Effects of 3D Magnetic Field on Fast Ion Loss and Alfvénic Activities in KSTAR

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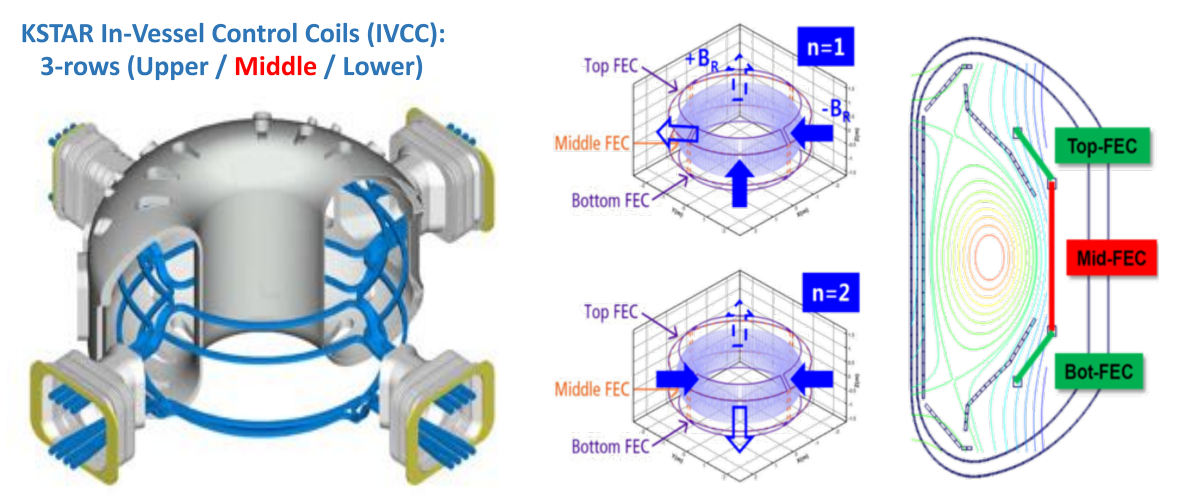
Introduction

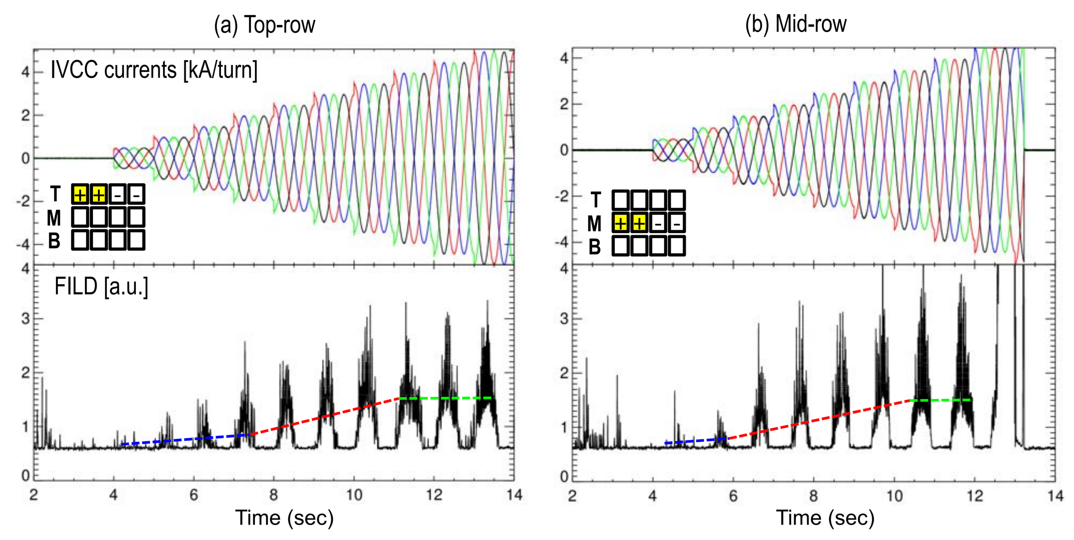
- Controlled 3D magnetic field is one of important control knobs for plasma transport and stability in tokamaks – ELMs, rotation, turbulence, divertor heat load
- Transport and confinement of energetic particles impact on fusion performance via interacting with MHD instabilities, fluctuations, and 3D magnetic field
- This presentation reports analysis of (1) Enhanced Fast Ion Loss & (2) Excitation of Alfvénic Eigenmode due to application of 3D magnetic field in KSTAR
  - (1) Analysis with full orbit following simulation + ideal plasma response
    - Modification of phase-space fast ion distribution → Threshold behavior of fast ion prompt loss
  - (2) Reduction of plasma rotation → Modification of Alfvén continuum
    - Change in fast ion confinement due to excitation of Alfvén Eigenmodes

Non-Axisymmetric Magnetic Field Coils in KSTAR



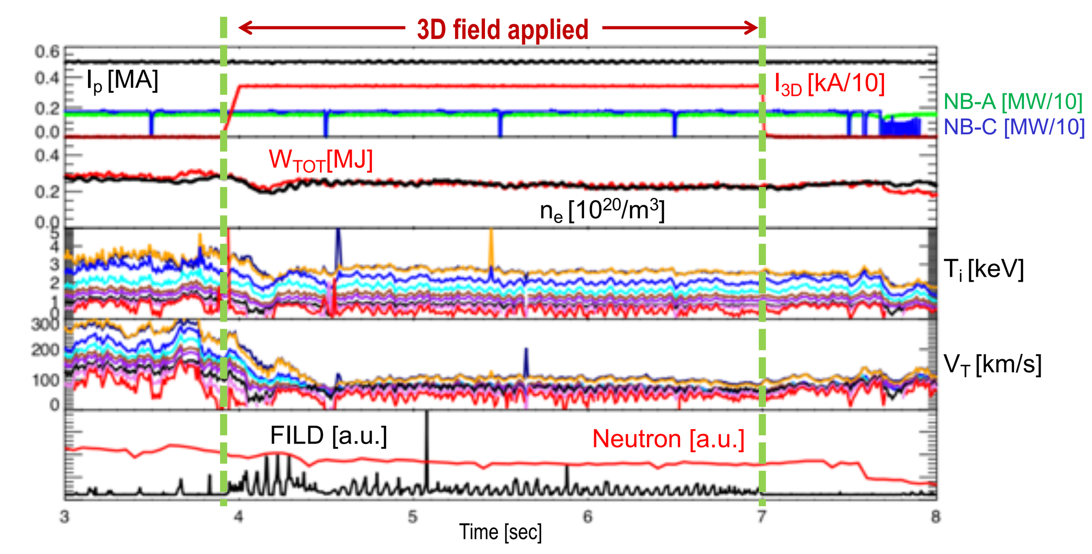
- In-vessel control coils (IVCC) in KSTAR provide various static or rotating non-axisymmetric magnetic fields of n=1 & n=2
- Demonstrate ELM suppression, toroidal rotation braking, divertor heat flux splitting, etc.
- Active use for control of fast ion transport & confinement

Enhanced Fast Ion Loss Measured by FILD during RMP Application



- Application of n=1 rotating RMP using single-row (top/middle) 3D field coils
  - FILD measures fast ion loss during stepwise increase of RMP amplitude
    - Compensate for toroidal phase dependency of localized FILD measurement
- Slow increase of fast ion loss at the early stage, rapid increase above a certain level of RMP amplitudes (threshold), and saturation

Magnetic Braking Experiment Using n=1 3D Magnetic Field

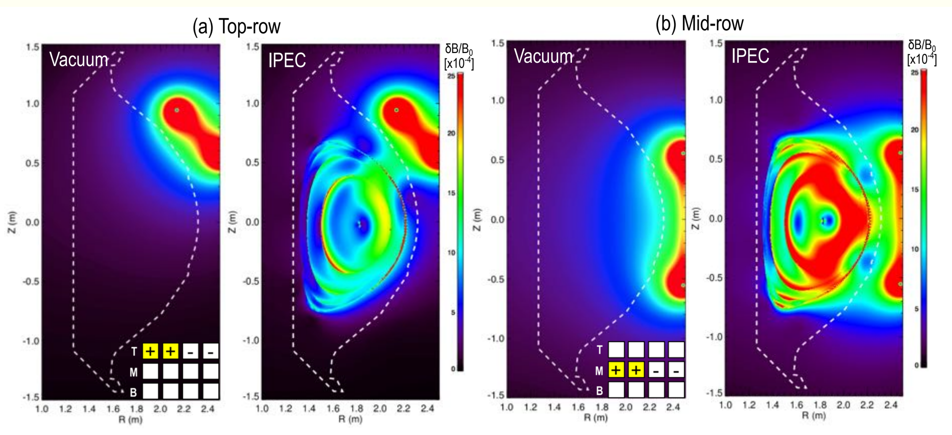


- I_p = 500 kA, B_T = 1.6 T, β_N = 2.3, q_{95} = 5
- P_{NBI} = 3.3 MW
- 3D field of n=1, 0-phasing applied to drive toroidal rotation braking

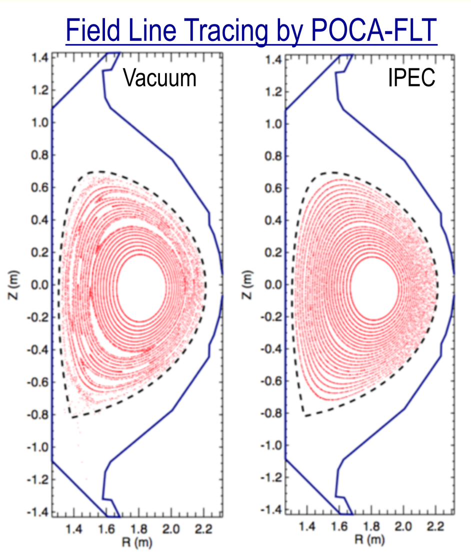
Top	+	+	-	-	3.5 kA/turn
Mid	+	+	-	-	4.0 kA/turn
Bot	+	+	-	-	3.5 kA/turn

- Slow degradation of confinement
- FILD captures enhanced fast ion loss due to 3D field

Perturbed Equilibrium Illustrates Importance of Plasma Response

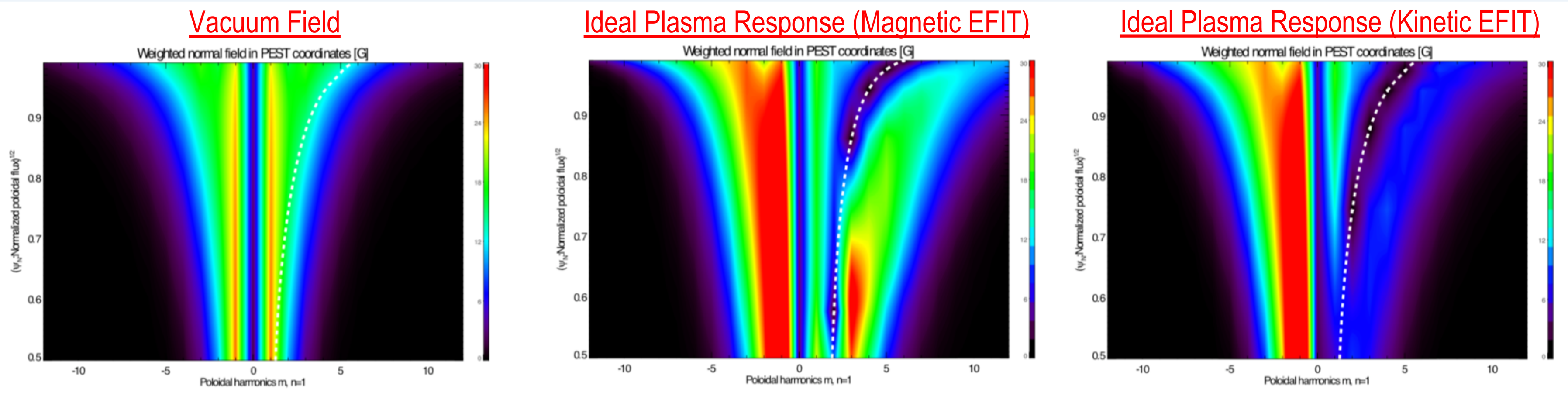


- Amplification & deformation of perturbed fields by ideal plasma response



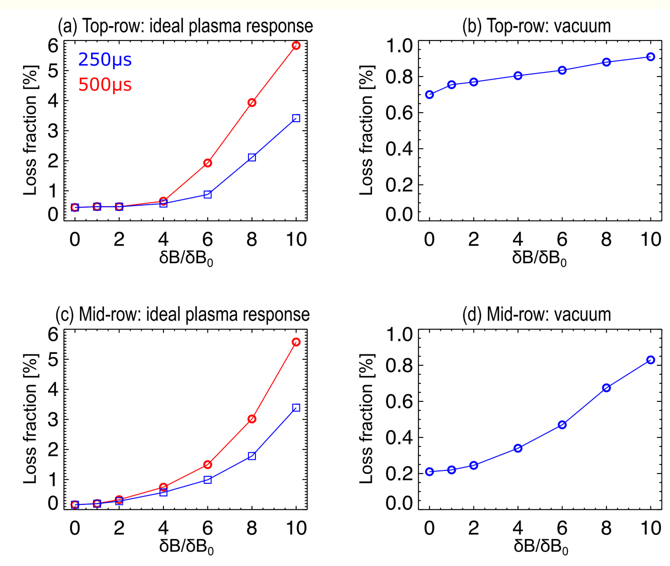
- Vacuum
  - Magnetic islands on the rational surfaces
  - Stochastic field layer near the plasma boundary
- Ideal plasma
  - Suppression of magnetic islands
  - Cross-surface transport dominant

Perturbed 3D Field Spectrum – Effect of Plasma Response & Pedestal



- Enhanced shielding due to inclusion of pedestal structure, moderating resonant response → More consistent to observation

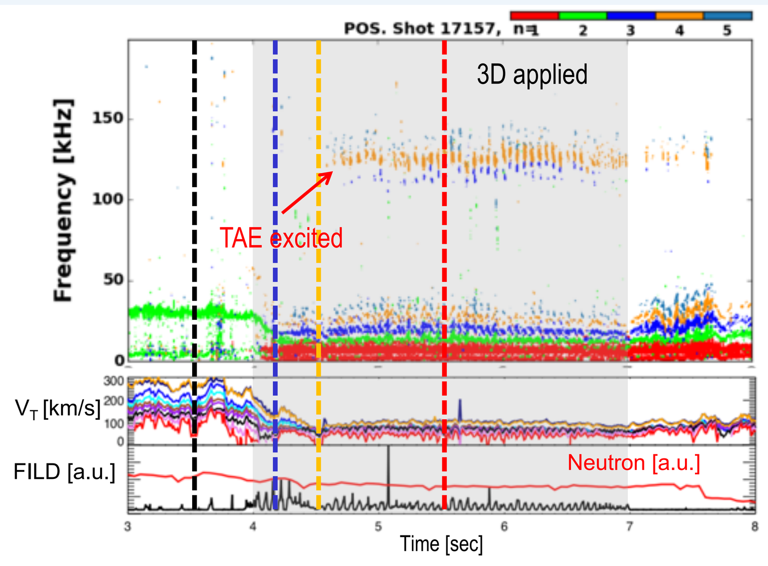
Full Orbit Simulation Reproduces Threshold Behavior of Fast Ion Loss



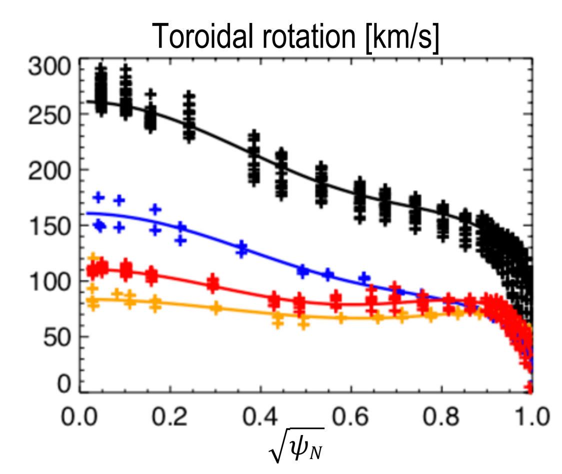
Fast ion loss fraction v.s. RMP amplitude

- Linear increase of RMP amplitudes v.s. non-linear increase of fast ion loss
  - Threshold RMP amplitudes for rapid increase of fast ion loss ($\delta B/\delta B_0$=2-4) → Reproduce experimental trend
  - Saturation phase not reproduced → Another physics mechanism?
- Only small increase of fast ion loss by vacuum field
  - Not strong enough to drive stochastic diffusion of fast ions

Excitation of TAE after Significant Braking of Toroidal Rotation

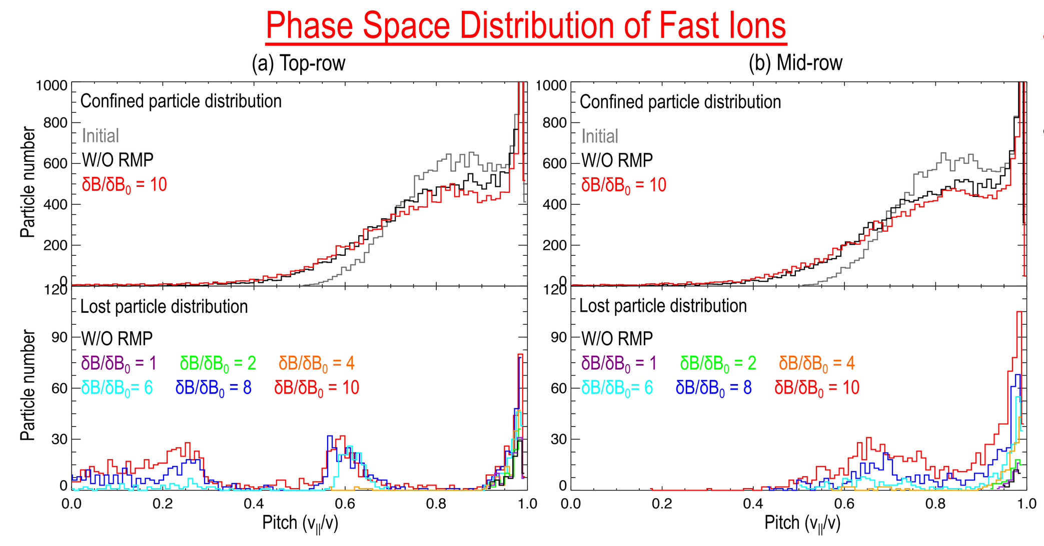


- 70% reduction in core rotation, leading to flat rotation profile
  - Zero-rotational shear
- TAE excited at the minimum rotation during magnetic braking driven by 3D field
  - n=4 mode dominant
  - Low frequency modes arise, along with strong n=1 tearing mode



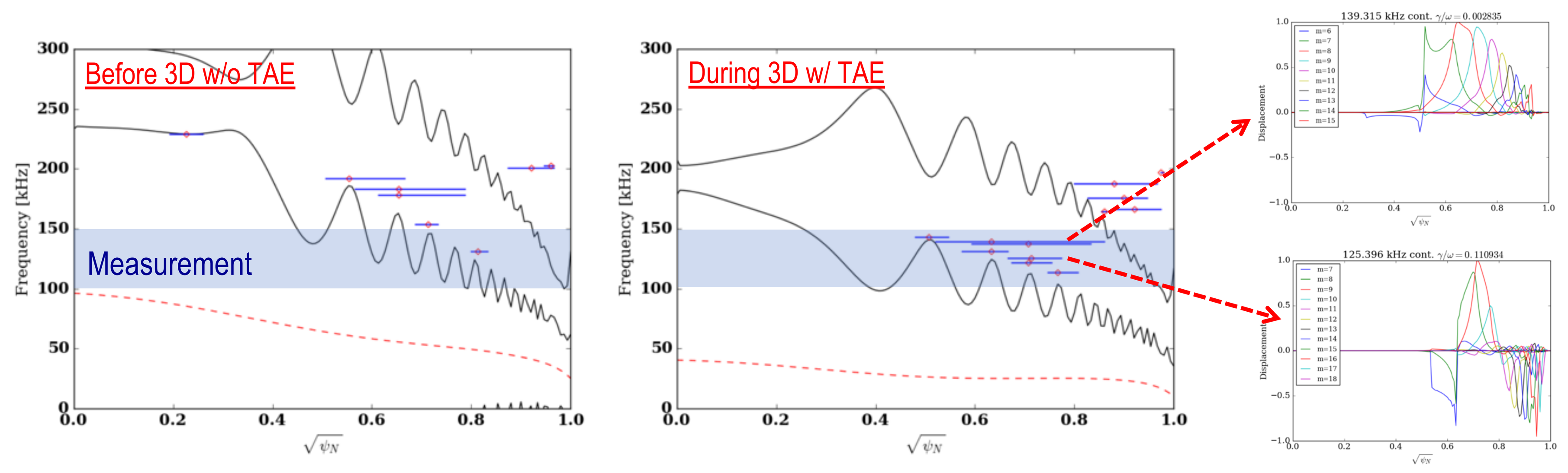
Lost Particle Pitch is Correlated to Threshold RMP Amplitude

Phase Space Distribution of Fast Ions

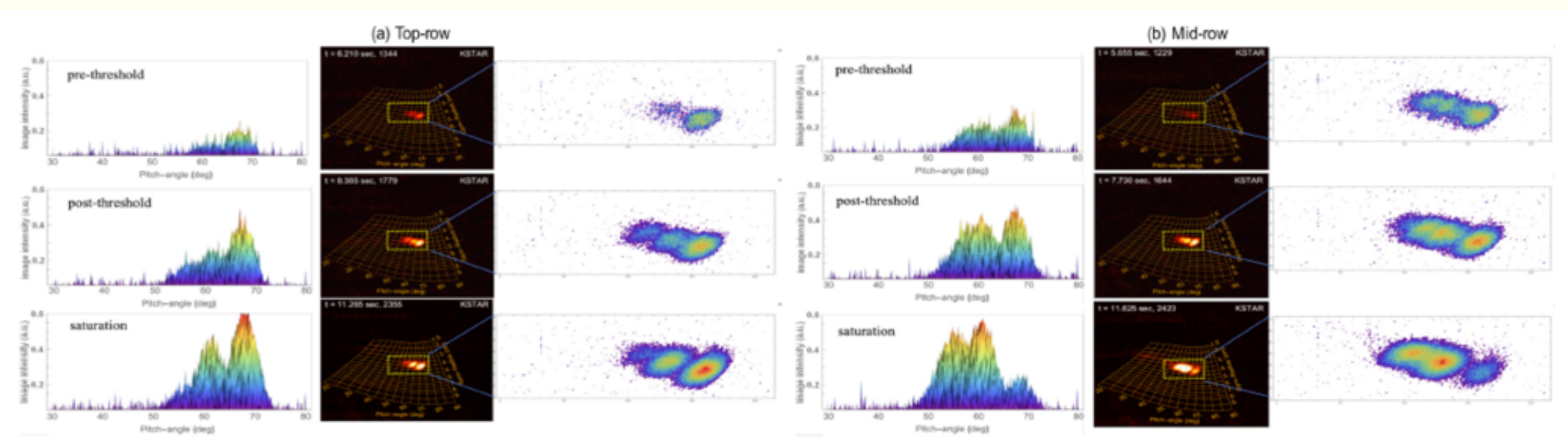


- Without RMP, most losses are from high pitch passing particles
- Losses of low pitch particles in the strong RMP amplitude
  - Below threshold → Increase of high pitch particle loss by RMP
  - Above threshold → Losses of intermediate pitch passing particles & low pitch trapped particles
  - Phase-space distribution significantly depends on the RMP amplitude & structure

NOVA Prediction Indicates TAE at Measured Frequency (n=4)

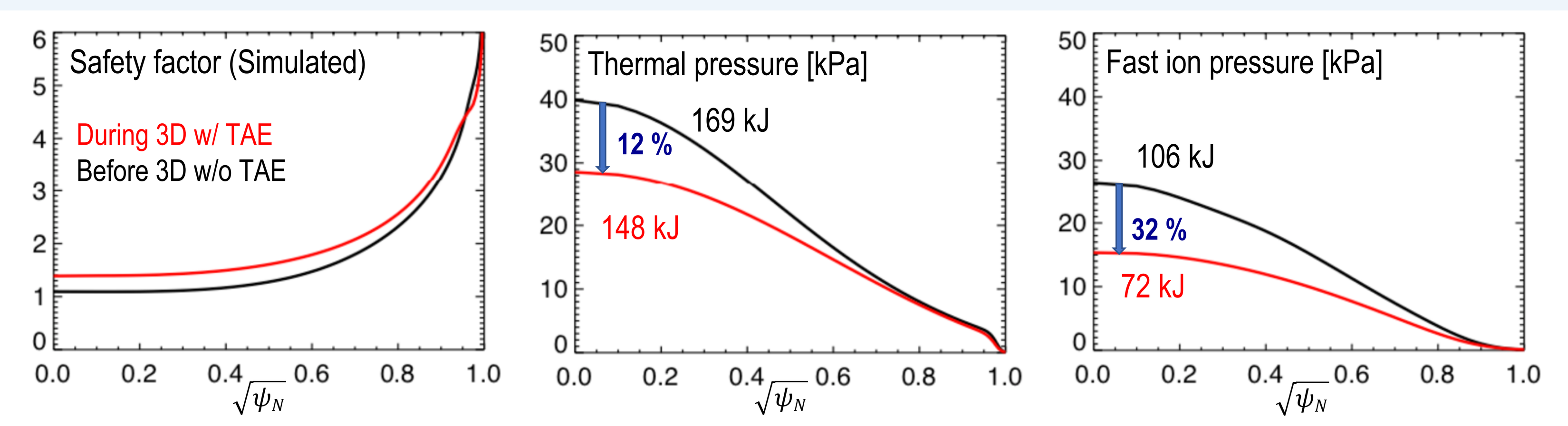


FILD Measurements Show Broadening of Pitch Distribution



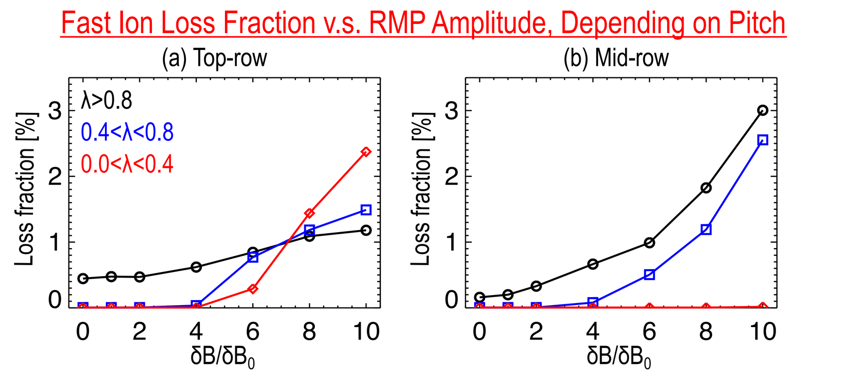
- Band-like structure in the pitch angle at the post-threshold & saturation phase, near the trapped and/or trapped-passing boundary

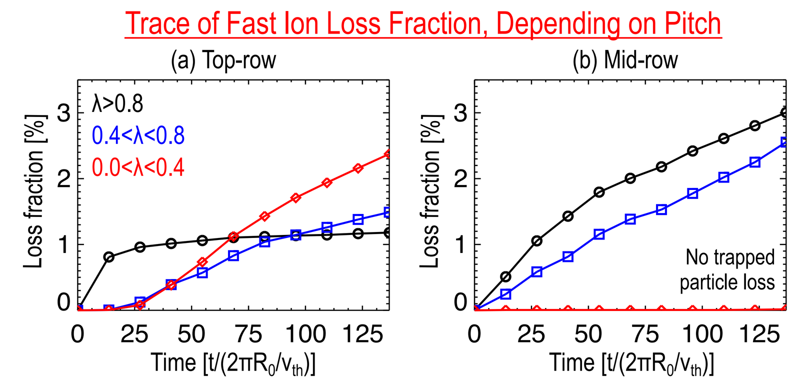
TRANSP Prediction Indicates Loss of Fast Ion Confinement



- Significant reduction of fast ion confinement, interacting with excited TAE during 3D field application
  - Decrease of NB confinement & power deposition ↔ Modification of safety factor profile

Threshold Behavior is Mainly Caused by Lower Pitch Particles





- Clear threshold behavior in low & intermediate pitch particles with increase of RMP amplitude
  - High pitch particles escape very fast in the early phase
  - Particles converted to intermediate & low pitch trapped orbits escape after long transits

Summary

- Effects of 3D magnetic field on fast ion prompt loss & Alfvénic activities in KSTAR are analyzed
- Full orbit + ideal plasma response simulations reproduce enhanced fast ion loss & threshold behavior of fast ion loss driven by 3D magnetic field in KSTAR
  - Find redistribution of fast ion phase-space distribution is responsible for the threshold behavior
- Toroidal rotation braking by 3D magnetic field can excite Alfvén Eigenmodes
  - Modify Alfvén continuum by significant reduction of toroidal rotation & change of q-profile
  - Degradation of fast ion power deposition and confinement