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OCCURRENCE OF SAWTEETH IN ITER AND THEIR EFFECTS ON ALPHA PARTICLES AND STABILITY

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I - Introduction Sawteeth alter the plasma, current, and fast ion profiles in present tokamak experiments. The central electron temperature, density, and neutron emission profiles are observed to flatten within the radius where the safety factor, $q_\psi = 1$; so sawteeth reduce the central reactivity and fusion power. The plasma current also mixes to some degree since the safety factor in the center, $q_\psi(0)$, is observed to increase after sawtooth crashes [1]. Sawteeth may have beneficial effects as well. In TFTR, discharges with sawteeth do not have major high-β disruptions, suggesting that sawteeth and/or fishbones may inhibit these disruptions.

It is not known whether sawteeth will occur in ITER. If they do, they could have both beneficial and detrimental effects. Since ITER must achieve sustained ignition, it is important to know to what extent and how the alpha particles will mix during sawteeth crashes, since this mixing will affect the alpha heating, and thus the reheat rate. The alpha particle mixing might shift alphas to regions where the losses are large, possibly damaging wall components. Also, the MHD and TAE stability will depend sensitively on the total pressure, p_{tot}, and q_ψ profiles, which are altered by sawtooth mixing.

This paper studies the occurrence and effects of sawteeth in ITER. Many of the plasma parameters in present tokamak experiments are very different from those anticipated in ITER, so large extrapolations are needed to predict ITER conditions and performance. This paper uses codes and semi-empirical models to study ITER plasmas. Since sawtooth mixing of alphas has been observed in TFTR, we use these measurements to calibrate the sawtooth mixing models. We apply them to sets of profiles for two representative ITER plasmas from the Interim Design database [2] producing 1.5 GW of fusion power, one with a flat electron density, and one with a more peaked density. Profiles are shown in Figures a-c.

The TRANSP plasma analysis code [3] is used to derive profiles for q_ψ and p_{tot} and the effects of current and alpha particle mixing after sawtooth crashes. The stability of sawteeth in these plasmas is assessed using a semi-empirical model of ω^* stabilization. The MHD and TAE stability before and after the sawteeth crashes is calculated using the PEST and NOVA-K codes. The ripple losses of alpha particles is computed by TRANSP and FPPT. These codes and models for predicting the sawteeth stability and sawteeth effects in TFTR are in approximate agreement with measurements.

II - Steady state conditions in ITER The TRANSP plasma analysis code has been used to analyze these ITER plasmas [4]. The vertically asymmetric flux surfaces are computed from the equilibrium modeling. The code also models the alpha source, orbits, slowing down, and heating profiles. The central alpha pressure is approximately 10% of the thermal pressure. Total pressure profiles are shown in Fig. c.

One of the present unknowns of the ITER design is how the non-inductive plasma currents will be driven. The bootstrap currents for the flat and peaked profile cases are 3.0 and 5.5 MA respectively, out of a total current of 21 MA. Several methods have been proposed to drive the extra current, including using energetic neutral beam injection and fast wave current drive. The profile of the driven current will greatly effect the total current and q_ψ profiles. We assume that the driven current profile will have the same shape as if the ohmic current were used. This current profile depends on the Z_{eff} profile (taken from the ITER database) and the assumed neo classical resistivity. The computed q_ψ profiles (shown in Fig. c) have $q_\psi = 1$ near $x \equiv$ \R(,normalized toroidal flux)) $\approx 0.40 - 0.50$.

Another unknown is the amount of current mixing during sawteeth crashes in ITER. This is discussed in Section IV. The conclusions of this paper are that the sawtooth effects on sustained ignition appear to be benign for standard ITER plasmas if the $q_\psi = 1$ surface is not greater than $x \approx 0.5$.

III - Sawtooth stability A semi-empirical model of ω^* stabilization [5] is consistent with the sawtooth stability observed in TFTR plasmas with auxiliary heating. The stability criterion is expressed as a critical shear at the $q_\psi = 1$ surface. The prediction of this criterion for ITER is that the peaked profile plasma is stable, and the flat profile plasma is unstable to sawteeth.

Trapped fast ions might stabilize sawteeth [6]. In beam-heated supershots in TFTR there does not appear to be enough deeply trapped energetic beam ions to stabilize sawteeth [7]. One important parameter for the trapping is the average energy of the trapped ions. The beam ions in TFTR have $\langle E_{bm} \rangle \approx 40$ keV. The alpha particles in the ITER cases are computed to have $\langle E_\alpha \rangle \approx 1.5$ MeV in the center.

Other models have been used to analyze the stability of ITER plasmas to sawteeth. A model invoking a threshold criterion and alpha stabilization has been used to predict ITER sawtooth periods of 120 sec [8].

IV - Current and alpha particle mixing in ITER TRANSP models sawteeth assuming Kadomstev mixing of flux surfaces [3]. Partial current mixing is modeled by computing a weighted average of the fully mixed and unmixed plasma currents after the crash. The q_ψ profiles in TFTR L-mode and supershot plasmas are generally simulated accurately with this model by assuming that about 20% of the current is mixed [1]. A comparison of pre-crash q_ψ profiles assuming 20% and 100% mixing is shown in Fig. c. The sawtooth period is assumed here to be 50 sec. Longer periods allow $q_\psi(0)$ to decrease further between crashes.

TRANSP models the fast ion sawtooth mixing by shifting the guiding centers with the flux surfaces, randomizing the poloidal distribution, and conserving v_{par} and μ [3]. The TRANSP model has been generalized using a Fokker-Planck Post TRANSP processor (FPPT) [9], which solves the bounce averaged drift kinetic equation using the plasma parameters from TRANSP. The FPPT mixing model is based on the ExB drift of fast ions at the crash. This mechanism has negligible effects on passing particles, and on the total fast ion density profile, but alters the distribution of the trapped particles.

Comparisons of simulations and alpha profile measurements in TFTR are shown in Figs. d-e. The pellet charge exchange (PCX) data [10], shown in Fig. d, are normalized to calculations in a similar sawtooth free discharge. Only deeply trapped alphas contribute to the measurement, and the FPPT modification of the TRANSP mixing is in approximate agreement with the measurements.

The TRANSP alpha mixing model alone achieves good agreement with the alpha energy measured by alpha charge exchange recombination spectroscopy (alpha CHERS). Comparisons with measurements [11] before and after a sawtooth crash are shown in Fig. e. This measurement averages a wide range of alphas with positive pitch angles, and thus includes mainly passing alpha particles.

TRANSP predictions for the alpha mixing in ITER are shown in Fig. f. The central alpha density and heating power are reduced to about 1/2 for 1-2 sec. The shifted profile depends strongly on the location of $q_\psi = 1$. We have not modeled the mixing of the thermal plasma.

V - Consequences of alphas mixing in ITER The driven current profile and sawteeth can have considerable effects on the MHD stability by changing the p_{tot} and q_ψ profiles. If the $q_\psi = 1$ surface is pushed to large radii then the poloidal mode m = 1 can couple to the high m modes in the edge, causing instability. PEST code [12] results indicate the two ITER plasmas are ideal MHD stable to low-n modes. Their β_{norm} values of around 2.5 can be increased by about 15% before reaching the critical β_{norm} for high-n ideal MHD stability.

The TAE stability of these ITER plasmas has been analyzed using the kinetic-MHD code NOVA-K [13]. It is found that TAE global modes, at least up to n=10 are stable due to large ion Landau damping for both the flat and peaked profile cases. For the peaked profile case, core-localized TAE modes can exist and are unstable at relatively higher temperatures and lower plasma densities. The stability of these localized modes is reduced as the shear of q_ψ is reduced. As discussed above, the shear is affected by the amount of current mixing. The TAE stability after crashes needs to be investigated further.

Sawteeth in TFTR have been observed to increase the ripple losses of energetic alpha particles. The ripple losses are calculated by TRANSP [14] and FPPT. Calculations of these losses by both codes show good agreement in TFTR plasmas. For instance, for the supershot shown in Fig. d, the number of alpha particles that are ripple lost as a result of the sawtooth crash is calculated by TRANSP to be 1.5×10^{15} and by FPPT to be 1.4×10^{15}. FPPT does not have Coulomb pitch angle scattering, which is the reason of additional losses in TRANSP.

TRANSP calculates the ripple losses for the ITER plasmas considered here to be less than 1% of the alpha power during steady state. The alpha mixing shown in Fig. f increases the loss rate by less than 1% [14].

VI - Conclusions The q_ψ profile has important consequences for alpha mixing, MHD stability, and TAE activity in ITER. With the assumed current and sawtooth mixing assumptions in this paper, the $q_\psi = 1$ radius is at $x \approx (0.4\text{-}0.5)$. We conclude that sawteeth in the ITER plasmas studied are not likely to adversely affect the MHD stability, or the TAE activity, or to significantly increase the ripple losses. Specification of the method of current drive in ITER will be important for substantiating these consequences.

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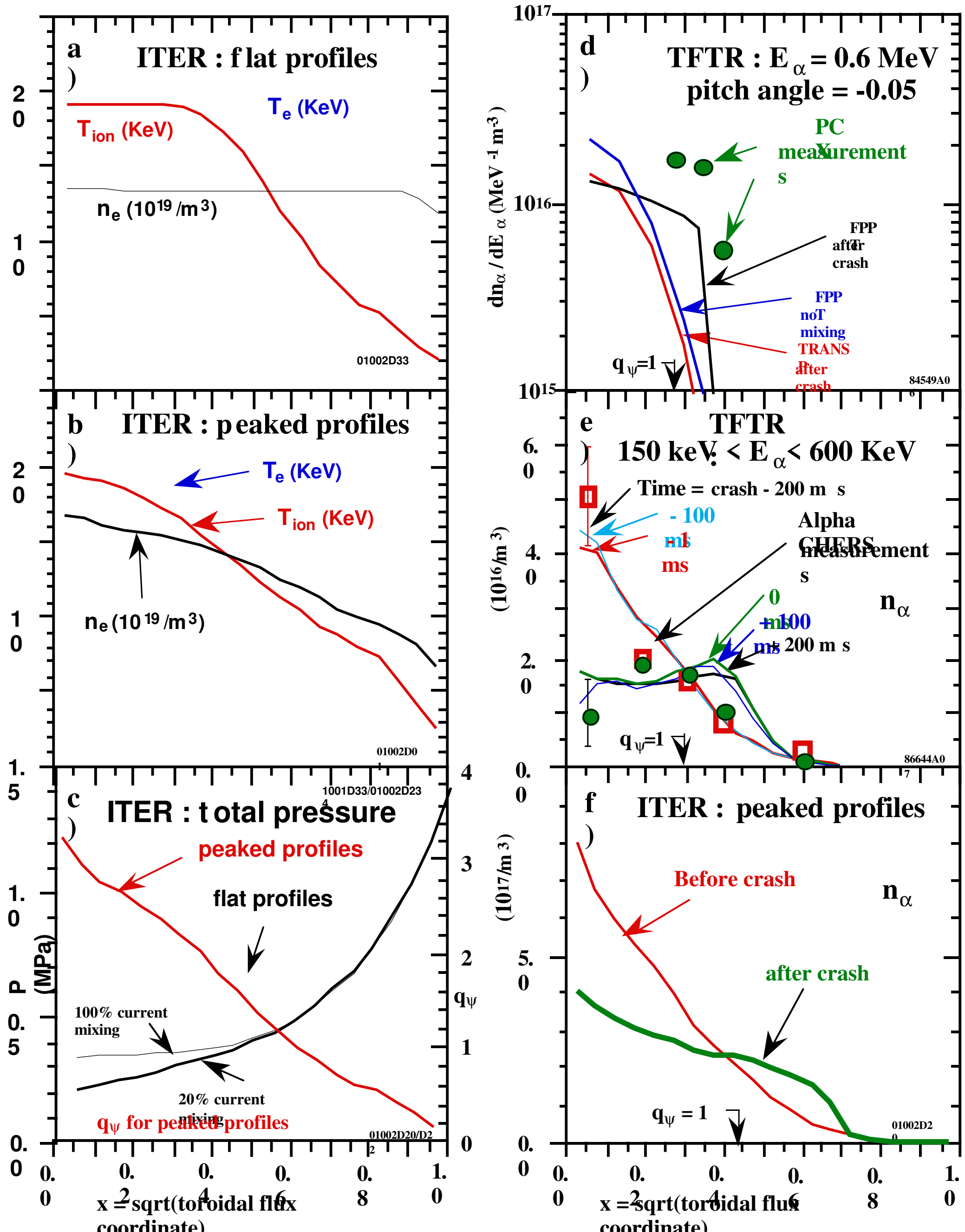

Profiles of the temperatures and electron density for an ITER discharge with a) flat, and b) peaked profiles; c) total pressure for both cases, and q_ψ for the peaked case before a sawtooth crash, computed with two choices of current mixing; d) comparison of TRANSP and FPPT simulations and measurements of the alpha particle energy in a TFTR supershot deduced from alpha charge exchange with a Li pellet cloud; e) comparison of TRANSP simulations and measurements of the alpha energy in a TFTR supershot deduced from spectroscopy of emission from He^0 resulting from charge exchange with beam ions before and after a sawtooth crash; f) predicted alpha density in the peaked ITER discharge before, and 1 sec after a sawtooth crash.