Abstract Submitted
for the DPP99 Meeting of
The American Physical Society

Sorting Category: 5.1.1.2 (Experimental)

High Harmonic Ion Cyclotron Heating in DIII-D: II. Sawtooth Stabilization[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.

[1] Supported by Subcontract SC-G903402 to U.S. DOE Contract DE-AC03-99ER54463,and U.S. DOE Contracts DE-AC05-96OR22464, DE-AC02-76CH03073, DE-AC03-99ER54463, and W-7405-ENG-48.

☐ Prefer Oral Session
☒ Prefer Poster Session

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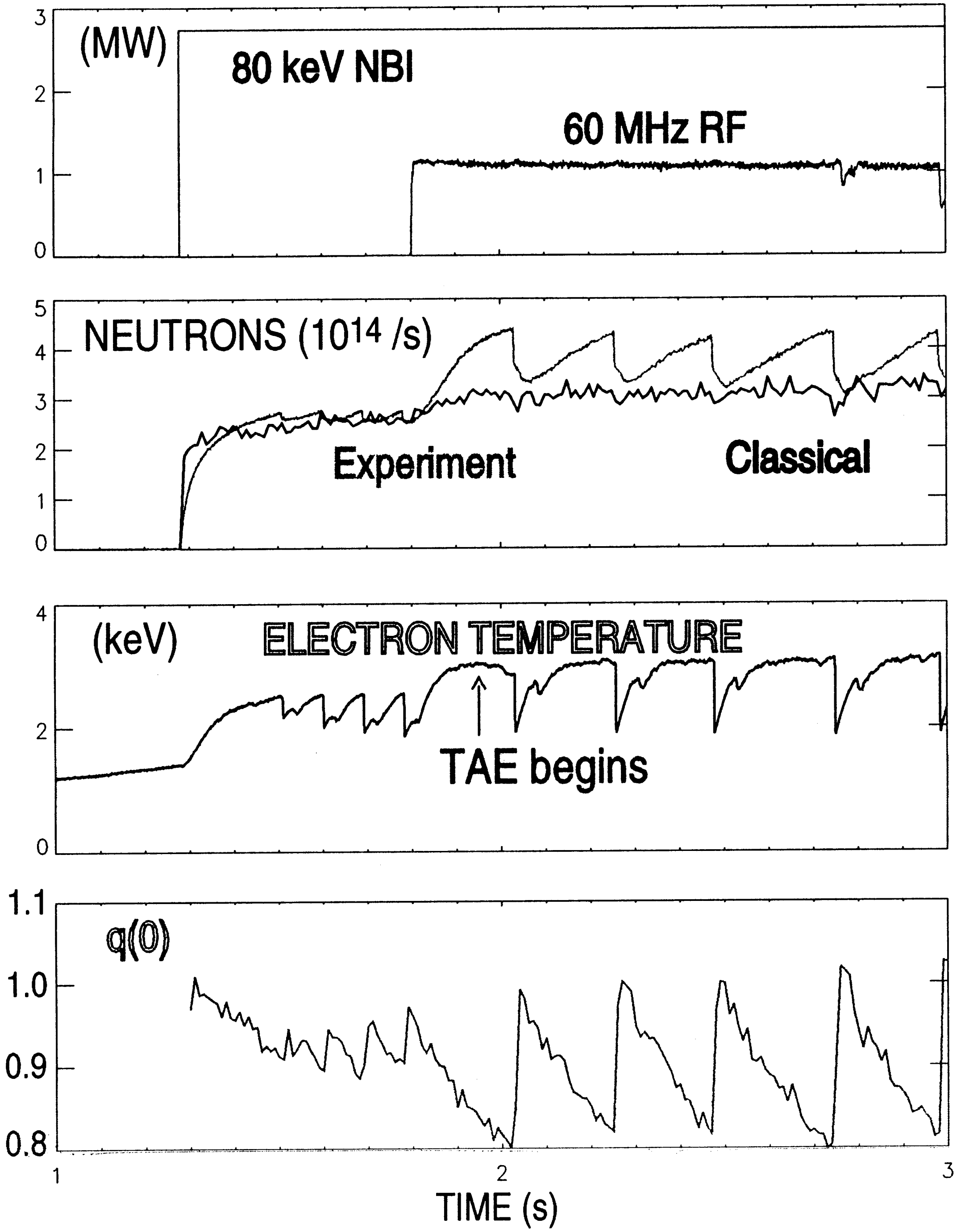
Special instructions: DIII-D Poster Session 2, immediately following RI Pinsker

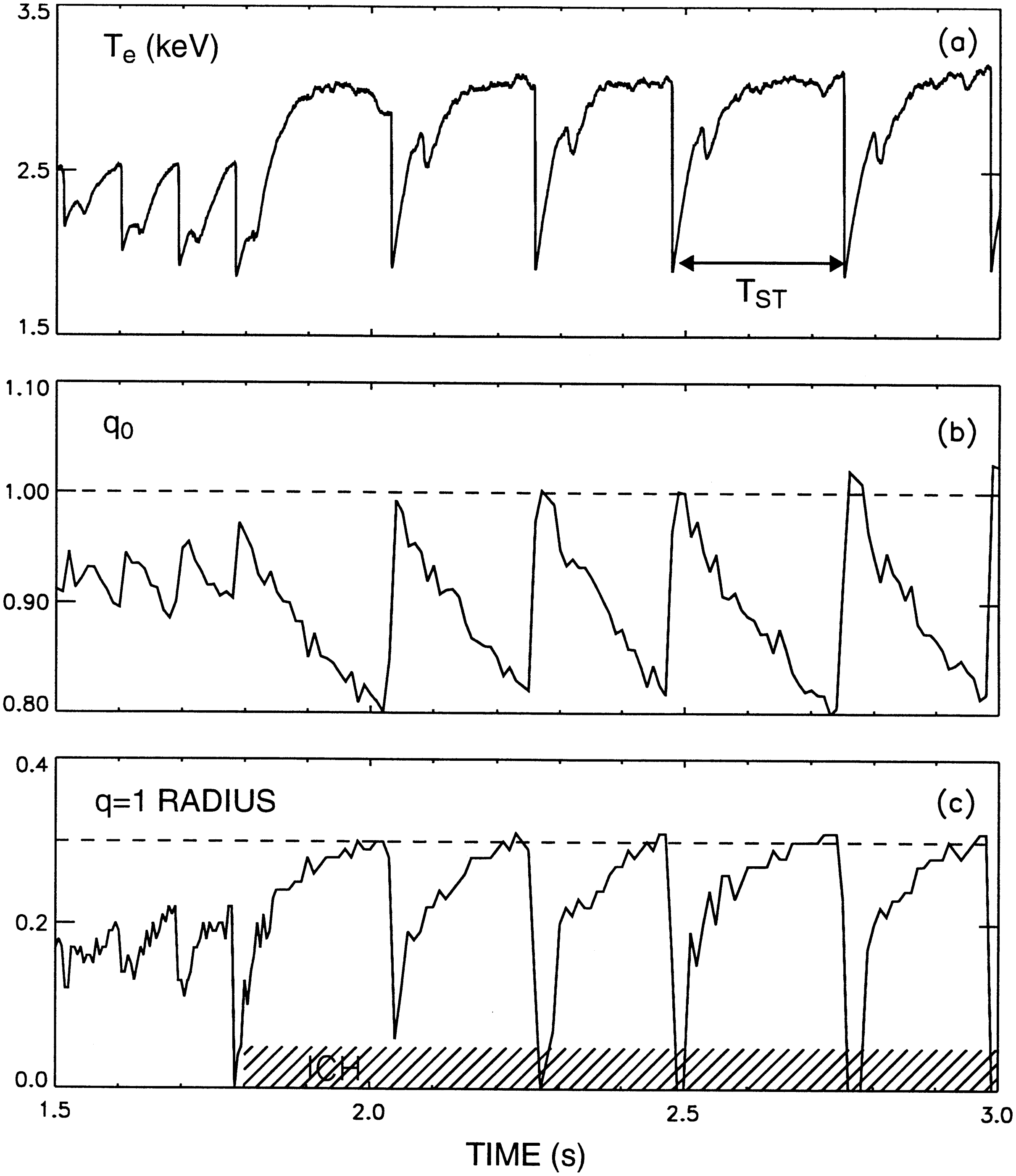
Date printed: July 16, 1999

Electronic form version 1.4

COMBINED NEUTRAL BEAM AND 4th HARMONIC HEATING

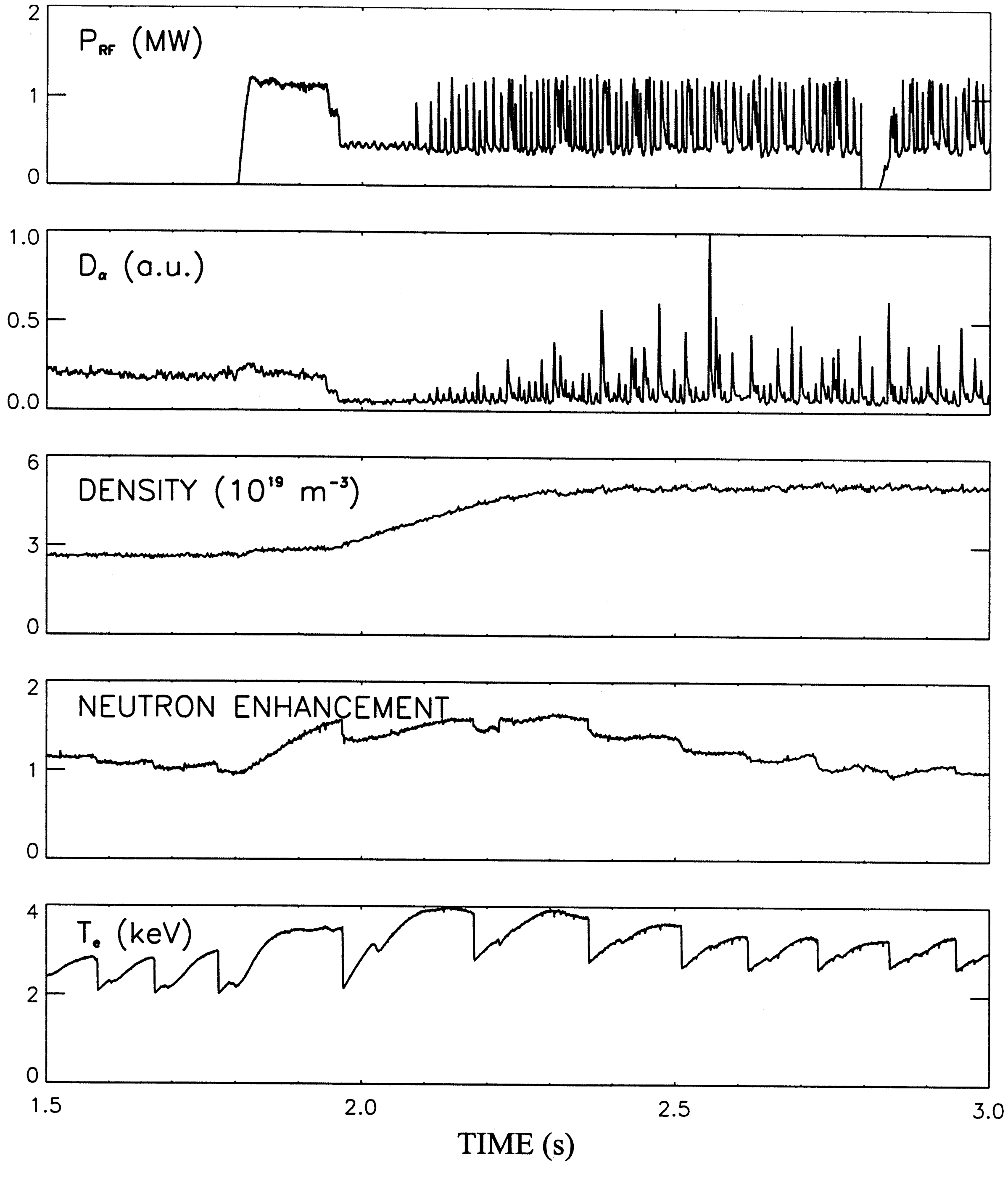


- The RF accelerates deuterium beam ions inside q=1.
- The precessing beam ions transiently stabilize the internal kink.
- The beam ions destabilize the TAE, which limits the central electron temperature.
- Current accumulates on axis and the q=1 radius expands until kink stability is lost.
- Complete reconnection occurs at the sawtooth crash.

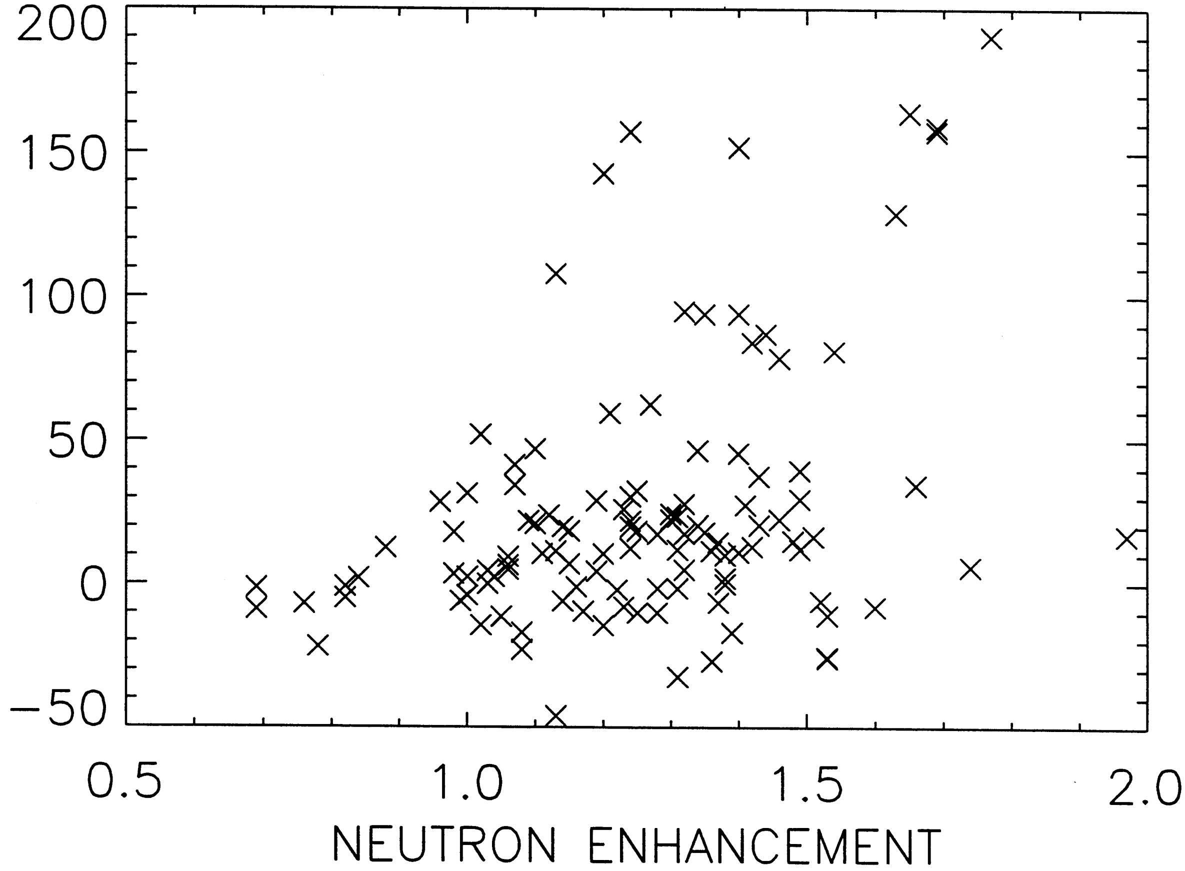

3.5
2.5
1.5
T_e (keV)
(a)
T_ST
1.10
1.00
0.90
0.80
q_0
(b)
0.4
0.2
0.0
q=1 RADIUS
(c)
ICH
1.5
2.0
2.5
3.0
TIME (s)

At an H-mode transition:

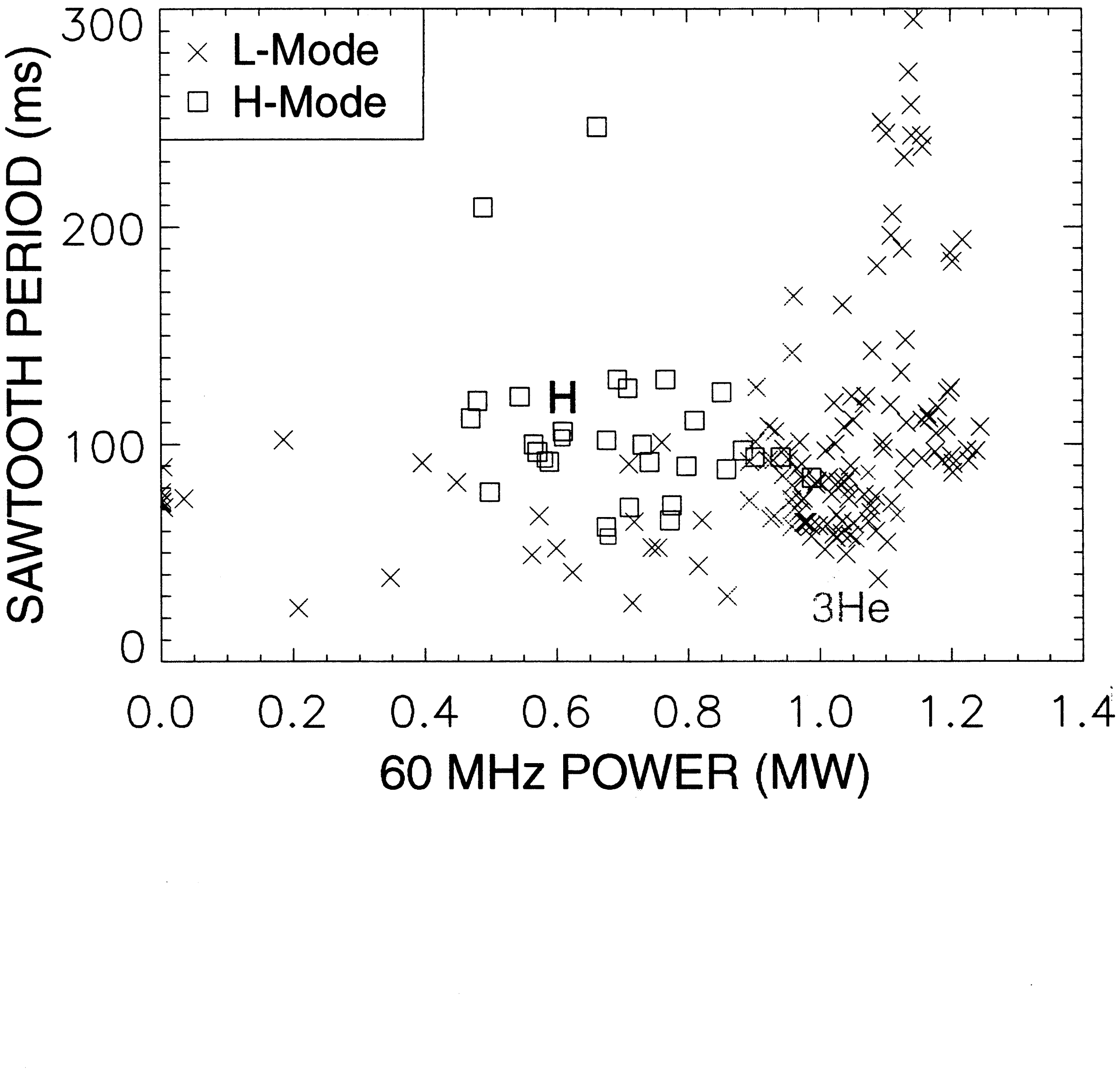
- The RF power drops
- The density rises
- Sawtooth period shortens as tail disappears



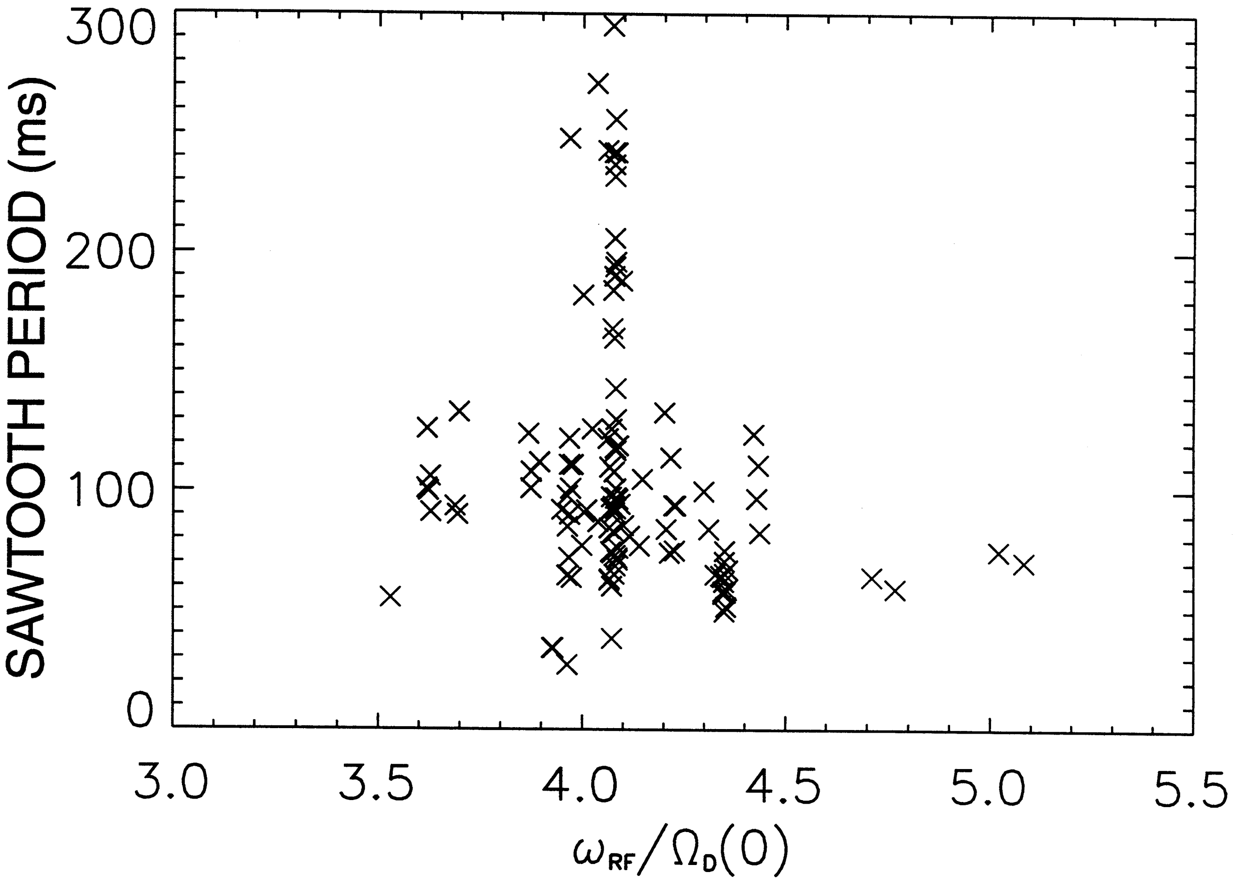
Beam-Ion Tail Necessary but not Sufficient for Stabilization



1.0 MW Needed for Stabilization



Central Heating Required



CONDITIONS FOR SAWTOOTH STABILIZATION

- Enhanced Neutron Rate
  Precessing Beam Ions Stabilize

- Adequate RF Power
  Need Beam-Ion Tail

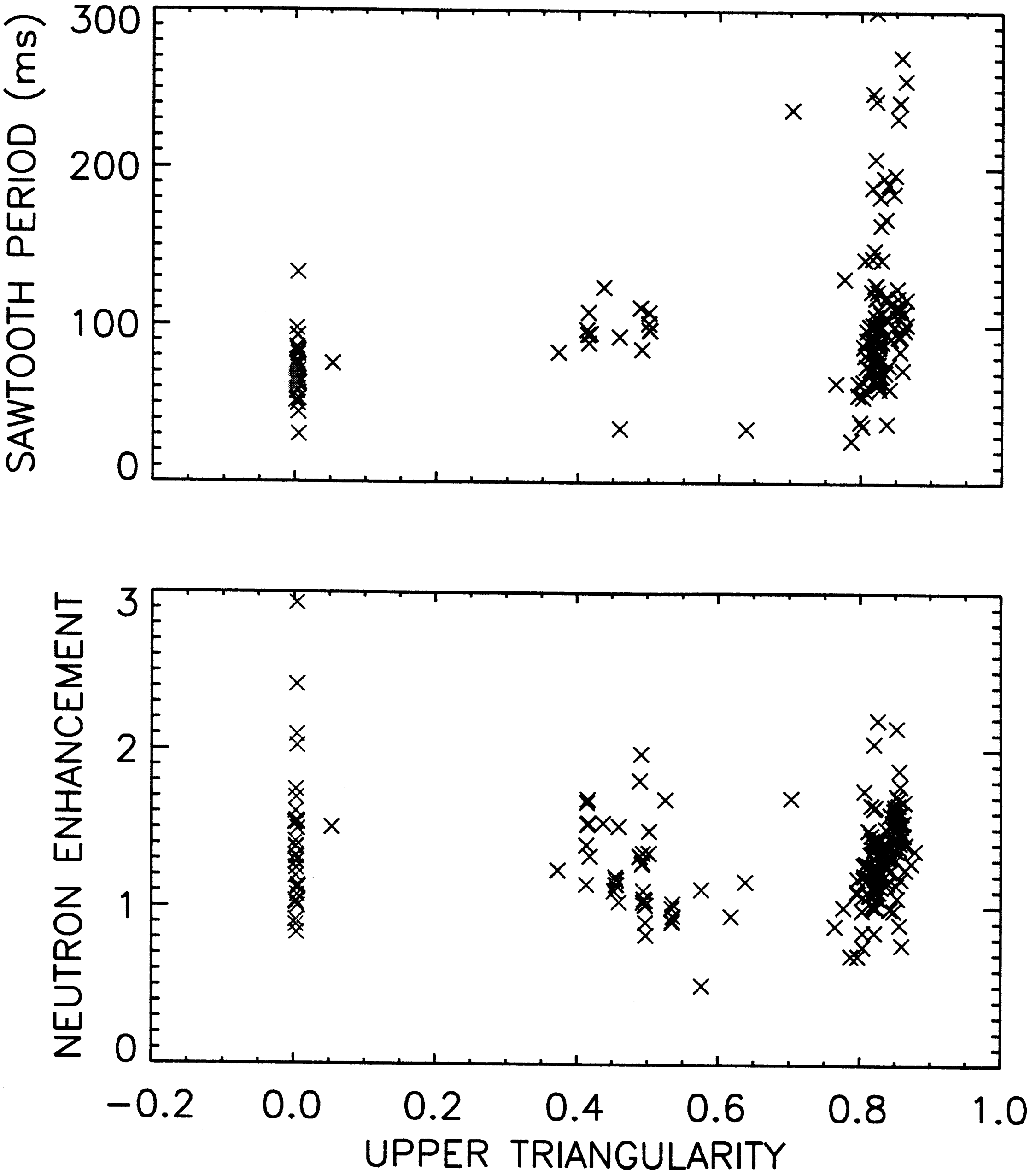
- Low-to-Moderate Density
  Long Slowing-Down Time

- Central Heating
  Beam ions inside q=1

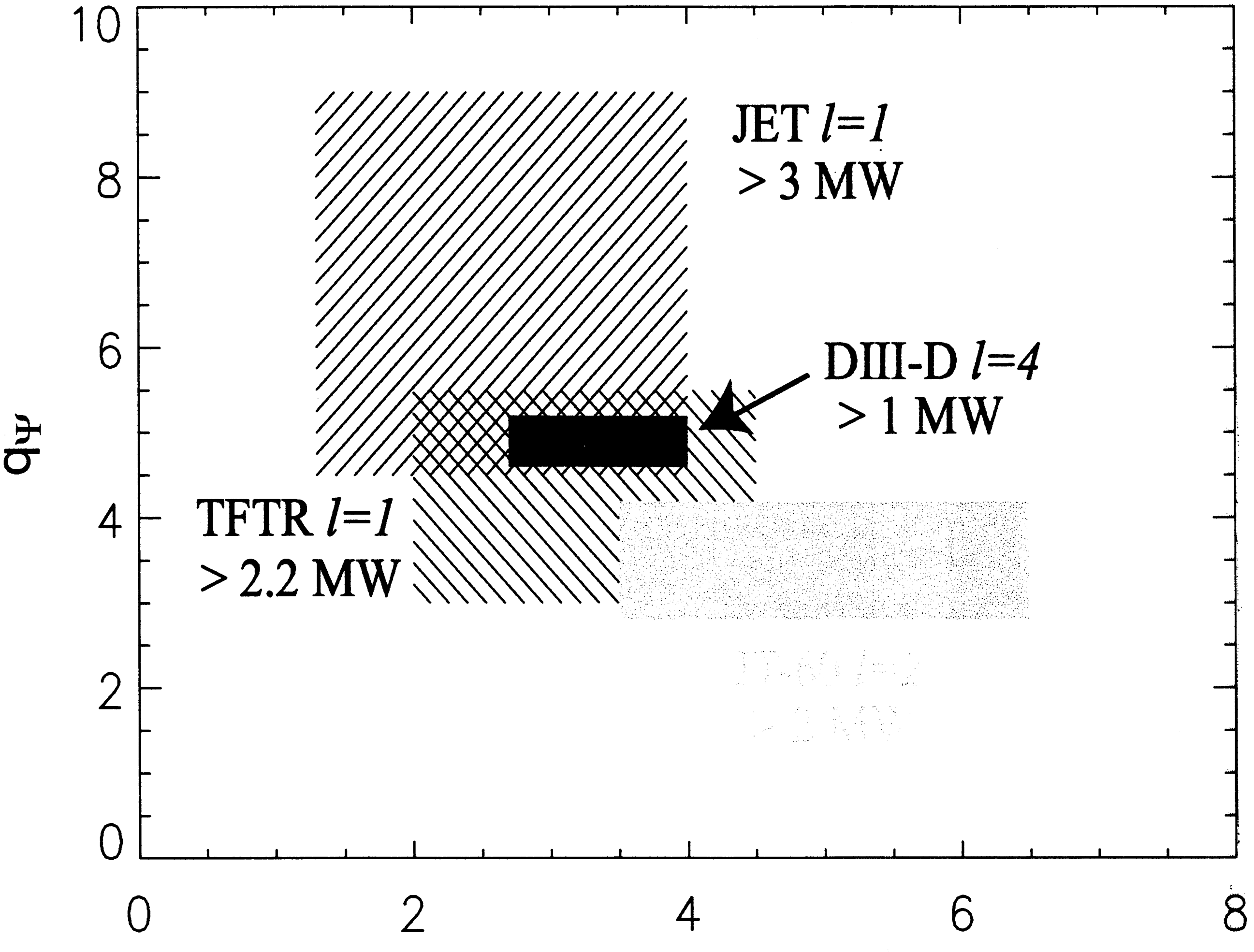
- Threshold Power Density similar to JET, TFTR, JT-60
  Different heating schemes all create fast-ion tails

- Favorable shape
  Competition between Tail formation and MHD Stability

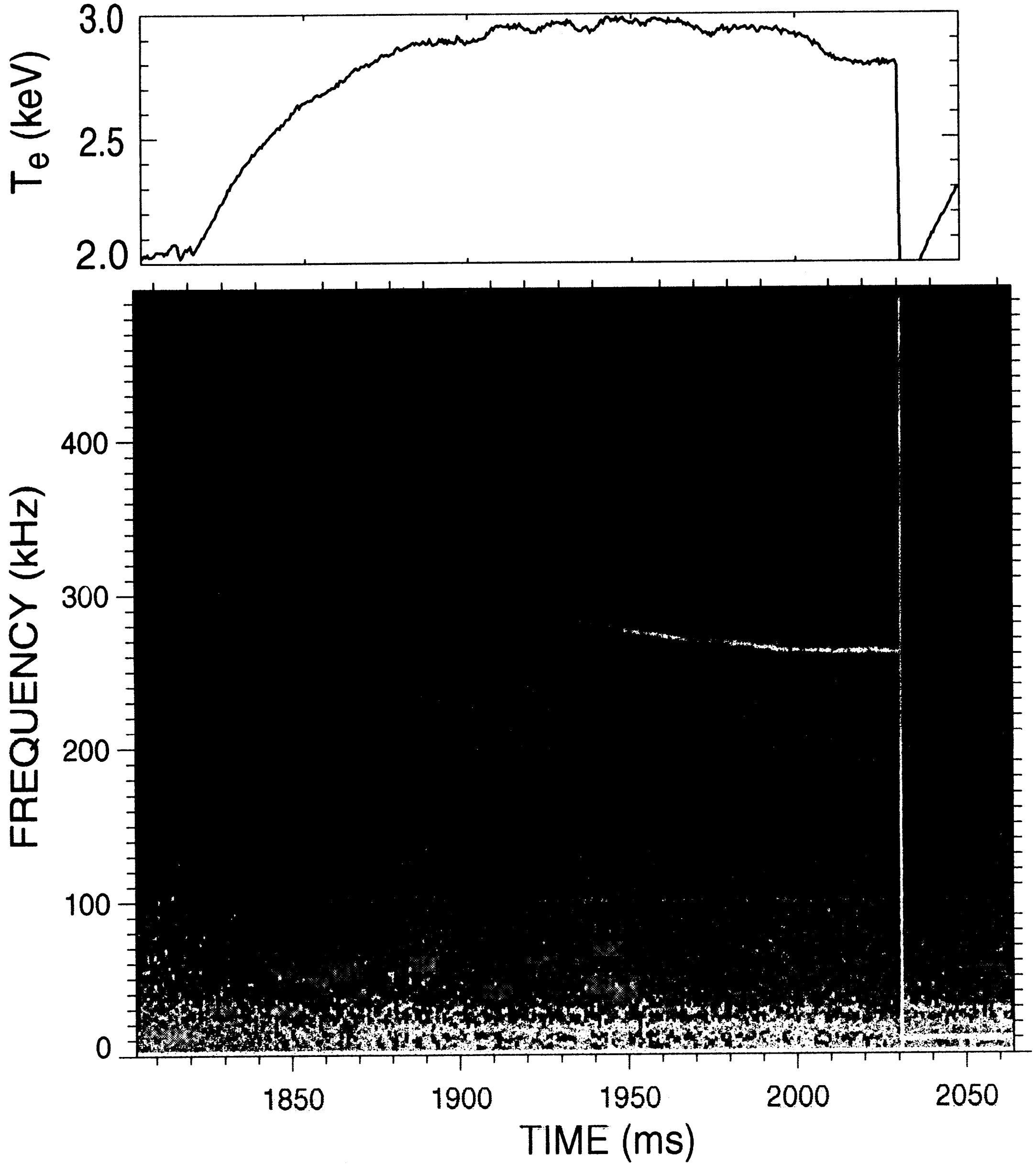
Shape Impacts Stability Not Beam-Ion Absorption



Power Density for Stabilization is similar for other heating schemes



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)

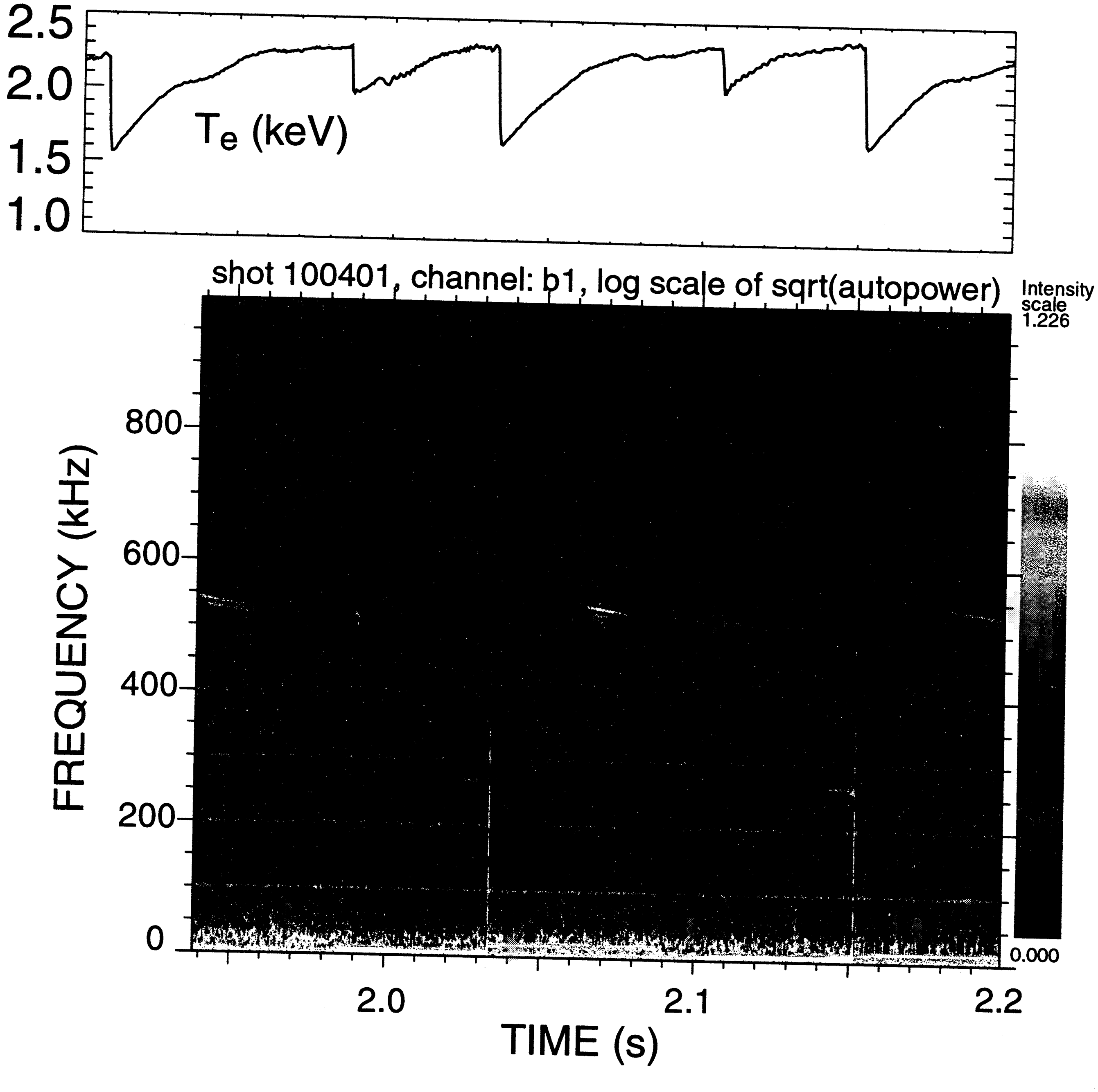
- TAEs appear midway in sawtooth cycle.
Critical beam-ion beta for instability.

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

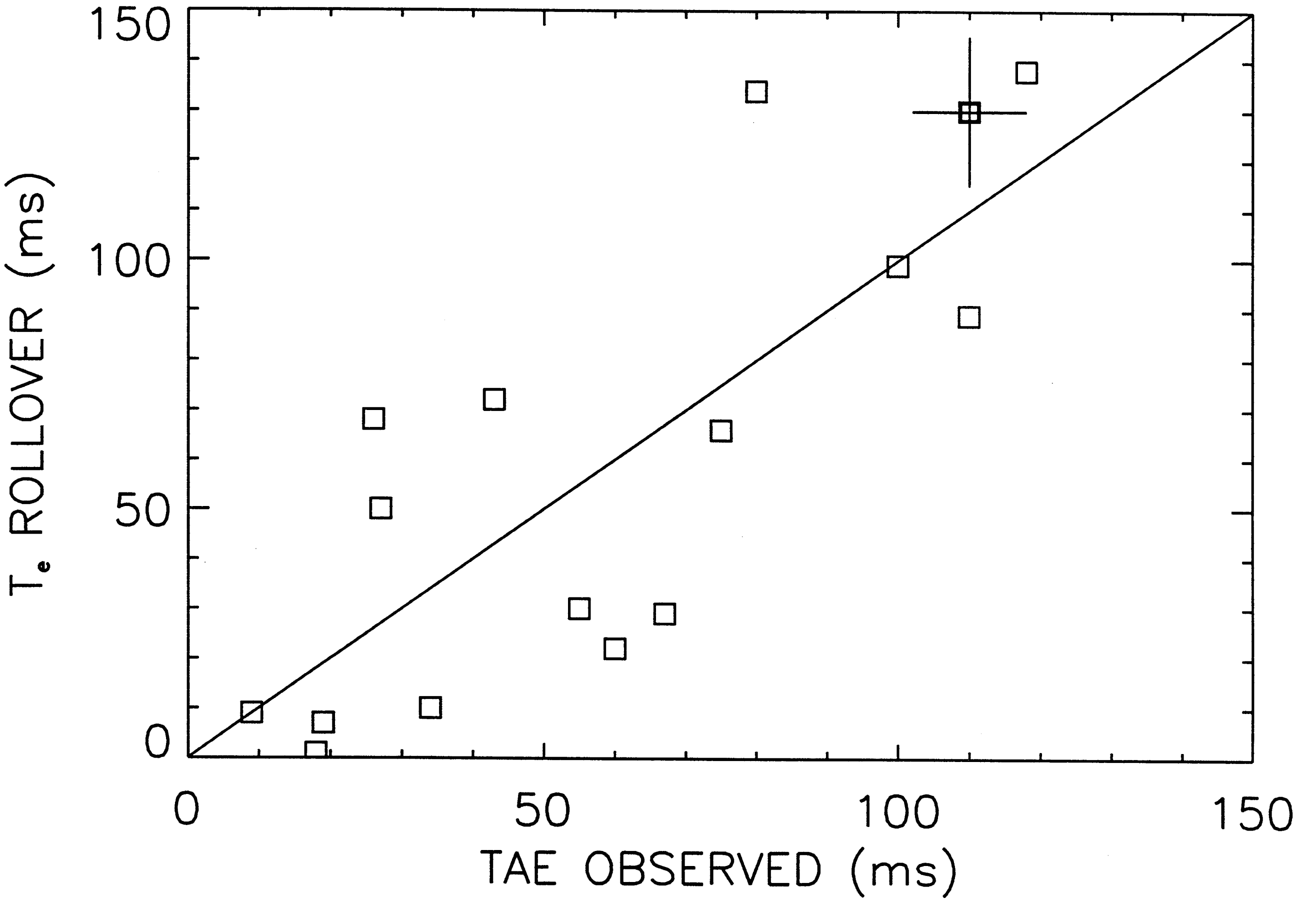
- TAEs cause saturation of central T_e.
Central beam-ion density clamped by TAE.

- Only single modes observed.
System close to marginal stability.

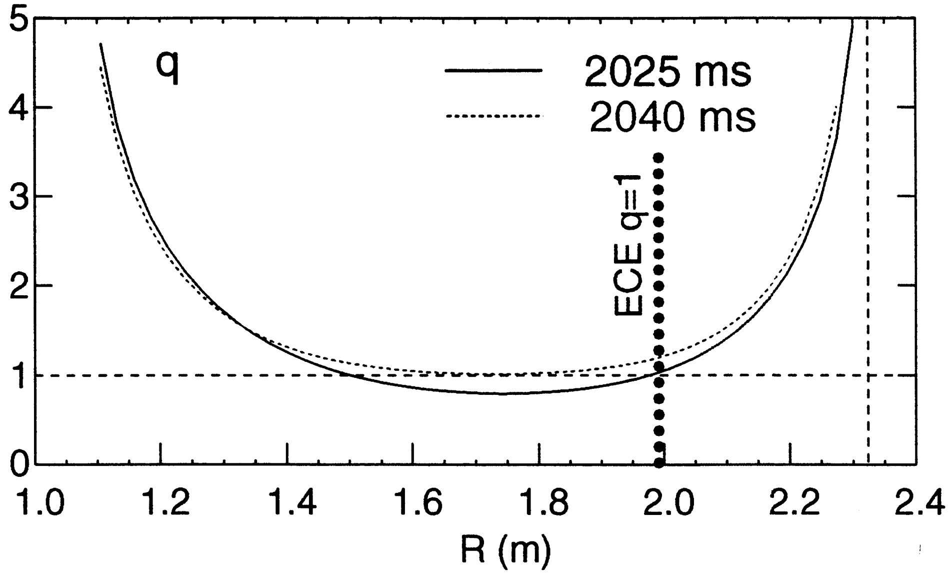
EAE and TAE

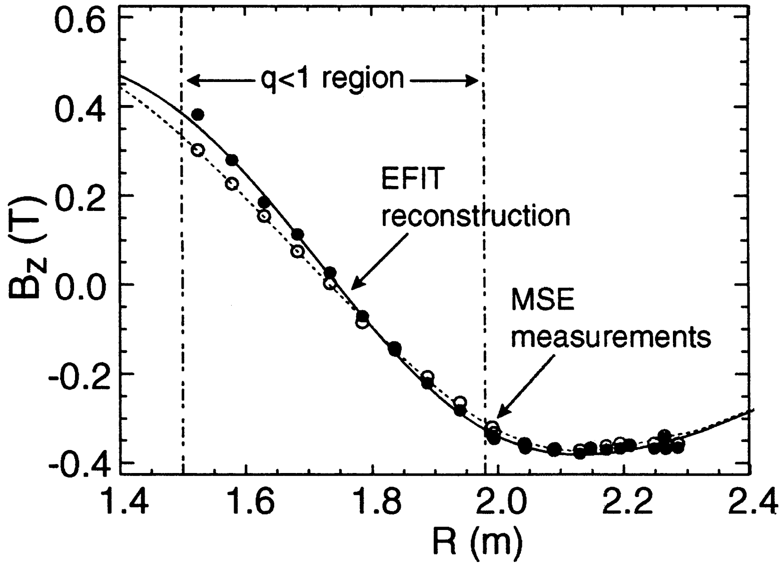

2.5
2.0
1.5
1.0
Te (keV)
shot 100401, channel: b1, log scale of sqrt(autopower)
Intensity scale 1.226
0.000
FREQUENCY (kHz)
800
600
400
200
0
2.0
2.1
2.2
TIME (s)

TAE Causes Saturation of Central Electron Temperature



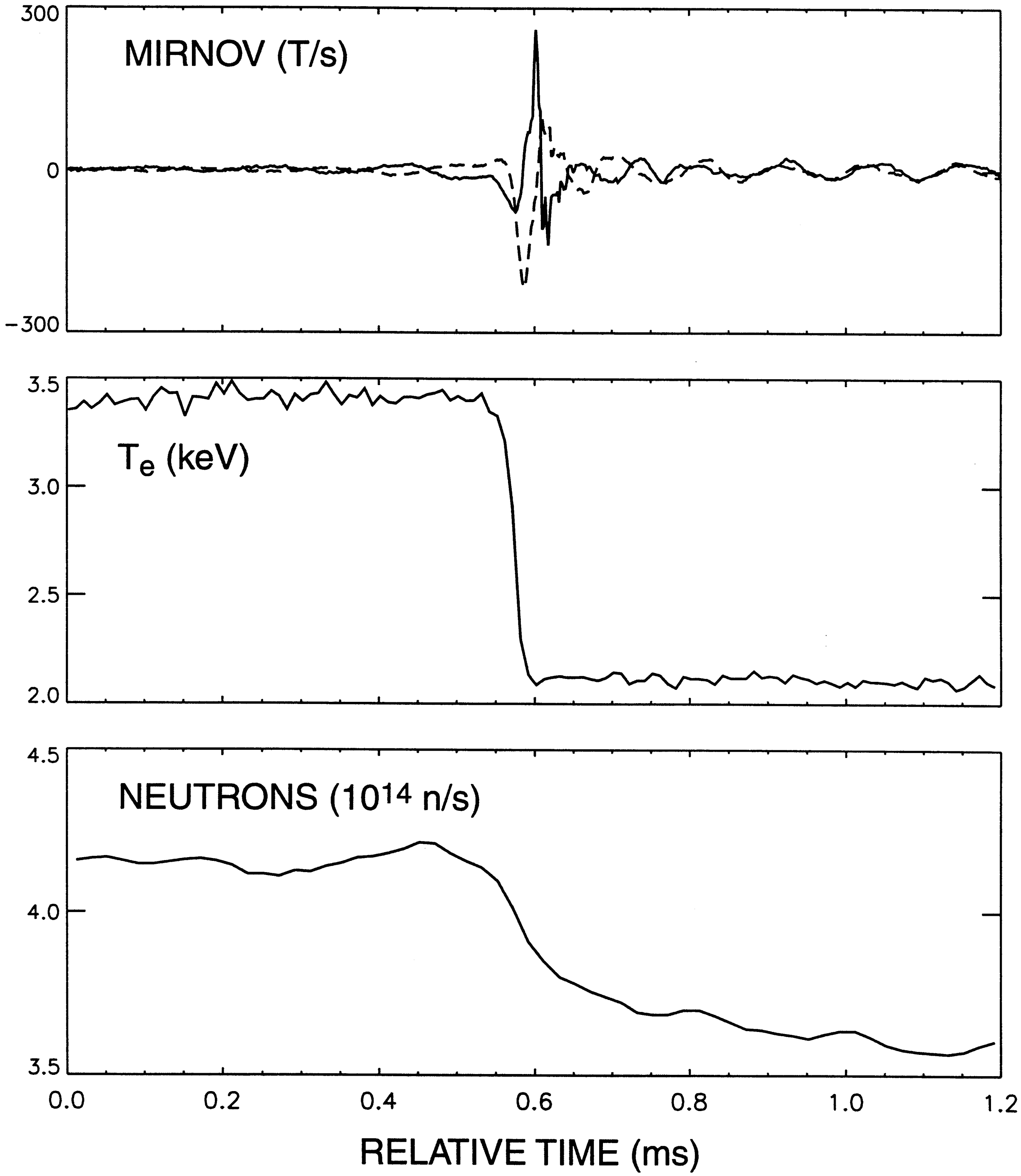
COMPLETE RECONNECTION



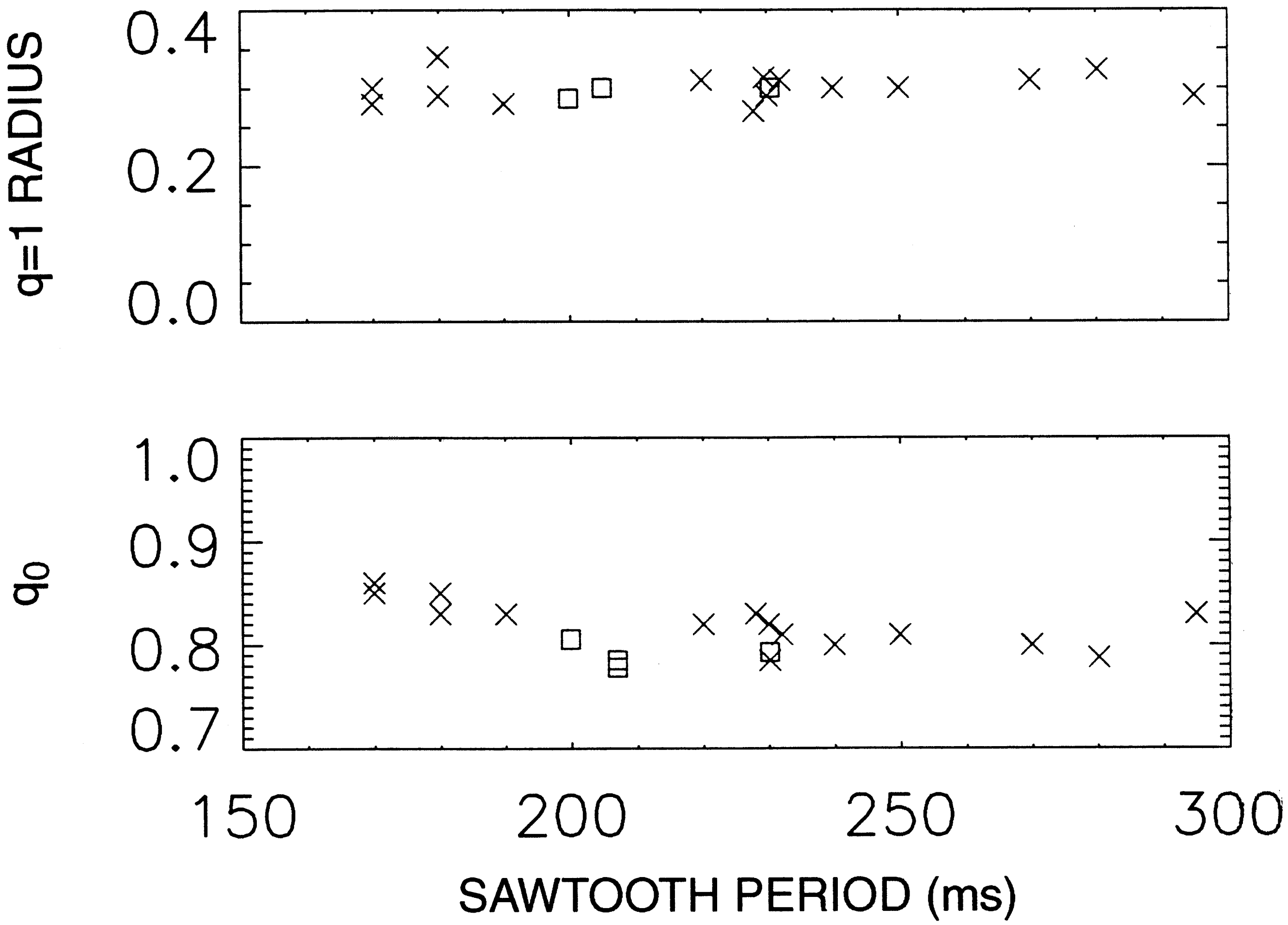


- n=1 magnetic precursor grows at 3/ms
- Very small island on ECE; rapid crash
- Partial reconnection events early in cycle
  => q not monotonic after crash?

Rapid Crash Redistributes Beam Ions as Theoretically Expected



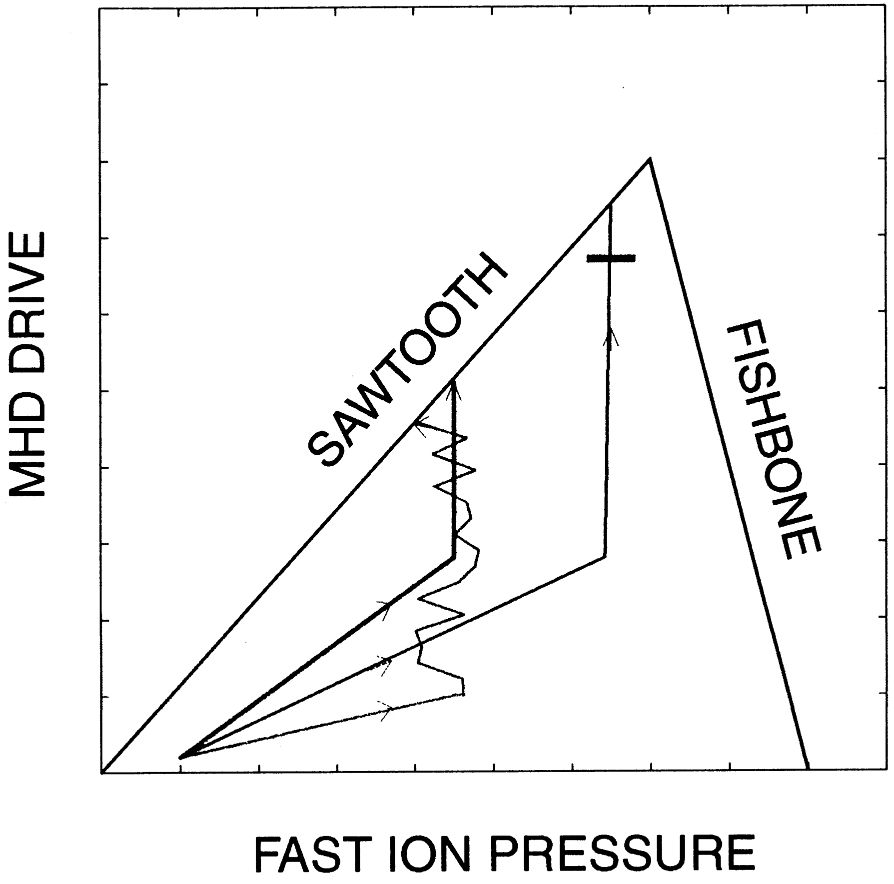
CURRENT DIFFUSION CAUSES SAWTOOTH CRASH



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

=> Crash always occurs at the same radius

INDEFINITE SAWTOOTH STABILIZATION



- More RF Power does not work
  Just excite TAE sooner

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

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

- Must halt current diffusion
  => **Use bootstrap and off-axis ECCD**

How to stabilize sawteeth indefinitely?

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

➔ Can't increase the beam density past the TAE threshold.

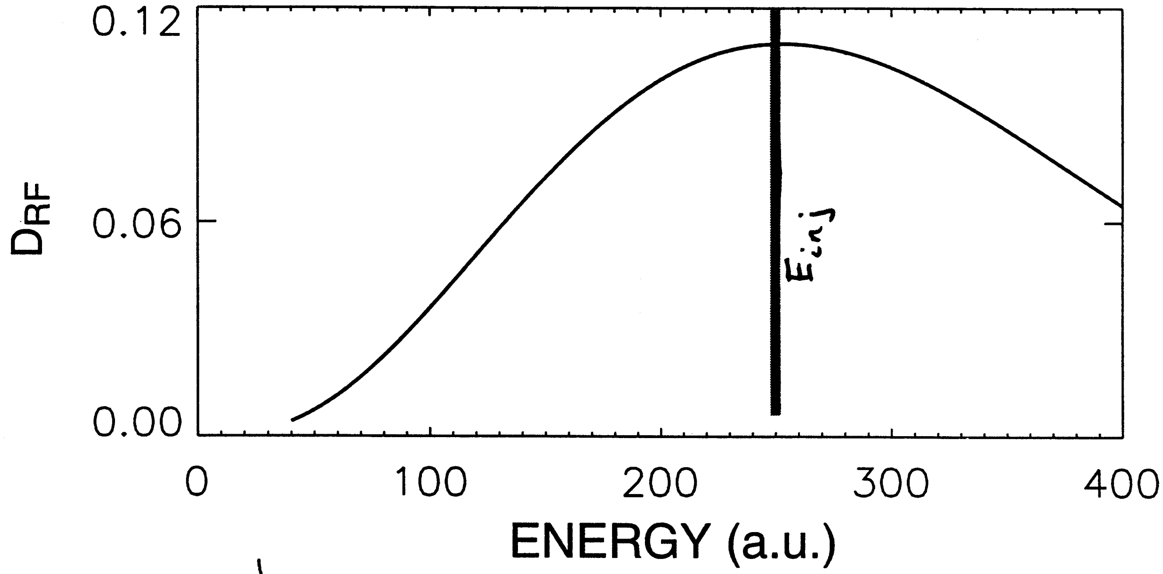
Is there an optimal distribution function for sawtooth stability without TAE instability?

Is there a condition with stronger TAE damping?

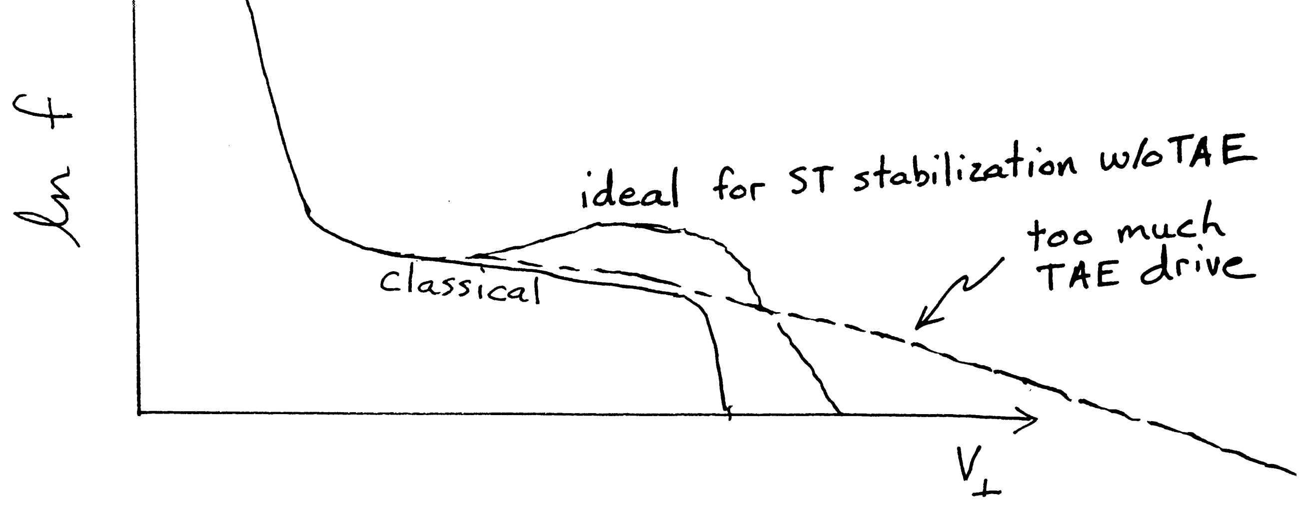
2nd Problem: Stability is lost when the q=1 surface grows too large. The "natural" inductive current profile is too peaked for steady-state operation.

➔ Use non-inductive current drive to halt the current diffusion.

Arrange Conditions so Minimum Stabilizing Precession Speed and Injection Speed Coincide With Peak of Velocity Diffusion Coef.



$$\frac{\gamma_{TAE}}{\gamma_{ST}} \propto \frac{\langle \omega_d^2 f\rangle}{\langle \omega_d f\rangle} \simeq \frac{\langle W^2 f\rangle}{\langle W f\rangle}$$



Future Work

- Study the effect of shape, q profile, and Alfven 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 sawooth occurs.

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

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.