ELM-suppression using low-n RMPs in KSTAR

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\begin{itemize}
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2013.02.26
\textit{KSTAR Conference}
\textit{Lotte Buyeo Resort, Chungnam, Korea}
ELM control is critical to ITER

• **Significant reduction of ELM energy density required (>1/10)**
  - Expected / Limit ~ 7.0MJ/m² / 0.5MJ/m² ~ 14

• **Various approaches under investigation in KSTAR**
  - ELM pace-making: pellet injection (plan), vertical jogging
  - edge perturbation by SMBI
  - 3D magnetic field perturbation: RMP
  - small or no ELM regimes: type II, grassy, QH-mode, I-mode etc

• **3D magnetic field (RMP) has been actively investigated from KSTAR 2011 as the most plausible technique**
  - ELM suppression by n=1 RMP (2011)
  - ELM suppression by n=2 RMP (2012)

* Y.M. Jeon, et al., IAEA-FEC, EX/3-3 (2012)
ELM-suppression by n=1 RMP revisited showing similar \( q_{95} \)-window and significantly extended

Revisited with different plasma parameters except \( q_{95} \)

(2012) \( I_p=0.5\text{MA}, B_T=1.8\text{T} \)
\( \rightarrow q_{95}=6.0\sim6.5 \)

(2011) \( I_p=0.6\text{MA}, B_T=2.0\text{T} \)
\( \rightarrow q_{95}=6.0\sim6.5 \)

\[ \frac{\Delta n_e}{<n_e>} \leq 10\% \]
\[ \frac{\Delta W_{tot}}{W_{tot}} \leq 15\% \]
\[ \frac{\Delta \beta_p}{\beta_p} \leq 15\% \]
ELM-suppression by n=2 RMP successfully demonstrated in a consistent way

Dependent on $q_{95}$
- $B_T=1.5T$, $I_p=0.65MA \Rightarrow q_{95} \sim 3.7$
- Use n=2 mid-plane coil alone

- Significant $V_\phi$ drop
  - Due to strong magnetic damping via JxB and NTV
1. Experimental conditions for ELM-suppression by RMP

2. Physics mechanism of RMP-driven ELM suppression
1. DIII-D vacuum field guidance for RMPs
   - Sufficient edge stochasticity
   - Field pitch alignment → optimal $q_{95}$ window exists
   - Low edge collisionality

2. Non-resonant RMP fields may have no meaningful role on ELMs
   - The effect on ELMs has not been found clearly in experiments
   - Only it affects the rotation via electro-magnetic torque or NTV torque

⇒ Assumed that ‘resonant fields ONLY on $q_{95}$’ is important
n=1 RMP was consistent with DIII-D vacuum field criterion

\[ \delta B_r(q_{95}) \approx 13.7 \, \text{G} \]

- Analysis for #7821 at t=2.53s with n=1, +90 RMP
- Well aligned field pitch
- Sufficient edge stochasticity (island overlaps)
n=2 even RMP has similar pitch with n=1 RMP, but ...

- Similar field-pitch alignment for both
- Thus we started from #7821 (ELM-suppressed discharge by n=1 RMP)
  : $I_p=0.5$, $B_T=1.8T \rightarrow q_{95} \approx 6.5$
n=2 even RMP has similar pitch with n=1 RMP, but ... 

- Similar field-pitch alignment for both

- Thus we started from #7821 (ELM-suppressed discharge by n=1 RMP) : \( I_p=0.5, B_T=1.8T \Rightarrow q_{95}\sim6.5 \)

- However, almost no ELM response observed with \( q_{95}\geq6.0 \)
  - \( I_{FEC} > I_{FEC,\text{threshold}}: H\rightarrow L \) transition
  - \( I_{FEC} < I_{FEC,\text{threshold}}: \) no ELM change
Much smaller resonant field on $q_{95}$ by $n=2$ even RMP

$n=1, +90$ RMP (4kAt) on #7864

$\delta B_R(q_{95}) \approx 11.22 \text{G}$
Much smaller resonant field on $q_{95}$ by $n=2$ even RMP

- $dBr$ at $q_{95}$:
  - $11.2$ G for $n=1$
  - $04.7$ G for $n=2$

- $dBr(q_{95}) / dBr(max)$:
  - $80\%$ for $n=1$
  - $51\%$ for $n=2$

- Not optimal alignment
- Weak resonant component with large non-resonant ones
- Lower $q_{95}$ or larger mag. perturbation required
ELMs showed clear resonant responses to n=2 even RMP

No response
ELMs showed clear resonant responses to $n=2$ even RMP

No response

ELMs mitigated
ELMs showed clear resonant responses to n=2 even RMP

No response

ELMs mitigated

ELMs partially suppressed
ELMs showed clear resonant responses to $n=2$ even RMP

- #7864 ($q_{95} \approx 6.4$)
  - No response

- #7955 ($q_{95} \approx 4.7$)
  - ELMs mitigated

- #7961 ($q_{95} \approx 4.1$)
  - ELMs partially suppressed

$\rightarrow$ Clear resonant response and getting close to optimal $q_{95}$
Further reducing $q_{95}$ made ELMs suppressed in 2012

- BT = 1.5T, IP = 0.65MA
- $q_{95} \sim 3.7$
- n=2 mid-FEC alone with 8.0kAt

- Small decreases of $n_e$, $W_{\text{tot}}$
- Significant $V_\phi$ drop (Maybe due to strong magnetic damping)

- Oscillatory $D_\alpha$ is due to sawteeth
n=2 mid-RMP alone needs doubled RMP currents to get ELM suppression with optimal $q_{95}$

![Graph showing $\delta B_R(q_{95}) \approx 10.97G$ and $n=2$, mid-RMP alone (8kAt) on #8060]
n=2 mid-RMP alone needs doubled RMP currents to get ELM suppression with optimal $q_{95}$

Both have similar dBr at $q_{95}$:
- 11.0 G for mid-alone
- 09.3 G for even

dBr($q_{95}$) / dBr(max):
- 52% for mid-alone
- 96% for even

- Clearly mid-alone is not the best in view of perturbed field spectrum, but has enough resonant fields
- Even parity could be optimal (small non-resonant fields)
1. DIII-D vacuum field guidance for RMPs
   - Sufficient edge stochasticity
   - Field pitch alignment $\rightarrow$ optimal $q_{95}$ window exists
   - Low edge collisionality

2. Non-resonant RMP fields may have no meaningful role on ELMs
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$\Rightarrow$ Suggests that ELM-suppression requires (1) optimal $q_{95}$ and (2) sufficient $\delta B_R(q_{95})$ above a threshold
1. From DIII-D
   - RMP discharge is P-B stable
   - Edge rotation increase due to RMP
   - Steeper $T_e$ pedestal due to RMP
Most of edge profiles showed pedestal weakening due to RMP fields

When ELMs suppressed by n=1 RMP

- $V_{\phi,\text{edge}}$ decreased
- $T_{i,\text{edge}}$ decreased
- $T_{e,\text{edge}}$ didn’t change much
- $n_{e,\text{edge}}$ may decreased (pump-out)

→ Reduced pressure gradient
→ Maybe stable to edge (PB) instability

Worth reminding the increased $V_{\phi,\text{edge}}$ in DIII-D ELM-suppressed discharge with a strong correlation with $E_r$ change

→ Rotation change may not be the dominant role on ELM-suppression in KSTAR
Physics mechanism of RMP-driven ELM-suppression?

1. From DIII-D
   - RMP discharge is P-B stable
   - Edge rotation increase due to RMP
   - Steeper $T_e$ pedestal due to RMP

$\Rightarrow$ Still not clear what made plasma get into the edge-stable regime
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2. P. B. Snyder’s hypothesis (PoP 2012)
   - A necessity of a certain stopping mechanism such as “island opening near pedestal top”
   - But still not clear how those things stop the pedestal evolution
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➔ KSTAR may suggest that RMP made a transition (or bifurcation) to a new state, where the electro-magnetic turbulence is significant
A clue can be found on a transient phase

Event - A
: base-level dropped before ELM
  ➔ Enhanced particle confinement
  ➔ Mag. Fluctuation disappeared
  - Consistent with 2011

Event - B
: base-level dropped twice with clearance of magnetic fluctuation
  ➔ What happened ??
Dα in isolated ELMs shows a novel behavior

Event - A

- base-level dropped before ELM crash
  → Particle confinement enhanced

- Mag. Fluctuation cleaned up

- nₑ and Tₑ also increased
A transition-like novel behavior of $D_\alpha$ found during RMP turning off

- When the $I_{\text{RMP}}$ reached to $\sim 1.0\text{kA/t}$, it suddenly have a fast transition which resembles L/H transition.
- Also the magnetic fluctuation and the edge density fluctuation cleaned up simultaneously
- Note that the decreased level of $D_\alpha$ in event-B is different than one in event-A

$\Rightarrow$ Might be A novel transition/bifurcation due to RMP
Transition is distinguishable

Base-level of $D_\alpha$ increased due to RMPs
$\leftarrow$ Mainly due to density pump-out, but not all ...

$\leftarrow$ Distinguishable transition
Robust ELM suppression by using low-n RMPs in KSTAR
- Both n=1 (2011) and n=2 (2012) RMP led ELM suppressions in a same experimental logic
- Obviously the resonance condition of applied fields is of most importance

A fast transition accompanying enhancement of EM turbulence may explain how ELMs were suppressed under RMPs
- Possibly there might be a fast transition or bifurcation of state to enter the ELM-suppression phase in application of RMP under a certain condition
Base-level of $D_\alpha$ on ELM-suppression is changed

Base-level of $D_\alpha$ increased due to RMPs
$\Leftarrow$ Mainly due to density pump-out, but not all ...

$\Leftarrow$ Different base-level on ELM-suppression
Occasional bunch of ELMs were seen on ELM-suppression phase
(2011) Saturated $T_e$ evolution and broadband increase of magnetic fluctuations were observed under RMP.

- Could be an experimental evidence of P.B. Snyder’s hypothesis
- Similar observations made in 2012, too
Longer ELM suppression (~8.0s) tried but was incompletely suppressed

- A few bundles of high frequency ELMs appeared (the reason is not clear yet)
- Although, it didn’t lose the characteristics of ELM suppression
By fitting q95, n=2 RMP also suppressed ELMs in 2012

- BT=1.5T, IP=0.65MA
- q95 ~ 3.7
- n=2 mid-FEC alone with 4.0kA/t

- ELMs were suppressed
- Oscillatory D_α is due to sawteeth
Revisited with extended ELM suppression by n=1 RMP

(2012)
IP=0.5 MA, BT=1.8 T
→ q95 = 6.0~6.5

(2011)
IP=0.6 MA, BT=2.0 T
→ q95 = 6.0~6.5

10% density pump-out
15% $W_{\text{tot}}$ degradation
15% $\beta_p$ degradation

#7820
Edge $T_e$ evolution was altered due to RMP

ELMs suppressed

$T_e$ (keV)

A: linear build-up
B: saturated by RMP
C: stably saturated
Saturated edge Te evolution under RMPs

Plasma boundary (LCFS)