RMP ELM control studies in the EAST tokamak

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ELM control is a significant issue for ITER

[Hawryluk et al., *NF* (2009)]

- The expected type I Edge Localized Mode (ELM) size on ITER should be reduced by a factor of **20** (10 → 0.5 MJ/m$^2$) for present wall and divertor materials.

- Resonant magnetic perturbations (RMPs) are one of the simplest and the most effective tools.

**edge magnetic topology change → pedestal reduction → stabilize ELM**
RMP coils in EAST and DIII-D in support of ELM control for ITER

DIII-D, 2x6

EAST, 2x8

ITER, 3x9
Previous joint experiments in DIII-D and EAST on ELM control using mixed-n RMPs

<table>
<thead>
<tr>
<th></th>
<th>DIII-D</th>
<th>EAST</th>
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<tbody>
<tr>
<td>General</td>
<td>Standard type-I ELMy H-mode:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( q_{95} \approx 3.5-3.8 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \beta_N \approx 1.5-2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( &lt;N_e&gt; \approx 4 \times 10^{19} \text{ m}^{-3} )</td>
<td></td>
</tr>
<tr>
<td>RMP coils</td>
<td>mixed ( n = 2 ) &amp; ( 3 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 X 6</td>
<td>2 X 8</td>
</tr>
<tr>
<td>shape</td>
<td>LSN</td>
<td>USN</td>
</tr>
<tr>
<td></td>
<td>( R/a \approx 2.9 ) (1.70/0.59)</td>
<td>( R/a \approx 4.4 ) (1.85/0.42)</td>
</tr>
<tr>
<td>( \nu_{e,\text{ped}} \relax )</td>
<td>( \sim 0.2 )</td>
<td>( \sim 0.5 )</td>
</tr>
<tr>
<td>( \Omega_{\phi_0} \text{(krad/s)} )</td>
<td>( &gt; 100 )</td>
<td>( &lt; 50 )</td>
</tr>
<tr>
<td>Divertor</td>
<td>C</td>
<td>W</td>
</tr>
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</table>

Comparison of Experimental Conditions in DIII-D and EAST
ELM Suppression Achieved Using a Rotating $n=2$ + Static $n=3$ RMP Field in DIII-D and EAST

- Reduce required coil current for ELM suppression
- Good for control of heat flux on the divertor while maintaining ELM suppression
  - Periodic changes of target particle flux observed

[DIII-D # 170068](#)

[DIII-D](#)

Rotating $n=2$ + Static $n=3$

EAST

EAST # 79013

[Sun Y, APS2017, IAEA2018](#)

[M. Jia et al., Phys. Plasmas 25, 056102 (2018)](#)

[S. Gu et al, Nucl. Fusion 59, 026012 (2019)](#)
Collaboration on n=2 RMP penetration studies in EAST

Thresholds for n=2 RMP are also correlated with the “overlap” field computed with the IPEC code

Highlight unique requirements for n>1 field control

[Lanctot et al., Phys. Plasmas 24, 056117 (2017)]
Multimode plasma response directly observed in EAST

- The n=2 plasma response was measured to be multimodal (clear phase shift) using two LFS mid-plane sensor arrays.
- GPEC ideal MHD modeling captures this transition from single-mode to multimode.

[N. C. Logan et al, NF 58, 076016 (2018)]
Identification of multiple eigenmode growth rates in EAST

• 3D MHD spectroscopy is validated in EAST
• Good correspondence between the multimode transfer function and experimental measurements

[Z.R. Wang et al/ Nucl. Fusion 59 (2019) 024001]
Previous results: Full ELM suppression achieved using low \( n \) RMPs in pure RF heating plasmas in EAST

- RF heating, \( \Omega_\Phi \sim 0 \), \( n=1,2 \) RMPs, \( \nu_{e,ped} \sim 1 \)
- Long pulse fully non-inductive operation with \( W \) divertor \( \sim 20 \)s
- Large range of \( q_{95} \sim [3.2 -6] \) for ELM suppression with low \( n \) RMPs

**Extend to ITER-like conditions**

\( n=4 \) RMP, low torque, low \( q_{95} \), high density, high \( \beta_N \) plasmas
Outlines

• First demonstration of full ELM suppression by $n=4$ RMP in low torque plasmas for ITER in EAST

• Understanding of RMP ELM suppression window

• Heat flux control during ELM suppression
Challenge for accessing ELM suppression in low torque plasmas

- ELM suppression is lost in low torque plasmas in DIII-D
- Possibly linked to the inward shift of rotation zero-crossing away from the pedestal top

New observation: Full ELM suppression by $n=4$ RMP in low torque plasmas demonstrated for the first time in EAST

- Experimental condition is close to low torque ITER type-I ELMy H-mode
  - low torque $T_{\text{NBI}} \rightarrow 0.44 \text{ N} \cdot \text{m} (< 0.9 \text{ N} \cdot \text{m ITER equivalent torque in EAST})$
  - $n=4$ RMP
  - $q_{95} \sim 3.65$, $v_{e,\text{ped}} \sim 0.5$, $\beta_N \sim 1.5$
  - $T_i \sim T_e \sim 1.5\text{-}2\text{keV}$
- No obvious drop of energy confinement, but clear density pump out

[Sun et al, IAEA FEC(2021)]
Lower torque plasmas is even better for achieving ELM suppression

- It is easier to get into ELM suppression at lower torque plasmas
- **Threshold** RMP current for ELM suppression is reduced 10%
  
  \[ \text{2.9kA} \quad \text{---} \quad \text{2.6kA} \]
Two $q_{95}$ windows identified for $n=4$ RMP ELM suppression

- A clear $q_{95}$ window for ELM suppression is observed
  - $q_{95}$ window $\sim [3.6, 3.75]$
  - Another window $\sim 3.95$
- Reliable ELM suppression is only obtained with **good control of $q_{95}$**
Optimized density window for ELM suppression is observed

- Both lower and upper density limits for ELM suppression is observed by adjusting feedforward gas puffing
  - \( N_e \sim [3.3-4.4] \times 10^{19} \text{m}^{-3} \) (or [0.44-0.6] \( N_{GW} \))
  - \( N_{e,ped} \sim [2.5-3.5] \times 10^{19} \text{m}^{-3} \) (or [0.33-0.47] \( N_{GW} \))
Demonstrated the advantage of $n=4$ RMP for ELM suppression

- **Threshold RMP currents** for ELM suppression are **similar**

- Impacts on plasma confinement are very different:
  - No obvious drop in stored energy and **minor** density pump out in $n=4$ case
  - **Significant drop** of stored energy and strong density pump out in $n=2$ case

\[ \downarrow 20-30\% \]

[Loarte et al, IAEA FEC(2021)]
Outlines

• First demonstration of full ELM suppression by $n=4$ RMP in low torque plasmas for ITER in EAST

• **Understanding of RMP ELM suppression window**

• Heat flux control during ELM suppression
Spectrum effect of n=4 RMP on ELM suppression is observed

- Type-I ELMs are completely suppressed by \( n=4 \) RMP with upper-lower odd coil phasing, but not for the even one.

- Density pump out and rotation braking observed in both RMP spectra

- \( W \) concentration decreased during the application of RMP
Odd $n=4$ coil configuration provides stronger edge resonant magnetic field with plasma response

- Resonance is **stronger** for **odd** coil configuration, when resistive MHD **plasma response** is taken into account using MARS-F
  - Stronger **shielding** in the **even** case
  - Stronger **kink-like** resonant response in the **odd** case
Odd $n=4$ coil configuration provides stronger edge resonant magnetic field with plasma response

- Resonance is **stronger** for **odd** coil configuration, when resistive MHD **plasma response** is taken into account using MARS-F
  - Stronger **shielding** in the **even** case
  - Stronger **kink-like** resonant response in the **odd** case
  - **All edge** resonant harmonics are stronger in the odd case
- This explains better effect of odd $n=4$ RMP on ELM suppression
Modeling result demonstrates the resonant $q_{95}$ window for $n=4$ ELM suppression

- Edge resonances, indicated by different criteria, taking into account plasma response using MARS-F code, shows a similar dependence on $q_{95}$
  - Stochastic layer width, Chirikov parameter near pedestal top, x point displacement, edge RMP amplitude
- Multiple resonant peaks observed in the modeling
  - $3.05, 3.35, 3.65, 3.95, ...$
Lower rotation might enhance plasma response

- The toroidal rotation is reduced to be closer to zero in low torque case
- The zeros of ExB rotation and electron perpendicular rotation shifted inwards
- ExB rotation is reduced to be closer to zero near the pedestal top
Periodic getting into and loss of ELM suppression correlated to edge perpendicular rotation

- ELM suppression is achieved, when edge perpendicular rotation becomes zero
  - \( u_\perp \) is the propagating velocity of density fluctuation near the very edge \((\rho \approx 1)\) measured by Doppler Reflectometry
  - ELM suppression is lost, when \( u_\perp \) drifts away from zero
  - ELM suppression is sustained, when the \( u_\perp \) is locked to zero
Outlines

• First demonstration of full ELM suppression by $n=4$ RMP in low torque plasmas for ITER in EAST

• Understanding of RMP ELM suppression window

• Heat flux control during ELM suppression
Challenge in control of heat flux during ELM suppression

Modeling results predicted the problem of second strike point (SSP) remains attached with increasing upstream density

RMP ELM suppression is compatible with Pellet Fueling

- **Effective fueling** is achieved using pellet injection during ELM suppression
- **No big ELMs** triggered by pellets
  - Small ELMs appears when density exceeds the threshold
Heat fluxes on both OSP and SSP are substantially reduced by injected pellets without triggering large ELMs.

- The heat flux on both OSP and SSP decrease after the pellet injection.

- Effect pellets on heat flux:
  - slight increase followed by a substantial decrease
  - small ELMs between the pellets
A similar upper density limit is observed using gas puffing fueling after ELM suppression

- ELM suppression sustained during gas puffing fueling before reaching the upper density limit
  
  Upper limit (~ $4.5 \times 10^{19} \text{m}^{-3}$ or $0.6 \, \mathcal{N}_{GW}$)

- Stored energy slightly dropped (-6%) during density ramp
Heat fluxes on both OSP and SSP are reduced with gas puffing during $n=4$ RMP ELM suppression.

- $D_2$ gas puffing from mid-plane on LFS is increased during the $n=4$ (odd) RMP ELM-suppression phase.

- Compared to the case before gas puffing:

<table>
<thead>
<tr>
<th></th>
<th>OSP</th>
<th>SSP</th>
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<tbody>
<tr>
<td>heat flux</td>
<td>↓</td>
<td></td>
</tr>
<tr>
<td>particle flux</td>
<td>↑</td>
<td></td>
</tr>
</tbody>
</table>
Heat fluxes on both OSP and SSP are reduced with impurity seeding during $n=2$ RMP ELM suppression

- Heat flux change compared to the case without impurity seeding:
  
  **OSP:** ↓
  
  **SSP:** ↓

- Heat flux is further reduced with increasing impurity radiation level
Summary and conclusions

• Full suppression of ELMs in low torque plasmas by $n=4$ RMP has been demonstrated for ITER for the first time in EAST
  
  – low torque ($T_{\text{NBI}} \sim 0.44\text{Nm}$), $N_e \sim 0.6$ $N_{\text{GW}}$, $q_{95} \sim 3.65$, $\beta_N \sim 1.5$ with W divertor

• ELM suppression window is consistent with the modeling of plasma response to RMP using the MARS-F code

• Heat fluxes on both OSP and SSP are reduced by gas puffing, pellet injection and impurity seeding during RMP ELM suppression

• These results expand physical understanding and demonstrate the potential effectiveness of RMP for reliably controlling ELMs in future ITER high Q plasma scenarios