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

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Introduction

- Controlled 3D magnetic field is one of important control knobs for plasma transport and stability in tokamaks – ELMy, 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 MIV 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 (ICVC) on the KSTAR provide various static or rotating non-axisymmetric magnetic fields of n=1, 2, 3
- 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
  - Plasma response can be resonant or non-resonant depending on q-profile

Vacuum field spectrum of n=1, 0-phasing field

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

Vacuum field spectrum of n=1, 0-phasing field

Improved Fast Ion Confinement Observed

- FIDA indicates improved fast ion confinement in the 3D & 3D+ECH phases
  - FIDA intensity increased and sustained during 3D & 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

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

Full orbit simulation with ideal plasma response

Improved confinement identified by enhanced transport barrier under 3D field

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  - Ion temperature at core pedestal raised by up to 50% (~2)
  - Rotation braking leads to stronger rotation shear (~1, 0) / Bechack (A, I) transport impacted by ECH (~B)
  - Turning-off 3D field recovers toroidal rotation, moderates rotation shear to Thermal (A fast ion) confinement degraded in the whole volume (~C)

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

- TAE destabilized at the minimum rotation driven by magnetic braking (NOVA launched)
  - ~70% reduction of core rotation
  - Near-zero rotation shear
  - May related to gradual confinement decrease

TAE continuum by NOVA with rotation reduction

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

TAE destabilization by 3D Magnetic Braking

- TAE destabilized at the minimum rotation driven by magnetic braking (No ECH launched)
  - ~70% reduction of core rotation
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Steady rotation braking achieved by 3D & 3D+ECH Global rotation reduction

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

Modification of Kinetic Properties in the Multi-Transport Channels

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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

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 ($t_1$)
  - Turbulent transport mitigated or suppressed (see below)
  - Neutron rates increase with rotation reduction ($t_2$)
  - $t_3$: Increases slowly with density pump-out from the 3D field flat-top ($t_2$)
  - Raise fast ion slowing-down time along with $n_e$ decrease Rotation shear builds up ($t_4$), when close to minimum rotation level
  - All fast, stored energy increases ($t_5$)

Particle transport promptly increased, but soon recovered

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ELM suppression, toroidal rotation braking, divertor heat flux splitting, etc.

Activation use for control of toroidal rotation & associated transport

Active use for control of toroidal rotation & associated transport

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

ECCI cross power spectrum near pedestal top

- ECI indicates high frequency turbulent fluctuations (150-200 kHz) near pedestal top ($R_e$=2.15 m) are suppressed in the improved confinement phase
- Reduced turbulent transport correlated to confinement improvement
- Transport suppression occurs at $t_1$=4550, 4600
- Corresponds to rotation reduction ($t_1$), 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

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FIDA signal with stored energy evolution

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