KOREA INSTITUTE OF FUSION ENERGY

ID: 1214

Active Control of Toroidal Alfvén Eigenmodes Using the Electron Cyclotron Waves in KSTAR High-Performance Discharges

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1. 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 in the KSTAR advanced scenarios.*

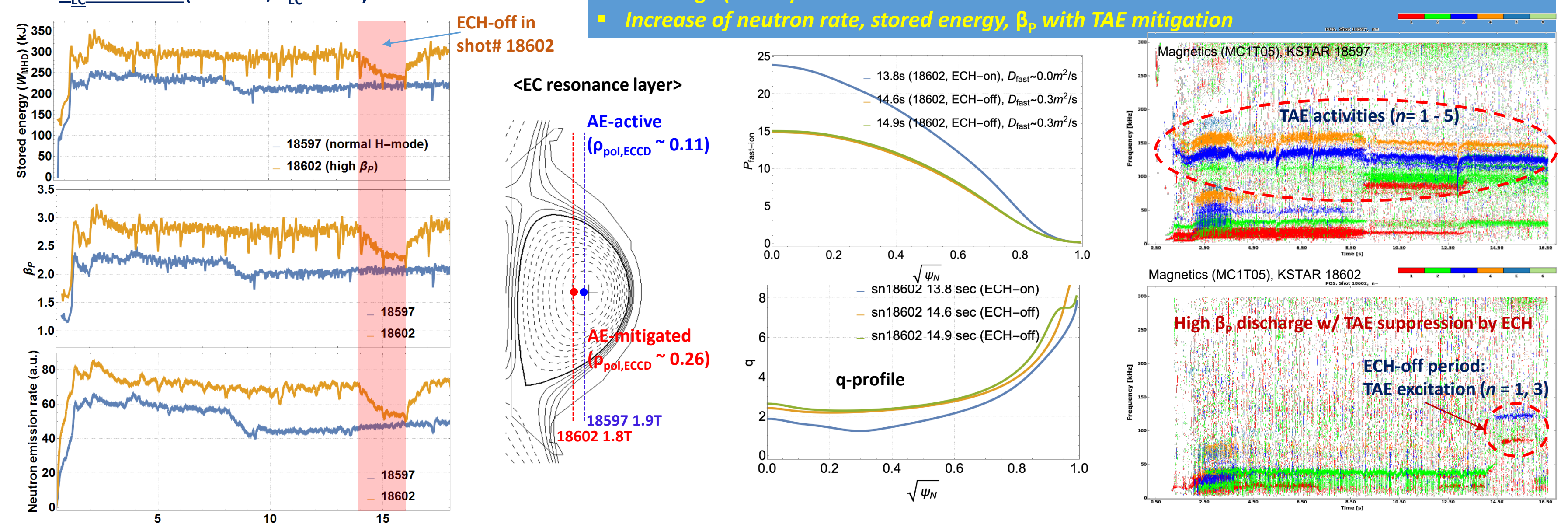
2. Experimental Observations:

- Experimental observations on the TAE mitigations have drawn the attention to significant enhancement of performance in the advanced operation scenarios (high β_P).
- 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
- Primary mechanism of AE mitigation is based on Alfven continuum damping.
- ECCD scan is one of promising techniques to control the TAEs

1.1. Previous study: AE suppression by co-ECCD scan in high β_P long-pulse discharges enhances the plasma performance

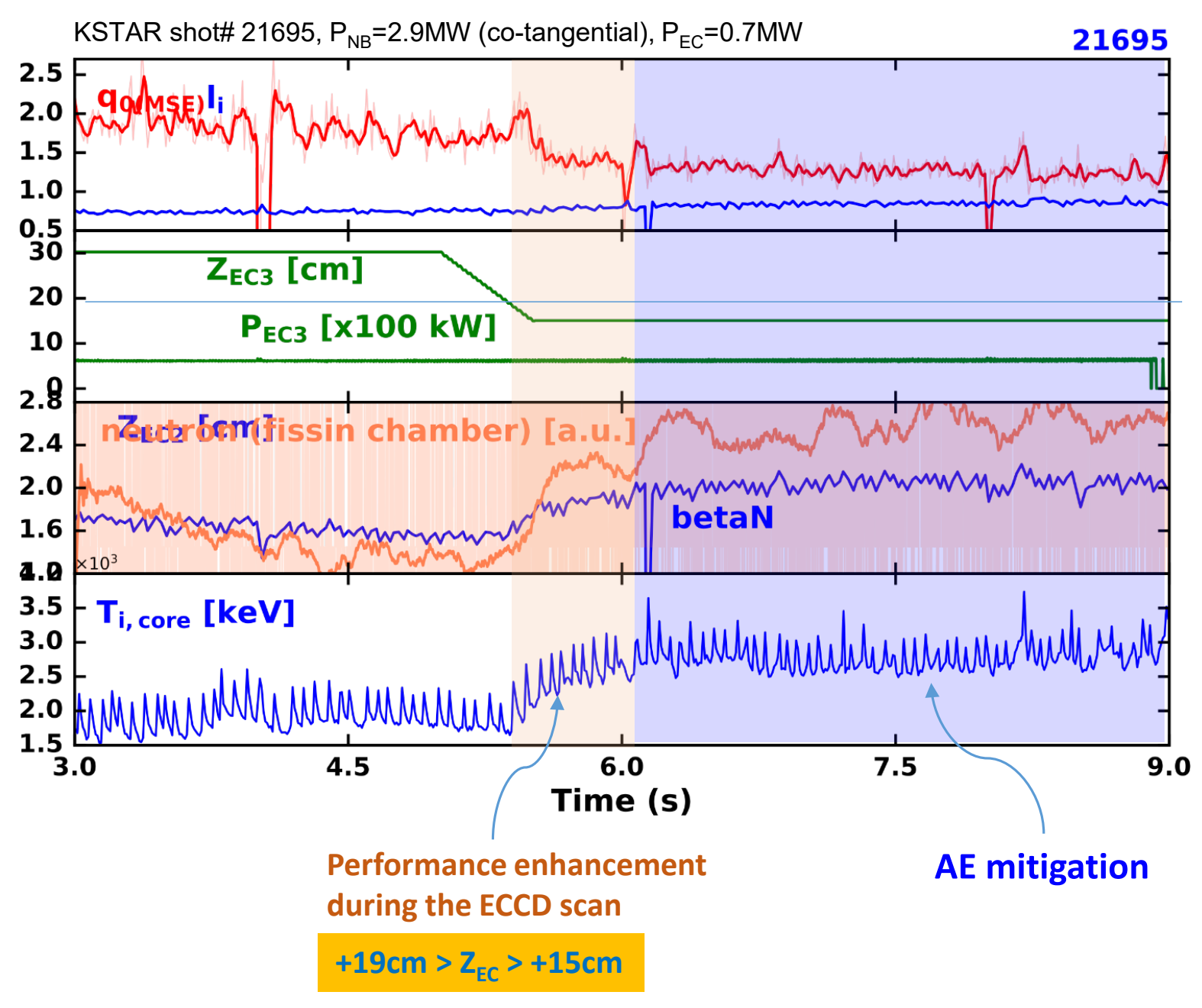
B_{T0} = 1.9T (18597), 1.8 T (18602), I_P = 0.4 MA
NBI1-A/B/C = 100/70/70 keV (3.8 MW),
P_{EC} = 0.7 MW (105 GHz, Z_{EC} ~ 0cm)

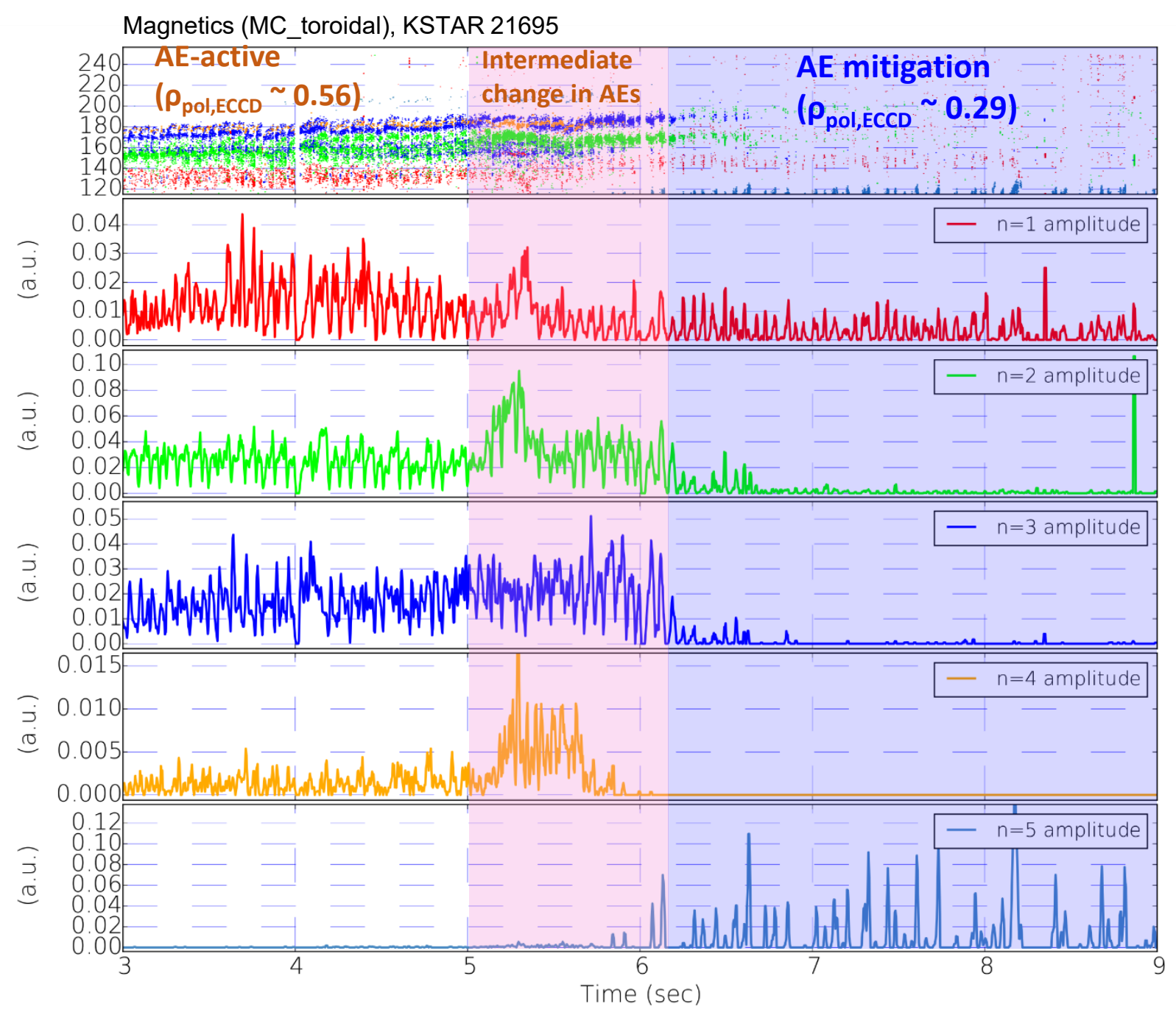
- Same heating power, but different injection location of ECCD
- Proper ECCD injection location → *TAE mitigation* → achievement of steady-state high β_P (~ 3.0) discharge (18602).
- *Increase of neutron rate, stored energy, β_P with TAE mitigation*



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

1.2. Previous study: AE suppression by co-ECCD scan in high q_{min} (q_0 > 1.5) discharge

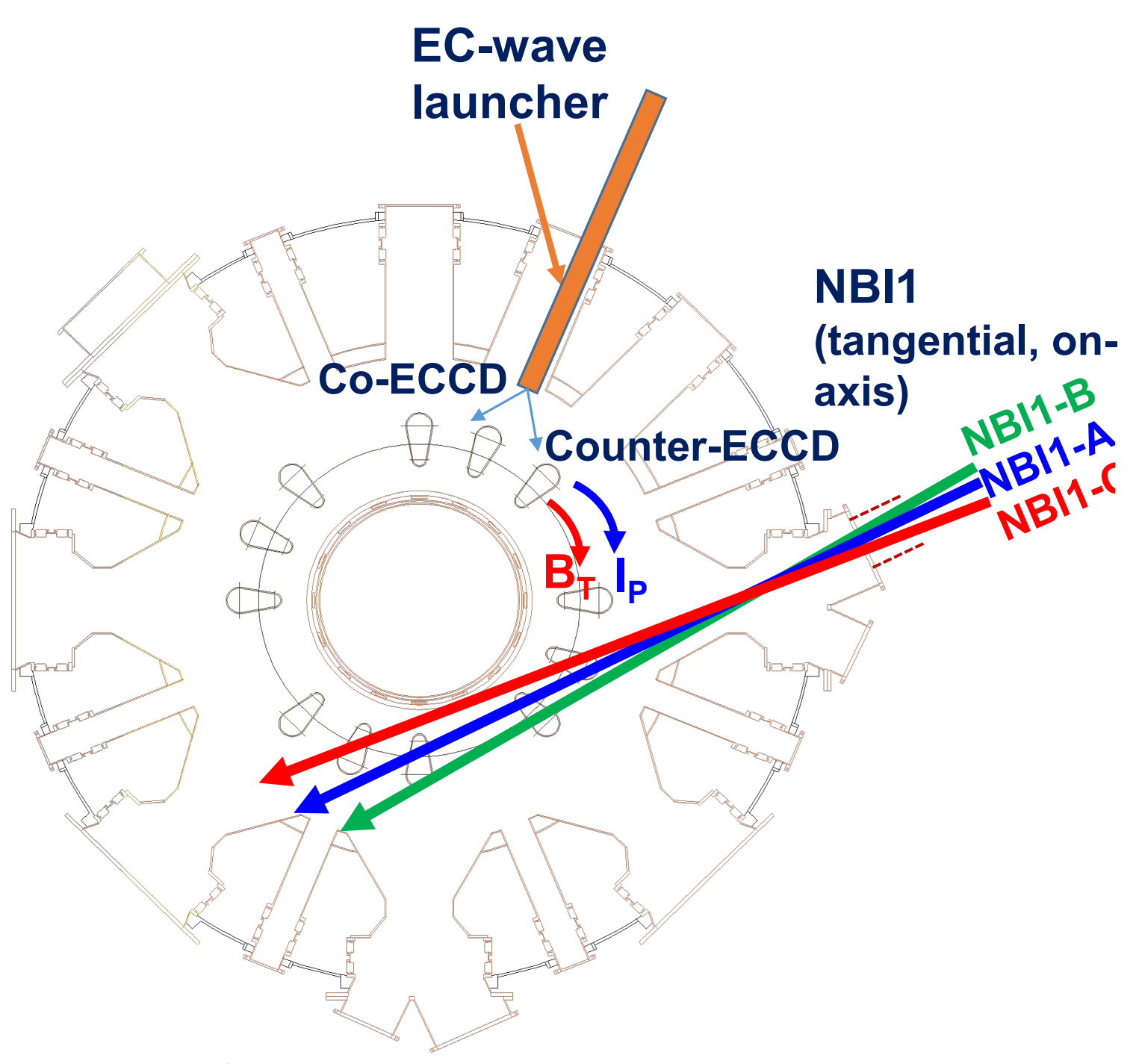


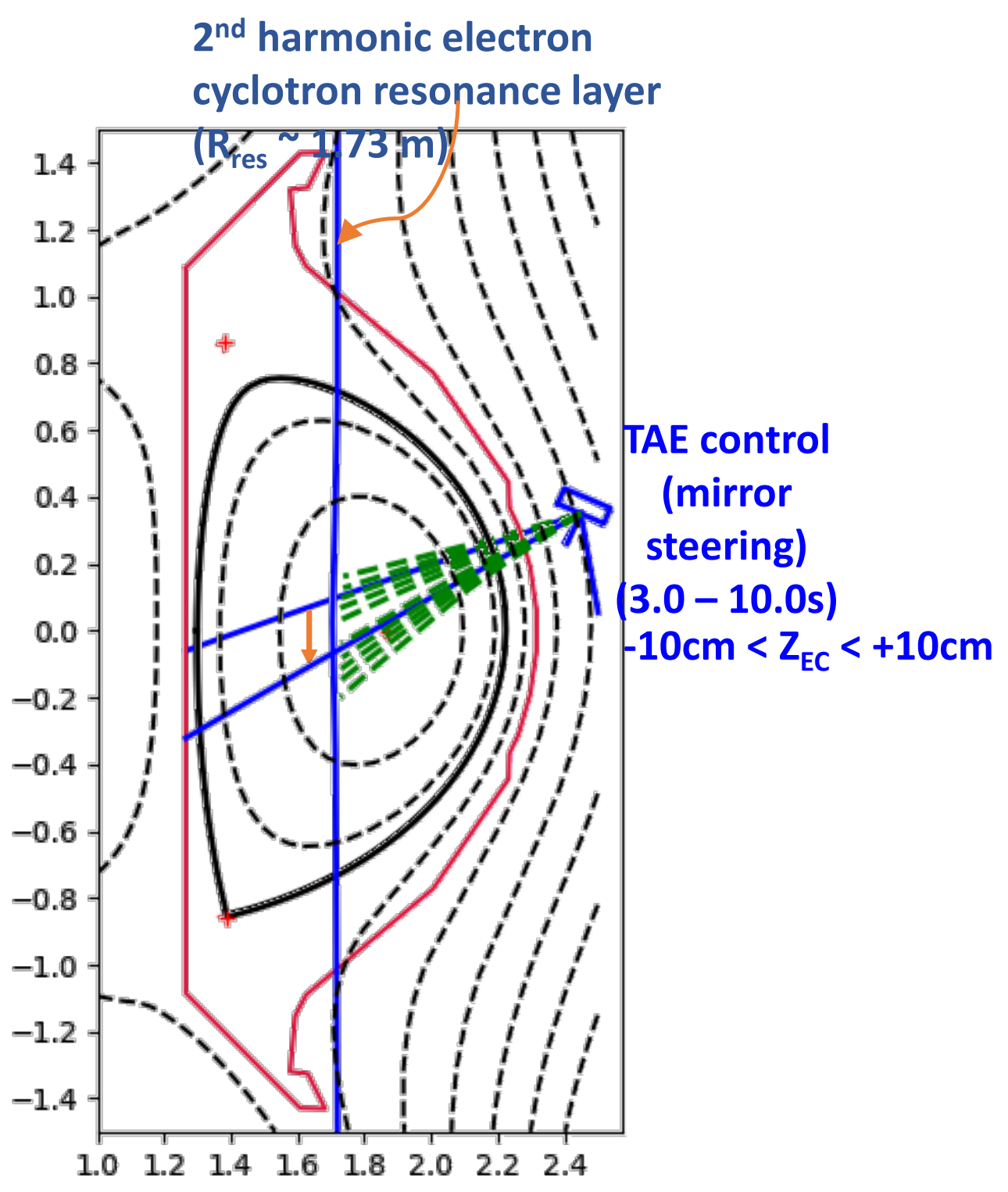


NB1-A/B @ 80 keV / 90 keV (2.9 MW), co-ECCD (105GHz, 0.7MW, ϕ_{tor} = +20°) scan: Z_{EC} = +30cm → +15cm (during 5.0 – 5.5s) :

- Z_{EC} approaches +15cm. ➔ Alfvénic activity is disappeared and the 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. Experimental Setup (Investigations on Co- & Counter-ECCD applicability)





- **Experimental condition:**

(B_T, I_P) = (1.8 T, 0.5 MA), q_0 > 1.5 @ flat-top, l_i ~ 0.75 – 0.85

Heating: NB1-A & B & C (70 - 90 keV), P_{NB} ~ 3.4 – 4.5 MW, P_{ECCD} ~ 0.7 – 1.3 MW

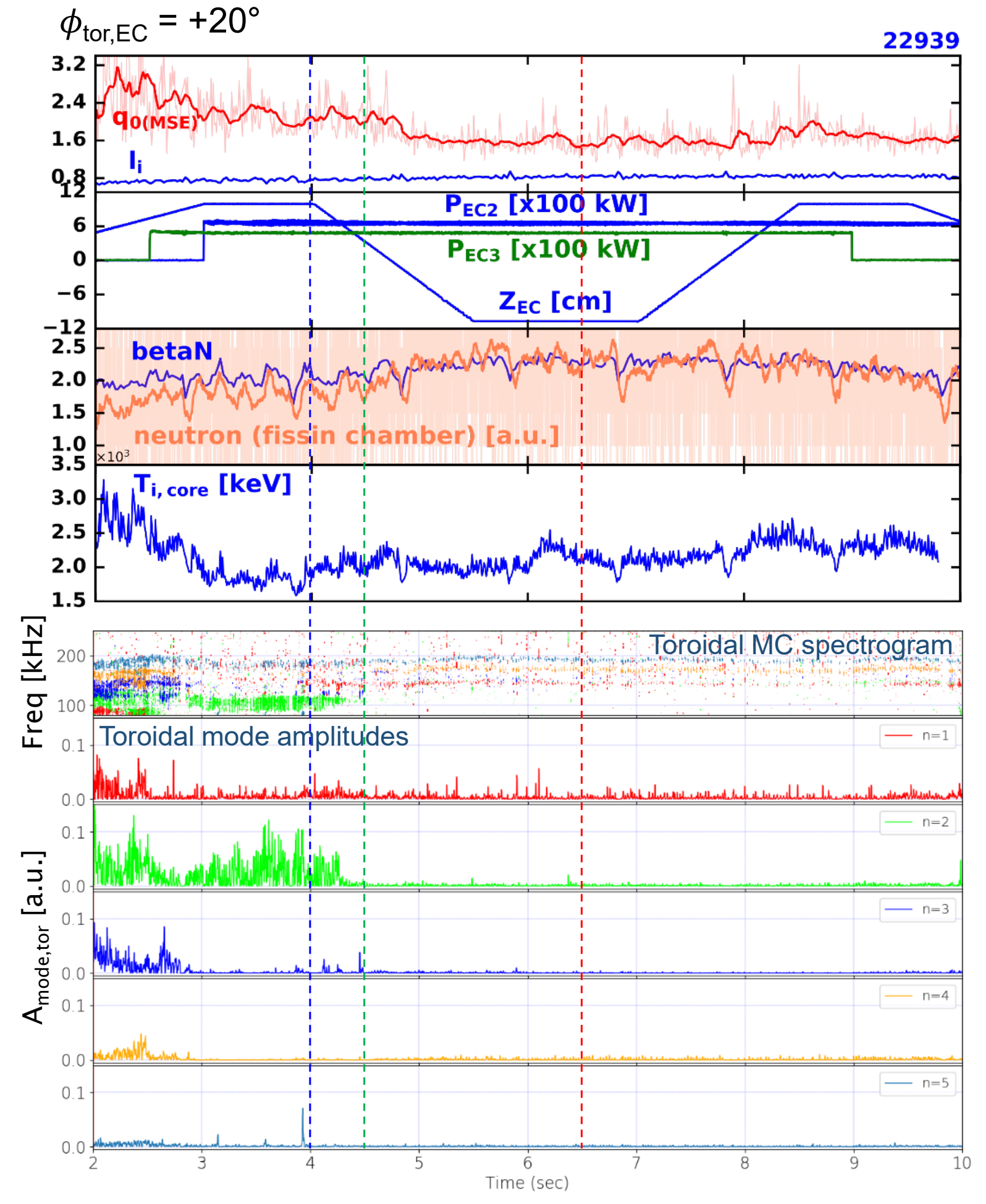
1. ***co-ECCD (ϕ_{tor} ~ 20°, off-axis) scan* (-10cm < Z_{EC} < +10cm)** across the possible mode location **by steering mirror to see if AEs are excited or mitigated. Neutron rate signal is an indicator to optimize the EC-wave deposition location (Z_{EC}).**
2. **Two EC-wave launchers: 1 central ECH (fixed) & 1 co- and counter-ECCD (scanning)**

ACKNOWLEDGEMENTS

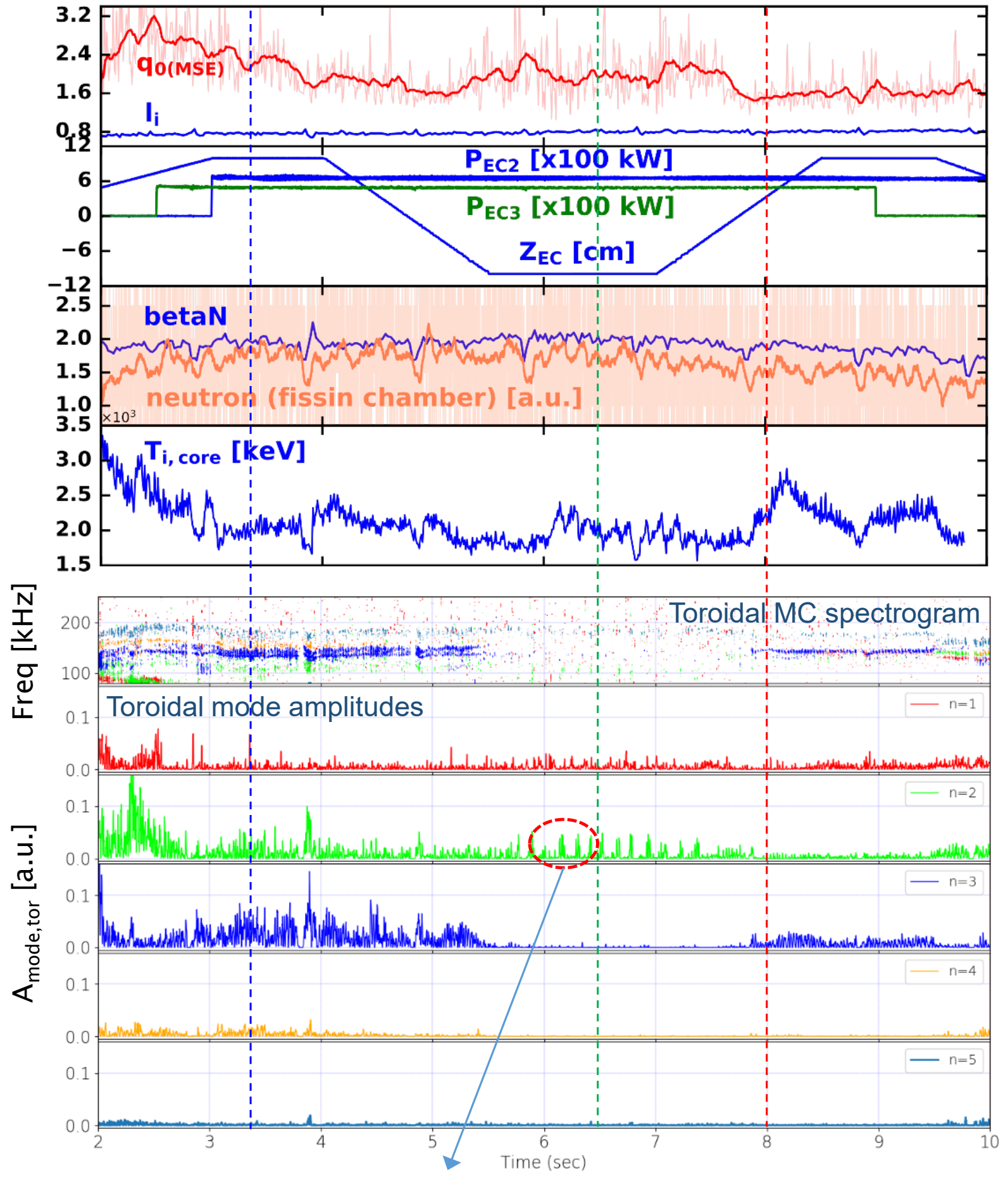
This work was supported by the Ministry of Science and ICT under the KSTAR project and the ITER Technology R&D Program.

3.1. Experimental Results

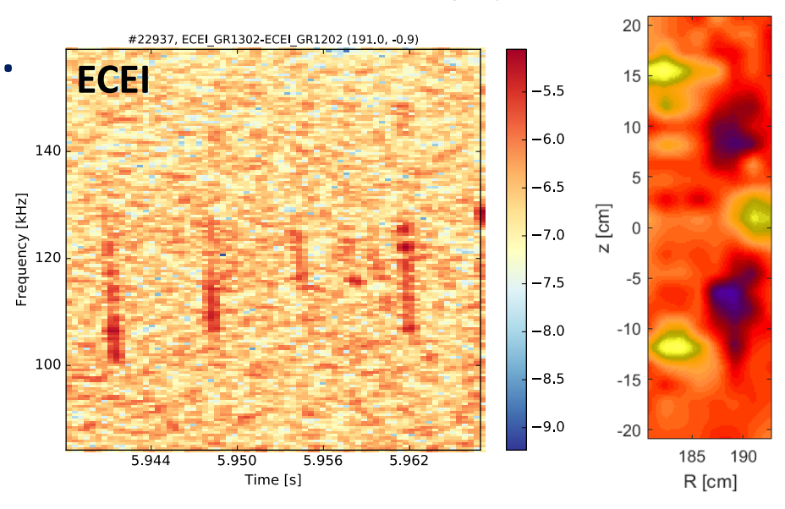
P_{NB} ~ 3.4 MW (on-axis, co-NBI), P_{EC} ~ 1.3 MW **Co-ECCD**, $\phi_{tor,EC}$ = +20°



P_{NB} ~ 3.4 MW (on-axis, co-NBI), P_{EC} ~ 1.3 MW **Counter-ECCD**, $\phi_{tor,EC}$ = −20°

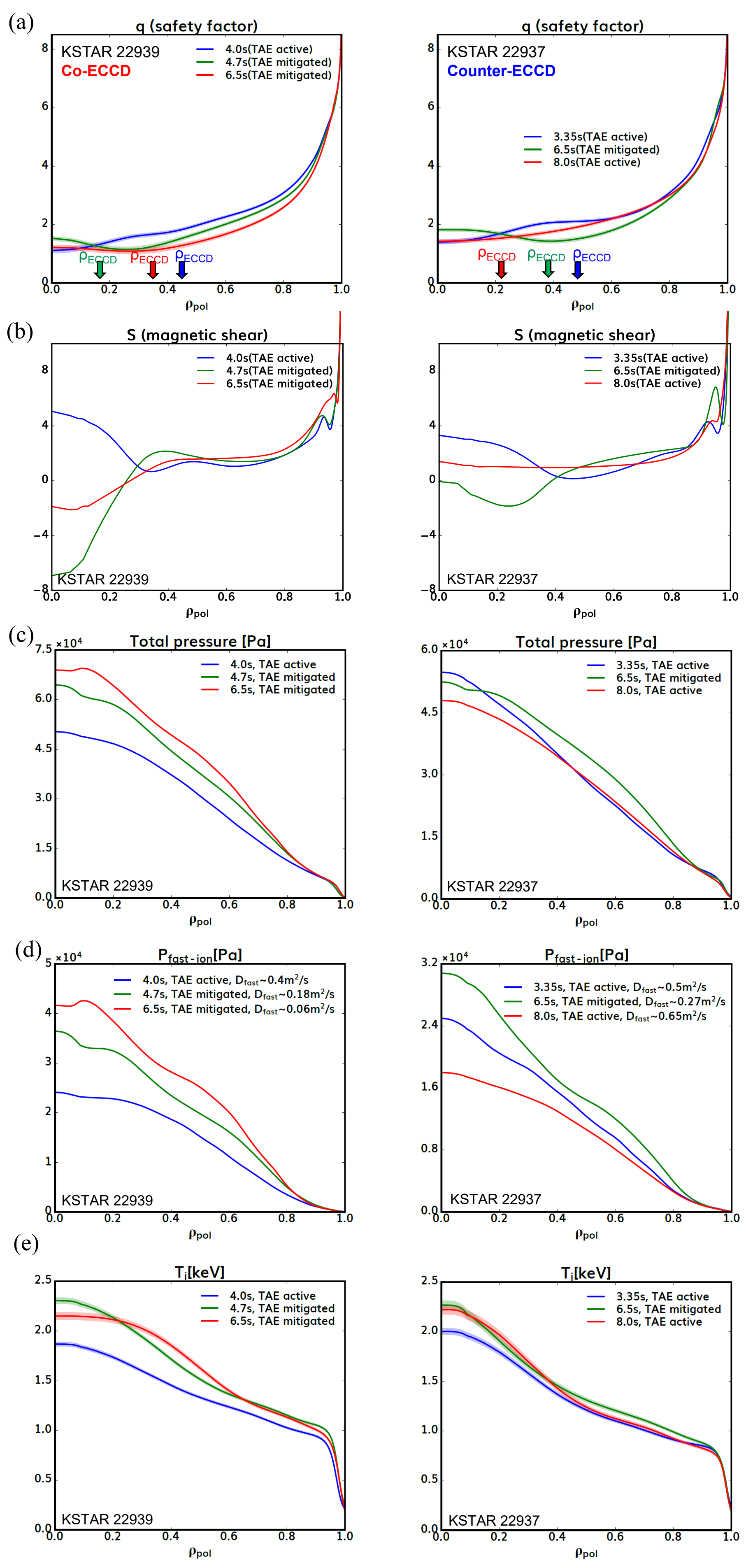


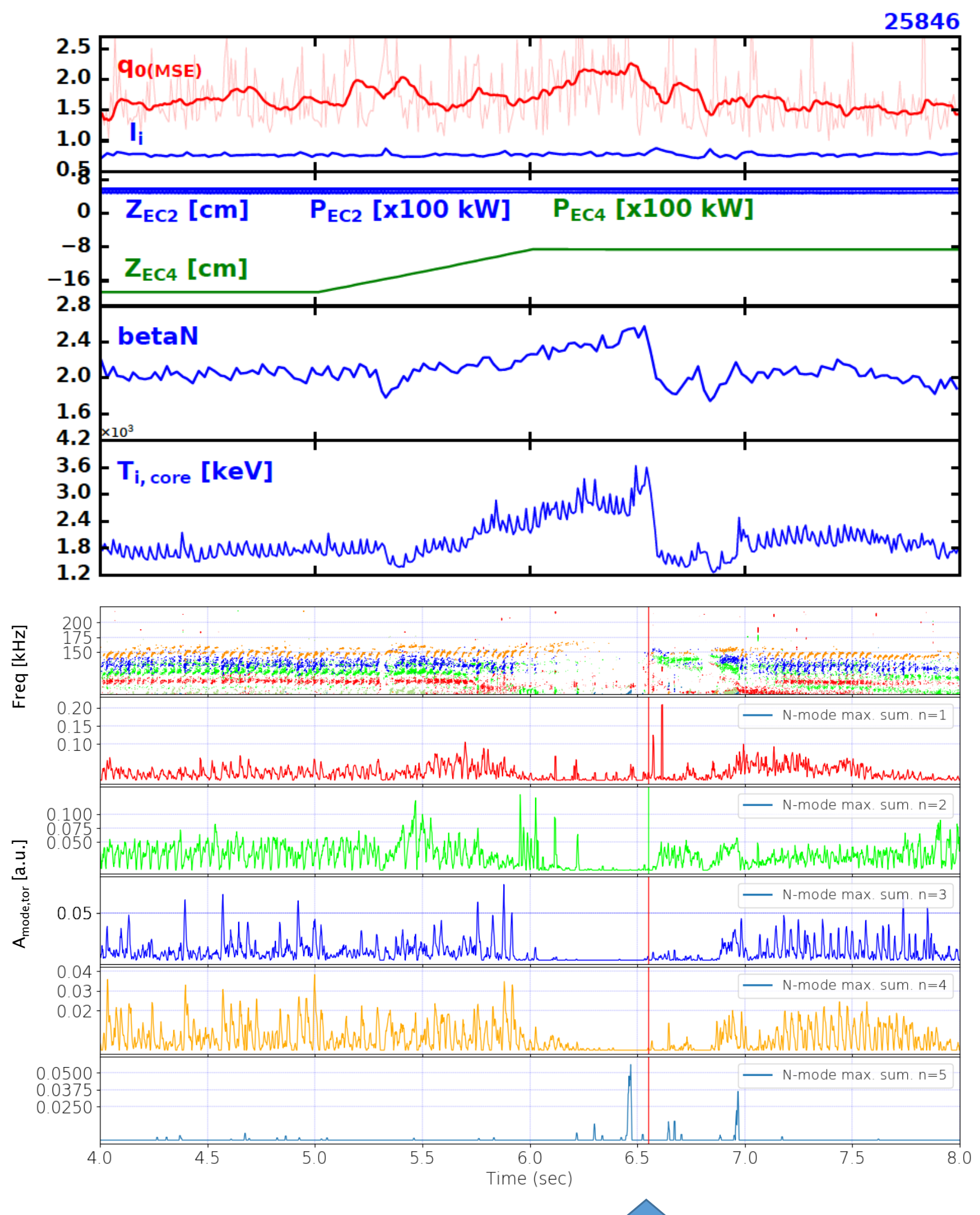
- Both co- & couter-ECCD cases can mitigate or suppress the TAEs in elevated q_0 scenario.
- Primary control mechanism: Increase in continuum damping by tailoring core *q*-profile shape
- Overall plasma **β** increases. → Beneficial to TAE stabilization (same in high β_P case)
- Co-ECCD is superior than counter-ECCD to control TAEs for over tens of τ_E.
- Counter-ECCD has shown the possibility of TAE control under the elevated q_0 scenario.
- Unexpected excitation of *n*=2 EPM in counter-ECCD-assisted mitigation stage prevents the enhancement of the plasma performance (including core fast-ion pressure).



unexpected chirping n=2 EPM during n=3 TAE suppression in the counter-ECCD application

3.2. Profiles (safety factor, fast-ion / total pressure, shear, …)





- Co-ECCD (shot# 25846) suppresses TAEs in the elevated beam-power (P_{NB} ~ 4.3 MW), however the control was lost due to tearing mode excitation.
- Excessive core total pressure gradient is a candidate cause.
- Need to investigate the TAE control without large-amplitude tearing-modes.

- Central T_i change is not so significant in 22937, 22939. → Thermal-ion Landau damping seems to be weak in TAE-mitigation stage.
- Normalized pressure gradient (α) > Critical level (α_{crit}) ➔ Stabilization in the enhanced β (suppression of core TAEs)
- Fast-ion pressure increases as the AEs are mitigated.
- TRANSP calculated D_{fast} for the co-ECCD-assisted TAE mitigation case is close to the classical transport.

DISCUSSIONS

- High q_0 (> 1.5) & q_{min}, low l_i (~ 0.8) by mild off-axis ECCD provided good testbed for driving & controlling the AEs.
- Co-I_P directional ECCD (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 ➔ Increase of continuum damping & β increase are beneficial to increase whole damping ➔ Weak AE activities & EP confinement enhancement
- Co-ECCD is better to control the TAEs by means of increasing continuum damping.
- Tearing-mode amplitude (small) can increase as ECCD approaches core, but AEs are mitigated without performance degradation. (β ⇧, Neutron ⇧, core T_e, T_i ⇧) However, in higher P_{NB} (~ 4.3 MW), AE-control was lost by large-amplitude TM. Dynamic control using the multiple launchers can be suggested.
- Not into the fast-ion profile stiffness since the P_{NB} is ~ 3.0 MW in the previous works. P_{NB} ~ 4.3 MW seems to be marginal. Broadening beam-ion profile may be effective for reducing fast-ion drive.