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ICRF HEATING ON TFTR

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ABSTRACT

The objectives of the ICRF heating program on TFTR are discussed along with a summary of the progress made to date towards achieving those goals. A more detailed analysis of experimental observations of ICRF sawtooth stabilization is given along with a comparison of the data to a theoretical model based on energetic ion stabilization of m=1 kink instabilities. A qualitative correlation is observed between the experimental observations and model predictions, but further development of the theory coupled with more detailed experimental measurements is required in order to gain a quantitative understanding of the phenomenon.

INTRODUCTION

The ICRF heating system on TFTR has been designed to provide up to 12.5 MW of core plasma heating to complement the 35 MW of neutral beam

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injection heating which will be used to drive TFTR plasmas towards the Q=1 breakeven point during D-T operations. The ability to selectively heat core electrons or ions is a key property of ICRF heating that will be utilized to optimize fusion reactivity, Q_{DT}, and alpha particle beta, β_α, in the high density, high temperature regimes expected during D-T operations on TFTR and ultimately in BPX. By applying ICRF heating to high density pellet fueled discharges in TFTR, it will be possible to directly test the ICRF heating scenarios which have been proposed for the BPX device under similar operating conditions.

To date, ICRF power levels up to 6 MW at 47 MHz have been coupled into the plasma in the out-of-phase launch mode with two out of the four antennas which will comprise the completed system[1]. The most significant results obtained thus far include the stabilization of sawteeth in RF only as well as in combined RF and NBI heated plasmas[1], the reduction of core transport as well as the verification of efficient core heating in RF-heated pellet-fueled plasmas[1], and the measurement of the diffusion rates of the RF-produced energetic minority ions which demonstrates that these hot ions experience very little radial transport in comparison to the strong anomalous transport of the thermal plasma[2]. In addition, experiments are in progress to determine if it is possible to stabilize sawteeth in NBI-driven supershots by applying high power ICRF heating[1,2]. The mechanism is potentially important at high plasma currents when NBI heating alone is not sufficient to stabilize the sawtooth oscillations.

Stabilization of sawtooth oscillations using ICRF heating may be of particular importance during D-T operations on TFTR, if the accompanying increase in the energy confinement time and strong peaking of the core plasma temperatures leads to an enhancement of the fusion reactivity or β_α. Theory[4-7] suggests that the fast ions produced by the ICRF heating suppress sawteeth by stabilizing the m=1 instabilities which are believed to be responsible for the sawtooth oscillations. Details of the experimental observations on sawtooth stabilization as well as the comparisons with predictions of the theoretical model will be presented in the remainder of this paper.

ICRF SAWTOOTH STABILIZATION STUDIES

Observations of the Sawtooth Stabilization (SST) phenomenon in TFTR[1] to date are comparable to those reported by JET[3,4]. SST has been observed in both D and ^{4}He majority plasmas with minority H heating, as well as with ^{3}He minority heating in D NBI-produced plasmas. In D(H) plasmas, stabilization has been achieved for RF power levels as low as 2.2 MW with plasma currents ranging from 1.0 to 1.8 MA. For operation near the threshold power

in D(H) plasmas, stabilization is observed only with on-axis heating, as shown in Fig. 1. The power threshold for stabilization in ^{4}He majority plasmas has empirically been found to be higher than the threshold for stabilization in D majority plasmas for reasons which are not well understood. In addition, the threshold power in ^{4}He majority plasmas is dependent on plasma current, as seen in Fig. 2. A higher threshold power for stabilization at the lower plasma current is consistent with theoretical models[4,5,6,7], which suggest that the stabilizing influence of energetic trapped hot ions decreases if the hot ion pressure profile is not peaked and well-contained within the q=1 volume. At 1.2 MA, approximately 75% of the RF power is deposited within the q=1 volume, while at 1.4 MA, as much as 90% of the power is deposited within the q=1 volume.

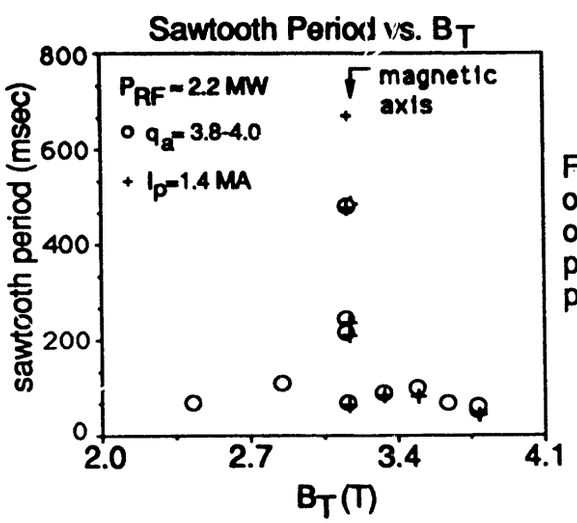

Fig. 1 Stabilization is achieved only with on-axis heating for operation near the threshold power of ~2.2 MW in D(H) plasmas.

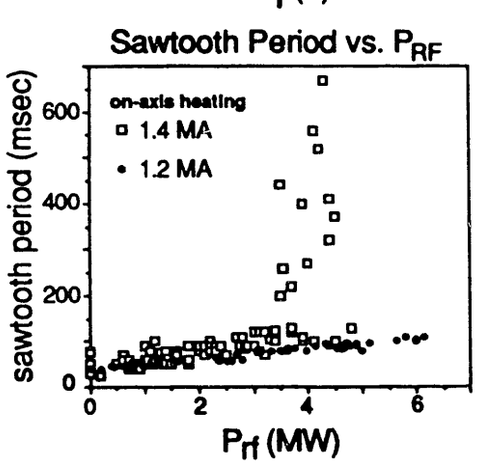

Fig. 2 In ^{4}He(H) plasmas, the threshold power for stabilization is higher than in D(H) plasmas and is dependent on I_p.

The ICRF sawtooth stabilized phase in TFTR experiments has been observed to last up to many times the energy confinement time, as indicated in Fig. 3. The stabilized phase typically terminates with a very rapid growth of the m=1 island, leading into a large sawtooth crash. The growth rate is so

rapid that the plasma does not rotate significantly prior to the actual crash. Hence, the growth of the m=1 perturbation is detectable only with the two channel x-ray viewing system on TFTR, which does not require plasma rotation to be present in order to detect the m=1 MHD oscillations.

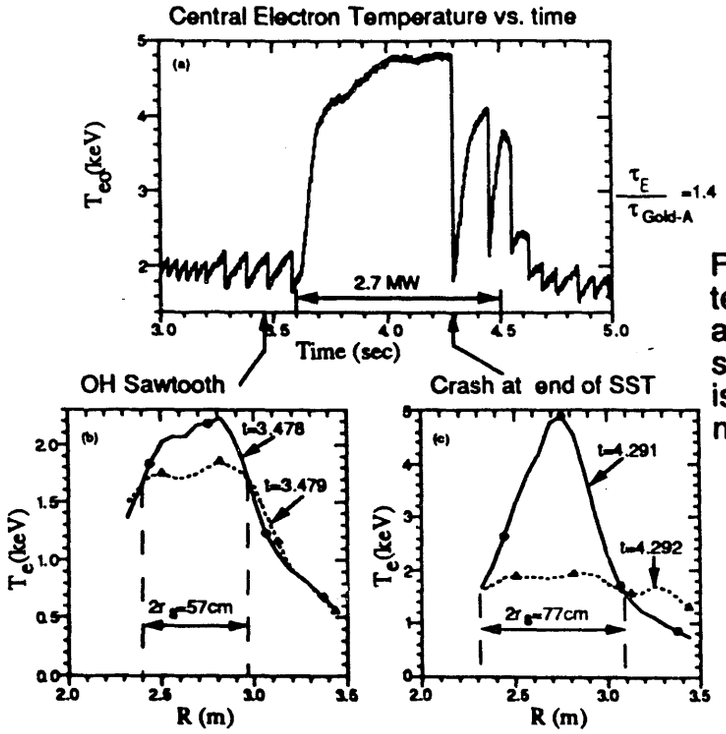

Fig.3 The peaking of the temperature profile as well as the growth of the sawtooth inversion radius is shown. [D(H); I_p=1.8 MA; ne=2.5x10^{13}cm^{-3}].

During the stabilized period, the electron temperature profile peaks significantly relative to the OH phase profile. The sawtooth inversion radius measured at the termination of the stabilized phase is also significantly larger than the corresponding radius during the OH phase, as shown in Fig. 3, implying that the current profile has also peaked up as a result of the stabilization.

Preliminary measurements of the q profile, obtained using Li pellet injection[8], indicate that q_0 drops as low as 0.6 during the stabilized phase, consistent with the JET measurements[9] and with TRANSP calculations of the magnetic diffusion. The technique involves obtaining a spatial profile of the poloidal magnetic field by observing the orientation relative to the total magnetic field of the cigar-shaped emission cloud formed by the ablation of an injected Li pellet. A q profile is inferred by combining the internal field profile measurements with external magnetics data and using an iterative equilibrium solver to find a least squares fit to the Grad-Shafranov equation. Figure 4 shows the inferred q profile for an ^{4}He-D(H) plasma heated by 4 MW of ICRF power. Because of the high electron temperature ($T_e(0)$~6 keV) in this discharge, the pellet penetrated to just inside the q=1 radius. The inferred q_0 is based on an implicit assumption that q and q′ are smooth, monotonically in-

creasing functions of the minor radius for $r<r_1$, where $q(r_1)=1$. By repeating the experiment under conditions which should lead to better pellet penetration and by comparing the results with q measurements obtained with a new diagnostic based on the motional Stark effect, a more definitive measurement of the q profile near the magnetic axis should be obtained.

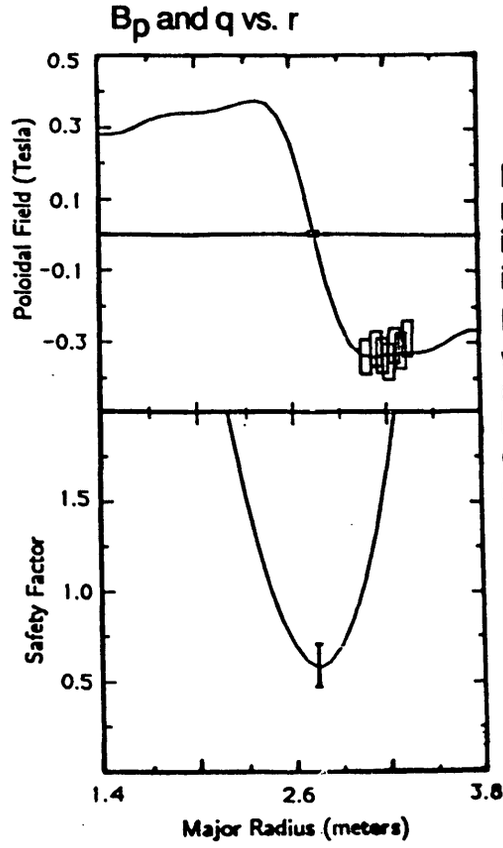

Fig.4 The poloidal magnetic field, as measured by Li pellet injection, and the inferred q profile are shown. The uncertainty in the inferred q_0 is estimated to be ± 0.1, based on an implicit assumption that q' is well behaved between the innermost measured point and the magnetic axis. The location of the magnetic axis was determined from ECE temperature profile measurements and external magnetics.

Theory suggests that the fast ions produced by the ICRF heating suppress sawteeth by stabilizing m=1 internal kink instabilities believed to be responsible for sawtooth oscillations[4-7]. Assuming that the RF-driven energetic ions can be adequately described in terms of a tail distribution function, the dispersion relation governing m=1 ideal internal kink instabilities can be written as:

$$\hat{\gamma}_I + i\,[\,\Omega(\Omega-\Omega_*)]^{1/2} = \hat{\beta}_h[\pi^{1/2} - 2\,\Lambda_k(0)]\,[\frac{1}{2} + \Omega + \Omega^{3/2} Z(\Omega^{1/2})\,] \qquad (1)$$

where Z is the plasma dispersion function, $\Lambda_k(0)$ represents the zero frequency response of the hot trapped ions[4,6,7], $\Omega=\omega/\omega_d$, $\omega_d=cT_h/(eBr_1Rz_h)$=the

precession frequency of a hot ion with effective temperature T_h and charge z_h, $\Omega_* = \omega_{*i} / \omega_d$ where ω_{*i} is the ion diamagnetic frequency, $\hat{\gamma}_i = \gamma_i / \omega_d$, β_h is the hot ion beta (defined below), $\hat{\beta}_h = \beta_h \, \omega_A / \varepsilon \, \omega_d$, with $\varepsilon = r_1/R$, and ω_A is the Alfven frequency. Comparison of the experimental stabilized discharge parameters to the m=1 ideal internal kink stability boundaries qualitatively supports the interpretation that the stabilization is due to the pressure of the hot ions. However, the experimental uncertainties and the theoretical simplifications can lead to changes of factors of 2 to 3 in the location of either the data points or the stability boundaries. A comparison of some TFTR data points to the predicted stabilization boundaries is displayed in Figs. 5 and 6. Since the boundaries depend sensitively on $\Lambda_k(0)$, a parameter which is not well determined[4,6,7], the stable regions have been drawn for two representative values of $\Lambda_k(0)$. The ideal MHD growth rates for the data have been evaluated with the ARES resistive MHD stability code[10]. Experimental parameters are obtained directly from measurements or else are inferred from SNAP or TRANSP analyses. Estimates for β_h have been evaluated in Fig. 5 using the integral formulation proposed by Coppi et.al.[6]:

$$\langle \beta_h \rangle_I = \int_0^1 d\tilde{r} \; \tilde{r}^{3/2} \frac{d}{d\tilde{r}} \left[\tilde{r}^{1/2} \, p_{\perp h} \right] \qquad \text{where} \quad \tilde{r} = \frac{r}{r_1} \tag{2}$$

and where $p_{\perp h}$ is the perpendicular pressure of the energetic ions,

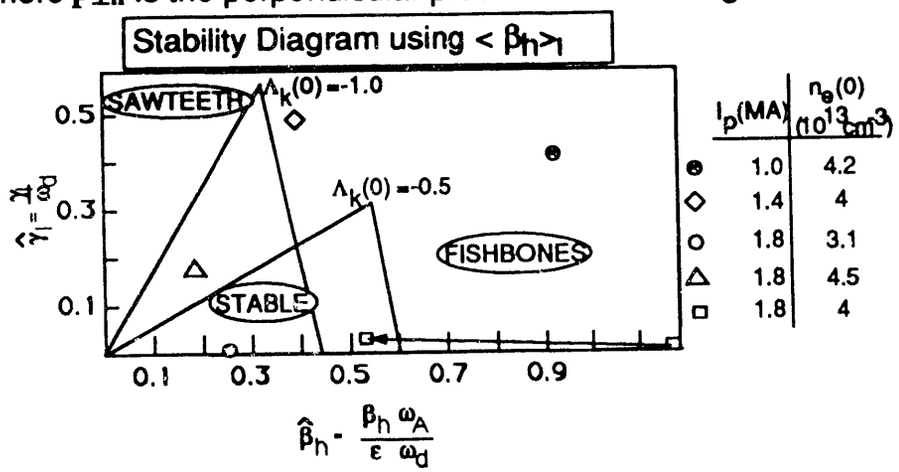

Fig.5 TFTR data is plotted on the theoretical stability diagram using the integral form for β_h. The arrow indicates the direction of increasing time for a shot analyzed with TRANSP.

or else a volume estimate:

$$\langle \beta_h \rangle_V = \left[\frac{8\pi}{B_1^2}\right]\left[\frac{W_{\perp h}}{V}\right] \tag{3}$$

where $W_{\perp h}$ is the perpendicular stored energy in the hot ions, as used in Fig. 6. The time evolution for one specific discharge through stability phase space has been indicated in Figs. 5 and 6 with arrows. Throughout the SST phase, the discharge evolves towards the region of phase space characterized by sawtooth oscillations.

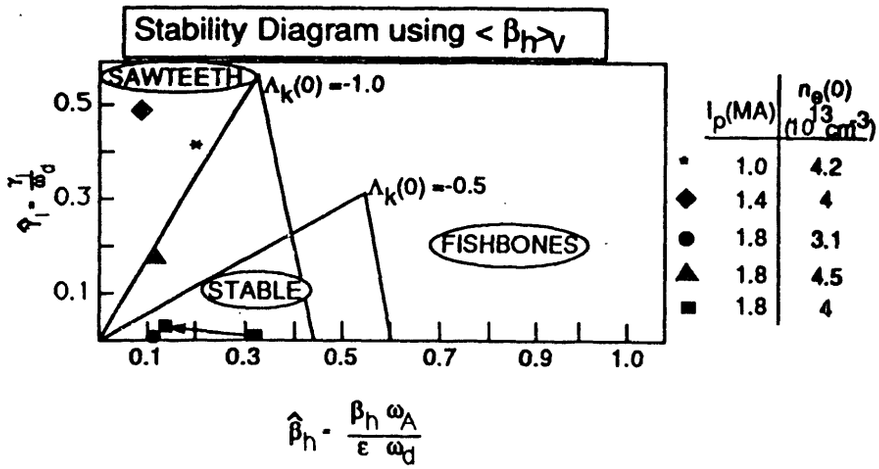

Fig.6 TFTR data is plotted on the theoretical stability diagram using a volume average for β_h. The arrow indicates the direction of increasing time for a shot analyzed with TRANSP.

SUMMARY AND CONCLUSIONS

ICRF power levels up to 6 MW have been coupled into TFTR plasmas using two antennas in the out of phase launch mode. Sawtooth stabilization has been observed during ICRF heating of gas, beam, and pellet fueled discharges. Experiments are underway to determine if it is possible to stabilize sawteeth using ICRF in NBI-driven supershots at high plasma current. Core heating of high density pellet-fueled discharges has been demonstrated[1]. Measurements of the ICRF-generated fast ions indicate that these ions experience very little cross field transport relative to the large anomalous transport of the bulk species[2]. Characteristics of ICRF sawtooth stabilization in TFTR are comparable to those reported on JET. A qualitative correlation has been found between the experimental observations and the theoretical predictions, given the large uncertainties in both the measurements and the theory.

Further development of the theory coupled with more precise measurements should provide a more reliable basis on which projections for using the stabilization mechanism during D-T operations in TFTR and ultimately in BPX can be made.

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