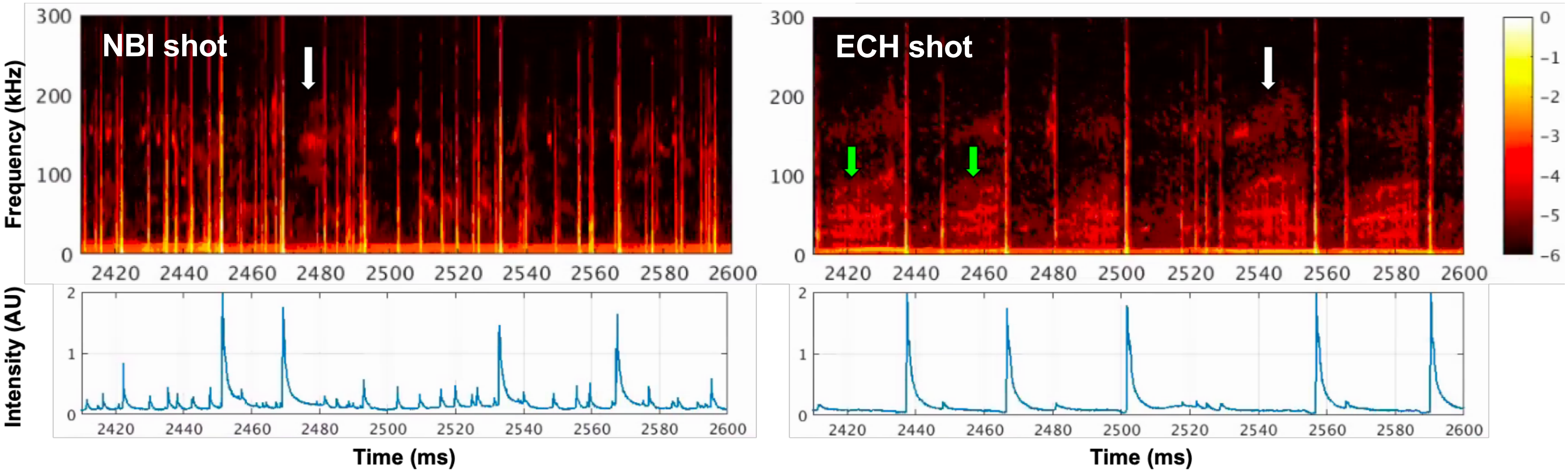
Distinct low frequency magnetic modes (in $\dot{B}_\theta$) in the inter-ELM period for the ECH shot

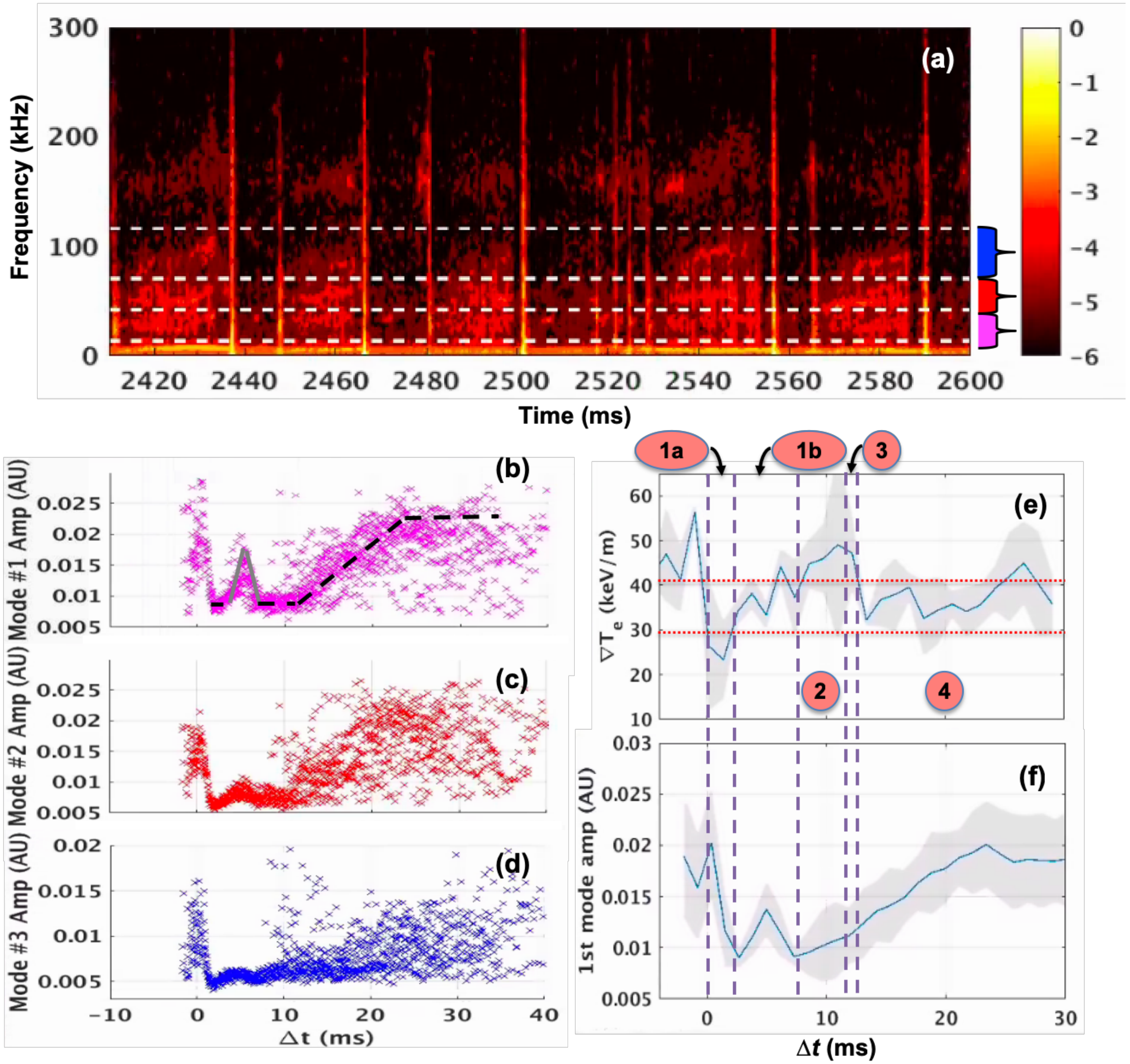
- 2 MHz acquisition in fast-magnetics
- ~150 kHz mode prior to each ELM is present in both cases (white arrows)
- Low frequency quasi-coherent modes (13~116 kHz) present in the ECH case (green arrows), prior to major ELMs



- Caveats:
  - Only 2 probes; Lab frame measurements, $v_{turb} = v_{ExB} + v_{ph}$
  - $v_{ExB} >> v_{ph}$ – Further, fairly large uncertainties in v_{ExB}
  - Mode analysis also not possible: poloidal/toroidal Mirnov arrays do not see these modes due to gain settings (to avoid saturation by core modes)

Evolution of magnetic modes in the inter-ELM period of the ECH shot

- **Mode amplitude evolution shows growth after ~12 ms**
- **Note: a small bump at ~5 ms**
- **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



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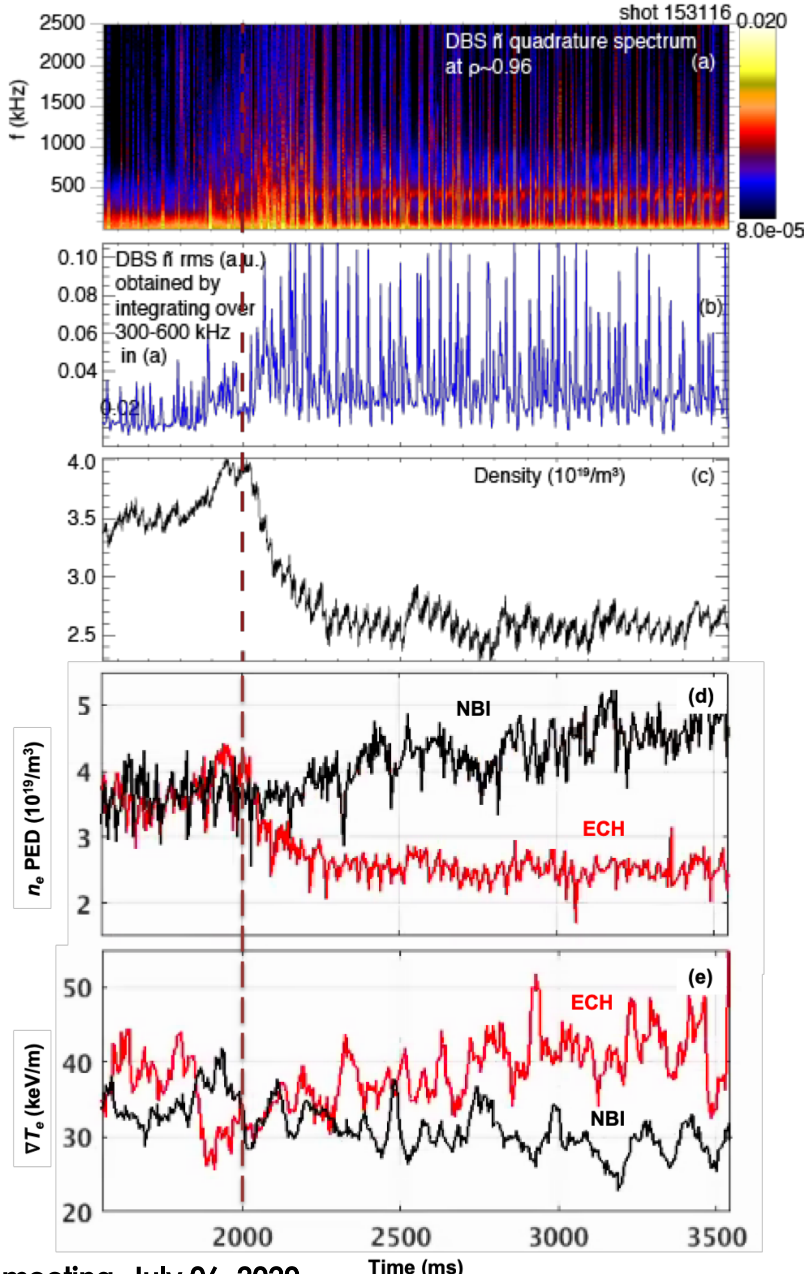
DBS – 400 kHz mode evolution; density pump-out with ECH

- 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



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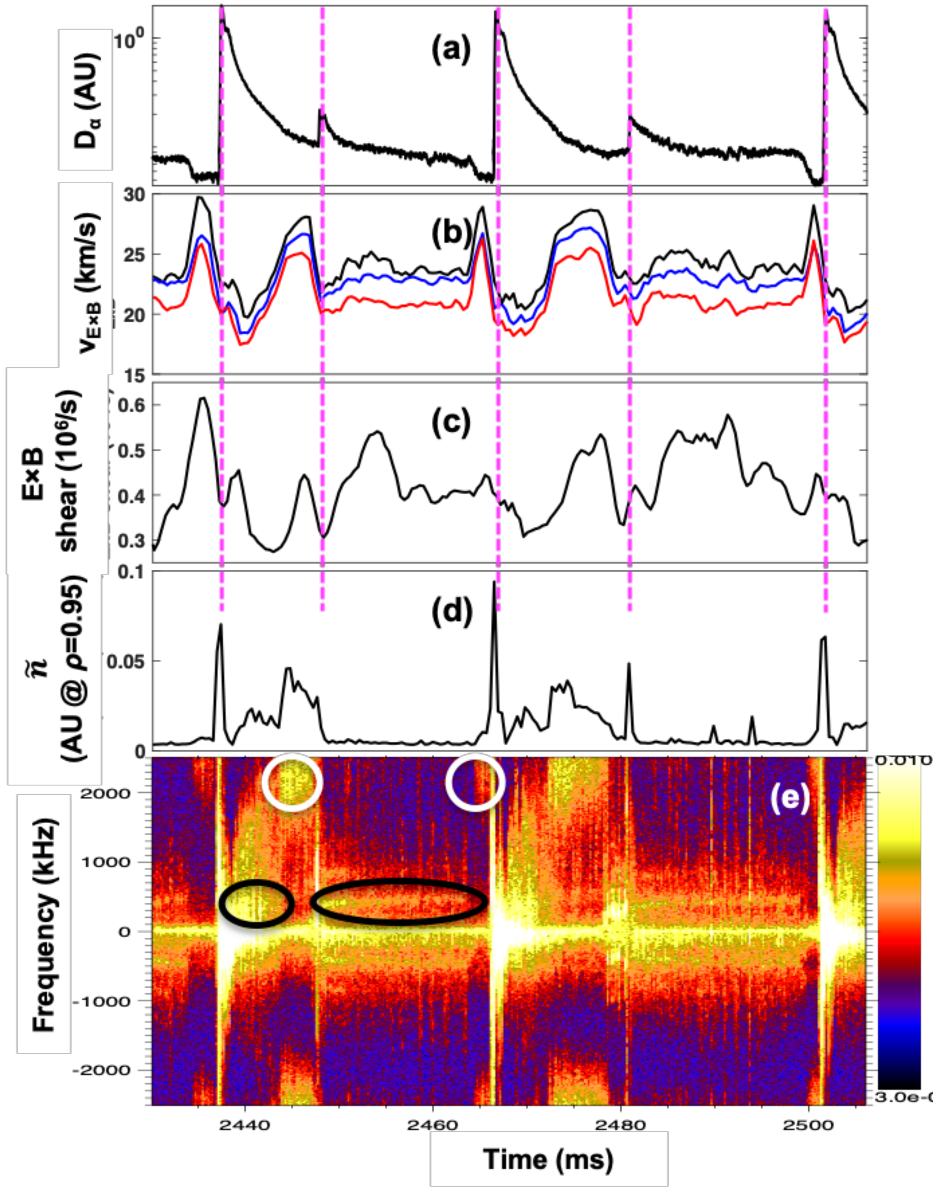
DBS spectra: Interplay of modes and correlation with pedestal recovery

- Last 4 channels on the pedestal gradient not moving appreciably
- Fig. (e): DBS Frequency spectrogram at ρ = 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 Dα spikes
- v_{ExB} increase well correlated with the growth of ~2 MHz mode



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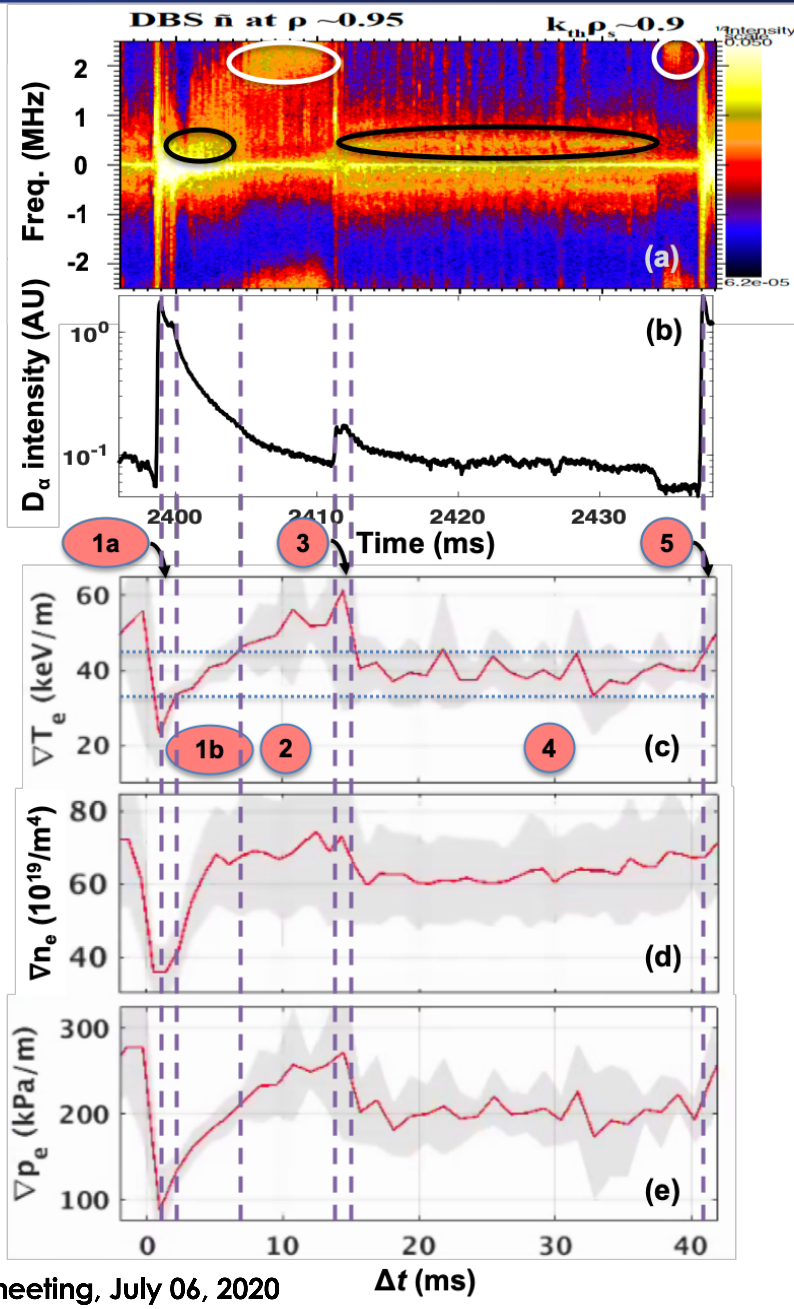
DBS spectra: Interplay of modes and correlation with pedestal recovery

- 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



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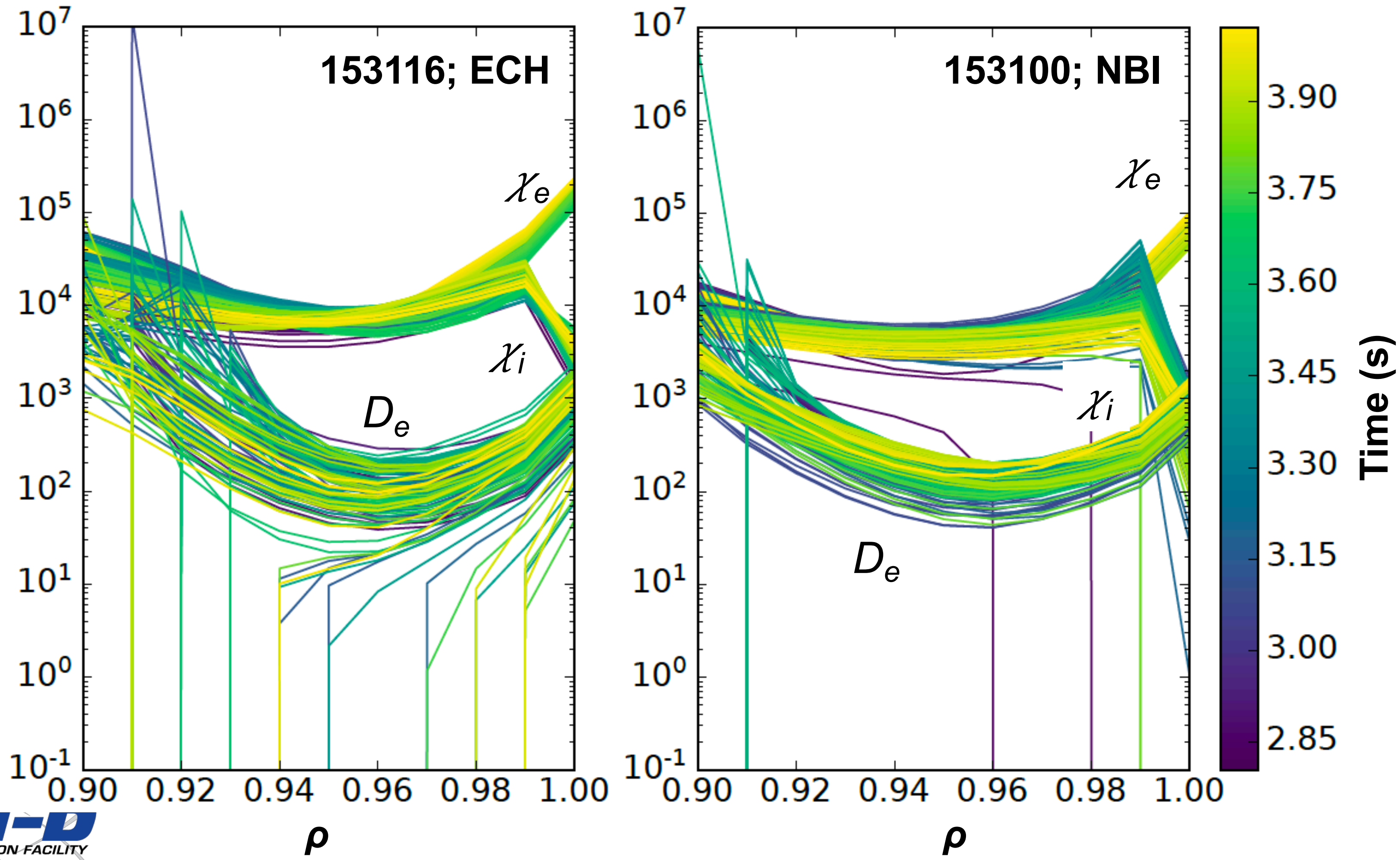
Transport coefficients (TRANSP)

- $D_e << \chi_e$ (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 possible



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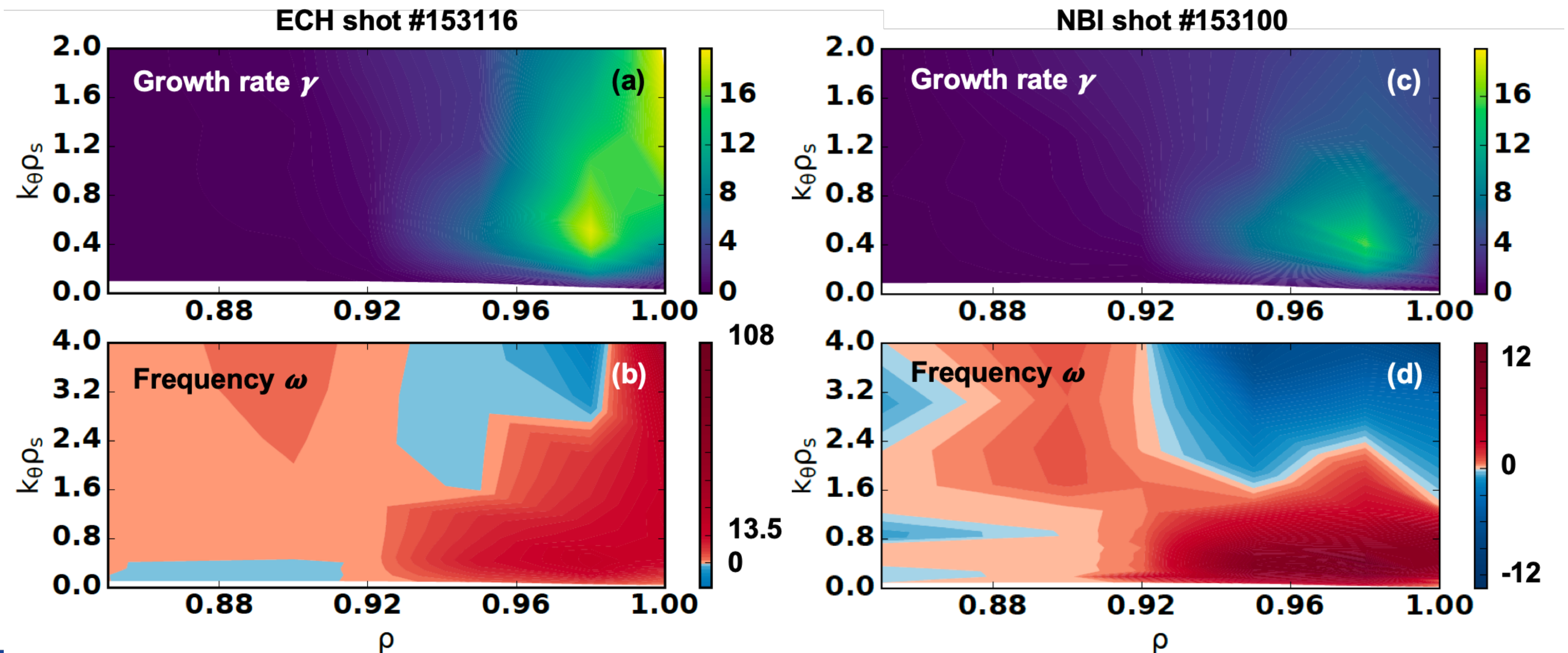
Linear gyrofluid simulations show that frequencies are in the electron direction at ion scale

- **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 $k_y\rho_s < 1$
  - Could be MTM dominant as MTM almost exclusively accounts for electron heat transport and no particle transport, ion-scale, electron temperature gradient driven and frequencies in electron direction



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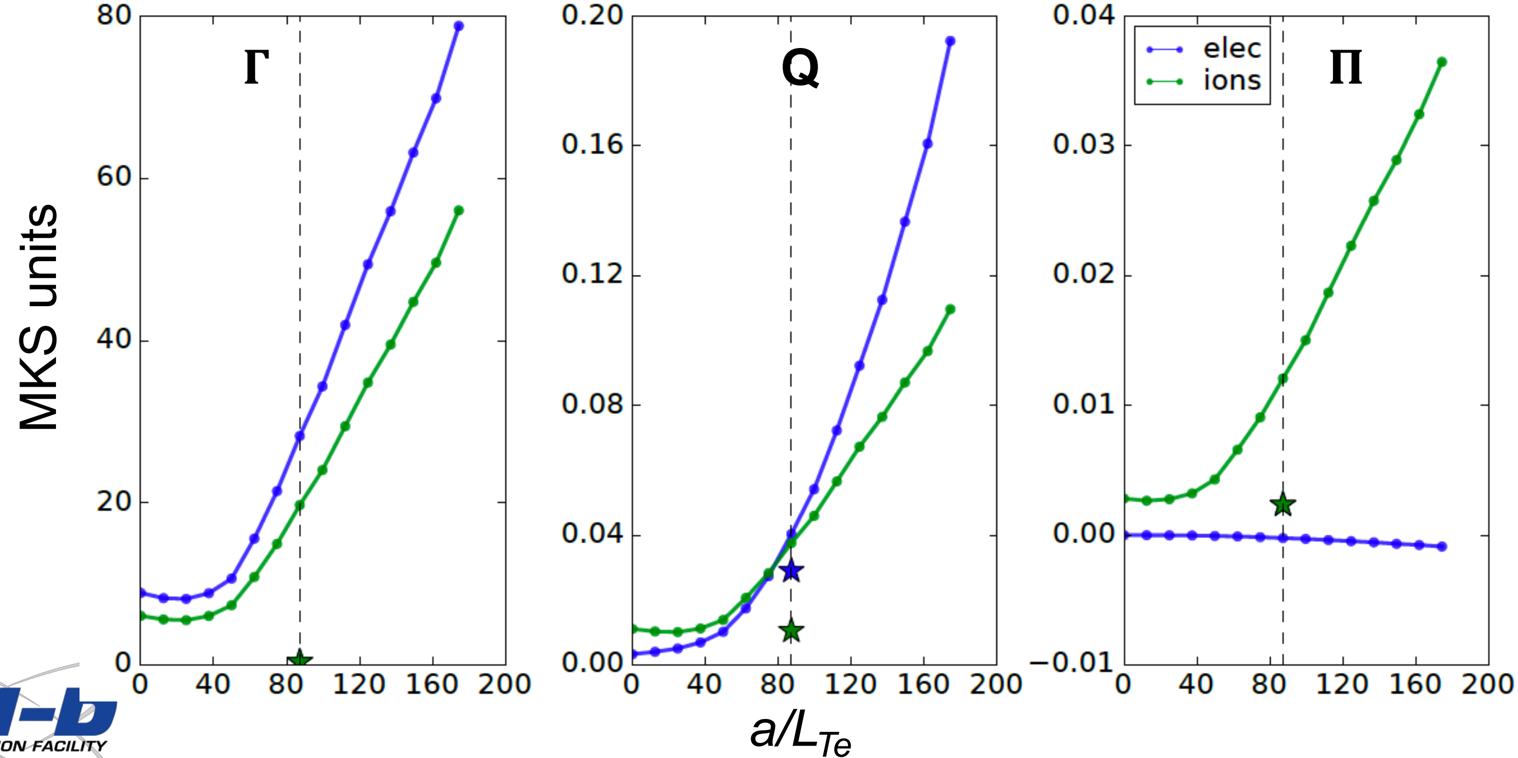
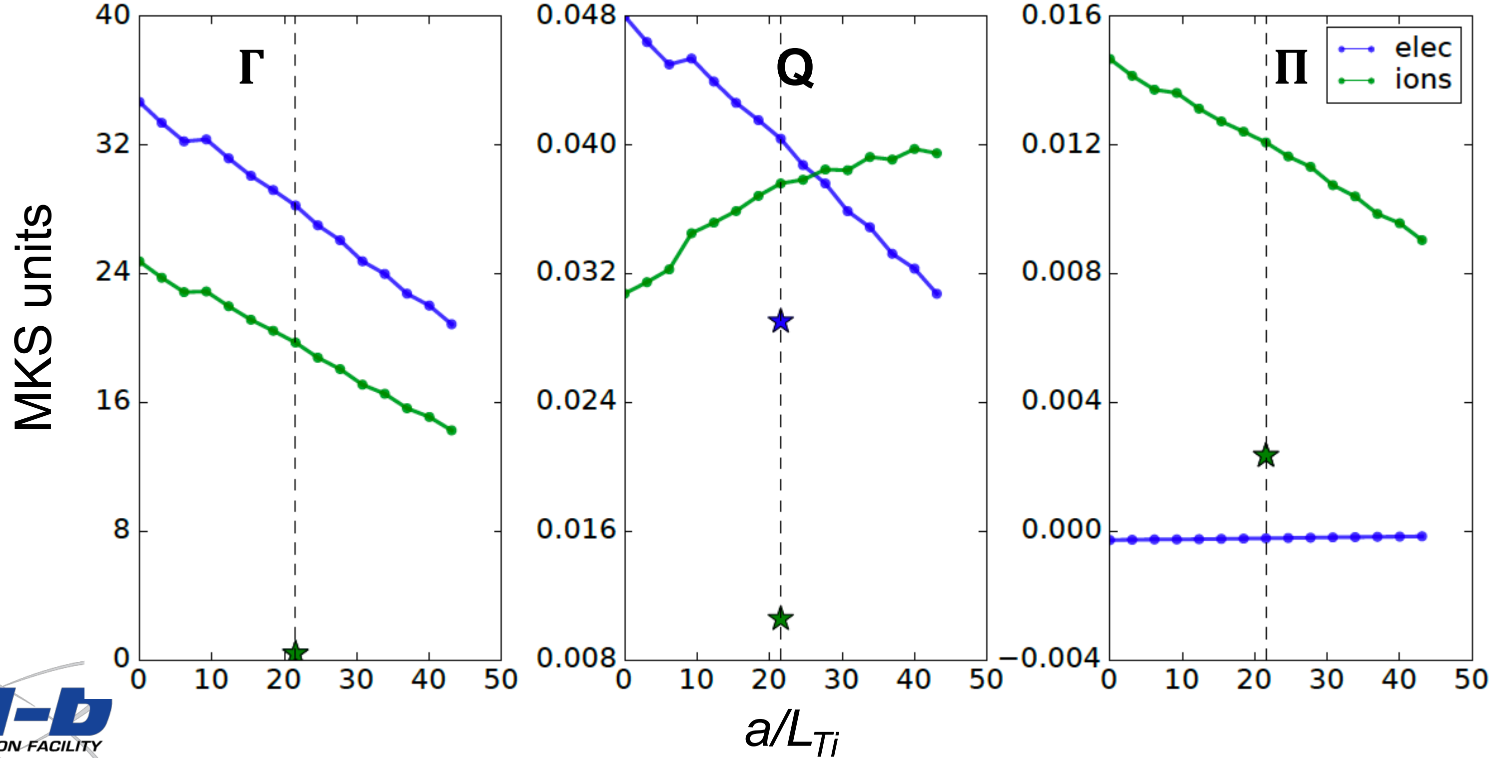
ECH discharge: (a/L_{Te}) scan in TGLF at ρ = 0.98 (pedestal steep gradient region)

- **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 ρ = 0.98 (pedestal steep gradient region)

- **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



Summary – I

- **Type I ELM frequency decreases by 40% in ECH dominated plasmas compared to pure NBI**
  - May be a mixed ELM regime in the ECH shot
- **Density and temperature pedestals are different in NBI vs ECH; pressure pedestal is similar**
- **Phase locked analysis shows ∇T_e recovering simultaneously with ∇n_e and ∇p_e in ECH shot**
  - Pedestal recovery. patterns look different in ECH and NBI shots
- **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 occurrence 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
    - *enhances transport and holds gradients lower for ELMs to occur for a longer period of time*

Summary – II

- **Transport coefficients suggests MTM and/or TEM are the most likely candidates for observed fluctuations**
- **Linear eigenmode analysis shows**
  - Frequency of most dominant mode peaks at steep gradient region of pedestal
  - frequencies are in electron direction at ion-scale
- **a/L_{Te} and a/L_{Ti} scans confirm**
  - Turbulence at steep gradient region is ∇T_e driven
  - Plasma ITG stable at that radius (steep gradient)

- **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**

- **Collisionality, ratio of heating mix (NBI to ECH) and ECH deposition radius are crucial parameters to study further the effects on turbulence and associated transport**
  - Planned for upcoming campaign

Thank you for your attention