Decoupling of peeling and ballooning thresholds of pedestal stability and reduction in ELM frequency via enhanced turbulence with edge ECH in DIII-D

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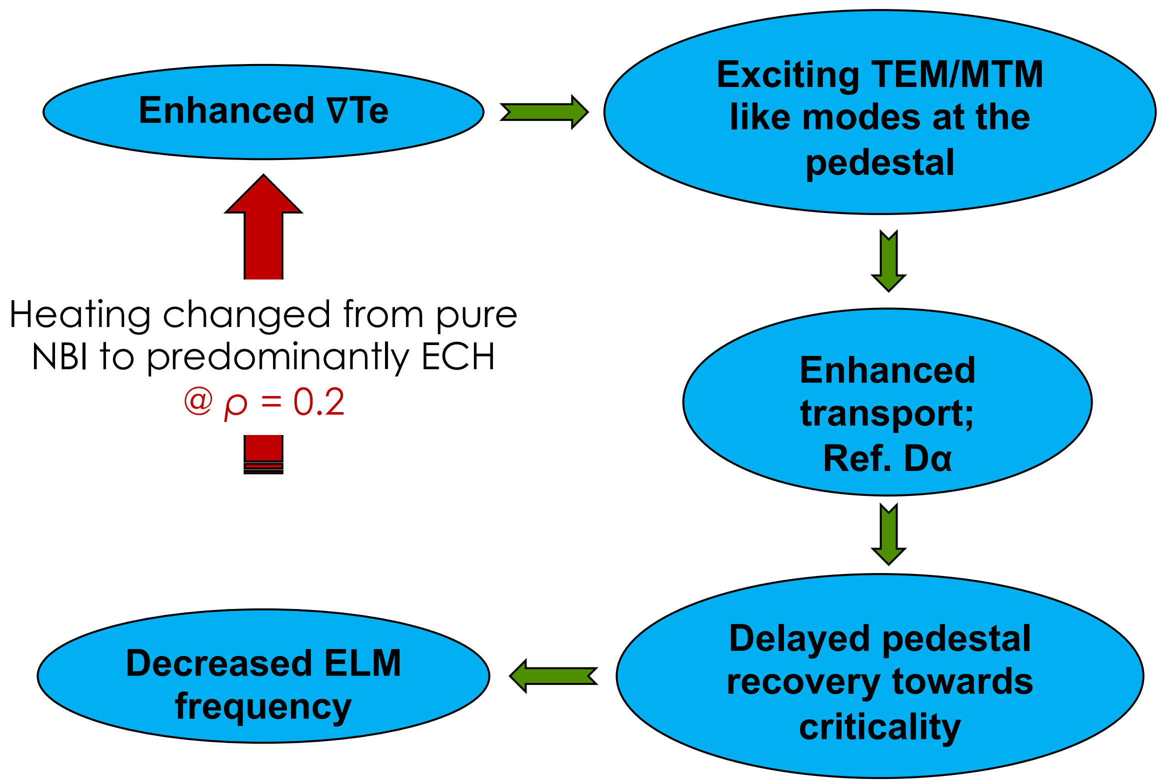
Foreword – motivation, goals and approach

- ELM frequency decreased by 40% in ECH (at ρ = 0.2) dominated plasmas compared to pure NBI
- Fast-magnetics show distinct MTM-like modes in inter-ELM period
- DBS shows growth of 400 kHz TEM-like QCM and high frequency ~2 MHz broadband turbulence in the inter-ELM period

- Can we gain further control on ELM freq. by changing ECH location and heating mix ratio
- What's the role of turb. transport?

Enhanced ∇T_e excites MTM-like and/or TEM-like modes and hence increased turbulence driven transport – resulting in delayed gradient recovery and thereby reducing ELM frequency in ECH dominated discharges



S. Banerjee et al., Nucl. Fusion 61 (2021) 056008

Outline

- **Experimental detail**
  - ELM frequency
  - pedestal evolution
  - pedestal profiles
- **Edge stability**
- **Inter-ELM pedestal evolution**
- **Fluctuations**
  - magnetics, BES and DBS
- **Some transport analysis**
- **Summary**

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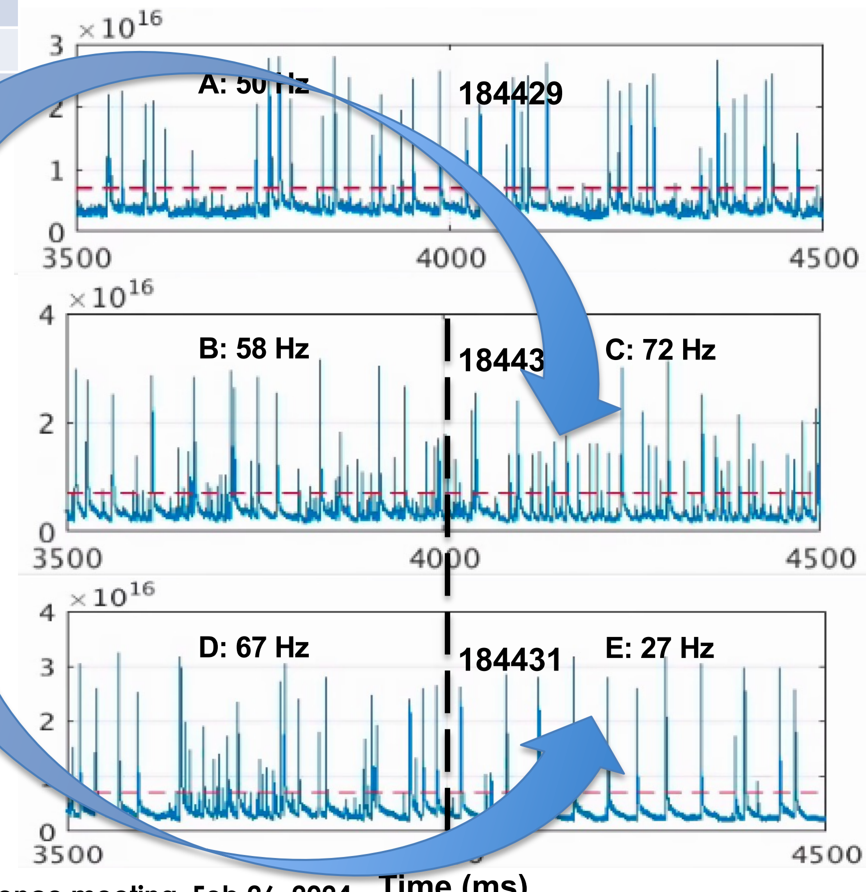
Scan of heating mix (NBI/ECH) and ECH dep. location shows different ELM behaviors in scanned regimes

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

ECH deposition	NBI (MW)	ECH (MW)	(NBI:ECH)	Total (MW)	ELM freq. (Hz)
None A	3	0	1:0	3	50
ρ = 0.4 B	2	1	2:1	3	58
ρ = 0.4 C	1.6	1.4	~1.1	3	72
ρ = 0.8 D	2	1	2:1	3	67
ρ = 0.8 E	1.6	1.4	~1:1	3	27

- **ELM frequency increased by ~40%, compared to the pure NBI discharge, when P_{NBI}/P_{ECH} ~1 is applied with the ECH at ρ = 0.4**

- **But ELM frequency reduced by ~50% when P_{NBI}/P_{ECH} ~1 is applied with the ECH deposition at ρ = 0.8**



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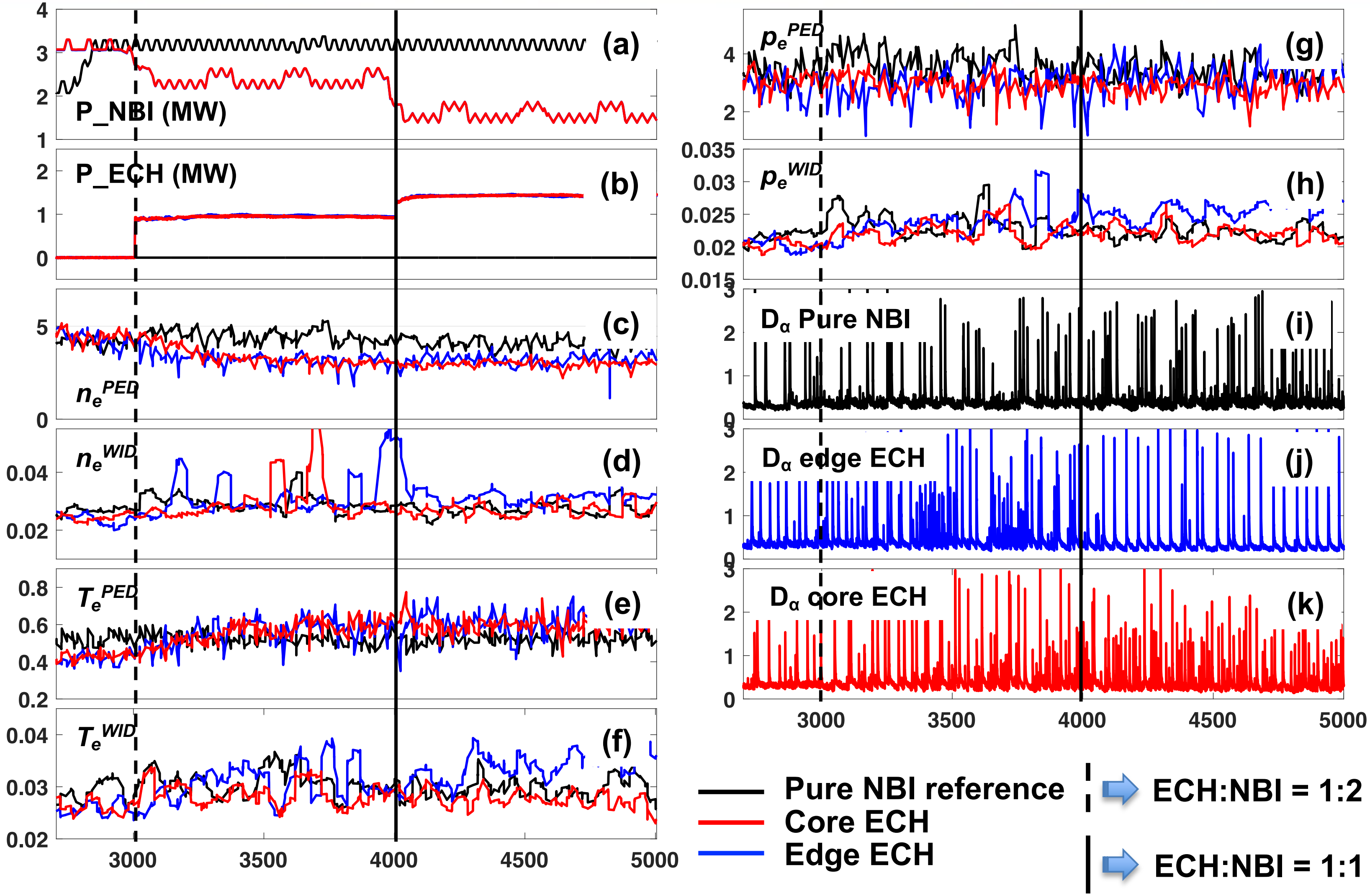
n_e, T_e and p_e at pedestal vary as per heating; pedestal width increases with f_{ELM} drop



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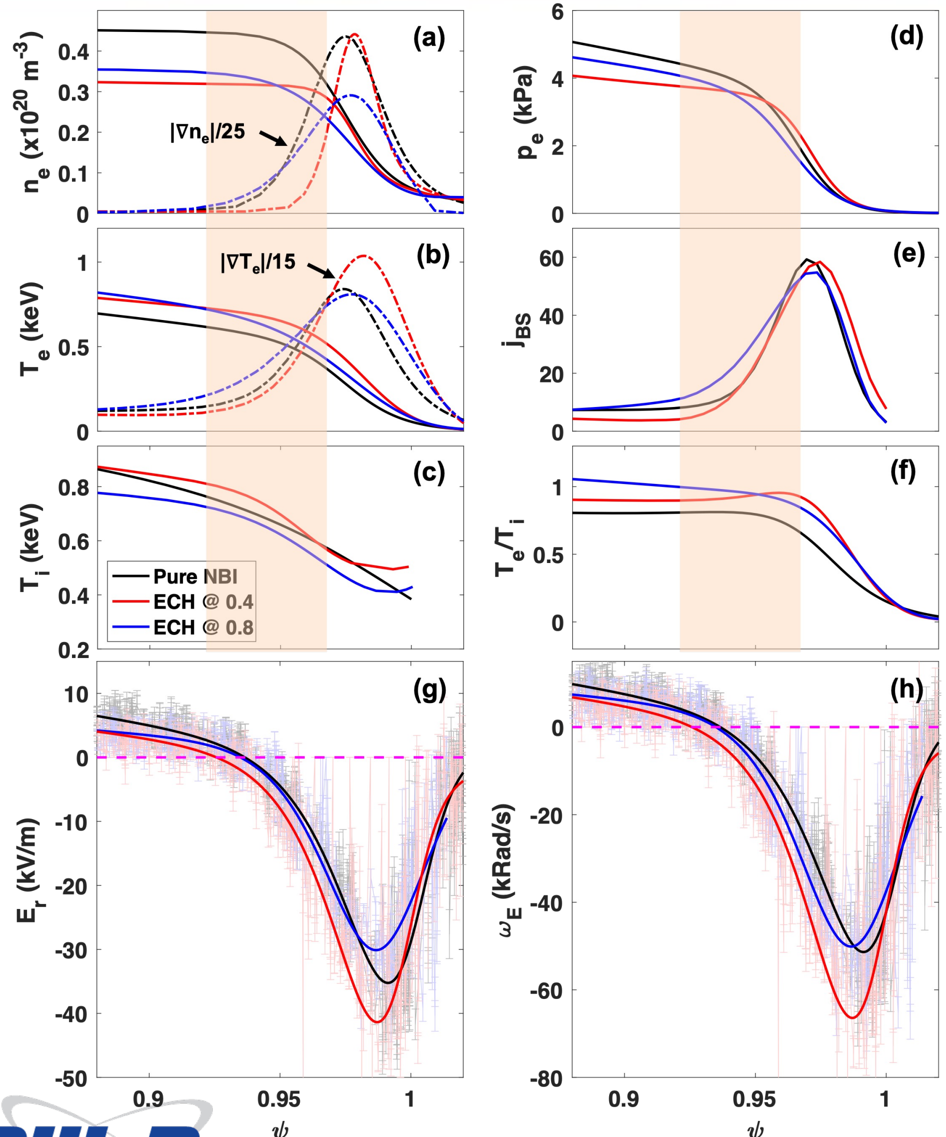
Pedestal avg profiles show range of values and grad for different heating mix ratio and ECH location



- Pedestal n_e lower and T_e higher in ECH substituted shots
- ∇T_e highest in red – profiles towards foot but highest in blue @ ρ = 0.92-0.97
- Same in ∇n_e between core and edge ECH
- T_e / T_i similar in both ECH cases
- v^* is 1.5 in pure NBI but 0.8 in ECH cases
- E_r well is significantly shallower for the edge ECH case compared to the core ECH case.
- Absolute value of ω_E and hence $E{\times}B$ rotation shear is highest in the core ECH case

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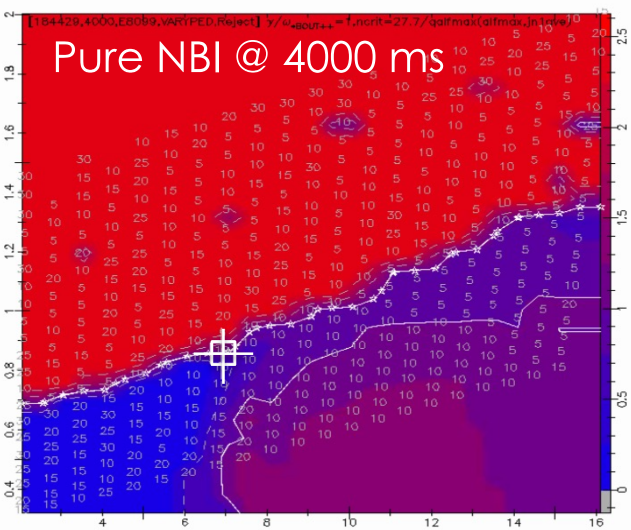
Stability (ELITE) for pure NBI and NBI+ECH shots (core & edge) – decoupling in pure NBI and preservation

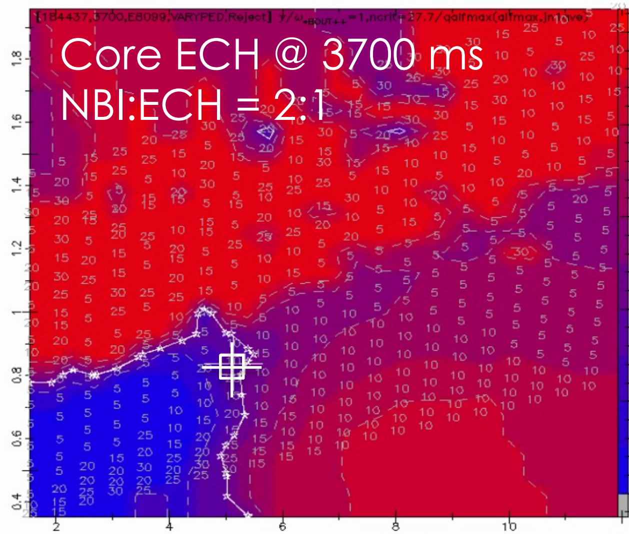
Shot #184429

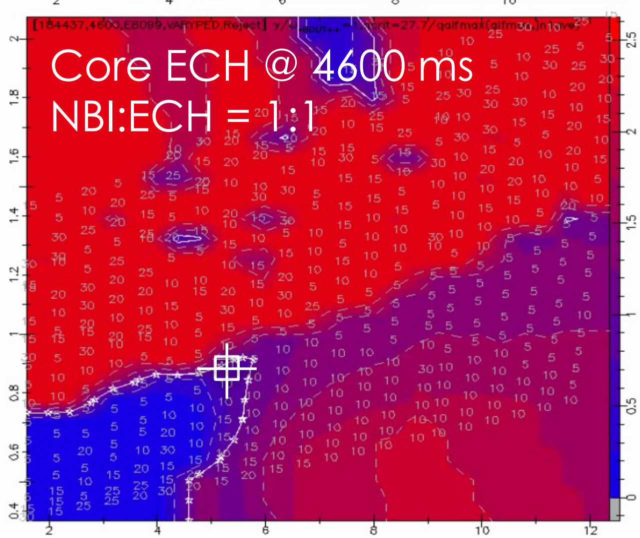
- Decoupling of peeling and ballooning stability limits in pure NBI
- Decoupling preserved in edge ECH, but not in core ECH



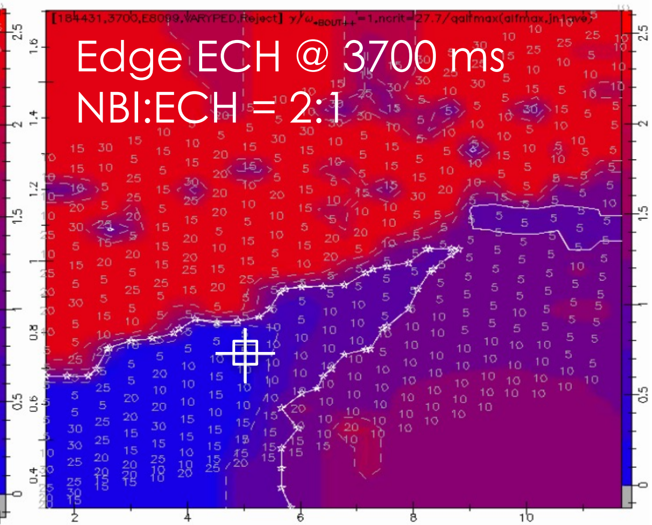
Note: Total input power is constant for all shots

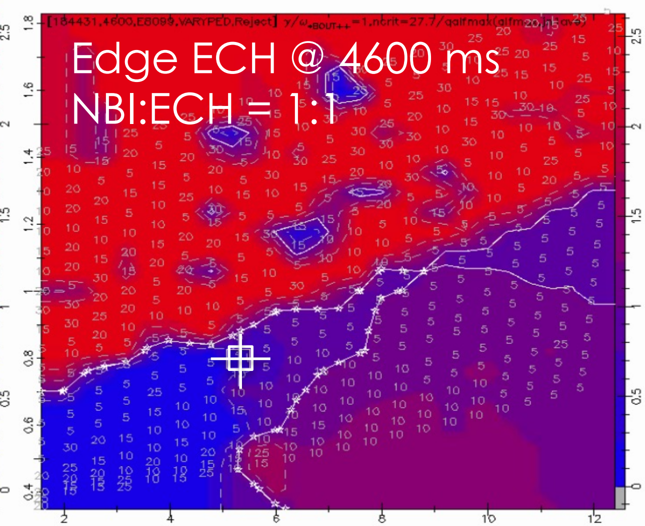
Shot #184437





Shot #184431

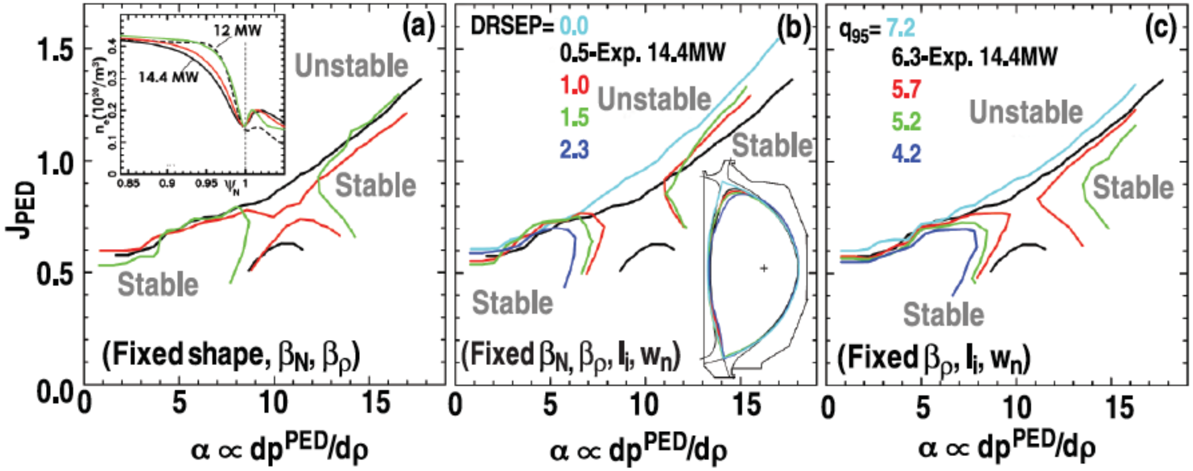




What can cause decoupling of peeling and ballooning stability limits and how it can be preserved

Analysis of Petrie's cases showed that the decoupling could be increased by

- Widening the pedestal – But is that true across regimes of operation?
- Increasing q_{95}
- Reducing dr_{sep} toward 0
- Increasing power which seemed to act through an increase in the ion diamagnetic stabilization level.



DND vs LSN?

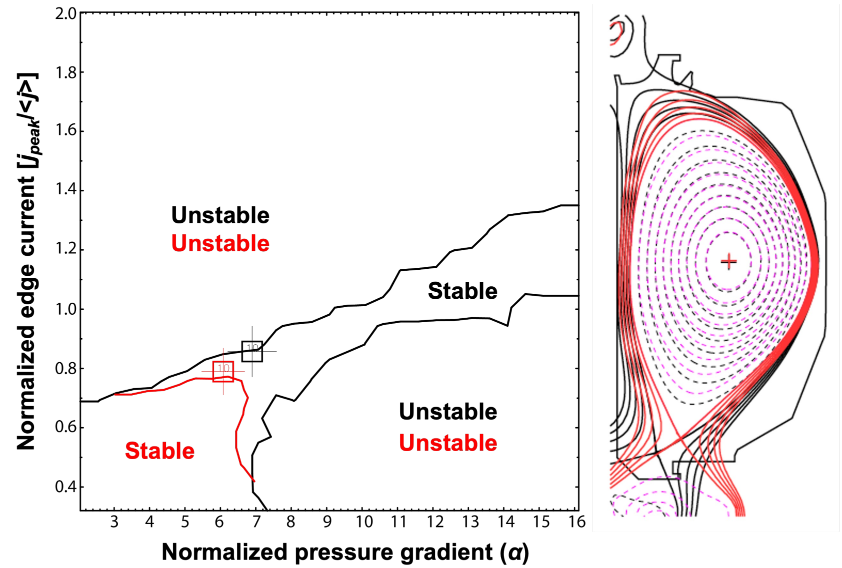
In our case:

- No variation in dr_{sep} (0.4) among the pure NBI and ECH shots
- Also, no variation in q_{95} (6)

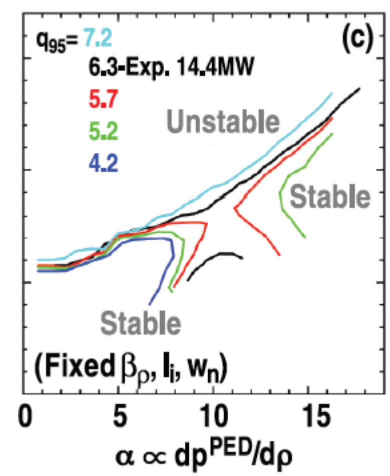
T. W. Petrie et al., Nucl. Fusion 57 (2017) 086004

Target 170868 (red) has many differences from the new pure NBI reference discharge, 184429 (black)

- **170868 (one of the target scenarios for this experiment)**
- **Why the stability is different?**

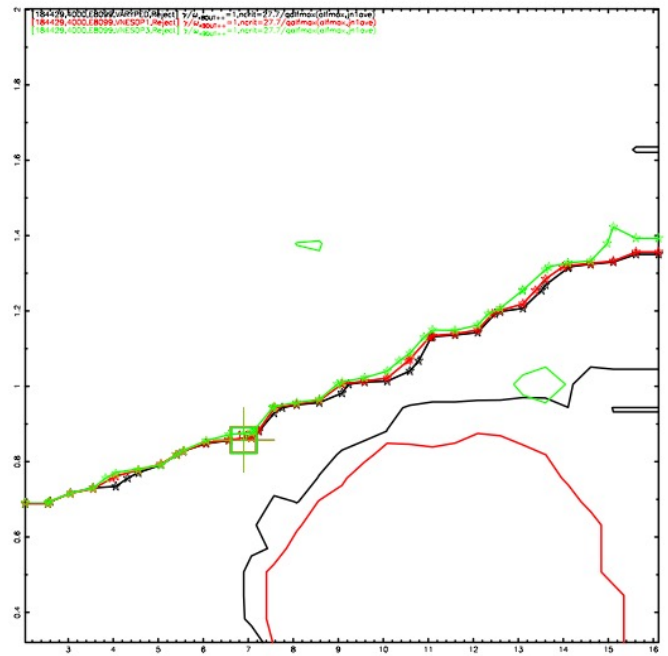


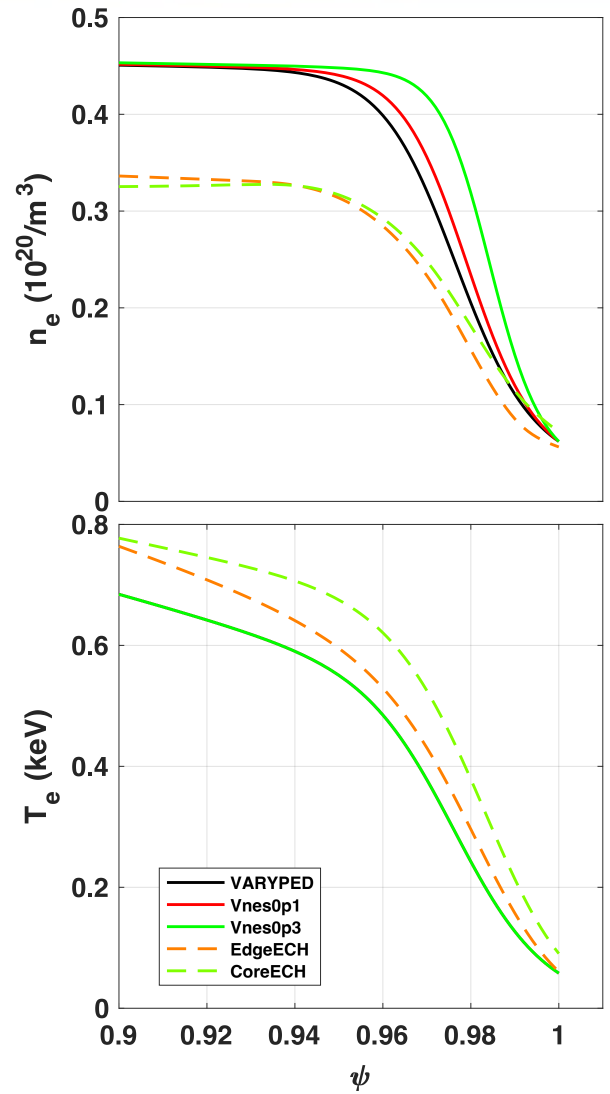
- **Similarities**
  - drsep same, Ip same
  - <ne> similar 5e13
  - ne_ped similar
  - ne_wid, Te_wid, pe_wid similar
- **Differences**
  - q95 higher (6) in 184429 vs 170868 (5)
  - P _inj: 3.2 MW(184429) vs 2.2 MW(170868)
  - Te_ped (184429: 520 eV) vs (170868: 420 eV)
  - Accordingly, pe_ped is higher in 184429
  - v*: 1.5(184429) vs 1.9(170868)
  - T_inj: 0.5 Nm(184429) vs 2.2 Nm(170868)



ne_wid scan shows decoupling increases with steeper density pedestal

- Nothing except the ne_wid is changed
- Decoupling tends to increase with decrease in ne_wid
- This is contrary to Petrie's observations

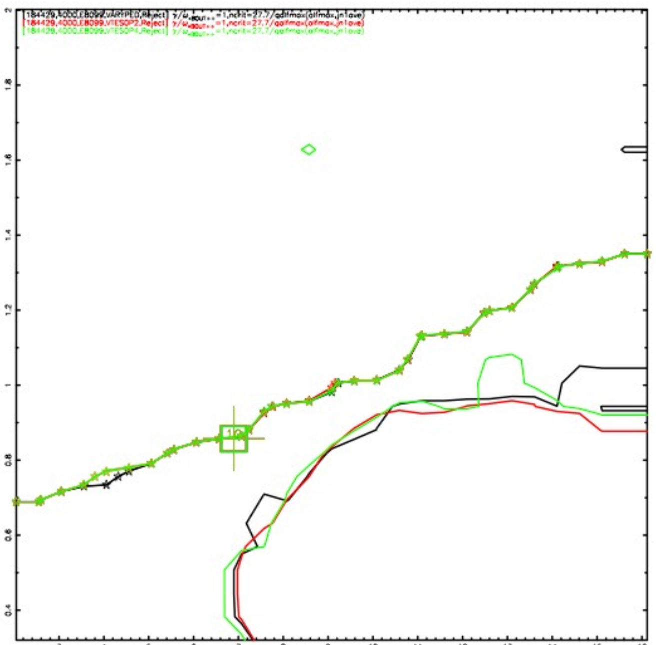


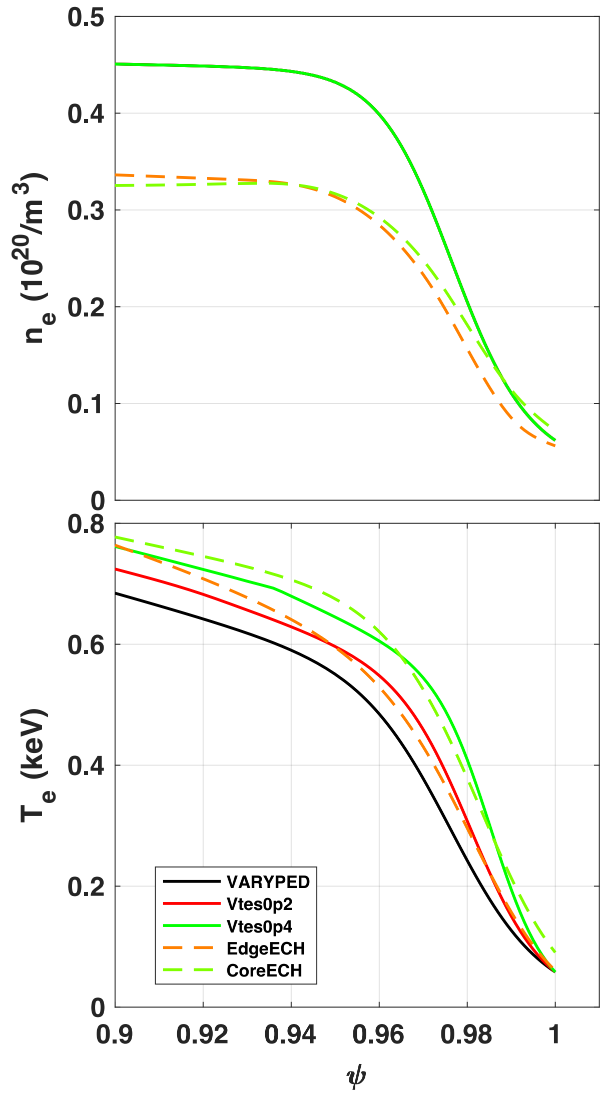


T. W. Petrie et al., Nucl. Fusion 57 (2017) 086004

Te_wid scan shows no appreciable change with Te_ped width

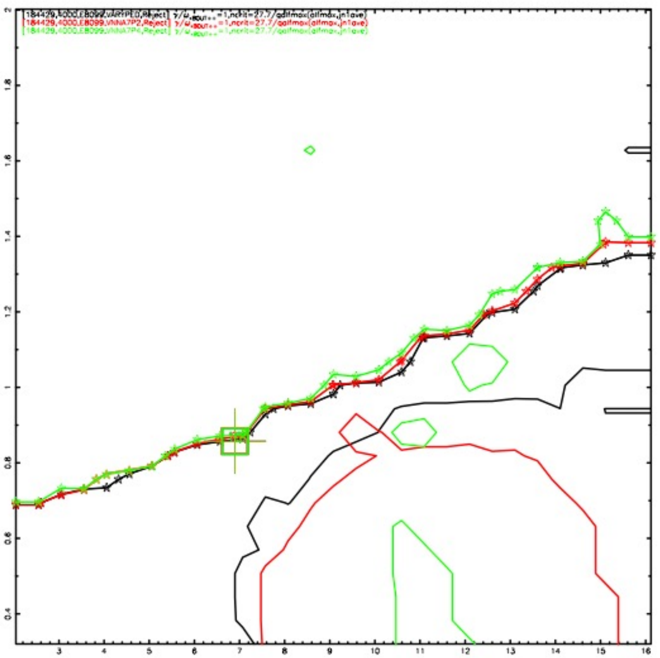
- If ne_wid is kept as it is and only Te_wid is scanned, no appreciable change observed

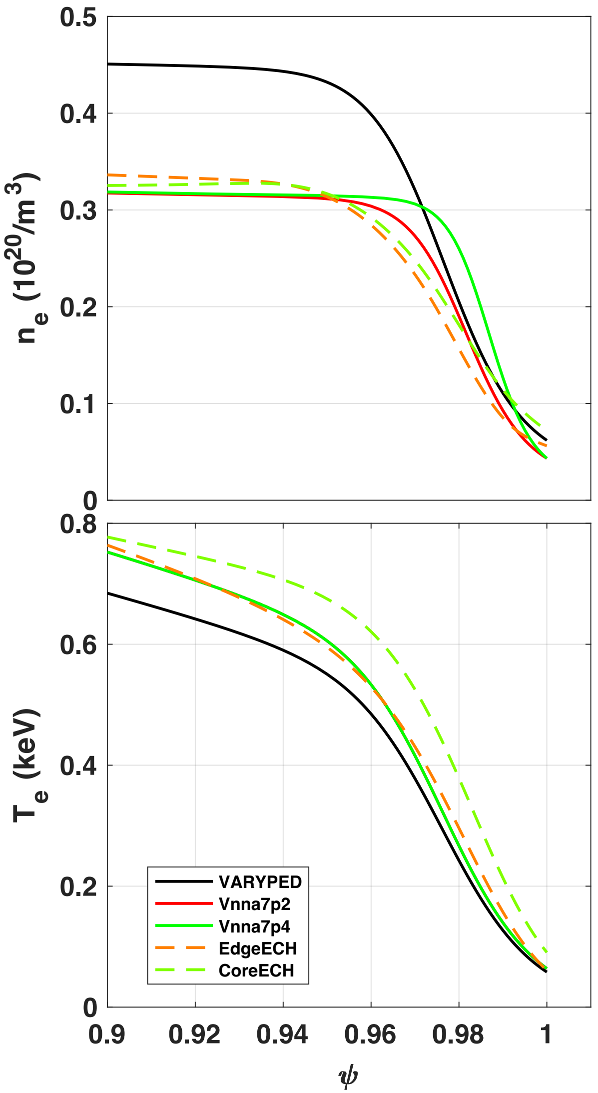




ne_ped & Te_ped scaled to Edge ECH case and then ne_wid scan shows increased decoupling

- ne_ped & Te_ped scaled to edge ECH case
- Then ne_wid scanned
- Decoupling again increases with steeper density pedestal as earlier





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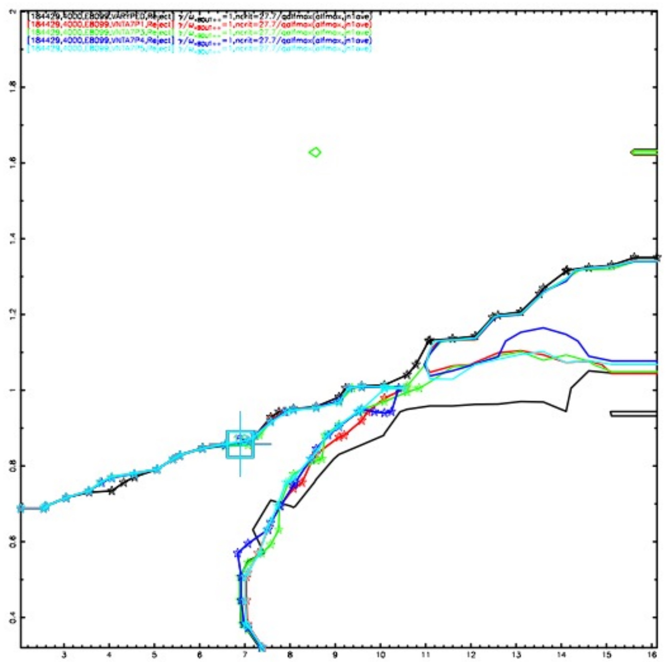
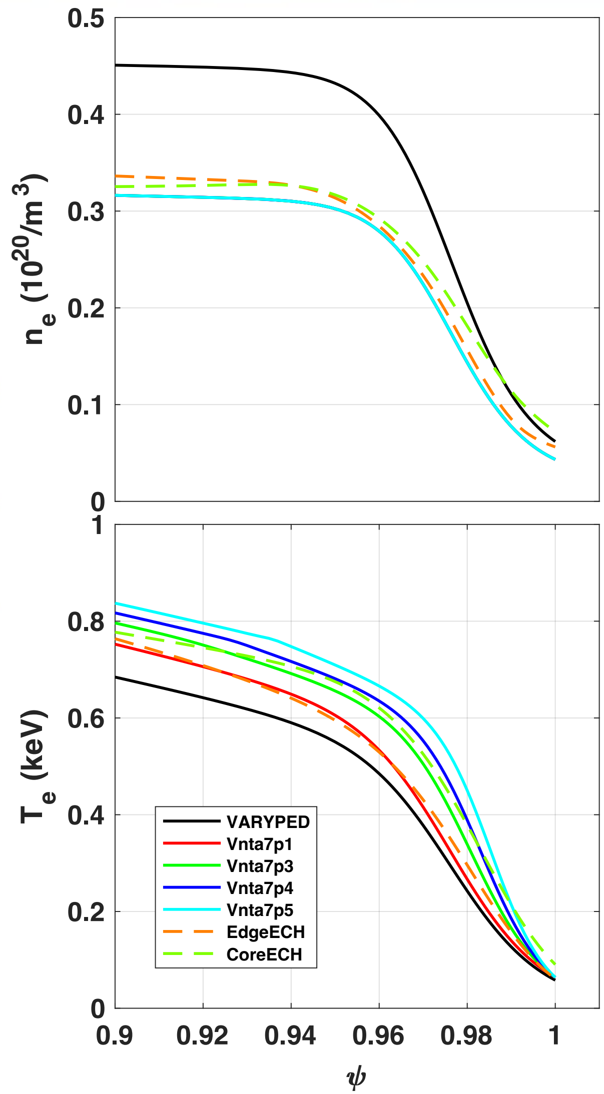
ne_ped & Te_ped scaled to edge ECH case and then Te_wid scan shows decrease in decoupling

- ne_ped & Te_ped scaled to edge ECH case
- Then Te_wid scan
- Decoupling decreases and peeling and ballooning limits tend to close off with steeper temperature pedestal
- Might be the case with core ECH



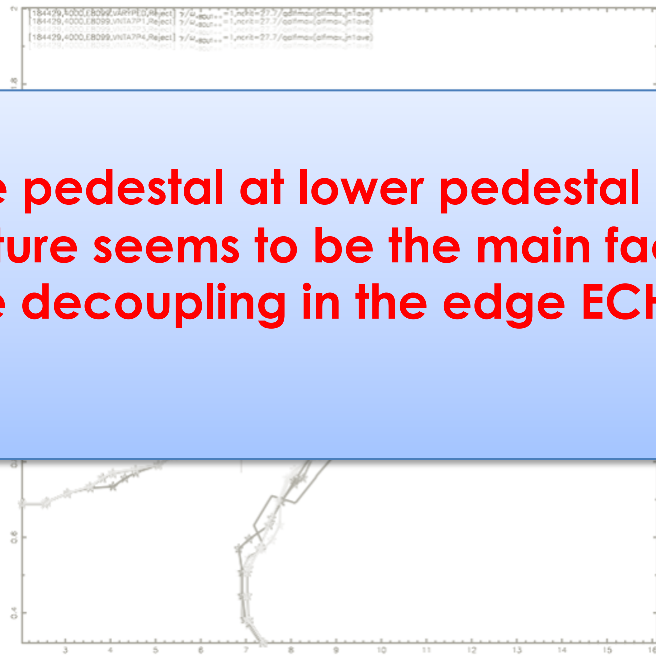


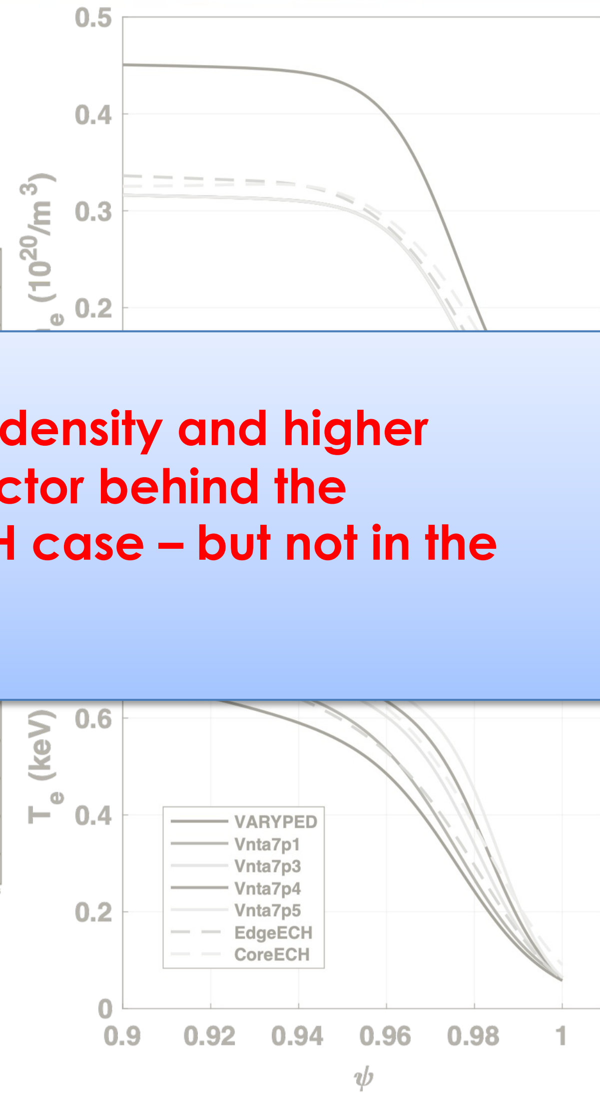
ne_ped & Te_ped scaled to edge ECH case and then Te_wid scan shows decrease in decoupling

- ne_ped & Te_ped scaled to edge ECH case
- Then Te_wid

temperature pedestal

- Might be the case with core ECH





Wider temperature pedestal at lower pedestal density and higher pedestal temperature seems to be the main factor behind the preservation of the decoupling in the edge ECH case – but not in the core ECH case

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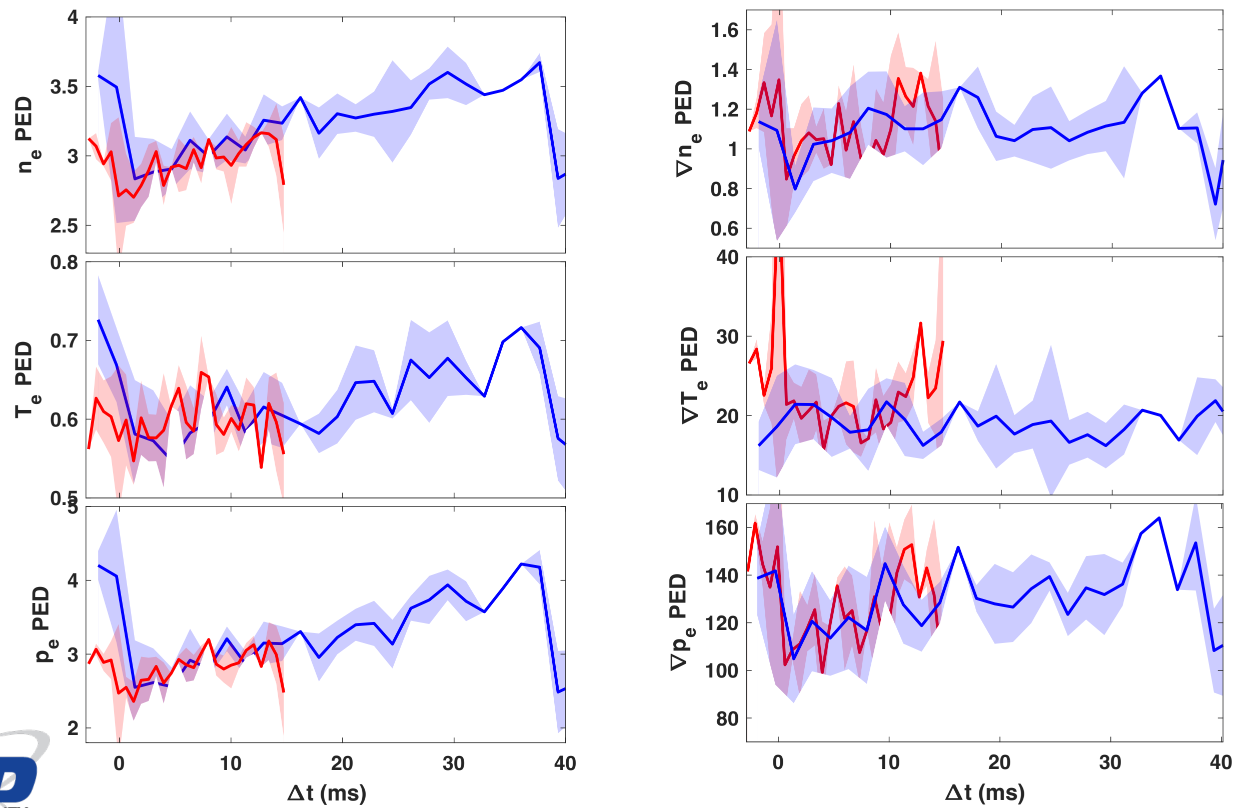
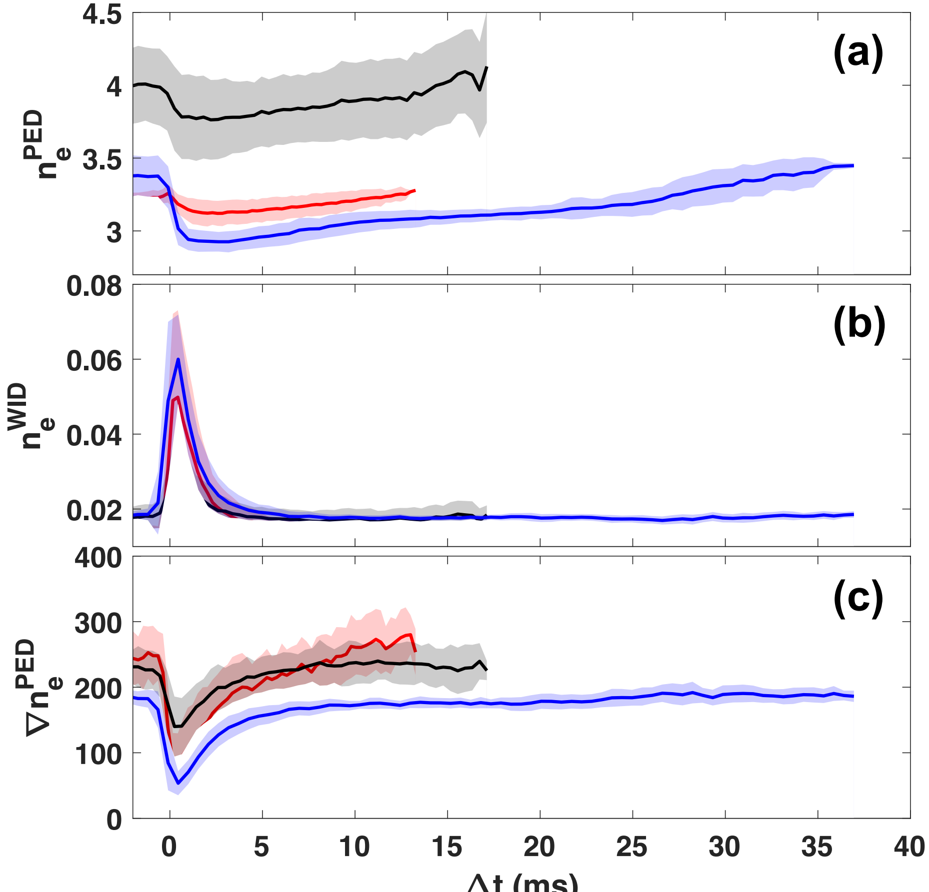
ELM-sync analysis shows faster pedestal recovery with core ECH

- Faster recovery of ne_ped in 184437 (red)
- Te_ped recovery follows ne_ped recovery in 184431 (edge ECH, blue); But for 184437 (cre ECH, red) Te_ped recovery is simultaneous or even faster
- pe_ped recovery reflects the differences in recovery of ne_ped and Te_ped for 184431 and 184437



Reflectometry – ELM synced showed similar behavior

- Pre-ELM ne_ped height is higher in the NBI discharge, but comparable for ECH cases
- Drop in density pedestal, following ELM event, higher in edge ECH case
- ne_ped and its gradient takes much longer time to recover in the edge ECH case



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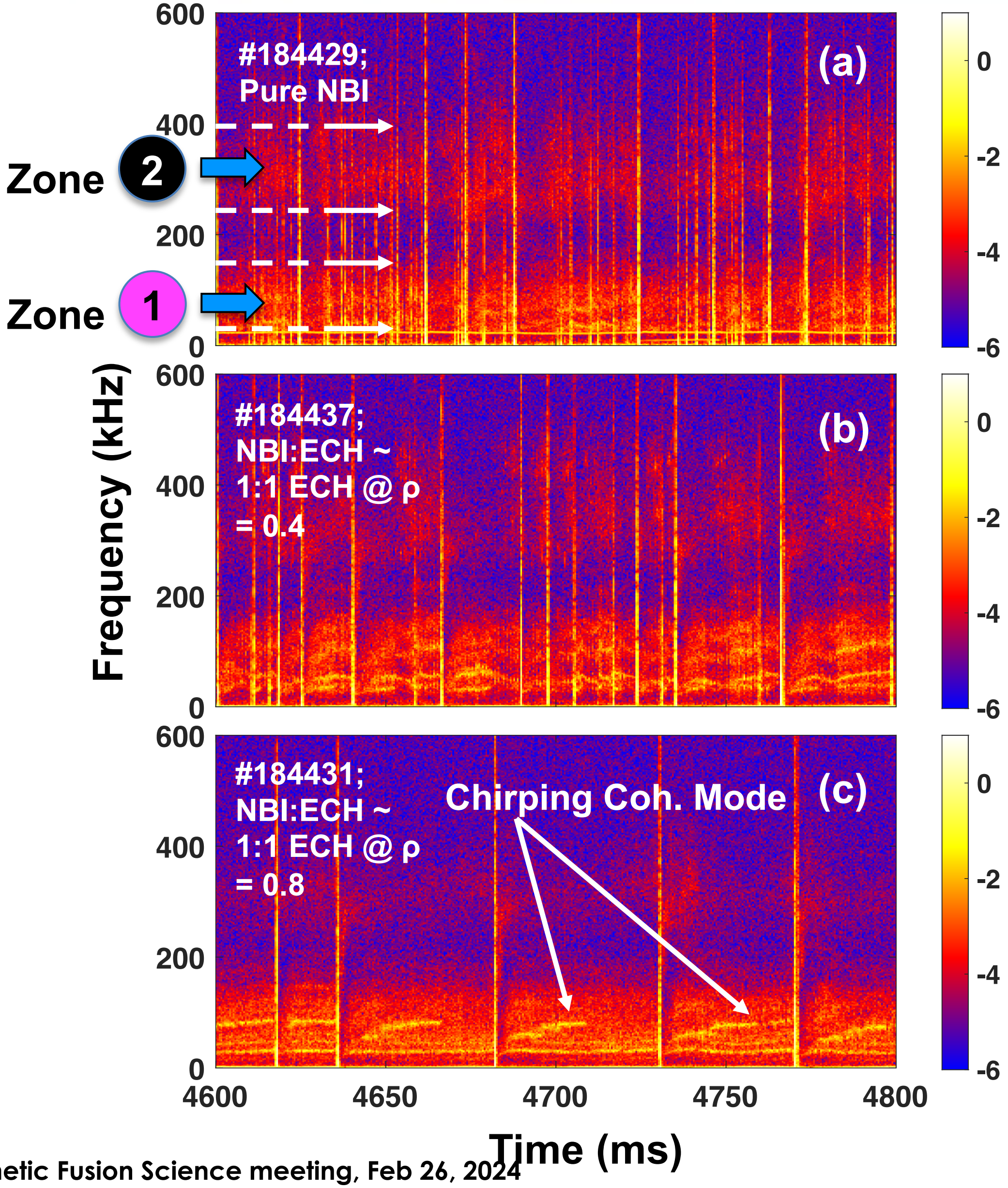
Variation in magnetic modes in different regimes

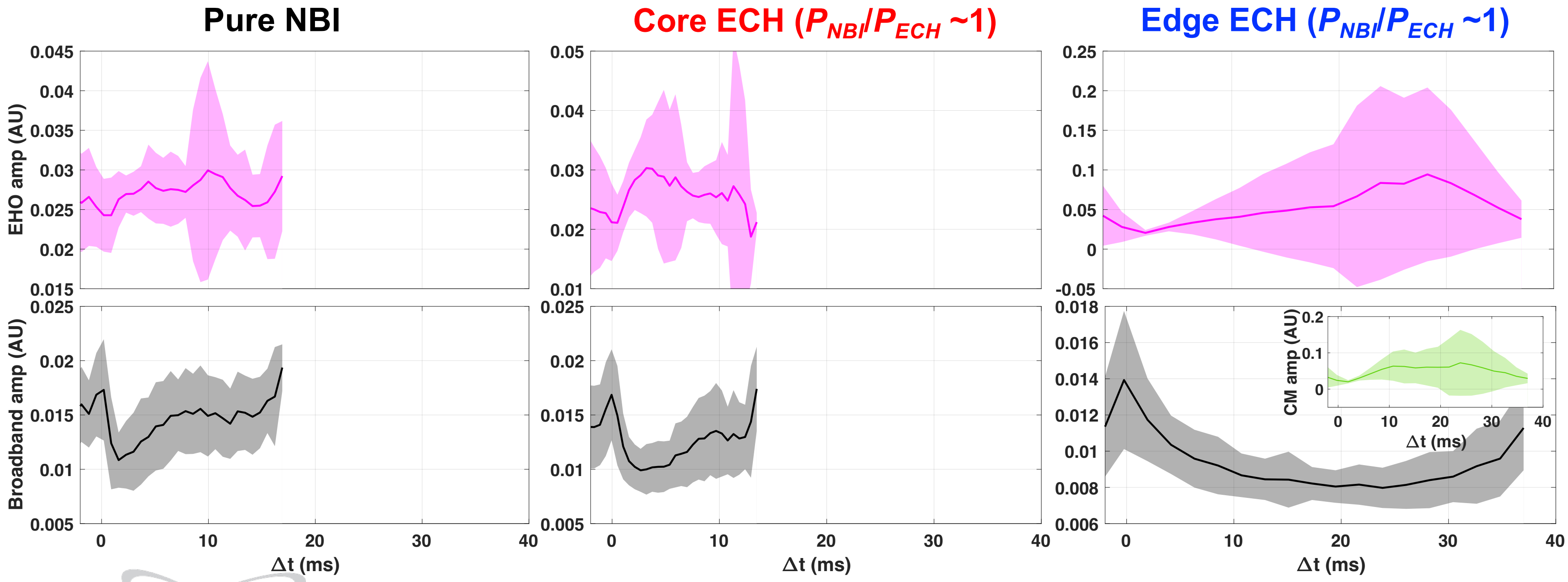
- Variation in both the high freq. (250-400 kHz) broadband activity and low freq. (<150 kHz) quasi-coherent modes
- Broadband activity goes weaker with ECH compared to pure NBI – transport 'fingerprint' implications?
- Low freq. quasi-coherent modes grows strongest when ECH at 0.8
- Also, a low frequency chirping coherent mode appears when ECH at 0.8

- High frequency broadband activity – MTM-like?
- Low frequency quasi-coherent modes – EHO-like?



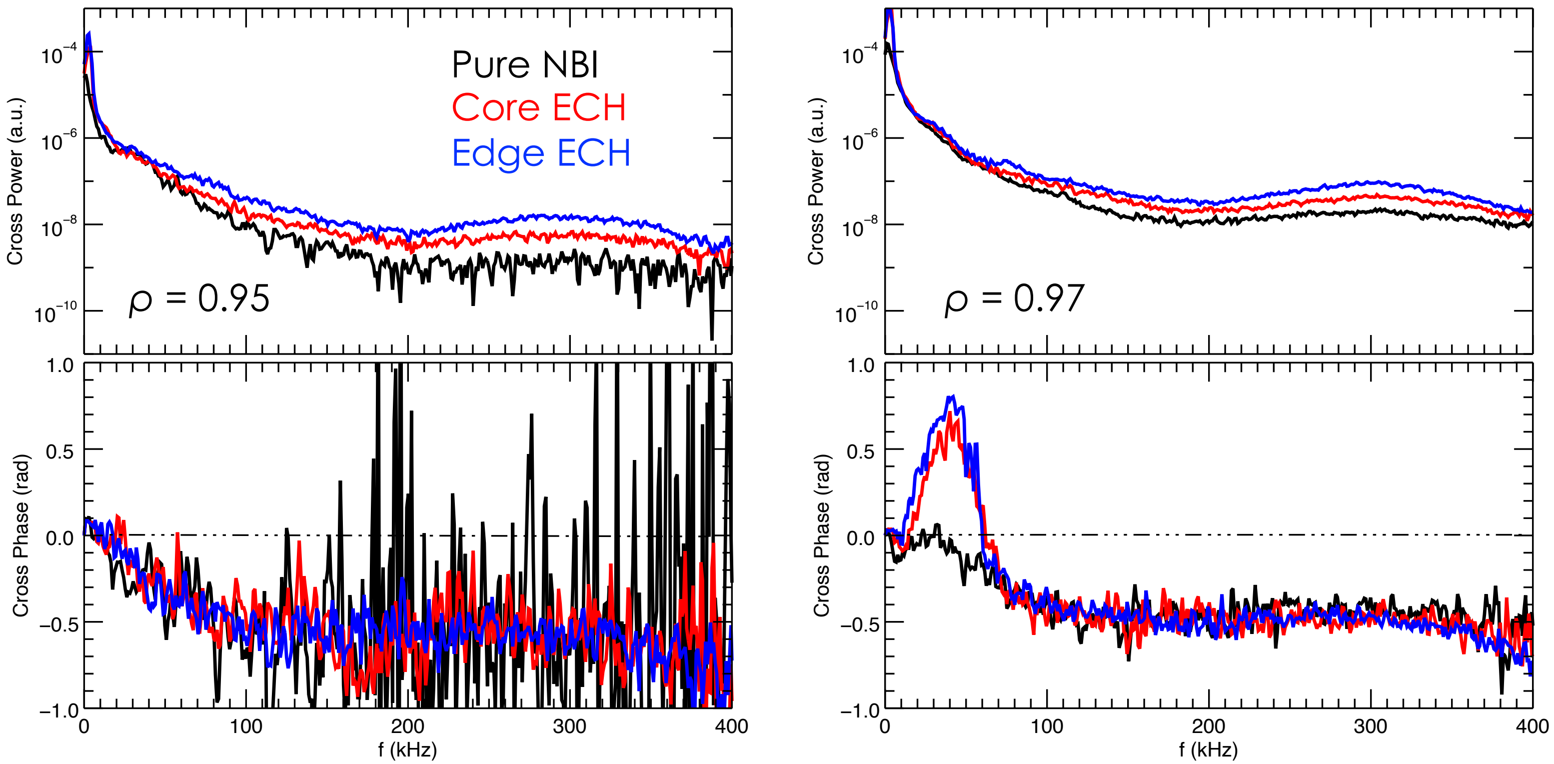
ELM-sync. analysis of mag modes show comp'tary behavior for EHO-like and Broadband modes

- Edge ECH case shows slower evolution of both EHO-like and broadband fluctuations
- If low freq. fluctuations are indeed EHO-like then mainly responsible for particle transport early on in the inter-ELM period
- If broadband fluctuations are indeed MTM-like: mainly heat transport – continues till the end of the ELM cycle

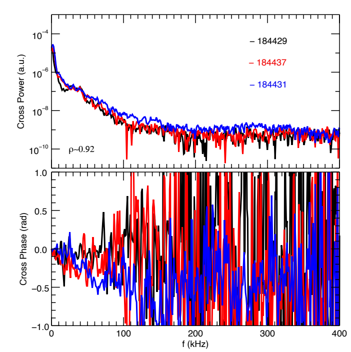


S. Banerjee/ NSTX-U/Magnetic Fusion Science meeting, Feb 26, 2024

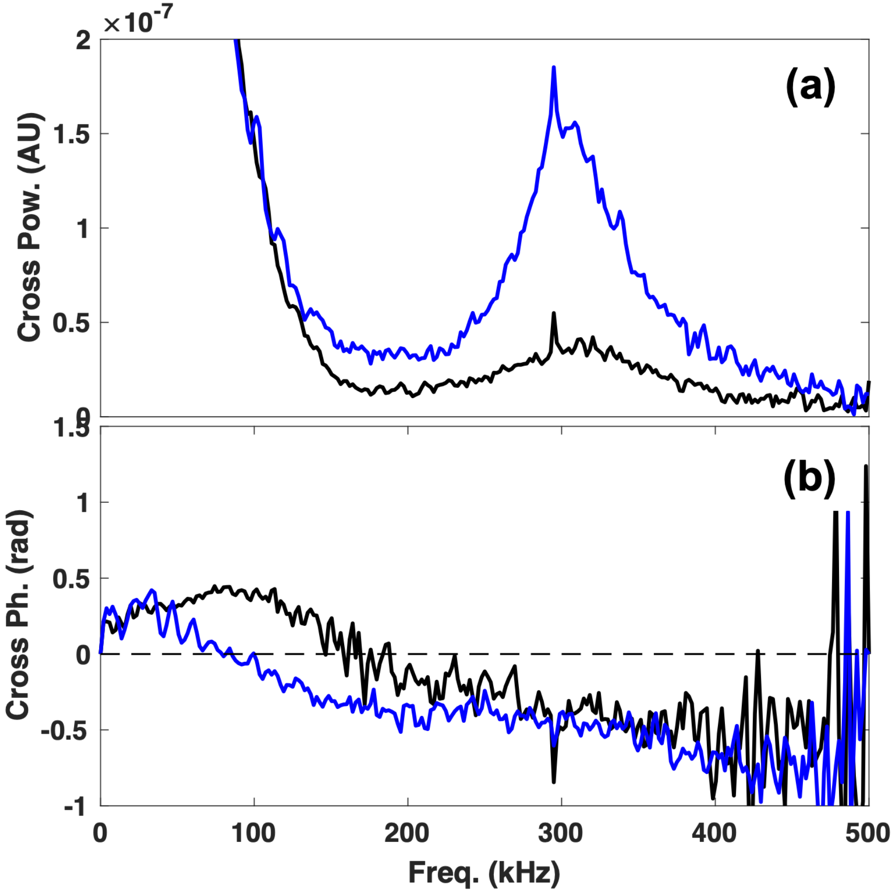
BES shows enhanced turbulence amplitude with ECH injection and dep. radius; Also, counter-prop. modes



- P_{NBI}/P_{ECH} ~ 2
- No BES data for these shots with P_{NBI}/P_{ECH} ~ 1
- We have another shot for pure NBI to P_{NBI}/P_{ECH} ~ 1 comparison

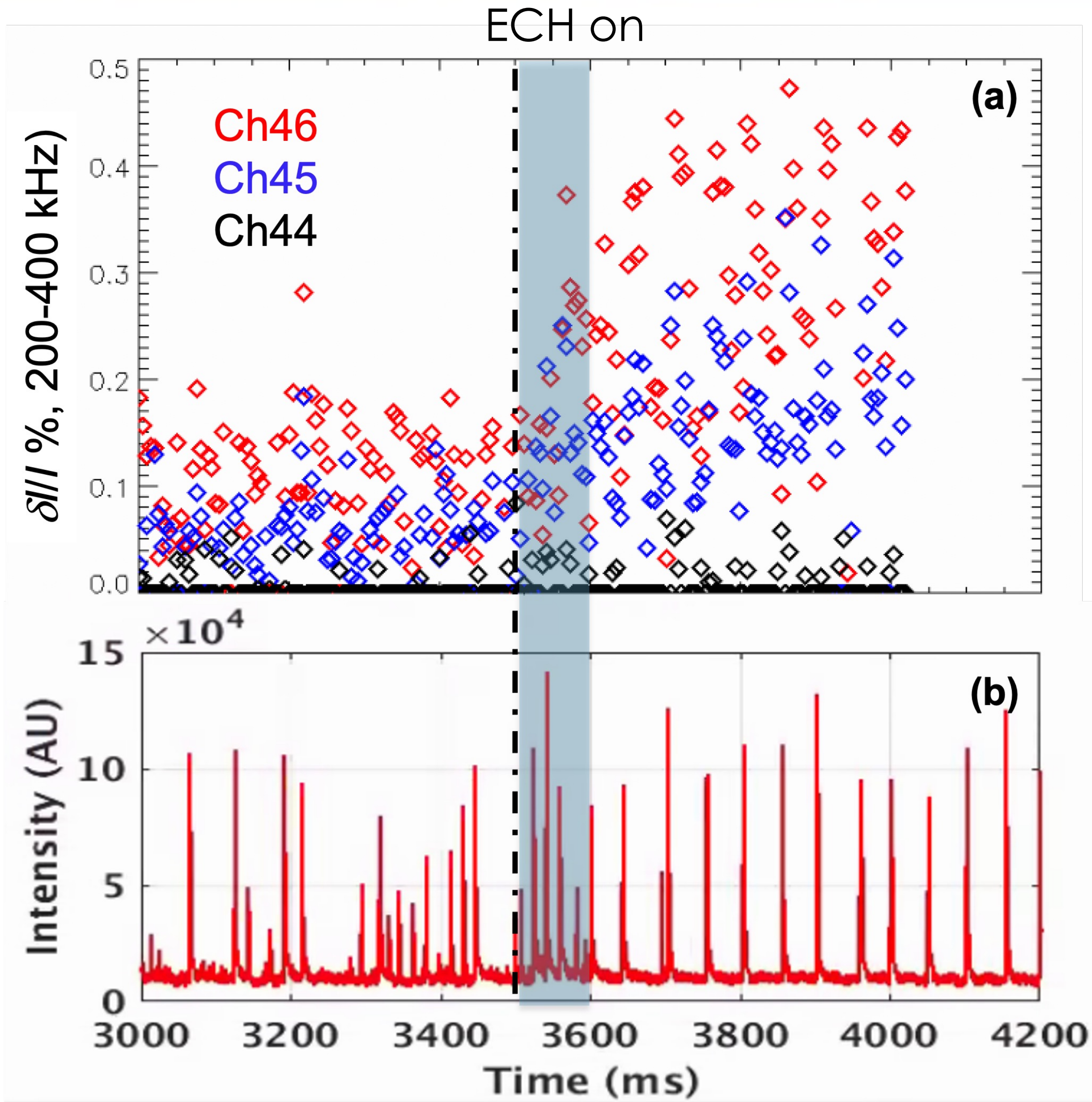


179494: BES shows enhanced electron direction mode with ECH at the edge and $P_{NBI}/P_{ECH} \sim 1$



BES shows enhanced turbulence amplitude with edge ECH; ~ 100ms delay after edge ECH to increase

- Relative density fluctuation amplitude (frequency integrated over 200-400kHz) increase after ECH is on
- The increase is only in the pedestal max gradient region
- ELM frequency does not drop immediately with ECH but only after the fluctuation amplitude reaches some threshold



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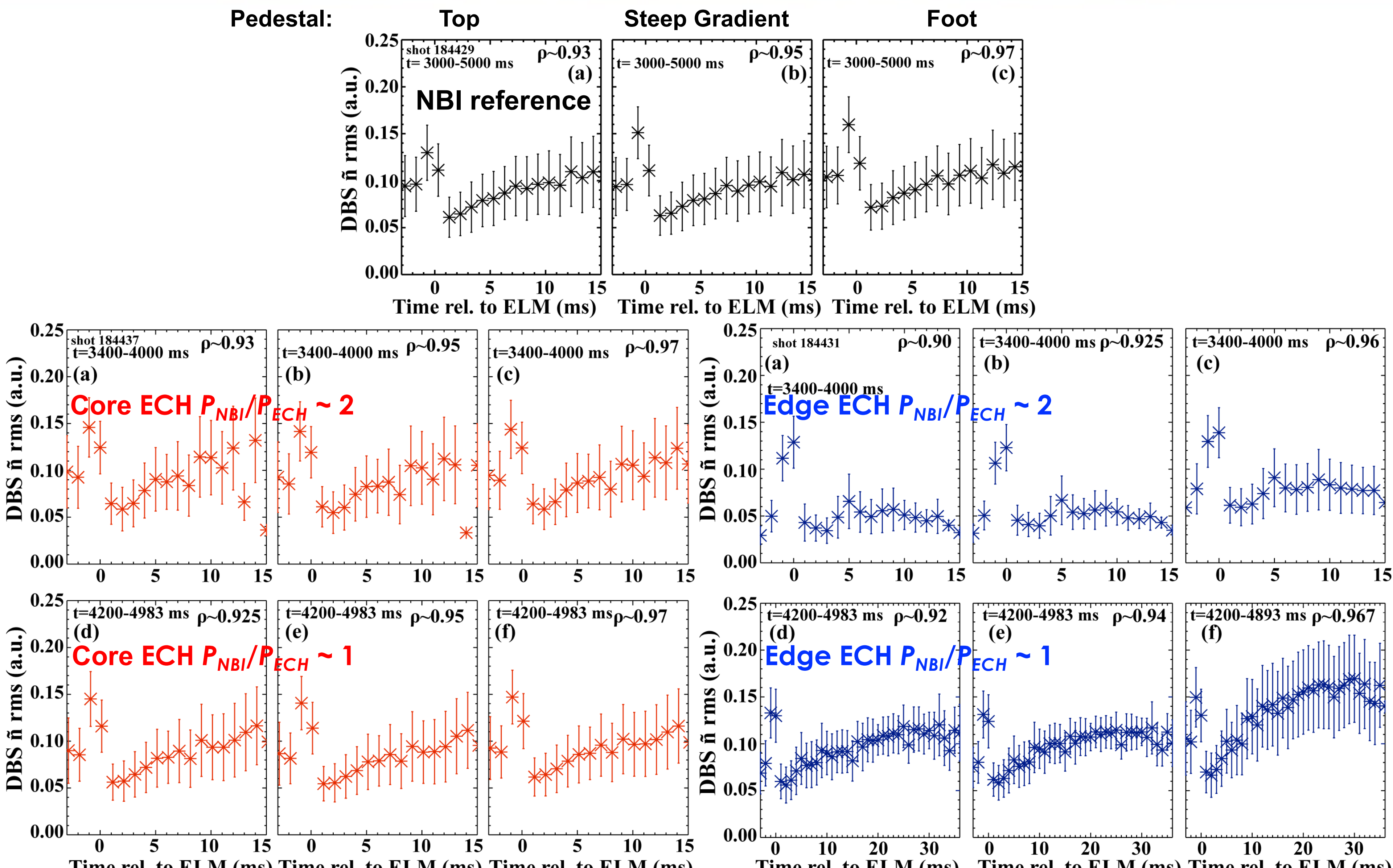
Doppler Backscattering shows significant increase in TEM-scale turbulence with P_{NBI}/P_{ECH} ~ 1 (@ ρ = 0.8)



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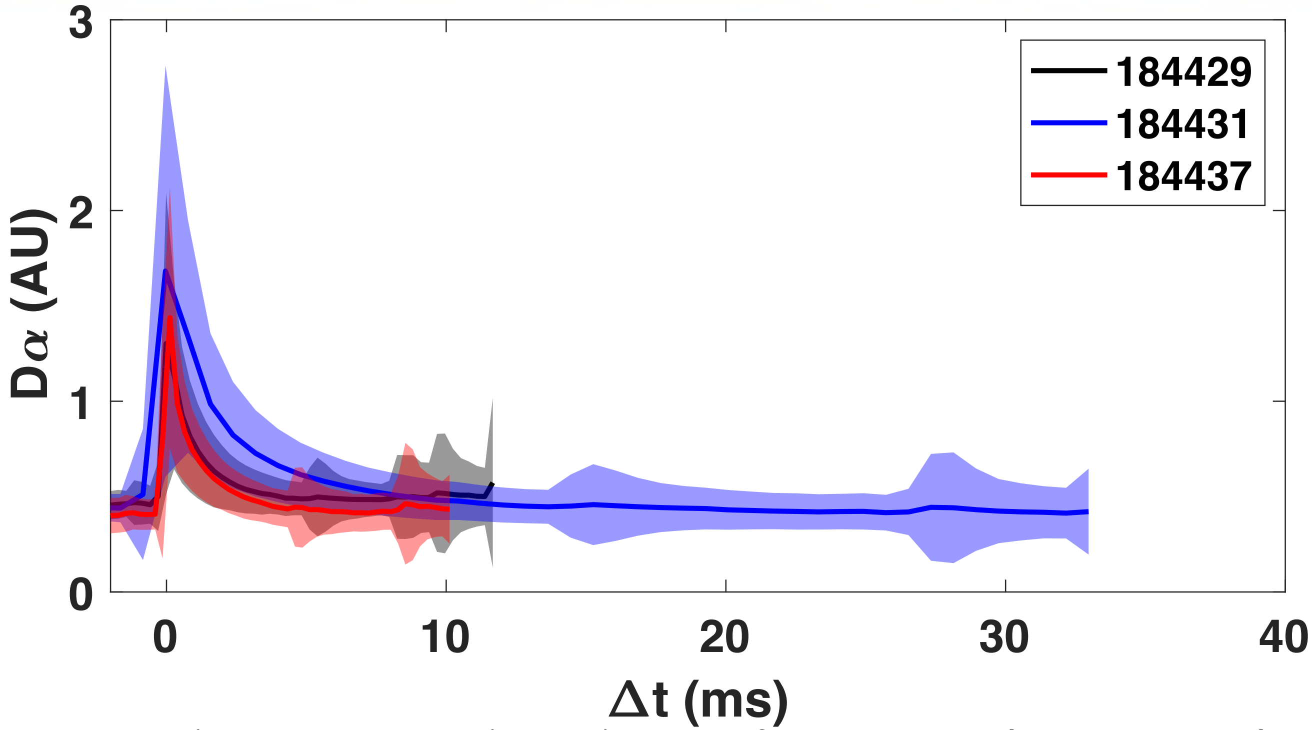
D_α baseline shows enhanced transport for edge ECH (1:1) case



- ELM-synchronized D_α Baseline highest for 184431 (edge ECH) and takes much longer to come down to pre-ELM value, while lowest for 184437 (core ECH)
- This could be indicative highest cross-field transport in the edge ECH case and lowest in core ECH – consistent with ELM frequency and pedestal recovery

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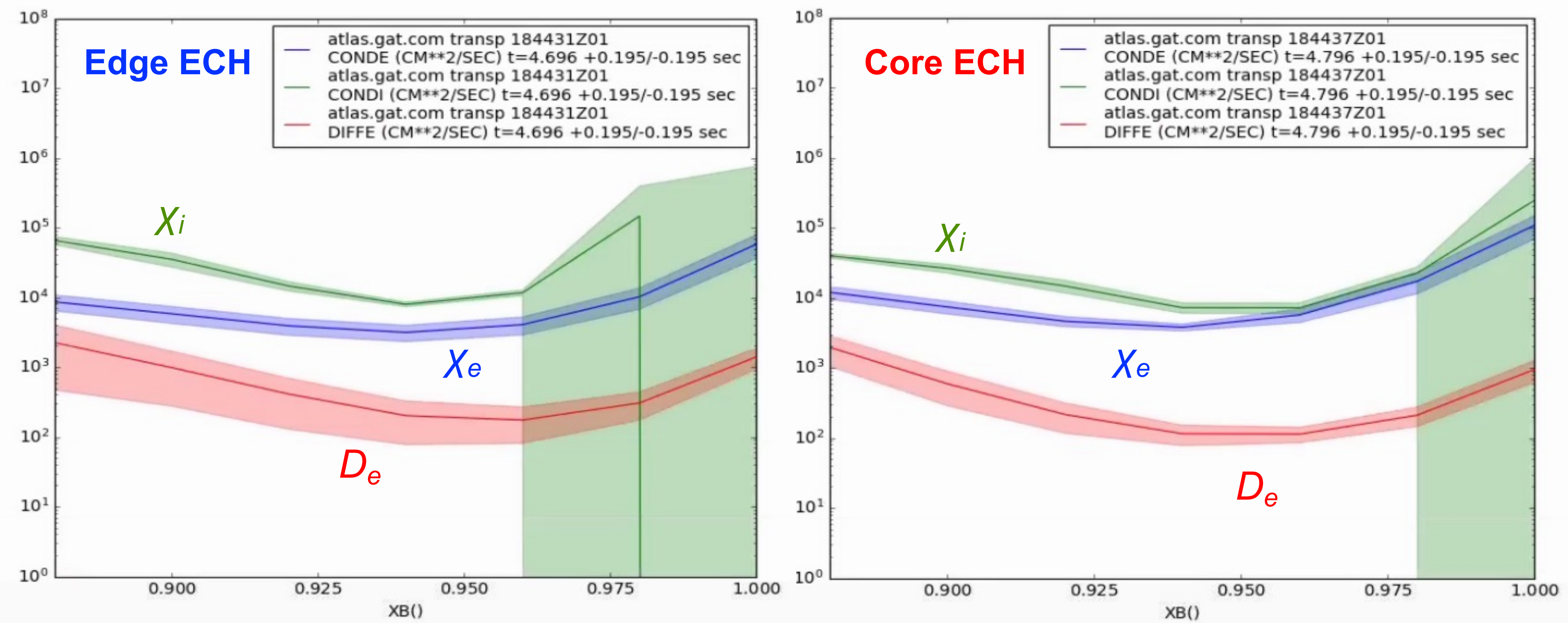
TRANSP – ITG/TEM as possible transport mechanisms

- TRANSP shows higher ion transport in the pedestal for the edge ECH case
- Electron transport is similar for both these cases
- χ_i is always higher than or equal to χ_e, hence ETG and/or MTM might not be the major heat transport mechanisms (ref. ‘transport fingerprints’)
- $D_e << \chi_e$ and $\chi_i >= \chi_e$ in the pedestal, hence both ITG/TEM are possibilities in the pedestal for both these discharges.

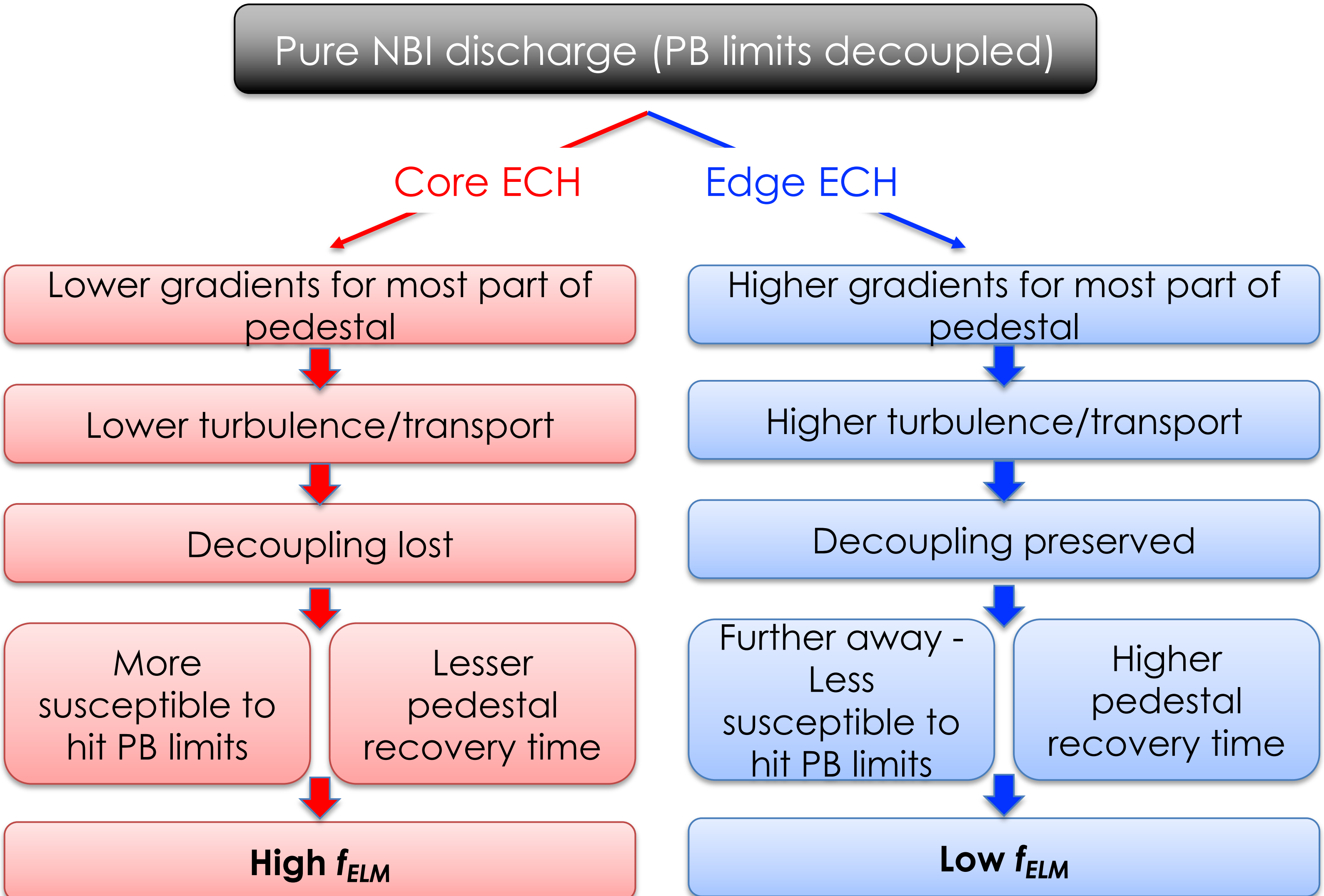


Summary

- 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 $\rho = 0.4$
- But ELM frequency reduced by ~50% when 1:1 heating mix ratio is applied with the ECH deposition at $\rho = 0.8$
- Pedestal width increases when ELM frequency is reduced
- Decoupling of peeling and ballooning boundaries are preserved from the pure NBI case in the edge ECH $P_{NBI}/P_{ECH} \sim 1$ case
- Increased TEM-scale turbulence with edge ECH ($P_{NBI}/P_{ECH} \sim 1$ case) observed in DBS
  - conforming with the reduced ELM frequency
- BES shows growth of a ~ 300 kHz mode propagating in electron direction, with ECH
  - mode is strongest when ELM frequency reduced (edge ECH $P_{NBI}/P_{ECH} \sim 1$ case)
  - Also, an ion direction mode evolves at the pedestal top

- Increased turbulence could be instrumental in preserving the stability boundary decoupling from the pure NBI to the edge ECH $P_{NBI}/P_{ECH} \sim 1$ case
- Hence, increased turbulence driven transport could also be reason for slower inter-ELM pedestal recovery and reduced f_{ELM} in the edge ECH $P_{NBI}/P_{ECH} \sim 1$ case

Summary


Pure NBI discharge (PB limits decoupled)
Core ECH
Edge ECH
Lower gradients for most part of pedestal
Lower turbulence/transport
Decoupling lost
More susceptible to hit PB limits
Lesser pedestal recovery time
High f_{ELM}
Higher gradients for most part of pedestal
Higher turbulence/transport
Decoupling preserved
Further away - Less susceptible to hit PB limits
Higher pedestal recovery time
Low f_{ELM}

Backups

- What does this mean during the ELITE run:

PROCESS ELITE_1628 WITH PID 30729 ON localhost CLUSTER iris PARTITION preemptable RECEIVED SIGKILL 143. RESTARTING AFTER 30 s

184429 scans

VARYPED: Original; varyped184429_4000_e8099_VARYPED - /fusion/projects/xpsi/pedelm/banerjees/

VNES0P1 – ne_shift = 0.01 - /fusion/projects/xpsi/pedelm/banerjees/

VNES0P3 – ne_shift = 0.03 - /cscratch/banerjees *

VNTA7P2 – ne_shift = 0.01, scale_den = 0.7, scale_temp = 1.2 - /cscratch/banerjees *

VTES0P2 – te_shift = 0.02 - /cscratch/banerjees *

VTES0P4 – te_shift = 0.04 - /cscratch/banerjees *

VNTA7P1 – ne_shift = 0, scale_den = 0.7, scale_temp = 1.1, te_shift = 0 - /cscratch/banerjees *

VNTA7P3 – ne_shift = 0, scale_den = 0.7, scale_temp = 1.1, te_shift = 0.02 - /cscratch/banerjees *

VNTA7P4 – ne_shift = 0, scale_den = 0.7, scale_temp = 1.1, te_shift = 0.03 - /cscratch/banerjees *

VNTA7P5 – ne_shift = 0, scale_den = 0.7, scale_temp = 1.1, te_shift = 0.04 - /cscratch/banerjees *

VNNA7P2 – ne_shift = 0.02, scale_den = 0.7, scale_temp = 1.1, te_shift = 0 - /cscratch/banerjees *

VNNA7P4 – ne_shift = 0.04, scale_den = 0.7, scale_temp = 1.1, te_shift = 0 - /cscratch/banerjees *

184431 scans

varyped184431_3700_e8099_VARYPED - /fusion/projects/xpsi/pedelm/banerjees

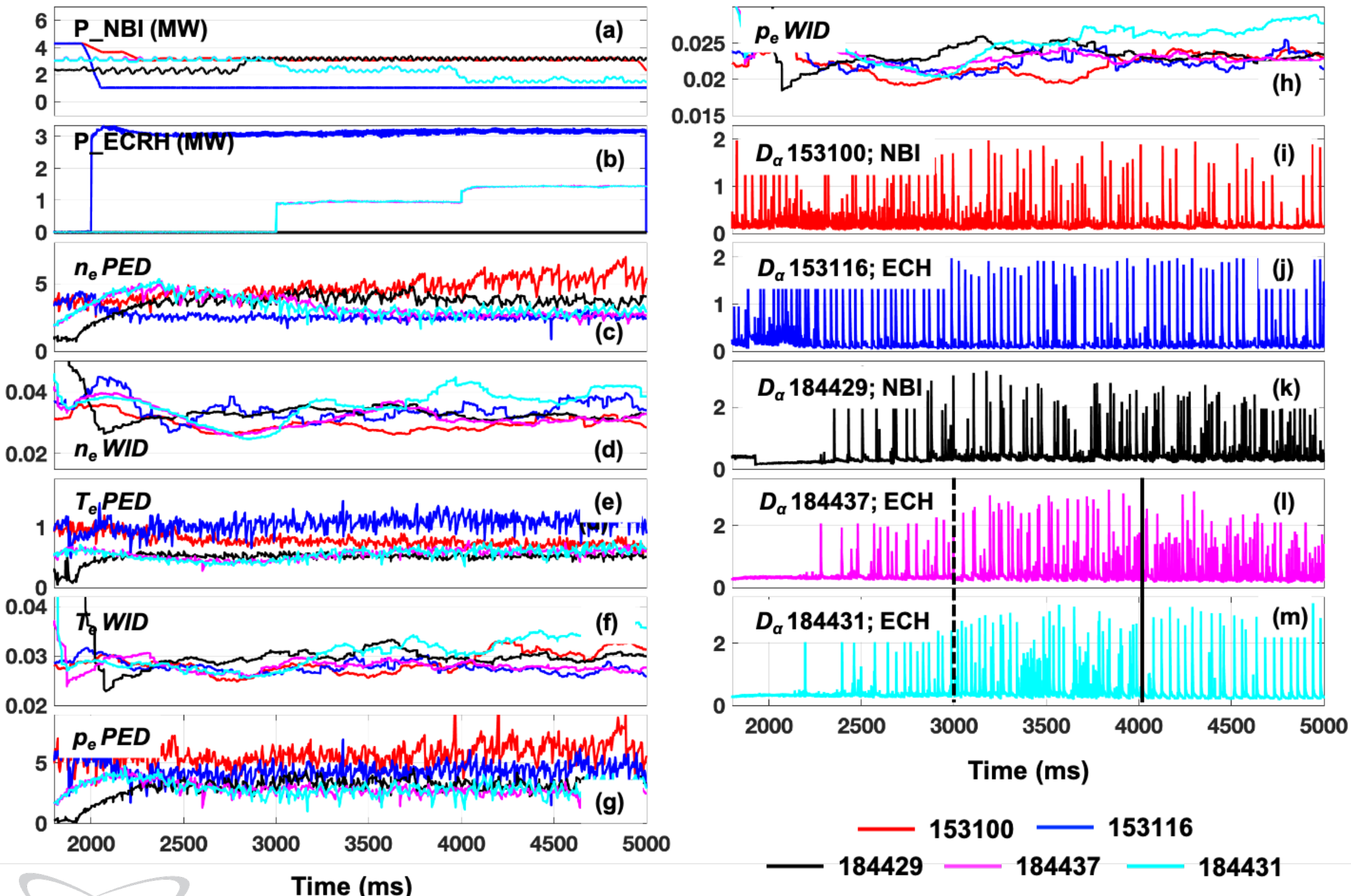
varyped184431_4600_e8099_VARYPED - /fusion/projects/xpsi/pedelm/banerjees

184431 scans

varyped184437_3700_e8099_VARYPED - /fusion/projects/xpsi/pedelm/banerjees

varyped184437_4600_e8099_VARYPED - /fusion/projects/xpsi/pedelm/banerjees

n_e, T_e and p_e at pedestal vary as per heating; pedestal width increases significantly with f_{ELM} drop



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S. Banerjee/ NSTX-U/Magnetic Fusion Science meeting, Feb 26, 2024