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SAWTEETH DYNAMICS IN JT-60SA BASELINE SCENARIOS WITH EFFECTS ON NTM ONSET

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Abstract

Sawteeth stabilization is investigated for JT-60SA Baseline plasma scenarios extrapolated from experimental data of JET and JT-60U, which are similar in size and operational regimes. These plasmas scenarios in Deuterium and Hydrogen are provided by METIS transport code for 4.6 MA and B=2.2 T taking into account 10 MW of perpendicular negative Neutral Beam Ions (N-NBI), 3 MW of perpendicular P-NBI, 3 MW of tangential NBI and 1.5 MW central Electron Cyclotron. First scope is to carry out predictive evaluations of conditions under which the sawtooth crashes can be occurred for these scenarios. Different criteria for the triggering of a sawtooth crash described by Porcelli with some modifications by Sauter are considered. The dependence of this stability mode on toroidicity, plasma shaping, trapped ions, fast particles (NBI here) or on resistive internal kink where the resonant layer dominates are used looking at a potential energy functional dW driving the stability conditions for the kink mode. The second purpose of this study is the investigation of the possible synchronism in time among ST crash, NTM onset and the presence of impurities due to high Zeff (~ 1.8 in the considered scenarios) for the mechanism of the seed island formation as found in JET discharges at high Ip . In these scenarios there are two impurities spatially distributed and peaked on the plasma axis: Carbon with Z=6 and Oxygen with Z=8 taking into account that JT-60SA will start its operations in C-wall.

1. INTRODUCTION

JT-60SA Baseline plasmas scenarios characterized by low central magnetic shear and on-axis safety factor $q_0 <1$, extrapolated by experimental data of JET and JT-60U, which are similar in size and operational regimes [1-4], are predicted with METIS code [5] for 4.6 MA considering hydrogen and deuterium main ions compositions with carbon and some oxygen impurities. These simulations take into account 10 MW of negative Neutral Beam Ions (N-NBI), 3 MW of perpendicular P-NBI, 3 MW of tangential NBI and 1.5 MW central Electron Cyclotron (EC) heating sources with various density profiles with β_N around 1.3 in H and 1.7 in D plasmas. Simulations with these main ions can predict different loss of confinement due to unstable perturbations, as the neoclassical tearing modes (NTMs), triggered at the crashes of long sawtooth (ST) periods. As it is well known [6] that the appearance of these modes should be more favoured in D plasmas than in H because the ST periods t_{ST} tend to increase with isotope mass (τ_{ST} (H) < τ_{ST} (D)), predictive evaluations of conditions under which the sawtooth crashes occur are shown for these scenarios [7 -8]. Different criteria for the triggering of a sawtooth crash described by Porcelli [9] with some modifications by Sauter [10] give the dependence of this stability mode on toroidicity, plasma shaping, trapped ions, fast particles (NBI here) or on resistive internal kink where the resonant layer dominates. A potential energy functional δW drives stability conditions for the kink mode. The objectives of this work is first to predict the Sawteeth stability looking at the their crash conditions This issue is investigated using central auxiliary powers with the dependence of the ST dynamics on the fast particles or on resistive internal kink where the resonant layer dominates. The evolution towards a relaxed plasma density and safety factor profile q are calculated after a ST crash based on the following theoretical arguments. The second purpose of this study is the investigation of the possible synchronism in time among ST crash, NTM onset and the presence of impurities leading to high Zeff (~ 1.8 in the considered scenarios) for the mechanism of the seed island formation as found in JET discharges at high Ip [12]. In these scenarios there are two impurities spatially distributed and peaked on the plasma axis: Carbon with Z=6 and Oxygen with Z=8 taking into account that JT-60SA will start its operations in C-wall. These analyses are carried out using a new version of the European Transport Simulator (ETS6) [13], a modular package solving transport equations for the modeling of plasma discharges embedding various physics modules as a generalized Rutherford equation describing the NTM evolution [14] and soon a self-consistent ST model. The input data are given in IDS format .

2. PREDICTIVE EVALUATIONS OF THE SAWTEETH STABILITY

The objectives of this work is first to predict the Sawteeth stability looking at their crash conditions This issue is investigated using central auxiliary powers with the dependence of the ST dynamics on the fast particles or on resistive internal kink where the resonant layer dominates. The predictive evaluations of conditions under which the sawtooth crashes occur are shown for these scenarios. The criteria for the triggering of a sawtooth crash give the stability mode depending on toroidicity, plasma shaping, trapped ions, fast particles (NBI here) or on resistive internal kink where the resonant layer dominates. A potential energy functional δW drives the stability conditions for the kink mode.

The criterion for the stability of m = 1 internal kink modes, which are responsible for the sawtooth crash, is based on a potential energy functional δW. This potential energy functional is calculated considering Ideal-MHD contributions and the kinetic modifications related to the fast particles and to the thermal trapped ions (Kruskal-Oberman) [15] .

The m=1, n=1 becomes unstable when one of the 3 triggering conditions listed below is satisfied:

1) the internal kink growth rate $\gamma = -\delta W_{core}/\tau_A = -(\delta W_{MHD} + \delta W_{KO})/\tau_A > c_h\, \omega_{Dh}$ meaning that high energy ions (subscript *h*) have an insufficient stabilizing influence where the ω_{Dh} is the fast particles precession frequency (c_h=0.4 assumed in this work).

2) the internal kink growth rate $\gamma = -\delta W/\tau_A = -(\delta W_{MHD} + \delta W_{KO} + \delta W_{Fast})/\tau_A > 0.5\, \omega_{*i}$ meaning that the internal kink growth rate is sufficiently large to overcome stabilization due to the thermal ion diamagnetic effects with significant contribution of the fast particles , ω_{*i} being the ion diamagnetic frequency

3) The linear growth rate is determined by microscopic effects in a narrow layer (as the Larmor radius) and the mode becomes a resistive internal kink $-c_\rho\, \rho < -\delta W < 0.5\, \omega_{*i}\, \tau_A$ and $\gamma_{eff} > c_\rho\, (\omega_{*e}\, \omega_{*i})^{1/2}$ where $\gamma_{eff} > \max(\gamma_\rho, \gamma_\eta)$ depending on the dominant layer width (c_ρ=1.0 assumed in this work).

We note that the KO term for δW_{core} is positive and relatively large when the q profile is nearly flat with a value $q \approx 1$ in the central core plasma region. In other words, the KO term is stabilizing for flat $q \approx 1$. Consequently, the value of q on axis, q_0, must drop below unity and the magnetic shear at the q=1 radius, s_1, must develop before a sawtooth crash is triggered. Thus, the relevant trigger condition becomes either condition (1) or (2) (depending on the fast ion energy). Since s_1 also affects the values of the various term contributing to δW, the implication is that the onset of the sawtooth crash can be related to the achievement of a critical value of s_1, although this value can be larger than the one implied by condition (3) (see also Eq. (15a) of Ref. [9]).

The reconnection layer width is in general determined either by the resistive layer width δ_η or by the ion Larmor radius ρ_i. The internal kink can be destabilized in the different instability regimes:

- If $\delta_\eta > \rho_i$ mode becomes unstable in the resistive regime
- If $\rho_i > \delta_\eta$ mode reconnection in ion kinetic regime determined by ρ_i

We apply these criteria for the D and H plasmas of the 6 scenarios of METIS in order to investigate the kink stabiity under the external heating applied. A long flattop phase from 15.5s to 116s is taken (FIG.1).The q profile is constant in all the scenarios with q=1 up to rhotor_norm=0.4, the normalized squareroot of the toroidal flux radial coordinate. Our analysis has considered also other reliable q <1 within the q=1 zone for the modelling of the kink mode stability. In FIG.2 the consiered q profiles are shown.

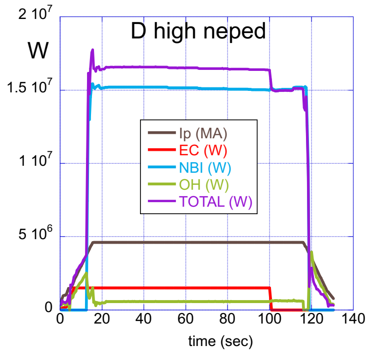

FIG. 1. 1 Traces of plasma current and heating sources

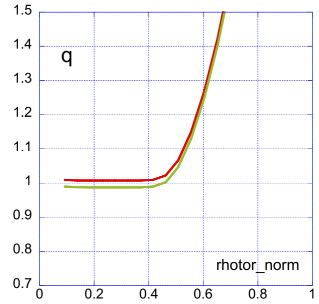

FIG.2 Reference q profile (red) and assigned with q0 <1

Three different density profiles in D and H are considered with high densiy pedestal, with quasi flat profile and high pedestal and with peaked density (FIG.3)

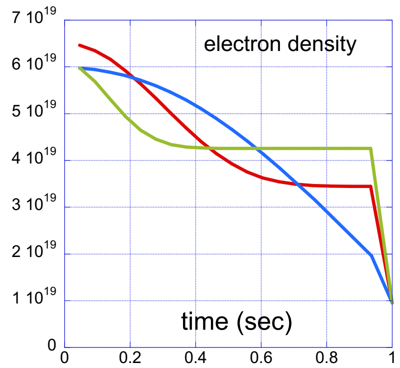

FIG. 3 Electron density profiles with different peaking

The functional δW have been caculated for 3 values of the magnetic shear at the rsonant position of the NTM (4/3). In FIG.4 we compare them in order to find which critrion has been verified for a magnetic shear of 0.2 . It can be see that the first condition is verified meaning that the NBI role is negligible.

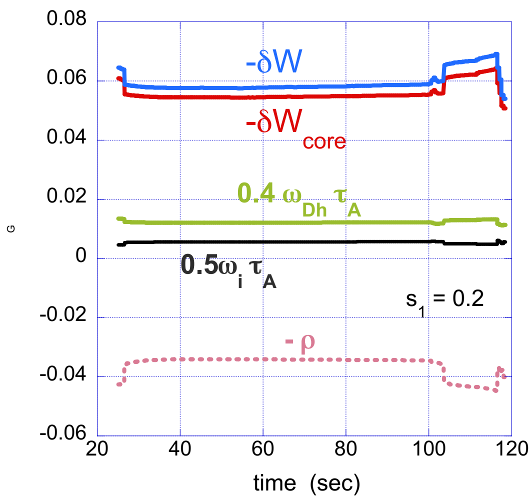

FIG. 4 The triggering is verified for both the first and second conditions.

In FIG.5 same traces as in FIG.4 are shown for s_1 = 0.3 and 0.4. Similar values in ref. 16.

It should be noted that as the magnetic shear increases the term δW_{core} and δW decrease .

dW_{MHD} includes effects of toroidal and plasma shaping, dW_{KO} includes kinetic effects from trapped thermal particles, dW_{Fast} includes kinetic effect from the fast particles.

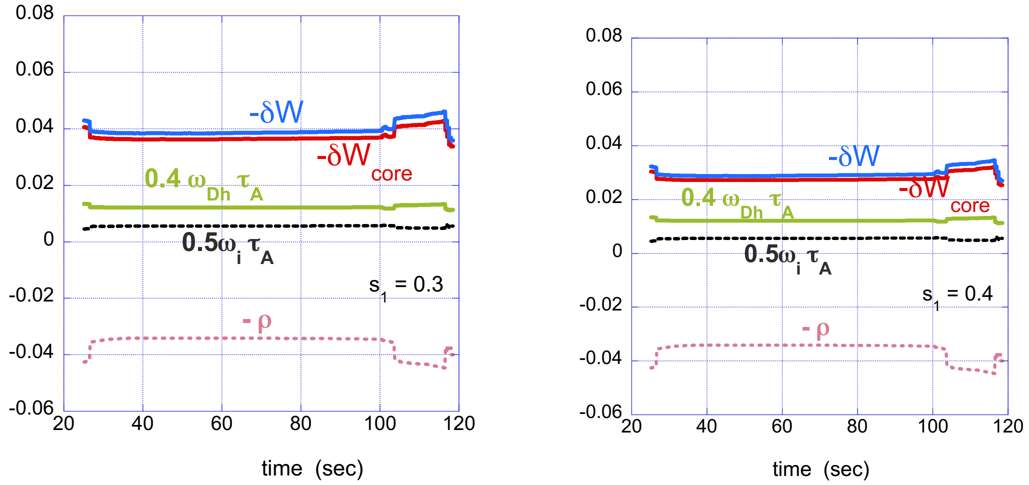

FIG. 5 For s_1 = 0.3 and s1 = 0.4 both the first and second conditions are satisfied,

In these scenarios in order to have non negligible effects of stabilization for the fast particles the precessional drift frequency ω_{Dh} is required to be larger than the ion diamagnetic frequency as in these examples.

3. PREDICTIVE SEED ISLAND BY IMPURITIES FOR NTM ONSET

Triggering of Neoclassical Tearing Mode (NTM) by a seed island formation due the perturbation of the current density J consequent to the influx of impurities is investigated. Considering the definition of the current density the quasi neutrality condition and impurity perturbation reads as:

$$J = e\, n_i\, v_i - e\, n_e\, ve \quad \text{and} \quad n_e = n_i + Z_j\, \delta n_j$$

where n_e and n_i are the electron and main ion densities respectively and nj the impurity density with charge number Zj (=6 for Carbon in these simulations) . The density impurity perturbation δnj affects the plasma current density of the relevant current parallel to the magnetic field. The readjustment of the current density under the quasi neutrality condition occurs on a time scale of the inverse of the plasma frequency which is much shorter than the dissipative time scales. So assuming that the current is essentially carried by electrons, the quasi neutrality constraint, imposed by the presence (influx) of impurities, leads to:

$$J// = J = -\, n_e\, v_e = -e\, (n_i + Zj\, \delta nj)\, v_e \quad \text{with} \quad \delta J = -e\, Z_j\, \delta n_j\, v_e = J\, Z_j\, \delta n_j \,/\, ne$$

If the trigger is sufficiently small, we can consider the tearing mode equation under the constant Ψ approximation where Ψ is the normalized helical flux: $\Psi_1 = \Psi s \,/\, a\, B_0$ and island width $w = 4\, (\Psi s\, L_s \,/\, B_0)^{1/2}$ with L_s=q L_q R/ r_s is the magnetic shear length.

From this we can estimate: $\mu_0\, \delta J \sim -\Delta'\, \Psi s \,/\, \lambda_\eta$ with λ_η is the resistive tearing layer width.

The relation between the current perturbation and the tearing stability parameter Δ' shows that current perturbation at the resonant mode location produces effects on the safety factor q and on the helical current parallel to the magnetic field within the mode leading to a modification of Δ' .

Combining this equation with δJ expression we get: $\Psi s = \mu_0 J (Z_j \delta n_j / n_e) \lambda_\eta / \Delta'$

Δ' being the tearing stability parameter. The order of magnitude of the seed island forced by the external current perturbation can be estimated from the general espression ($w = 4 (\Psi s L_s / B_0)^{1/2}$) :

$$w_{seed} \sim 4 (\mu_0 J (Z_j \delta n_j / n_e) \lambda_\eta r_s / m L_s / B_0)^{1/2}$$

with Ls the magnetic shear length and B_0 the magnetic field on axis. The already observed interplay of the possible synchronism in time among ST crash, NTM onset and the presence of impurities for the mechanism of the seed island formation as found in JET discharges at high Ip [12] is investigated.

This interplay suggests, for the description of a mode onset, a phenomenological relation between the TM index Δ'_0 and a variation of the radiated power δP_{rad} associated with the global and local modification of the impurity's density. This modelling seems to be reasonable because direct interaction of ST with high poloidal m and toroidal n modes is weak, but sawteeth can affect the mode onset through an indirect modification of Δ'_0 for variations of density and current density $J \sim e(n_i V_i - n_e V_e)$.

When there are low Z impurities in the plasma core, which tend to be uniformly distributed, a ST crash leads to impurities ejection with a change δn_z which induces an electron density perturbation $\delta n_e = Z \delta n_z$ from the quasineutrality condition $n_e = n_i + Z n_z$. This can modify directly the equilibrium current profile $\delta J = -\delta n_e V_e$ on an inertial time scale. The sudden local density perturbations δn_z is then associated to a variation of the observable radiated power δP_{rad} . Then an effective phenomenological criterium for the TM onset can be given assuming a linear response $r_s \Delta'_{0,mn} = -m + k \delta P_{rad} / P_{rad} > 0$ where P_{rad} can be taken as a threshold below which the mode destabilization does not occur and k is a coefficient evaluated in a stable point rs $\Delta'_{0,mn} = 0$. This is consistent with experimental observation where the ST crash can lead to synchronous impurities ejection and variation of P_{rad}. It can be conjectured that the net positive growth is due to the prevalent direct modification of the plasma current, while effects of island neoclassical dynamics in unsteady conditions come into play with neoclassical mode destabilization when an initial seed island w exceeds a critical width w_{cr} and the poloidal beta β_p becomes larger than a critical value β_{cr}.

In the present work the considered plasma scenarios assume a constant flat q=1 profile for all times and the ST crashes in the transport code are not calculated. However critical islands width w_c associated to the onset of NTM are calculated and compared with the seed islands by the density impurity perturbation shown before.

The critical width w_c corresponds to the stationary point at small islands of the NTM growth rate dw/dt = 0 (being the second stable stationary point the saturated island width) and it is given in the Rutherford equation by the balance between the ion polarization (taken stabilizing in this case) and the bootstrap currents:

$$w_c = \left[\frac{a_{pol}\Delta_{pol_0}\rho_{\theta i}^2 + \sqrt{\left(a_{pol}\Delta_{pol_0}\rho_{\theta i}^2\right)^2 - 4 a_{bs}\Delta_{bs_0}\left(a_{bs}\Delta_{bs_0} w_p^4 - a_{pol}\Delta_{pol_0}\rho_{\theta i}^2 w_d^2\right)}}{2\, a_{bs}\Delta_{bs_0}} \right]^{0.5}$$

From impurity the seed island width in D plasma is found = $3.2\ 10^{-2}$ and 10^{-2} in H , while the critical width for the NTM onset is $1.95\ 10^{-2}$ m in D and $9.8\ 10^{-3}$ m in H. This means that in these scenarios the role of impurities on the seed island assume a non-negligible role.

4. CONCLUSIONS

Sawteeth stabilization has been investigated for JT-60SA Baseline plasma scenarios extrapolated from experimental data of JET and JT-60U and provided by METIS transport code for Hydrogen and Deuterium plasmas at 4.6 MA, 2.2 T heated with 16 MW NBI and 1.5 MW EC.

First scope was to carry out predictive evaluations of conditions under which m = 1 internal kink modes, responsible for the sawtooth crash, were stable using the model described by Porcelli and modified by Sauter. The criterion for the stability is based on a potential energy functional δW calculated considering ideal-MHD contributions and the kinetic modifications related to the fast particles and to the thermal trapped ions .

In the D and H scenarios, characterized by a long flattop phase of 100 s, 3 profiles with different peaking and a q profile constant with q=1 up to rhotor_norm=0.4, other reliable q <1 profiles within the q=1 zone were used for the stability modelling for changing the values of the magnetic shear s_1 .
We found that ST crashes were triggered by unstable kink mode both for positive effects of the trapped and fast particles with s_1 between 0.2 and 0.4.

The second purpose of this study was the investigation of the possible synchronism in time among ST crash, NTM onset and the presence of impurities leading to high Zeff (~ 1.8 in the considered scenarios) for the mechanism of the seed island formation as found in JET discharges at high current.
Triggering of Neoclassical Tearing Mode (NTM) by a seed island formation due the perturbation of the current density J consequent to the influx of impurities is investigated.

Combining the quasi neutrality constraint, imposed by the presence (influx) of impurities and the relation between the current perturbation and the tearing stability parameter Δ' the order of magnitude of the seed island forced by the external current perturbation has been estimated and compared with the critical width calculated using the Rutherford equation.

From impurity the seed island width in D plasma was found = $3.2\ 10^{-2}$ m and 10^{-2} in H , while the critical width for the NTM onset was $1.95\ 10^{-2}$ m in D and $9.8\ 10^{-3}$ m in H. These results have shown that in these scenarios the role of impurities on the seed island assume a non-negligible role.

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