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Investigations of plasma behavior in vicinity of q_{min}=1

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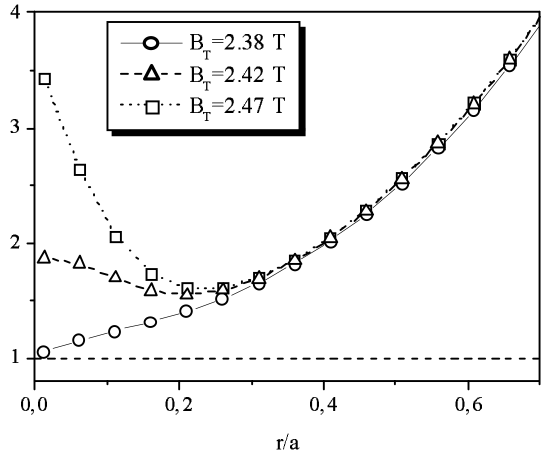
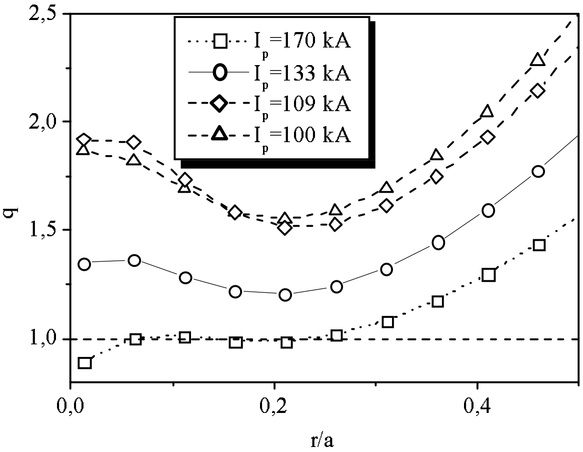
Investigations of the possibility of an Internal Transport Barrier (ITB) formation in regimes with reversed shear region in the plasma core (r≤0.35a) were carried out on T-10 tokamak (R=1.5 m; a_L=30 cm) under dominating electron transport (pure electron heating by ECRH). Reversed shear in these T-10 experiments was produced by on-axis Electron Cyclotron Current Drive in opposite direction to the ohmic plasma current (Counter-ECCD). HF-wave on 2nd harmonic ECR, X-mode, is launched to the tokamak at ψ=21° to major radius.

1. As it was shown in previous experiments [1] reversed shear q(r) profiles with q_{min} value closed to rational one ($q_{min}\cong$2;3) and two resonant surfaces q=2;3 are dangerous for plasma confinement because of double-tearing modes development. It leads to intensification of plasma MHD activity which is accompanied by central electron temperature $T_e(0)$ drop at ~ 30%. To produce an ITB under conditions when $1<q_{min}<1.5$ and $q(0)<2$ during HF pulse some efforts were made. It allows us to avoid double-tearing modes appearance.



a)



b)

Fig. 1 Range of q(r) profiles (calculation results) which can be obtained by B_T variation at I_p=100 kA, P_{ab}=0.4 MW (a) and at I_p variation at B_T=2.42 T, P_{ab}=0.4 MW (b). In both cases $\overline{n}_e \cong 1.25\times10^{19} m^{-3}$

To vary a shear value $(s = \frac{r}{q}\frac{dq}{dr})$ in the area inside of q_{min} surface, experiments were carried out at several values of toroidal magnetic field B_T in range B_T=2.38÷2.52 T. Under these conditions calculated q(r) profile changes in the core as it is shown on fig. 1,a.

Main experiments were carried out at Counter-ECCD. However experiments at Co-ECCD, when EC-current was co-directed to ohmic one, were made also. In the latter case q(r) profile remained monotonous. Experiments with Co- and Counter-CD allow us at first to carry out the detail comparison of plasma behavior at monotonous and reverse shear q profiles under the same conditions. q(r) profiles were calculated using ASTRA transport code [2]. EC driven current profile $j_{CD}(r)$ and I_{CD} value were calculated by TORAY code [3]. Furthermore a new method to determine I_{CD} value based on the sawtooth suppression was proposed and results of these experiments were used for correction of TORAY calculations.

q_{min} variation was realized by changing of the total plasma current value I_p shot to shot from 170 to 100 kA (fig. 1,b). Upper boundary of this range was chosen from the condition of the sawtooth suppression. This fact gave an additional condition to control the calculated q(r) profile reliability.

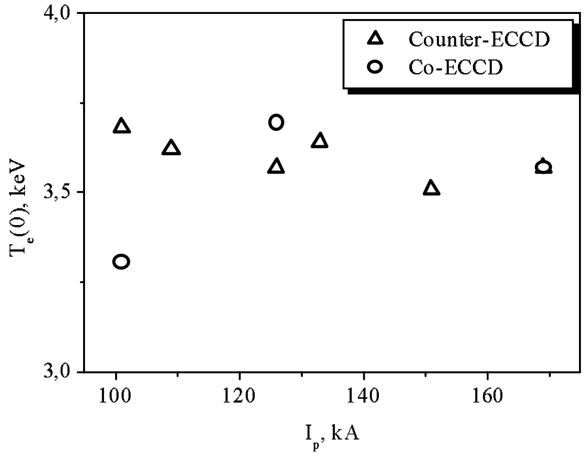


Fig. 2 Dependence of $T_e(0)$ on plasma current for regimes with reversed shear (Counter-ECCD) and monotonous (CO-ECCD) q(r) profiles

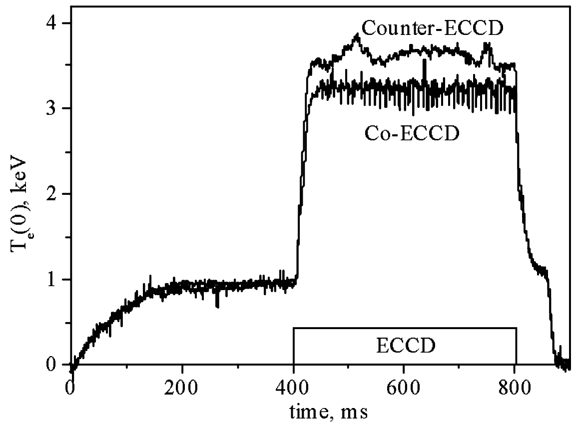


Fig. 3 Difference between $T_e(0)$ at Co- and Counter-ECCD, i.e. monotonous and reversed shear ($q_{min}\cong 1.5$) q(r) profiles.

$T_e(0)$ variation in experiments with different plasma current values is shown on fig. 2 in both Counter-ECCD regimes and in test experiments with Co-ECCD. It is seen that under I_p decrease (q_{min} increase at Counter-ECCD case) $T_e(0)$ is weakly changed and $T_e^{Counter}(0) \cong T_e^{Co}(0)$. $T_e(r)$ profile in these experiments was measured by 8 channels of ECE radiometer, $T_e(0)$ value was controlled by SXR spectra. Error bars for the measurements of absolute temperature values are 10 %. But difference in the temperatures between two pulses (if the sensitivity of the diagnostic channels was not changed) is determined with error ≤5%. $T_e(0)$ traces for regime with I_p=100 kA (fig. 3) also does not show any sufficient peculiarities in reversed shear regime in comparison with monotonous q(r) profile discharges. All results discussed here were obtained at line average density $\bar{n}_e \cong 1.25\times10^{19} m^{-3}$ and absorbed EC-power $P_{ab}\cong$0.4 MW. However P_{ab} increase up to 0.6 MW and increase of $\bar{n}_e$ value up to 2.6×10^{19} m^{-3} at $P_{ab}\cong$0.85 MW did not change qualitative picture. These results supply the conclusion made in [1]: attempts to produce an ITB in regimes with negative central shear and different s values (fig. 1) under condition with on-axis EC-power absorption on T-10 were not a success.

The cause of this misfortune seems to be following. As it was noted above, pure electron auxiliary heating is used on T-10. In experiments discussed EC-power is absorbed in the central region (r/a<0.3÷0.4). It leads to increase of short wave length turbulence in this area. In addition to that ion plasma temperature T_i on T-10 is essentially lower than electron one, $T_i<<T_e$. According to the modern theory (see, for example [5]) the fulfillment of the condition

$$\omega_{E\times B}>\gamma_{turb} \quad (1)$$

is required for transport barrier formation (here $\omega_{E\times B}$ – velocity shear flow, γ_{turb} – increment of the most unstable mode of turbulence). Since electron modes are prevailing in T-10 (low wave length, high γ_{turb}) then in such conditions the relation (1) is not satisfied on T-10.

2. Results of T-10 experiments discussed allow us to test the ITB existence near resonant magnetic surfaces observed in experiments on RTP [2]. Accordingly to [2] the strongest transport barrier is placed near q=1 magnetic surface (1<q<1.08). So in T-10 experiments the loss of this barrier at q_{min}>1.1 should lead to strong enough decrease of $T_e(0)$ with factor ~1.5. However, as it can be seen from fig. 1,b q(r) profile in T-10 experiments discussed here goes out through the q_{min}=1.1 at plasma current I_p=133 kA, but no strong $T_e(0)$ drop is observed.

Therefore, these T-10 results are not in agreement with the RTP results. It is necessary to note that the EC-beam on T-10 is wider than on RTP, but total EC - power is absorbed inside the q=1 surface and it seems to be not crucial. It is necessary to note an essential difference in T-10 and RTP experiments. On RTP the q(r) and $P_{ab}(r)$ profiles have changed together while on T-10 the $P_{ab}(r)$ profile did not changed at q(r) profile variation.

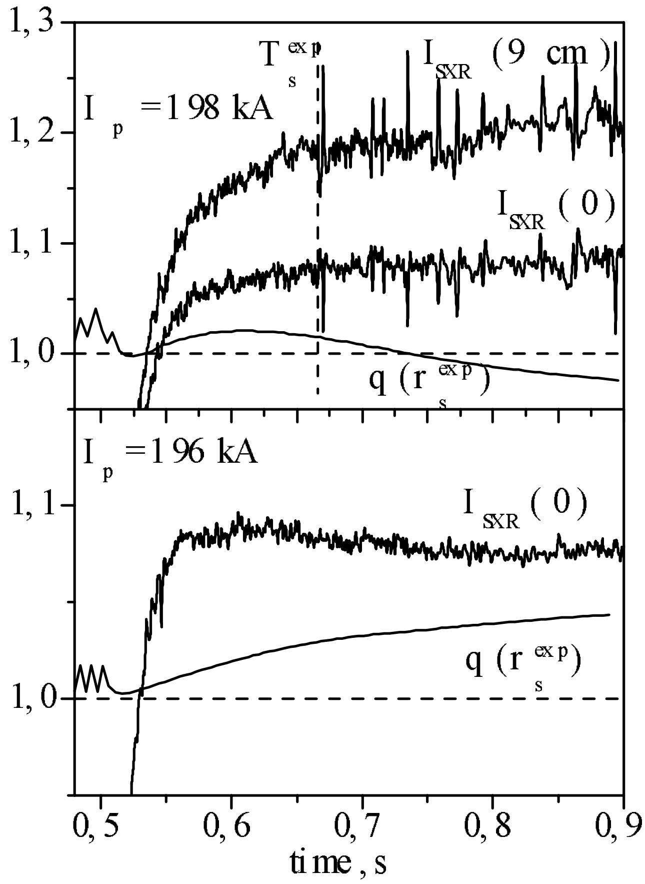


Fig. 4 Determination of I_{CD} value from the boundary of sawtooth suppression: traces of $I_{SXR}(0)$ together with calculated dynamics of $q(r_s^{exp})$.

3. Analysis given here is based on knowledge of q(r) profiles. It assumes knowledge of the $j_{CD}(r)$ profile and I_{CD} value. As it was noted above a new method for determination of I_{CD} value was used in these experiments. This method is based on use of the sawtooth suppression boundary under I_p decrease. At on-axis Counter-ECCD I_{CD} decreases the total plasma current (and hence increases q value) in the central region. Above the suppression boundary the I_p decrease leads to delay of sawtooth appearance instant T_s^{exp} (fig. 4). Further I_p decrease leads to sawtooth disappearance. To determine the I_{CD} value the narrow I_p range (I_{p1}>I_{p2}) is found out, when the sawtooth exists at I_{p1} and disappears at I_{p2} (fig.4). The I_{CD} value is determined under simultaneous satisfaction of following conditions:

a) achievement of q^{calc}=1 surface on experimental inversion radius r_s^{exp} at T_s^{exp} instant (I_p=I_{p1});

b) disappearance of q^{calc}=1 at I_p=I_{p2}.

8 experimental sets were analyzed distinguished on $\bar{n}_e$ ($1.1\div1.56\times10^{19}m^{-3}$) and on absorbed power value P_{ab}=0.36÷0.85 MW.

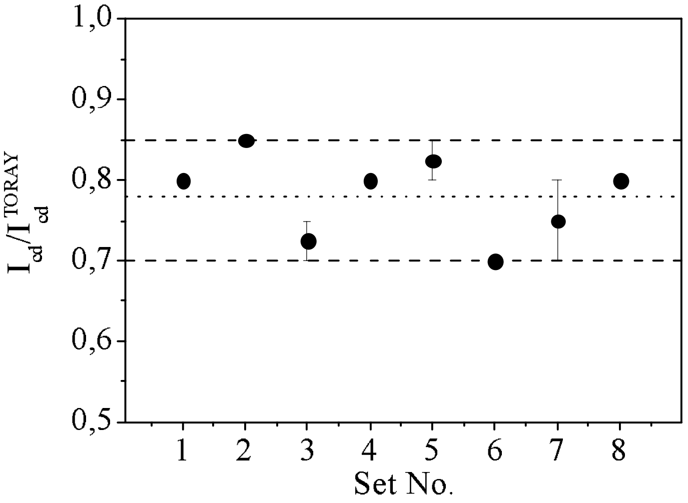


Fig. 5 I_{CD} value in comparison with one predicted by TORAY code.

The time behavior of $q(r_s^{exp})$ value for one experimental set are shown on fig. 4,b together with traces of measured intensity of soft X-ray emission from the plasma center, $I_{SXR}(0)$. Values of EC-current for all experimental sets in question are given on fig. 5 in comparison with the value predicted by TORAY code. I_{CD} in experiments discussed was in the range 19÷35 kA depending on P_{ab} and $\bar{n}_e$.

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