The Physics of Sawtooth Stabilisation

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* See the Appendix of M.L. Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu) IAEA
Outline – Sawtooth Stability

• Motivation
  – Sawteeth can trigger Neo-Classical Tearing Modes (NTMs)

• Methods for Sawtooth Control

• Sawtooth Control Using Neutral Beam Injection
  – MAST: Flow Effects
  – JET: Kinetic Effects
  – TEXTOR: Flow and Kinetic Effects

• Sawtooth Control Using Ion Cyclotron Resonance Heating
  – Experiments on JET
  – Physics Explanation

• Sawtooth Control in ITER
  – ECCD and Negative-ion Neutral Beam Injection
Motivation – Sawtooth Seeding of NTMs

- Why are sawteeth important?
  - Reduce thermal insulation of the core
  - Trigger other modes like ELMs or NTMs
    - Short $\tau_{saw} \rightarrow$ no NTM
    - Long $\tau_{saw} \rightarrow$ NTM seeding

Sauter et al, PRL, 88, 2002
<table>
<thead>
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<th>Methods for Sawtooth Control</th>
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<td>• <strong>MAST Neutral Beam Injection</strong></td>
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• JET and MAST experiments show sawtooth control using NBI
  - NBI heating in co-current direction causes an increase in period
  - NBI heating in counter-current direction causes a decrease in period
Modelling sawtooth stability with flow in MAST

- **Kink mode stabilised by strong toroidal rotation**
  - As sawtooth period, $\tau_{st}$, increases, radial location of $q = 1$ increases
  - Marginally stable $q = 1$ radius expected to correlate with $\tau_{st}$

Toroidal velocity at which $q = 1$ radius for marginal stability is minimised agrees with minimum in sawtooth period

*Chapman et al, Nucl Fusion, 46, 2006*
Methods for Sawtooth Control

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JET Rotation Profiles

- Toroidal Rotation is an order of magnitude smaller than MAST
  - Much slower rotation speeds than MAST, only small effect on stability of kink mode
  - Strong flow shear at radial location of q=1 (compared to MAST)

(Rotation Profiles from Charge Exchange)
What is the rôle of trapped and passing particles?

- Sawtooth stabilisation by energetic particles is usually attributed to the presence of trapped fast ions [Porcelli, PPCF, 33, 1991]
  - In JET, fast beam ions are mainly passing
  - Passing ions can be stabilising when co-NBI, but destabilising when counter-NBI. [Graves, PRL, 92, 2004]

- HAGIS code
  - Drift Kinetic code for exploring wave-particle interactions
  - Calculates change in potential energy:
  \[ \delta W_h = \frac{1}{2} \int \left( m v^2 + \mu B \right) \delta \xi \cdot \delta \xi^* d^3 x d^3 v \]
  Pinches, CPC, 111, 1998
δW has a term dependent upon curvature: 

\[ \delta W \sim -\int_{0}^{r_1} (\xi \cdot \nabla \langle P_{h} \rangle)(\xi \cdot \kappa)dr \]

\[ \nabla B \quad Z \quad q=1 \text{ surface} \]

**Co-passing**

- Good Curvature
- Adverse Curvature

\[ \text{Co-pass, } \langle P_{h} \rangle' \bigg|_{r_1} < 0 \rightarrow \text{stabilising} \]
\[ \text{Co-pass, } \langle P_{h} \rangle' \bigg|_{r_1} > 0 \rightarrow \text{destabilising} \]

**Counter-passing**

- Good Curvature
- Adverse Curvature

\[ \text{Ctr-pass, } \langle P_{h} \rangle' \bigg|_{r_1} < 0 \rightarrow \text{destabilising} \]
\[ \text{Ctr-pass, } \langle P_{h} \rangle' \bigg|_{r_1} > 0 \rightarrow \text{stabilising} \]

Graves, PRL, 92, 2004
Effects of Flow Shear

- Flows change the **electric field** by adding a factor: $rB\cdot \Omega \quad$ NB: Electric potential depends

- The flow shear can change number of particles in resonance. $\delta W_h > 0$ when:

$$\left\langle \omega_d \right\rangle + \Delta \Omega - \left( \omega - \Omega_{r_1} \right) > 0$$

**Graves, PPCF, 42, 2000**

- At very large flows ($\Delta \Omega > \langle \omega_d \rangle$) flow shear dominates the numerator and denominator of expression for $\delta W_h \rightarrow$ asymptotic limit
How does $\delta W_h$ change with respect to beam power?

- Modelling the effect of energetic particles on the ideal n=1 internal kink mode **WITHOUT flow shear** in JET:

![Graph showing the change in $\delta W$ with NBI Power (MW) for different conditions: Non-adiabatic, Adiabatic, Passing, and MHD.](image)
How does $\delta W_h$ change with respect to beam power?

- Modelling the effect of energetic particles on the ideal $n=1$ internal kink mode **WITH flow shear** in JET:

$$\delta W$$ against NBI Power (MW)

Chapman et al, 
Phys Plasmas, 2007
- Minimum in sawtooth period and $\delta W_h$ agrees well (at ~ 4MW)
- Minimum in $\delta W_h$ is dependent upon details of the distribution function and the exact rotation shear at $q=1$
- In JET, asymmetry and minimum is explained by energetic particle effects
- In MAST, asymmetry and minimum is explained by flow effects
Methods for Sawtooth Control

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  - Flow Effects dominate

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- TEXTOR Neutral Beam Injection
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- Ion Cyclotron Resonance Heating
  - Raise Magnetic Shear at q=1
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Sawtooth Control by NBI in TEXTOR

- TEXTOR shows different behaviour of sawteeth with NBI heating
  - Sawtooth Period minimised in co-NBI direction
  - Sawtooth Period reaches a maximum in counter-NBI direction
  - Minimum in sawtooth period when plasma rotation stops (precursor frequency → 0)
• **Competition between gyroscopic and fast ion effects**

**Kinetic Effects**
Counter-passing fast ions destabilise kink mode & dominate when flow tends to upper limit.
Co-passing and trapped ions.

**Flow Effects**
Minimum \( \tau_{ST} \) occurs when rotation stops. Strong toroidal flows stabilise mode, but rotation is not linear with respect to \( P_{NBI} \).

Intrinsic Rotation (counter-\( I_p \) driven by \( E_t \) balances beam rotation.)
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Sawtooth Control by ICRH in JET

- JET experiments show that ICRH can destabilise long sawteeth
  - Sawtooth period increases with on-axis +90° phasing ICRH
  - Fast ion deposition near/outside q=1, -90° ICRH destabilises sawteeth
  - Sawtooth period v. sensitive to deposition location w.r.t. q=1 location

Eriksson et al, Nucl Fusion, 46, 2006
Modelling Sawtooth Control Using ICRH

- Modelling also exhibits dependence upon resonance location
  - ICRH inside \( q=1 \) gives strong stabilising contribution to \( \delta W_h \)
  - Stabilisation is reduced as deposition moves outside \( r_{q=1} \)

\[
\delta W_h \text{ has a term dependent upon hot ion pressure gradient:}
\]

\[
\delta W \sim -\int_0^{r_1} \xi_1 \left( \frac{r}{r_1} \right)^{3/2} \nabla \left( \frac{P_{h \perp}}{P_{h \parallel}} \right) dr
\]

Graves, Varenna Lausanne, 2006
Sawtooth is triggered when one of three criteria is met
[Porcelli et al, PPCF, 38, 2163 (1996)]

- Most relevant for plasmas with energetic ions is:
  \[ \pi \frac{\delta W}{s_1} < c \frac{\rho}{r_1} \quad \text{and} \quad \gamma_\eta > c_\eta \sqrt{\omega_\ast_i \omega_\ast_e} \]

- This can be written in terms of a critical magnetic shear:
  \[ s_1 > \max \left\{ s_{\text{crit}} = \pi \frac{\delta W}{\hat{\rho}}, s_{\text{crit}}(\omega_\ast) \right\} \]

Effect of ICRH is two-fold:

1. Reduce critical shear from the large critical shear which occurs with on-axis fast ions
2. ICCD increases magnetic shear
   (This is how ECCD destabilises sawteeth too [Mück, PPCF, 2005])

Graves, Conf. Active Control MHD, 2006
ITER Sawtooth Control with Negative-ion NBI

- Sawtooth control even more important in ITER where the alpha particle population is likely to lead to long period sawteeth
  - ECCD (and ICCD) has been proposed as a mechanism to destabilise sawteeth to a tolerably small period

\[ T_e \]
\[ \rho_{res} \]

Mück et al, Plasma Phys Cont Fus, 47, 2005
ITER Sawtooth Control with Negative-ion NBI

- Sawtooth control even more important in ITER where the alpha particle population is likely to lead to long period sawteeth
  - ECCD (and ICCD) has been proposed as a mechanism to destabilise sawteeth to a tolerably small period
  - Can off-axis NNBI co-passing ions be used? (ITER NNBI has a large passing fraction) [Graves, PPCF, 47, 2005]
Conclusions

- **Sawtooth Control** by different methods in different machines has been explained by a model including flow and kinetic effects.

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<th>FLUID EFFECTS</th>
<th>KINETIC EFFECTS</th>
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<td>ICRH</td>
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<tr>
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- **Achievable Sawtooth Control in ITER**
  - Off-axis co-NNBI to destabilise internal kink mode
  - ECCD to raise magnetic shear at $q=1$