Interactions between MHD instabilities in the wall-stabilized high-$\beta$ plasmas

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Toward fusion reactor, high-$\beta_N$ plasmas are being exploited based on MHD controls of
- Resistive Wall Mode (RWM),
- Edge localized Mode (ELM), etc...

In JT-60U wall-stabilized high-$\beta_N$ plasmas, energetic particle-driven mode named as "Energetic particle driven Wall Mode (EWM)" that can induce RWM, has been observed.


Energetic particle becomes important for MHD stability in high-$\beta_N$ burning plasmas.

Moreover, in JT-60U wall-stabilized high-$\beta_N$ plasmas, interactions between EWM, RWM and ELM have been observed.
Inducing RWM even with enough rotational stabilization

Unacceptable heat load to first wall

ELM avoidance & mitigation, small ELM operation

Achievable-β limit

Plasma rotation and/or feedback control

Interactions
Previously, energetic particle driven instability has been observed in wall-stabilized high-$\beta_N$ plasmas.

“Energetic particle driven Wall Mode (EWM)”

Temporal characteristics:
- Initial frequency ~ precession frequency
  - Driving of trapped energetic ions
- Frequency chirping down
  - Interaction with energetic ions

Spatial characteristics:
- Toroidal : n=1
- Poloidal : m~3 larger amplitude at LFS
- Radial : global around q~2

→ Energetic particle-driven “wall-stabilized ideal kink-ballooning mode”
Outline of this talk

- Introduction
- EWM-triggered ELM
  - Observation of EWM-triggered ELM
  - SOL behaviors due to EWM
  - Possible interpretation with edge stability
- Summary
ELM behavior changes during EWM appearance

In wall-stabilized high-\(\beta_N\) plasmas, “EWM-triggered ELM” is observed.

Compared with Type-I ELM,

- Repetition frequency becomes \(\sim 3\) times higher:
  \(f_{\text{ELM}} \sim 40\text{Hz} \rightarrow 150\text{Hz},\)
- Energy release becomes half:
  \(\Delta W_{\text{dia}} \sim 40\text{kJ} \rightarrow 20\text{kJ}\)

\(I_p = 0.9\text{MA} / B_t = 1.5\text{T}\)
\(\beta_N \sim 3.0, \beta_N^{\text{no-wall}} \sim 2.3\)
Comparison of waveforms of type-I ELM, EWM and EWM-triggered ELM

**Type-I**: No clear precursor; large energy release of $\sim 50\text{kJ}$

**EWM alone**: EWM grows and decays gradually

**EWM triggered ELM**: Clear drop of pedestal region; EWM decays rapidly after ELM crash
Radial affected region of EWM-triggered ELM is narrower than that of type-I ELM.

Type-I ELM: \( r/a > 0.6 \)

EWM-triggered ELM: \( r/a > 0.7 \)

\[
I_{sx} \propto Z_{eff}n_c^2 \sqrt{T_e} \exp \left( -\frac{E_c}{T_e} \right)\\
E_c \approx 3.0 \text{ keV} \ [\text{Be : 200 } \mu\text{m}]
\]
EWM can not always trigger ELM; EWM-triggered ELMs occur even before full recovery of pedestal.

- $\Delta w_{\text{dia}}$ does not depend upon EWM amplitude.
SOL measurements indicate that EWM enhances outward transport of ion

\[ D_\alpha : \text{deuterium recycling} \]
\[ I_{D_\alpha} \sim \left\langle \sigma_{(D \rightarrow D^+)} v_e \right\rangle n_e n_D \]
\[ \rightarrow \text{Ion impacts to wall} \]

\[ C_{II} : \text{carbon sputtering} \]
\[ I_{C_{II}} \sim \left\langle \sigma_{(C \rightarrow C^2+)} v_e \right\rangle n_e n_C \]
\[ \rightarrow \text{Ion impacts to wall} \]

Floating potentials:
- global SOL behavior along magnetic field lines round core plasma
- Ion transport arises SOL potential?

**EWM enhances outward transport of ion**
Ion transport is linearly enhanced as EWM amplitude increases.

- Clear correlation between EWM amplitude and $D_\alpha$ (D-recycling).
- As EWM amplitude increased, $D_\alpha$ linearly increased.

Ion transport is linearly enhanced with EWM amplitude.
EWM can enhance “energetic” ion transport at LFS

**Temporal characteristics**
- Initial mode frequency is close to precession frequency of trapped energetic ions,
- EWM decays with frequency chirping.

**SOL behavior**
- EWM enhances outward transport of ion.

**EWM enhances “energetic” ion transport**
Trapped energetic ions (EWM driving source) are transported outward

**Spatial characteristics**
- n=1 toroidal
- m~3 poloidal with large amplitude at LFS
  → Enhanced transport are considered to be localized toroidally at LFS

**Discussion:**
- Banana orbits of energetic ions injected by PERP-NB calculated by EPOC
- 2D eigen function of ideal kink ballooning mode calculated by MARG2D
**Discussion:**

Edge stability can be locally violated by energetic ion transport due to EWM.

\[
p_{\text{ped}} = \frac{p_{\text{th}}}{\text{global}} + \frac{p_h}{\text{local}} + \delta p_h^{\text{EWM}}
\]

- Enhanced transport can increase pedestal pressure additionally.
- Edge stability can be locally violated even before full recovery of pedestal.

"Energetic" ions are effective to act even with small amount of particles.

\[
\delta p_h^{\text{EWM}} \sim E_B \delta n_h^{\text{EWM}},
\]

\[
E_B \approx 90\text{keV},
\]

\[
\delta n_h^{\text{EWM}} \sim \left(\frac{\Delta W_{\text{dia}}}{W_{\text{ped}}}\right)p_{\text{ped}}/E_B \approx 10^{16}\text{m}^{-3}
\]
Edge stability is evaluated by MARG2D.

- Before type-I ELM; close to finite-n MHD limit
- Before EWM triggered ELM; lower left
- “Energetic” Ion transport by EWM can act as additional $\alpha$
- Type-I ELM $\rightarrow n=21$
- EWM-triggered ELM $\rightarrow n=46$
- Eigen-function of $n=46$ is narrower than that of $n=21$
  $\rightarrow$ This is consistent with observations.

**Whether EWM can trigger ELM is determined by**

- EWM amplitude (energetic ion transport)
- Edge stability (distance to MHD limit).
In the JT-60U wall-stabilized high-$\beta_N$ plasmas, interaction between MHD instabilities “EWM-triggered ELM” is observed.

**Experimental results:**
- Compared with type-I ELM, EWM-triggered ELM has
  - higher repetition frequency,
  - smaller energy release,
  - narrower affected region.
- EWM can not always trigger ELM.
- EWM-triggered ELM occurs even before full recovery of pedestal.
- SOL behavior indicates that EWM enhances ion transport.

**Possible interpretation:**
- EWM enhances “energetic” ion transport.
- It can act as additional pressure $\delta p_h^{EWM}$.
- $\delta p_h^{EWM}$ can move closer to MHD limit.
- ELM trigger is determined by EWM amplitude and edge stability.