Soft Beta Limits in T-10 Tokamak.


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Phenomenon of the so-called “soft” $\beta$ limit has been observed in a number of tokamaks [1-6] at $\beta$ 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 $\beta$ 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 $\beta$ increase in T-10 ECRH plasmas (140GHz - second harmonic, $P_{HF}$ up to 1.4MW) with high $\beta_p$ values (up to 2.5). Waveforms of a shot suffered a destabilization of (3,2) mode that terminates smooth $\beta$ 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 $\tau_E$ depends almost linearly on $n_e$ in T-10 L-mode plasmas [7]. We use preprogrammed $n_e$ increase during HF power injection in our experiments in order to provide smooth $\beta$ 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 $\beta$ 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.

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 $\Delta W/W=20/3(1-r_s^2/a^2)(1-(1-r_s^2/a^2)^3)r_w/a^2$ [8], where $w$ – the island width estimated from Mirnov data.

Several reasons allow us to suppose observation of NTM: 1. Critical $\beta$ (in the regimes with different $n_e, I_p, B_z, P_{HF}$) is required for a mode onset. Beta limit occurs in its “soft” form. 2. The values of $\beta_N$ (0.6+1.2) are well below the values, required for ideal instabilities. SXR oscillations observed after a soft $\beta$ limit event have the characteristics of an island. Thus, tearing modes should be supposed. 3. The value of tearing mode stability parameter $\Delta_0'$ at an onset of (3,2) is always negative. The $\Delta_0'$ parameter was calculated numerically using $j(r)$.
profile from calculations of modified Rutherford Equation:

\[ \frac{\mu_0}{1.22\eta} \int dw = \Delta' + a_1 \beta_0 \varepsilon^{1/2} L_q \frac{w}{L_p} - a_2 \beta_0 g(\varepsilon, \nu_{\perp}) \rho \left( \frac{L_q}{L_p} \right)^2 \frac{1}{w^2} \]

where \(\eta\) - the resistivity, \(\Delta'\) - the standard tearing mode stability parameter, \(\beta_0 = 2\mu_0/\beta_0^2\) - local poloidal \(\beta\), \(\varepsilon = \nu_{\perp}/\nu_{\parallel}\), \(L_q = q/q'\), \(L_p = p/p'\), \(g(\varepsilon, \nu_{\perp})\) - collisionality dependent factor, \(\rho\) - 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 \(\chi_{\nu_{\perp}}\) model [12]). Simplified, this gives rise to \(w_p\) critical island in neoclassical bootstrap current destabilizing term (second term in Eq.1). Second, ion polariisation 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 \(\beta_N \approx 5.2\nu_{e*}^{0.3}\) for NTM onset has been proposed in Ref.[15]. We show \(\beta_N\) 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 \(\beta_N\) on \(\nu_{e*}\). As it can be clearly seen from Fig.2 critical \(\beta_N\) for T-10 is well below the \(\beta_N\) values required for MHD onset on other devices with similar \(\nu_{e*}\). We suppose the following reason for this: Roughly, destabilizing neoclassical bootstrap current term is sensitive to \(j_{bs}/j_{tot}\) \(r_{res}\). T-10 experimental points have been obtained in the regimes with high \(q_\nu\) (6+10), while the data from other devices are for \(q_\nu \approx 3+4\). Considerable values of \(\beta_n\) have been achieved in these regimes in spite of relatively low values of \(\beta_N\). This provides a sufficient fraction of bootstrap current \(I_{bs}/I_p \propto \sqrt{\varepsilon_{bp}}\), and, hence, a sufficient neoclassical bootstrap current destabilizing term. To illustrate this, two shots, marked by
arrows in Fig.2 (from DIII-D and from T-10) with similar $\nu_e^*$ but considerably different $\beta_N$, are compared in Table 1. The data for DIII-D shot #86144 have been taken from Ref.[16]. Similar values of $\beta_{0e}^{1/2}L_c/L_p$ allow to suppose similar neoclassical bootstrap current destabilizing terms.

Table 1.

<table>
<thead>
<tr>
<th></th>
<th>#</th>
<th>m/n</th>
<th>$\beta_N$</th>
<th>$\beta_{0e}^{1/2}L_c/L_p$</th>
<th>$\Delta_0/\Gamma$</th>
<th>$\nu_e^*/\varepsilon\Omega_\ast$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIII-D</td>
<td>86144</td>
<td>3/2</td>
<td>2.1</td>
<td>0.52</td>
<td>-2.8</td>
<td>0.042</td>
</tr>
<tr>
<td>T-10</td>
<td>23131</td>
<td>3/2</td>
<td>0.76</td>
<td>0.5</td>
<td>-1.7</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The dependence of critical $\beta_N$ on $\nu_e^*$ first observed in DIII-D [2] can be explained in the framework either of $\chi_\perp/\chi_\parallel$ model or of ion polarization model. The critical island width that is determined by $\chi_\perp/\chi_\parallel$ ratio increases with $\nu_e^*$. Ion polarization current term, that is usually stabilizing, can depend on collisionality through $\rho_0$ $g(\varepsilon, \nu_i)$. The function $g(\varepsilon, \nu_i)$ can be sensitive or almost independent on $\nu_e^*/\varepsilon\Omega_\ast$ [13]. Critical $\beta$ is almost independent on $\nu_e^*$ in T-10 experiments (Fig.2) that contradicts the scaling $\beta_N\sim 5.2\nu_e^*$. In contrast to the wide range of $\nu_e^*$ values in the T-10 experiments moderate changes of $\nu_i$ ($\sim \pm 30\%$) was observed. The ratio $\nu_e^*/\varepsilon\Omega_\ast$ ($0.03+0.2$) at the mode onset in T-10 is similar to that in one almost all other devices. The value of $\nu_e^*$ changes considerably around $\sim 0.005$ in the T-10 experiments is of order $\rho^*$ 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 $\beta_p$ in order to compare the thresholds with and without sawtooth oscillations. As it is shown in Fig.3 critical $\beta_p$ 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 $\Delta_0'$ could give rise to the seed island required for the (2,1) mode development.

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

Dependence of the critical $\beta$ 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 $\leq 1$ to $= 2.5$ can be produced.
applying ECCD [in 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 $\beta_p$ at MHD onset is systematically lower for the shots with $q_{min} \approx 1.3$ (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 $q_{min} \approx 1$ due to a higher values of $n_e$ (lower ECCD efficiency). We suppose that the observed difference of critical $\beta$ for the regimes with co- and counter-ECCD can originate from a difference in $\Delta_0'$. (As it follows from Modified Rutherford Equation critical $\beta$ can depend on $\Delta_0'$ value.) Contrary to DIII-D [16] we have observed a decrease of critical $\beta$ when the $q_{min}$ rises above unity. This may be caused by difference in $q(r)$ profiles (and, hence, $\Delta_0'$) and by a difference in the triggering mechanisms.

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