3rd Trilateral International Workshop on Energetic Particle Physics

Interplay of KSTAR high β_N Mission and fast-ion transport

Jisung Kang

Korea Institute of Fusion Energy, Daejeon, Republic of Korea

Introduction

Since I have conducted high β_N steady-state mission,
I have thought how KSTAR experiment result could contribute for fusion community

Relatively good points

Pulse-length(Plasma current & Neutral Beam)

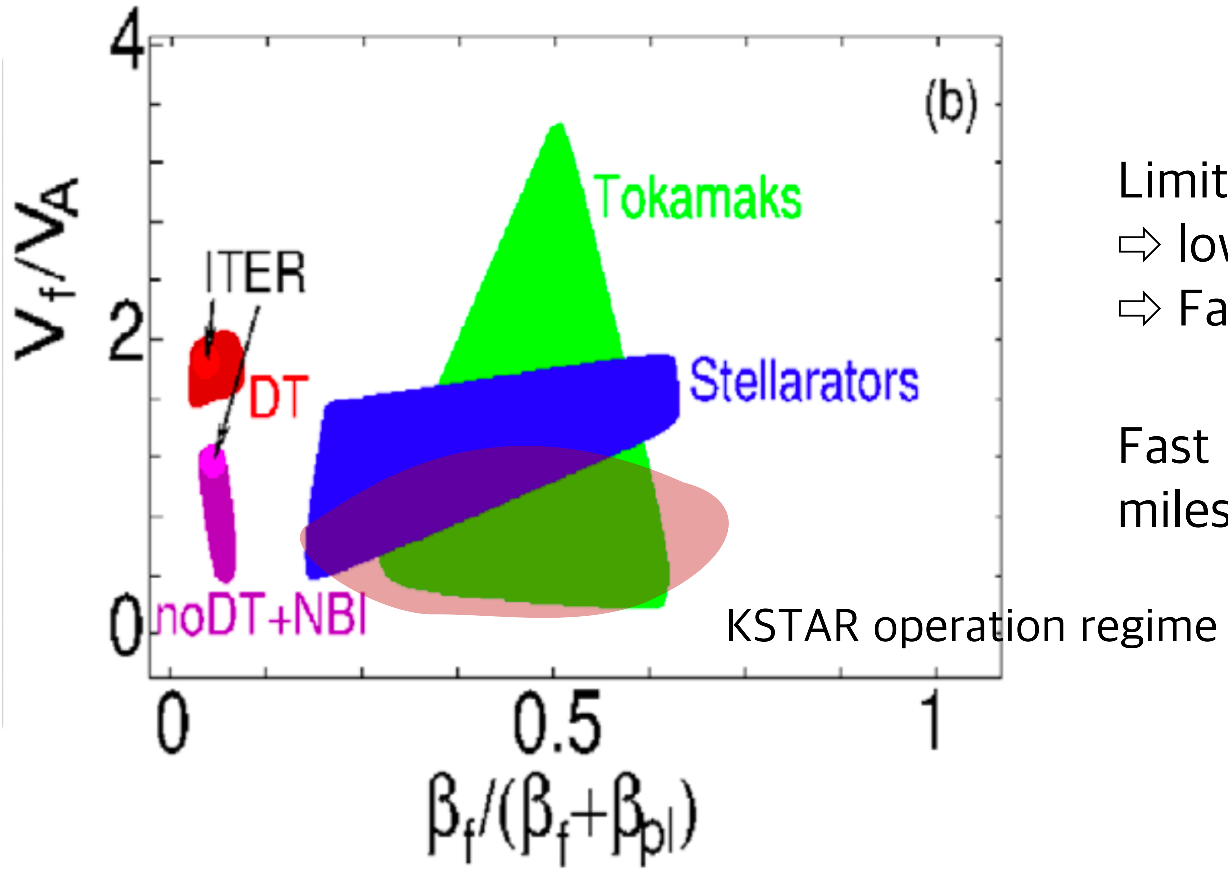
Relatively bad points

Low heating power, still needs time for diagnostic upgrade.
Overall magnetic coil controllability since it is superconductor

⇨ **KSTAR must demonstrate long-pulse steady-state high β_N operation feasibility.**

Introduction

For High β_N steady-state operation, fast particle transport is crucial in KSTAR



Why?

Limited heating power
⇨ low density operation to avoid radiation power
⇨ Fast ion energy fraction is high.

Fast particle pressure is crucial for short term milestone in KSTAR: β_N ~ 3 for 30s.

KSTAR data is overlapped at Gorelenkov NF 2014 Figure 45. (b)

Contents

What we have observed (mainly performance improvement) related with fast-ion modes.

How much we have experimentally achieved high β_N mission.

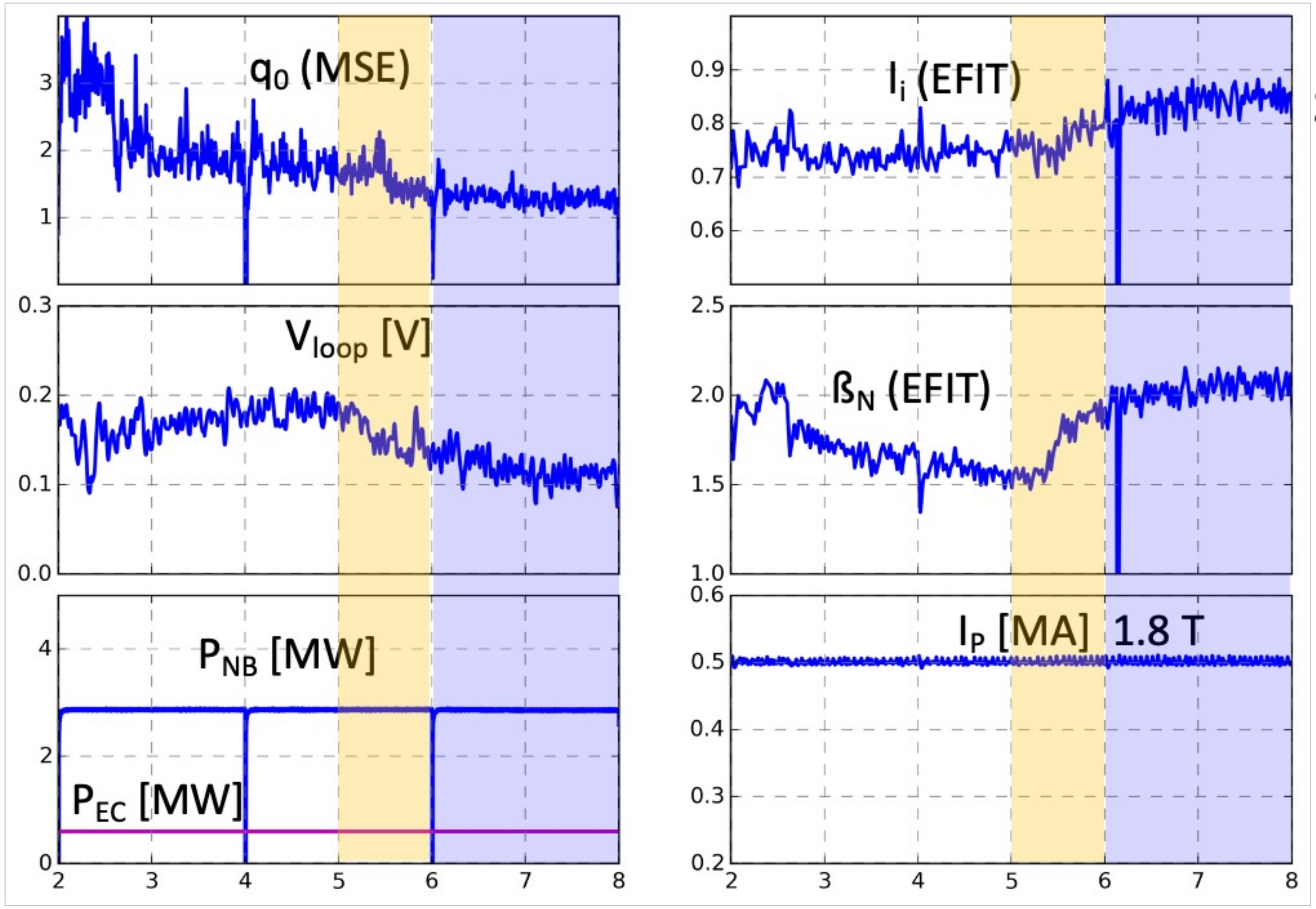
Remaining issues on long-pulse operation

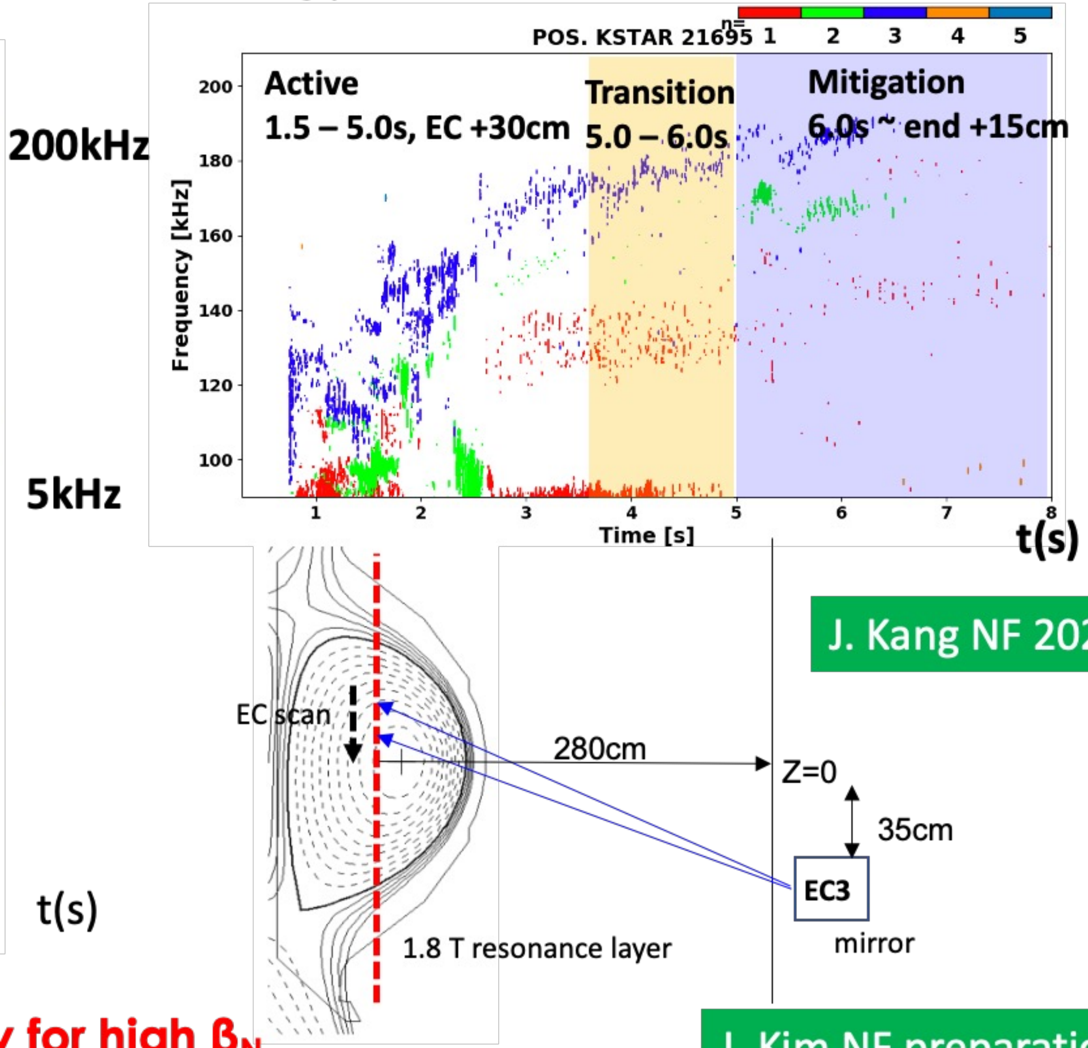
AE suppression by co-ECCD scan in high q_{min} ($q0 > 1.5$) discharge in 2018

High q_{min} AE control experiments in 2018

Only one Control Knob | Z_{EC} scan: +30cm → +15cm (5.0s – 5.5s)

AE control reproduced by ECCD heating position even low q95 and beam heating power.





J. Kang NF 2020

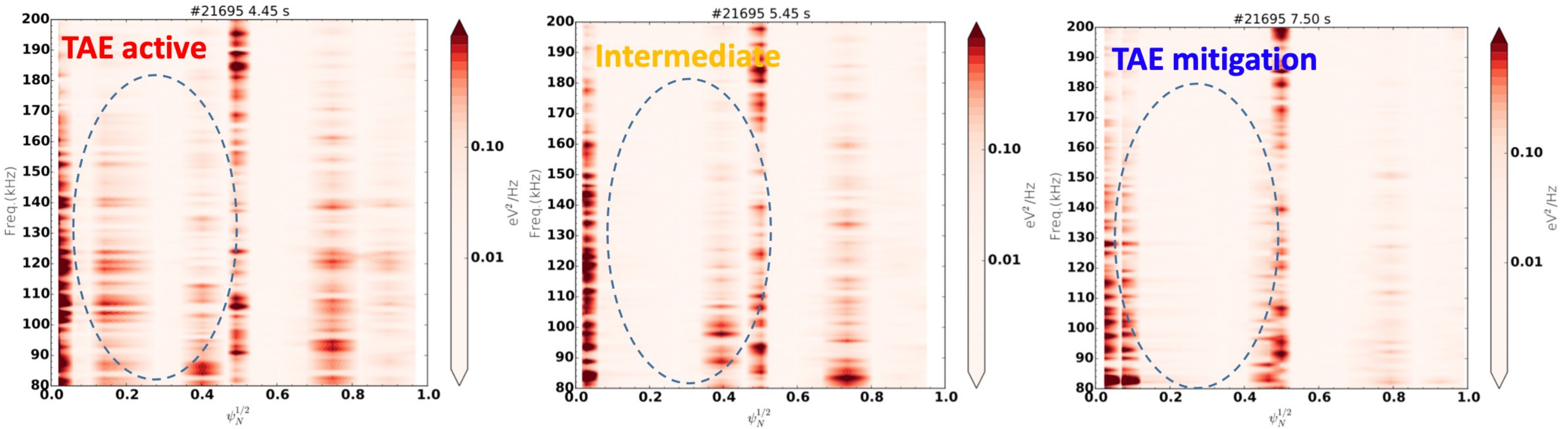
J. Kim NF preparation

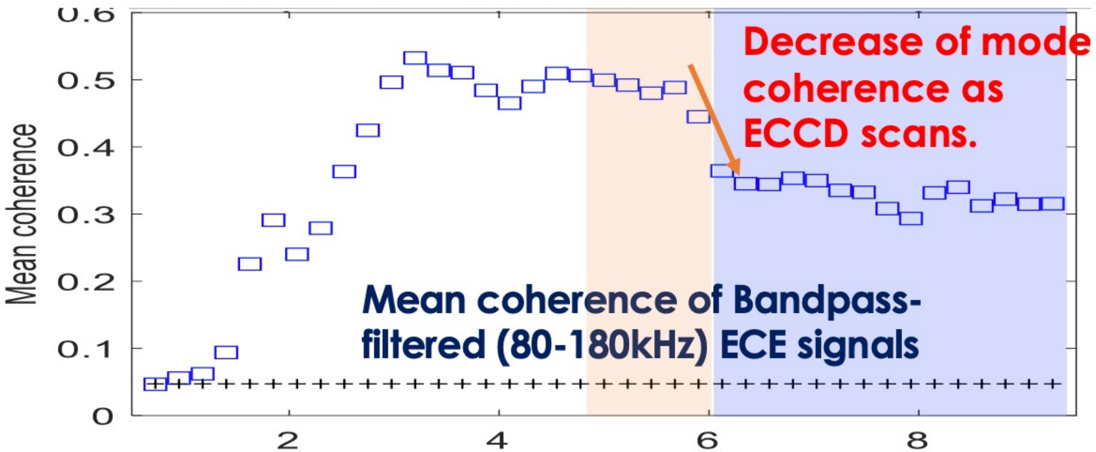
✓ **Fast ion confinements and related NB heating is the key for high β_N**

ECE spectrogram & coherence → it could be Alfvènic (internal) modes

High q_{min} AE control experiments in 2018

Comparison with the internal measurements (ECE)



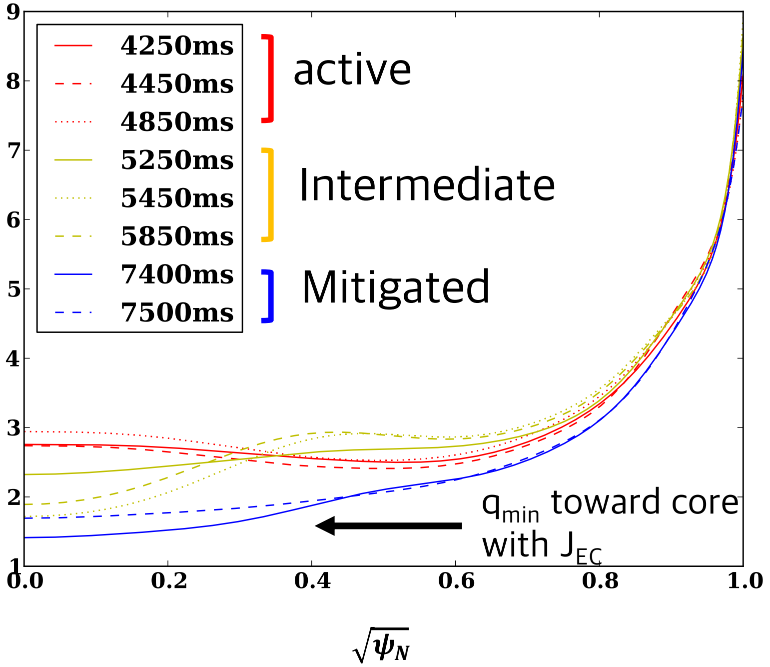


- ***Mean coherence of band-passed (80 – 180 kHz) ECE signals shows the Alfvenic mode mitigation.***
- ***AE-active & Intermediate phases exhibit the strong core modes in the core ECE signal.***
- ***AE-mitigation phase shows weak or no core modes.***

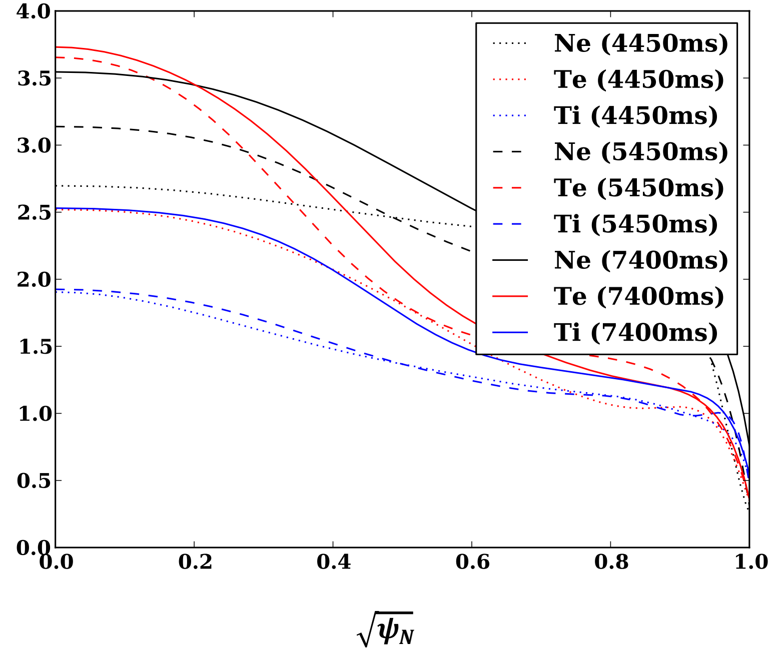
J. Kim et al., IAEA TM on EP (EPPI) 2019

Insight from sequence of kinetic equilibrium reconstruction
- q & kinetic profile evolution

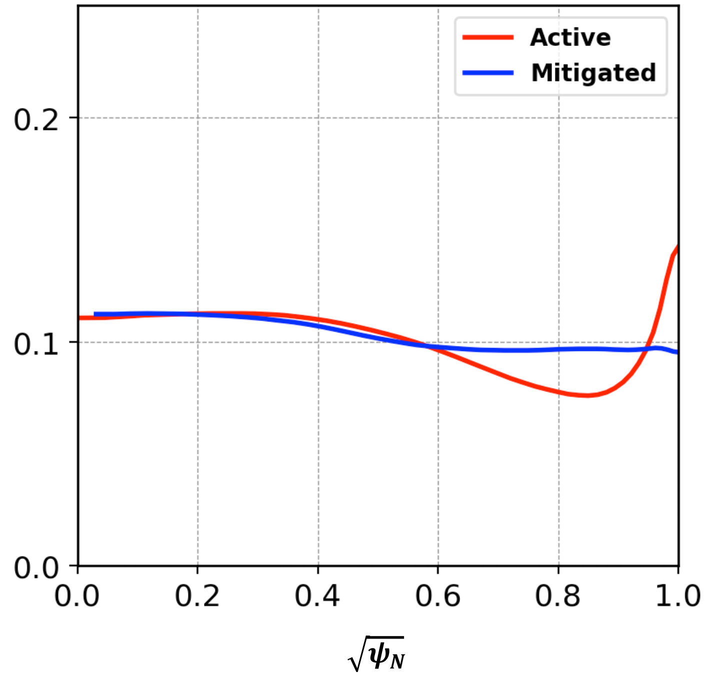
Safety Factor



Kinetic profiles [n_e - 10^{19} #m^{-3} , T_e/T_i - keV]

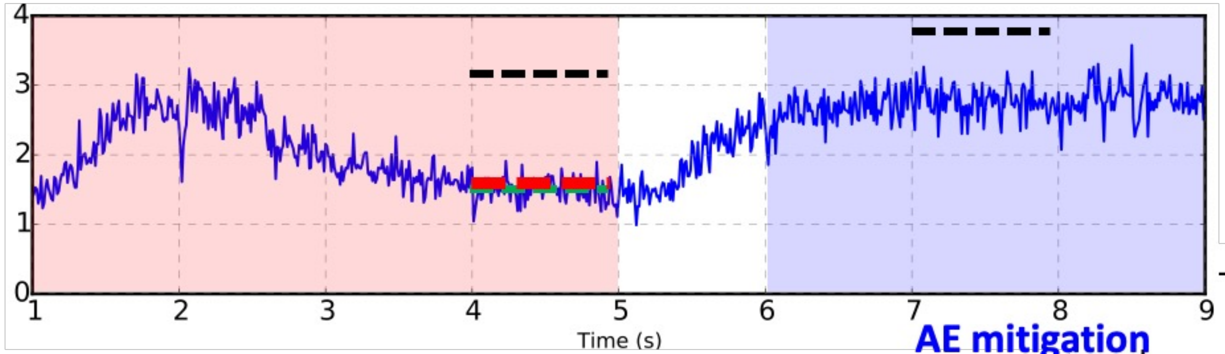


$\tau_{S,FAST}$ from kinetic profiles

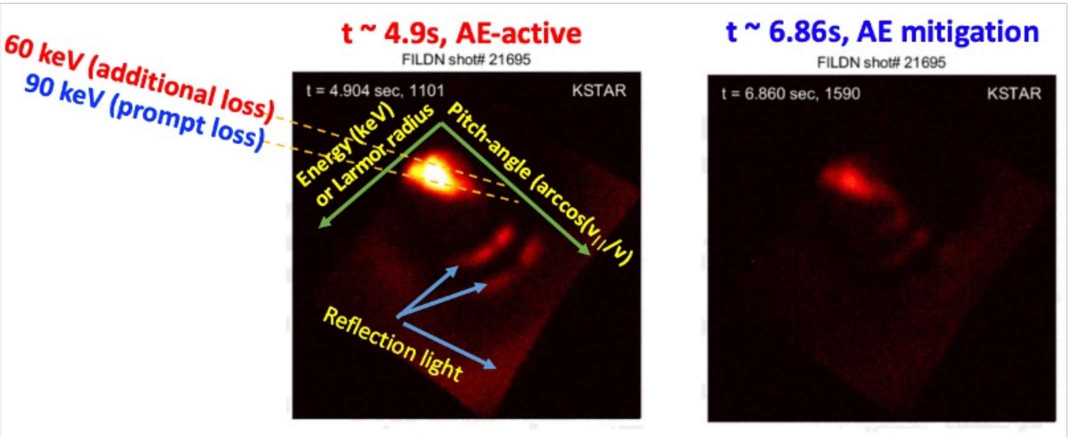


- Kinetic equilibrium reconstruction shows q profile evolution of each phase.
  Almost consistent for stable region and dynamic for evolution phase.
  (>0.5 is TRANSP constrained and other region is MSE constrained)
- Increment of core kinetic profile is also observed.
- Classical fast ion slowing down time is almost consistent among active/mitigated phase.
  → Mode is responsible for fast ion transport.

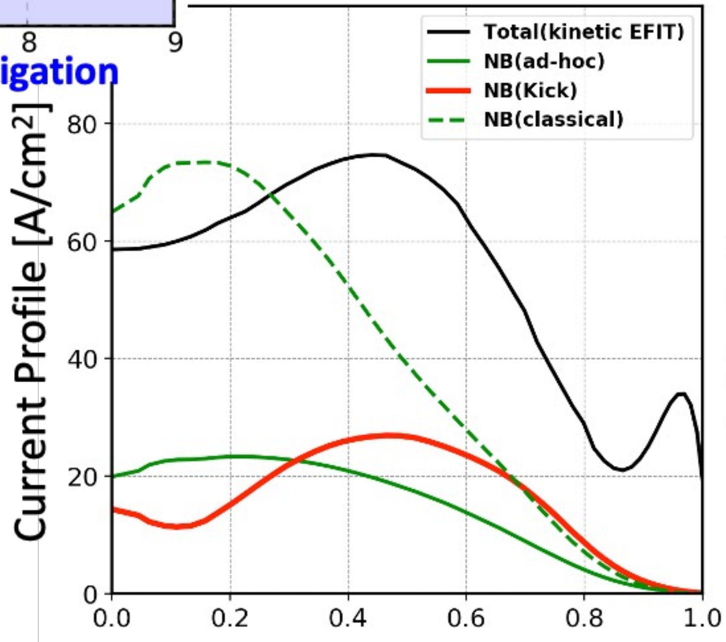
Kick-model propose that
Off-axis NBCD due to Alfvénic activity → main candidate to sustain high q_{min}

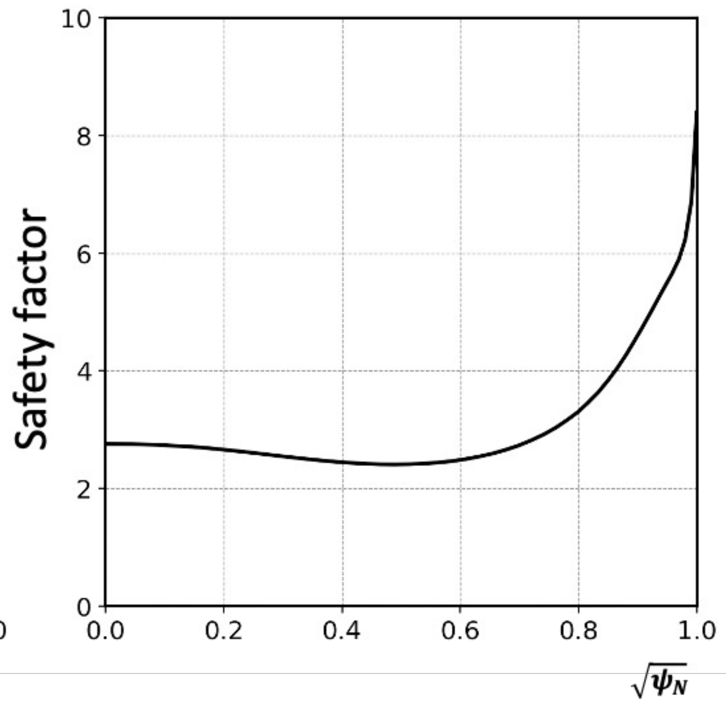


Active Phase **4450ms**



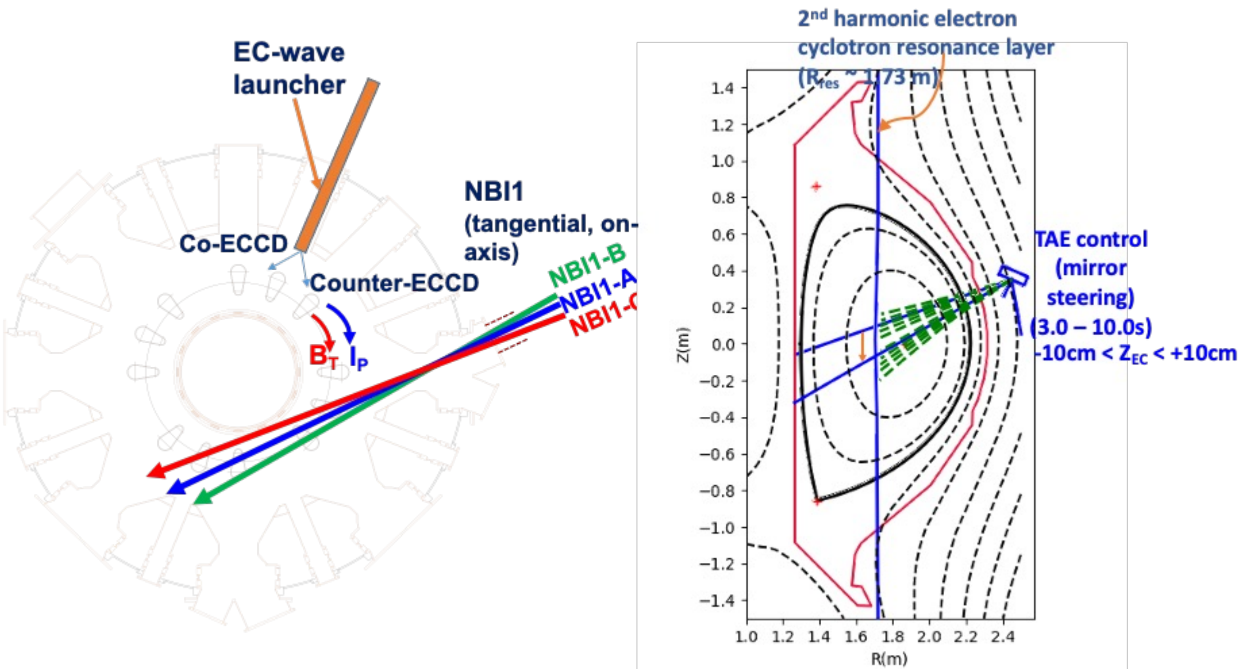
Fast-ion loss (Scintillator-based FILD)

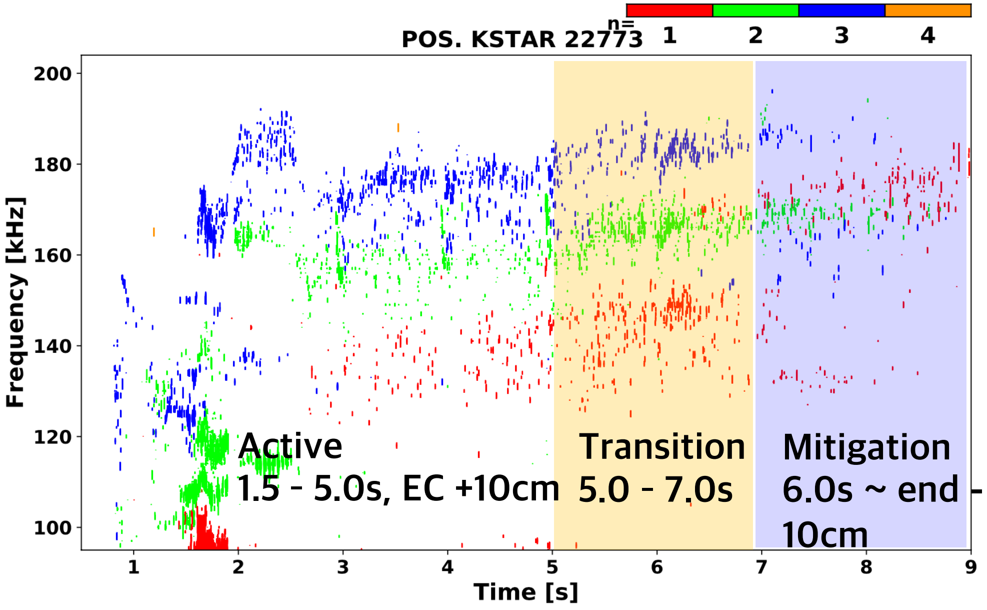


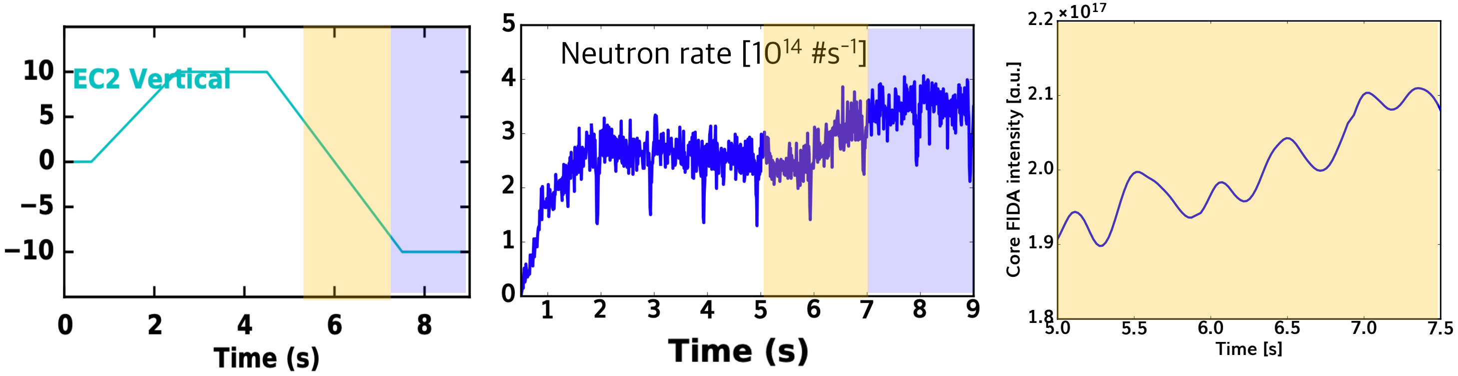


Beam driven current is bit over-estimated than ad-hoc method at off axis.
→ However, kick model shows more consistent current profile with reconstructed one.
Beam is the main current driver for this shot.

In 2019, AE mitigation is reproduced in different NB pitch & EC heating

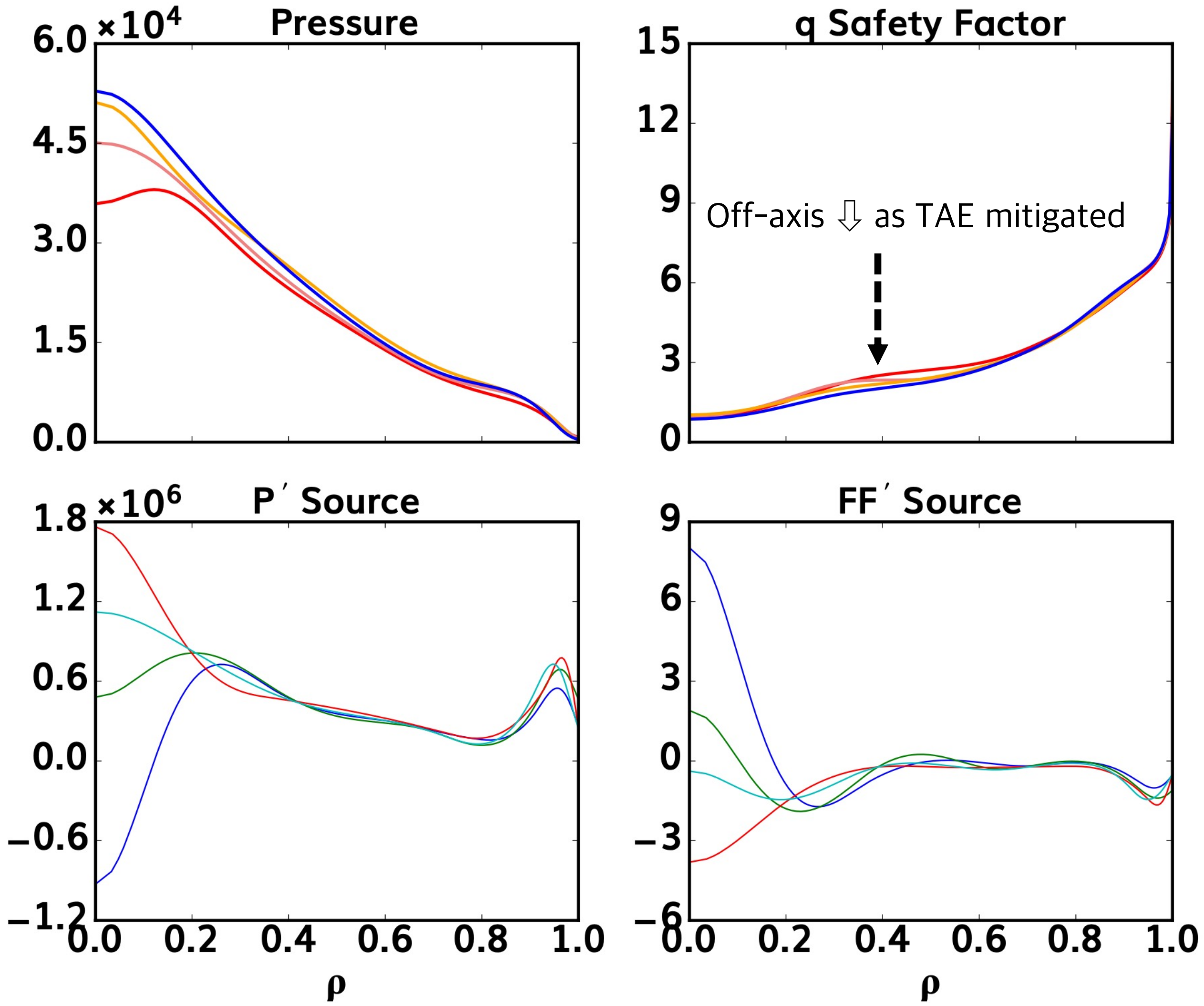






- 1.9 T similar NB power but different pitch
- Even with different beam combo & EC heating shows AE mitigation
- Got a better quality MSE data & FIDA intensity profile

Safety factor and total pressure profile evolution is a bit different



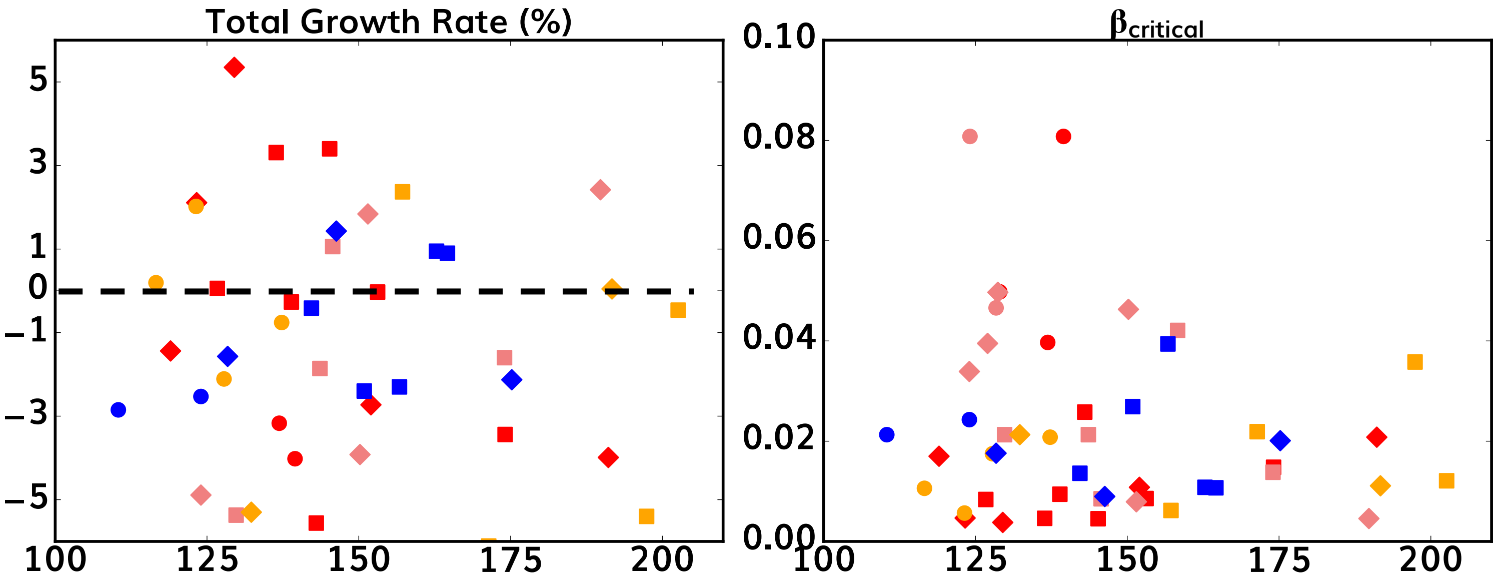
active (5600 ms) mitigated (7800 ms)
intermediate (6400ms) intermediate(6800 ms)

- q profile was not so much differed since EC heating (different toroidal angle as 2018).
  ➔ NBCD profile change at off-axis region leads q-profile variation
- Fast-ion pressure increases as the AEs are mitigated.
  Normalized pressure gradient (α) > α_{crit}
  ➔ Stabilization in the enhanced β
  (related to suppression of core TAEs)
- Fast ion pressure enhancement is the main factor of total pressure improvement
  as in FIDA & neutron rate.

NOVA-K reflects measured Alfvén modes

● n = 1 ◆ n = 2 ■ n = 3

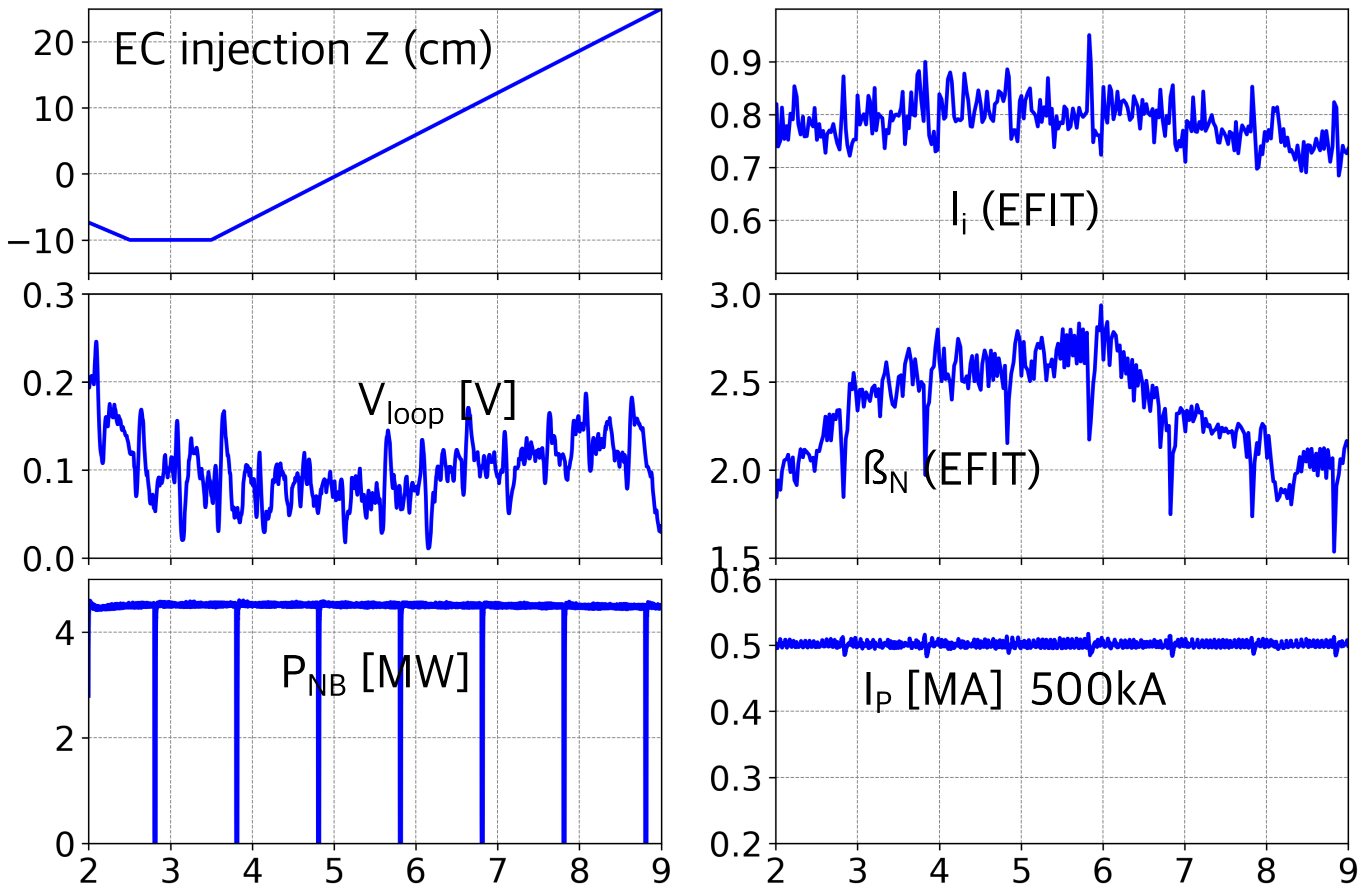
active (5600 ms) mitigated (7800 ms)
intermediate (6400ms) intermediate(6800 ms)

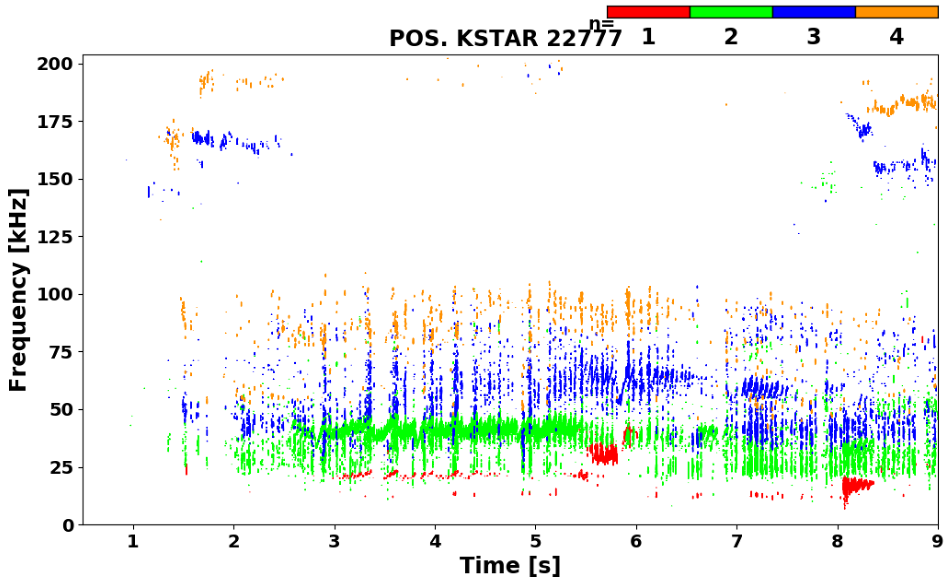


- Active and mitigated modes are distinguished across 0 line.
- Unstable modes are matched with mode number estimated with Mirnov.
- Central T_i change is not so significant
  → Thermal-ion Landau damping seems to be weak in TAE-mitigation stage, also in Nova-K.
- Major damping mechanisms are
  radiative, continuum, and Landau, damping. Detail analysis are on-going.

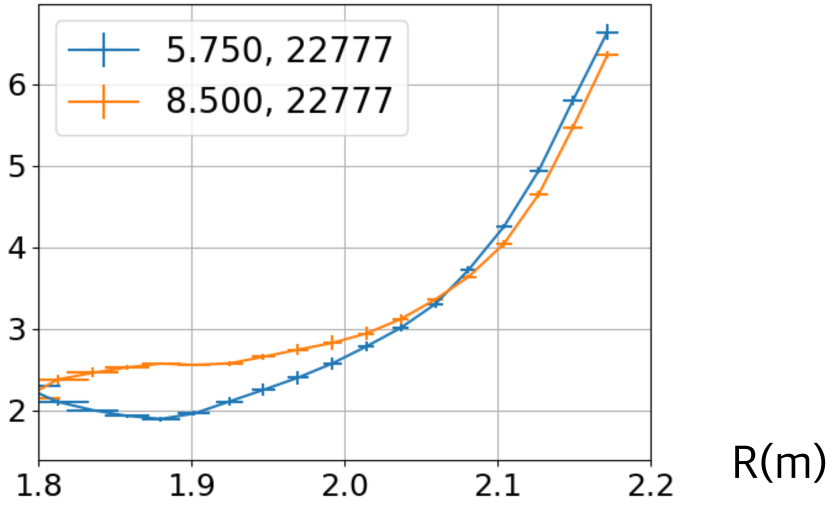
TAE suppression strategy is adopted to high β_N and P_{NB} in 2019

The same EC vertical heating seems not so successful.
Misaligned EC triggered TAE after 8 s.
The first try at 2019 leaves unsolved question.
⇨ Need a reference with TAE at higher beta.

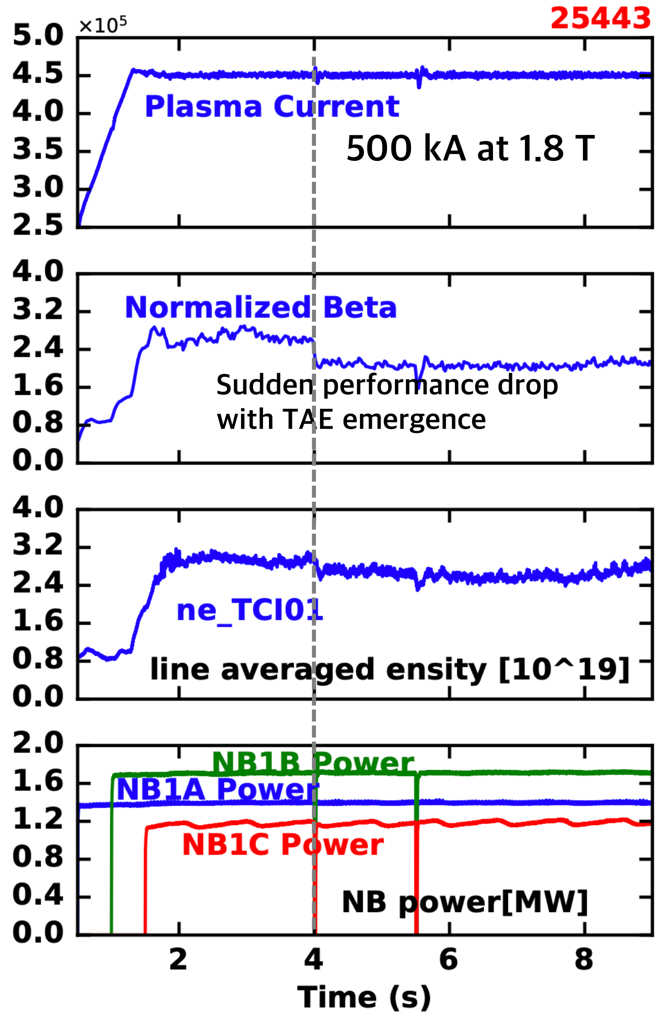


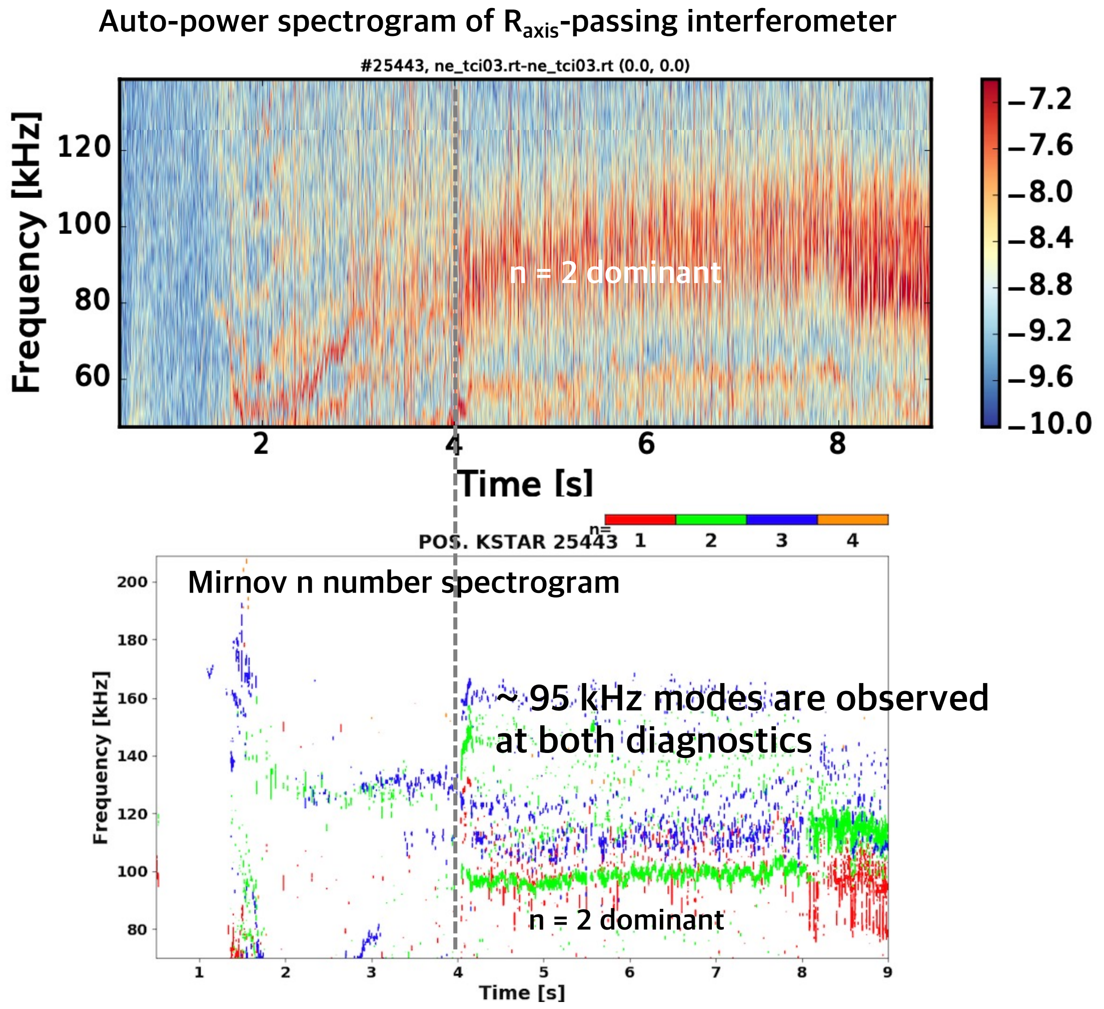


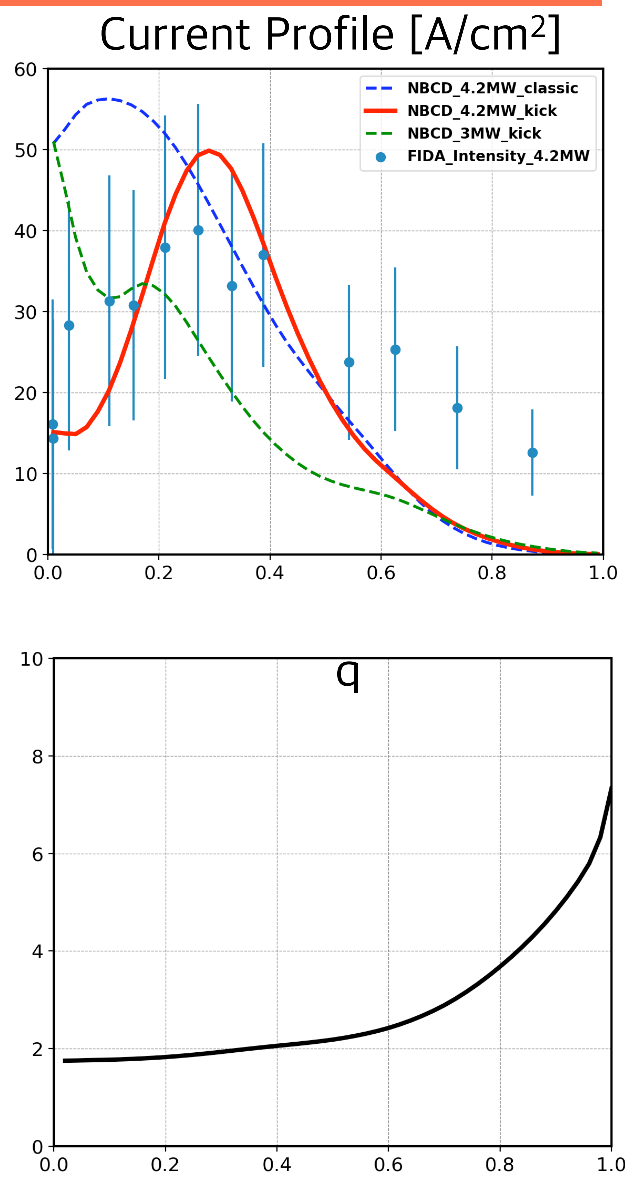
q profile from MSE reconstruction



In 2020, q-profile broadening has been confirmed at higher beam power

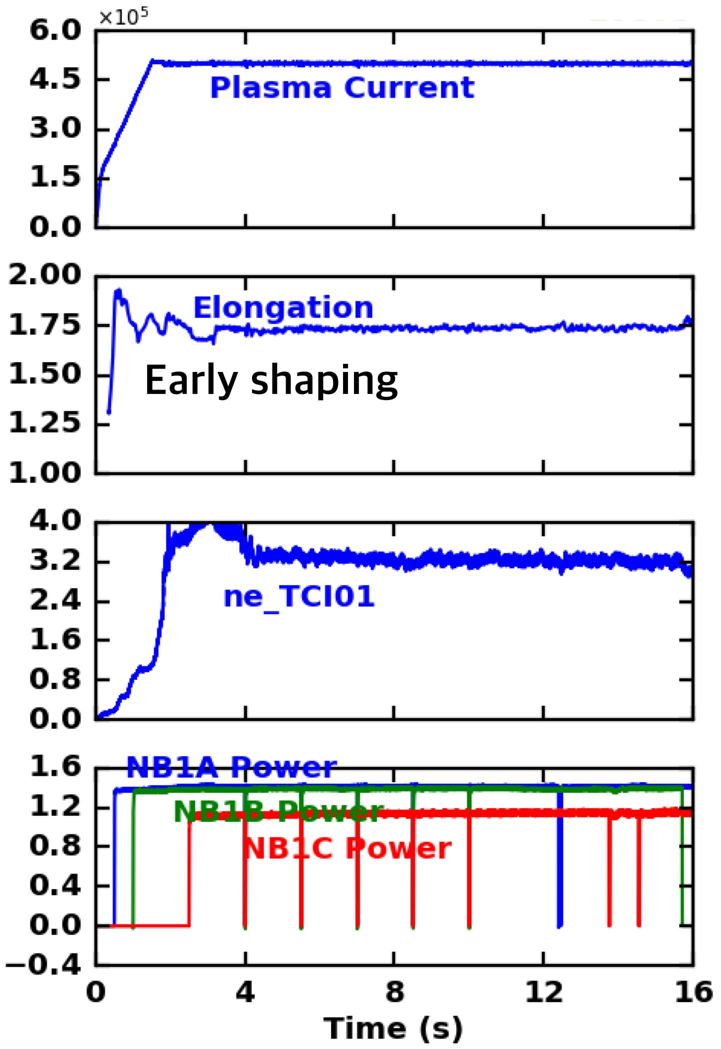


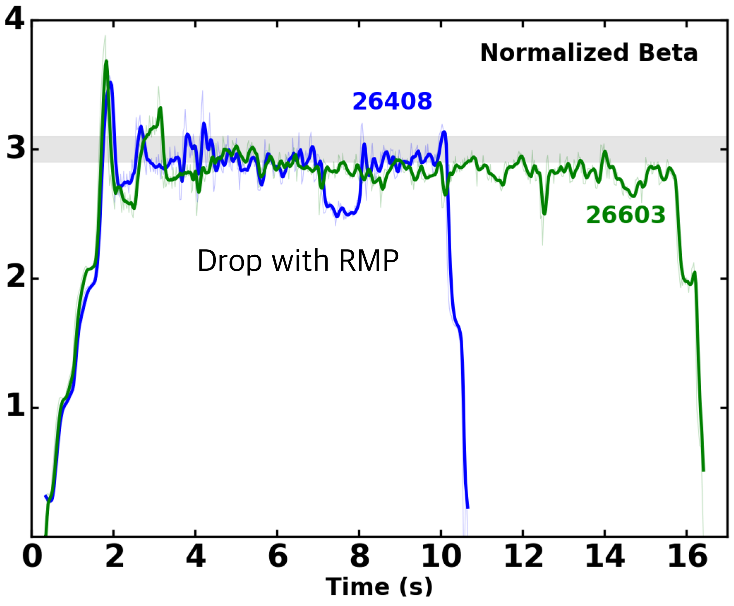


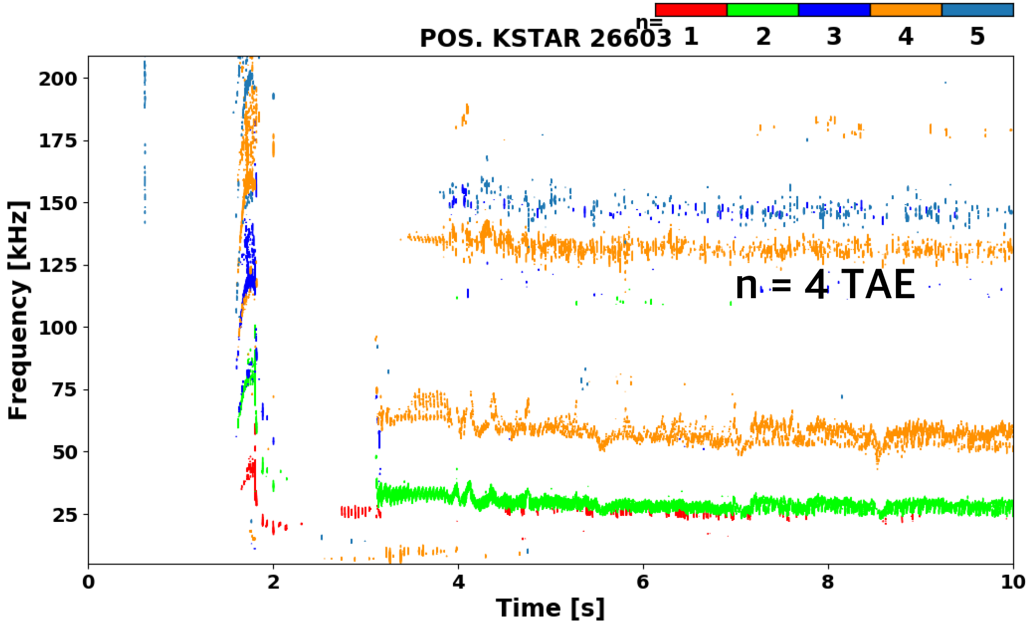


ITPA EP 2020 (JEX EP-8)

In 2020, KSTAR has achieved high β_N & q_{min} operation

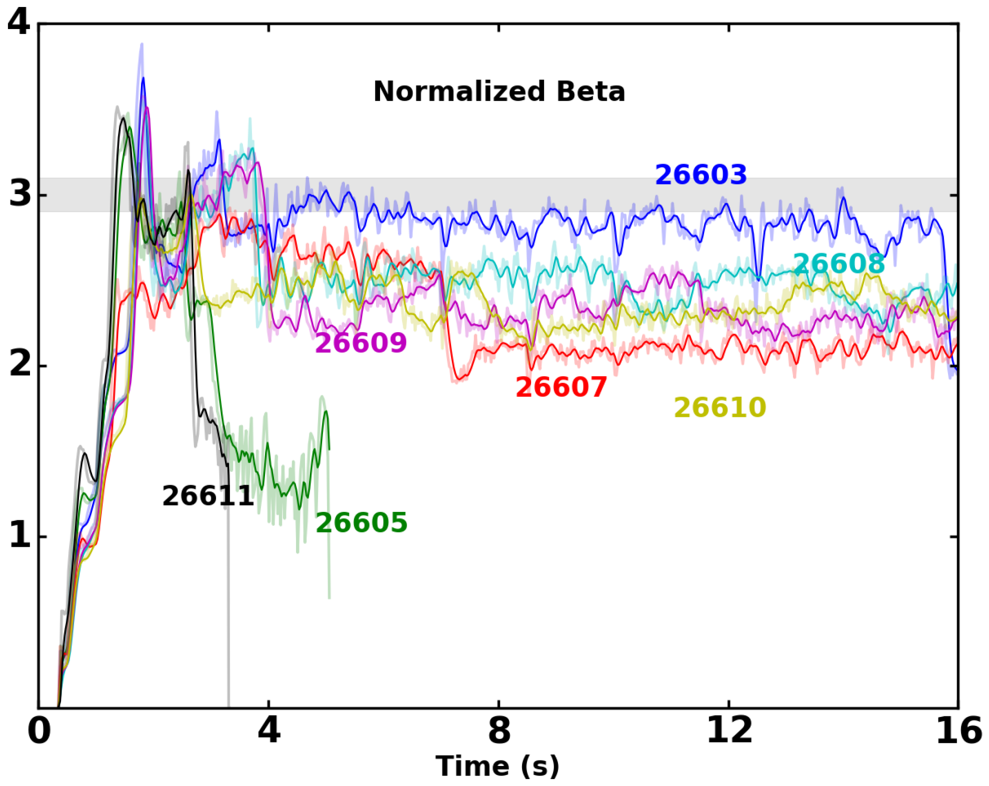




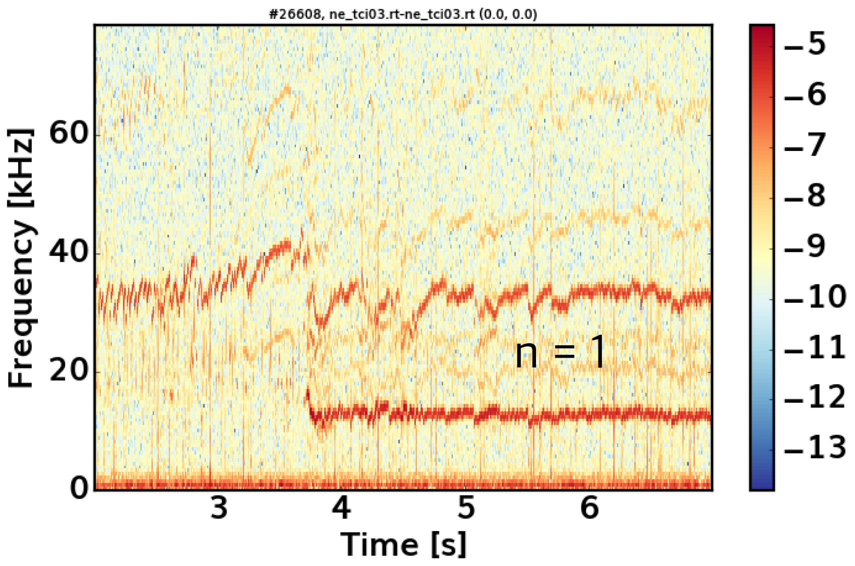


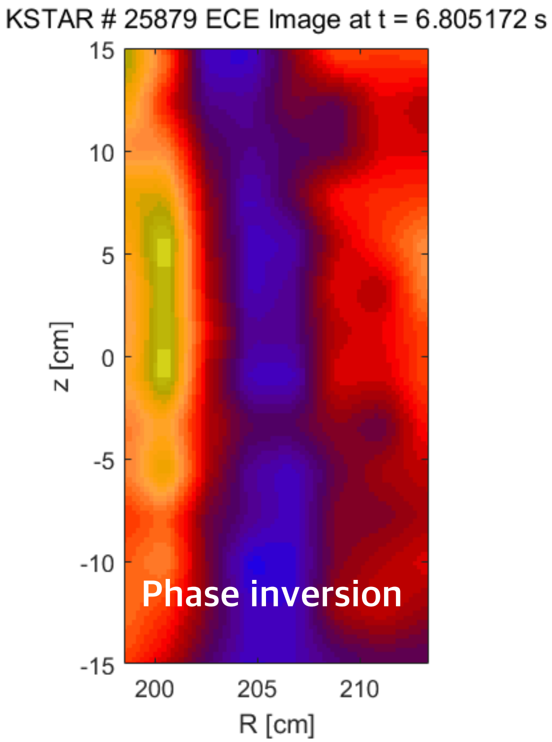
- H_{98} ~ 1.2, 1.5 T - 1.4 T, 4.0 MW
- With the aid of early shaping (collaboration with ORNL), High q min scenario is developed.
- Even with clear n = 4 TAE, high β_N is achieved. Kick/NOVA analysis is on-going.

However, excitation of n = 1 tearing modes comes to a big concern at higher beta



Core-passing interferometer spectrogram (#26608)





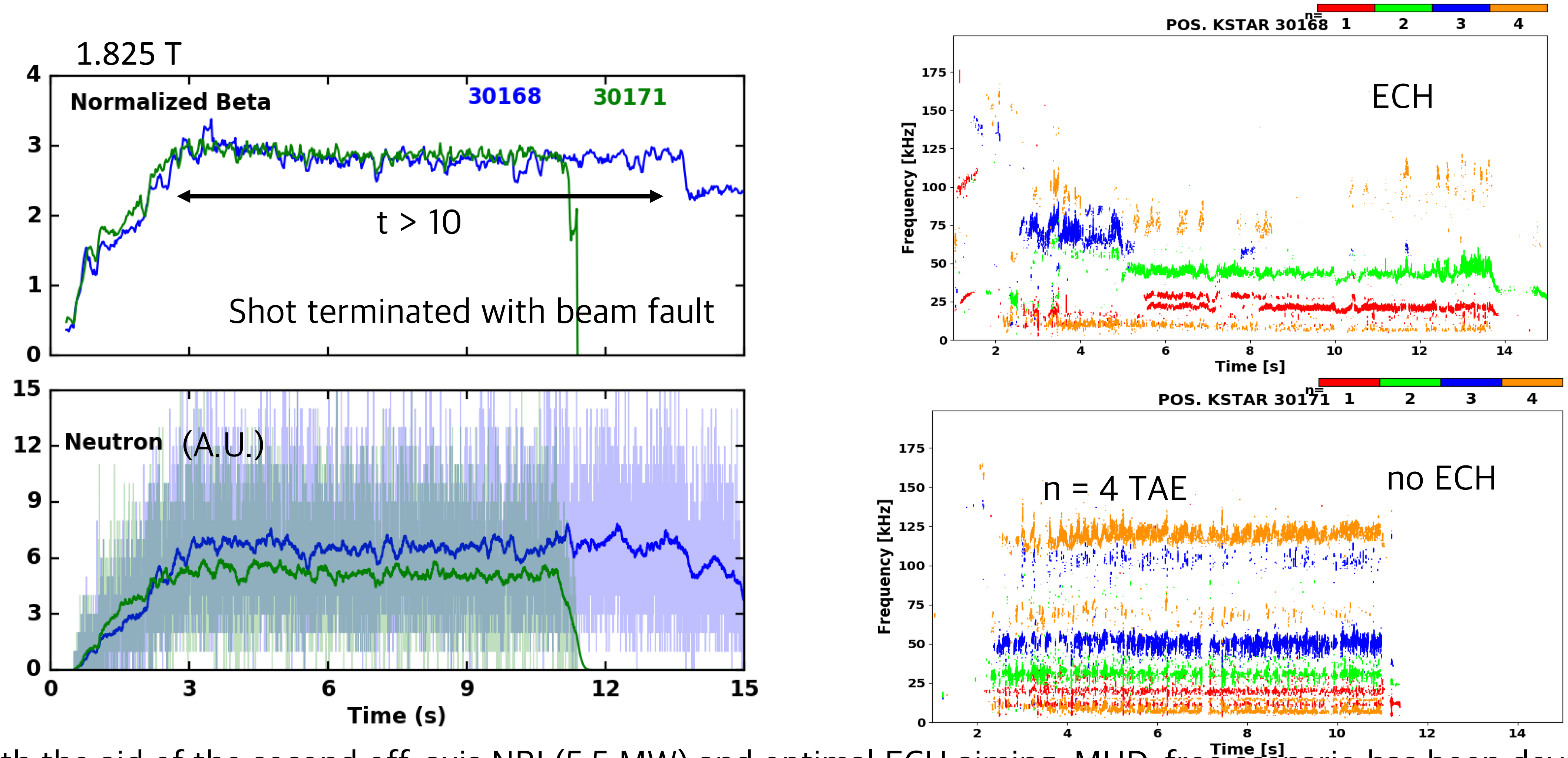
Most of performance drop is from n = 1 tearing modes.

Many tries on active-control of this mode was not so successful.

Database with various n = 1 TM islands width are collected.

⇨ Quantitative modeling on fast-ion transports with NTM is planned.

Long Pulse High β_N scenario Development status, $\beta_N > 3$ & t > 10 s



- With the aid of the second off-axis NBI (5.5 MW) and optimal ECH aiming, MHD-free scenario has been developed. With ECH and without ECH shot has been succeded. ECH case shows higher neutron rate and no TAE
- Intepretative analysis (EFIT/TRANSP/NOVA/KICK) is on-going.
- Nice shot to compare the effect of fast-ion transport with TAE and low frequency modes at highger beta.

Summary and Future Work

- Fast-ion transport does matters to achieve high β_N milestone in KSTAR.

- TAE mitigation with ECH/ECCD are main strategy.
  - High q0 (> 1.5) & qmin, low li (~ 0.8) by mild off-axis ECCD & ECH provided good testbed for controlling & driving the AEs.
  - Co-IP directional ECCD (0.7MW) mitigates AEs successfully in the high q_{min} scenarios of KSTAR
  - NOVA-K guides that TAE mitigation by EC enhanced radiative and continuum damping

- β_N ~ 3 stationary operation is achieved
  - But still vague MHD is remained, detail analysis would leads us more higher β_N and long-pulse operation

Future work

For higher $\boldsymbol{\beta_N}$
- Low & high frequency mode stabilization to maximize $\boldsymbol{\beta_N}$ (Control knob: ECH, 3D field)
- Numerical modeling on fast-ion transport and modes.

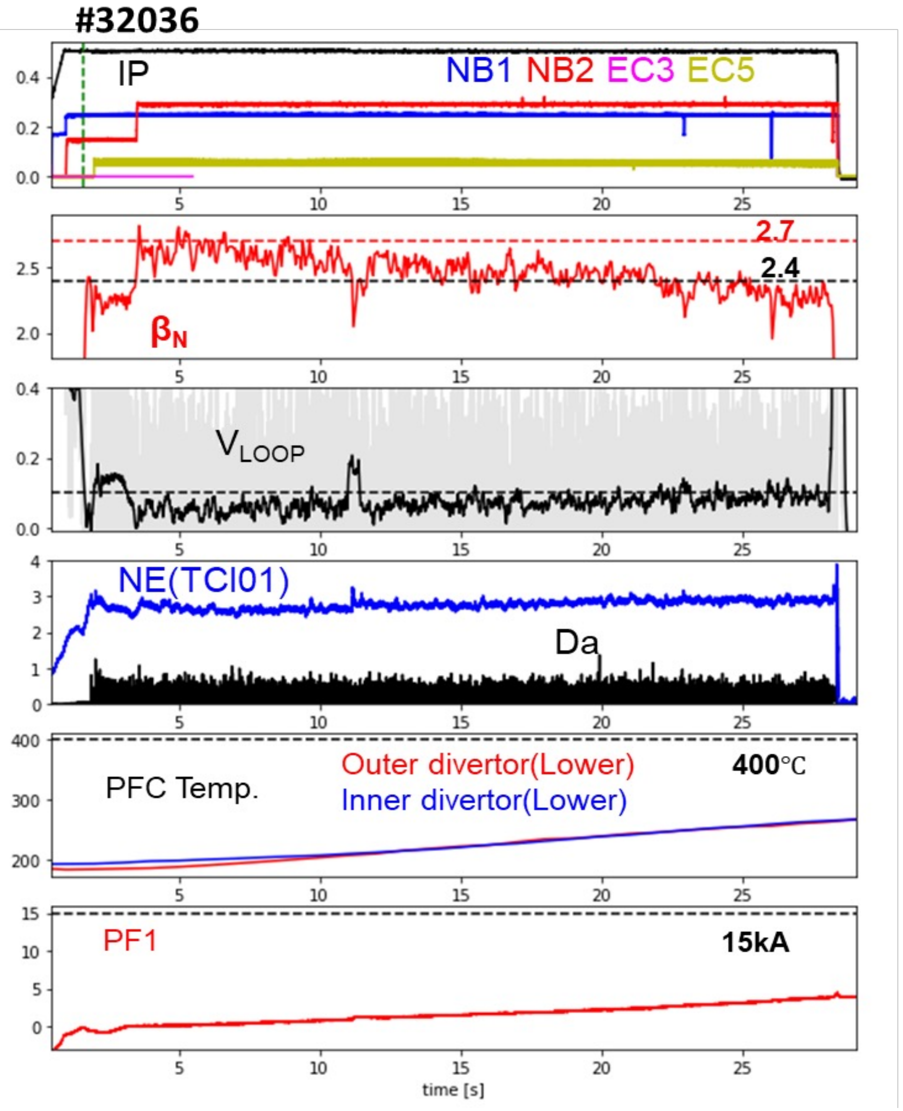
Address optimum q-profile or q_{min} which has no MHD activity & high $\boldsymbol{\beta_N}$
- Less fast-ion related modes, fully non-inductive discharges.

Issues on long-pulse operation

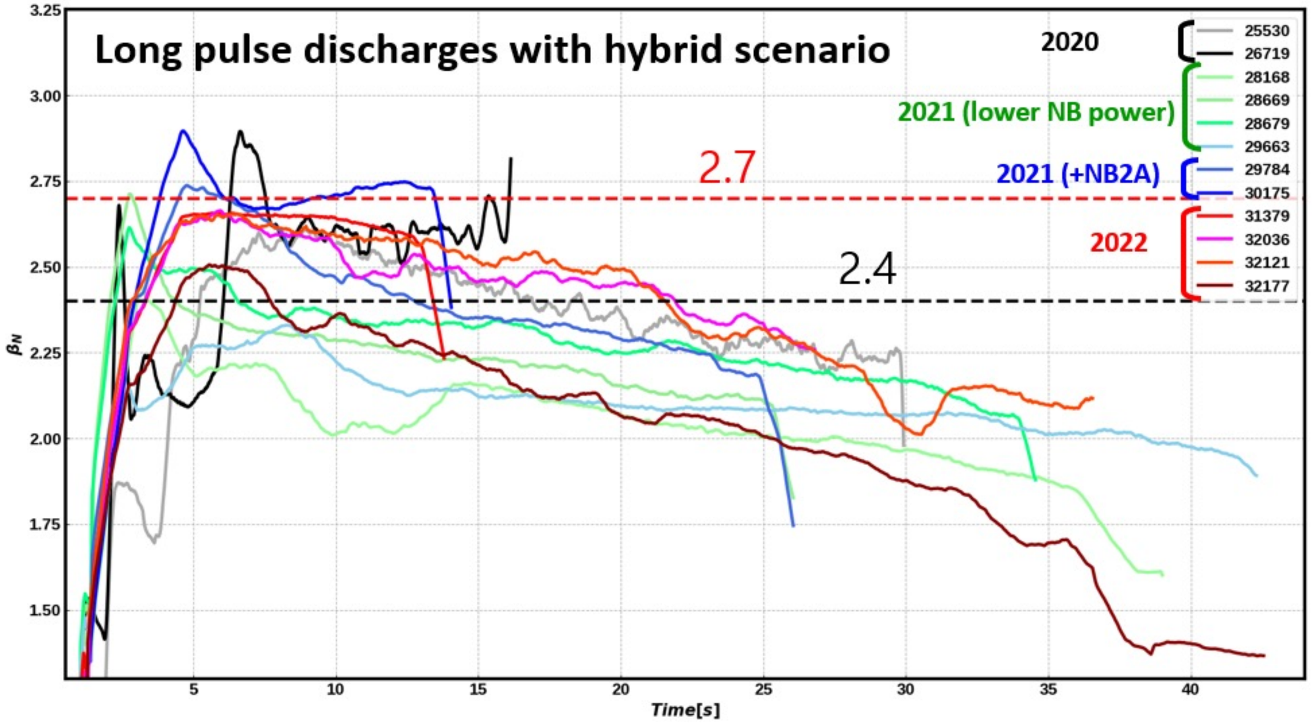
SEOUL NATIONAL UNIVERSITY

Y. S. Na

Commonly observed phenomena when KSTAR increase pulse-length



Long-pulse with β_N > 2.4 for > 20 s



- By controlling fueling, external heating, and plasma shaping
- Limitations of PFCs temperature and flux consumption
- Discharge lasted up to 40 s but degrades performance