Sawtooth Control Relying on Toroidally Propagating ICRF Waves

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Outline

• Motivation for sawtooth control – NTM avoidance.
• Hybrid Kinetic-MHD.
• New mechanism of ICRH controlled sawteeth.
• Creation of JET experiments verifying theory.
• JET high performance and ITER relevant ICRH experiments.
• Conclusions.
Two similar consecutive JET-DT pulses.

The second is absent of sawteeth, and a fusion power world record was obtained.

In the first pulse, the stored energy and fusion power stopped rising after the sawtooth crash.

But, why didn’t the rise in stored energy and fusion power recover?

F. Nave et al, NF (2002)
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But, why didn’t the rise in stored energy and fusion power recover? A 4/3 NTM was triggered following the sawtooth crash.

F. Nave et al, NF (2002)
NTMs Triggered by Sawteeth at low $\beta$

I. T. Chapman et al, NF 2010
NTMs Triggered by Sawteeth at low $\beta$
NTMs can be triggered by long sawteeth even in L-mode.

Low $\beta$ NTMs saturate in amplitude during sawtooth crash time $\sim 50\mu s$. Faster than ECH feedback response on, e.g., 3/2 surface.

Two possible solutions:
1) Apply ECH on 2/1 or 3/2 surface just before predicted crash time.
2) Reduce period.
The Sawtooth Trigger

Well known simple sawtooth triggering criteria [F. Porcelli PPCF, (1996)]:

Resistive two-fluid instability: \[ \pi \frac{\delta \hat{W}}{s_1} < \hat{\rho}_i \text{ and } s_1 > s_c(\beta) \]

Generally accepted that sawteeth can be controlled via modifying \( s_1 \).
Well known simple sawtooth triggering criteria [F. Porcelli PPCF, (1996)]:

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Generally accepted that sawteeth can be controlled via modifying $s_1$.

There are two obvious issues to be addressed however:

1) In ITER, $\delta W$ will be large and stabilising, and $\hat{\rho}_i$ small. Control via shear modification alone might be more difficult.

2) Sawteeth in JET are controlled with very modest current drive perturbations. Auxiliary ions directly contribute to $\delta W$ instead.
• Require solution to drift kinetic equation for very energetic ions when the radial drift excursion is comparable to the radial scale length of the system or mode.

• Porcelli [PoP 1, 470 (1994)] and Helander [Phys. Plasmas 4, 2182 (1997)] derived:

\[ \delta F = \delta F_f + \delta F_k \]

**Kinetic contribution:**

\[ \delta F_k = \sum_{l=-\infty}^{\infty} \delta F_k^{(l)} \exp \left[ -i \left( \omega + l \omega_b + n \left\langle \dot{\phi} \right\rangle \right) t \right], \]

\[ \delta F_k^{(l)} = -\frac{\omega - n \omega_\ast}{\omega + n \left\langle \dot{\phi} \right\rangle + l \omega_b} \frac{\partial F}{\partial \mathcal{E}} \left\langle \left( v_\parallel^2 + \frac{v_\perp^2}{2} \right) \mathbf{\kappa} \cdot \mathbf{\hat{\xi}} \right\rangle \exp \left[ i \left( \omega + l \omega_b + n \left\langle \dot{\phi} \right\rangle \right) t \right] \]
Generalised Kinetic-MHD

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\]

- Fluid-like contribution is not just convection about a surface, \(\delta F_{fc} = -\boldsymbol{\xi} \cdot \nabla F(\psi)\)
There is a correction which has an important effect on stability/instability [Graves, PRL 2004], since:

\[
\delta F_f = -(Ze/m)(\boldsymbol{\xi} \cdot \nabla \psi_p) \frac{\partial F}{\partial \mathcal{P}_\phi}
\]
Invariance of toroidal canonical momentum enables derivation of radial motion:

\[ r(t) = \bar{r} + \Delta_r(t) \quad \text{with} \quad \Delta_r = \sigma q\left[|v_\parallel| R - pR_0^2 q\omega_b\right]/(r\Omega_c) \]

\[ \sigma = \text{sign}(v_\parallel) \]

Taylor expanding in small orbit width identifies correction to fluid term:

\[ \delta F_f = -(Ze/m)(\xi \cdot \nabla \psi_\rho) \frac{\partial F}{\partial P_\phi} \quad \rightarrow \quad \delta F_f = \delta F_{fc} - \xi_r \left(\frac{\Delta r}{r}\right) \left\{ (2 - s) \frac{\partial F}{\partial r} - \frac{\partial}{\partial r} \left[ r \frac{\partial F}{\partial r} \right] \right\} \]
Radial Drift Excursion

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- For the internal kink mode, eigenfunction can be approximated as a top-hat in \( r \). One can identify an important finite orbit contribution to the potential energy:

\[ \delta W = -m \pi \xi_0^2 \int_0^{2\pi} d\theta \int dv^3 \left( v_\parallel^2 + \frac{v_\perp^2}{2} \right) \sum_\sigma \Delta_r \cos \theta \left. r \frac{\partial F^\sigma}{\partial r} \right|_{r_1} \]

- Asymmetry in parallel velocity is possible for passing population. Describes effect of ions intersecting \( q=1 \) surface. Intuition easy for deeply passing population since

\[ \Delta_r = \sigma q v \cos \theta / \Omega_c \]
Effect of Passing Energetic Ions on $\delta W$

- Only get net effect on stability when distribution asymmetric:
  \[ F_h(v_+^+) \neq F_h(v_-^-) \]

- Effect increasingly strong for increasing $\Delta_r$ (increasing fast ion energy)

- Destabilisation for: $F_h(v_+^+) > F_h(v_-^-)$ and $\nabla F_h|_{r_1} > 0$
  or: $F_h(v_+^+) < F_h(v_-^-)$ and $\nabla F_h|_{r_1} < 0$
Asymmetric $F_h$ in toroidally propagating ICRF Waves

- The internal kink theory extended for general distribution functions including one applicable for toroidally propagating ICRF waves [Graves, PRL 2009]
- Parallel velocity asymmetry in $F_h$ seen e.g. in the ICRH current [SELFO code]

Passing ion current (-90 phasing)

\[ j_\phi(r) \approx c Z_h \int dv^3 \sum_\sigma v_\parallel F_h \]

\[ r_{res} \]

Excess of co-passing ions

Excess of ctr-passing ions
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\[ j_\phi(r) \approx e Z_h \int dv^3 \sum_\sigma v_\parallel F_h \]
\[ \delta W \propto - \int dv^3 \sum_\sigma \left( \frac{v^2_\perp}{2} + v^2_\parallel \right) \Delta_r \frac{\partial F_h}{\partial r} \bigg|_{r_1} \sim - T_h \frac{dj_\phi}{dr} \bigg|_{r_1} \]
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Design of experiments to verify fast ion mechanism

- Despite this success, there was still some doubt as to the possible role of the net magnetic shear driven by ICCD in JET experiments.
- The net driven current is the pure fast ion current multiplied by a plasma drag coefficient [Fisch, Rev. Mod. Phys 1987]:

\[ j_{\text{tot}} = j_h \times j_d \]

\[ j_d = 1 - \left[ \frac{Z_h}{Z_{\text{eff}}} + \frac{m_h \sum_j Z_j n_j (1 - (Z_j / Z_{\text{eff}}))}{Z_h \sum_j n_j m_j} - G \left( \frac{Z_h}{Z_{\text{eff}}} - \frac{m_h \sum_j n_j Z_j^2}{Z_h Z_{\text{eff}} \sum_j n_j m_j} \right) \right] \approx 2e^{1/2} \]

- Removing effect of ICRH driven net magnetic shear in an experiment will remove MHD effect, and therefore validate fast ion mechanism empirically. Under what conditions is \( j_d \sim 0 \)?
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\[ G \approx 2e^{1/2} \]

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• **Choose \(^3\text{He} \) minority for which \( Z_h/Z_{\text{eff}} \approx 1 \) and so the net current is diminished.**

• Moreover \(^3\text{He} \) minority will be used in ITER, so very important to test in JET.
$^3\text{He}$ minority with HFS resonance

[Graves et al, NF 2010]
Verification of Fast Ion Mechanism(1)

76189 (-90, cntr-propagating)

\[ \tau(s) \]

\[ \delta W^h \]

Sawtooth Period

\[ \frac{\left( r_{inv} - r_{res} \right)}{a} \]

76190 (+90, co-propagating)

\[ \tau(s) \]

\[ \delta W^h \]

Sawtooth Period

\[ \frac{\left( r_{inv} - r_{res} \right)}{a} \]

[Graves et al, NF 2010]
Verification of Fast Ion Mechanism(1)

76189 (-90, cntr-propagating)

Sawtooth Period

76190 (+90, co-propagating)

Sawtooth Period

SELFO/HAGIS simulations

[Graves et al, NF 2010]
Verification of Fast Ion Mechanism (2)

- Final verification of the predicted fast ion mechanism is undertaken by experimental variation of fast ion tail temperature $T_h$

- Recall that the mechanism is a finite orbit effect, which diminishes with reduced $T_h$

- Vary $T_h$ by varying minority concentration

Sawtooth Period (78737 and 78740)

- High concentration, small $T_h$
- Low concentration, large $T_h$

[Graves et al, NF 2010]
Verification of Fast Ion Mechanism (2)

Sawtooth Period (78737 and 78740)

SELFO/HAGIS simulations

[Graves et al, NF 2010]
Destabilisation of Fast-Ion Lengthened Sawteeth

• Alpha lengthened sawteeth simulated using NBI. Long sawteeth were successfully controlled using ICRH.
• Long sawteeth were successfully controlled using ICRH in H-mode.
Conclusions

• Analytical treatment employing a generalised kinetic MHD framework has identified important finite orbit effects.

• Verification of the fast ion mechanism was achieved by creating experiments capable of eliminating all other known control mechanisms.

• Used $^3$He minority counter propagating ICRF waves with resonance on the HFS to destabilise monster (NBI lengthened) sawteeth in H-mode.

• That fast ions can so dramatically, and directly, affect sawteeth is encouraging for ITER, especially where control solely via the magnetic shear could be more difficult.

• ITER modelling and predictions for relevant low field side (LFS) resonance $^3$He minority are underway. Initial results with 20MW of ICRH show that stabilising effect of alpha particles can be neutralised.

• LFS resonance $^3$He minority experiments are planned in JET.
Sawtooth Control using ICRH

(counter propagating wave)

2.9T<B<2.96T

[Graves et al, NF 2010]
Sawtooth Control using ICRH

78737(−90) and 78739(+90): B/I = 2.9T / 2.0A (co-, cntr- propagating)

$2.9T < B < 2.96T$

$L$-mode

$\beta_N = 0.8$

(Long sawtooth triggering of NTMs seen earlier: Campbell PRL 1988; Sauter PRL 2002)