High Harmonic Ion Cyclotron Heating in DIII-D: II. Sawtooth Stabilization\textsuperscript{1} W.W. HEIDBRINK, T. DANG, UC Irvine, F.W. BAITY, E.A. LAZARUS, Oak Ridge National Laboratory, S. BERNABEI, E.D. FREDRICKSON, Princeton Plasma Physics Laboratory, J.S. DEGRASSIER, C.C. PETTY, R.I. PINSKER, General Atomics, B.W. RICE, Lawrence Livermore National Laboratory — Combined neutral beam injection and fast wave heating at the fourth cyclotron harmonic can produce an energetic, perpendicular deuterium beam-ion population inside the $q = 1$ surface. The beam-ion tail transiently stabilizes the sawtooth instability but destabilizes toroidicity-induced Alfvén eigenmodes (TAE). Saturation of the central heating correlates with the onset of the TAE. Continued expansion of the $q = 1$ radius eventually precipitates a sawtooth crash; complete magnetic reconnection is observed. In recent experiments, the effect of plasma shaping, harmonic number, and beam species on these findings are investigated.

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- The RF accelerates deuterium beam ions inside q=1.

- The precessing beam ions transiently stabilize the internal kink.

- The beam ions destabilize the TAE, which limits the central electron temperature.

- Current accumulates on axis and the q=1 radius expands until kink stability is lost.

- Complete reconnection occurs at the sawtooth crash.
At an H-mode transition:

- The RF power drops
- The density rises
- Sawtooth period shortens as tail disappears
Beam-Ion Tail Necessary but not Sufficient for Stabilization
1.0 MW Needed for Stabilization

SAWTOOTH PERIOD (ms)

60 MHz POWER (MW)
Central Heating Required

![Graph showing the relationship between sawtooth period (ms) and \( \omega_{RF}/\Omega_0(0) \).]
CONDITIONS FOR SAWTOOTH STABILIZATION

- Enhanced Neutron Rate
  Precessing Beam Ions Stabilize

- Adequate RF Power
  Need Beam-Ion Tail

- Low-to-Moderate Density
  Long Slowing-Down Time

- Central Heating
  Beam ions inside $q=1$

- Threshold Power Density similar to JET, TFTR, JT-60
  Different heating schemes all create fast-ion tails

- Favorable shape
  Competition between Tail formation and MHD Stability
Shape Impacts Stability
Not Beam-Ion Absorption

![Graph showing sawtooth period vs upper triangularity and neutron enhancement vs upper triangularity.](image-url)
Power Density for Stabilization is similar for other heating schemes.

TFTR \( l=1 \) > 2.2 MW

JET \( l=1 \) > 3 MW

DIII-D \( l=4 \) > 1 MW
ALFVEN EIGENMODES DESTABILIZED BY BEAM IONS

- Modes only occur when beam ions are accelerated. Driven by beam-ion tail.

- Frequency is $V_A/2qR$ or $V_A/qR$.
  Toroidicity-induced Alfven eigenmode (TAE)
  Ellipticity-induced Alfven eigenmode (EAE)

- TAEs appear midway in sawtooth cycle.
  Critical beam-ion beta for instability.

- TAEs disappear at sawtooth crash.
  Beam ions redistribute at sawtooth crash.

- TAEs cause saturation of central $T_e$.
  Central beam-ion density clamped by TAE.

- Only single modes observed.
  System close to marginal stability.
EAE and TAE

$T_e$ (keV)

shot 100401, channel: b1, log scale of \sqrt{\text{autopower}}

Intensity scale 1.226

TIME (s)

FREQUENCY (kHz)
TAE Causes Saturation of Central Electron Temperature
- n=1 magnetic precursor grows at 3/ms
- Very small island on ECE; rapid crash
- Partial reconnection events early in cycle
  \[\Rightarrow\] q not monotonic after crash?
Rapid Crash Redistributes Beam Ions as Theoretically Expected

MIRNOV (T/s)

$T_e$ (keV)

NEUTRONS ($10^{14}$ n/s)

RELATIVE TIME (ms)
CURRENT DIFFUSION CAUSES SAWTOOTH CRASH

- Required beam-ion population for sawtooth stability is proportional to \((q=1 \text{ radius})^3\)
- Beam-ion population is clamped by the TAE

\[ \Rightarrow \text{Crash always occurs at the same radius} \]
INDEFINITE SAWTOOTH STABILIZATION

- More RF Power does not work
  Just excite TAE sooner

- Want $\omega_{\text{pre}} >> \omega_{\text{ST}}$ but $\omega_{\text{pre}} << \omega_{\text{TAE}}$
  Stabilize sawtooth without driving TAE

- A fast-ion distribution with lots of moderate-energy ions but no tail is optimal $\Rightarrow$ High-harmonic heating of beam ions can work well

- Must halt current diffusion $\Rightarrow$ Use bootstrap and off-axis ECCD
How to stabilize sawteeth indefinitely?

1\textsuperscript{st} Problem: Sawtooth stability and TAE instability are both caused by precessing beam ions.

\textbf{⇒} Can’t increase the beam density past the TAE threshold.

\textit{Is there an optimal distribution function for sawtooth stability without TAE instability?}

\textit{Is there a condition with stronger TAE damping?}

2\textsuperscript{nd} Problem: Stability is lost when the q=1 surface grows too large. The “natural” inductive current profile is too peaked for steady-state operation.

\textbf{⇒} Use non-inductive current drive to halt the current diffusion.
Arrange Conditions so Precession Speed and Injection Speed Coincide With Peak of Velocity Diffusion Coef. 

\[
\gamma_{\text{TAE}} \propto \frac{\langle \omega_d f \rangle}{\langle \omega_d f \rangle} = \frac{\langle w^2 f \rangle}{\langle w f \rangle}
\]
Future Work

- Study the effect of shape, $q$ profile, and Alfvén activity on the evolution of the electron temperature (partial reconnection events).

- Calculate MHD stability for different shapes. Develop a semi-empirical model that explains when a monster sawtooth occurs.

- Use current drive and a beam-ion tail to stabilize the sawtooth indefinitely in a plasma with $q_0 < 1$. 
Conclusions

- Need a beam-ion tail inside the $q=1$ surface for a monster sawtooth. Consistent with Porcelli's theory of stabilization by precessing ions.

- A favorable shape helps. Shape affects MHD stability and/or the initial $q$ profile.

- At the monster crash, complete reconnection occurs and beam ions are redistributed. Consistent with Kadomtsev model and Kolesnichenko theory.

- The TAE clamps the beam density. Current diffusion causes the crash. Must suppress the TAE and use non-inductive current drive to operate with $q_0<1$ without sawteeth.