27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** *(2000) 584 -587*

Soft Beta Limits in T-10 Tokamak.

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Phenomenon of the so-called "soft" β limit has been observed in a number of tokamaks [1-6] at β values that can be well below the Troyon limit. Neoclassical tearing mode (NTM) has been identified as an instability that is responsible for the soft β limits. The paper is focused on MHD instabilities that determine soft beta limit in T-10 (R_0=1.5m, a=0.3m).

Destabilization of (3,2) or (2,1) mode can terminate a β increase in T-10 ECRH plasmas (140GHz - second harmonic, P_{HF} up to 1.4MW) with high β_p values (up to 2.5). Waveforms of a shot suffered a destabilization of (3,2) mode that terminates smooth β increase, and, later, suffered a destabilization of (2,1) mode, are demonstrated in Fig.1. Electron temperature drops inside $r_{q=1.5}$ and $r_{q=2}$ after the development of (3,2) and (2,1) modes respectively. Energy confinement time τ_E depends almost linearly on $\bar{n}_e$ in T-10 L-mode plasmas [7]. We use preprogrammed $\bar{n}_e$ increase during HF power injection in our experiments in order to provide smooth β increase more frequently than standard procedure of staircase-like power rise.

We have found that an onset of (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 (2,1) mode also can be triggered by a sawtooth, but in many shots the mode onset occurs without any observable trigger.

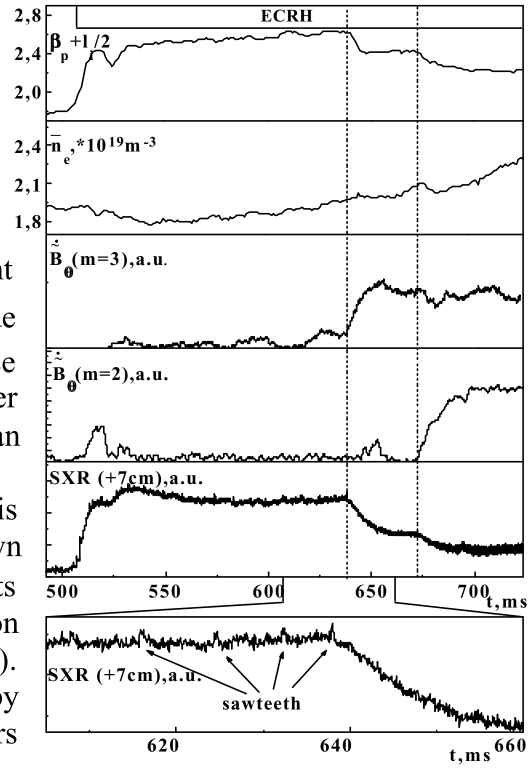

Fig.1 A shot suffered destabilization of (3,2) and (2,1) modes. The (3,2) mode is triggered by a sawtooth.

Development of a mode results in a soft (confinement degradation) beta limit. The observed energy deterioration (typically $\Delta W/W\approx$10-30%) is usually in accordance with "belt" model that uses $\Delta W/W=20/3(1-r_s^2/a^2)(1-(1-r_s^2/a^2)^3)r_s w/a^2$ [8], where w – the island width estimated from Mirnov data.

Several reasons allow us to suppose observation of NTM: 1. Critical β (in the regimes with different $\bar{n}_e$, I_p, B_z, P_{HF}) is required for a mode onset. Beta limit occurs in its "soft" form. 2. 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. Thus, tearing modes should be supposed. 3. The value of tearing mode stability parameter Δ_0' at an onset of (3,2) is always negative. The Δ_0' parameter was calculated numerically using $j(r)$

profile from calculations by ASTRA code [9] (experimental $T_e(r)$ and $n_e(r)$ profiles were used) with $j_{cd}(r)$ from TORAY code [10]. The Δ_0' parameter for a (2,1) mode was found to be marginal. The value of the Δ_0' parameter is very sensitive to $j(r)$ profile and, hence, the calculations are rather uncertain. Similar results of calculations of Δ_0' for a (2,1) mode at a soft beta limit have been reported in [2,8]. We note that, according to calculations Δ_0' changes negligibly during HF power injection before MHD onset. So, the observed growth of the island cannot be explained by an evolution of Δ_0'. 4. Considerable local fraction of bootstrap current ($(j_{bs}/j_{tot})|_{r=rs}$ up to 50% according to calculations by ASTRA+TORAY)) can provide a destabilizing effect in the case of a magnetic island formation. More detailed discussion of the destabilizing term see below. 5. A trigger is required for an onset of (3,2) mode. However, no triggers have been observed in a number of shots for (2,1) mode. Spontaneous start (without triggers) of NTM has been reported in a few cases in ASDEX-U [11].

Stability of NTM is usually analyzed in the framework of the simplified form of Modified Rutherford Equation:

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

where η - the resistivity, Δ' - the standard tearing mode stability parameter, $\beta_\Theta = 2\mu_0 p/B_\Theta^2$ – local poloidal β, $\varepsilon = r/R$, $L_q = q/q'$, $L_p = p/p'$, $g(\varepsilon, \nu_{ii})$ – collisionality dependent factor, $\rho_{\Theta i}$ – ion poloidal gyroradius, a_1 and a_2 – coefficients, that depend on profiles of plasma parameters. 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 $\chi_\perp/\chi_{||}$ model [12]). Simplified, this gives rise to w_d critical island in neoclassical bootstrap current destabilizing term (second term in Eq.1). Second, ion polarisation current effect, that is usually stabilizing [13], gives rise to the third term in Eq.1 (also simplified). The exact form of this term is still under investigation [14].

The scaling $\beta_N \sim 5.2\nu_{e*}^{0.3}$ for NTM onset has been proposed in Ref.[15]. We show β_N values at the mode onset in T-10 (shots without counter-ECCD are shown) plotted versus $5.2\nu_{e*}^{0.3}$ in Fig.2 together with the points from other devices taken from Ref.[15]. We do not show recently reported JET points [6] that, in contrast to the scaling, has weak negative dependence of critical β_N on ν_{e*}. As it can be clearly seen from Fig.2 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, 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. To illustrate this, two shots, marked by

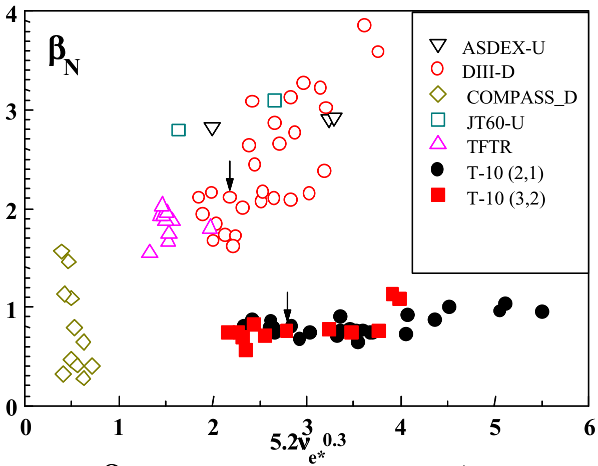

Fig.2 β_N at NTM onset versus ν_e (ν_e*$=0.012\, n_e(10^{20}m^{-3})qR(m)/\varepsilon^{3/2}\, Te^2(keV)$, Zeff=1, the data on a resonance surface used).*

arrows in Fig.2 (from DIII-D and from T-10) with similar ν_{e*} but considerably different β_N, are compared in Table 1. The data for DIII-D shot #86144 have been taken from Ref.[16]. Similar values of $\beta_\theta\varepsilon^{1/2}L_q/L_p$ allow to suppose similar neoclassical bootstrap current destabilizing terms.

Table 1.

	#	m/n	β_N	$\beta_\theta\varepsilon^{1/2}L_q/L_p$	$\Delta_0'r$	$\nu_{ii}/\varepsilon\omega_{e*}$
DIII-D	86144	3/2	2.1	0.52	-2.8	0.042
T-10	23131	3/2	0.76	0.5	-1.7	0.07

The dependence of critical β_N on ν_* first observed in DIII-D [2] can be explained in the framework either of $\chi_\perp/\chi_{||}$ model or of ion polarization model. The critical island width that is determined by $\chi_\perp/\chi_{||}$ ratio increases with ν_{e*}. Ion polarization current term, that is usually stabilizing, can depend on collisionality through $\rho_{\theta i}^2 g(\varepsilon,\nu_{ii})$. The function $g(\varepsilon,\nu_{ii})$ can be sensitive or almost independent on $\nu_{ii}/\varepsilon\omega_{e*}$ [13]. Critical β is almost independent on ν_{e*} in T-10 experiments (Fig.2) that contradicts the scaling $\beta_N \sim 5.2\nu_{e*}^{0.3}$. In contrast to the wide range of ν_{e*} values in the T-10 experiments moderate changes of ν_{ii} (~±30%) was observed. The ratio $\nu_{ii}/\varepsilon\omega_{e*}$ (0.03÷0.2) at the mode onset in T-10 is similar to that one in almost all other devices. The value of ρ^* changes inconsiderably around ~0.005 in the T-10 experiments is of order ρ^* in ASDEX-U [11], DIII-D [12] and JET [6]. So, ion polarization current term similar to that one in other devices could be supposed.

A role of sawtooth trigger in destabilization of the mode has been investigated. Sawtooth oscillations can be suppressed by off-axis co-ECCD [17]. We have performed a B_z scan of critical β_p in order to compare the thresholds with and without sawtooth oscillations. As it is shown in Fig.3 critical β_p is almost independent on the presence of sawtooth oscillations. Besides that, we note that either (3,2) mode or (2,1) can determine a soft beta limit event in the case of almost identical sawtoothing shots (as it is in the shots with sawteeth in Fig.3). However, when sawteeth are suppressed (under off-axis co-ECCD or on axis counter-ECCD), only (2,1) mode can be destabilized. In such a case unobserved MHD event or a change of Δ_0' could give rise to the seed island required for the (2,1) mode development.

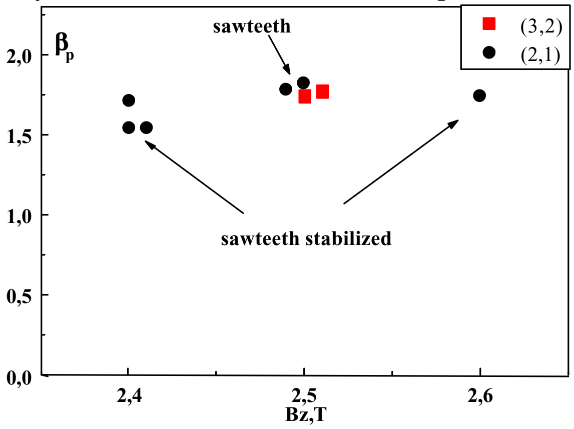

Fig.3 Critical β_p *versus* $\hat{A}_z$.

Dependence of a critical β on q_a has been investigated. Critical β_p is shown in Fig.4 for a one-day I_p scan. Available power was insufficient to obtain values of β_p required for a mode destabilization for a higher current than that one shown in Fig.4. Thus, β_p looks like a candidate for the critical parameter that determines MHD onset in the T-10 experiments.

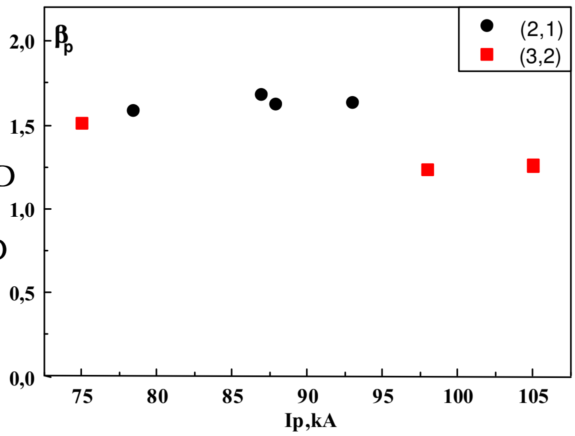

Fig.4 Critical β_p *versus Ip.*

Dependence of the critical β on $q(r)$ profile has been studied in the T-10 experiments. A wide spectrum of $q(r)$ profiles with the range of q_{min} from ≤1 to ≈2.5 can be produced applying ECCD [n the current flat-top 18]. Typical profiles of *q(r)* calculated by ASTRA+TORAY codes for shots with co-ECCD (profile A) and counter-ECCD (profiles B,C for different power levels) are shown in Fig.5. The value of β_p at MHD onset is systematically lower for the shots with q_{min}~1.3 (on-axis counter-ECCD) than in the shots with $q_{min}\leq 1$ (on-axis co ECCD) (Fig.6). The shots with higher values of q_{min} ($\geq$1.5) usually has a region of negative magnetic shear and MHD activity in such a shot (that can be associated with double-tearing stability [18]) differs strongly from that one observed in a soft beta-limit event. We do not take such a shot into this consideration. The shots with counter-ECCD without MHD (Fig.6) usually has q_{min}~1 due to a higher values of $\bar{n}_e$ (lower ECCD efficiency). 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'. (As it follows from Modified Rutherford Equation critical β can depend on Δ_0' value.) Contrary to DIII-D [16] we have observed a decrease of critical β when the q_{min} nises above unity. This may be caused by difference in *q(r)* profiles (and, hence, Δ_0') and by a difference in the triggering mechanisms.

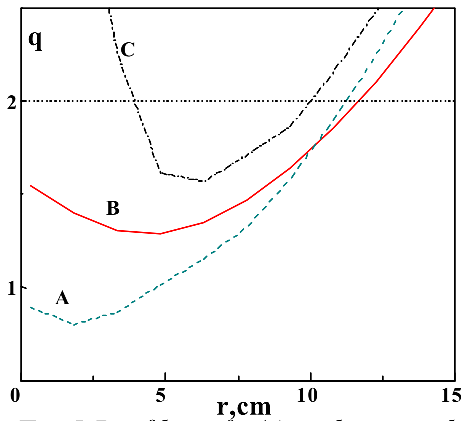

Fig.5 Profiles of q(r) with co- and counter-ECCD

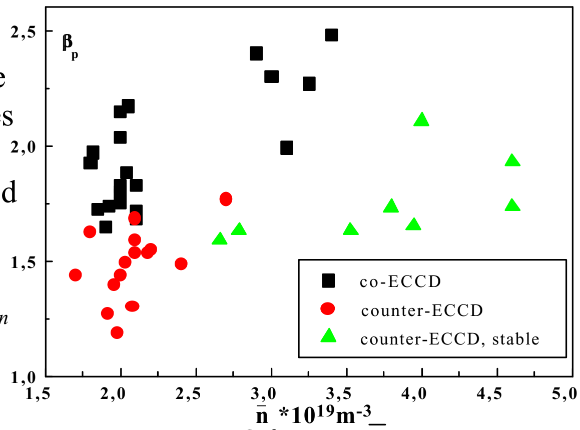

Fig.6 Critical β_p *versus* $\bar{n}_e$ *with co- and counter ECCD*

This work is supported by Ministry of Atomic Energy of Russia (contract 69F) and by Ministry of Science and Technology of Russia (Federal Program “Controlled Thermonuclear Fusion and Plasma Processes”).

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