Beta Limit Due to Resistive Instabilities in T-10

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Abstract. Soft beta limiting phenomena have been observed in T-10 in ECRH heated plasmas. Neoclassical tearing modes are supposed to be responsible for the beta limitation. The MHD onset was observed at high β_p but low β_N values. Critical β has been found to be almost independent of collisionality parameter ν_e^*. Sawtooth stabilization by ECCD does not result in an increase of critical β. Dependence of the critical β on the q(r) profile (modified by ECCD) has been observed.

1. Introduction

Limitation of achievable β by resistive tearing modes at values well below the predictions of ideal MHD theory has been observed in a number of tokamaks. The beta limit in these experiments was usually observed in its ″soft″ (confinement degradation) form. The destabilizing effect of neoclassical bootstrap current was considered to explain the formation and evolution of magnetic islands. These instabilities are called neoclassical tearing modes (NTM) and can be destabilized even in the conditions when classical tearing mode should be stable. This paper is focused on MHD instabilities that determine the soft beta limit in T-10 (R_0 = 1.5 m, a= 0.3 m, P_{ECRH} up to 1.4 MW).

The stability of NTM is usually analysed in the framework of the simplified form of Modified Rutherford Equation:

$$\frac{\mu_0}{1.22\eta}\frac{dw}{dt} = \Delta' + a_1\beta_\theta\varepsilon^{1/2}\frac{L_q}{L_p}\frac{w}{w^2+w_d^2} - a_2\beta_\theta g(\varepsilon,\nu_{ii})\rho_{\theta i}^2\left(\frac{L_q}{L_p}\right)^2\frac{1}{w^3} \qquad (1)$$

where η is the resistivity, Δ' is the standard tearing mode stability parameter, $\beta_\theta = 2\mu_0 p/B_\theta^2$ is the local poloidal β, ε=r/R, L_q=q/q′, L_p=p/p′, $g(\varepsilon,\nu_{ii})$ is the collisionality dependent factor, $\rho_{\theta i}$ is the ion poloidal gyroradius, a_1 and a_2 are coefficients that depend on profiles of plasma parameters. The destabilizing effect of a deficit of neoclassical bootstrap current inside the island is given by the second term in the RHS of Eq.1. Thus, a large magnetic island can be formed even in the case of negative Δ' when (1) critical β has been achieved, (2) a sufficient ″seed″ island has been produced by an external magnetic field perturbation. Two effects are usually considered for explanation of the threshold character of NTM destabilization. First, finite island width is required to provide pressure equalization within the island (the so-called $\chi_\perp/\chi_\parallel$ model [1]). Simplified, this gives rise to w_d, the critical island width, in the neoclassical bootstrap current destabilizing term. Second, the ion polarisation current effect, which is usually stabilizing [2], gives rise to the third term in the RHS of Eq.1 (also simplified). The exact form of this term is still under investigation [3].

2. Experimental results and discussion

Soft beta limits have been observed in T-10 plasmas with ECRH (140 GHz, second harmonic, P_{HF} up to 1.4 MW) with high q_L (~6-10). A significant fraction of bootstrap current (up to 30%) can be obtained in these regimes with high β_p (up to 2.5) and high l_i values (up to 2). However, the value of β was found to be limited in these regimes by destabilization of large-scale MHD instabilities in the plasma core.

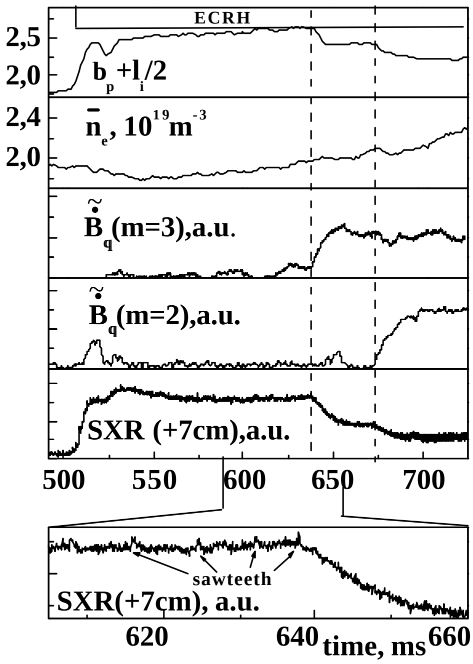

FIG. 1. Waveforms of the shot suffered destabilization of (3,2) and (2,1) modes. The (3,2) mode is triggered by a sawtooth

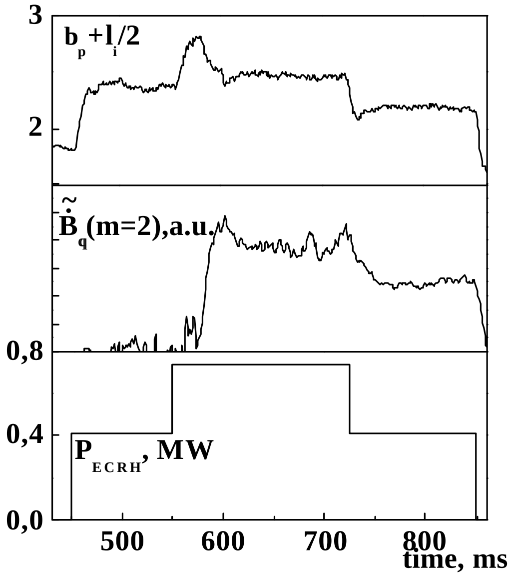

FIG. 2. The characteristic power hysteresis effect.

A β increase can be terminated by destabilization of the (3,2) or (2,1) mode. Energy confinement time τ_E depends almost linearly on $\bar{n}_e$ in T-10 L-mode plasmas with direct electron heating [4]. We use a preprogrammed $\bar{n}_e$ increase during HF power injection in our experiments to increase β smoothly more frequently than the standard procedure of staircase-like power rise. Waveforms of the shot suffered destabilization of the (3,2) mode that terminates the smooth β increase and later suffered a destabilization of the (2,1) mode, are shown in Fig.1. The electron temperature drops inside $r_{q=1.5}$ after the onset of the (3,2) mode and inside $r_{q=2}$ after the onset of the (2,1) mode. Development of a mode results in a degradation of confinement. The observed energy deterioration (typically $\Delta W/W \approx 10\text{-}30\%$) is usually in accordance with a "belt" model that uses $\Delta W/W=20/3(1-r_s^2/a^2)(1-(1-r_s^2/a^2)^3)r_s w/a^2$ [5], where w is the island width estimated from Mirnov data. We have found that an onset of the (3,2) mode is always triggered by a sawtooth crash. As it is shown in Fig.1 β starts to decrease (and the (3,2) mode starts to grow) just after a sawtooth crash (after a spike on the SXR chord between $r_{q=1}$ and $r_{q=1.5}$). Destabilization of the (2,1) mode also can be triggered by a sawtooth, but in many shots the mode onset occurs without any observable trigger.

Experimental data allow us to suppose observation of NTM: (1) Critical β is required for the mode onset. The beta limit occurs in its "soft" form. The values of β_N (0.6-1.2) are well below the values required for ideal instabilities. SXR oscillations observed after a soft β limit event have the characteristics of an island, i.e. a phase jump of 180° at the rational surface. Thus, resistive tearing modes can be supposed. (2) The value of the Δ' parameter that determines the stability of the classical tearing mode has been calculated numerically in cylindrical geometry for a number of tokamak discharges. Profiles of j(r) have been taken from calculations by the ASTRA code [6] (experimental $T_e(r)$ and $n_e(r)$ profiles were used) with $j_{cd}(r)$ from the TORAY code [7]. The value of the Δ_0' parameter is very sensitive to the j(r) profile and hence the calculations are rather uncertain. The value of the tearing mode stability parameter Δ_0' at an onset of (3,2) was found to be always negative. Thus, the destabilizing effect of neoclassical bootstrap current is required to explain the mode onset. However, for the (2,1) mode it was found to be marginal in most cases. Since according to calculations Δ_0' changes negligibly during HF power injection before MHD onset, the observed growth of the island cannot be explained by an evolution of Δ_0'. (3) A trigger is required for an onset of the (3,2) mode. However, no triggers have been observed in a number of shots for the (2,1) mode. A spontaneous start (without triggers) of NTM has been reported in a few cases in ASDEX-U [8]. The characteristic hysteresis effect [9] has been observed in T-10. Once destabilized, the (2,1) mode persists throughout the discharge, in spite of the decrease of ECRH power to the value before the mode onset (Fig.2). (4) A significant local fraction of bootstrap current $((j_{bs}/j_{tot})\,|_{r=rs}$ up to 50% according to calculations by ASTRA+TORAY) has been obtained in the experiments. Thus, a deficit of the bootstrap current inside the island due to high parallel heat conductivity could result in a sufficient destabilizing effect for NTM development.

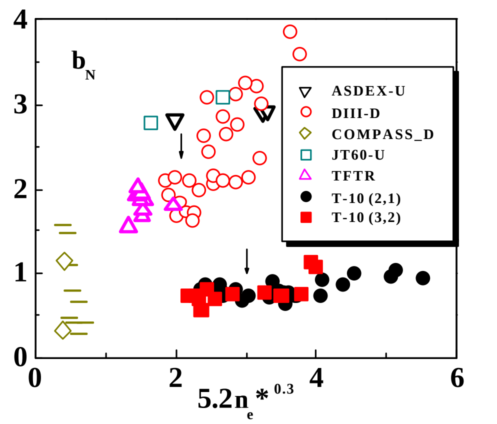

*FIG. 3. b_N at NTM onset versus n_e**
(n_e=0.012 $n_e(10^{20}m^{-3})qR(m)/e^{3/2}$ Te^2(keV), Z_{eff}=1, the data on a resonance surface are used).*

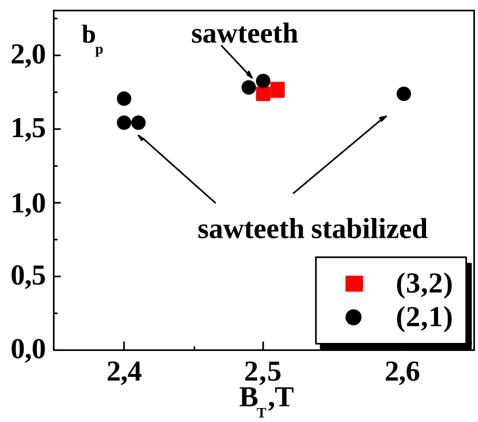

FIG. 4. Critical b in sawtoothing and sawtooth-free discharges.

We present T-10 points at an NTM onset in the well-known β_N vs ν_e^* diagram, proposed in Ref. [10], to compare critical β with that one in other devices. (Recently reported JET points [11], which have a weak negative dependence of critical β_N on ν_e^*, are not shown in the diagram.) As can be clearly seen from Fig.3, critical β_N for T-10 is well below the β_N values required for MHD onset on other devices with similar ν_e^*. We suppose the following reason for this: Roughly, the destabilizing neoclassical bootstrap current term is sensitive to $(j_{bs}/j_{tot})\,|_{r=rs}$. T-10 experimental points have been obtained in the regimes with high q_a (6-10), while the data from other devices are for $q_{95}\approx$3-4. Considerable values of β_p have been achieved in these regimes in spite of relatively low values of β_N. This provides a sufficient fraction of bootstrap current ($I_{bs}/I_p \propto \sqrt{\varepsilon}\beta_p$), and hence a sufficient neoclassical bootstrap current destabilizing term.

As is shown in Fig.3, critical β is almost independent of ν_e^* in T-10 experiments. Collisionality dependence of critical β_N was first observed in DIII-D [12]. It can be explained in the framework either of the $\chi_\perp / \chi_\parallel$ model or of the ion polarization model. The critical island width w_d, which depends on $\chi_\perp / \chi_\parallel$, ratio increases with ν_e^*, and thus critical β increases as well. The ion polarization current term, whih is usually stabilizing, can depend on collisionality through $\rho_{\theta i}^2 g(\varepsilon,\nu_{ii})$. In the framework of the ion polarization model an NTM onset occurs in the low collisional regime, where $g(\varepsilon,\nu_{ii})$ is small and can be independent of collisionality for sufficiently low $\nu_{ii}/\varepsilon\omega_e^*$. The ratio $\nu_{ii}/\varepsilon\omega_e^*$ (0.03-0.2) at the mode onset in T-10 is similar to that in almost all other devices. Thus, the possible reason for the lack of a collisionality dependence in the T-10 experiments is that the ion polarization effect rather than the $\chi_\perp / \chi_\parallel$ effect determines the mode stability. The value of ρ* (≈5×10^{-3}) is of order ρ* in ASDEX-U [8], DIII-D [13] and JET [11]. It does not change appreciably in the T-10 experiments, thus any dependence of critical β on ρ* has not been studied.

The experiment for clarifying the role of the sawtooth oscillations in NTM triggering in T-10 conditions has been performed. Sawtooth oscillations can be suppressed by off-axis co-ECCD [14]. We have performed a B_z scan of critical β_p in order to compare the thresholds with and without sawtooth oscillations. As is shown in Fig.4, the critical β_p is almost independent of the presence of sawtooth oscillations. Besides that, we note that either the (3,2) or the (2,1) mode can determine a soft beta limit event in the case of almost identical sawtoothing shots (as in the shots with sawteeth in Fig.4). However, in all the shots with sawteeth suppressed (under off-axis co-ECCD or on-axis counter-ECCD), the (2,1) mode determines a soft beta limit

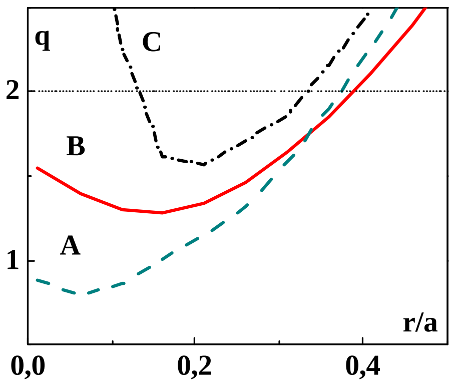

FIG. 5. Typical profiles of q(r) in the regimes with on-axis co- and counter-ECCD.

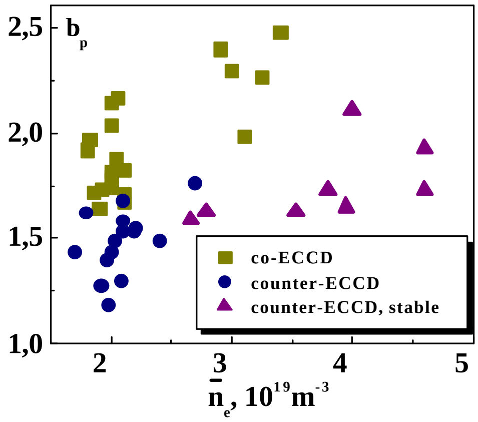

FIG. 6. Critical b_p versus $\bar{n}_e$ in the regimes with on-axis co- and counter ECCD.

event. The following interpretation of these experimental data is proposed. The calculated tearing mode stability parameter Δ_0' at an onset of the (3,2) mode is always negative. Thus, an external perturbation of the magnetic perturbation is required to produce a seed island sufficient for the mode onset. We note that Δ_0' for the (2,1) mode is usually marginal for the conditions of the experiments. Thus, it could be supposed that the evolution of Δ_0' during the ECRH pulse results in the formation of the seed island that is required for an NTM onset.

The dependence of the critical β on the q(r) profile has been studied in the T-10 experiments. The profiles of q(r) with a range of q_{min} from ≤1 to ≈2.5 can be produced by applying ECCD in the current flat-top [15]. Fig.5 shows typical profiles of q(r) calculated by

ASTRA+TORAY codes for shots with on-axis co-ECCD (profile A) and on-axis counter-ECCD (profiles B, C for different power levels). The value of β_p at MHD onset is systematically lower for the shots with on-axis counter-ECCD (with q_{min} around 1.3) than in the shots with on-axis co-ECCD (with $q_{min} \leq 1$) (Fig.6). The shots with higher values of q_{min} (≥ 1.5) usually have two q=2 surfaces and MHD activity in these shots (which can be associated with double-tearing stability [15]) differs strongly from that one observed in a soft beta-limit event. We do not take these shots into consideration. The shots with counter-ECCD without MHD (Fig.6) usually have q_{min} close to unity due to the higher values of $\bar{n}_e$ (lower ECCD efficiency). According to the calculations, the value of Δ_0' is higher for the shots with q_{min} around 1.3 than for the shots with q_{min} close to unity. We suppose that the observed difference of critical β for the regimes with co- and counter-ECCD can originate from a difference in Δ_0'. (According to the Modified Rutherford Equation, critical β can depend on the Δ_0' value.)

3. Conclusion

Limitation of the maximum achievable beta by instabilities interpreted as Neoclassical Tearing Modes has been observed in T-10 in high q_a regimes. A significant fraction of bootstrap current can be obtained in these regimes with high β_p values (up to 2.5) (despite a low β_N value). This provides a sufficient destabilizing effect in the case of a seed magnetic island formation. Critical β has been found to be almost independent of the collisionality parameter ν_e^*. This effect could be explained in the framework of the ion polarization current model. The value of critical β has been found to be independent of the presence of sawtooth oscillations. The hypothesis of NTM triggering by Δ_0' evolution has been proposed to explain this experimental observation. The dependence of the critical β on the q(r) profile (modified by ECCD) has been investigated. Critical β has been found to be systematically lower for the regimes with q_{min} around 1.3 than in the regimes with q_{min} close to unity.

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