Control of Alfvén Eigenmodes by Non-Axisymmetric Magnetic Field

Kimin Kim, Jisung Kang, Tongnyeol Rhee, Minho Kim, and Junghee Kim

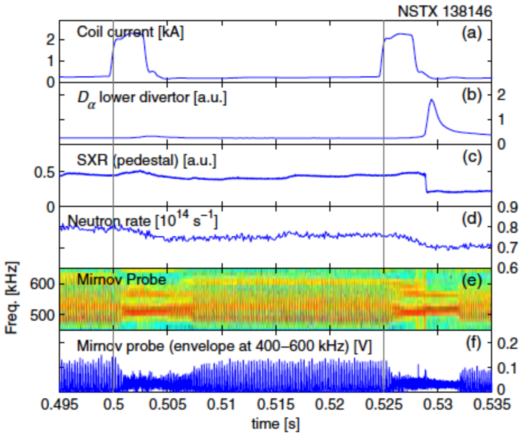
Korea Institute of Fusion Energy, Daejeon, Korea

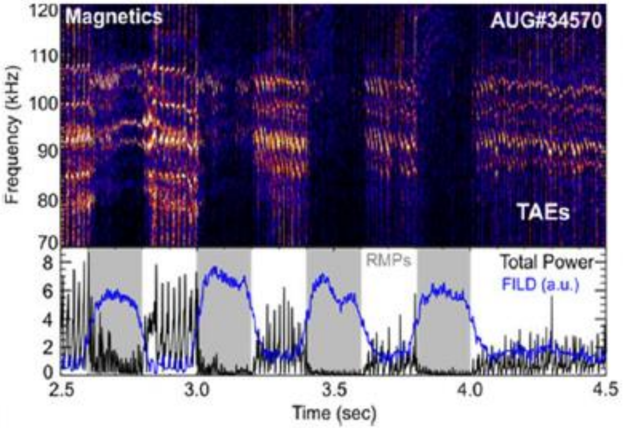
4th Trilateral International Workshop on Energetic Particle Physics
October 26 – 27, 2024
Hangzhou, China

KOREA INSTITUTE OF FUSION ENERGY

Background and Motivation

- **Potential utilization of 3D field for AE control has been demonstrated**
  - GAE suppression by n=3 field in NSTX [Bortolon PRL 2013]
  - TAE suppression by n=2 field in ASDEX-Upgrade [Gonzalez-Martin PRL 2023]





  - 3D field induced fast ion losses modifying fast ion distribution & fast ion AE drive

- **Destabilization of the TAEs in the non-resonant magnetic braking in KSTAR**
  - Reduced toroidal rotation modified the Alfven continuum to drive the TAEs [K. Kim, NF 2020]

Background and Motivation

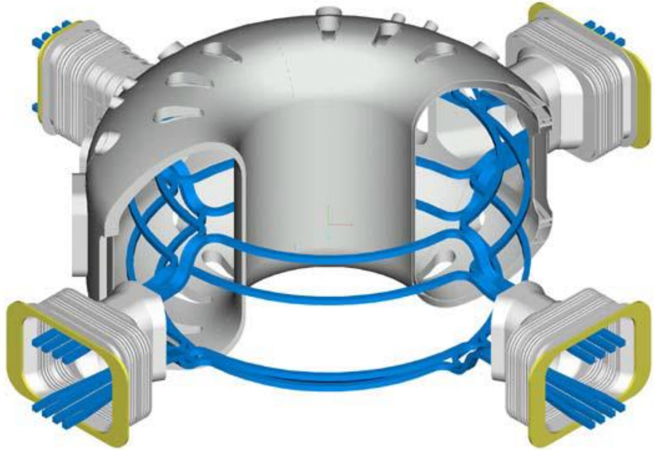
- Potential utilization of 3D field for AE control has been demonstrated
  - GAE suppression by n=3 field in NSTX [Bortolon PRL 2013]
  - TAE suppression by n=2 field in ASDEX-Upgrade [Gonzalez-Martin PRL 2023]
- AE stability associated with 3D field is a complicated function of plasma responses
  - Toroidal rotation, fast ion redistribution, pedestal transport, ELMs, etc.
  - → Requires identification of AE control parameters
- KSTAR is the best test bed to AE control study with 3D magnetic field
  - High flexibility of 3D field coils and NBI heating
- This Work presents investigation of control capability of the Alfvén eigenmodes utilizing 3D magnetic field [K Kim NF 2024]
  - Optimal 3D field phase & amplitude for AE control by application of n=1 phase-sweeping 3D magnetic field

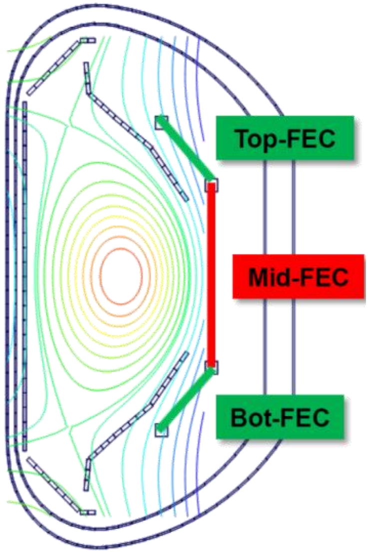
Outline

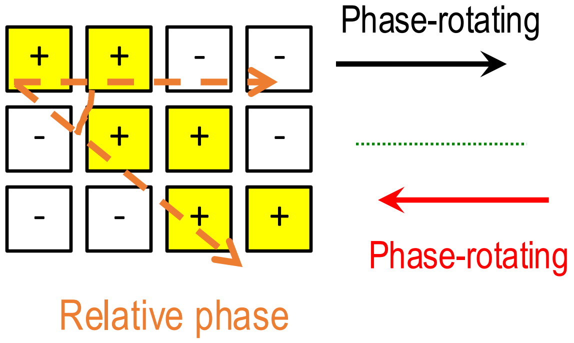
- Background and Motivation
- Experimental Observations
  - AE Control Experiment: Window of 3D Field Phase and Amplitudes
  - Fast Ion Transport
- AE Suppression Mechanism
  - Alfvén Continuum
  - Fast Ion Phase Space Distribution
- Phase-Amplitude Operating Space for AE Control
- Summary

Non-Axisymmetric Magnetic Field Coils in KSTAR

KSTAR In-Vessel Control Coils (IVCC):
3-rows (Upper / Middle / Lower)



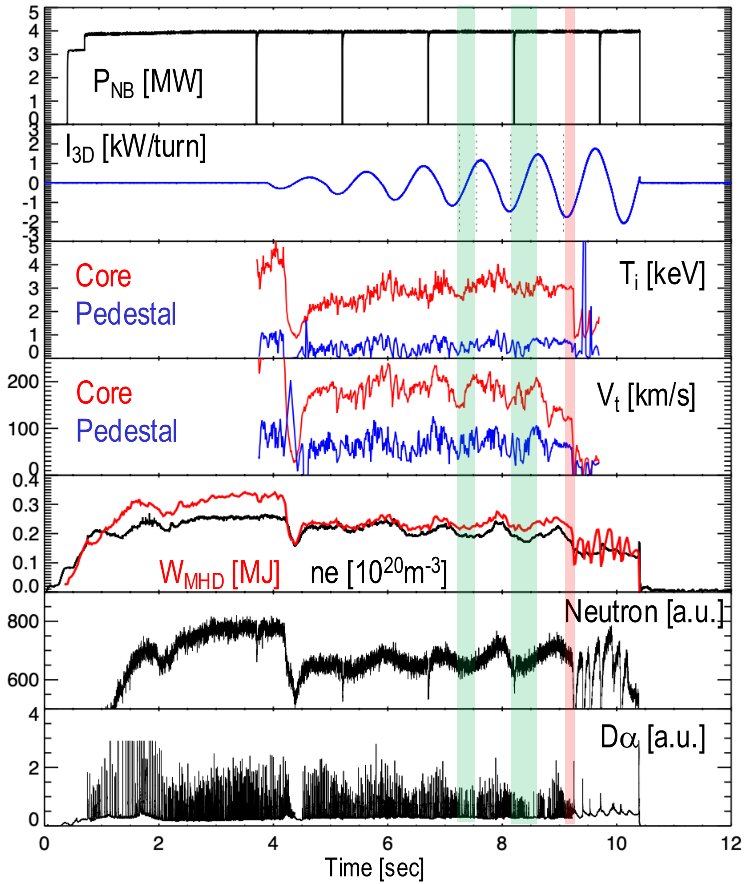


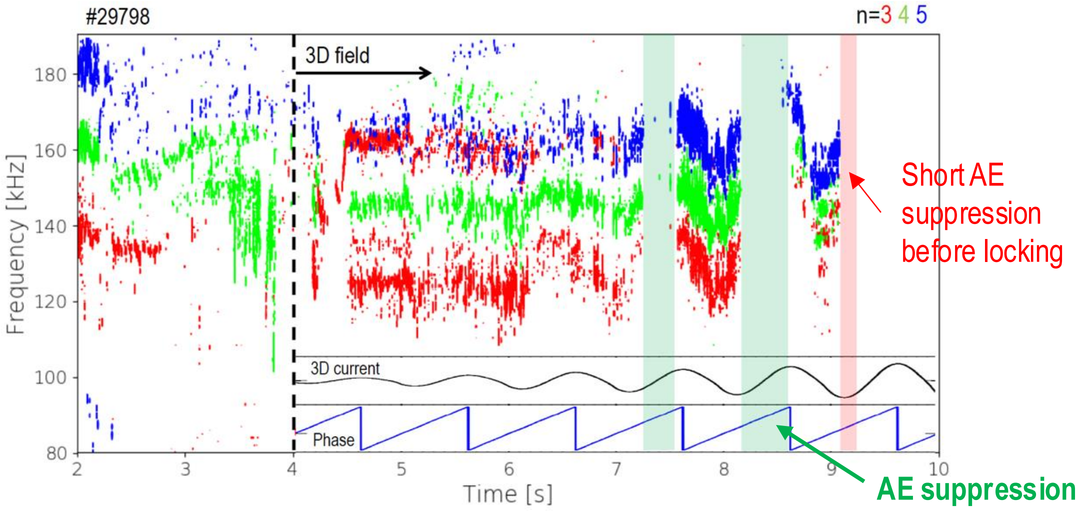


- In-vessel control coils (IVCC) in KSTAR provide various static or rotating non-axisymmetric magnetic fields of n=1 & n=2
- Demonstrate ELM suppression, toroidal rotation braking, divertor heat flux, etc.
- Phase-sweeping 3D field allows examination of AE control, via phase-scanning of plasma response and AE stability

Full phase scan shows signature of AE suppression by 3D field

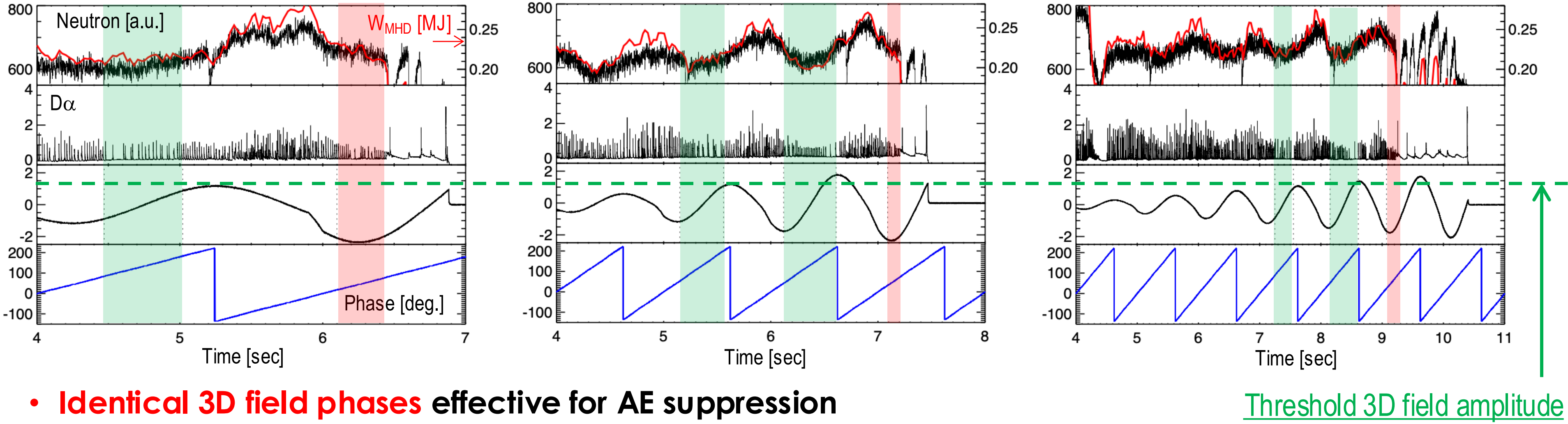
(I_P = 560 kA, B_T = 1.7 T, q_{95} ~ 4.8, $n_e \geq 2\times10^{19}$ m^{-3}, β_N ~ 2.7, P_{NB} = 4.1 MW)





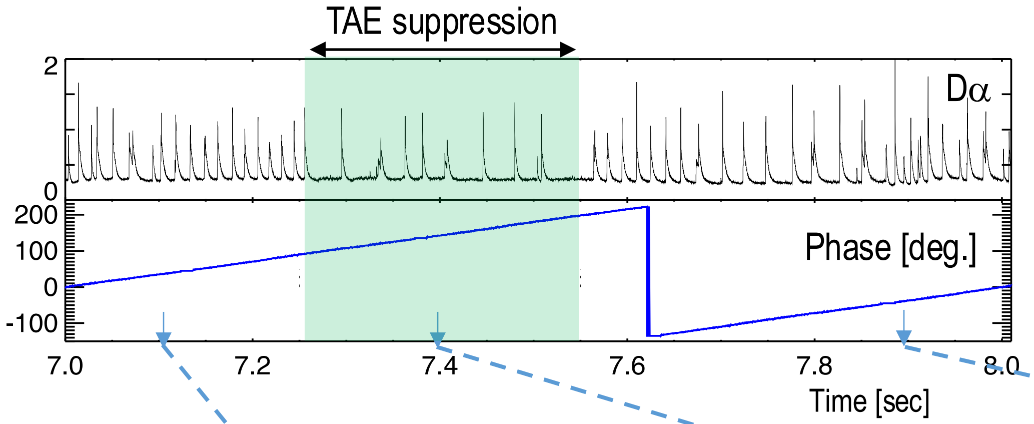
- **Phase-sweeping n=1 3D field with stepwise increase of 3D field amplitude**
- **Clear signature of AE suppression**
- **Plasma disrupted due to mode locking**
- **Identify threshold and amplitude & phase window for AE suppression**

A series of 3D field discharges show identical AE stability responses

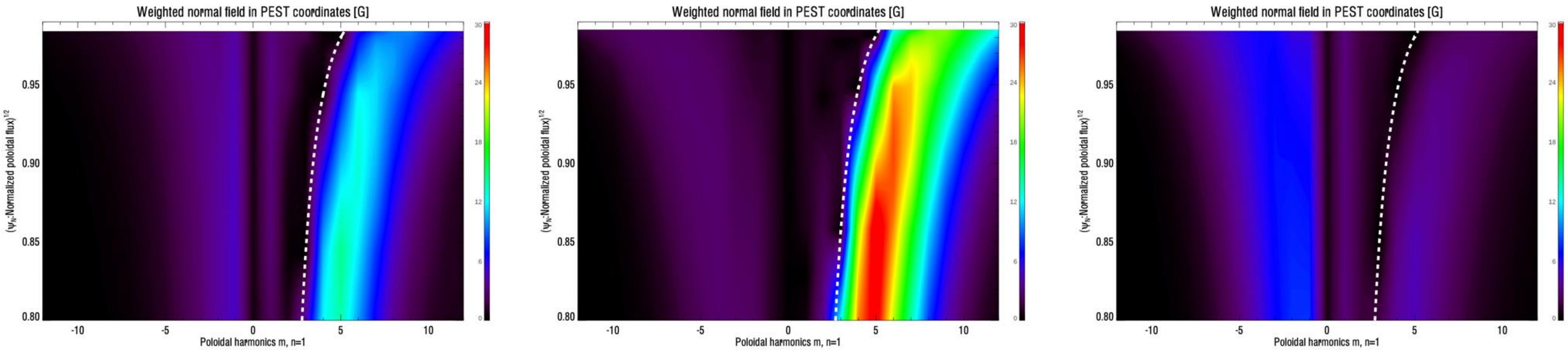


- **Identical 3D field phases** effective for AE suppression
  - Phase window for AE suppression becomes wider with stronger 3D field amplitudes
- **ELMs mitigation** observed with resonant plasma response
  - 3D phase window for AE suppression overlapped with windows for ELM mitigation & Locking
- **3D field threshold** for AE suppression → Weaker than disruption ($\delta B_{AE} < \delta B_{Disrup}$)
  - Narrow amplitude window for effective AE suppression w/o disruption
- Neutron production strongly depends on the W_{MHD}

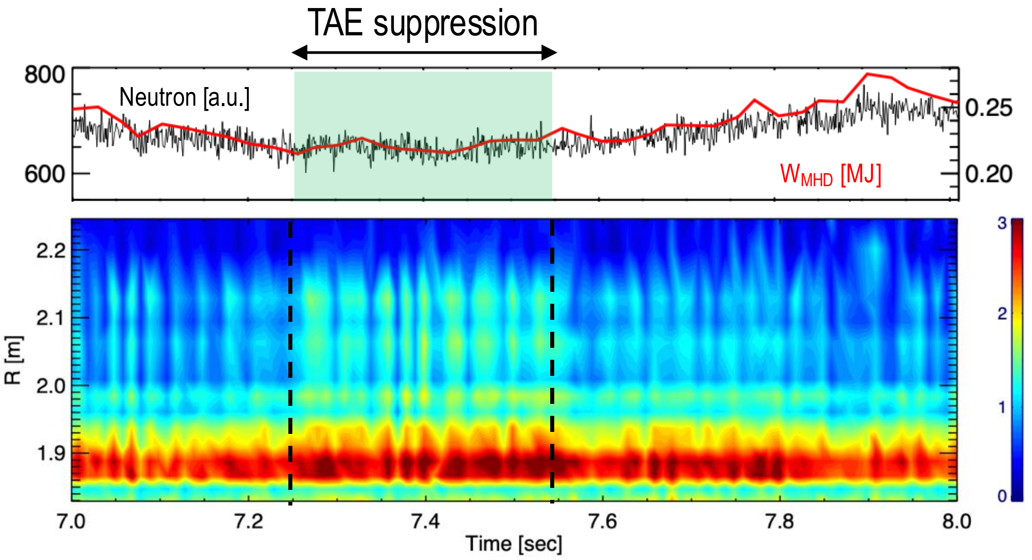
Perturbed 3D Field Computed with Ideal Plasma Response IPEC

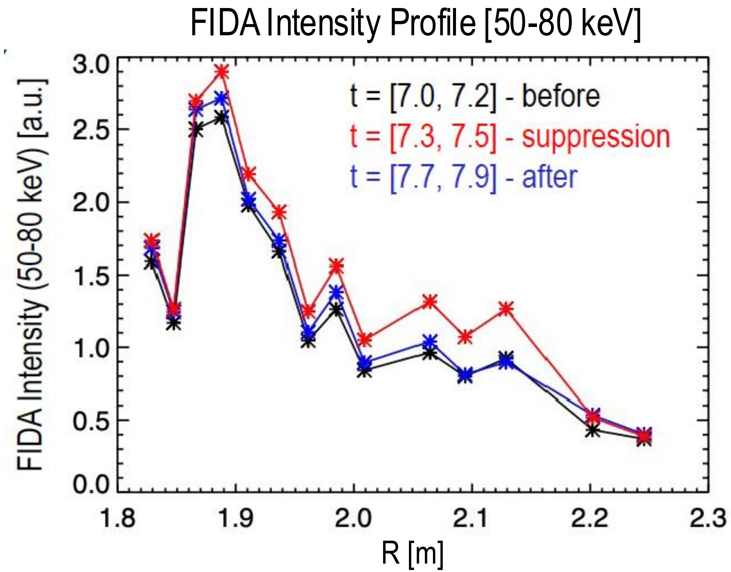


- **Strong resonant plasma responses in the AE suppressed phase**
  - **ELM mitigation**
  - **Prone to mode locking → Narrow amplitude window for AE suppression**
- **No AE stability response in the non-resonant phase**



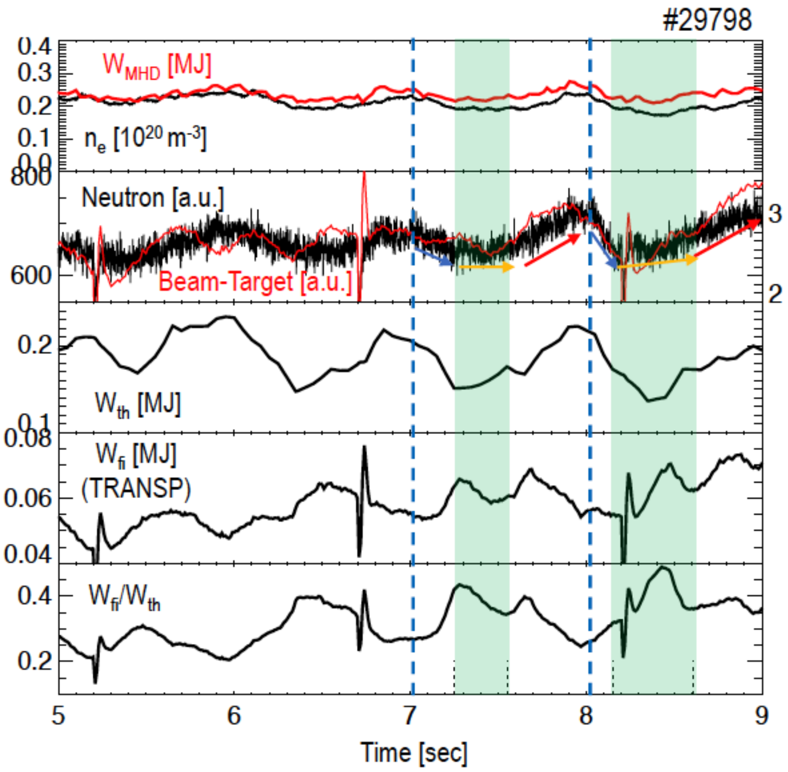
FIDA indicates improved fast ion confinement with AE suppression





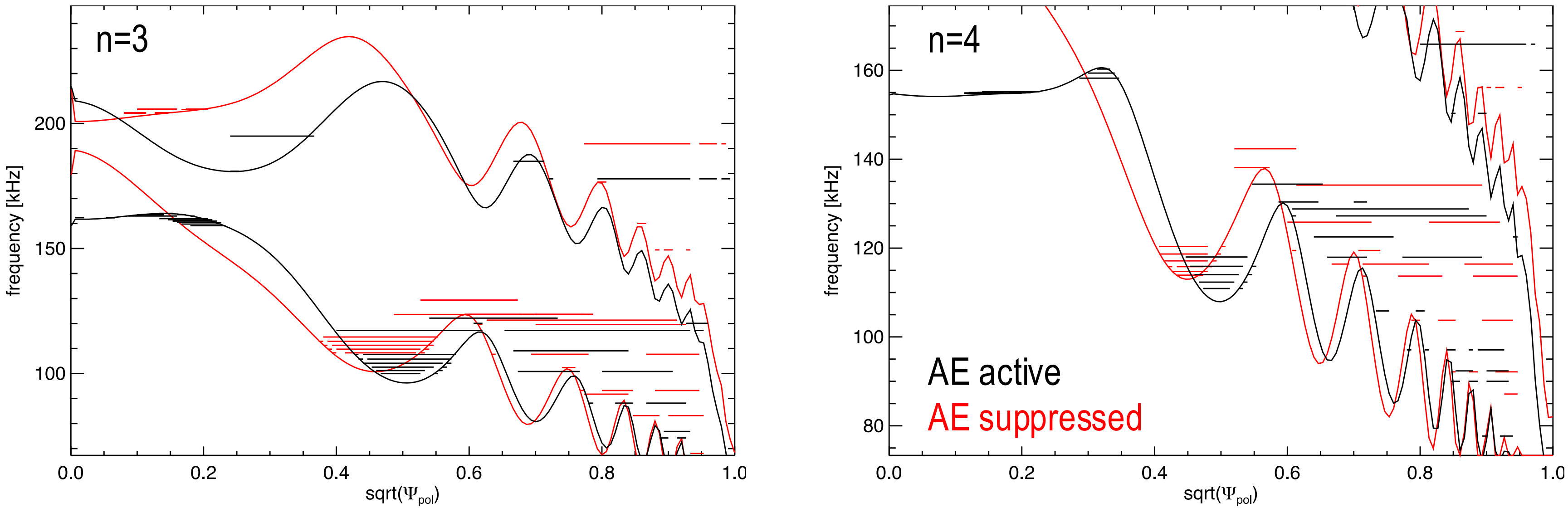
- **FIDA indicates improved fast ion confinement in the AE suppressed phase**
  - Stronger FIDA intensity in the whole volume
  - Gradients are likely moderated due to interactions of fast ions with 3D field
- **Fast ion confinement is NOT directly connected to neutron production**
  - Neutrons largely follow W_{MHD} evolution and/or particle transport (beam-target fusion)

TRANSP/NUBEAM shows details of fast ion transport



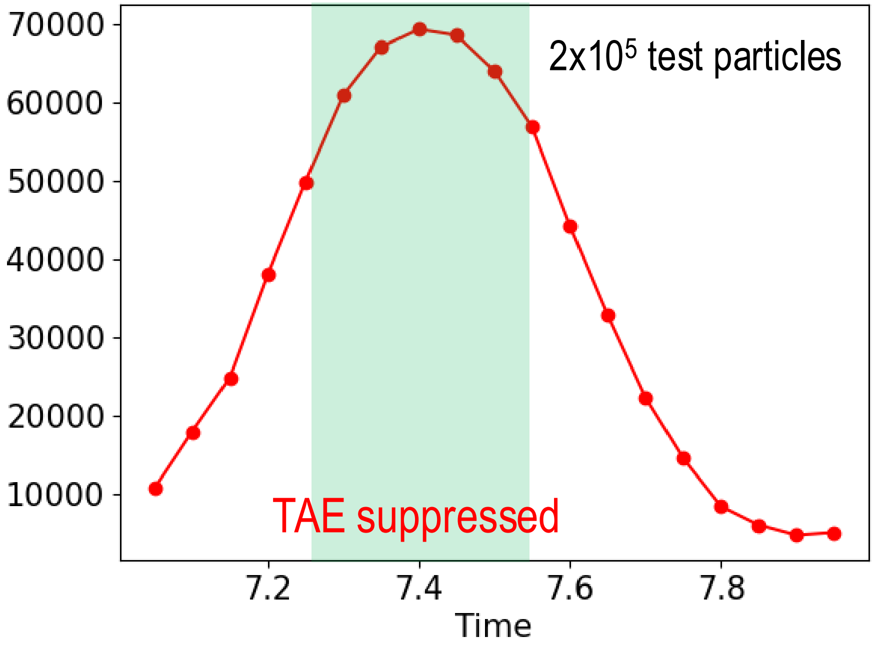
- W_{MHD} depends on the particle transport responding to 3D field → Identical behaviors of W_{MHD} & n_e
- Interplays btw. particle transport & neutron production
  - Neutrons decrease at the early phase with TAEs
    - Reduction of beam-target fusion by n_e decrease
  - Neutrons are maintained (recovered) with AE suppression
    - Increase of fast ion contents due to improved fast ion confinement
    - Compensate reduction of beam-target reaction due to n_e decrease
  - More significant interactions with stronger 3D field
    - Stronger effect of AE suppression on the fast ion confinement than thermal confinement
- 3D field amplitude is also a sensitive factor to maximize confinement

NOVA-K analsyis indicates mild modifications in Alfvén continuum



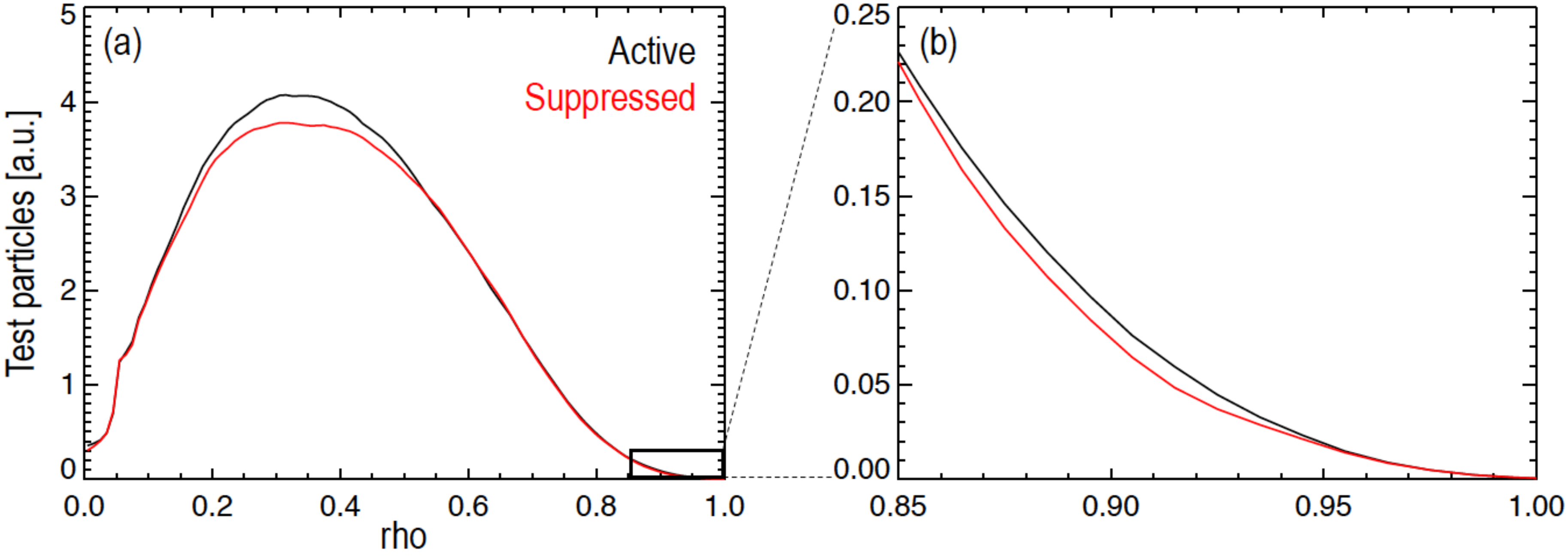
- **Reform of the Alfvén continuum in the AE suppressed phase is NOT significant, in spite of modifications of kinetic properties**
  - **TAE gap modes are still present even at the AE suppressed phase**
- **The Alfvén continuum & associated damping process are NOT critical in modification of the AE stability by 3D magnetic field → Another mechanism for AE suppression**

Fast Ion Prompt Loss during One Cycle of Phase-Sweeping for AE suppressed discharge



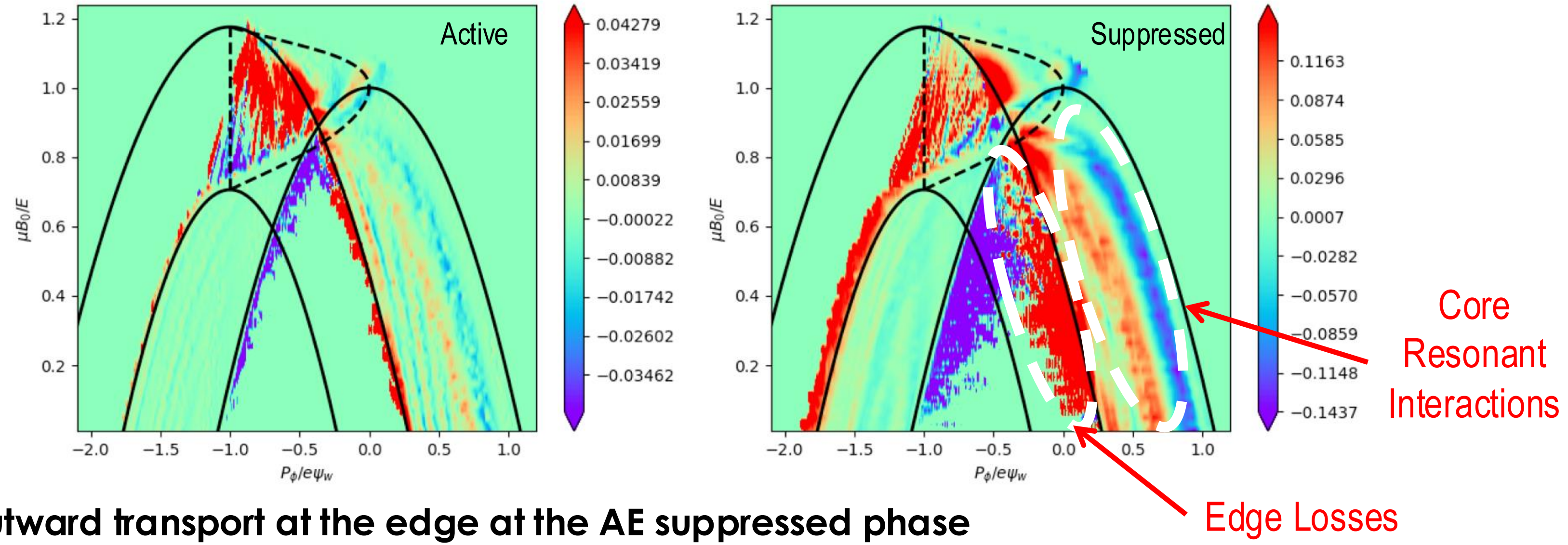
- **NuBDeC simulation** [Rhee NF 2022]
  - Use perturbed 3D field spectrum computed by IPEC
  - Compute fast ion motions from birth by neutral beam injection to the prompt loss induced by 3D field
- **Peaked fast ion prompt loss during the AE suppressed phase**
  - Fast ion loss is closely related to the resonant plasma response
  - Significantly reduced at the active AE phase, as 3D field is largely non-resonant

Spatial Redistributions of Fast Ions – NuBDeC Simulation



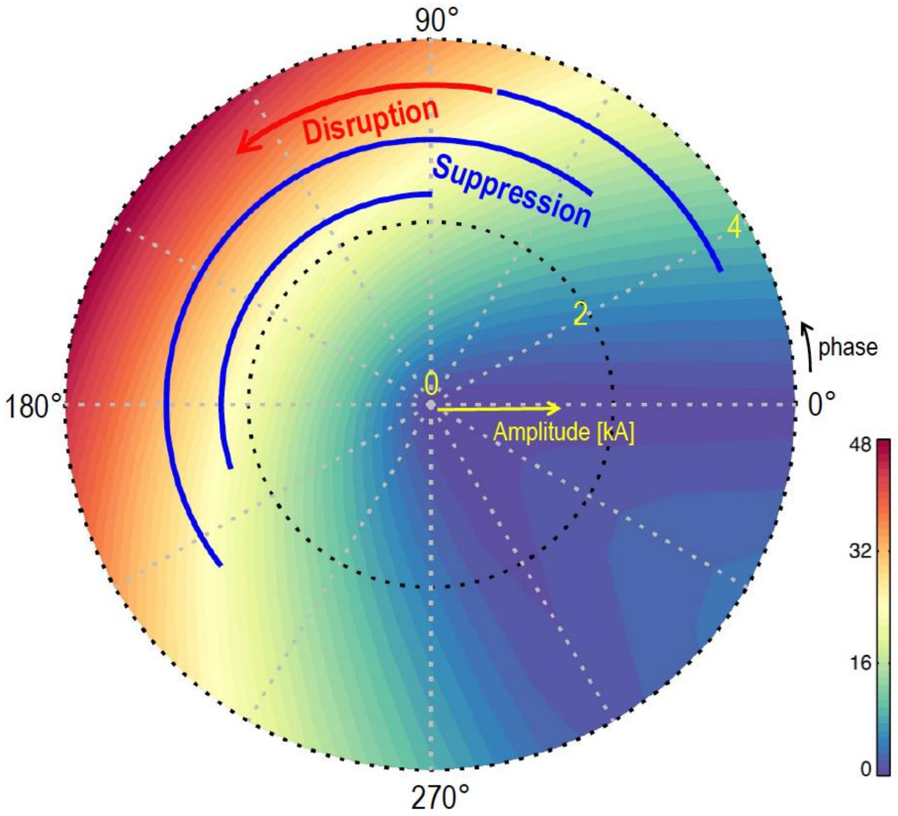
- **Redistribution of test particles at the AE suppressed phase is more pronounced**
  - **Decrease of test particles & spatial gradient**
    - **Reduced AE drive by resonant interactions between fast ions & 3D field**

Transport PDF indicates strong resonant interactions at the core by 3D field at the AE suppressed phase



- **Strong outward transport at the edge at the AE suppressed phase**
  - Large prompt losses of fast ions
- **Strong resonant interactions at the core at the AE suppressed phase**
  - Significantly modify the phase-space distribution of confined fast ions → Relaxation of the fast ion distributions and gradients → Suppression of the AEs
- **AE suppression mechanism by resonant interactions of 3D fields and fast ions**

Phase-Amplitude Operating Space of 3D Field Coils



- **Resonant field component is closely related to the AE suppression window**
  - **Window of 3D field coil currents & phase for AE suppression**
    - **Represented by resonant field at q=3 surface (IPEC)**
  - **3D field phase window widens as the amplitude increases until limited by locked modes leading to disruption**
- **3D field phase window may be further extended to more non-resonant field phases with higher amplitude**
  - **Potential for AE suppression by non-resonant 3D field to prevent disruption due to mode locking.**

Summary

- AE control using 3D magnetic field has been investigated in KSTAR
  - Demonstrate suppression of AEs by resonant-type 3D magnetic field
  - Threshold 3D field amplitude for AE suppression
- Resonant plasma responses in the AE suppressed phase
  - 3D phase window for AE suppression is overlapped with ELM mitigation
  - 3D field threshold for AE suppression is slightly lower than locking threshold → Narrow amplitude window
- Resonant interactions of fast ions as the AE suppression mechanism
  - Modification of phase-space distribution of confined fast ions → Relaxation & Reduction of fast ion drive → AE suppression
- Future work for optimal 3D field configuration for AE control
  - Avoid mode locking / Minimize thermal confinement loss / Maximize EP confinement
  - Integrate with pedestal stability & ELM control