Role of Alfvén instabilities in energetic ion transport

S. Bernabei,† M. G. Bell, R. Budny, D. Darrow, E. D. Fredrickson, N. Gorelenkov,a) J. C. Hosea, R. Majeski, E. Mazzucato, R. Nazikian, C. K. Phillips, J. H. Rogers,b) G. Schilling, R. White, J. R. Wilson, F. Zonca,c) and S. Zweben
Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey 08543

(Received 13 November 1998; accepted 11 January 1999)

Experiments with plasma heating by waves at the ion cyclotron resonance of a minority species have shown that the heating efficiency degrades above a certain power threshold. It is found that this threshold is due to the destabilization of a branch of shear Alfvén waves, the Energetic Particle Modes, which causes a diffusive loss of fast ions. These modes not only play a fundamental role in the transport of the fast ions, but appear closely related to the formation of giant sawteeth. © 1999 American Institute of Physics. [S1070-664X(99)92305-4]

I. INTRODUCTION

Heating of tokamak plasmas by waves in the Ion Cyclotron Range of Frequencies (ICRF) often employs the minority-ion fundamental resonance absorption mechanism.1 This mechanism creates an energetic population of ions of the minority species that equilibrates with the bulk ions and electrons through collisions. During such heating, the normal sawtooth relaxation instabilities are often suppressed. It has been postulated that the pressure exerted by the fast ion distribution created by ICRF minority heating stabilizes the $m = 1$, $n = 1$ oscillation and therefore eliminates the sawteeth. A concurrent effect of the fast ion tail in the distribution function is the excitation of Alfvén instabilities that can cause diffusion and, eventually, loss of fast particles. Several modes, different in structure and with a variety of toroidal numbers, can be destabilized. Since they affect the transport of fast particles, these modes also play a role in the sawtooth stabilization and the eventual giant sawtooth crash.2

Experimental conditions and heating results are presented in Secs. II and III. In Sec. IV we describe the kinds of Alfvén instabilities that are generated by the tail ions and their role in the transport of the fast ions. In Sec. V, the correlation between a particular kind of Alfvén instability and the formation and evolution of the giant sawtooth is described. Conclusions are in Sec. VI.

II. EXPERIMENTAL CONDITIONS

ICRF minority heating experiments were performed in a variety of plasma conditions in the Tokamak Fusion Test Reactor (TFTR),3 with the purpose of heating and current drive. In almost all cases, a lengthening of the sawtooth period was obtained during the ICRF pulse. The experiments were performed in deuterium or helium-4 plasmas with ICRF heating at the fundamental minority hydrogen resonance. Frequencies 43, 47, and 63.6 MHz were used with corresponding magnetic fields to produce the cyclotron resonance on axis. The average density ranged between 2 and $4.6 \times 10^{19} \text{ m}^{-3}$. The plasma current varied between 1.2 and 1.8 MA, in such a manner that $q(a) \approx 3.2$ in a great majority of cases. The magnetohydrodynamic (MHD) activity was monitored by means of a set of Mirnov coils,4 which comprised a poloidal array of coils to determine the poloidal mode number $m$, and a toroidal array of coils to determine the toroidal mode number $n$. These measurements were supplemented by data from a microwave reflectometer5 whenever available. The reflectometer gave information about density fluctuations caused by MHD modes in the core of the plasma. Energetic ions ejected from the plasma as a result of their interaction with the MHD activity were monitored by means of four probes placed at the edge of the plasma.6

III. ICRF MINORITY HEATING

During ICRF minority heating, the rf power is preferentially transferred to the minority species, creating an energetic tail in the minority distribution function at sufficiently high levels of input power. At low-power levels, the minority ions are quickly thermalized by collisions with bulk ions, and the tail contains very little total energy or velocity space anisotropy. At the high-power level the energy of the individual minority ions increases above the critical energy and they thermalize through collisions with electrons. At this point a fast ion tail begins to form. It is also approximately at this power level that Alfvén instabilities appear, and, since they cause losses, the rate of increase of the stored energy is smaller. Figure 1 shows that in TFTR the stored energy increases linearly with power up to $\approx 3 \text{ MW}$. Above this power the rate of increase of the energy is lower. The peak electron temperature presents a break in slope at the same power level, and at this power level the probes placed at the edge of the plasma register an increased flux of fast particles while the Mirnov loops detect activity in the Alfvén range of fre-
quantities (50–250 kHz). The intensity of the signal from the
lost ion detectors is closely correlated with the amplitude of
the Alfvén instabilities.

IV. ALFVEN INSTABILITIES

As shown in Fig. 2~a!, there are typically two distinct
groups of modes detected in the Alfvén range of frequencies:
one that displays the characteristic density \( (n_e)^{-1/2} \) depen-
dence of the Toroidal Alfvén Eigenmodes (TAE),\(^7\) the other
characterized by a “chirping” frequency.\(^8\) Both groups are
usually composed of several modes with well-defined toroi-
dal numbers. The TAE are global modes that are readily
detected by the Mirnov coils. The chirping modes are de-
tected as density fluctuations in the core by a reflectometer,\(^8\)
before appearing in the Mirnov loop signals. This suggests
that the frequency decrease is accompanied by an outward
radial movement of the modes into the region where they are
detected by the Mirnov coils.

In addition, burst modes at \(\sim 15 \text{ kHz} \) always appear in
conjunction with the higher-frequency modes; having \( n = 1 \),
they appear very similar to fishbones, as shown in Fig. 2~b!.
The role of these modes has yet to be established, but they do
not appear correlated to major ion losses.

In order to identify the modes, the NOVA-K code\(^9\) and the
HINST code\(^10\) have been run with the experimental condi-
tions. Since NOVA-K is a perturbative code that calculates the
destabilization of existing MHD modes caused by energetic
particles, it does not find a solution due to the very strong
continuum damping. On the other hand, HINST, being non-
perturbative, calculates a very strong growth rate for the En-
ergetic Particle Mode (EPM)\(^11^,\(^12\) (Fig. 3), which appears to
match the observed characteristics of the chirping modes.
The EPMs can be destabilized by the ICRF, by creating a
very energetic and very peaked fast ion distribution in the
core.

The EPMs rather than the TAEs appear to initiate most
of the fast ion losses. Figure 4 shows the correlation between
the onset of the EPMs, the fast ion losses, and the “clamping” of
the total stored energy. At \( t = 3.8 \text{ s} \) the fast ion losses
increase sharply, the stored energy, which was recovering
from the previous giant sawtooth stops increasing, and the
spectrum of the TAEs is modified. It is at this time that the
EPMs are destabilized in the core (as seen by the microwave
reflectometer), but are detected by the Mirnov loops after a
delay of \(\sim 30 \text{ ms} \) since, being localized modes, they have to
propagate far enough outward to be detected at the edge.
During the time between the giant sawtooth and the appear-
ance of the EPMs, the TAEs are present, but they do not
prevent the stored energy from increasing. The EPMs can be
destabilized at lower power, even if they are predicted to
require a stronger drive than the TAEs, because of the con-
centration of fast ions in the core\(^13\) (Fig. 5). It appears that
the TAEs may be destabilized by the radial displacement of
fast particles that cross the TAE location, displaced either by

FIG. 1. The correlation between stored energy, integrated mode amplitude,
and lost ions versus rf power. Conditions were plasma current 1.68 MA,
toroidal field 3.0 T, average density \( 2.8 \times 10^{19} \text{ m}^{-3} \) and rf frequency 43
MHz.

FIG. 2. (a) The frequency spectrum of the Alfvén instabilities from a
Mirnov loop; the numbers refer to the toroidal wave number of the modes.
TAEs are seen at an approximately constant frequency between 210 and 220
kHz, while the EPMs sweep in frequency. (b) Mirnov loop frequency spec-
trum of the fishbone-like burst modes.

FIG. 3. Frequency \( (\omega) \) and growth rate \( (\gamma) \) of the EPM, normalized to the
Alfvén frequency in the center, calculated by hinst code; \( P_{\text{rf}} = 6.3 \text{ MW} \).
a giant sawtooth (Fig. 6) or by the EPMs. A possible explanation can be found examining Fig. 7: it shows the radial distribution of the fast ion beta calculated by TRANSPI. The fast ion distribution created by ICRF is calculated to be well localized in the core. The steep gradient in the fast ion pressure does not extend to the TAE’s location. Until the fast ion distribution reaches the critical value for EPM destabilization, there is no transport mechanism for the fast ions. Once the EPMs or a giant sawtooth have broadened the fast ion population across the minor radius, TAEs continue to diffuse them outward: this explains the presence of TAEs and the continued losses after the sawtooth. In the meantime, the steep pressure profile is being created anew on top of the remnants of the old one: the stored energy increases until new EPMs are destabilized and the cycle repeats. Without a loss mechanism for the fast ions, TRANSPI predicts a linear increase of the stored energy, as seen in Fig. 8.

Evidence for the expulsion of fast ions from the core can be gained by measuring the difference in frequency of the various harmonics of the TAE. This difference is due to Doppler shift caused by the toroidal rotation of the plasma, with the frequency defined by $\omega_{\text{exp}} = \omega_{\text{real}} - n \omega_{\text{rot}}$, where $\omega_{\text{exp}}$ is the measured frequency, $\omega_{\text{rot}}$ the rotation frequency, and $\omega_{\text{real}}$ the real frequency. Before the appearance of the EPMs the rotation is calculated to be $\sim 28$ km/s, in very good agreement with other measurements. After the EPMs, the rotation is significantly increased, causing the TAEs to be expelled from the core.
agreement with the spectroscopically measured value of 30 km/s. During the EPM activity, it drops to \( \sim 22 \) km/s (Fig. 9). The countertorque could be provided by the force \( E_r \times B_\theta \), where \( E_r \) is the electric field induced by the expulsion of ions from the core, or equivalently the result of decrease of toroidal momentum due to loss of fast ions.

Initial modeling for the fast ions losses has been done with the ORBIT code. This code evolves the fast ion distribution generated by TRANSP modeling of the ICRF heating. This modeling can give only a qualitative description of the processes leading to fast ion losses, since some essential quantities such as amplitude are unmeasurable.

The results can be summarized as follows. Necessary conditions for ion transport and eventual losses are (1) there must be a locally resonant wave–particle interaction; (2) the modes must have a significant amplitude; (3) the modes must have a broad radial extent or move radially to convect the particles. The TAEs are stationary, global modes, but being heavily damped in the core where the fast ions created, do not contribute to significant ion losses. The EPMs, on the other hand, by sweeping across a portion of the radius, in combination with the TAEs, can produce a large diffusive loss of fast ions. This is seen in Fig. 10, where it appears that the fast tail formation is clamped during the mode chirping.

V. ROLE OF ALFVÉN INSTABILITIES IN GIANT SAWTEETH

Upon application of ICRF power to the plasma, the sawtooth period lengthens, as does the amplitude of the crash. It is believed that the fast ions contribute a rigidity to the plasma, stabilizing \( m=1 \) oscillations. In the same discharge there can be two kinds of sawtooth: one with a period up to three times longer than the Ohmic sawtooth and one that is about 20 times longer (600–700 ms). In Fig. 11 we see that the long sawteeth all have EPM activity, the shorter do not. It is also interesting to note that there are no intermediate values of the period, as if a bifurcation of state exists.

There is the possibility that EPMs develop as a result of the long sawtooth rather than the reverse. However, all the giant sawteeth present an interesting characteristic, which seems to imply that the EPMs play a fundamental role in their dynamics. The sawtooth crash does not occur at the maximum of the EPM activity, but only after the chirping of the EPM frequency almost stops (see Fig. 10).
VI. CONCLUSIONS

Experiments have been conducted in TFTR, employing the ion cyclotron heating of a minority species on the axis of the plasma in discharges at low $q(a)$. Under these conditions, the ICRF power creates a very energetic population of fast ions in the core of the plasma. Above a certain threshold power, this energetic tail drives Energetic Particle Modes unstable. The EPMs, characterized by a chirping frequency, cause radial displacement of the energetic particles, creating a diffusive loss of the particles themselves and degrading the heating efficiency. Giant sawteeth, characteristic of these low $q(a)$ discharges during ICRF heating, are always accompanied by EPMs.

The phenomenology of the ICRF fast ions in the core has several similarities with alpha particles, therefore modeling for reacting plasmas should take into account the possible excitation of EPMs by the alpha particles and their subsequent effect on the alpha confinement.

ACKNOWLEDGMENTS

We gratefully acknowledge very enlightening discussions with Professor L. Chen and Dr T. Hoang.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-76CH03073.