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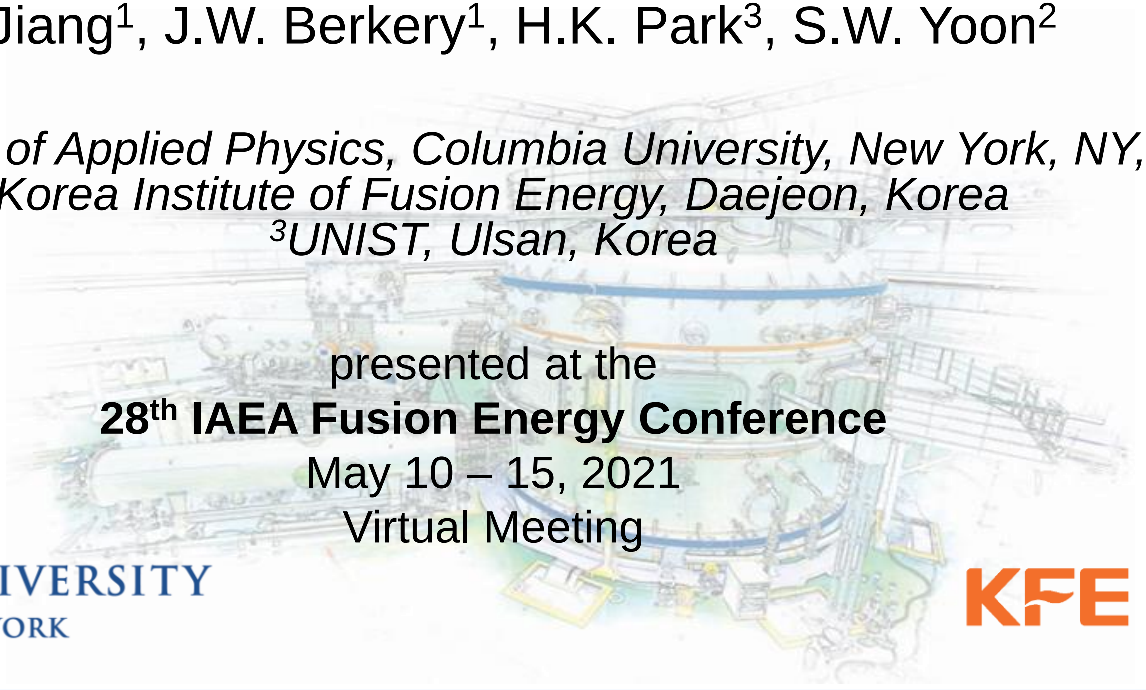
Stability of Neoclassical Tearing Modes and Their Active Stabilization in KSTAR*

Y.S. Park[1], S.A. Sabbagh[1], B.H. Park[2], M.H. Woo[2], M.J. Choi[2],
H.S. Kim[2], W.H. Ko[2], J.G. Bak[2], M. Joung[2],
Y. Jiang[1], J.W. Berkery[1], H.K. Park[3], S.W. Yoon[2]

[1]Department of Applied Physics, Columbia University, New York, NY, USA
[2]Korea Institute of Fusion Energy, Daejeon, Korea
[3]UNIST, Ulsan, Korea



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

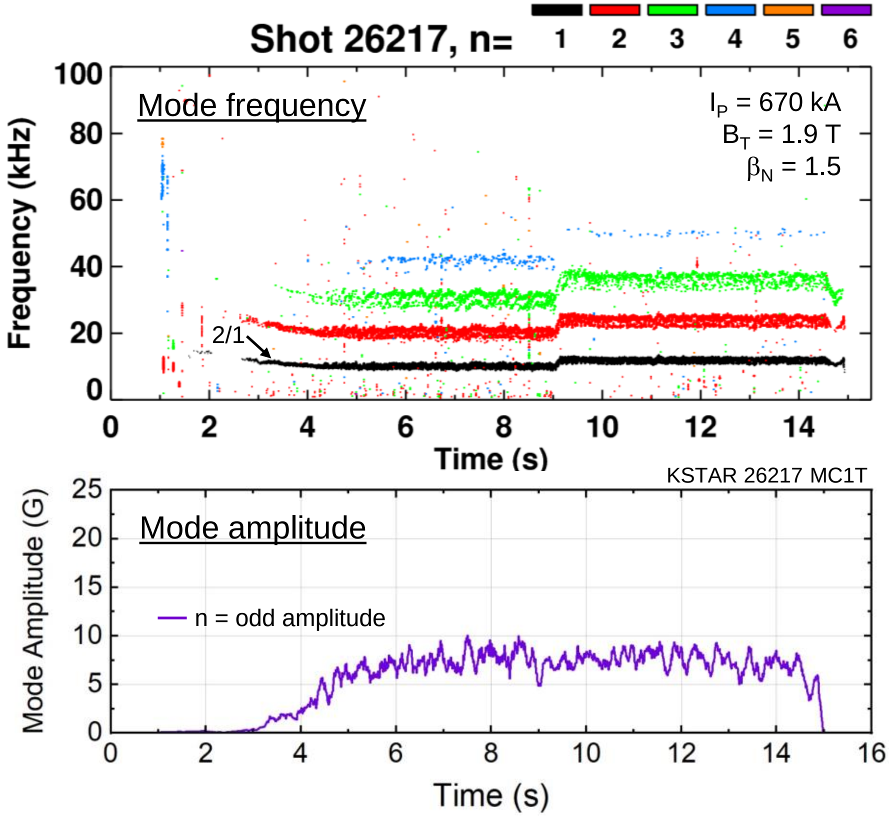
Motivation

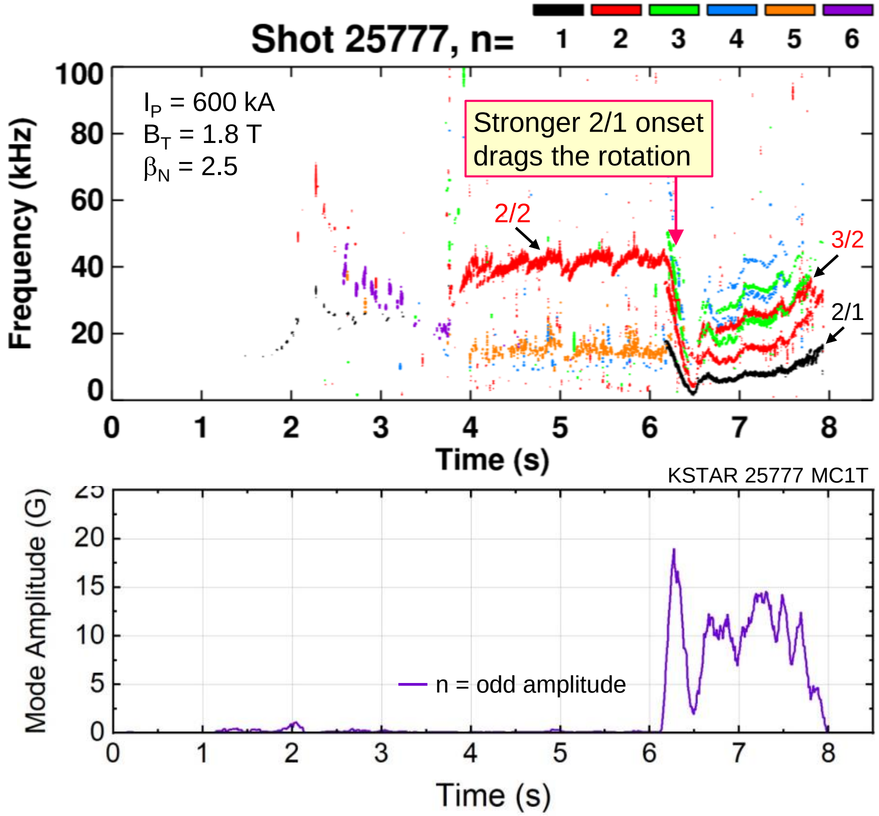
- Largely grown m/n = 2/1 NTM is limiting the sustained high performance plasma operation in KSTAR
- Avoidance and active control of NTMs using the present KSTAR actuators (ECCD/ECH) need to be investigated
- This study will contribute to construction of the NTM stability physics model and the NTM feedback 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





Stronger 2/1 onset drags the rotation

- Triggerless 2/1 mode destabilizes at intermediate β_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 β_N and W_{mhd} reduction

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

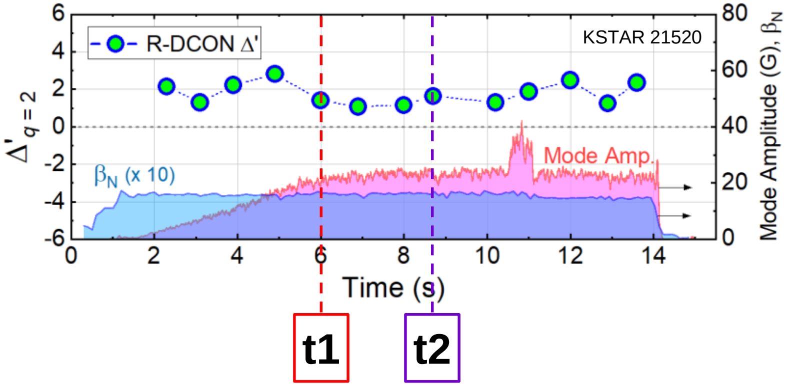
Modified Rutherford equation (MRE) describing NTM stability:

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

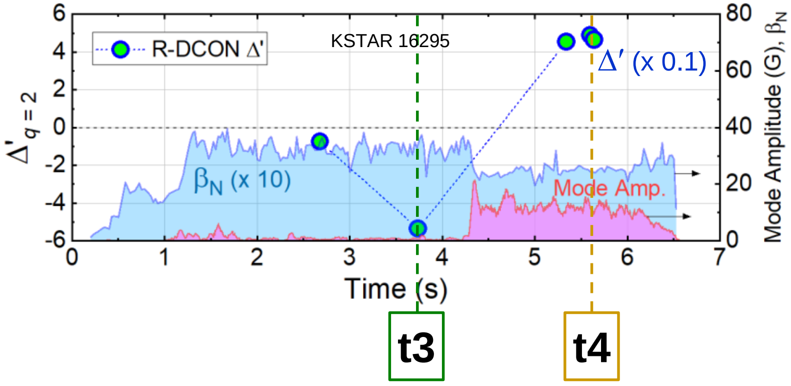
$$\tau_R \frac{dw}{dt} = \Delta'(w) + \underbrace{\boxed{k_{NC}\Delta_{NC}(w)}}_{\text{Neoclassical drive due to } J_{BS}} - k_{pol}\Delta_{pol}(w) - k_{GGJ}\Delta_{GGJ}(w) - \Delta_{CD}(w)$$

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

‘Triggerless’ 2/1 NTM with $\beta_{N,\ onset}$ ~1.6



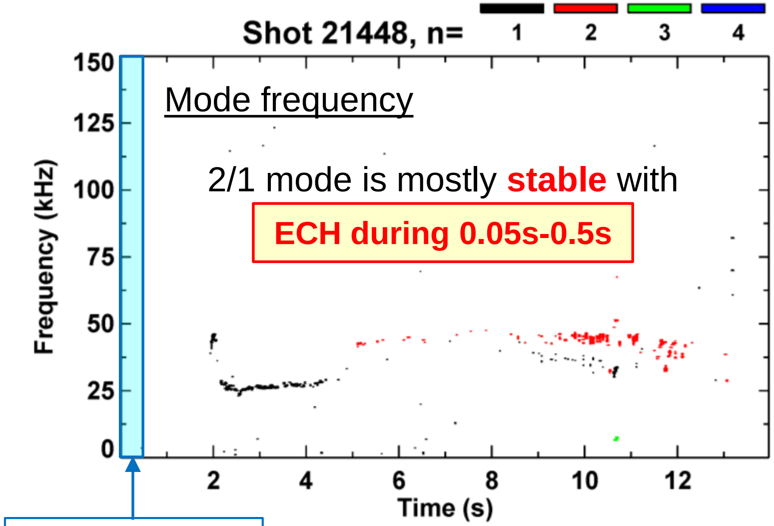
‘Triggered’ 2/1 NTM with $\beta_{N,\ onset}$ ~3.5



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

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

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

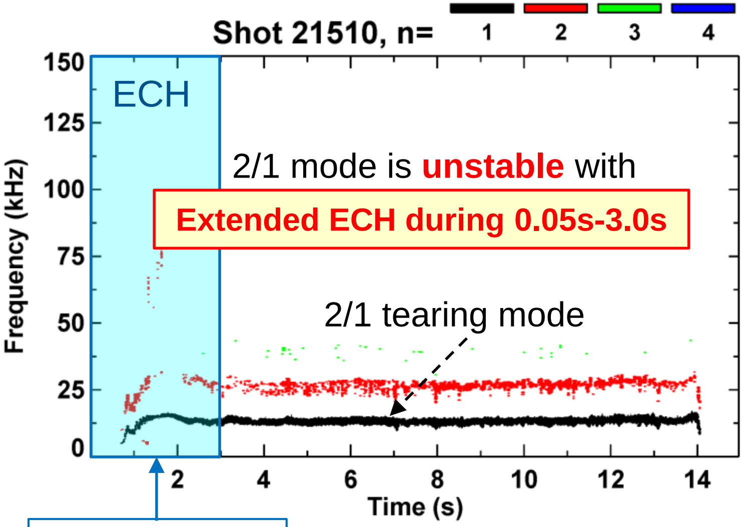


Mode frequency

2/1 mode is mostly **stable** with

ECH during 0.05s-0.5s

ECH duration



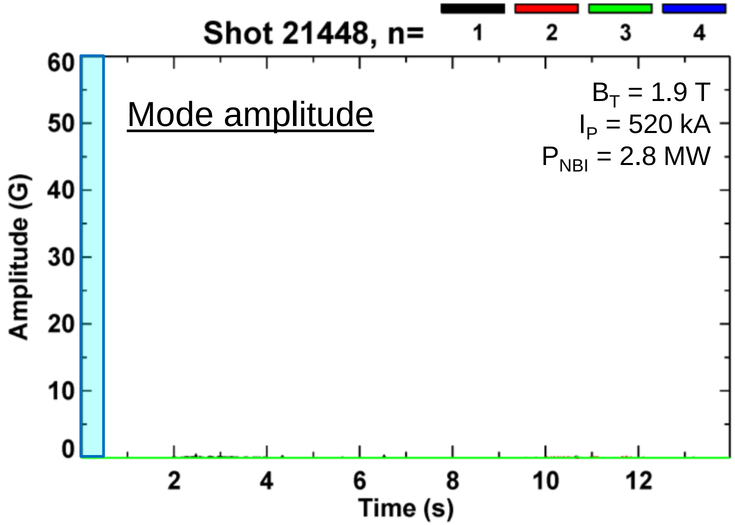
ECH

2/1 mode is **unstable** with

Extended ECH during 0.05s-3.0s

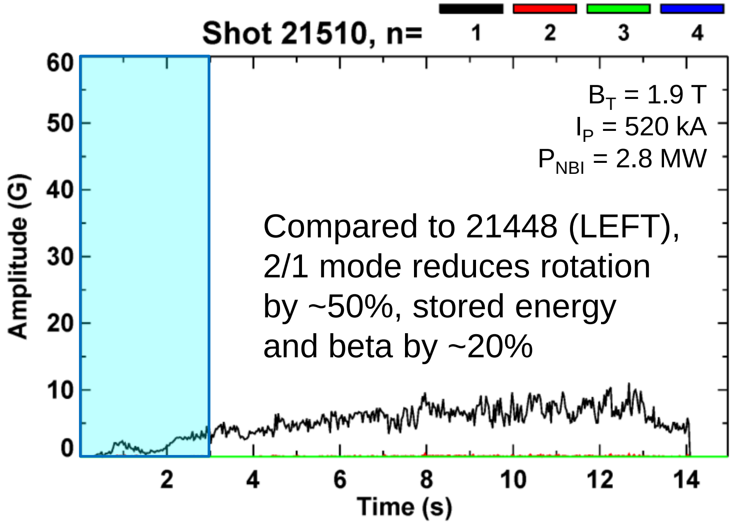
2/1 tearing mode

ECH duration



Mode amplitude

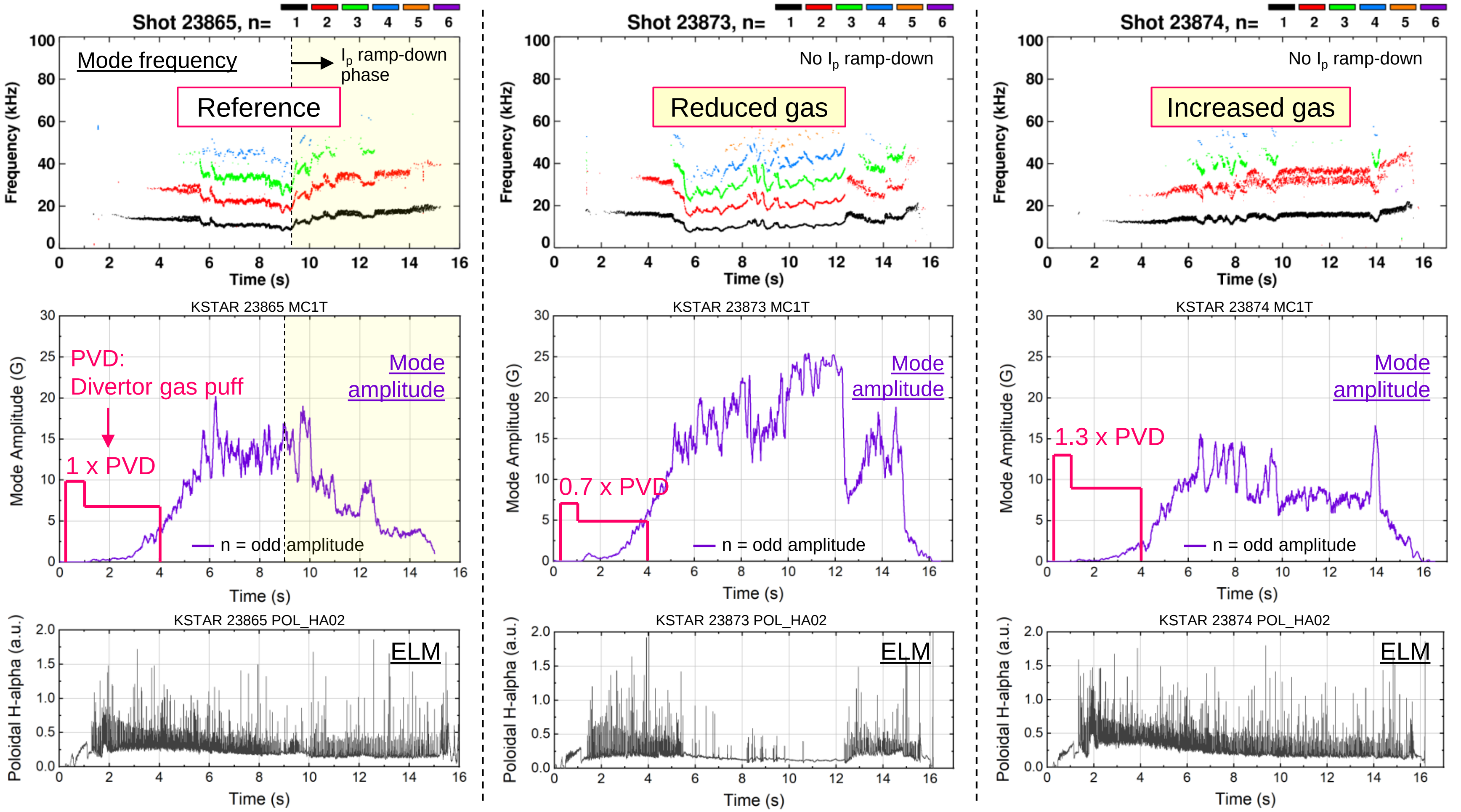
B_T = 1.9 T
I_P = 520 kA
P_{NBI} = 2.8 MW



B_T = 1.9 T
I_P = 520 kA
P_{NBI} = 2.8 MW

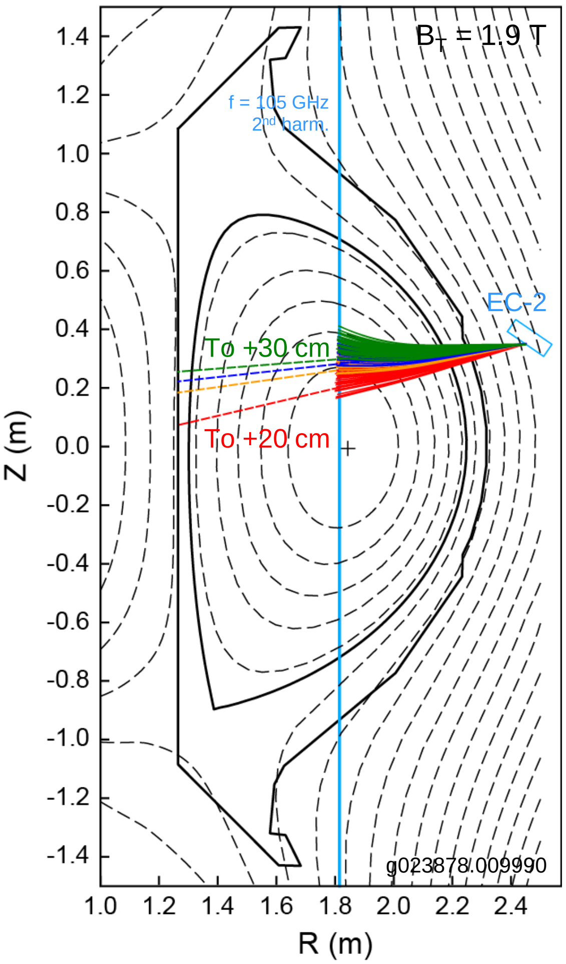
Compared to 21448 (LEFT), 2/1 mode reduces rotation by ~50%, stored energy and beta by ~20%

Triggerless 2/1 amplitude is more significant with reduced density

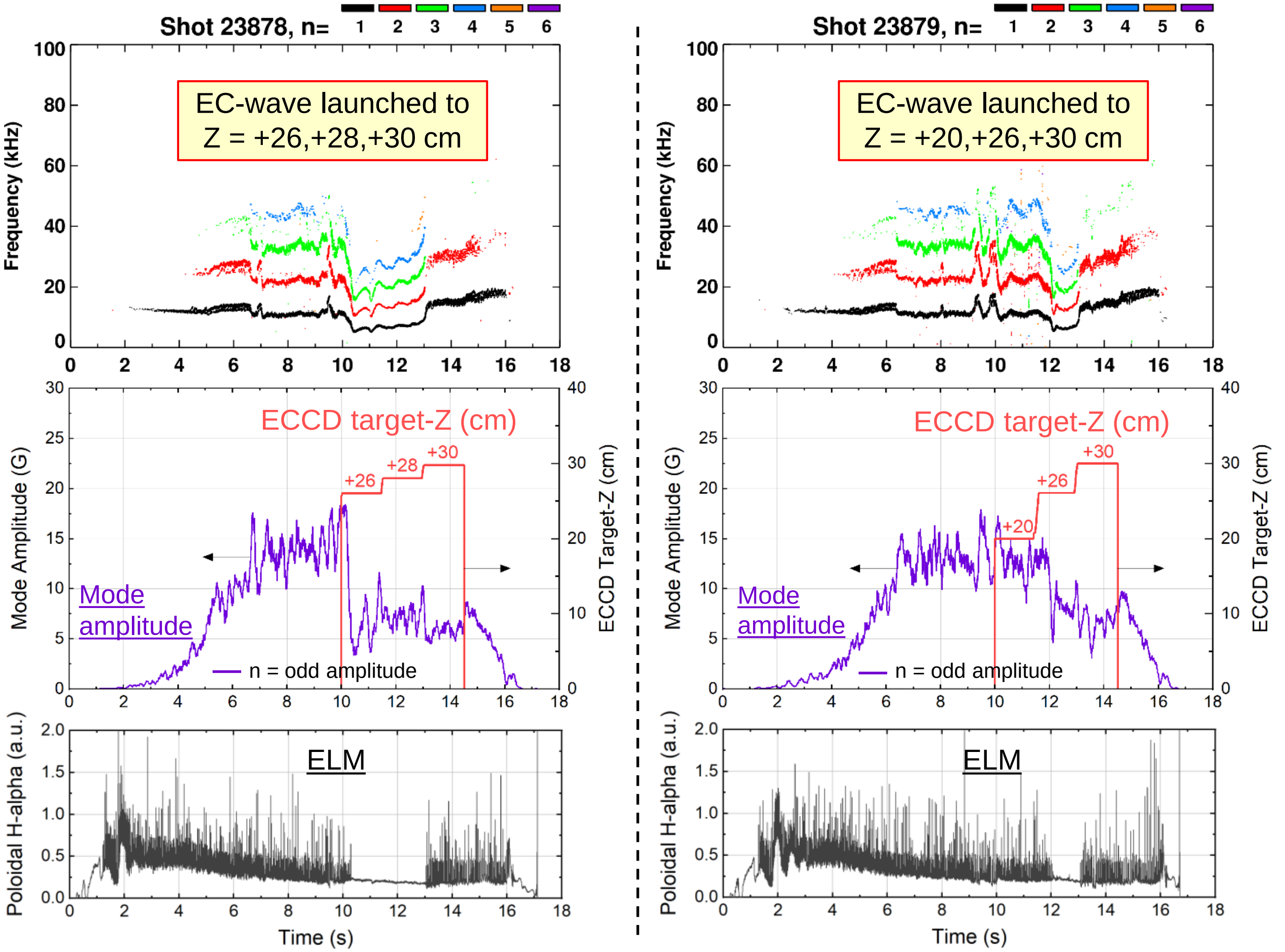


- ❑ Triggerless 2/1 saturated amplitude increases when the plasma density is decreased by reduced gas puff
- ❑ The ELM stability is observed to vary when the measured mode amplitude is high

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

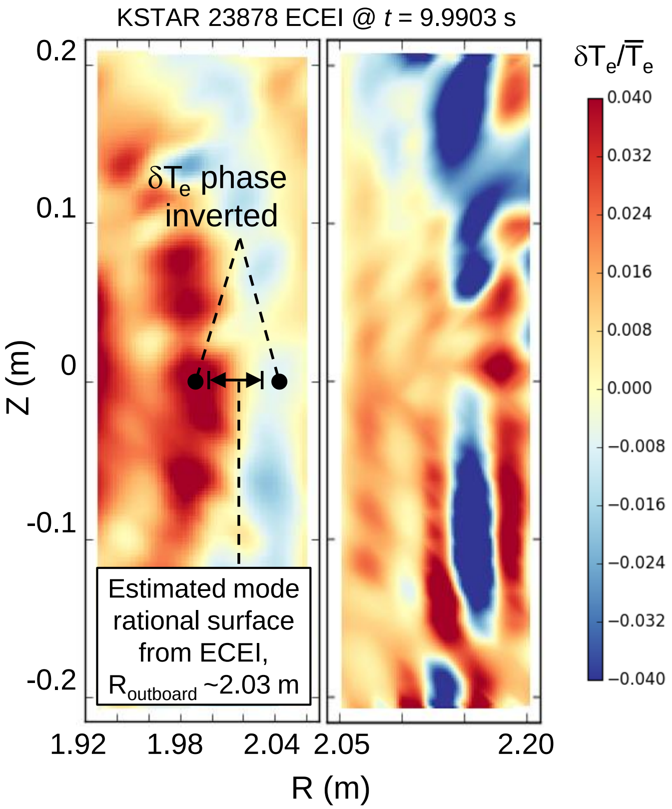


TORAY-computed EC ray trajectories ❑ launched to Z = +20, +26, +28, +30 cm along the resonance layer



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

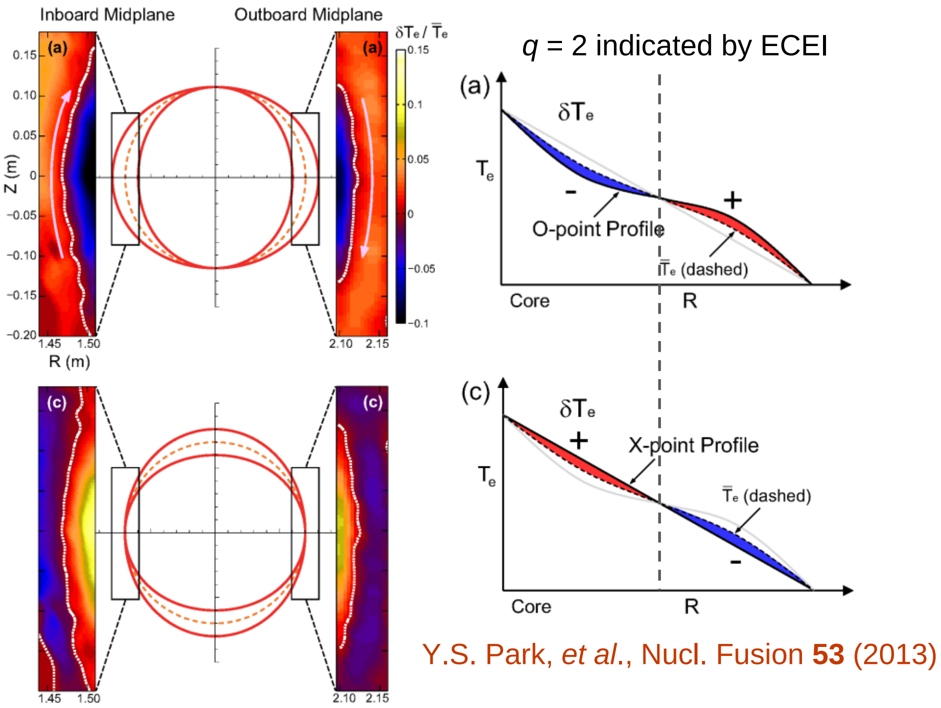
The ECCD which stabilized the triggerless 2/1 mode is estimated to be deposited near the mode rational surface inferred from ECEI



δT_e phase inverted

Estimated mode rational surface from ECEI, $R_{outboard}$ ~2.03 m

2D ECEI image of the triggerless 2/1 NTM



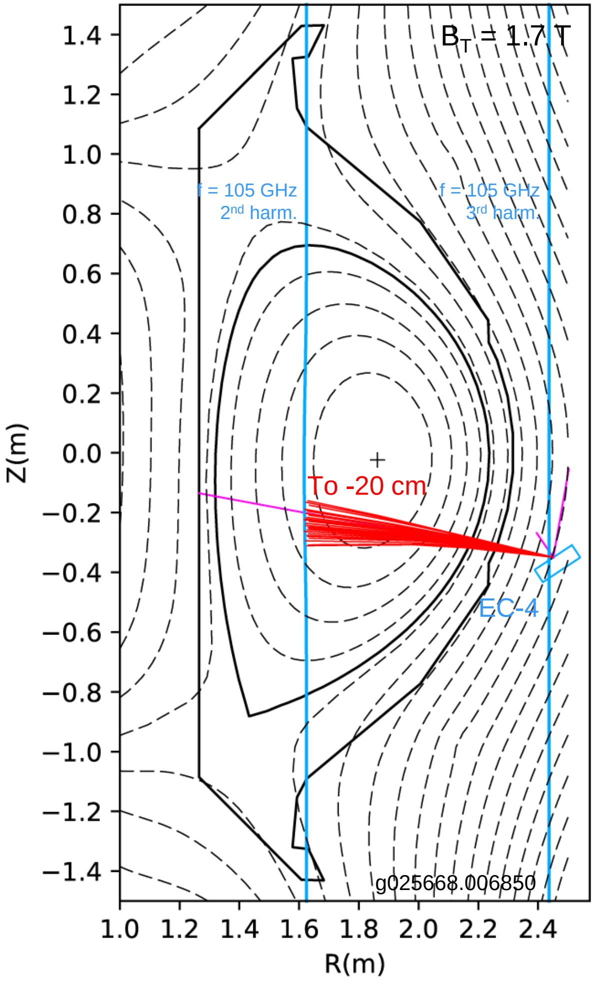
q = 2 indicated by ECEI

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

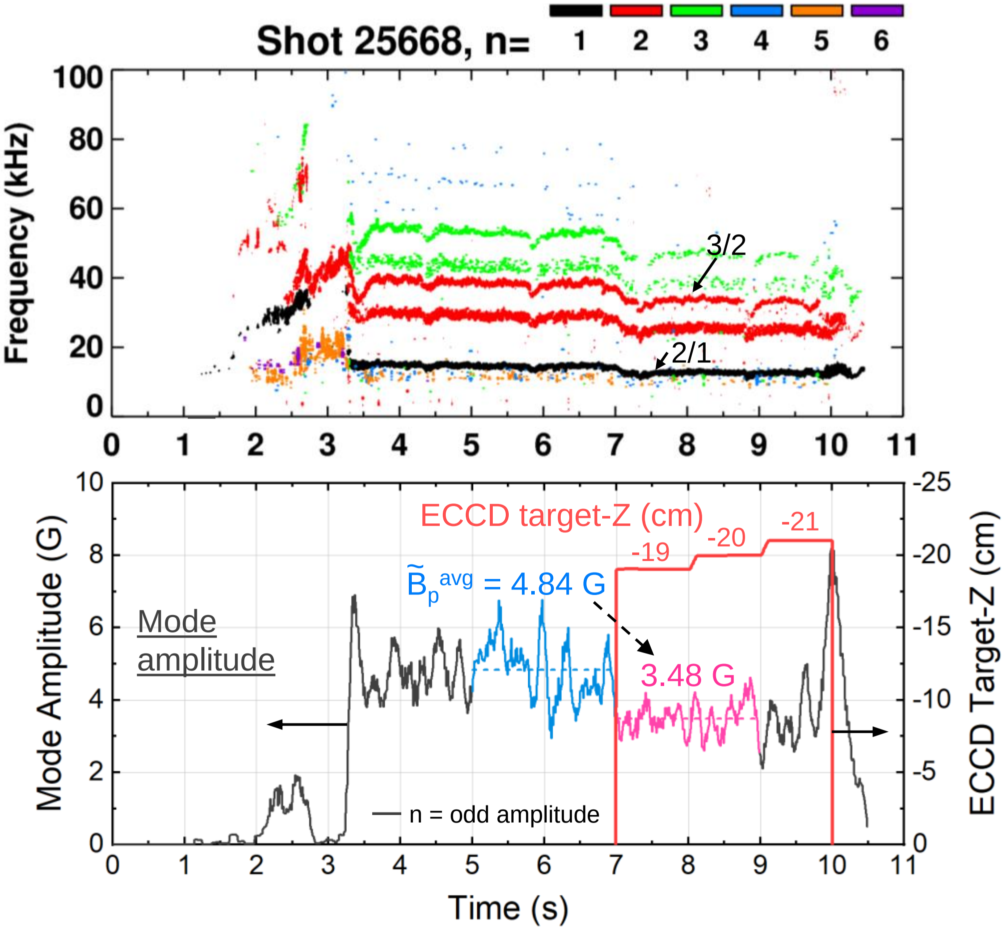
Structure of $\delta T_e/\overline{T}_e$ caused by rotating 2/1 tearing mode

- 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

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



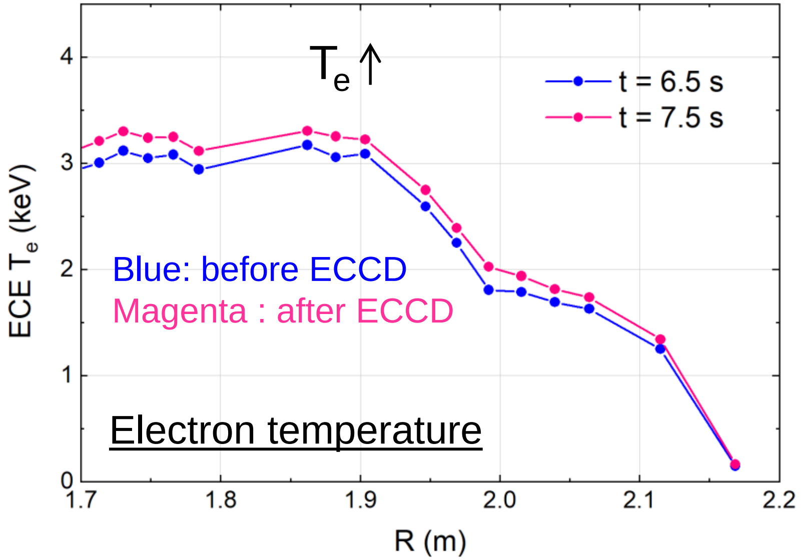
EC ray trajectory when target-Z = -20 cm along the EC resonance layer

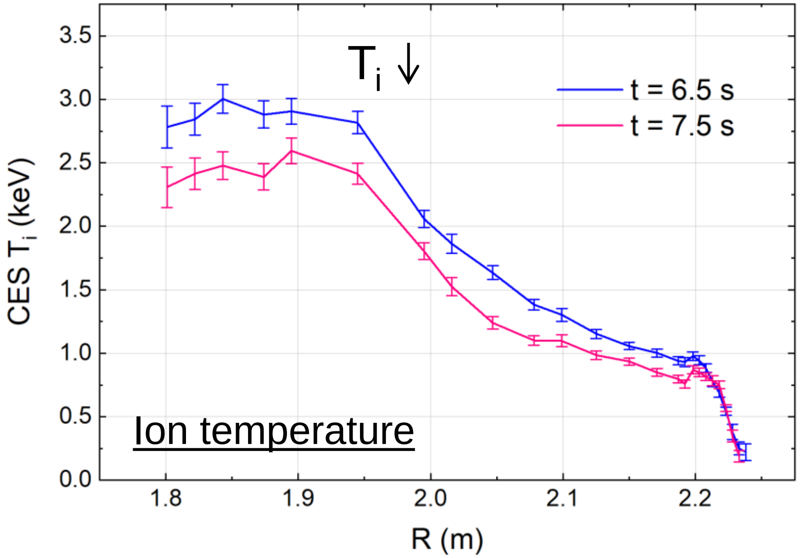


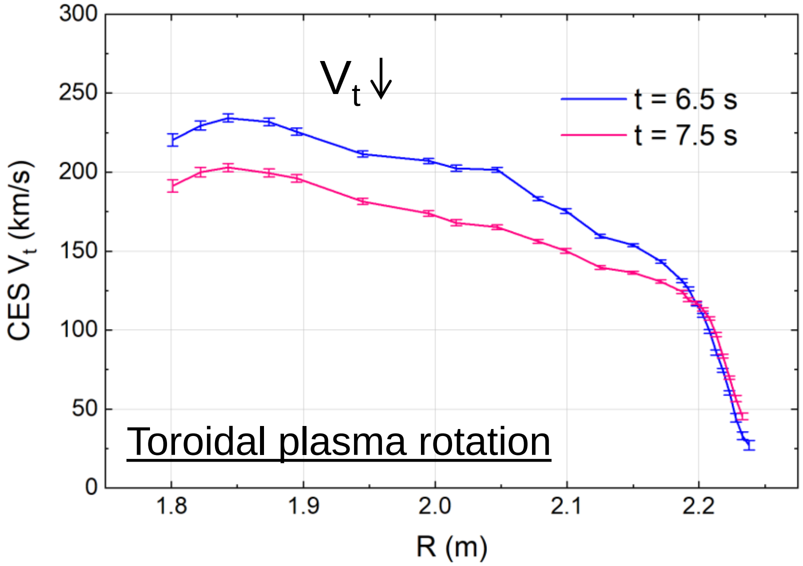
- The ECCD applied from t = 7 s in the shot reduced the measured mode amplitude by ~30%. The applied ECCD is approximately aligned with the 2/1 mode (not an ideal alignment condition)

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

KSTAR 25668 ECE, CES

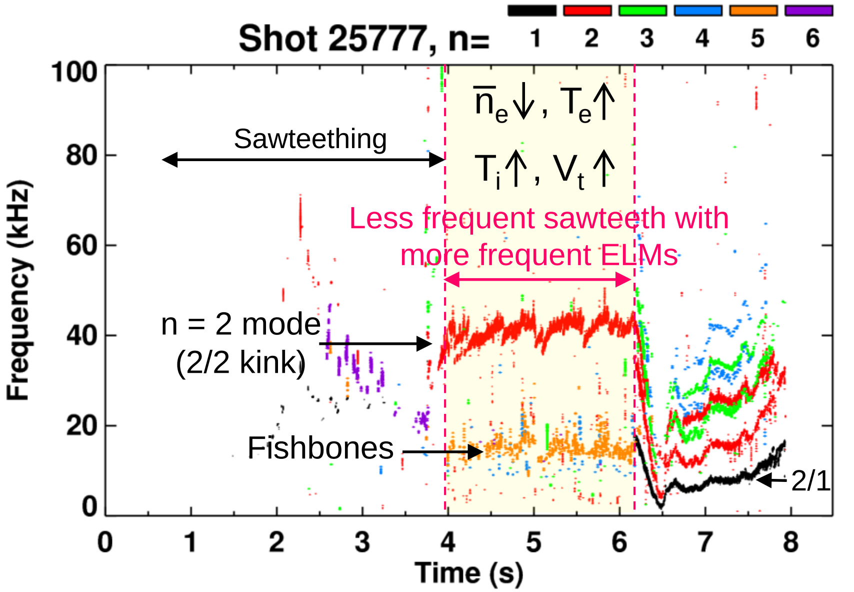


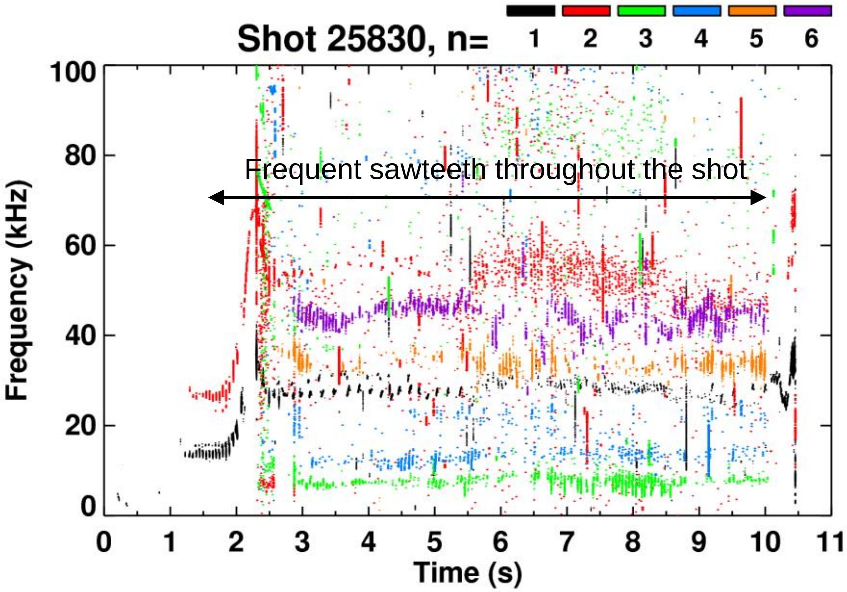




- ❑ The varied electron, ion, and plasma rotation profiles due to the applied off-axis ECCD may alter the tearing stability
- ❑ To clearly identify the stabilization effect from the perturbed bootstrap current compensation, the NTM stability analysis for the observed 2/1 modes is underway

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



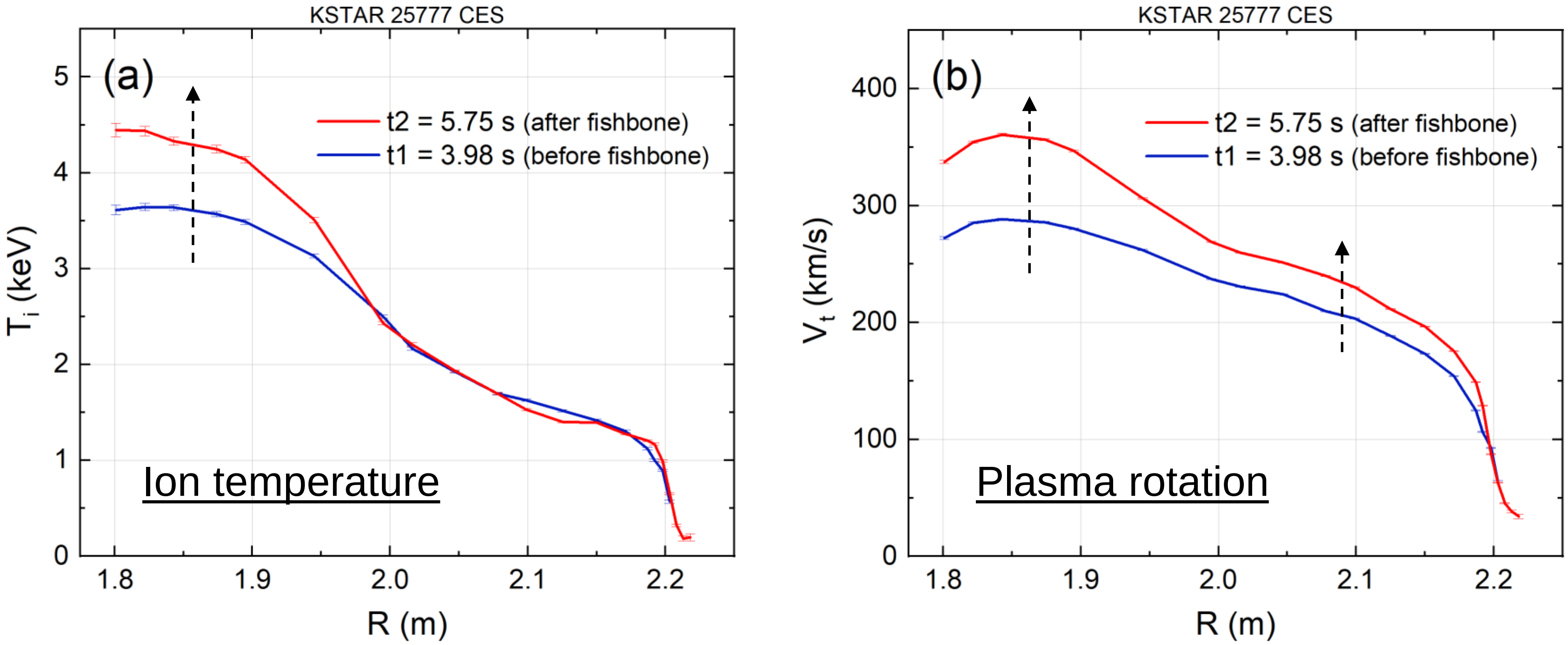


With n = 2 + fishbone → higher confinement → 2/1 onset

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

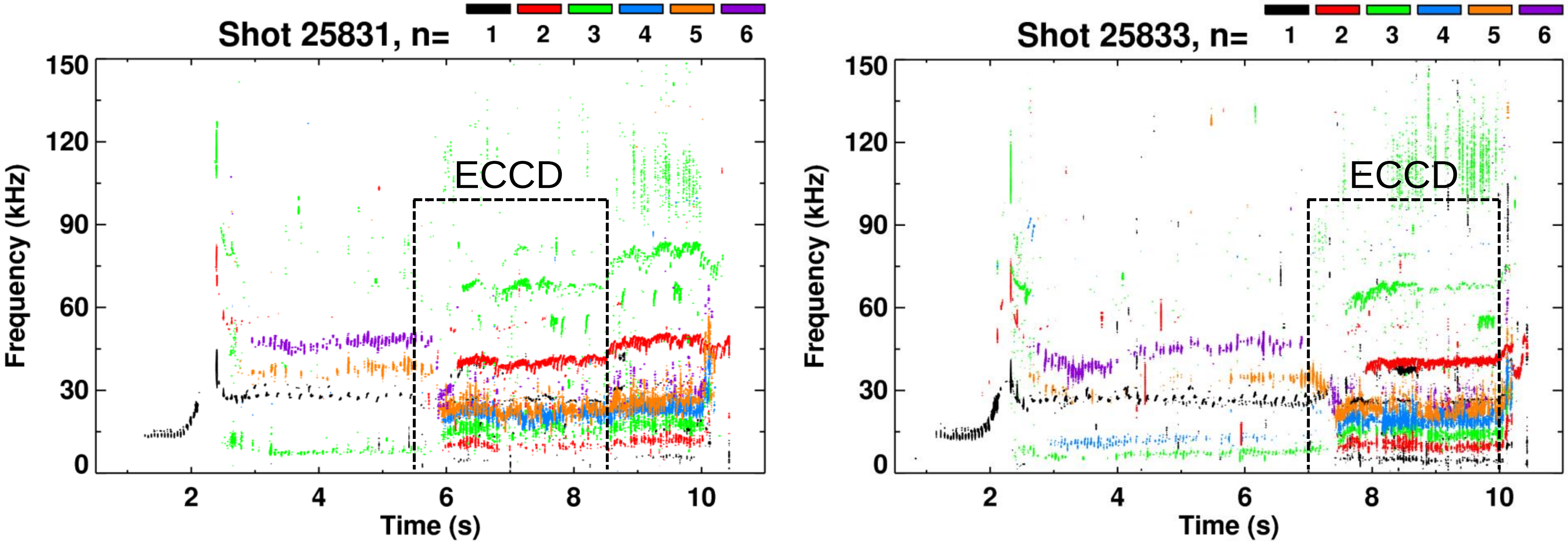
- The MHD activities in the neighboring discharges produced by using almost identical discharge setup were quite different which resulted in different NTM stability
- The low frequency fishbone instability which accompanies a weak n = 2 (presumably 2/2 kink) mode is observed in several discharges to improve β_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 are thought to be less stable to NTM consequently leading to a more frequent 2/1 NTM onset observed in the experiment

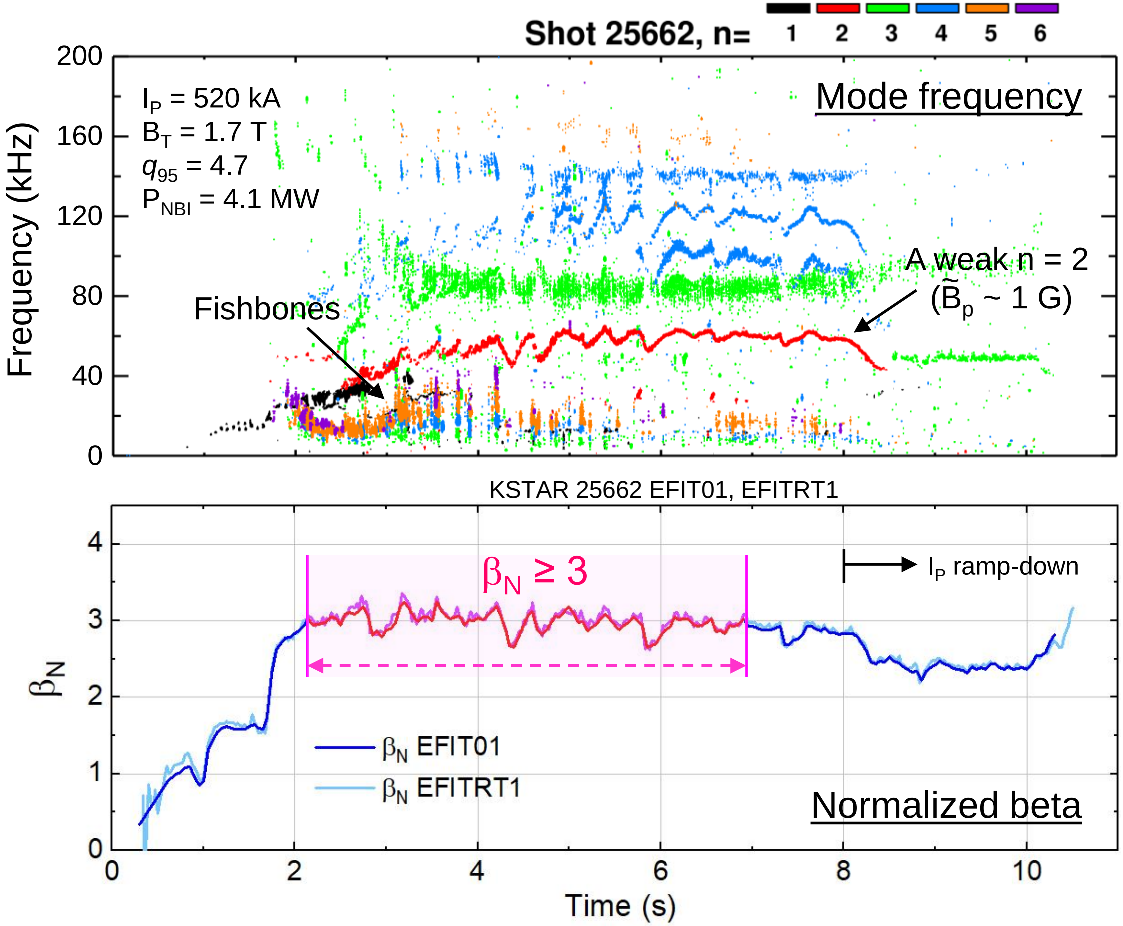
The off-axis ECCD destabilized fishbone and improved the plasma confinement



- 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 β_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 β_N phase



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

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 β_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 $B_T \sim 1.6$ T
  - NTM stability physics model will be constructed by fitting the equation to the data from the recent experiments