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ICRF SAWTOOTH STABILIZATION-APPLICATION ON TFTR AND CIT

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ICRF SAWTOOTH STABILIZATION -
APPLICATION ON TFTR AND CIT

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Abstract

The use of ICRF heating to stabilize the core plasma sawtooth relaxations has been extended to TFTR where such stabilization has been produced at relatively low power in the L Mode regime at moderate density ($P_{RF} \approx 4$ MW, 2.6 MW in helium and deuterium discharges, respectively, for the minority hydrogen ICRF heating regime with $\bar{n}_e \approx 2.5 \times 10^{13} \text{ cm}^{-3}$). These results, as in the case of those obtained on JET, are qualitatively consistent with energetic ion stabilization of the $m=1$, $n=1$ ideal/resistive kink mode. The relevance of sawtooth stabilization to the primary regimes of interest on TFTR - the high-Q supershot regime and the high density pellet injection regimes - and on CIT - the high density ICRF heated regime - is considered in the context of the present theory and the projected ICRF power deposition characteristics.

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INTRODUCTION

RF stabilization of sawtooth relaxations of the core plasma of tokamak discharges is highly desirable to achieve optimum performance in present and future tokamaks and ultimately in the toroidal fusion reactor regime. This is especially true with regard to the optimization of the fusion reactivity which is a strong function of density and temperature in a thermal plasma core: reactions/second $\sim n_i T_i^2$ for the usual range of $T_i < 30$ keV. Such stabilization was first observed during electron cyclotron heating (ECH) on T-10,¹ then during lower hybrid current drive (LHCD) on PLT² and Petula,³ and more recently during heating in the ion cyclotron range of frequencies (ICRF) on JET.^{4,5,6} The mechanisms of stabilization for these three rf methods are postulated to be basically different: (i) stabilization for ECH occurs when the resonance layer is placed just outside the $q=1$ layer thereby providing a positive energetic electron pressure gradient in the $q=1$ layer⁷; (ii) in the case of LHCD, the current distribution is broadened to make $q(r)$ exceed one throughout the plasma^{8,9}; and (iii) for ICRF heating the energetic ion population is centrally peaked inside the $q=1$ layer with sufficient density and effective temperature (energy) to make the plasma rigid to the kink-tearing mode.^{10,11} Potentially, all three of these rf stabilization schemes can be developed for application to the reactor regime but the focus of this paper is placed on ICRF sawtooth stabilization which has direct relevance to the optimization of performance on TFTR and CIT.¹²

Considerable effort has been applied on JET to characterize the ICRF sawtooth stabilization ("monster" sawtooth) phenomenon in terms of the energetic ion stabilization theory.^{13,14} The qualitative features of the stabilization theory appear to be observed in the experiments: the maximum stabilization time is obtained when the rf power deposition is focused on the plasma axis, well inside the $q=1$ surface; the general shape of the stability boundary in the $(\hat{\gamma}_i, \hat{\beta}_h)$ plane appears to be obtained from rather rough estimates based on deduced global fast-ion parameters; and the termination of the sawtooth free period upon switch-off of the rf power occurs in a time τ_d apparently related to the fast-ion slowing down time $\langle \tau_s \rangle$ and the final sawtooth

inversion radius $r_{inv} \sim \tau_d / \langle \tau_s \rangle \sim 2 - 0.2$ with the lower values of τ_s corresponding to larger r_{inv} cases presumably where the stabilization parameters are closer to those for marginal stability. (The normalized values of internal kink growth rate $\hat{\gamma}_i$ and profile dependent beta of the nonthermal ions $\hat{\beta}_h$ are discussed later in Section III.) However, as also noted in Ref. 14, a definitive confirmation of the energetic ion role in stabilizing the kink instability is elusive due to the difficulty in measuring the energetic ion properties and incorporating them quantitatively into the theory.

Subsequent to the discovery of ICRF sawtooth stabilization on JET, sawtooth stabilization has been achieved at relatively modest powers on TFTR^{15,16}: $P_{RF} \sim 4$ MW, (2.6 MW) in He, (D) discharges for the minority hydrogen heating regime with $\bar{n}_e \sim 2.5 \times 10^{13} \text{ cm}^{-3}$, $T_e \sim 5$ keV, and $q \sim 4.6$. These results, which extend the stabilization investigation to circular geometry, will be described in Section II. It is interesting to note that during the progression of ICRF experiments on PLT up to an rf power level of ~ 4.3 MW¹⁷ for plasma core parameters similar to those on TFTR, a general enhancement of the sawtooth period with power was observed (as also found on JET^{4,18} at P_{RF} below the stabilization level) but the $m=1$, $n=1$ instability was not removed¹⁹ and sawtooth stabilization did not occur. It is thought that the greater focalization of the rf power deposition^{20,21} inside the $q=1$ boundary and the better energetic ion confinement²² account for the stabilization on TFTR. A comparison of the TFTR stabilization conditions with the energetic ion stabilization theory including these considerations is presented in Section III.

Although the theory-experiment comparison is still qualitative, the theory is useful as a guide for applying ICRF stabilization to other regimes of interest on TFTR and for extrapolation to CIT. In Section IVa, initial results for ICRF stabilization of a supershot plasma are presented and the rf requirements for stabilization of ultimate supershot parameters - $P_{NBI} \sim 25\text{-}30$ MW, $I_p \sim 2.5$ MA are explored. In Section IVb, sawtooth stabilization application to CIT is considered and relevant confirming experiments with pellet injection on TFTR are outlined. Finally, a summary of the fundamental considerations for ICRF sawtooth stabilization is given in Section V.

ICRF SAWTOOTH STABILIZATION IN THE HIGH-RECYCLING REGIME ON TFTR

The initial sawtooth stabilization experiments on TFTR have been conducted in the high recycling (gas fueled) regime where the energy confinement τ scales as ~ 1.2 - 1.4 times the L Mode value.¹⁶ In the cases to be considered here, hydrogen minority heating on or near the axis of both helium and deuterium discharges has been employed to begin exploration of the power threshold for sawtooth stabilization and of the stabilization characteristics: notably in ^4He for $R = 2.62$ m, $a = 0.96$ m, B_ϕ (2.75 m) = 3.13 T, $I_p = 1.4$ MA, $\bar{n}_e = 2.5 \times 10^{13} \text{ cm}^{-3}$; and D for the same R , a , and B_ϕ , and $I_p = 1.0, 1.4, 1.8$ MA, $\bar{n}_e = 2-4 \times 10^{13} \text{ cm}^{-3}$. For these conditions, the plasma-antenna configuration is as shown in Fig. 1 for the large TFTR plasma (the face of the antenna is ~ 4 cm away from the $a = 0.96$ m surface). The focalization of the wave fields resulting from the limited poloidal extent of the antenna²⁰ is indicated in Fig. 1. This focalization provides a power deposition spot size of $r \approx 25$ cm in the vicinity of the plasma axis which serves to facilitate rf power deposition inside the $q=1$ surface.

The power threshold for stabilization in the helium case is found to be ~ 4 MW¹⁵ as revealed by axial T_e measurements in Fig. 2. For the similar deuterium case at $I_p = 1.4$ MA, $\bar{n}_e = 2.5 \times 10^{14} \text{ cm}^{-3}$, the power threshold is observed to be ~ 2.5 MW as indicated by X-ray emission measurements in Fig. 3. The scans of current and density were conducted at $P_{RF} = 2.7$ - 3 MW and stabilization was achieved in all cases,¹⁶ indicating that the threshold conditions are not strongly dependent on these parameters. The difference in threshold power between helium and deuterium for the same minority regime is perhaps significant and will be explored in the context of theoretical considerations in the next section.

During the stabilized (sawtooth free) period, the temperature and density peak up significantly as in the case of JET.⁴ In Fig. 4, the temperature profiles before and after an ohmic sawtooth and the monster sawtooth that terminates the stabilized phase are shown. The sawtooth instability inversion radius has increased over the stabilized period of ~ 0.7 sec from ~ 28 cm to ~ 38 cm,

indicating a peaking of the current profile following the peaking of the temperature profile.

Ohmic and monster inversion radii for all the deuterium scans are indicated in Fig. 5. These reveal that the current peaking effect is similar at the three currents over the range of densities ($\bar{n}_e = 2-4 \times 10^{13} \text{ cm}^{-3}$) investigated for sawtooth free periods of $0.5 \text{ sec} < \Delta T_{\text{FREE}} \leq 0.9 \text{ sec} \rightarrow \Delta r_{\text{inv}} \sim 10 \text{ cm}$ in all cases -- consistent with similar peaked T_e profiles being produced by the rf stabilization at the several I_p values. This result lends support to the conclusion derived from JET data (Fig. 5 of Ref. 14) that ΔT_{FREE} is greatest for smaller initial r_{inv} values (for sufficiently long rf pulses). That is, it suggests that the final monster inversion radii are comparable at different currents and that the time required to reach the monster inversion radius is increased as the current, and consequently the initial inversion radius, is decreased. However, it should be noted that this model may prescribe an upper limit on ΔT_{FREE} corresponding to the case where the rf deposition focalization over the reduced volume bounded by the $q=1$ surface at lower current is no longer sufficient to provide sawtooth stabilization according to the energetic ion stabilization theory.^{10,11}

After the monster sawtooth crash, a variety of MHD modes have been observed $(m,n) = (2,1), (3,1), (3,2)$ etc. - and recovery of the sawtooth stabilized phase tends to occur if the mode amplitudes are low, as in JET.⁵ However, close scrutiny of the stability behavior before the monster crash is required in most cases to detect the $m=1, n=1$ precursor instability. The instability precursor to the normal sawtooth early in the rf pulse of Fig. 3 (~3.7 sec) as measured with ECE detection at multiple radii is shown in Fig. 6a. Note that the oscillatory precursor builds up in time about the $q=1$ radius, indicating a rotating plasma up to the time (3.676+ sec) at which the plasma core kinks to the left in the figure and flattens after the sawtooth. An equivalent measurement for the monster crash of Fig. 4 (~4.3 sec) is shown in Fig. 6b. No oscillations are found in this case prior to the final kink phase where the $m=1$ instability is shown to grow rapidly over a few hundredths of a millisecond. This growth is so rapid that the plasma rotates very little during it. Reconstruction of the magnetic surfaces through rotation of the ECE data²³ highlights the $m=1$ character of the instability. (Note that the crash results in a dramatically flattened core extending from $R \approx 2.4 \text{ m}$ to $R \approx 3.3 \text{ m}$ corresponding to $r_{\text{inv}} = 38.5 \text{ cm}$ in Fig. 4). Prior to

some monster crashes, an $m=1$ oscillation over a short period of time ($f_{osc} \sim 1$ kHz) is observed very close to the inversion radius, especially when the crash is precipitated with the injection of a diagnostic neutral beam pulse. In all monster cases, the growth rate of the instability is very large and indicates that the plasma moves very rapidly away from the marginally stable regime.

It is clear from the JET results¹⁴ that the peaking of the current channel probably contributes to the termination of the sawtooth free period by bringing the plasma conditions back to and possibly through the marginal stability boundary (Fig. 3 of Ref. 14). If this is the dominant process, it should in principle be possible to arrive at a continuously sawtooth stable regime of arbitrary duration by tailoring the power deposition profile (possibly dynamically) to hold the *final inversion radius* at a stable value while providing a sufficiently stabilizing energetic ion population within the $q=1$ surface. However, it is quite likely that the dynamics of the energetic ions during the sawtooth free period play a role as well in the termination.

Redistribution of the energetic ions by sawteeth has long been proposed as the mechanism which causes a broadened radial rf power deposition profile in sawtooth dominated discharges.²⁴ Such effects on the energetic ions in the present experiments on TFTR are suggested by probe measurements of energetic protons (0.5-4 MeV) as illustrated in Fig. 7. Figure 7 is a measurement taken $\sim 45^\circ$ below the outer horizontal midplane for the helium regime of Fig. 3 where sawtooth stabilization is obtained near the end of the rf pulse (~ 4.6 sec). The amplitude of the energetic protons reaching the surface probe is modulated by the sawtooth relaxations with the maximum levels occurring just prior to the sawteeth crashes. The level reached in the stabilized regime (~ 4.8 sec in Fig. 7) is comparable to that for the ordinary sawtooth periods. The interpretation of this data is difficult due to the strong plasma profile dependence of the energetic ion source rate for the probe location. Simple movement of the central core plasma could produce some of the modulation effect if diffusion in space is a dominant effect for providing energetic ions with the appropriate trapped orbits. An alternative interpretation could be that the energetic ion population builds up inside the $q=1$ surface during the sawtooth period and is expelled elsewhere at the crash. In either case, the probe data indicate that the behavior of the energetic distribution is not static during the sawtooth free period and should be considered as a

possible destabilizing mechanism. In addition, a rapid redistribution of the energetic ions during the monster crash could help to account for the near ideal growth rates observed leading into the strong kink of the plasma core.

COMPARISON OF THE TFTR STABILIZATION RESULTS WITH THE ENERGETIC ION SAWTOOTH STABILIZATION THEORY

The dispersion relation for the $m=1$ internal modes, considering resistivity, is given by (Eq. 1 of Ref. 10, or equivalently Eq. 3 of Ref. 11)

$$\delta W_c + \delta W_k - \frac{i[\omega(\omega - \omega_{*e})]^{1/2}}{\omega_A} \times \frac{8\Gamma[(\Lambda^{3/2} + 5)/4]}{\Gamma[(\Lambda^{3/2} - 1)/4]} = 0 \quad (1)$$

where the notation of White et al.¹⁰ is used: $\Lambda = -i[\omega(\omega - \omega_{*e})(\omega - \omega_{*i})]^{1/3} / \gamma_R$, $\gamma_R = S^{-1/3} \omega_A$ is the resistive growth rate, S is the magnetic Reynolds number, $\omega_A = V_A / \sqrt{3} R r q'$ is the shear Alfvén frequency with V_A the Alfvén velocity, R and r are major and minor radii, respectively, $q' = dq/dr$ at $q=1$, and $\hat{\omega}_{*e}$ and ω_{*i} are the diamagnetic frequencies. δW_c is the minimized ideal variational energy for the internal kink defining its growth rate in the ideal limit ($\gamma_R \rightarrow 0$, $\delta W_k \rightarrow 0$), $\gamma_I = -\omega_A \delta W_c$, and δW_k is the kinetic variational energy coming from the trapped particle distribution F as given by Eq. 2 of Ref. 10. For ICRF produced energetic ions with $F(E, \mu, r) = \delta(E/\mu - \alpha) e^{-E/T_h} n(r)$, where μ is the magnetic moment and α is a single bounce angle, the following dispersion relation is obtained in Ref. 10 for the ideal limit $|\Lambda| \gg 1$:

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

where Z is the plasma dispersion function, $\hat{\gamma}_I \equiv \frac{\gamma_I}{\omega_d}$, $\hat{\beta}_h \equiv \frac{\beta_h}{\epsilon} \frac{\omega_A}{\omega_d} = \epsilon \beta_{ph} \frac{\omega_A}{\omega_d}$,

$\varepsilon = \frac{r_s}{R}$ with $q(r_s) = 1$, $\Omega = \frac{\omega}{\omega_d}$, $\Omega_* = \frac{\omega_{*i}}{\omega_d}$, and ω_d is the precession frequency of a particle with energy T_h $\omega_d = \frac{cT_h}{eBr_s R Z_h}$. Equating the real and imaginary parts of Eq. (2) to zero for real Ω defines the stable region in the $\hat{\gamma}_1$, $\hat{\beta}_h$ plane as shown in Fig. 8a for three values of Ω_* of interest in current experiments.

It is found that a curve of linear increase in $\hat{\gamma}_1$ vs $\hat{\beta}_h$ defines the upper boundary of stability at $\hat{\beta}_h \leq 0.8$ when Ω_* is small and that $\Omega \rightarrow \Omega_*$ along this boundary as $\hat{\beta}_h \rightarrow 0$ (see also Fig. 3 of Ref. 25). The approximately vertical boundary in $\hat{\gamma}_1$ at $\hat{\beta}_h \sim 0.8$ results from the term $[\frac{1}{2} + \Omega + \Omega^{3/2} \text{Re } Z(\Omega^{-1/2})]$ equating to ≈ 0 at large $\Omega \sim 1.8$ over the range of $\hat{\gamma}_1$ shown.

An important prediction of the analysis of Ref. 10 is that the maximum value of $\hat{\gamma}_{1m}$ for stabilization decreases approximately linearly with $\Omega_* - \Omega$ as $\Omega_* \rightarrow 0$ as is illustrated in Fig. 8a (see also Fig. 7b of Ref. 26). Taking the relation²⁷

$$\hat{\gamma}_1 = \frac{\omega_A}{\omega_d} \varepsilon^2 3\pi (1 - q(0)) (\beta_p^2 - \beta_{pcrit}^2) \quad (3)$$

where β_p is the plasma poloidal β and β_{pcrit} is ~ 0.1 to 0.3 ($\sqrt{13}/12$ for a quadratic q profile), this prediction suggests that the stable region will shrink to zero as the value of ω_d is increased so that the maximum β_p for stability will decrease toward a limiting value determined by ω_{*i} . This prediction is not supported by the analysis of Coppi et al.,¹¹ for which it is found that the linear stability boundary at $\Omega = \Omega_*$ is only a weak function of Ω_* for $\Omega_* \ll 1$.²⁸ This different prediction results from a δW_k term independent of Ω being obtained in

the analysis of Ref. 11. Replacement of $\hat{\beta}_h \pi^{1/2} \Omega$ in Eq. (2) with $\hat{\beta}_h (\pi^{1/2} \Omega - 2\Lambda_k(0))$ with $\Lambda_k(0)$ being defined as in Ref. 11, gives the result of Ref. 28 for $\Omega \sim \Omega_*$ with $\Omega_* \ll 1$. The stability boundary in the $\hat{\gamma}_I, \hat{\beta}_h$ plane in this case is illustrated in Fig. 8b for $\Lambda_k(0) = -1/2$. Indeed, the influence of Ω_* is reduced considerably over the result of Fig. 8a. However, it should be noted that $\Lambda_k(0)$ is shown in Ref. 11 to be a function of r_s/a , $\langle r_p \rangle/a$, $\hat{p}_{||h}(0)/\hat{p}_{\perp h}(0)$, and $1 - q(0)$ so that the maximum value of $\hat{\gamma}_I$ will depend critically on the specific plasma profile conditions [a is plasma radius, $r_p = -(d \ln p_{\perp h}/dr)^{-1}$, and $\hat{p}_{||h}(0)/\hat{p}_{\perp h}(0)$ is the energetic ion pressure component ratio at $r = 0$]. The value $\Lambda_k(0) = -1/2$ is typical of a variety of conditions at $q_0 \sim 0.8$ and will be used later for comparing to the TFTR stabilization data.

It should be noted that over the range of parameters in the TFTR stabilization experiments the condition $|\Lambda| \gg 1$ is typically not satisfied so that the resistive growth rate must be considered. White et al.^{10,26} conclude that stabilization does not occur at relatively small $|\Lambda|$ and hence that a minimum $\hat{\gamma}_I$ must be exceeded to have stabilization. However, Coppi et al. conclude that full stabilization is obtained for

$$\hat{\gamma}_I \leq -\Lambda_k(0)\hat{\beta}_h - \left(\frac{\hat{\gamma}_R^3}{\Omega_*}\right)^{1/2} \quad (4)$$

where Eq. 4 of Ref. 11 has been recast into the notation used here and $\hat{\gamma}_R = \gamma_R/\omega_{ci}$. Equation 4 indicates that the threshold boundary for $\hat{\gamma}_I = 0$ moves away from $\hat{\beta}_h = 0$ as Ω_* decreases for a given $\hat{\gamma}_R$ value; e.g., $\hat{\beta}_h(\hat{\gamma}_I = 0) \approx 0.2$ for $\hat{\gamma}_R = \Omega_* = 0.1$ and $\Lambda_k(0) = -0.5$. If Eq. 4 is correct, it would indicate that the boundary at low $\hat{\beta}_h$ could depend strongly on plasma conditions. It would appear that Eq. 4 was used to define the general stability boundary for comparing to the JET data at low $\hat{\beta}_h$ in Ref. 14 but that the

possibly large variations in $[\hat{\gamma}_h/\Omega_*]^{1/2}$ and in $\Lambda_k(0)$ were not considered. The different results obtained for the low $\hat{\beta}_h$ stability boundary in Refs. 10 and 11 appear to be due to the manner in which the limit was taken for the Γ function ratio of Eq. (1) as $|\Lambda|$ was decreased. To next order in Λ , Eq. (2) becomes

$$\hat{\gamma}_1 + i[\Omega(\Omega - \Omega_*)]^{1/2} - \frac{5}{4} \frac{\hat{\gamma}_h^3}{[\Omega, \Omega - \Omega_*]^{1/2} (\Omega - \Omega_*)} = \hat{\beta}_h \pi^{1/2} \Omega \left[\frac{1}{2} + \Omega + \Omega^{3/2} Z(\Omega^{1/2}) \right]. \quad (5)$$

Thus $\hat{\gamma}_1$ is increased above the curves in Fig. 10b as $\hat{\beta}_h \rightarrow 0$ and does not intercept the $\hat{\beta}$ positive axis for $\Omega > \Omega_*$. It would appear that the inclusion of a different damping mechanism is required to stabilize the mode in the resistive limit or that additional terms for δW_k are required. The inclusion of transverse ion viscosity in a manner similar to that formulated for the case without energetic ions²⁹ should lead to an equation similar to Eq. 4 but with transverse viscosity replacing parallel resistivity as the dominant damping mechanism and with the sign changed for the added term.

Pending further development in the resistive theory limit, the comparison of the stabilization data will be made with the two formulations embodied in Fig. 8. The global approach for estimating the relevant hot ion parameters as employed for the JET data^{13,14} will be used since these parameters are not as yet measured directly experimentally: (i) β_h is equated to

$$\langle \beta_h \rangle = \epsilon^2 (8\pi/\beta_p^2) (r_s^2) (W_{\perp h}/V) \text{ where } W_{\perp h} \text{ is the fast ion perpendicular energy content and } V \text{ is the plasma volume; and (ii) } \omega_d \text{ is replaced by } \omega_{dM} =$$

$cT_h(0)/eBr_sR$ where $T_h(0)$ is evaluated with an RF SNAP code³⁰ by matching calculated and measured stored energy. This approach might be expected to

yield lower values of $\hat{\beta}_h$ and $\hat{\gamma}_1$ than would in general be obtained from the spatial integrals of the theory.

The $\hat{\gamma}_1$, $\hat{\beta}_h$ parameters obtained in this approximate manner for the discharges of Section II and Ref. 16 are plotted in Fig. 9 for comparison to the two formulations of the stabilization theory presented in Fig. 8. Points for $\beta_{pcrit} = 0.1, 0.2$, and 0.3 are shown for each discharge condition and the SNAP runs give: $\beta_p \sim 0.13-0.37$ (high I_p to low I_p); $T_e(0) \sim 3-5$ keV; $T_i(0) \sim 2-4$ keV. $T_h \sim 0.4-0.75$ MeV; $\omega_{D,M} \sim 0.8-1.6 \times 10^5 \text{ sec}^{-1}$; $s_0 \sim 0.6-1.3$; $\omega_A \sim 1-2 \times 10^7 \text{ sec}^{-1}$; $S \sim 0.3-1 \times 10^9$; $\omega_{*i} \sim 3.6-5.4 \times 10^3 \text{ sec}^{-1}$ ($\Omega_* \sim 0.022-0.09$). In addition to the large uncertainties inherent in this approximate evaluation, the s_0 values obtained from the SNAP code are probably higher than those which would be obtained with the time dependent TRANSP code including current penetration dynamics. Thus the $\hat{\beta}_h$ values of the points in Fig. 9 are expected to increase somewhat when the TRANSP analyses are completed.

The most important effects shown in Fig. 9 are the strong dependences of $\hat{\gamma}_1$ on β_{pcrit} and I_p . First it is clear that a quantitative evaluation of β_{pcrit} ($\hat{\gamma}_1$) will be required in each case before a selection between the theories of Fig. 8 can be made. Second, the data strongly indicates that $\hat{\gamma}_1$ does go negative at the highest current for reasonable q profiles ($\beta_{pcrit} \sim 0.2-0.3$). This suggests that the resistive kink instability is being stabilized by pushing $\hat{\beta}_h$ through the appropriate resistive marginal stability curve for $\hat{\gamma}_1 < 0$.

One final observation is that the point for ^4He in Fig. 9 falls in the vicinity of the stability boundaries but does not elucidate the cause for the P threshold being higher in ^4He than D . Again, the need for a quantitative comparison between theory and experiment is indicated.

ICRF SAWTOOTH STABILIZATION FOR THE SUPERSHOT REGIME ON TFTR AND FOR CIT

It is clear from the results of the comparisons between experimental and theoretical stability conditions in Section III, as well as for the cases presented for JET in Ref. 14, that the crudeness of the data and the theory does not permit a definite conclusion regarding the general applicability of the present sawtooth stabilization theory. However, it is encouraging that the data as derived from global parameters does agree with the theory to within large factors of

uncertainty, suggesting that further development of the theory coupled with more precise measurements should provide a reliable format for applying ICRF sawtooth stabilization to any operating regime. Pending this development, the present theory will be used as a qualitative guide for extending this stabilization to the supershot regime on TFTR and to CIT, while verification of the theoretical assumptions will be explored experimentally in the relevant supershot and pellet-fueled regimes on TFTR.

a) ICRF sawtooth stabilization in the supershot regime on TFTR

The neutral beam heated, low recycling supershot regime on TFTR offers the plasma conditions for achieving relatively high reactivity, high Q operation in the planned D-T phase of operation. However, at the higher plasma currents desired for the D-T phase (~2.5 MA), the energetic beam ions no longer provide sawtooth stabilization reliably even at the highest neutral beam powers available (~30-35 MW).³¹ Thus ICRF heating is being added to the supershot regime to provide for reliable stabilization. In addition, to the extent that the presence of m=1 instability adversely affects the reactivity of the core plasma, ICRF m=1 stabilization could prove beneficial even when sawtooth relaxations are absent with neutral beam heating alone.

The key question regarding ICRF stabilization of the high neutral beam power, high-current supershot regime is how much rf power will be required.

Theoretically, optimum stabilization should occur for $\hat{\beta}_h \sim 0.5$ (Fig. 8), corresponding to a given minority ion tail density. Assuming this minority density is maintained at all beam powers and that a relatively energetic minority ion tail temperature is also maintained at all beam powers, a sufficient requirement for the ICRF power stabilization would be

$$\xi \propto \frac{P_{RF}(T_e)^{1/2}}{n_a n} \sim \text{constant} \quad (6)$$

where the tail temperature is assumed to be $T_h \sim T_e \xi$ with ξ as defined by Stix,³² and where the minority density n is chosen to give $n_h(P_{RF}) \sim \text{constant}$. Since central n_e increases approximately linearly with beam power and $(T_e)^{1/2}$ increases much less than linearly, Eq. (6) suggests that the rf power required for stabilization should increase substantially with beam power,

especially since n may need to be increased to maintain $\eta_{MIN} = n/n_e$ at a level favoring minority heating over second harmonic heating ($P_{\omega_c}/P_{2\omega_c} \sim \eta_{MIN}/\beta_{D,T}$).³³

Initial ICRF sawtooth stabilization experiments in the supershot regime have been conducted with $P_B \sim 7-9$ MW and $P_{RF} \sim 2.5-3.5$ MW. As shown in Fig. 10 where $P_{RF} \sim 2.5$ MW is applied to a $P_B \sim 9$ MW supershot which is sawtooth stable with the beam heating alone, the addition of the rf power peaks up the core temperature and removes the drop-off in time of the stored energy and neutron flux observed with the beam heating alone. Although the reason for the removal of the drop-off effect has yet to be resolved, it is possible that it is due to rf stabilization of the $m=1$ residual instability which has been observed near the sawtooth threshold in beam power.

With P_B reduced to 7 MW the sawtooth relaxations appear and $P_{RF} \sim 3.5$ MW is required to give sawtooth stabilization as shown in Fig. 11. This result suggests that up to ~ 4 times this rf power level could prove necessary for stabilization in the $P_B \sim 30$ MW, $I_p \sim 2.5$ MA range in keeping with the assumptions leading to Eq. 6 and the prediction that stabilization might be more difficult to achieve at higher current.¹⁴ Further investigation at higher P_B , P_{RF} , and I_p is planned to clarify the threshold requirements for optimizing ICRF sawtooth stabilization in the D-T supershot regime.

b) CIT considerations

CIT operation is planned at high central density [$n_{e(0)} \sim 4 \times 10^{14} \text{ cm}^{-3}$] and relatively high temperature [$T_{e(0)} \sim 20 \text{ keV}$].³⁴ Under these conditions, sustained with ICRF heating without the production of a substantial minority ion tail, modelling predictions show the onset of very large sawtooth relaxations.³⁵ In order to obtain the beneficial effects of sawtooth stabilization, it will be necessary to reduce the minority concentration and apply sufficient power to obtain tail densities and temperatures similar to those obtained on TFTR. Again using the relation of Eq. (6) and the power threshold observed for the deuterium discharges of Section II, extrapolation to CIT gives the threshold power of

$$P_{RF_{cr}} \sim P_{RF_{TFTR}} \times \frac{n_{a(0)_{cr}}}{n_{a(0)_{TFTR}}} \left(\frac{T_{e(0)_{TFTR}}}{T_{e(0)_{cr}}} \right)^{1/2} \sim 3 \text{ MW} \times \frac{40}{4} \times \left(\frac{5}{20} \right)^{1/2} \sim 15 \text{ MW}$$

assuming n does not have to be increased in CIT to reduce second harmonic damping. Since CIT is expected to have $\beta_{TD}(0)$ values of several percent, n will have to be increased so that $P_{RF\text{CIT}}$ will have to be increased for the parameters cited. Thus if ICRF sawtooth stabilization is to be a viable option for the planned ICRF capability on CIT, a lower stabilization power threshold must be demonstrated on TFTR at high density and possibly start-up scenarios at lower density and higher temperature must be considered for CIT.

Investigation of ICRF sawtooth stabilization of pellet-fueled discharges has been started to permit evaluation of higher density stabilization characteristics on TFTR. With the addition of modest neutral beam heating (~ 8 MW) it has been possible to produce plasmas at $n_e(\psi) \sim 4 \times 10^{14} \text{ cm}^{-3}$ and $B_0 \sim 5$ T (which is about a factor of two below the value projected for CIT³⁶). It should be possible to obtain similar parameters during ICRF stabilization studies at elevated rf powers so that extrapolation to CIT can be facilitated.

CONCLUSIONS

ICRF sawtooth stabilization characteristics in JET and TFTR are quite similar and form the experimental basis for extrapolating to other regimes of operation such as the supershot regime on TFTR and the ICRF heated D-T regime on CIT. It is clear from the ease of obtaining stabilization with central power deposition that the localization afforded by the finite poloidal extent of the antennas and the relatively large radius of the $q=1$ layer has benefited both devices in achieving this stabilization.

The virtual absence of MHD precursors to the kink event that terminates the sawtooth free period brings into question the mechanism of termination. The very large growth rate suggested for the $m=1$ instability leading to the monster crash would appear to be much larger than would be expected as marginal instability is approached as the plasma current channel expands. A fast redistribution of the energetic ion population in response to the instability could help account for the short time of the crash phase. However, even though it would appear that the energetic ion distribution is affected strongly during the crash, the cause-effect relationship is far from resolved with present measurements. Another possibility is that even at a very low $m=1$ level, the

magnetic shear in the $q=1$ layer is brought rapidly toward zero, causing the resistive growth rate γ_R to increase very suddenly.

The theory for ICRF stabilization has experienced a very rapid evolution over the past two years and contradictory results have been obtained. In particular, the results of White et al.^{10,26} and Coppi et al.^{11,28} do not agree in two important respects: $\delta W_k \rightarrow 0$ or constant as $\Omega(\Omega_*) \rightarrow 0$ and a lower $\hat{\gamma}_1$ limit exists or does not exist as $\hat{\beta}_h$ approaches small values, for the two treatments, respectively. The resolution of these discrepancies is necessary to arrive at a valid stability boundary for comparison to experiment and for determining the sawtooth stabilization requirements for reactor relevant regimes. Obviously, the constant in δW_k is desirable since it permits stabilization to higher ultimate β_p values as the temperature of the energetic ions is increased. This consideration is especially important for α particle sawtooth stabilization.²⁵

Comparison of the conditions for stabilization on TFTR, deduced roughly from global plasma/energetic ion characteristics and modelling, to the two theories does not permit a resolution between them in the large Λ limit considering the large uncertainties contained in the data. A selection between the theories in this limit on an experimental basis would require reasonably accurate profile measurements of the plasma and energetic ion phase space distributions to permit the integrals of the theory to be carried out for each threshold condition. However, it is found that stabilization is produced at Λ values well below the limit proposed by White et al.; i.e., $\Omega - \Omega_*$ values for the theory in Fig. 8 are sufficiently small to make $\Lambda \sim 0(1)$. Hence the lower limit to $\hat{\gamma}_1$ of Ref. 10 does not appear to apply.

Initial results for sawtooth stabilization in the supersonic regime on TFTR are encouraging and support application of this technique at the high beam power, high plasma current conditions planned for D-T operation in order to optimize the reactivity of the plasma core. The rf power level being prepared for this regime (~ 12.5 MW) is thought to be adequate to maintain an energetic ion population roughly equivalent to that produced in the present stabilization experiments.

Finally, a similar argument with regard to producing an energetic ion density and temperature on CIT as provided for stabilization on TFTR, leads to a

relatively large power requirement equaling or exceeding the planned capability of $P_{RF} \sim 20$ MW. Relatively high density experiments on TFTR are planned to further define the requirements for applicability of this technique to CIT.

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FIGURE CAPTIONS

- Fig. 1 TFTR antenna-plasma geometry
- Fig. 2 Stabilized sawteeth in He majority plasma ($I_p = 1.4$ MA, $\bar{n}_e = 2.5 \times 10^{13} \text{ cm}^{-3}$, H minority)
- Fig. 3 Sawtooth stabilization in a D majority plasma ($I_p = 1.4$ MA, $\bar{n}_e = 2.5 \times 10^{13} \text{ cm}^{-3}$, H minority)
- Fig. 4 Temperature profiles before and after ordinary and monster sawteeth (D, $I_p = 1.8$ MA, $\bar{n}_e = 2.5 \times 10^{13} \text{ cm}^{-3}$, $P_{RF} = 2.7$ MW for $t = 3.6\text{-}4.5$ sec).
- Fig. 5 Initial (0) and final (1) inversion radii versus I_p (D, $\bar{n}_e = 2.5 \times 10^{13} \text{ cm}^{-3}$).
- Fig. 6 Electron cyclotron emission temperature contours versus time for (a) the sawtooth crash of Fig. 3b at $t \sim 3.68$ sec ($R_{inv} \sim 241, 289$ cm) and (b) the monster sawtooth crash of Fig. 4 at $t \sim 4.29$ sec ($R_{inv} \sim 232, 309$ cm).
- Fig. 7 Loss of ICRF H⁺ minority tail for the He regime of Fig. 2 for a proton probe at $\sim 45^\circ$ below the midplane. (Transition to the stabilized regime occurs near the end of the $P_{RF} \sim 3.6$ MW pulse.)
- Fig. 8 Sawtooth stabilization boundaries in the $\hat{\gamma}_1, \hat{\beta}_h$ plane for (a) the theory of White et al.¹⁰ and (b) with a term independent of Ω added to δW_k of this theory to approximate the theory of Coppi et al.¹¹

Fig. 9 Comparison of the experimental $\hat{\gamma}_i, \hat{\beta}_n$ parameters for the stabilized discharges (derived as explained in the text) to the stabilization theory of Fig. 8 [D cases: $n_e(0) \approx 4 \times 10^{13} \text{ cm}^{-3}$ for $I_p = 1, 1.4 \text{ MA}$; $n_e(0) = 4.5, 4.0, 3.1 \times 10^{13} \text{ cm}^{-3}$ left to right for $I_p \approx 1.8 \text{ MA}$. He case: $n_e(0) \approx 4 \times 10^{14} \text{ cm}^{-3}$.]

Fig. 10 ICRF heating of a sawtooth stable supershot produced with 9 MW of balanced NBI. [$R = 2.62 \text{ m}$, $I_p = 1 \text{ MA}$, $\bar{n}_e \approx 2.5 \times 10^{13} \text{ cm}^{-3}$, D(H) regime.]

Fig. 11 ICRF sawtooth stabilization of a sawtooth unstable supershot produced with 7 MW of NBI (4.7 MW counter and 2.3 MW co). (Other parameters are those of Fig. 10.)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10