Aspects and Applications of Non-Axisymmetric Coils on KSTAR

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16th Workshop on MHD Stability Control
1. Overview of 3D Field Coils in KSTAR

2. Applications
   2-1. Axisymmetric Applications
   2-2. 3D (Non-axisymmetric) Applications
       - ELM suppression by n=1 RMP

3. Summary
1. Overview of 3D Field Coils in KSTAR

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3. Summary
KSTAR Has A Versatile In-Vessel Control Coil (IVCC) System Inside Vacuum Vessel

- Toroidally segmented 3D shaped coil system
  1. Combining axisymmetric and non-axisymmetric field coils
  2. Easier installation and maintenance

Applicable to Axisymmetric and Non-Axisymmetric Magnetic Applications

- **Axisymmetric applications**
  - Vertical stability control (IVC), fast radial control (IRC)
- **Non-axisymmetric (3D) applications**
  - Field error corrections (FEC), RWM, RMP etc
Full IVCC System Installed in 2010

Passive Stabilizer
Full IVCC System Installed in 2010
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3. Summary
Successful Vertical Stabilizations of Highly Shaped Plasmas by IVC ($\kappa \sim 1.85$ and $\delta \sim 1.0$)

- $\kappa \sim 1.85$ & $\delta \sim 1.0$ achieved successfully
Even LSN Plasmas Enforced by IVC Were Well Controlled

For LSN shaping, plasma pushed down by ~10cm using IVC
- $I_{ivc} \sim 2.0 \text{kA/t}$ applied to hold it
- Well controlled even though its worse field curvature
Integrated Shape Control Combined with IRC Can Enhance Control Performance Significantly

- IRC is not essential component, but ...
- Can enhance shape control performance significantly
- Improved shape control =
  “Fast $R_p$ control by IRC”
  + “isoflux control with $M_{ij}$-decoupling”
- Example: All volume shifted by $\Delta R = +2$ cm

⇒ IRC is on preparation for use in 2012
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3. Summary
KSTAR Can Provide Wide Spectra of 3D Magnetic Perturbations

- **3-by-4 3D field coils available having 2 turns for each**
  - all internal and segmented with saddle loop configurations
  - n=1 and 2 applicable

- **Wide spectra of magnetic perturbations are possible**
  - Poloidal helicity change for n=1
  - Even/odd parity change for n=2

Main applications of 3D fields
1. Resistive Wall Mode Control
2. Error Field Correction
3. RMP/NRMP Physics Study
RWM Controls Are Under Design and Study

Cu-Passive Stabilizer + RWM coils $\rightarrow \beta_{N,\text{Wall}}(\sim 5.0)$

In VALEN model

* Y.S. Park, S.A. Sabbagh, et al., Nucl. Fusion 51 (2011)

Middle FEC

Controlled within ~8ms

MISK predicts relatively large rotations are required for RWM stability
Applicable Spectra of $n=1$ and $n=2$ MP

- **n=1, -90 phase**
  - top: 
  - mid: 
  - bot: 

- **n=1, 0 phase**
  - top: 
  - mid: 
  - bot: 

- **n=1, +90 phase**
  - top: 
  - mid: 
  - bot: 

- **n=1, 180 phase**
  - top: 
  - mid: 
  - bot: 

- **n=1, mid-FEC alone**
  - top: 
  - mid: 
  - bot: 

- **n=2, even parity**
  - top: 
  - mid: 
  - bot: 

- **n=2, odd parity**
  - top: 
  - mid: 
  - bot: 

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Non-Axisymmetric Plasma Responses Were Investigated Using Two Different Phasings

* J.-K. Park, Y.M. Jeon, et al., in preparation for publication

- Two different phasings (+90 and -90) of the n=1 fields were applied to Ohmic discharges ($I_P=400\,\text{kA}$, $BT=2.0\,\text{T}$)
  - The +90 phasing induced a locking and disruption with $I_{\text{FEC}}\sim600\,\text{A/turn}$
  - The -90 phasing caused only a slight braking of rotation

\[ \phi \quad \theta \quad \text{B-field} \]

\[ \begin{array}{cccccc}
+ & + & - & - & - \\
- & + & + & - & - \\
- & - & + & + & + \\
+ & + & + & - & - \\
- & + & + & + & + \\
+ & + & - & - & - \\
\end{array} \]

\[ +90\,\text{(Resonant)} \]

\[ \begin{array}{cccccc}
+ & + & - & - & - \\
- & + & + & - & - \\
- & - & + & + & + \\
+ & + & + & - & - \\
- & + & + & + & + \\
+ & + & - & - & - \\
\end{array} \]

\[ -90\,\text{(Non-resonant)} \]
Non-Axisymmetric Plasma Responses Were Found In +90 Phasing By Locking

- A small non-axisymmetry was found in +90 phasing, by applying two different toroidal phases

  - Locking threshold $I_{\text{FEC}} \sim 1\text{kA/turn}$ for 0 phase, $I_{\text{FEC}} \sim 1.2\text{kA/turn}$ for 180 phase

  - A small intrinsic error-field ($\sim 100\text{A}$) found in KSTAR

\[ \Rightarrow \text{A small intrinsic error-field ($\sim 100\text{A}$) found in KSTAR} \]
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ELMs Suppressed by n=1 MPs in KSTAR 2011

- COMPASS-D \((n=1)\) triggered (2001)
- DIII-D \((n=3)\) suppressed (2004)
- JET \((n=1, 2)\) mitigated (2007)
- NSTX \((n=3)\) triggered (2010)
- MAST \((n=3)\) mitigated (2011)
- ASDEX-U \((n=2)\) mitigated (2011)

We are adding …

- KSTAR \((n=1)\) Suppressed (2011)

ELMs Suppressed For the First Time by n=1 MP (+90)

- +90 phased n=1 MP suppressed ELMs
  - In JET, ELM mitigated by n=1 (Y.Liang, PRL, 2007)

- Density (~10%) pumping out initially. Then, increased when ELM suppressed

- Stored energy drop by ~8% initially. Then slightly increased or sustained when ELM suppressed

- Rotation decreased (~10%) initially. Then sustained when ELM suppressed

- Te/Ti changes were relatively small

- Two distinctive phases observed
  (1) ELM excitation phase
  (2) ELM suppression phase
Threshold FEC Current for ELM Suppression

- $I_{FEC,\text{threshold}} \geq 0.75 \text{ kA/t}: \text{marginal suppression}
- > 1.00 \text{ kA/t}: \text{full suppression}
(vacuum analysis predicted $\geq 1.00 \text{ kA/t}$)

- $\Delta \beta_p$ is dependent on $I_{FEC}$
(similar $\Delta n_e, \Delta W_{\text{tot}}, \Delta V_\phi, \ldots$)

- Note that there was no clear change of ELM size on transition
(excitation $\rightarrow$ suppression), while the ELM frequency decreased dramatically
ELMs Suppressed For the First Time by $n=1$ MP (+90)

- +90 phased $n=1$ MP suppressed ELMs
  - In JET, ELM mitigated by $n=1$ (Y.Liang, PRL, 2007)

- Density ($\sim$10%) pumping out initially. Then, increased when ELM suppressed

- Stored energy drop by $\sim$8% initially. Then slightly increased or sustained when ELM suppressed

- Rotation decreased ($\sim$10%) initially. Then sustained when ELM suppressed

- Te/Ti changes were relatively small

- Two distinctive phases observed
  1) ELM excitation phase
  2) ELM suppression phase
Mid-FEC May Responsible for ELM-Excitation

- ELMs excitation observed as expected
- Similar evolutions of global parameters with those on the initial ELM-excited phase
- Note that ELM-excitation should be distinguished from ELM-triggering
- Therefore, mixed MPs made two phases ELMs i.e. ‘mid-FEC alone’ + ‘n=1, +90’
ELMs Were Suppressed Rather Than Mitigated

#6123

$I_{FEC} = 1.9 \text{kA/t}$

$A \approx 2.74 \text{s}$
$m \approx 40$
$n \approx 6$

$B \approx 3.62 \text{s}$
$m \approx 25$
$n \approx 4$

$C \approx 4.31 \text{s}$
ELM-free

* G.S. Yun, APS invited, YI2 (2011)
Unusual Pedestal Evolutions Observed Suggesting Edge Transport Change by MP

• **Observations are ...**
  - Pedestal buildup saturated in the intermediate level
  - When destabilized, it resume pedestal build-up until the original threshold level.
  - After crash, it became back to the original crashed level
  - Edge stability seems to be not much changed
Experimental Evidence for Edge Transport Change by MPs ➔ Saturation of Pedestal Evolution

- **Crash**
- Gradual build-up Of pedestal

![Graphs showing Te_edge comparison](image)

- ELM-suppessed
- Saturated build-up

* RMP fully applied in this time period
Specific Changes of Magnetic Fluctuation May Be A Clue Or Evidence for Edge Transport Change

ELM-suppressed
- Fluctuation rising
- Mid-plane dominant
- Broad (not specific) spectrum

ELM-excited
- Fluctuation reduced
- Both midplane and divertor
Vacuum Analysis for n=1 Magnetic Perturbations

-90 Phasing ($\sigma_{CH} \sim 0.04$)
Non-Resonant (NRMP)

0 Phasing ($\sigma_{CH} \sim 0.08$)

90 Phasing ($\sigma_{CH} \sim 0.27$)

180 Phasing ($\sigma_{CH} \sim 0.22$)

Midplane ($\sigma_{CH} \sim 0.17$)

Chirikov by n=1 SFEC with 3.6kAt

* $\sigma_{CH}$ = stochastic layer width in the edge

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IPEC With Plasma Responses Predicts Somewhat Differently

• 180 phase is the best for Chirikov
• 180 phase may have strongest rotation damping
Experimental Observations for Wide MP Spectra

• Variety of ELM responses to different MP spectra
• Various ELM controllability of MPs

→ ELM Suppression
→ H/L Back-transition / Locking
→ ELM (strong) mitigation ~ JET n=1
→ ELM Excitation
→ ELM Excitation
Occasionally, H→L Transition and Locking Observed Instead of ELM-Suppression, Responding to n=1 MPs

- Mode locking was one of expected plasma responses to n=1 MP
- A key difference in H→L/Locked discharges compared with ELM-suppressed ones is the larger increase of edge Te in H-mode by a factor of ~2.
- May correlated with edge collisionality
Strong Magnetic Braking by n=1 MP Observed: Complete Locking Without Killing Plasmas

![Graphs showing magnetic braking and plasma behavior](image)

**Graph 1:**
- Divertor and Midplane plasma profiles with time evolution.
- CES profile with time and major radius.

**Graph 2:**
- Heat deposition and magnetic field profiles.
- 2/1 tearing instability markers.

**Data Points:**
- Ti [keV] and Vt [km/sec] at different times and major radii.
- P_{ECH} and P_{NBI} = 1.4 MW.

**Key Points:**
- Enhanced braking without plasma killing.
- CES profile indicating temperature and velocity changes.
- 2/1 tearing stability analysis.
ELMs Triggered by $n=2$ With Odd Parity

- Two ELM-free H-mode periods
- $n=2$ with odd-parity triggered type-I ELMs
- $V_{\text{tor}}$ didn’t changed by L/H transition $\Rightarrow$ strong mag. braking
- Ref to ELM triggering on NSTX by $n=3$ MP
1. Versatile IVCC system in KSTAR
   - Axisymmetric + non-axisymmetric (n=1, 2)
   - Three poloidal coils \( \rightarrow \) wide spectra of MPs
   - Various applications: IVC, IRC + FEC, RWM, RMP

2. ELM control by applying non-axisymmetric MPs
   - ELMs suppressed completely by n=1 MP
   - Various ELM responses
     : suppression, excitation, mitigation, locking, triggering
   - Saturated pedestal evolutions with specific change of mag. fluctuations
   - Strong mag. braking by n=1 MPs

3. Worth to note that ...
   - Variety of ELM responses to different mag. spectra
   - Wide controllability of ELMs by applying MPs
   - Important to understand what made different responses such as
     mitigation \( \leftrightarrow \) excitation
     suppression \( \leftrightarrow \) triggering