Improved energy confinement triggered by non-axisymmetric magnetic field driven rotation braking in KSTAR

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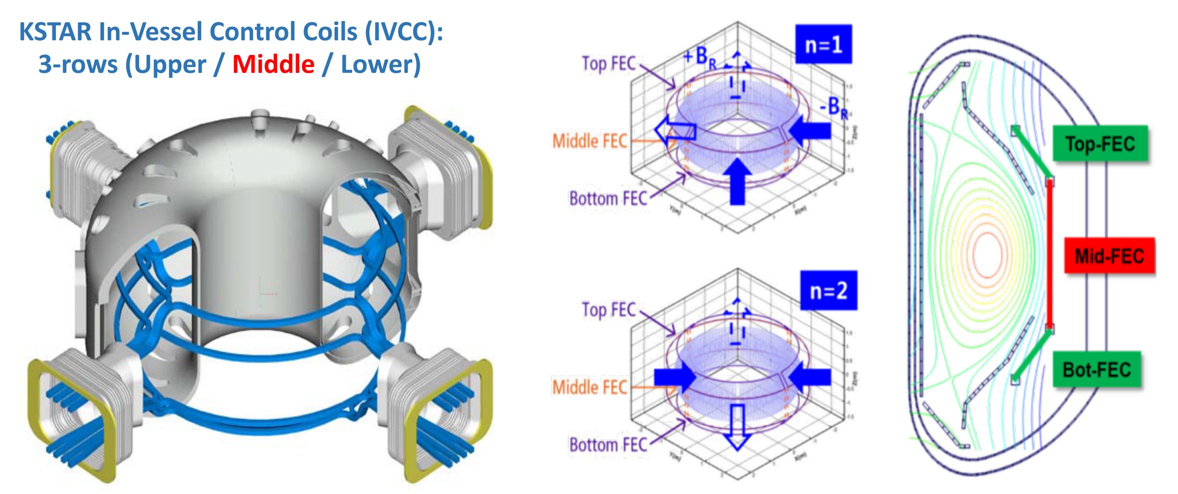
KSTAR

Introduction

- Controlled 3D magnetic field is one of important control knobs for plasma transport and stability in tokamaks – ELMs, rotation, turbulence, divertor heat load
- Dedicated experiment has been performed to explore confinement characteristics of slow rotating plasmas by utilizing 3D magnetic field to drive NTV for rotation braking in KSTAR
  - Expand operation space to ITER-relevant rotation conditions of near-zero torque
  - Build database to study confinement physics & predict confinement of slow rotating plasmas
- This presentation reports observations of improved confinement driven by 3D magnetic field induced toroidal rotation in KSTAR
- Supplementally, analysis of destabilization of toroidal Alfvén Eigenmodes due to 3D magnetic braking in KSTAR is presented

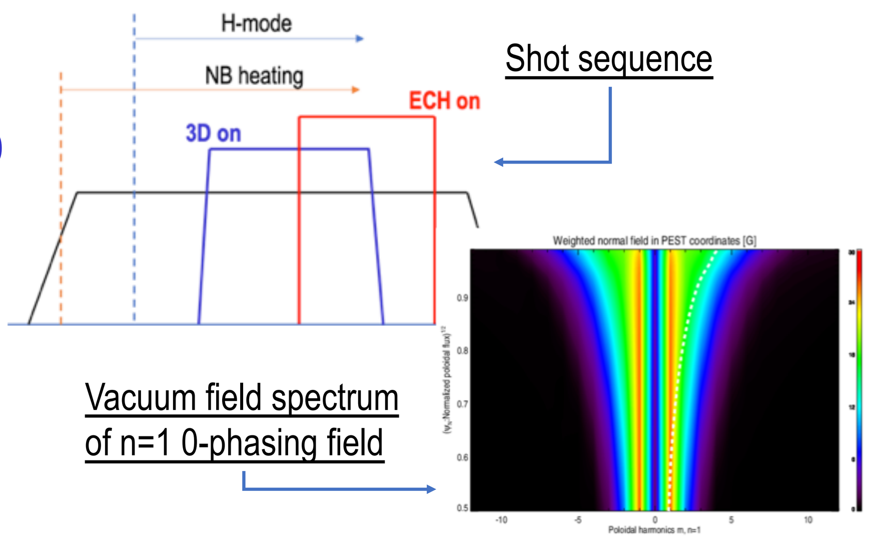
Non-Axisymmetric Magnetic Field Coils in KSTAR



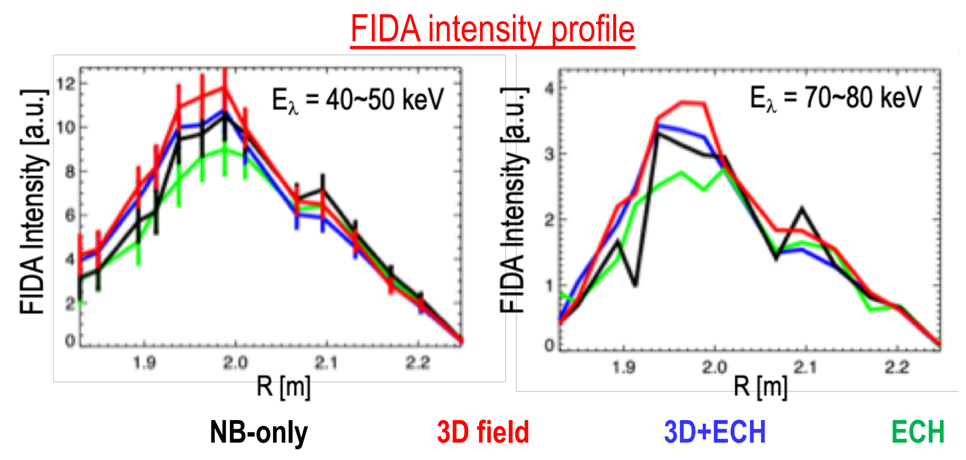
- In-vessel control coils (IVCC) in KSTAR provide various static or rotating non-axisymmetric magnetic fields of n=1 & n=2
- Demonstrate ELM suppression, toroidal rotation braking, divertor heat flux splitting, etc.
- Active use for control of toroidal rotation & associated transport

Dedicated Magnetic Braking Experiment in KSTAR

- Utilize 3D magnetic field and ECH to produce slow rotating plasma under NB heating and torque
  - Separate 4 phases depending on heating (NB & ECH) and 3D field mix
    - NB-only / Magnetic braking with 3D field / magnetic braking + ECH / ECH
    - NB heating (4 MW) is applied during whole discharge
  - n=1, 0-phasing 3D field + ECH (1.2 MW) for rotation reduction
    - Phase can be resonant or non-resonant depending on q-profile

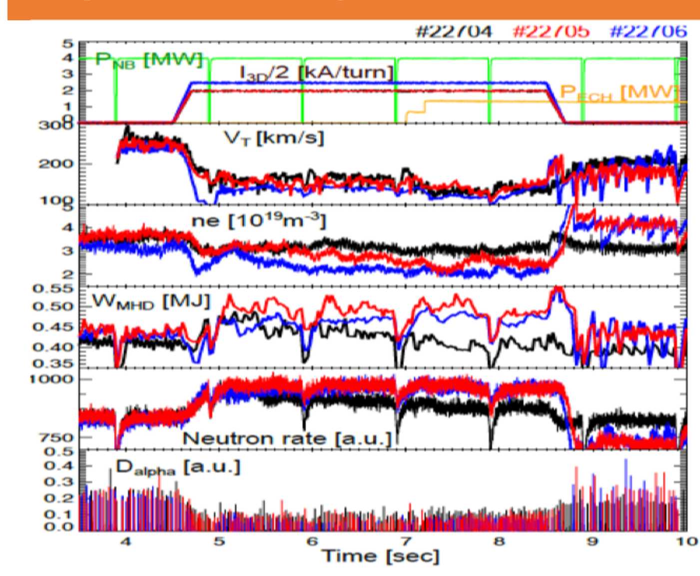


3D field drives multi-channel transport in a particular sequence



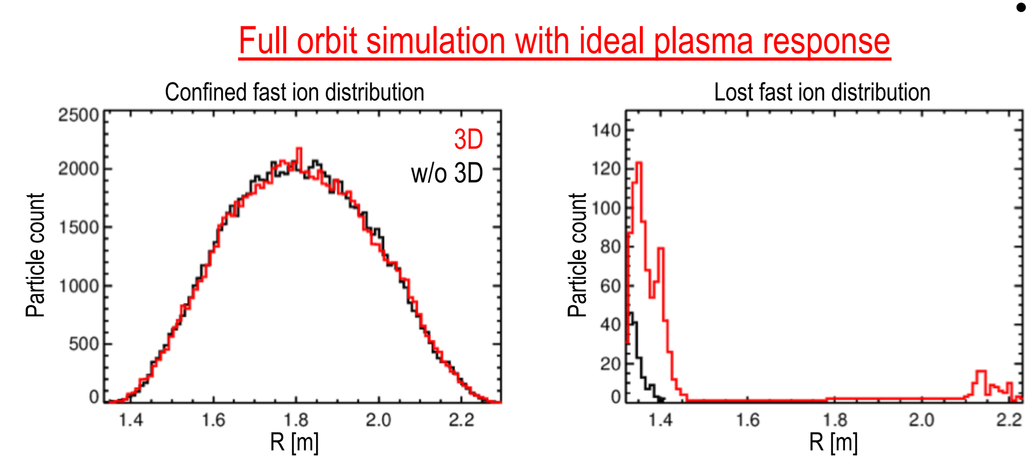
- Fast ion confinement improved during the 3D field (+ECH) phase
  - Improvement is not global, appears mainly at the inner core region (R)
  - Adding ECH (B) degrades confinement to similar level in NB-only phase (B)
- Removing 3D field significantly degrades fast ion confinement (G)
  - 3D field associated transport is the main mechanism

Improved energy confinement has been observed in the 3D magnetic braking discharge



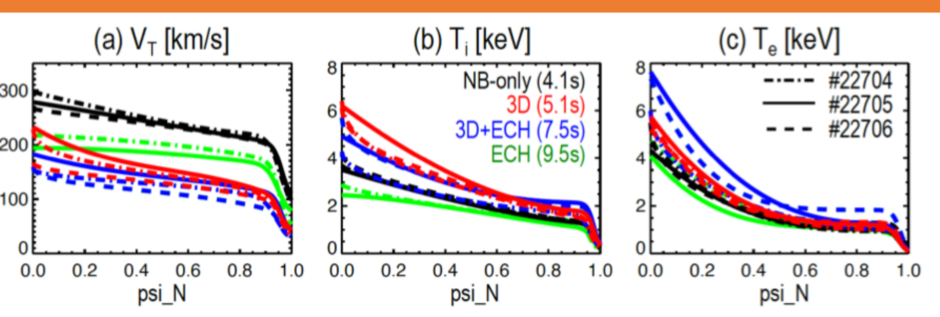
- Strong rotation braking achieved by 3D & 3D+ECH
  - Global rotation reduction
- Density pump-out
  - Dependent on q_{95}, 3D field amplitude
- Stored energy increased by 15-20%
  - Sustained during 3D & 3D+ECH, dropped after 3D turned off
- ECH modifies transport channel
  - Large decrease in T_i/T_e
  - Increased stored energy maintained
- Neutron rates raised / ELM mitigation observed

Full Orbit Simulation of Fast Ion Loss with 3D Magnetic Field



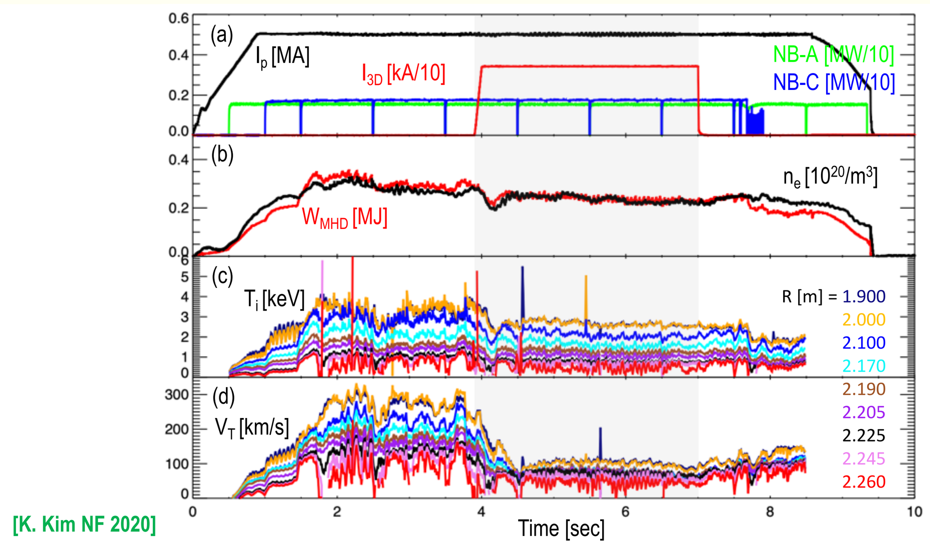
- Full orbit simulation predicts increase of fast ion loss by 3D magnetic field
  - Contradictory to observation, but may explain degradation at the edge
  - Existence of another transport mechanism
  - Turbulence associated transport reduction could be a candidate
    - Increase of slowing-down time due to improved core confinement

Modification of Kinetic Properties in the Multi-Transport Channels



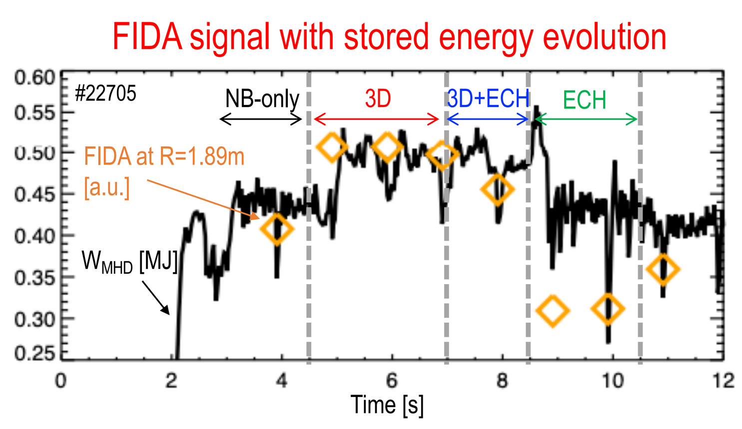
- Improved confinement identified by enhanced transport barrier under 3D field
  - Ion temperature at core & pedestal raised by up to 50% (R, B)
  - Rotation braking leads to stronger rotation shear (R, B) / Electron (& ion) transport impacted by ECH (B, G)
  - Turning-off 3D field recovers toroidal rotation, moderates rotation shear → Thermal (& fast ion) confinement degraded in the whole volume (G)

Magnetic braking impacts on Alfvénic activity



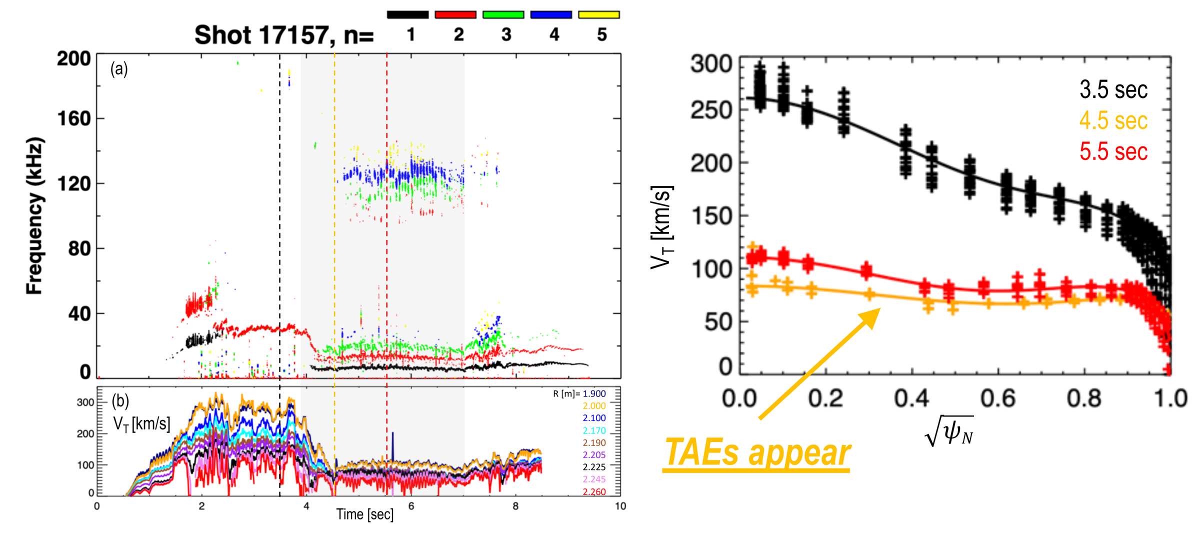
- Quiescent-like toroidal rotation braking discharge produced by highly non-resonant magnetic field
  - Significant reduction of toroidal rotation
  - Particle transport promptly increased, but soon recovered
  - Small impacts on confinement → gradual decrease

Improved Fast Ion Confinement Observed



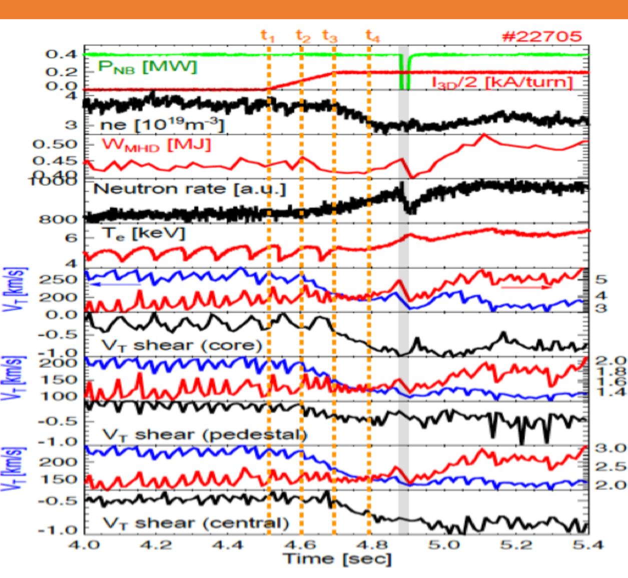
- FIDA indicates improved fast ion confinement in the 3D & 3D+ECH phases
  - FIDA intensity increased and sustained during 3D and 3D+ECH phases
  - Significantly drop after turning-off of 3D field in spite of the same heating power
    - 3D field plays a primary role for improving fast ion (and thermal energy) confinement
- Similar improvements in thermal energy & fast ion confinement in the improved confinement discharges

Destabilization of TAEs by 3D Magnetic Braking



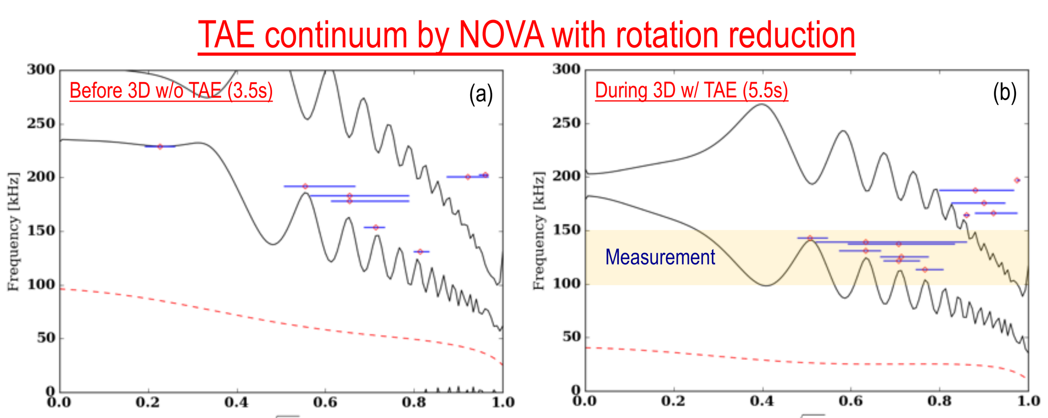
- TAE destabilized at the minimum rotation driven by magnetic braking (No ECH launched)
  - ~70% reduction of core rotation
  - Near-zero rotation shear
  - May related to gradual confinement decrease

3D field drives multi-channel transport in a particular sequence



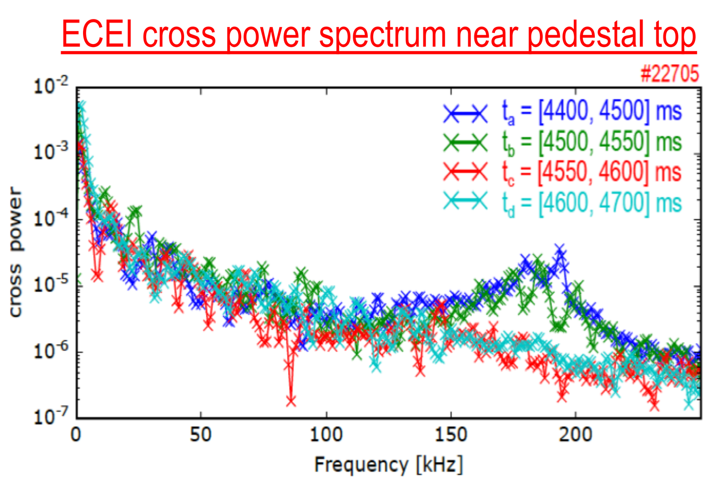
- Kinetic plasma responses are not prompt, but sequential
  - Rotation reduction first begins at the middle of 3D field ramp-up (t_2)
    - Turbulent transport mitigated or suppressed (see below)
  - Neutron rates increase with rotation reduction (~t_3)
  - T_e increases slowly with density pump-out from the 3D field flat-top (t_3)
    - Raise fast ion slowing-down time along with n_e decrease
  - Rotation shear builds up (~t_3), when close to minimum rotation level
  - At last, stored energy increases (t_4)

NOVA modeling predicts TAE continuum modified by 3D field driven magnetic braking



- Doppler-shift included in the NOVA calculation lowers modes frequency
- Modeling provides consistent predictions
  - Before 3D (w/o TAEs, w/o rotation reduction): No modes predicted in the experimentally measured frequencies around 100~150 kHz
  - During 3D: TAEs predicted around measured frequency along with reduction of toroidal rotation

Suppression of Edge Turbulent Fluctuation



- ECEI indicates high frequency turbulent fluctuations (150~200 kHz) near pedestal top (R~2.15 m) are suppressed in the improved confinement phase
  - Reduced turbulent transport correlated to confinement improvement
  - Transport suppression occurs at t_c=[4550, 4600]
    - Corresponds to rotation reduction (t_2), rather than rotation shear build-up
    - Rotation reduction is the main driver of confinement improvement

Summary

- 3D magnetic field induced rotation braking can modify transport and confinement of tokamak plasmas
  - 3D magnetic field significantly reduces toroidal rotation in the high beam power H-mode plasmas
  - Energy confinement and fast ion confinement can be improved, mainly driven by rotation reduction and shear build-up
  - Destabilization of Alfvénic activities by 3D magnetic braking
- Analyses to characterize confinement physics of slow rotating magnetic braking discharges are ongoing
  - Numerical analysis utilizing MHD & full orbit & gyrokinetic simulations