Integrated Modelling of Sawtooth Oscillations in Tokamak Plasmas


[1] Burning Plasma Research Group, Dept. of Energetics, Politecnico di Torino, Italy
[2] Lehigh University Physics Department, Bethlehem, PA 18015, USA
[3] Association EURATOM-CEA, CEA/DSM/DRFC, CEA-Cadarache, France
[4] CRPP, Ass. EURATOM-Confederation Suisse, EPFL, 1015 Lausanne, Switzerland
[6] CPHT Ecole Polytechnique, UMR-7644 du CNRS, Palaiseau, France
[7] Euratom/UKAEA Fusion Ass., Culham Science Centre, Abingdon OX14 3DB, UK
[8] Euratom/IST Fusion Association, Centro de Fusao Nuclear, Lisboa, Portugal
[9] SAIC, San Diego, CA 92121, USA
[10] Euratom/VR Fusion Association, Chalmers Univ. of Technology, Goteborg, Sweden
Part II

Nonlinear Simulations of Fishbone Instability and Sawteeth in Tokamaks and Spherical Torus

G.Y. Fu, J.A. Breslau, W. Park, S.C. Jardin, J. Chen

Princeton Plasma Physics Laboratory
Princeton, NJ, USA
OUTLINE

PART I
• Testing the sawtooth model against experimental data
• $\delta W$ expressions for Sawtooth Modelling Modules
• Sawtooth control by ICCD
• Assessing the effects of MHD perturbations on fast ion orbit distributions
• Supra-thermal electrons and grassy sawteeth on JET

PART II
• Fishbone instability
• Sawteeth in CDX-U
• Sawteeth in TEXTOR
The sawtooth model

- The sawtooth model in this talk was initially developed by Porcelli, Boucher and Rosenbluth, PPCF 1996.
- The model is based on the linear stability threshold for m=1 modes, including realistic effects such as plasma geometry and shaping, fast particle effects, diamagnetic and two-fluid kinetic effects.
- The model also contains a semi-heuristic prescription for partial (as opposed to full Kadomtsev) reconnection, on the basis of which plasma profiles in the relaxed state can be computed.
- Implemented in a transport code, this model allows for self-consistent predictions of the sawtooth period and amplitude.
- It also indicates possible strategies for sawtooth control in a fusion burning plasma.
Testing the sawtooth model against experimental data

Initial comparisons of the model predictions with data from TCV, FTU and JET tokamak experiments were fairly encouraging.

See, e.g.,
C. Angioni et al, Nuclear Fusion 44 (2002) 205
C. Angioni et al, Nuclear Fusion 45 (2003) 455

However, the evaluation of the linear stability threshold requires accurate knowledge of the plasma geometrical parameters and of several plasma profiles, including thermal plasma and fast particle profiles, which in turn are affected by the sawtooth dynamics itself.

At present:
Sawtooth model implemented ASTRA, JETTO, TRANSP, BALDUR
Now also available as a Fortran module in the National Transport Code Collaboration Module Library (http://w3.pppl.gov/NTCC).
Integrated BALDUR simulations of 5 JET H-mode and 12 TFTR L-mode discharges were used to calibrate and test the model. It was found that in these discharges sawtooth crashes are usually triggered by an $m=1$ internal mode in the semicollisional regime.

Figure: Triggering conditions for sawtooth crashes in a BALDUR simulation of JET 33131 with 40% magnetic reconnection. The time evolution of the central electron temperature is shown in the top panel while components of the sawtooth trigger condition are shown in the other four panels.
There is significant random variation in the sawtooth periods within each time interval in both the simulations and the experimental data. Consequently, we compared the median sawtooth period in each simulation with the corresponding quantity from experimental data. For the 20 time intervals within the 17 discharges simulated, the best average agreement with experimental data was obtained with approximately 37% magnetic reconnection fraction.

Normalized δW

\[ \gamma_I \tau_A = (\pi/s_I)\delta W = \delta W^P \]

Best fit

\[ \gamma^{\text{fitl}} \tau_A = 0.45 \frac{\epsilon_1 \kappa_1}{1 + 7 \epsilon_1 \kappa_1} (\beta_{p1} - \beta_{p1}^{c,\text{fitl}}), \]

\[ \beta_{p1}^{c,\text{fitl}} = 0.7 - 0.5 \kappa_1. \]

Improved analytic expressions have been derived for δW-fast

See:

J. Graves and C. Wahlberg, to be published
Best fit for $\delta W$

Showing (a) the comparison fitted growth rate with the growth rate from KINX over a wide range of plasma parameters, and (b) the marginal poloidal beta in a toroidal plasma as a function of shear at $q=1$ for differing $\lambda$. The latter is calculated from analytical corrections to the well known formula of Bussac et al, PRL '75.
Sawtooth control by ICCD

To what extent it is possible to destabilise fast ion induced long sawteeth by modifying the magnetic shear near the $q = 1$ surface?

Experiments were carried out at JET in 2003 using Ion Cyclotron Current Drive (ICCD).

A centrally peaked fast ion pressure was first created by ICRF heating with a near on-axis resonance and co-current propagating waves (M. Mantsinen et al., Phys. Rev. Lett. 91, 115004 (2002)). Then, ICCD was applied, resonance on the high field side near $q = 1$ and an antenna phasing launching waves in the counter current direction.

It was possible to shorten the sawteeth; process is rather sensitive to the exact distance between the $q = 1$ surface and the ICCD cyclotron resonance layer (L.-G. Eriksson et al., Phys. Rev. Lett. 92, 235004 (2004)).

Numerical analysis was performed on the basis of the SELFO codes (L.-G. Eriksson et al., Nuclear Fusion 46, S951 (2006)), combining self-consistently a full wave solver for the wave electric field and a 3D Fokker-Planck Monte Carlo solver for the resonating ion distribution function, including finite orbit width effects.

The analysis shows quite clearly that the shear near the $q = 1$ surface was significantly increased in the discharge where the application of ICCD produced a significant shortening of the sawteeth in the presence of a central fast ion pressure.
Assessing the effects of MHD perturbations on fast ion orbit distributions

Fast ion redistribution during sawteeth.
Drift-orbit particle-following HAGIS code (S. Pinches) extended for this purpose.
Poincaré plots for both the magnetic field lines and drift orbits of fast ions in the presence of finite amplitude MHD perturbations. This allows assessing both the regular and stochastic behaviour of the fast ions, so that the identification of the stochasticity thresholds for both the magnetic field lines and the drift orbits becomes also possible.
Orbits appear to be more complex than originally worked out by Kolesnichenko et al, Nucl. Fusion (2000).
Examples of particle orbits

Green line: original q=1 surface
Blue dots: Poincare’ plot for magnetic field lines in the presence of a kink perturbation
Red dots: Perturbed trajectories of particles originally on a passing orbit.
Supra-thermal electrons and grassy sawteeth on JET

“Grassy sawteeth” observed in JET plasmas with high-power ICRF-heating and plasma density below a critical value of about ne(0)<2x10E19 m-3 (S. Sharapov et al., Nuclear Fusion 45 (2005)).

The grassy sawtooth regime is characterised by a sawtooth period a few times shorter than the monster sawtooth period, while the relaxation time is much longer.

A supra-thermal electron population surrounding the q=1 magnetic surface may determine this highly unusual sawtooth behaviour.

Evidence: enhanced fast electron Bremsstrahlung observed during grassy sawteeth.

Furthermore, because of the relatively low plasma density, the inductive steady-state parallel electric field in the central region of the JET plasma becomes close to the critical electric field, at which electrons travelling near the speed of light can run away.

Under these conditions, the pulsed sawtooth reconnection electric field becomes comparable to Dreicer field, can generate a suprathermal electron population in the vicinity of the q=1 magnetic surface repeatedly at each sawtooth crash.

The near-critical electric field prevents a rapid deceleration of the suprathermal electrons due to Coulomb collisions, so that a suprathermal electron current may be present for a time long enough to affect the stability of the next sawtooth.

A relativistic Fokker-Planck equation has been derived and solved (P. Sandquist et al., Phys Plasmas 13 (2006)), for parallel electric field either below or above critical.

Possible role for energetic electron currents produced self-consistently during the sawtooth reconnection events.
Conclusions (Part I)

- A model for the prediction of the sawtooth period and amplitude (Porcelli, Boucher and Rosenbluth, PPCF 1996) has been further developed and tested against experimental data. Fair agreement with experimental observations. More importantly, the model is able to capture trends, such as the lengthening of the sawtooth period during NBI injection, and can be used in order to assess possible strategies for sawtooth control. Techniques such as ICCD localized near the q=1 surface are shown to be effective in inducing sawtooth crashes and therefore produce relatively mild sawteeth.

- In spite of the success, it is important to point out limitations and directions for further improvements. The sawtooth model is based on the linear stability threshold for m=1 modes, including realistic effects and actual geometrical factors. However, it is clear from experiments that sometimes relatively large amplitude m=1 oscillations are present on the sawtooth ramp long before the crash occurs. In this case, the use of a linear stability threshold is questionable.

- The open scientific question is what determines in the experiments the occurrence of partial sawtooth reconnection. The model proposed is partly heuristic. It appears that often-times a secondary instability is excited during the growth of the m=1 magnetic island, possibly related to the steep pressure gradients that tend to form across the island separatrix. Further thoughts and numerical investigations are needed to clarify this point. Eventually, the goal is to come up with a partial reconnection model that does not present any free parameters, such as the fraction of reconnected flux.
Nonlinear Simulations of Fishbone Instability and Sawteeth in Tokamaks and Spherical Torus

G.Y. Fu, J.A. Breslau, W. Park, S.C. Jardin, J. Chen

Princeton Plasma Physics Laboratory
Princeton, NJ, USA

1. Fishbone instability

2. Sawteeth in CDX-U

3. Sawteeth in TEXTOR
M3D Simulations of Fishbone Instability

G.Y. Fu
Particle nonlinearity causes distribution flattening and frequency chirping downward.
M3D Simulations of Sawtooth Oscillations in CDX-U

J. Breslau

R/a=1.4, R=33cm, 
B~ 0.23T, T~100ev 
n_e ~ 4x10^{13}cm^{-3}

Sawtooth period 1 ≈ 395 \tau_A ≈ 100 \mu s; 
Sawtooth period 2 ≈ 374 \tau_A 
Reference CDX sawtooth period ≈ 125 \mu s
Summary of Observed Two-Fluid Effects

• Plasma rotation.

• Oscillations in energy of higher-$n$ modes.

• Sawtooth period increases slightly.

• Magnetic field does not become stochastic over most of plasma cross-section.

• Reconnection is incomplete in second crash.
There have been attempts to explain how $q_\circ$ does not rise above one after a sawtooth crash, using either stochasticity or localized reconnection. These are closely related because the main effect of the localization is to produce stochasticity.

M3D simulations show that these effects are small, and the usual complete reconnection occurs raising $q_\circ$ above one.
Even when the localization is exaggerated so that the core region gets stochastic, and also even when $T$ is completely flattened in that region, $q$ values still reach higher than one. (Both for MHD and two-fluids)
Conclusions (Part II)

Fishbones

• New results of self-consistent nonlinear simulations of fishbone instability and sawtooth oscillations obtained using the extended MHD code M3D are reported.
• Hybrid simulations of energetic particle-driven fishbone instability in a circular tokamak show dynamic mode saturation as the particle distribution is flattened and the mode frequency is reduced strongly.
• MHD nonlinearity reduces the mode saturation level.

Sawteeth

• Resistive MHD simulations of the CDX-U spherical torus show repeated sawtooth cycles with calculated periodicity consistent with the experimental observation.
• The two-fluids simulations show that the induced sheared plasma rotation suppresses the island growth so that the magnetic field no longer passes through a stochastic state as observed in the MHD simulations.
• M3D simulations of sawtooth crashes in the TEXTOR tokamak show that the localization effect of reconnection is rather small. Even when the localization effect is exaggerated so that the temperature in the core is flattened due to stochasticity, q(0) still rises above unity.