Suppression of Toroidal Alfvén Eigenmodes by the Electron Cyclotron Current Drive in KSTAR Plasmas

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P1-2

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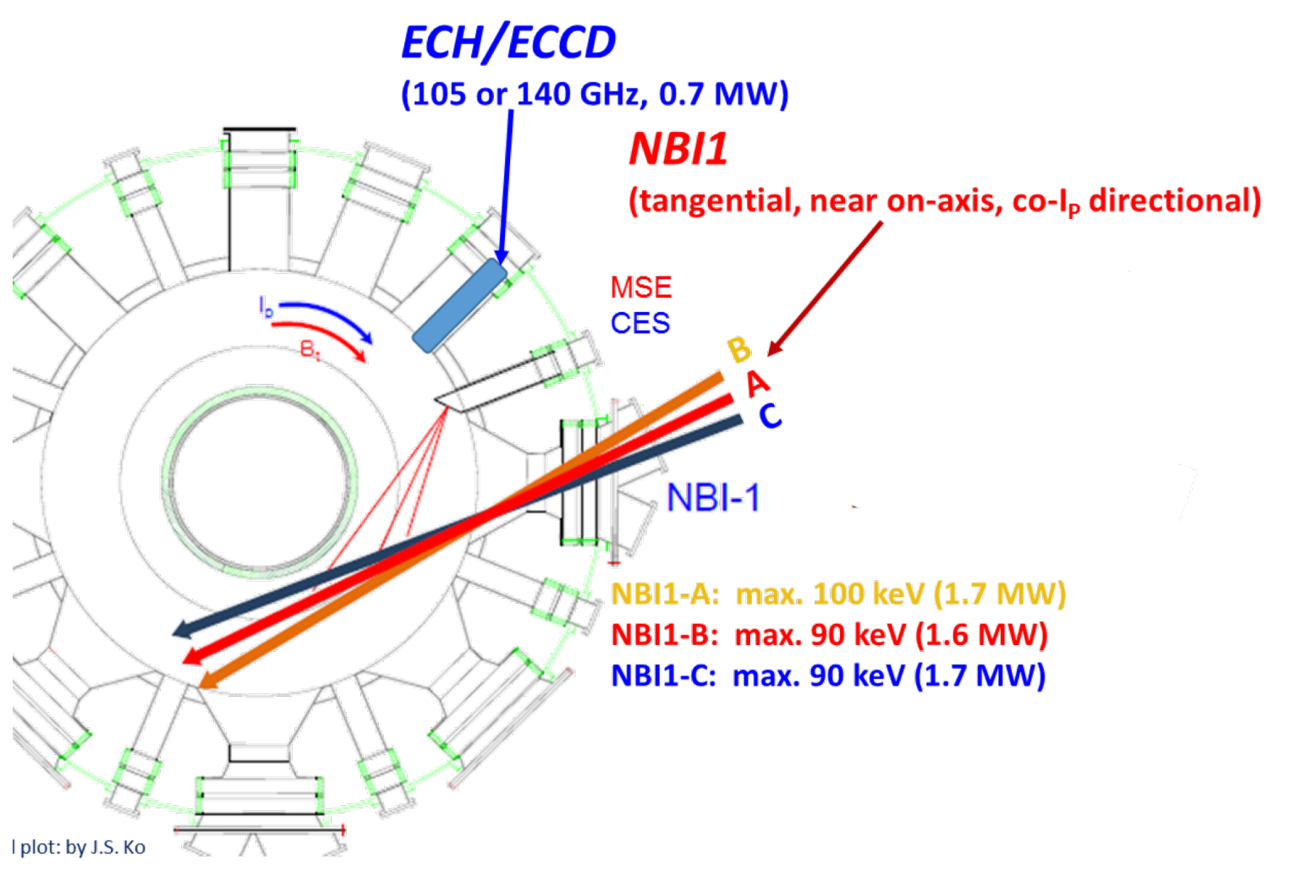
Introduction

1. Motivation:

- **Alfvén eigenmodes (AE) in the high-performance discharges lead to**
  - **I. Redistribution of core fast-ion pressure → Degradation of fusion yield**
  - **II. Fast-ion loss → Damage on the first-wall**
- ***Need of AE mitigation to avoid performance degradation[1,2] in the KSTAR advanced scenarios.***

2. Experimental Observations:

- **Experimental observations have drawn the attention to significant enhancement of performance in high β_P discharges.**
- **Off-axis co-ECCD applications in the high q_{min} (or q_0) scenario show TAE mitigation (for several tens of τ_E), resulting in fast-ion confinement enhancement**
- **Mechanism of AE mitigation (Alfven gap movement and shrink)**
- **Diagnostics and Modelling: Comparison with the ECE signal (coherence), Alfven continuum/gap (NOVA-k), Change in fast-ion pressure profile, NBCD, …**

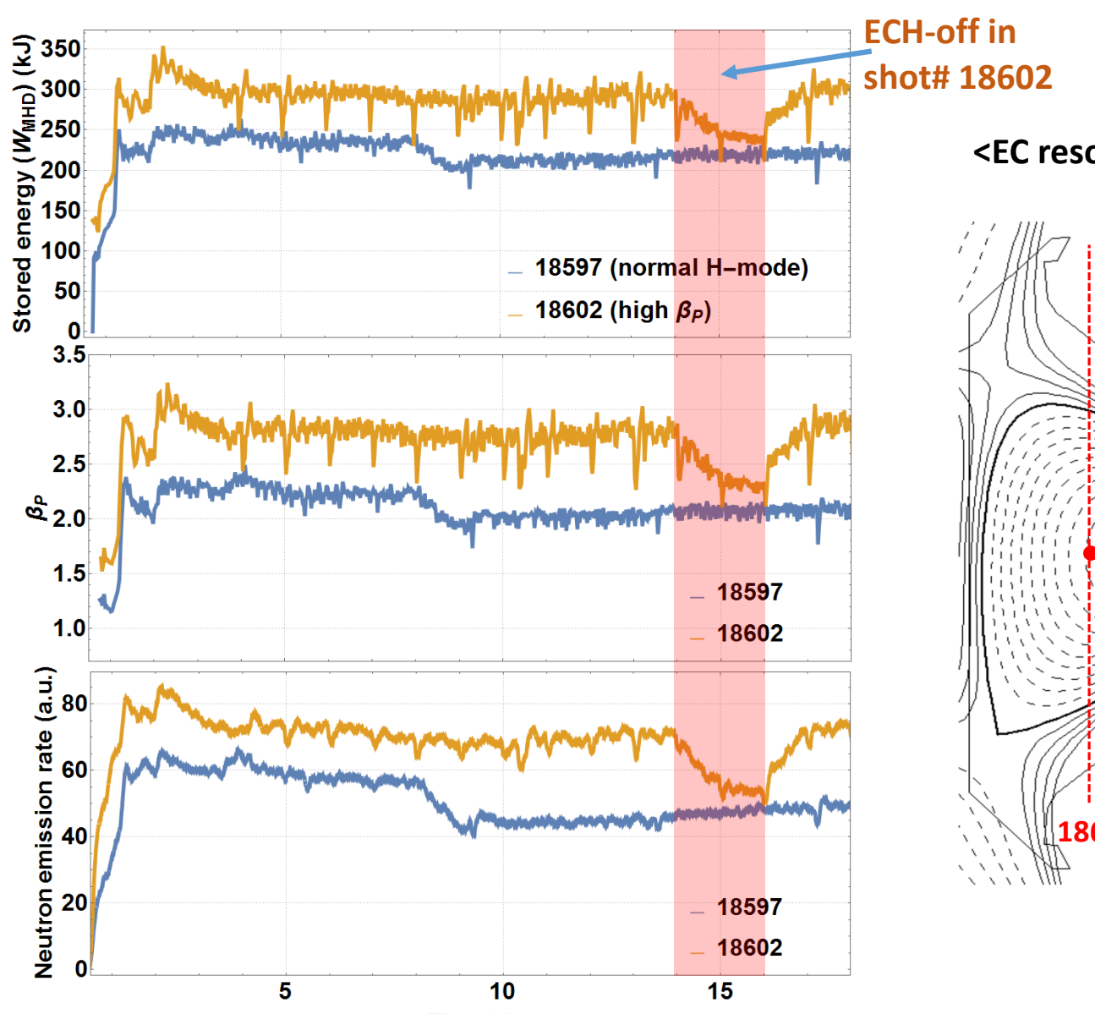


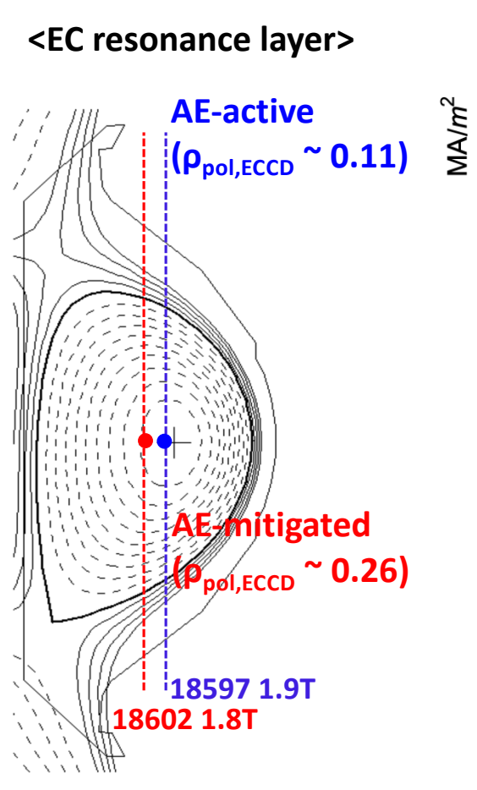
l plot: by J.S. Ko

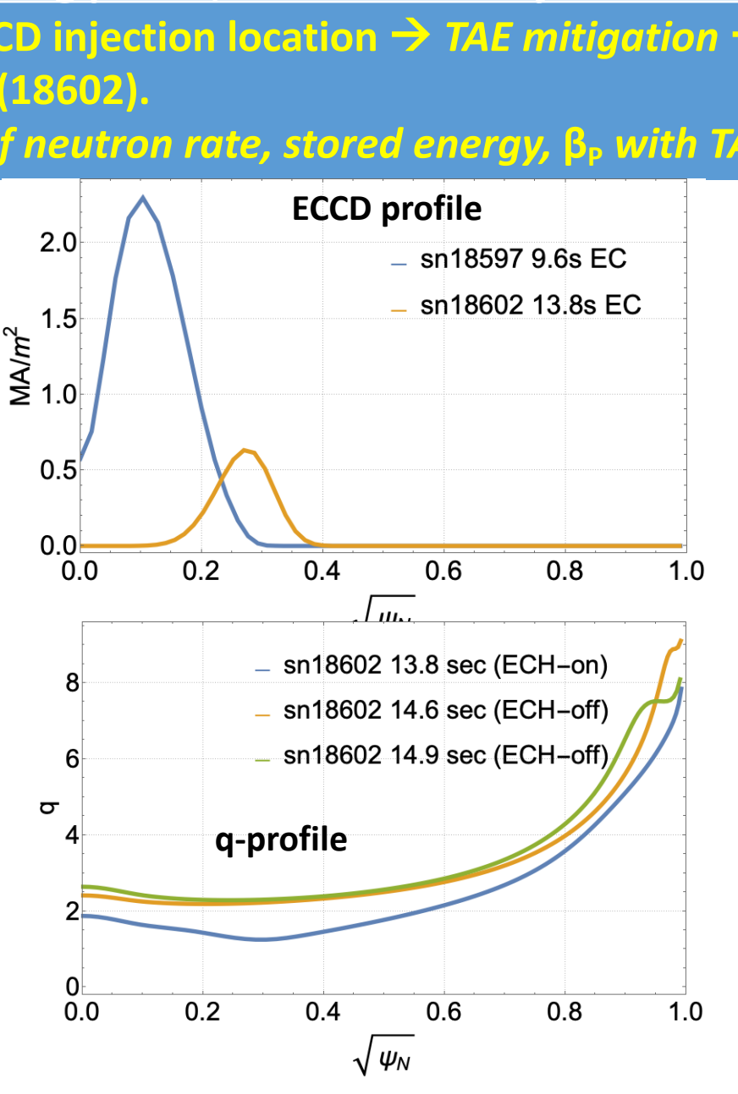
1. Difference in performance of high β_P long-pulse discharges by changing ECCD deposition location[3,4]

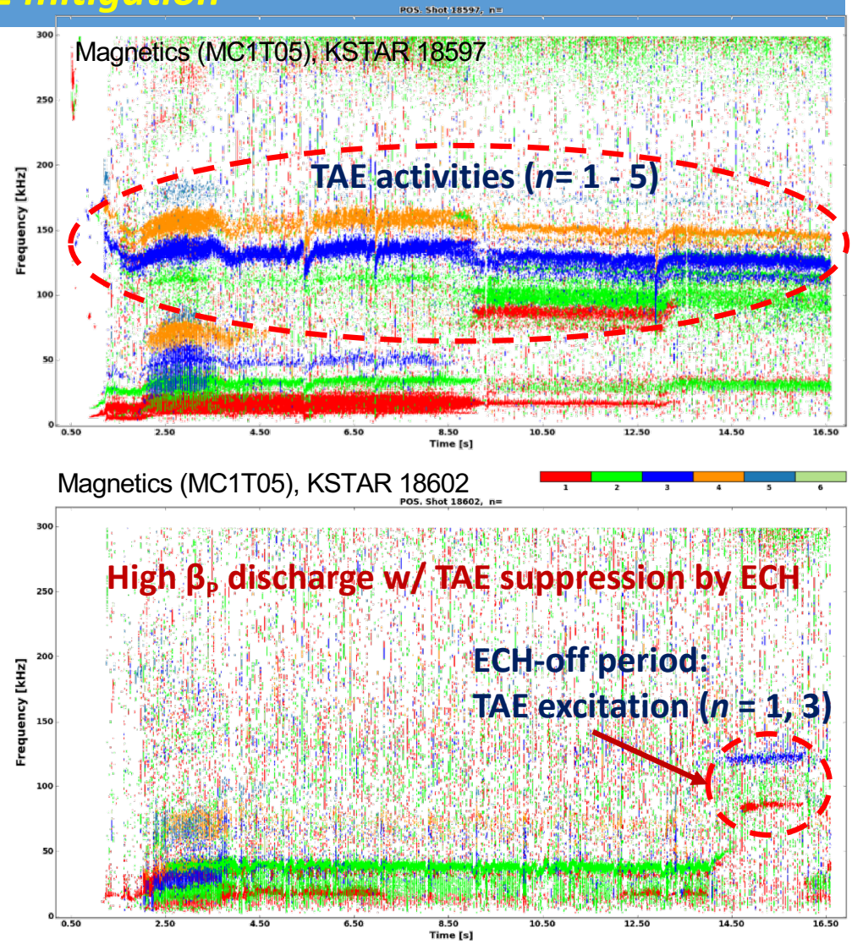
B_{T0} = 1.9T (18597), 1.8 T (18602), I_P = 0.4 MA
NBI1-A/B/C = 100/70/70 keV (3.8 MW),
P_{EC} = 0.7 MW (105 GHz, Z_{EC} ~ 0cm)

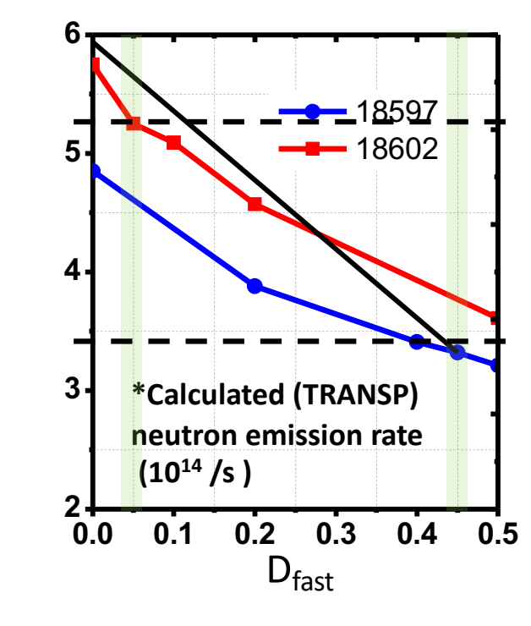
- **Same heating power, but different injection location of ECCD**
- **Proper ECCD injection location → *TAE mitigation* → achievement of steady-state high β_P (~ 3.0) discharge (18602).**
- ***Increase of neutron rate, stored energy, β_P with TAE mitigation***





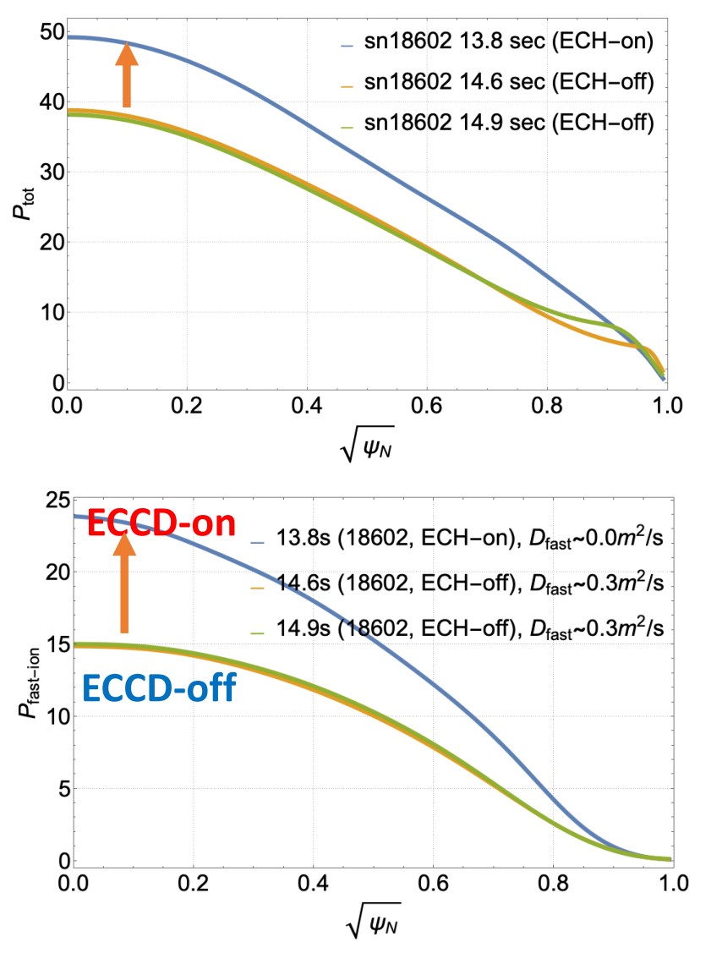


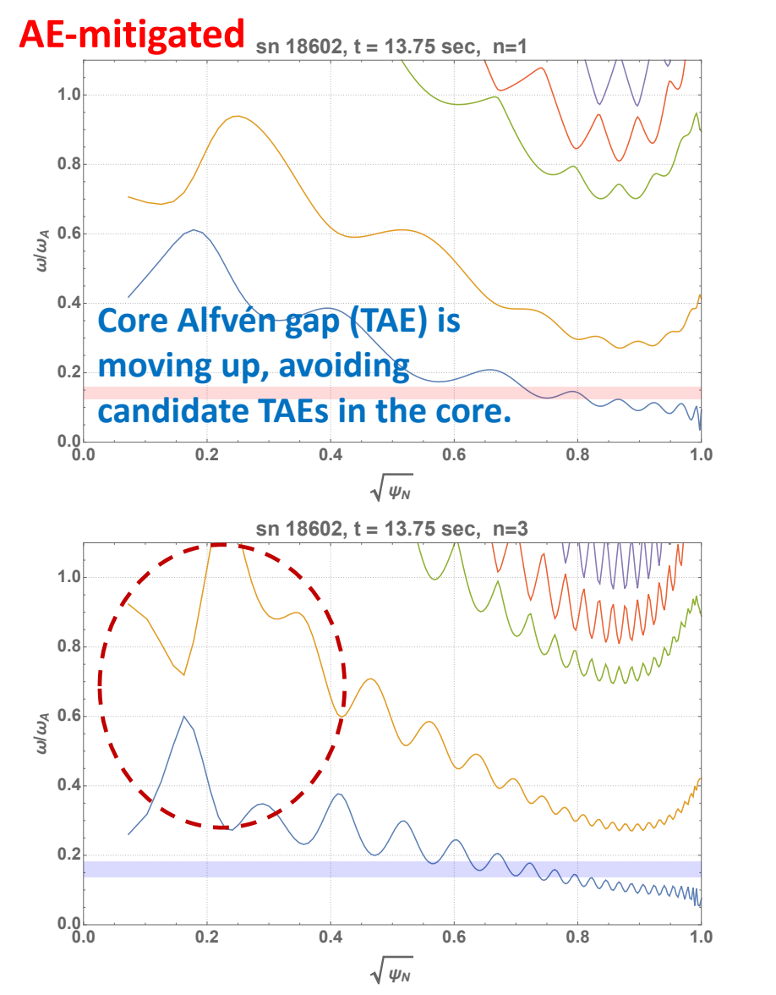




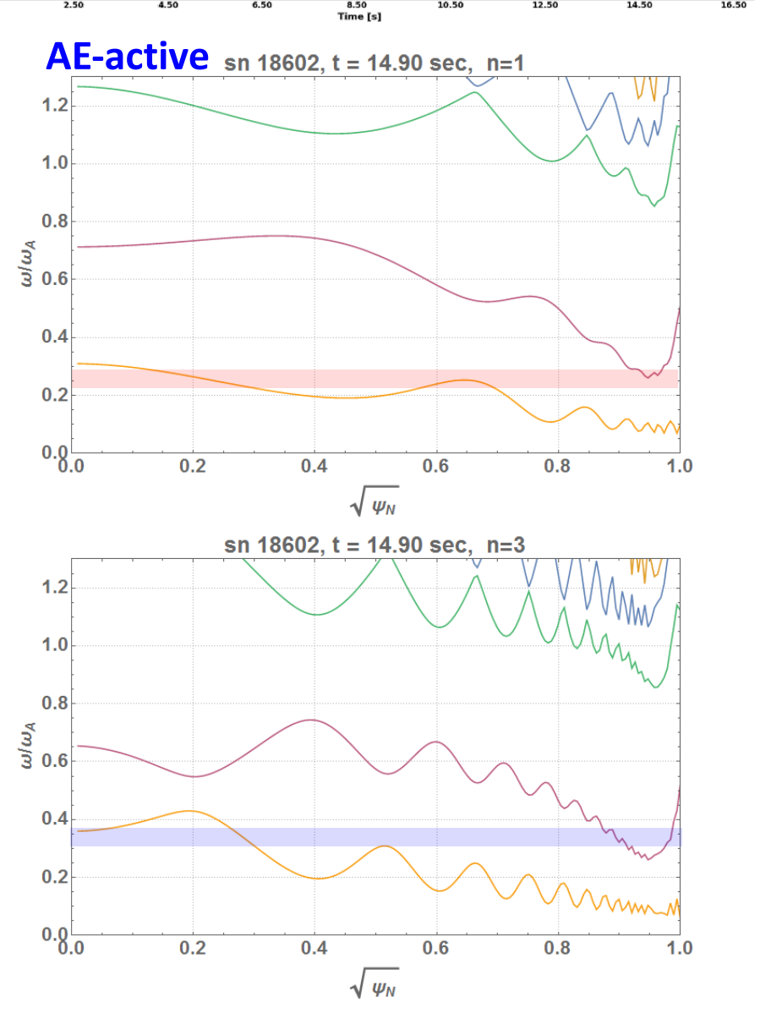
Ad-hoc D_{fast} estimation:
Total thermal energy and fast ion energy is equal to the total energy estimated from the EFIT, and the D_{fast} value is estimated.

$$W_{total} \equiv W_{thermal} + W_{fast}(D_{fast})$$



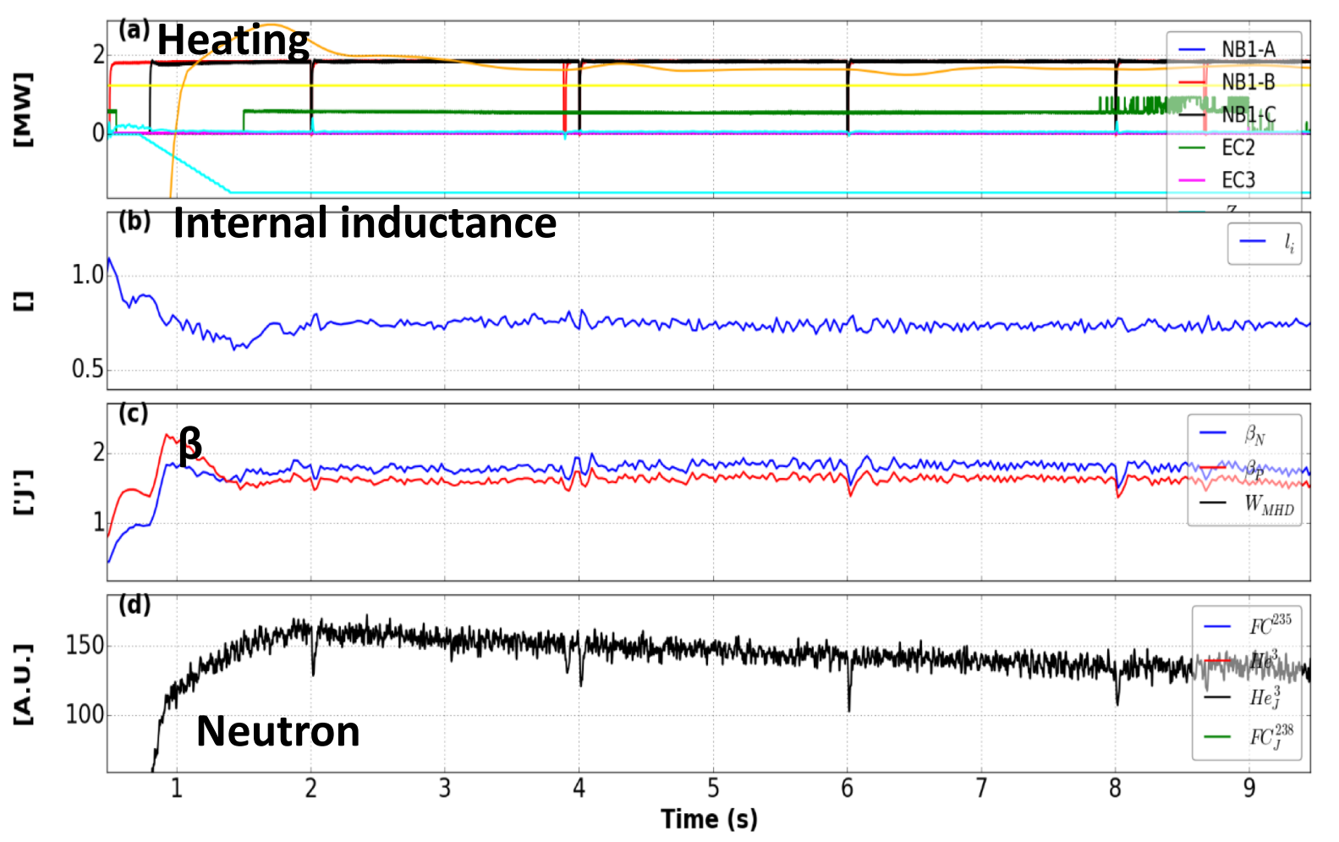


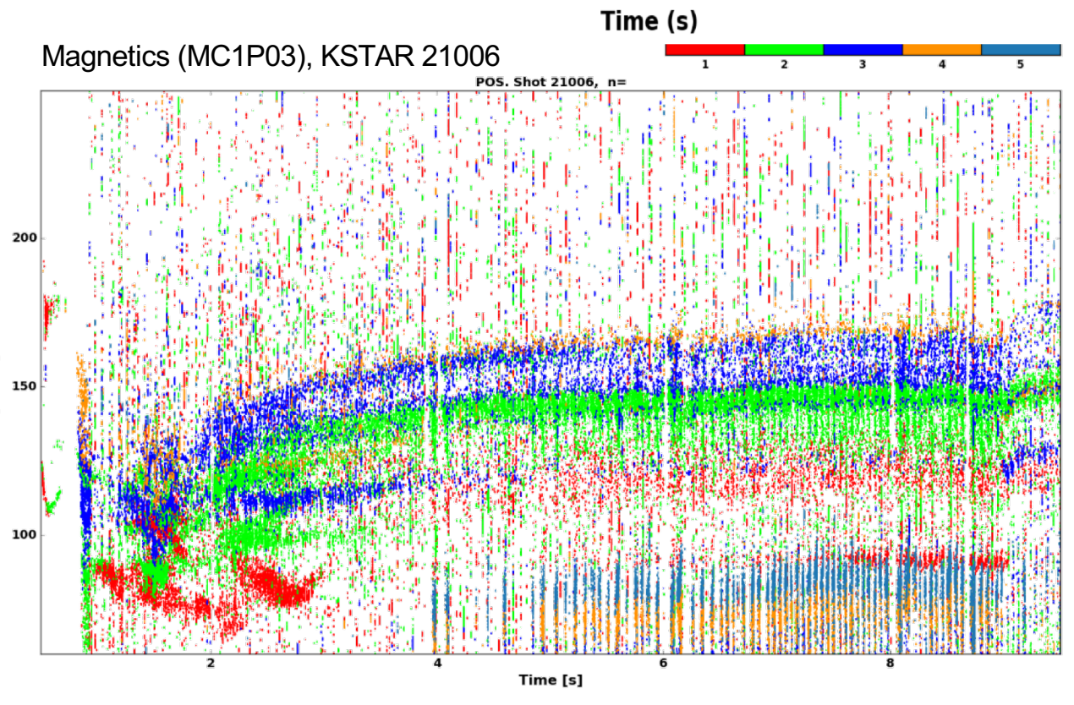
Alfvén gap is wide in the core due to weakly reversed-shear (ECCD) q-profile, but gap location is higher than normal TAE frequency.

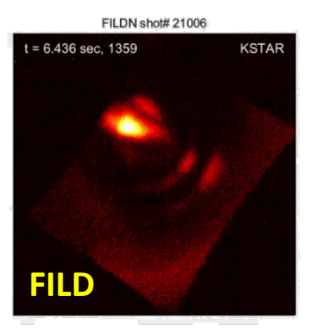


Alfvén gaps move into the region close to the core. → More chance to destabilize the TAEs, enhancing fast-ion transport.

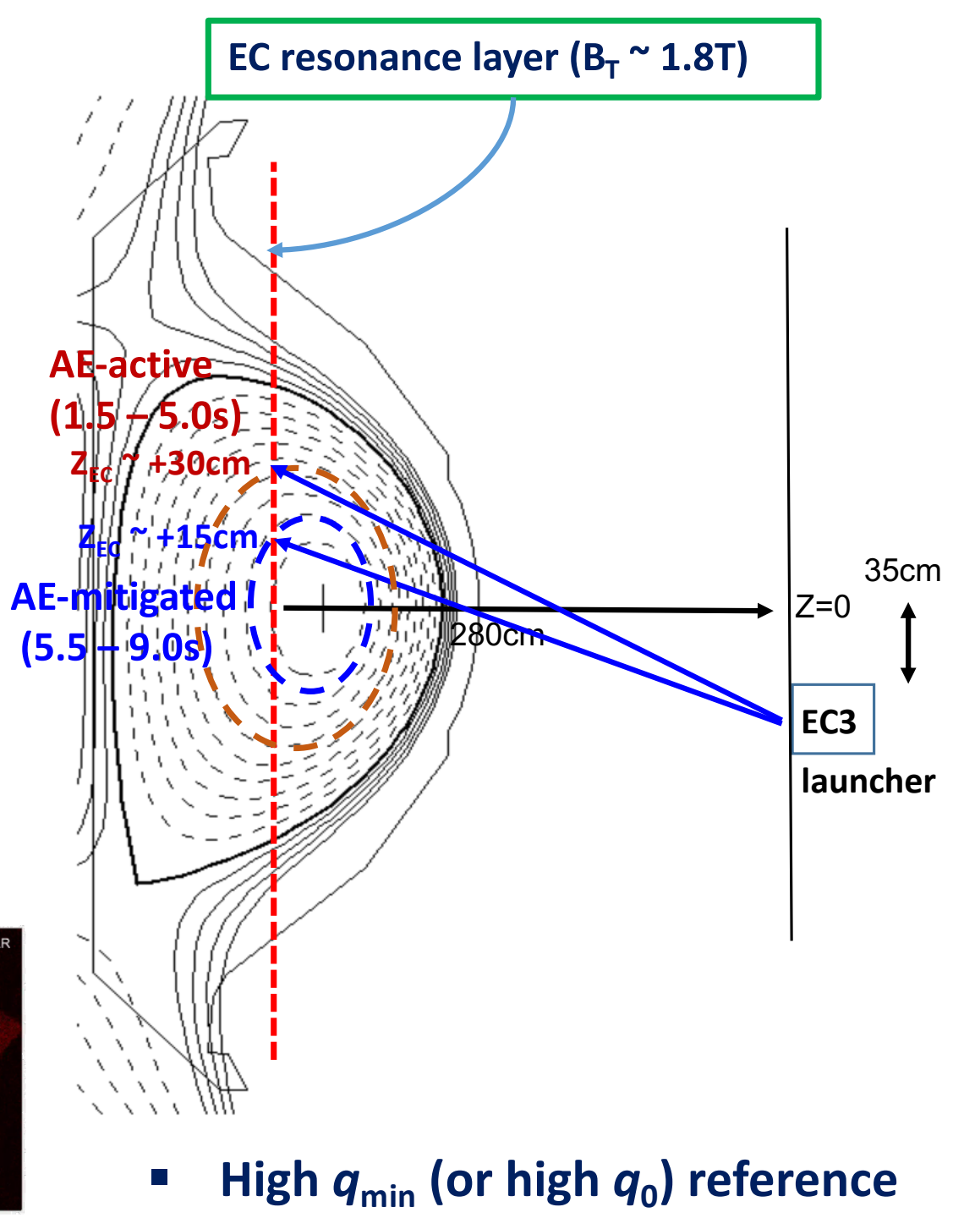
2.1. High q_{min} configurations open wide Alfven gap[5] → Active AEs







High q_{min} scanerio: Inter-ELM fast-ion loss is strong even in the H-mode.



- **Experimental condition:**

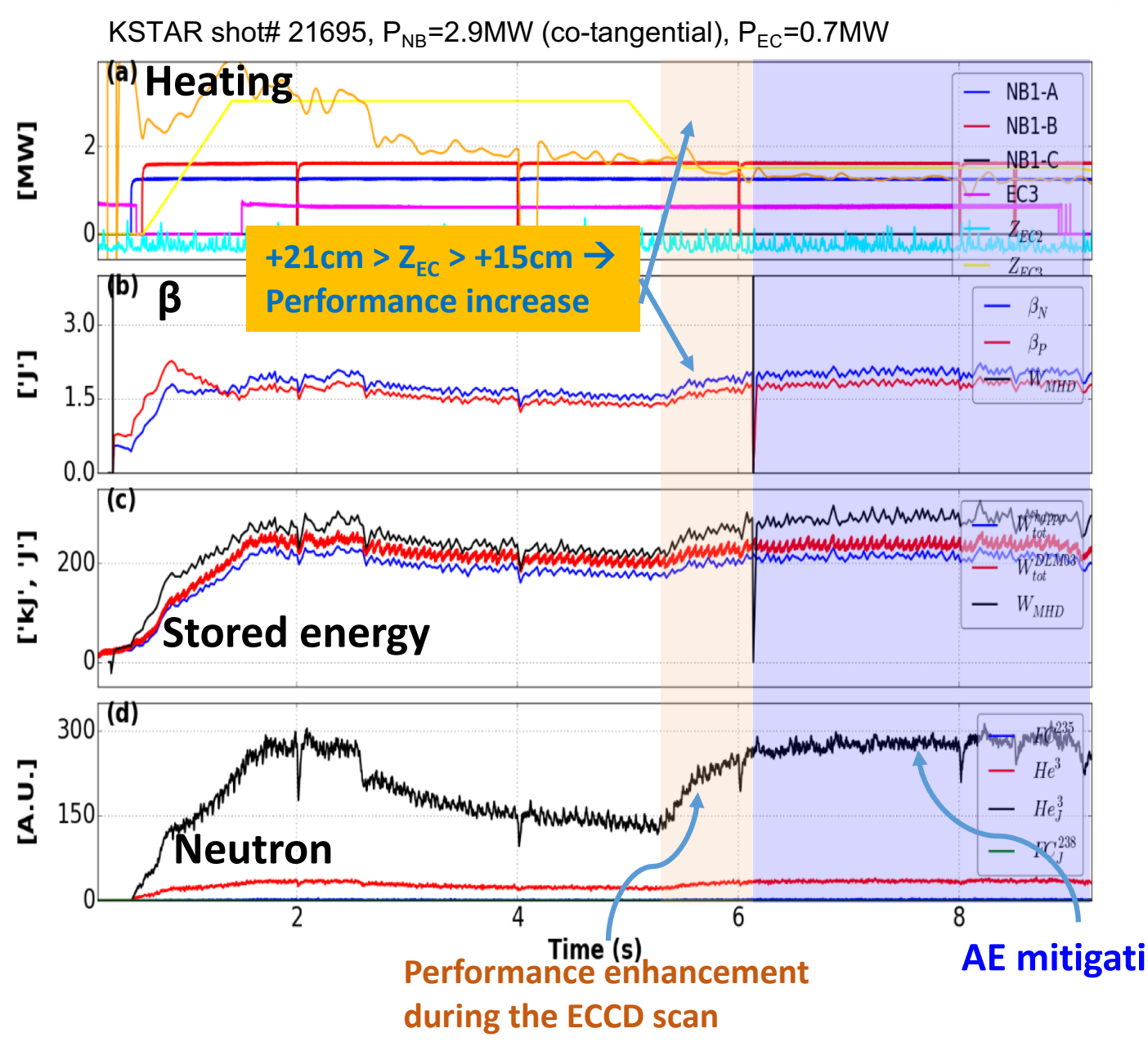
(B_T, I_P) = (1.8 T, 0.5 MA), q_0 > 1.5 @ flat-top, l_i ~ 0.7 – 0.9

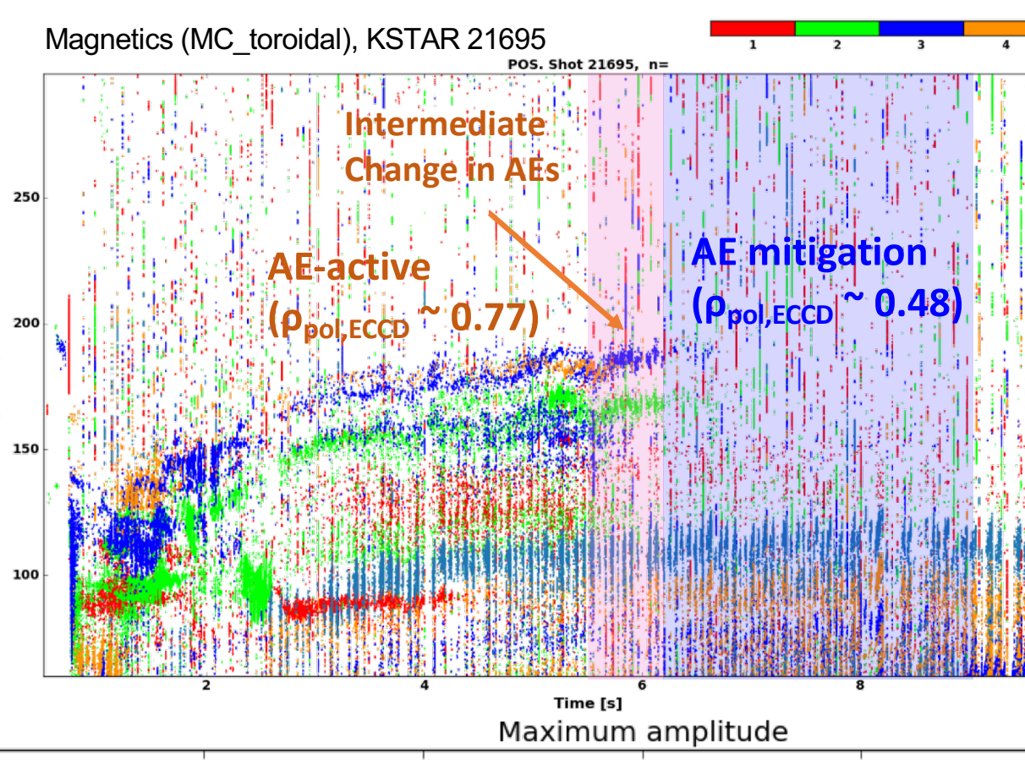
Heating: NBI1-A & B (80/90 keV, P_{NB} ~ 2.9 MW), P_{ECCD} ~ 0.7 MW

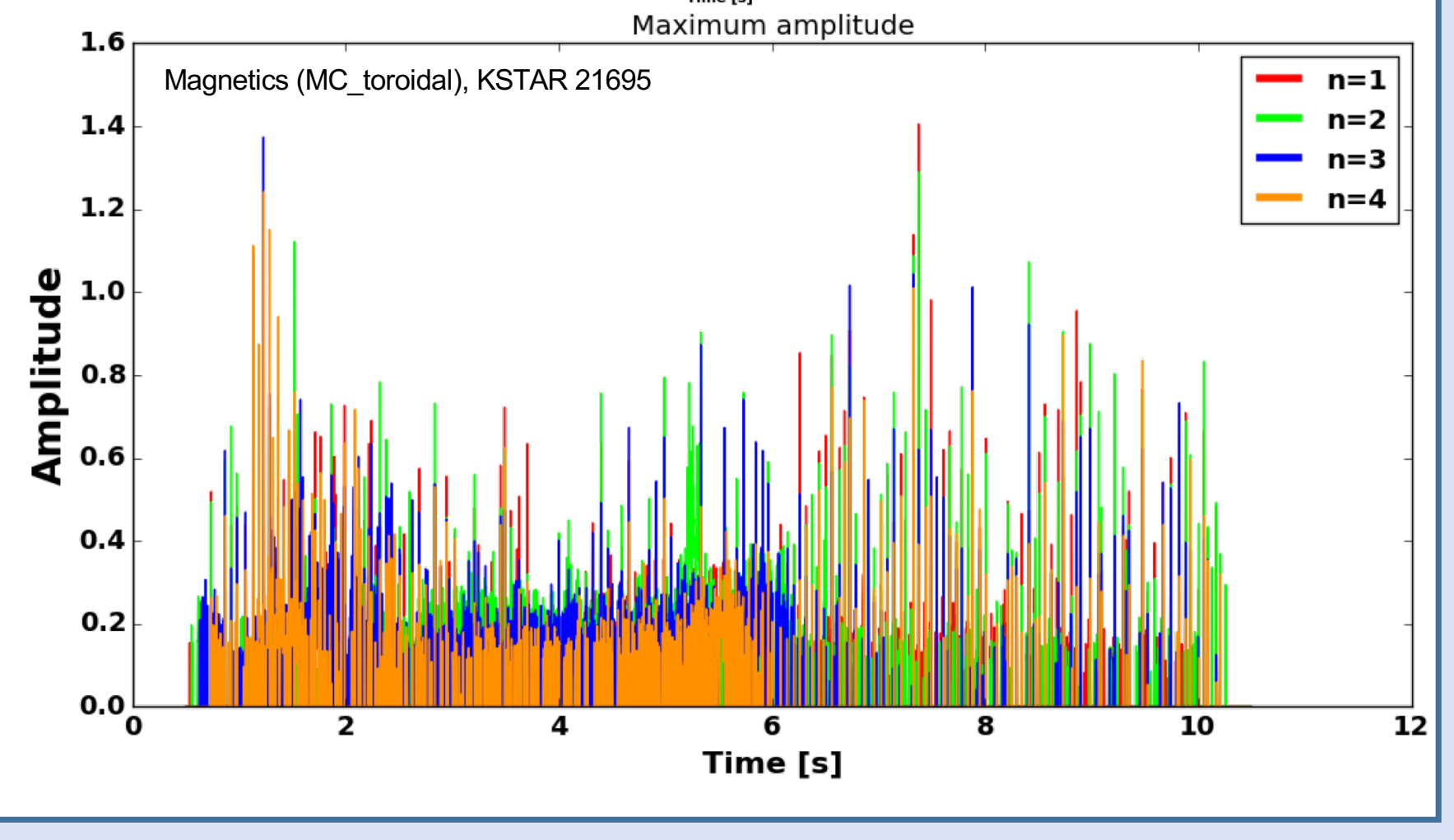
1. **Early *beam-timing* to start with high q_0 and Alfvenic activities.**
2. ***co-ECCD (ϕ_{tor} ~ +20°, off-axis) scan* (+15cm < Z_{EC} < +30cm) across the possible mode location by steering mirror to see if AEs are excited or mitigated.**

- **High q_{min} (or high q_0) reference**
  - ✓ **Early heating with P_{NB} ~ 3.7 MW (NBI1-B, C)**
  - ✓ **High q_{min} & low l_i → q_0 ~ 1.5 – 2.0 @ flat-top, l_i ~ 0.75 – 0.8**
  - ✓ **Wide Alfvén gap that can contain large # of TAEs**
  - ✓ **Active Alfvénic activities → Substantial decrease in neutron rate & increase in fast-ion loss**

2.2. AE suppression by co-ECCD in high q_{min} (> 1.5) discharge



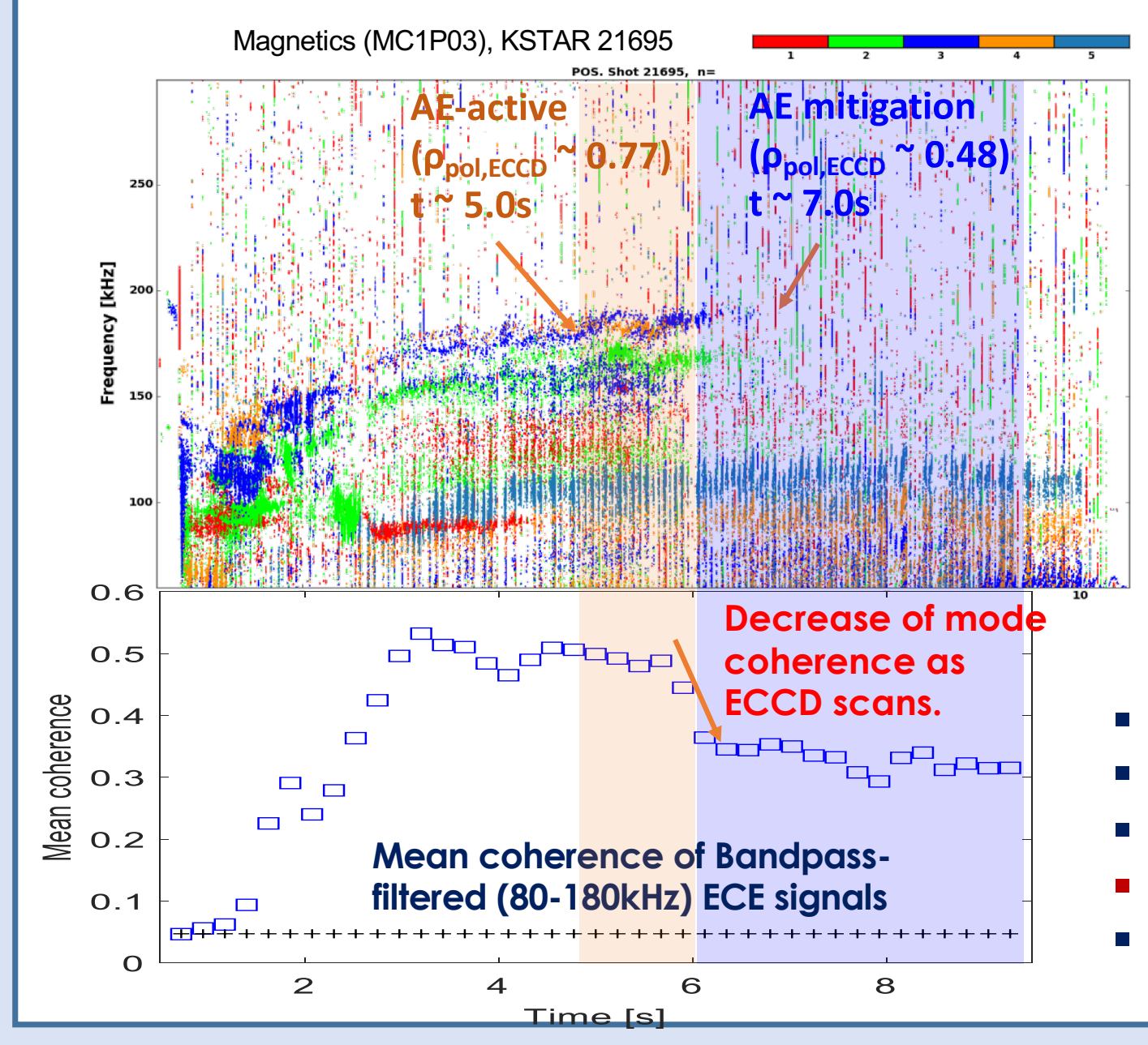


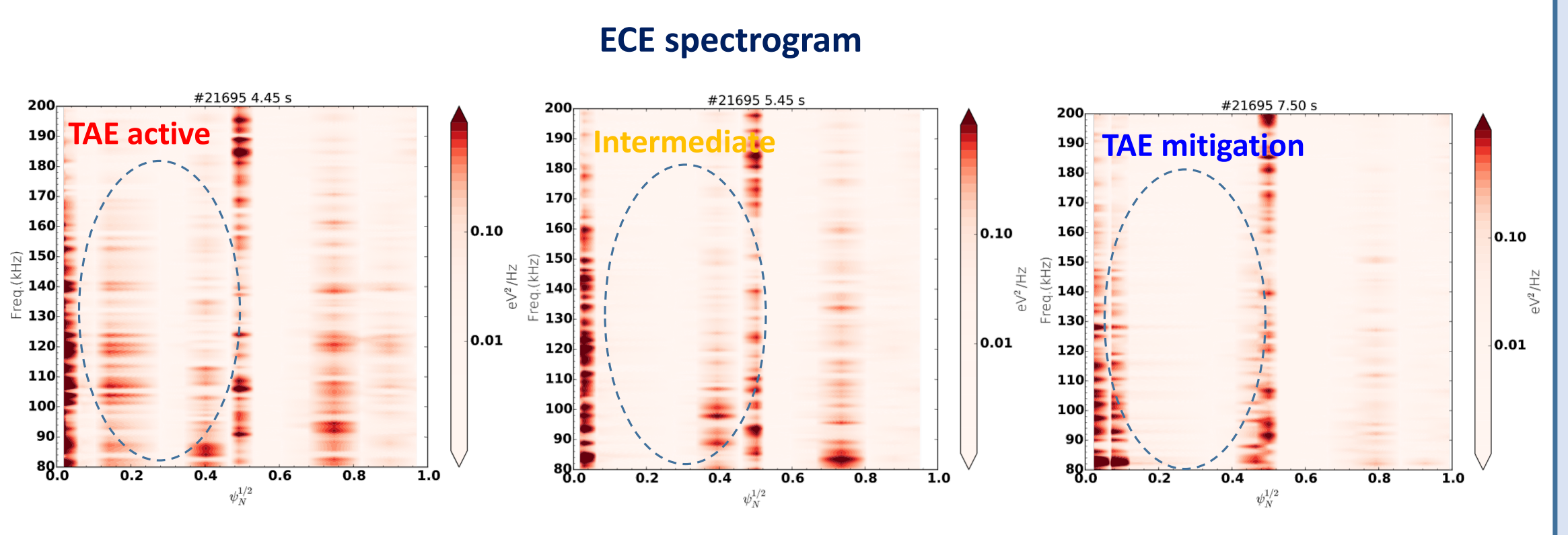


NBI1-A/B @ 80 keV / 90 keV (2.9 MW), ECCD (105GHz, 0.7MW, ϕ_{tor} = +20°) scan: Z_{EC} = +30, → +15cm (during 5.0 – 5.5s) :

- **Z_{EC} approaches +15cm. → Alfvenic activity is disappeared and the mean coherence of ECE signals in the Alfvenic range decreases.**
- **Overall performance increase → Stored energy and β_N: ~ 25% increase, Neutron rate : almost doubled**
- **Far-off axis ECCD touches TM, but not affect to AEs. Optimal deposition needed!**

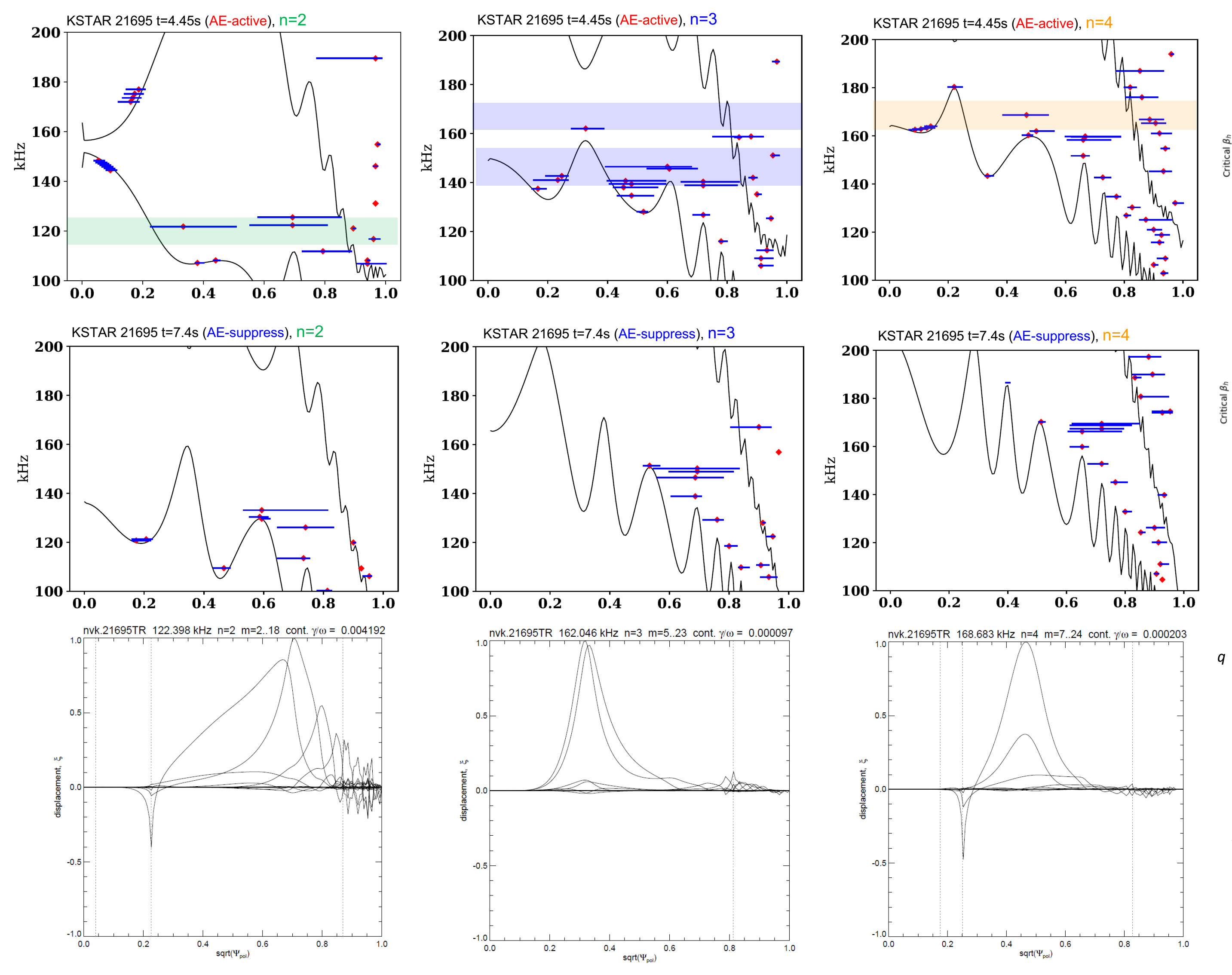
2.3. Comparison with the internal measurements (ECE)

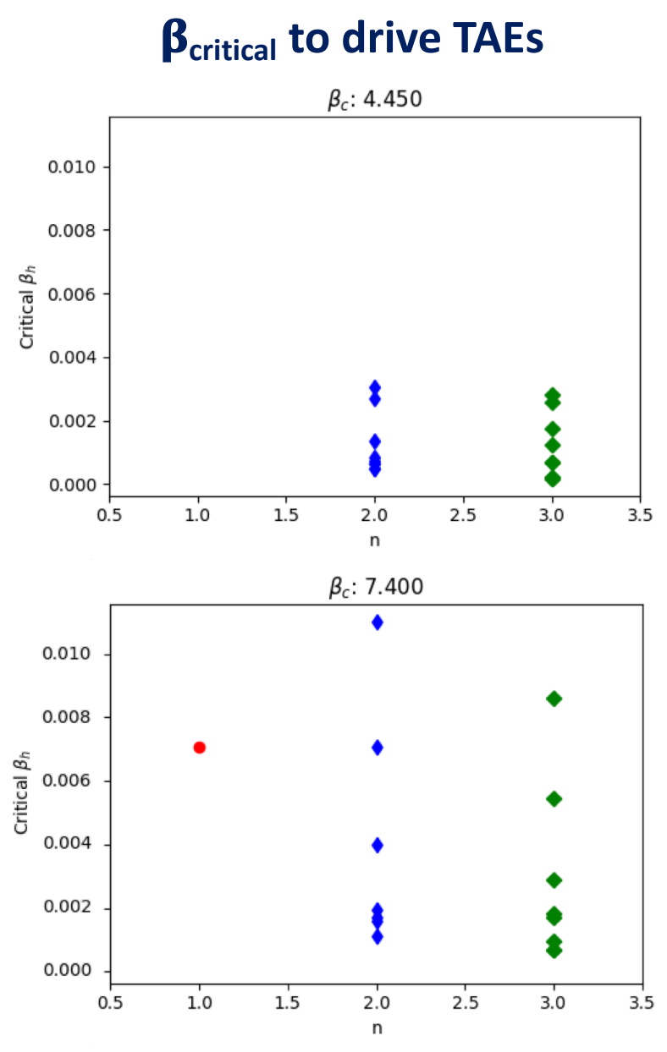


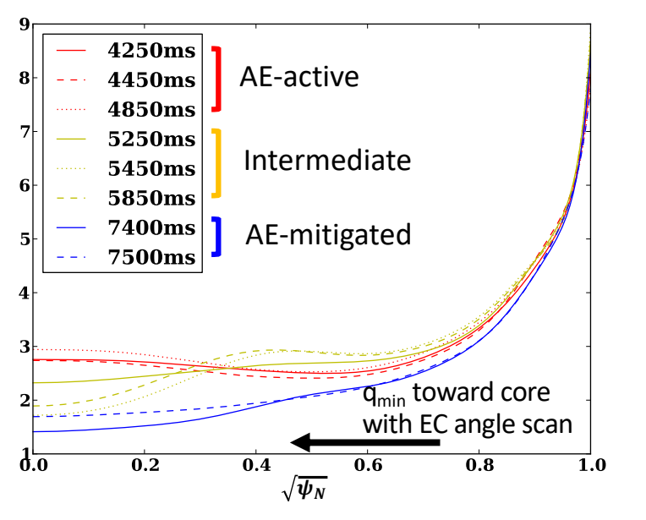


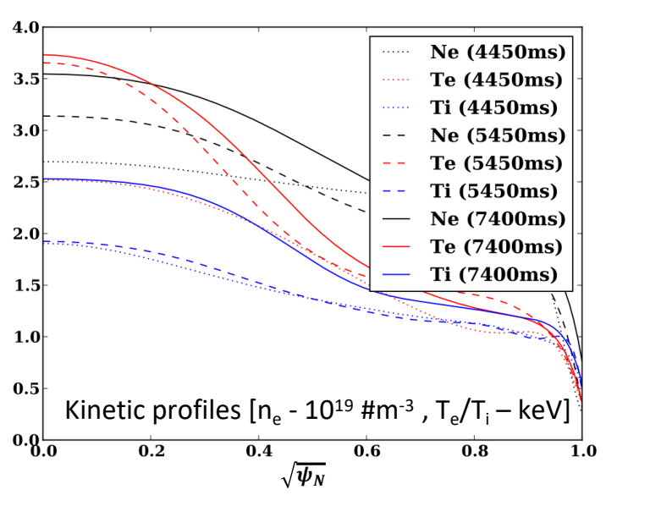
- ***Mean coherence of band-passed (80 – 180 kHz) ECE signals shows the Alfvenic mode mitigation.***
- ***AE-active & Intermediate phases exhibit the strong core modes in the core ECE signal.***
- ***AE-mitigation phase shows weak or no core modes.***
- ***Edge Alfvenic modes are visible in the AE-active & Intermediate phases.***
- ***AE-mitigation phase does not show the clear edge activity.***

3.1. Alfvén gap mode analyses (NOVA-k[6])



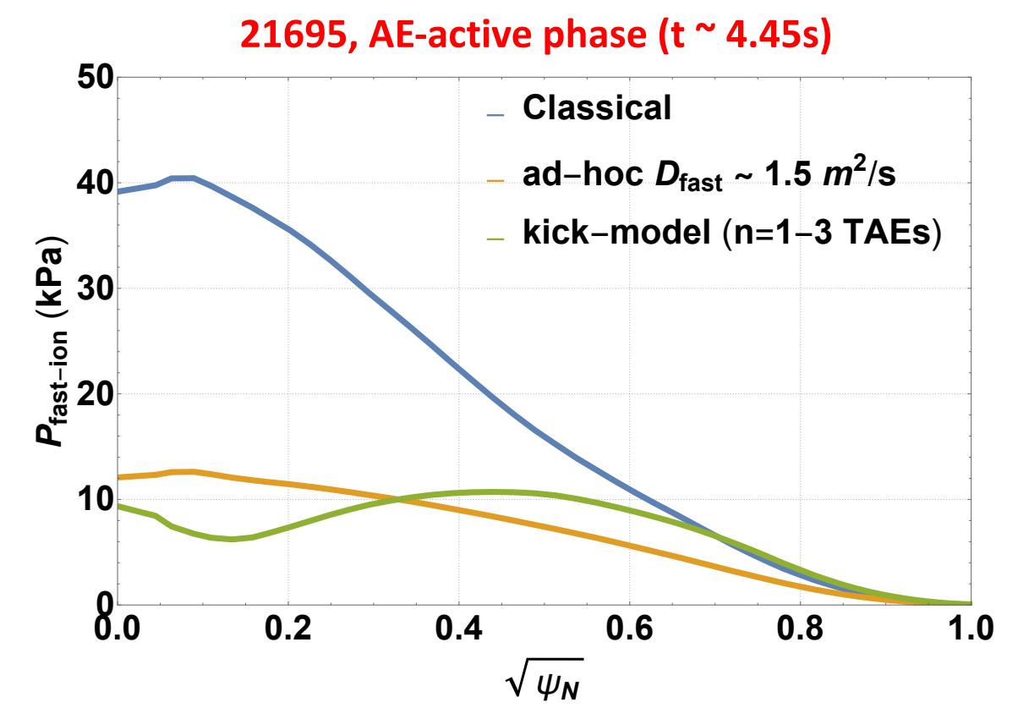


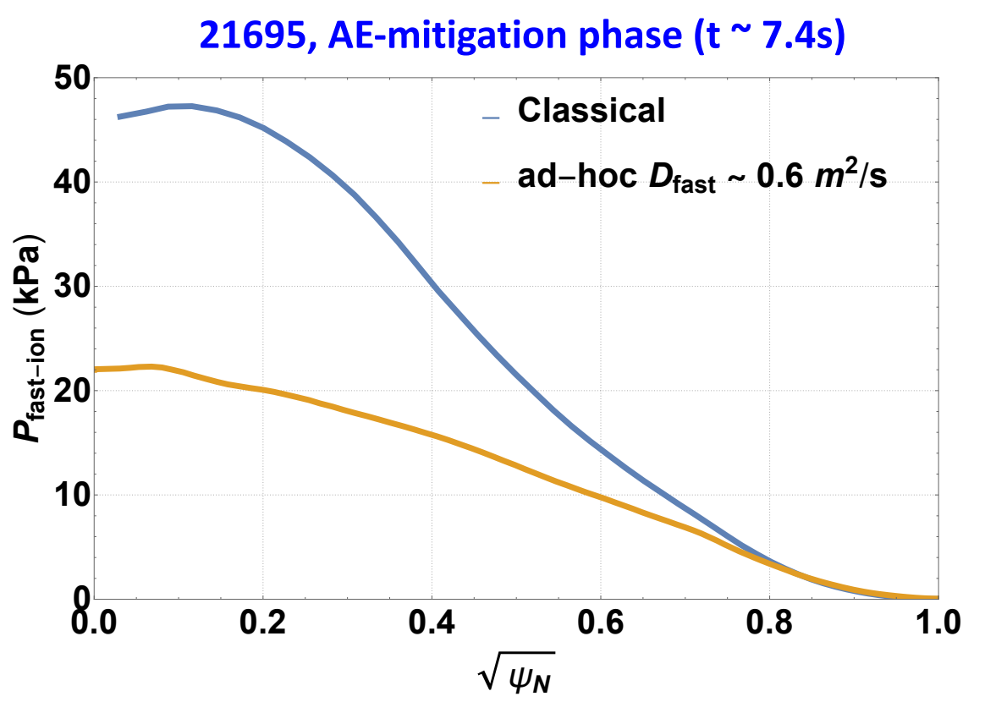


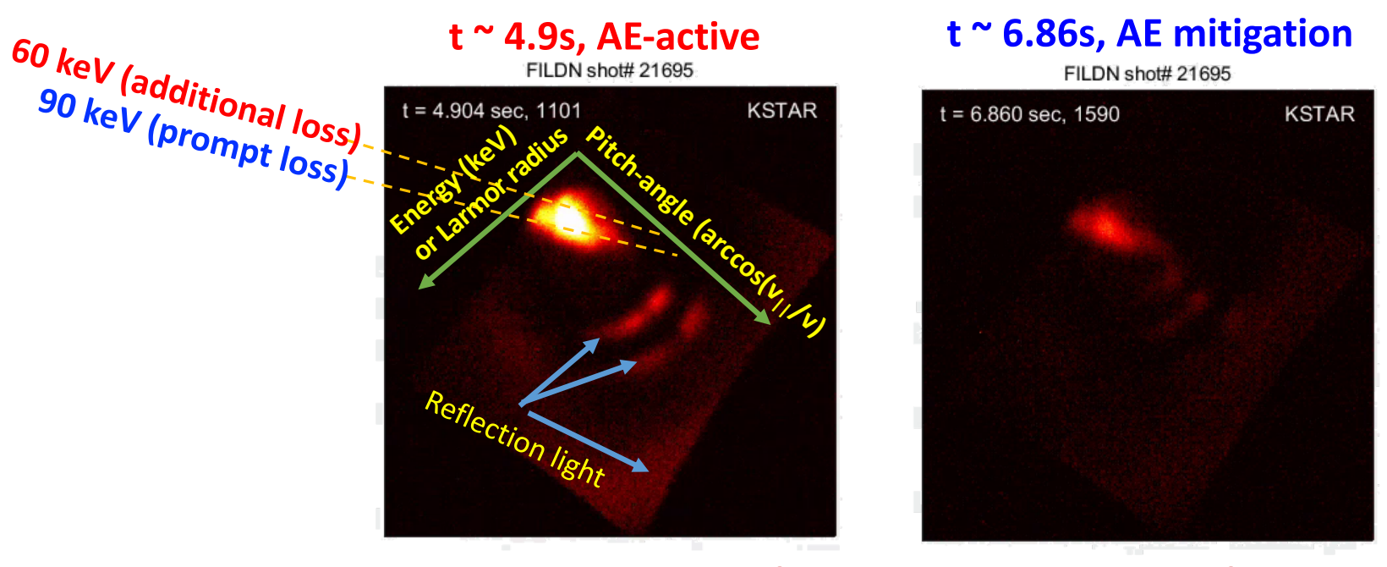


- **Growing TAEs in the core: much less @ AE-suppression phase**
- **Due to increase of continuum damping and Landau damping (increased core T_e), not sensitive to n_e change**
- **Overall plasma β increases. → Beneficial to TAE stabilization (same in high β_P case)**
- **Critical fast-ion pressure (β_c) driving Alfven eigenmodes in the AE-suppression phase is higher than AE-active phase. Higher fast-ion pressure is required to overcome the damping components.**

3.2. Profiles (fast-ion pressure, NBCD[7], neutron (TRANSP))

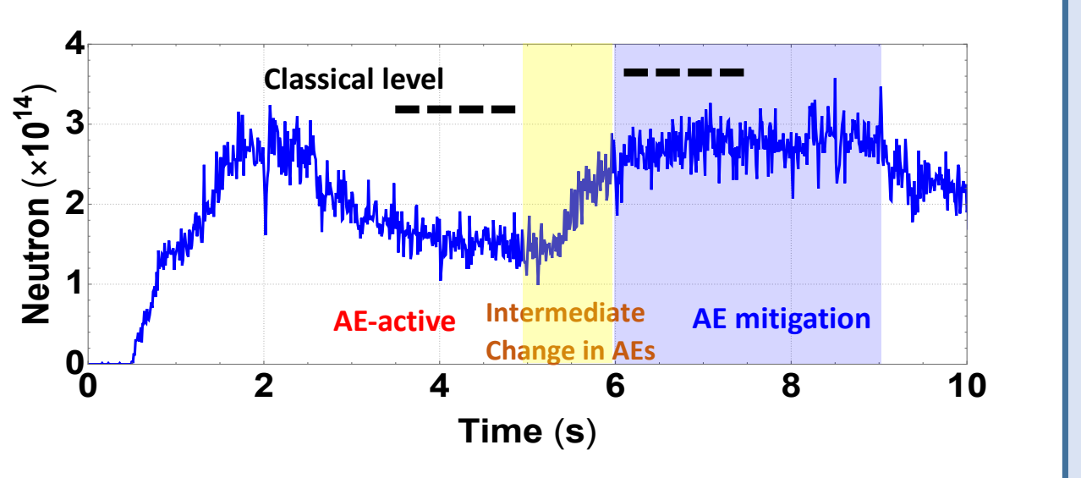


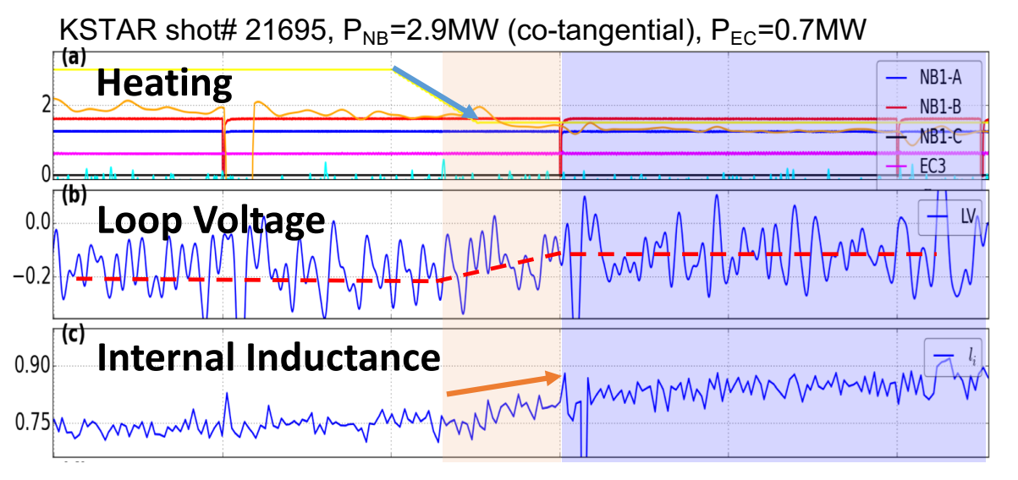




Fast-ion loss (Scintillator-based FILD)

- **Fast-ion pressure profiles (TRANSP) modelled and matched to the measured neutron emission rate.**
- **Fast-ion pressure increases as the AEs are mitigated. But the measured neutron emission is still below the classical level.**





- Decrease of loop voltage (-200 mV → -110 mV, f_{NI} 0.75 → 0.95) while the AE is mitigated.
- **AE mitigation** while applying the ECCD to the proper location → **Enhanced fast-ion confinement (mainly co-passing by co-tangential NBI)** → Increase of non-inductive current fraction (NBCD, J_{BS} ⇧) → Overall performance increases.

CONCLUSION

- **High q_0 (> 1.5) & q_{min}, low l_i (~ 0.75) by off-axis ECCD provided good testbed for driving & controlling the AEs.**
- **Co-directional ECCD (off-axis, 0.7MW) mitigates AEs successfully in the high β_P or high q_{min} scenarios of KSTAR → Performance enhancement, but the on-axis co-ECCD is not so effective.**
- **q_0 drop (~2.0 → ~1.5) and core q-profile shaping, core T_e increase → preventing wide gap in the core (plus, higher β could move gaps up) → Increase of continuum damping & core T_e (Landau damping) & β increase are beneficial to increase whole damping → Weak AE activities & EP confinement enhancement**
- **AE mitigation → Decrease in fast-ion loss, Increase of non-inductive current fraction**
- **Tearing-mode amplitude (small) can increase as ECCD approaches core, but AEs are mitigated without performance degradation. (β ⇧, Neutron ⇧, core T_e, T_i ⇧)**
- **Effective window of ECCD location is narrow, and the EC beam-width / efficiency depending on the ECCD injection geometry need to be considered.**
- **Not into the fast-ion profile stiffness since the P_{NB} is ~ 3.0 MW. Future experiment will expand the AE mitigation region in higher fast-ion pressure gradient.**

ACKNOWLEDGEMENTS / REFERENCES

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[1] B. Geiger et al., 45th EPS Conference on Plasma Physics, P1.1081 (2018).
[2] G.J. Kramer et al., Nucl. Fusion **57** (2017) 056024.
[3] Y.-M. Jeon et al., (M3) 16th International Workshop on H-mode Physics (2017).
[4] J. Kim et al., 60th APS DPP (NO.00005) (2018).
[5] C.T. Holcomb et al., Phys. Plasmas 22, 055904 (2015).
[6] C.Z. Cheng, M.S. Chance, J. Comput. Phys. **71** (1987) 124-46.
[7] J.S. Kang et al., 16th IAEA Technical Meeting on Energetic Particle Physics, P1-17 (2019).