# Stability of Neoclassical Tearing Modes and Their Active Stabilization in KSTAR

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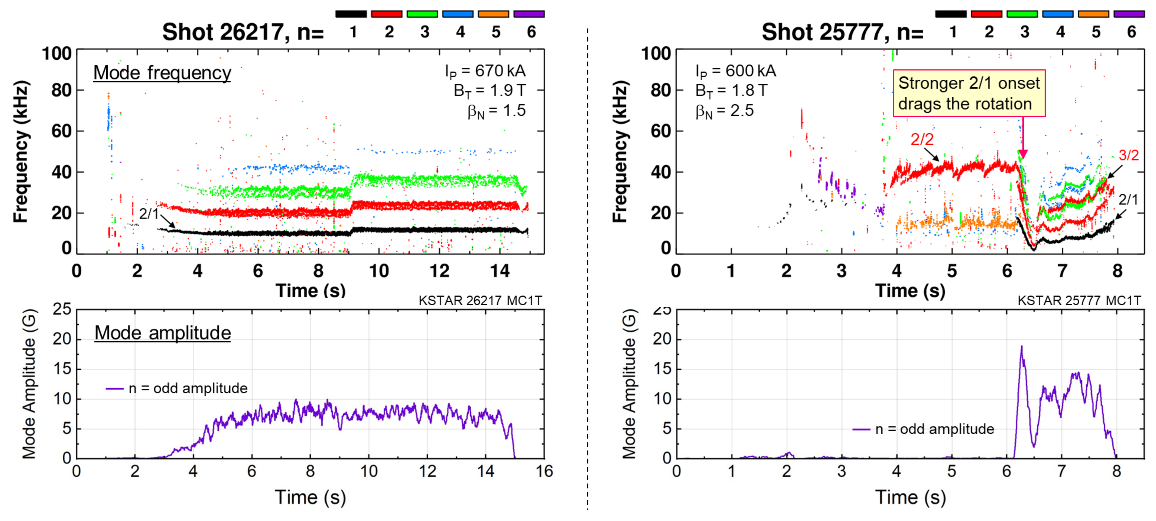
## INTRODUCTION

### In the recent KSTAR operation, experiments for NTM stability alteration and active mode control have been conducted

- Motivation
  - Largely grown m/n = 2/1 NTM is limiting the sustained high performance plasma operation in KSTAR
  - Avoidance and active control of NTMs using the present KSTAR actuators (ECCD/ECH) need to be investigated
  - This study will contribute to construction of the NTM stability physics model and the NTM feedback control system for KSTAR
- Outline
  - Triggerless and triggered 2/1 NTMs destabilized in different H-mode operational regimes
  - Stability alteration and active stabilization of triggerless 2/1 NTMs
  - Active stabilization of triggered 2/1 NTMs and effect of the fishbone instability on NTM destabilization

### 2/1 tearing modes destabilized in different H-mode operational regimes



- Triggerless 2/1 mode destabilizes at intermediate $\beta_N$ ~ 1.5 with no obvious mode triggering activity (could be driven by unstable current profile having $\Delta'$ > 0)
- Triggered 2/1 mode destabilizes at higher $\beta_N \geq 2.5$ with observed mode triggering by sawteeth or ELMs consequently leading to a significant $\beta_N$ and $W_{mhd}$ reduction

### Destabilizing perturbed bootstrap current effect in NTM stability is computed by using TRANSP

Modified Rutherford equation (MRE) describing NTM stability:

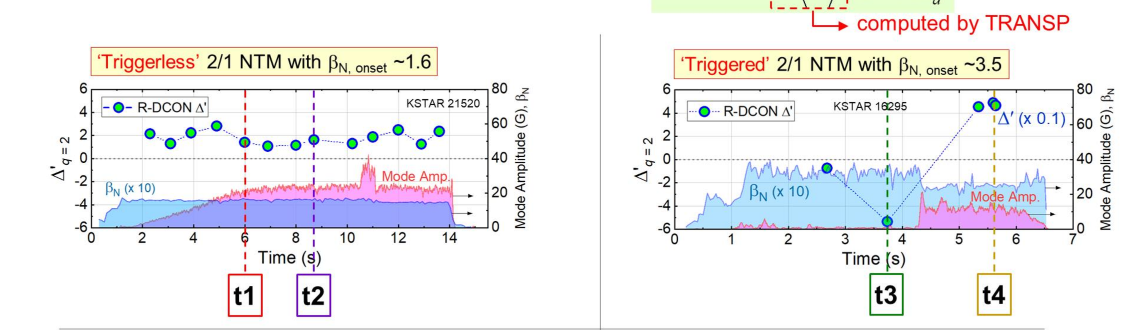
R. Fitzpatrick, Phys. Plasmas 2 (1995)
E.D. Fredrickson, Phys. Plasmas 9 (2012)

$$\tau_R \frac{dw}{dt} = \Delta'(w) + \boxed{k_{NC}\Delta_{NC}(w)} - k_{pol}\Delta_{pol}(w) - k_{GGJ}\Delta_{GGJ}(w) - \Delta_{CD}(w)$$

Neoclassical drive due to $J_{BS}$

where, $\Delta_{NC}(w) = \boxed{\frac{16 J_{BS}}{s\langle J\rangle}} \frac{w}{w^2 + w_d^2}$

computed by TRANSP

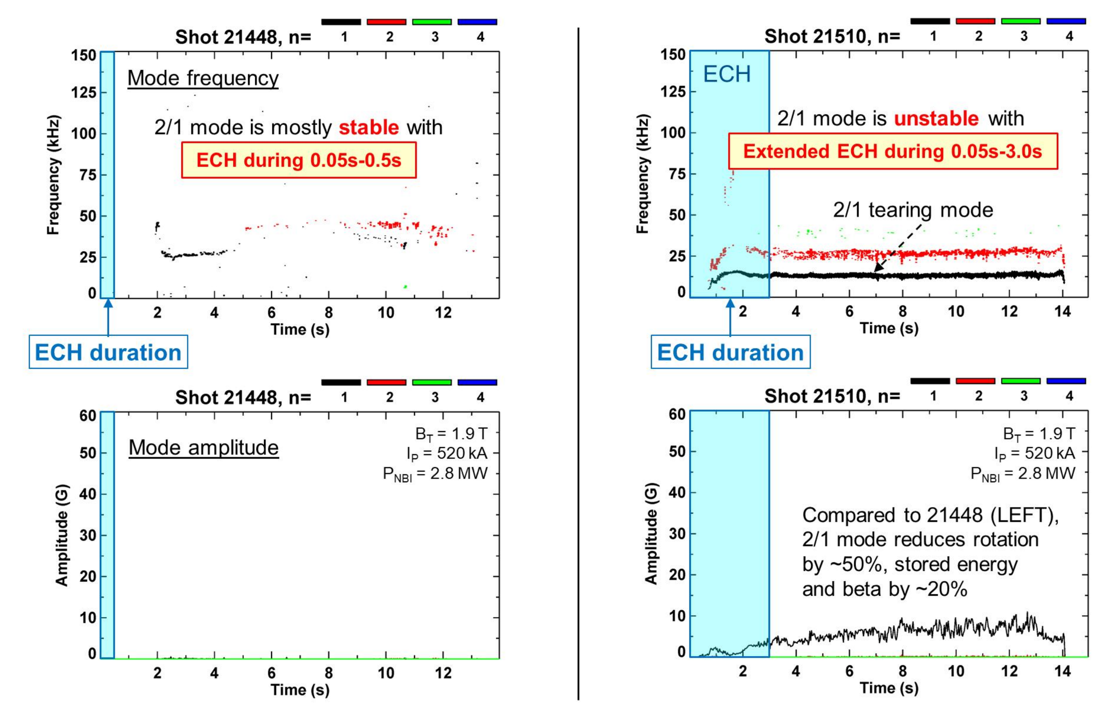


| $\lvert\Delta_{NC}\rvert = \frac{16 J_{BS}}{s\langle J\rangle}$ | t1 Triggerless NTM saturated | t2 Triggerless NTM saturated | t3 Triggered NTM unstable | t4 Triggered NTM saturated |
|---|---|---|---|---|
| | 1.58 | 1.36 | 2.80 | 0.77 |

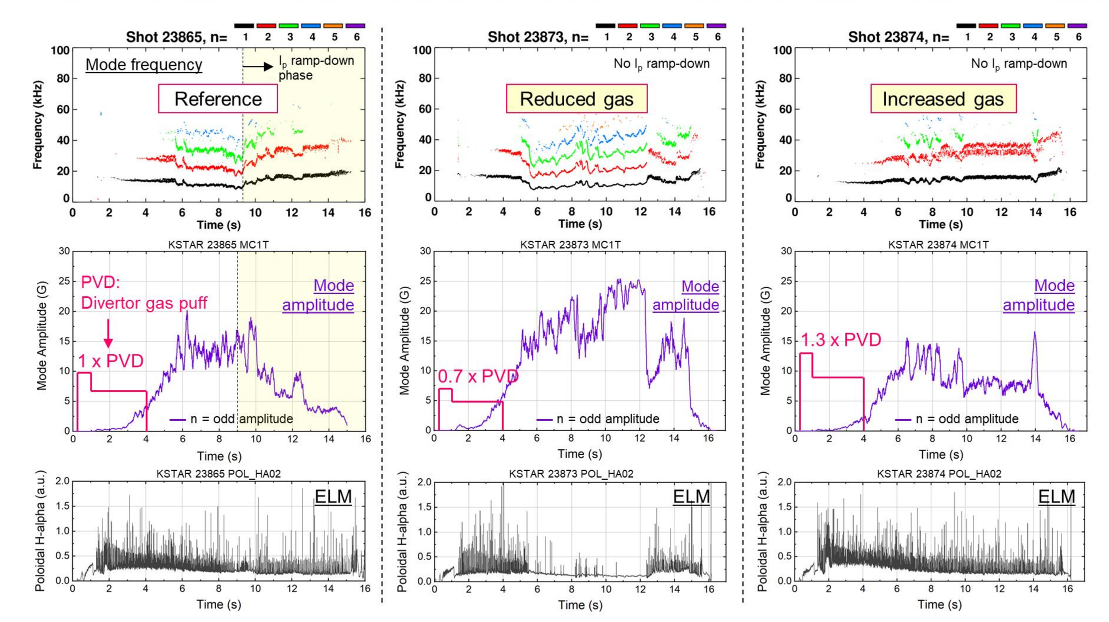
- Destabilizing effect of $J_{BS}$ is computed to be finite in both tearing mode cases

## STABILITY ALTERATION AND ACTIVE STABILIZATION OF TRIGGERLESS 2/1 NTMs

### Duration of early ECH injection is critical for triggerless 2/1 mode destabilization

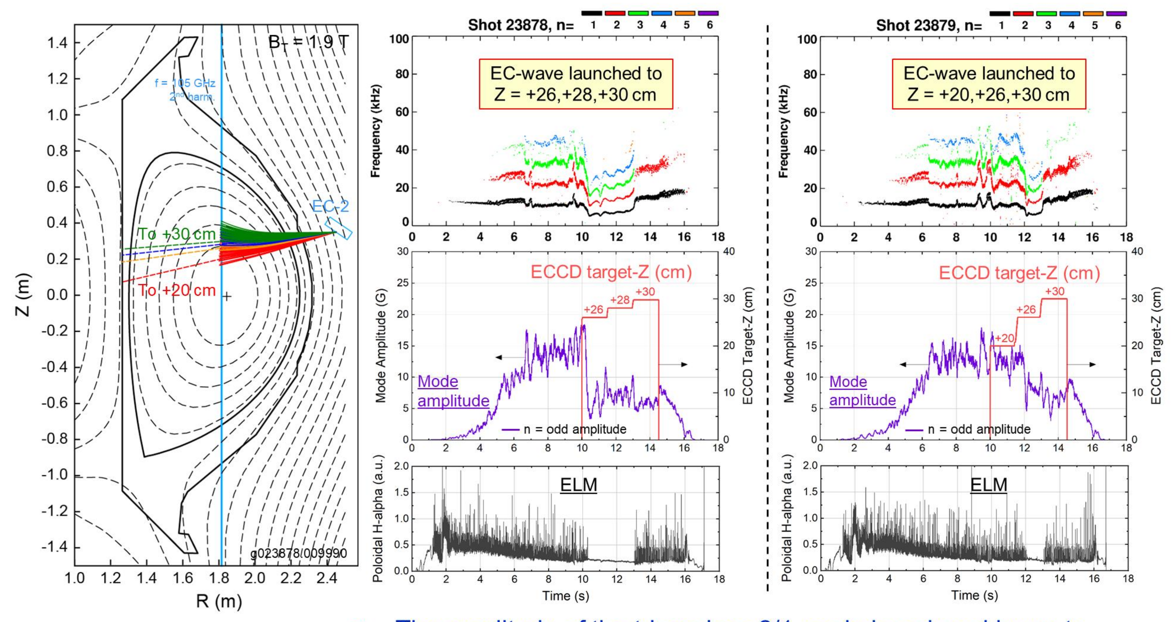


### Triggerless 2/1 amplitude is more significant with reduced density



- Triggerless 2/1 saturated amplitude increases when the plasma density is decreased by reduced gas puff
- The ELM stability is observed to vary when the measured mode amplitude is high

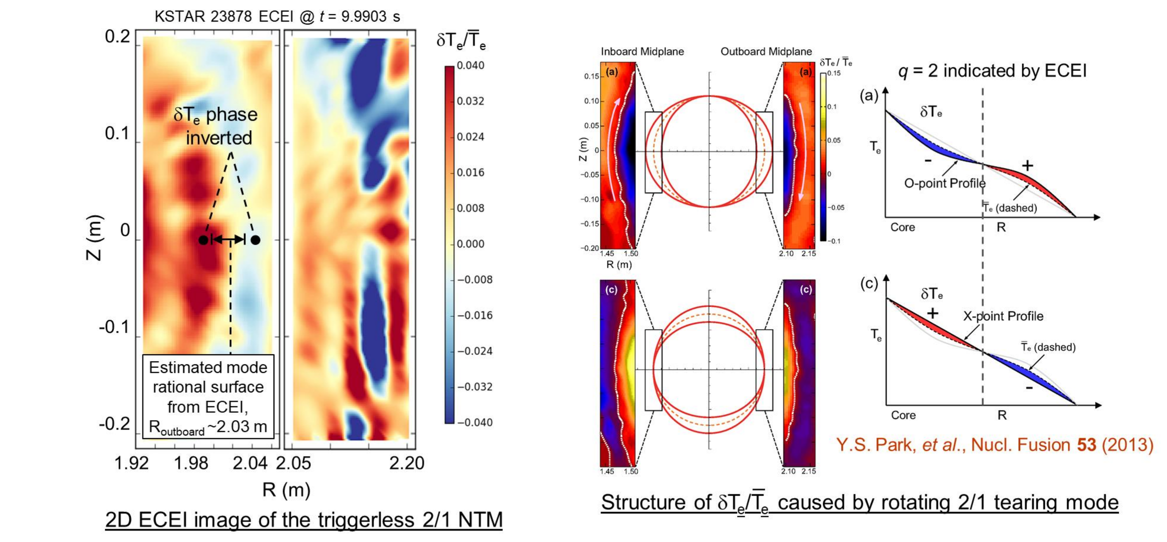
### The off-axis ECCD reduced the amplitude of triggerless 2/1 mode



TORAY-computed EC ray trajectories launched to Z = +20, +26, +28, +30 cm along the resonance layer

- The amplitude of the triggerless 2/1 mode is reduced by up to ~80% with the observed ELM quiescent phase when the ECCD is localized at Z = +26 ~ +28 cm region along the resonance layer

### The ECCD which stabilized the triggerless 2/1 mode is estimated to be deposited near the mode rational surface inferred from ECEI



2D ECEI image of the triggerless 2/1 NTM

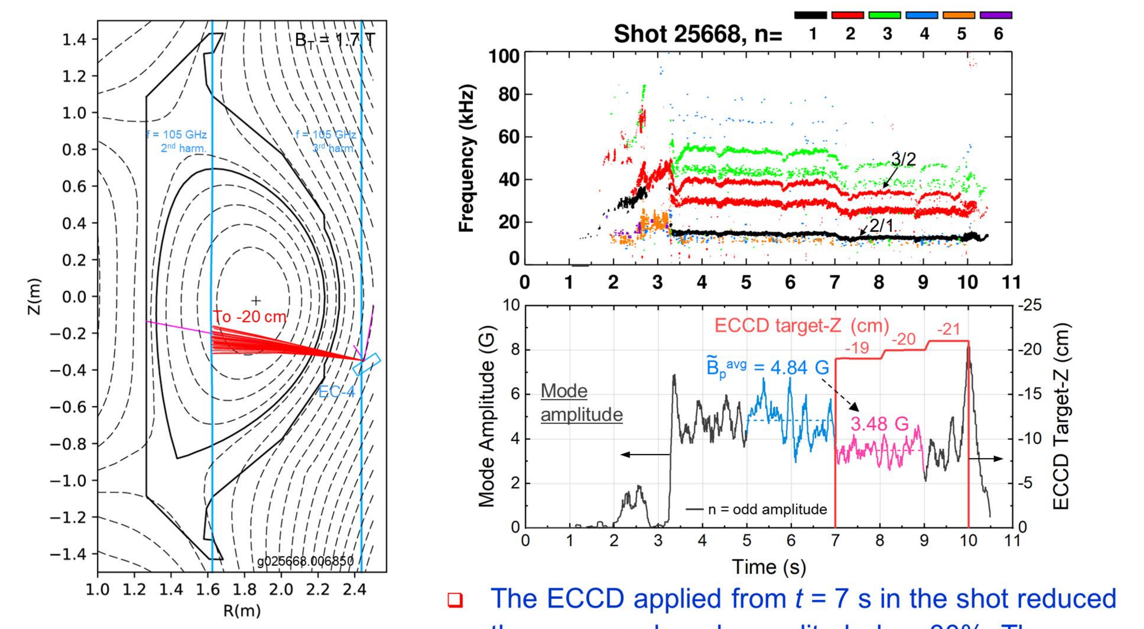
Structure of $\delta T_e/\bar{T}_e$ caused by rotating 2/1 tearing mode

Y.S. Park, et al., Nucl. Fusion 53 (2013)

- TORAY analysis indicates that the ECCD launched to the Z = +26 ~ +30 cm region that partially stabilized the 2/1 mode drives current on R = 2.03 ~ 2.06 m along the outboard midplane which is consistent with the mode rational surface location inferred from ECEI

## ACTIVE STABILIZATION OF TRIGGERED 2/1 NTMs

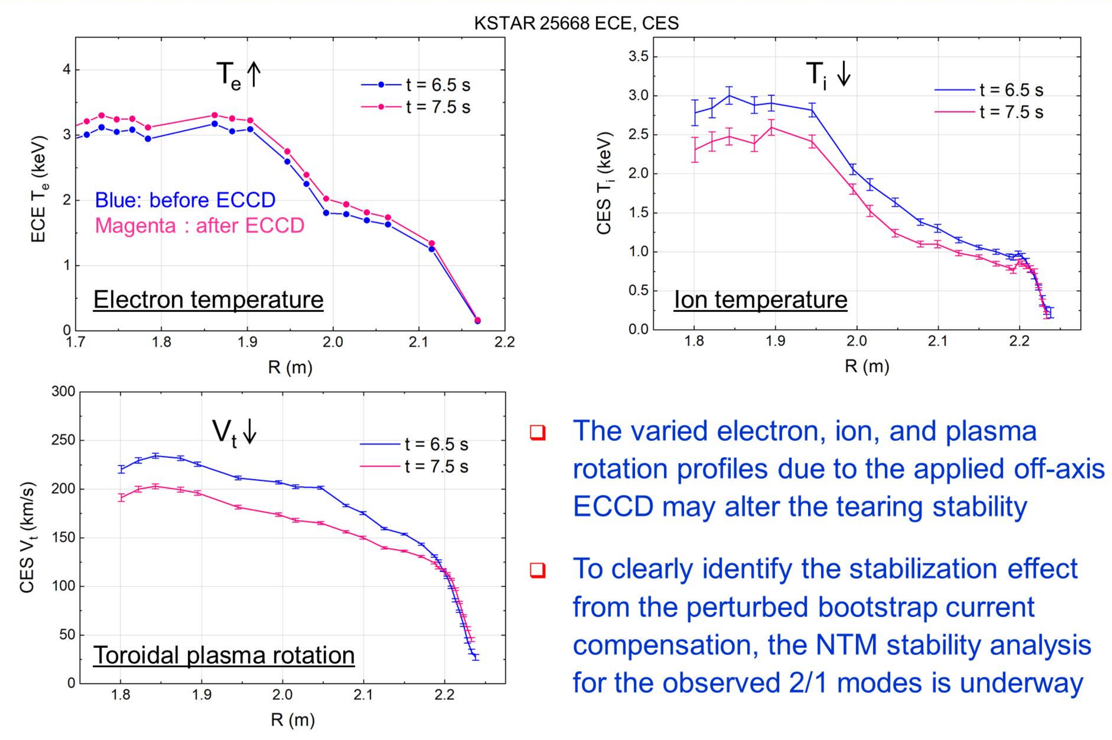
### The triggered 2/1 mode amplitude is partially stabilized by ECCD



EC ray trajectory when target-Z = -20 cm along the EC resonance layer

- The ECCD applied from $t$ = 7 s in the shot reduced the measured mode amplitude by ~30%. The applied ECCD is approximately aligned with the 2/1 mode (not an ideal alignment condition)

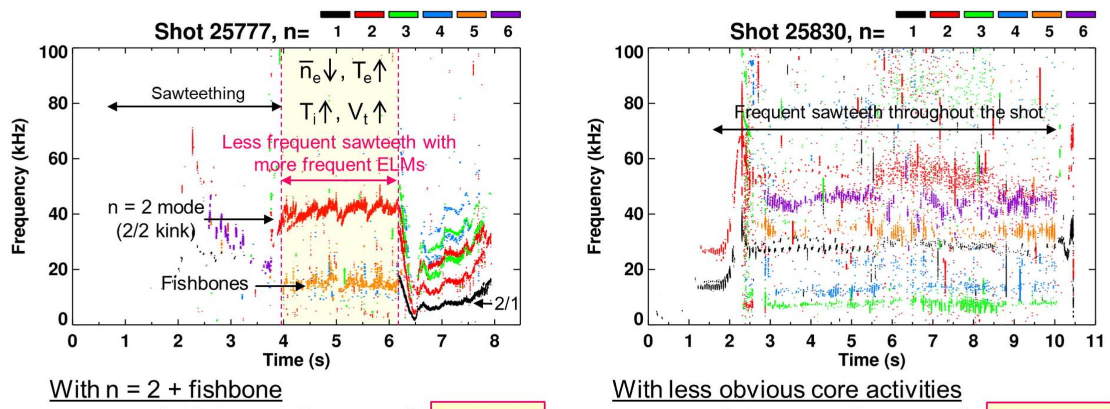
### Plasma internal profiles varied by applied ECCD can affect the NTM stability



- The varied electron, ion, and plasma rotation profiles due to the applied off-axis ECCD may alter the tearing stability
- To clearly identify the stabilization effect from the perturbed bootstrap current compensation, the NTM stability analysis for the observed 2/1 modes is underway

## EFFECT OF FISHBONES ON NTM DESTABILIZATION

### Obvious core instabilities observed in the improved confinement phase lead to triggered 2/1 NTM

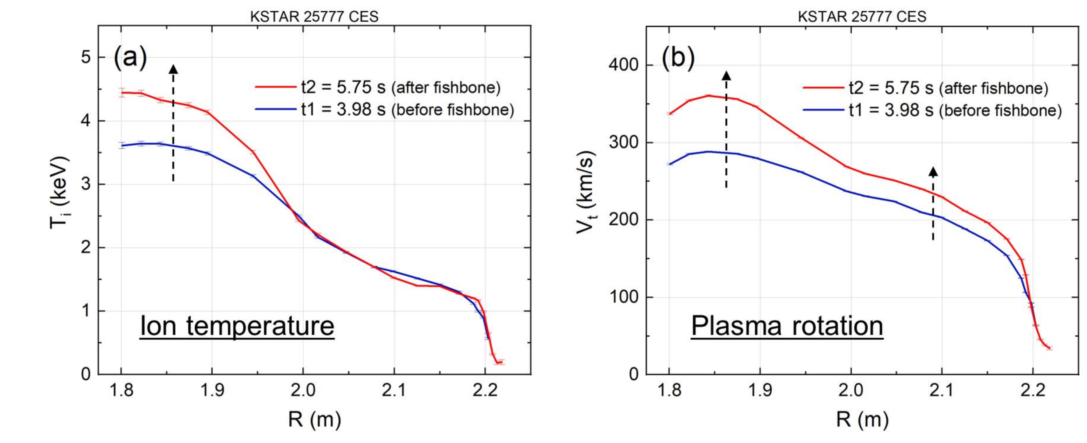


With n = 2 + fishbone → higher confinement → 2/1 onset

With less obvious core activities → lower confinement → 2/1 stable

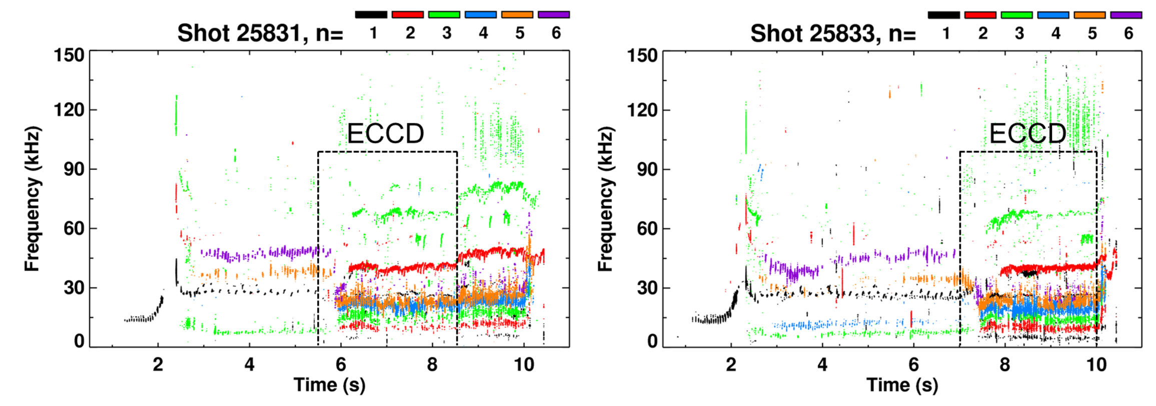
- The MHD activities in the neighboring discharges produced by using almost identical discharge setup were quite different which resulted in different NTM stability
- The low frequency fishbone instability which accompanies a weak n = 2 (presumably 2/2 kink) mode is observed in several discharges to improve $\beta_N$ and stored energy

### Plasma profiles altered by fishbone unstable to 2/1 NTM



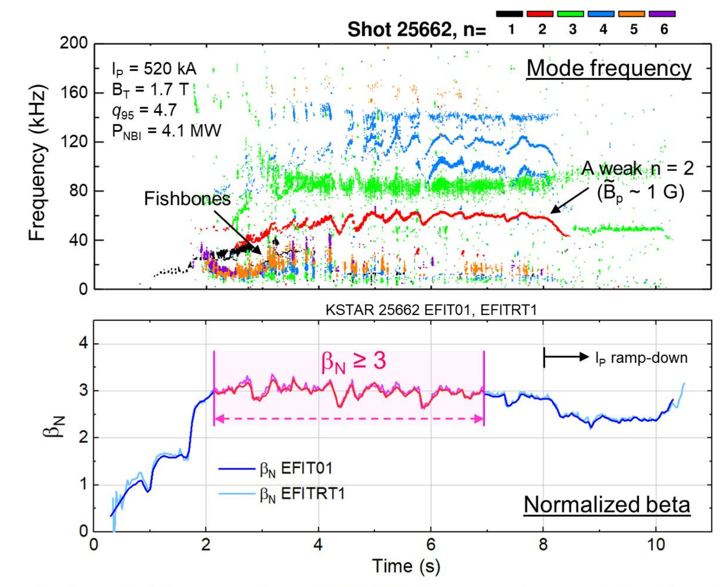
- In the period having fishbone, $T_i$, $T_e$ and $V_t$ gradually increase while $\bar{n}_e$ decreases
- The plasma profiles redistributed by fishbone is thought to be less stable to NTM consequently leading a more frequent 2/1 NTM onset observed in the experiment

### The off-axis ECCD destabilized fishbone and improved the plasma confinement



- By the off-axis ECCD applied to the discharges having no tearing mode, the fishbone with the co-existing n = 2 mode is commonly triggered shortly (~0.5 s) after the ECCD
- Both $\beta_N$ and stored energy are increased by ~10% by comparing the values before and after the ECCD

### High $\beta_N \geq 3$ is sustained for a long period with the similar fishbone instabilities existing in high $\beta_N$ phase



- With the existing fishbone, the 2/1 NTM onset is avoided in the discharge which resulted in high $\beta_N$ values greater than 3 sustained for a long time period (~5 s) with a nominal $B_T$ of 1.7 T

## CONCLUSIONS

### NTM stability and active control analysis in KSTAR

- NTM stability and active control analysis in different operational regimes
  - Triggerless 2/1 NTM stability has been altered by varied plasma density
  - The mode localized ECCD significantly reduced the triggerless NTM amplitude
  - Triggered 2/1 NTM onset now becomes a big hurdle for achieving high $\beta_N$ in KSTAR, and the observed partial stabilization of the mode will be analyzed to identify the source of the stabilization effect
  - Effect of fishbone on the plasma internal profiles and the 2/1 NTM destabilization has been confirmed
- Next Steps
  - In future NTM experiment, active NTM stabilization using feedback-actuated ECCD will be attempted
  - A higher ECCD figure-of-merit for NTM stabilization is planned to be realized by optimizing the EC launch conditions for equilibria at a lowered $B_T$ ~ 1.6 T
  - NTM stability physics model will be constructed by fitting the equation to the data from the recent experiments

## ACKNOWLEDGEMENTS

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