High Density Experiments with Strong Gas Puffing under ECRH in T-10

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Abstract. High density experiments were carried out in T-10 with gas puffing under ECRH (P_{ec} up to 1.8 MW) with oblique and perpendicular HF power launch. Densities exceeding the Greenwald limit (n_{Gw}) by up to a factor of 1.8 were achieved in a regime with a high value of the edge safety factor, q(a) ≅ 10. The decrease of q(a) to a value of 3 led to the reduction of the ratio $(\overline{n}_e)_{\lim}/n_{Gw}$ to 1. Confinement degradation with density growth was not significant up to the density limit. However, the typical T-10 linear growth of the energy confinement time with density saturates at $\overline{n}_e \geq 0.6 n_{Gw}$. The saturated τ_E values exceeded the ITER L-mode scaling predictions by up to a factor of 1.2 and were close to the value predicted by the ITER H-mode scaling.

1. Introduction

As was shown in previous T-10 experiments for densities up to $\overline{n}_e \cong 0.5 n_{Gw}$, energy confinement time in the T-10 plasmas with electron cyclotron heating (ECRH) increases with plasma density as $\tau_E \sim \overline{n}_e$ [1]. This allows us to expect high confinement time at densities close to the Greenwald limit, n_{Gw}. That is why high density experiments were carried out in T-10 under ECRH and gas puffing with the following aims: 1) determination of the maximum available density (in comparison with n_{Gw}); 2) confinement analysis at high densities ($\overline{n}_e \sim (\overline{n}_e)_{\lim} \geq n_{Gw}$) and 3) determination of the effect of the gas-puffing rate on confinement. The peculiarities of the plasma confinement in the vicinity of the density limit together with a comparison of the achieved τ_E values with the predictions of the ITER scaling laws for L- (ITER L-96) and H- (IPB98(y,2)) modes also were studied in these experiments.

These experiments were carried out under second harmonic ECR heating (f=140 GHz) with an absorbed power value up to P_{ab}=1.4 MW. The gyrotron pulse duration was 0.3-0.4 s, which led to the necessity to use strong gas puffing (up to $d\overline{n}/dt \sim 3.5\times10^{20}\ \mathrm{m^{-3}s^{-1}}$) at least during the first 50-70 ms after auxiliary heating switch-on to achieve high density. A typical scenario of the experiments is shown in *FIG. 1*. Both oblique (Ψ=21° to the B_z direction) and perpendicular power launches were used. This allowed us to estimate the effect of the HF wave refraction in the obtained value of the limit density (the cut-off density for the second harmonic EC wave with f=140 GHz in X-mode is $1.2\times10^{20}\ \mathrm{m^{-3}}$). The main experiments were carried out at the following values of the plasma current: I_p=90 kA (q(a)=8.2), I_p=150 kA (q(a)=4.8), I_p=250 kA (q(a)=3.1) at B_z=2.4 T (oblique EC power launch) and I_p=200 kA (q(a)=3.7) at B_z=2.5 T (perpendicular EC power launch).

2. Limit density value and role of EC wave refraction

The limit density achieved with gas puffing and ECRH in T-10 exceeds the Greenwald limit by a factor of 1.8 in discharges with high q(a) (q(a)≈10) as is seen in *FIG. 2,a*. However, the

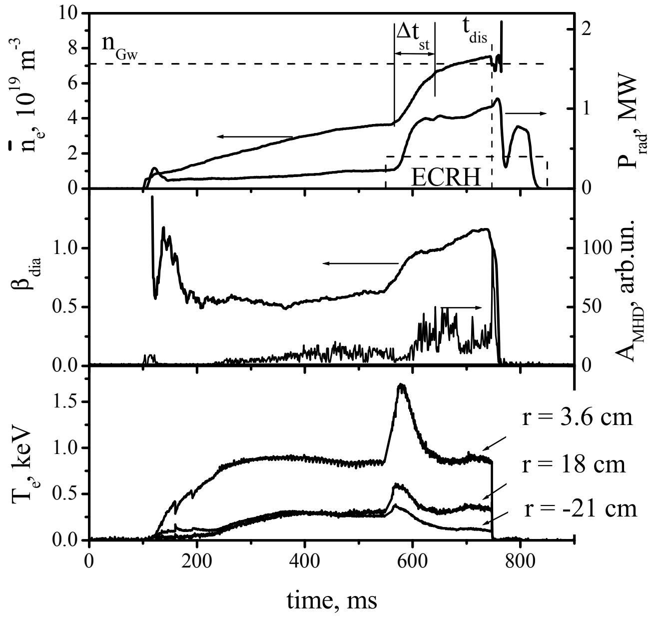

FIG. 1. Typical scenario of the density limit experiments in T-10 (Shot 34044). P_{rad} is the radiation power; β_{dia} is the ratio of the volume averaged kinetic pressure to the poloidal magnetic field pressure derived from the diamagnetic measurements; A_{MHD} is the amplitude of MHD mode m=2; T_e is the electron temperature from second harmonic ECE measurements; t_{dis} is the instant of the disruption.

value of $(\bar{n}_e)_{lim}/n_{Gw}$ decreases with I_p increase and becomes close to unity at q(a)=3.0. This could possibly be explained in the following way. In T-10 the current density profile peaks with q(a) increase. Also, experimental data show that changes of the limiter radius (in certain limits) at high q(a) do not lead to a change of the density limit value. This means that in T-10 conditions the radius of the current channel, a_{cur}, is a more adequate parameter in the Greenwald formula than the limiter radius. The relation of $(\bar{n}_e)_{lim}/(n_{Gw})_{mod}$, where $(n_{Gw})_{mod}=I_p/\pi(a_{cur})^2$, remains unchangeable with q(a) value if the limiter radius in the Greenwald formula is replaced by a_{cur} (*FIG. 2,a*). Here a_{cur} was chosen as the size of the area inside of which the plasma current value is equal to 95% of I_p.

Calculations with the TORAY-GA code [3] show (*FIG. 2,b*) that the relative value of the single-pass absorbed power, $(P_{ab})^{TOR}/P_{ab}$, at perpendicular HF power launch is close to 1 up to

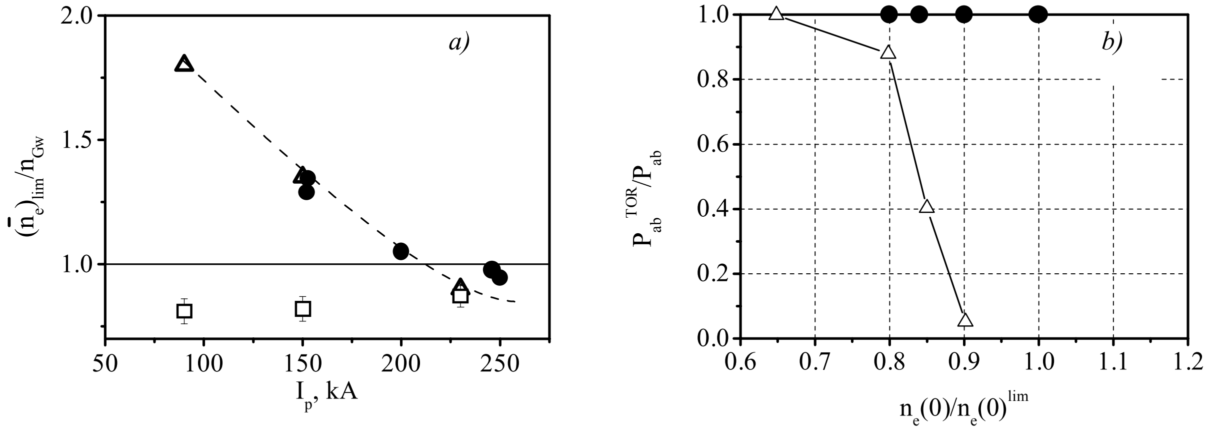

FIG. 2. (a) Dependence of $(\bar{n}_e)_{lim}/n_{Gw}$ on the plasma current value. Δ - $\Psi=21°$ [2], • - perpendicular power launch, □ - $(\bar{n}_e)_{lim}/(n_{Gw})_{mod}$; (b) calculated changes of the value of single-pass absorption with plasma density rise.

the density limit, $(n_e(0))^{\lim} = 1.1\times10^{20}$ m^{-3}. In contrast, $(P_{ab})^{TOR}/P_{ab} \le 10\%$ [2] at $n_e(0) = 0.9\times(n_e(0))^{\lim}$ under oblique power launch. However, the dependence of the ratio of $(\overline{n}_e)_{\lim}/n_{Gw}$ on plasma current under oblique power launch is the same as that in the perpendicular power launch case (*FIG. 2,a*). This is evidence of the fact that the power crossing the plasma edge plays a more important role in prevention of the edge cooling (and therefore in prevention of the disruption) than $P_{ab}(r)$ profile variations inside the plasma core. This agrees well with the qualitative picture of the limit density disruption found in previous T-10 experiments [2,4] and in the experiments discussed here. The increase of the plasma density in T-10 leads to the increase of the radiation losses (*FIG. 1*). Edge cooling becomes detectable at 20-30 ms before disruption: plasma temperature at the external 1/3 of the minor radius and in the SOL drops. This leads to plasma current profile peaking, which is accompanied by development of MHD activity with poloidal wave number m=2.

3. Confinement investigation

The main experiments for investigation of the changes of plasma confinement in a wide range of densities (up to the limit density) were carried out at I_p=200 kA, B_z=2.5 T in both ohmic and ECR heated plasmas. As was shown in [4], the limit density increases as $(\overline{n}_e)_{\lim} \sim \sqrt{(P_{ab}+P_{OH})/P_{OH}}$ in T-10 under ECRH. This kind of dependence allows experiments to be carried out in a wide range of plasma densities $\overline{n}_e \cong (1.5-7.5)\times10^{19}$ m^{-3} =$(0.2-1.1)n_{Gw}$ at the ECRH power level ~900-1150 kW. Ohmic discharges were also analysed to investigate features of the confinement variation with the density rise in more detail.

The maximum achievable plasma density in ohmic discharges was $\overline{n}_e = 5.1\times10^{19}$ m^{-3} $\cong 0.7n_{Gw}$. At the sufficiently low plasma densities ($\overline{n}_e \le 0.5n_{Gw}$), growth of τ_E is observed (*FIG. 3,a*). A further increase of the plasma density up to the limit density leads to τ_E reduction (in spite of the increase of plasma energy content (*FIG. 3,b*)) due to an increase of ohmic power. The increase of the loop voltage, U_L, due to the drop of the plasma temperature is the reason for this ohmic power increase.

As is seen from *FIG. 4,a,* the growth of τ_E with $\overline{n}_e$ increase in ECR heated plasmas is maintained up to $\overline{n}_e \cong 4\times10^{19}$ m^{-3} $\cong 0.6n_{Gw}$. At higher densities a saturation of the τ_E growth is observed. Nevertheless, at densities $\overline{n}_e \ge 0.6n_{Gw}$ and up to the density limit the energy confinement time remains up to 20 % higher than is predicted by the ITER scaling law for the L-mode [5] (ITER L-96) and exceeds the H-mode scaling (IPB98(y,2)) predictions by ~10% (*FIG. 4, b,c*). The increase of the auxiliary heating power does not change these enhancement factors.

Is the saturation of the $\tau_E(\overline{n}_e)$ dependence observed in both ohmic and ECR heated plasmas a result of the appearance of an additional mechanism of energy loss? It is often assumed [5] that in ohmic discharges the transition from the linear $\tau_E(\overline{n}_e)$ dependence (LOC) to the saturated one (SOC) is the result of ion temperature gradient mode (ITG) development. To estimate the role of ion turbulence in T-10 conditions and the influence of other mechanisms of energy loss (possible development of electron modes of turbulence), investigation was carried out based on the analysis of the electron density profiles, transport modelling and a comparison of the tendencies in plasma confinement with the measurements of plasma turbulence.

The experimental dependencies of total energy content, W_{tot}, and electron energy content, W_e, (defined from experimental T_e and n_e profiles) on plasma density are shown in *FIG. 5,a*. The ion part of the plasma energy is estimated as $W_i=W_{tot}-W_e$. It is seen that W_{tot} saturates at densities higher than $\bar{n}_e \cong 0.6n_{Gw}$ following electron energy content, whereas W_i increases with plasma density. Transport analysis shows that this kind of $W_i(\bar{n}_e)$ dependence can be described with the assumption of ion thermal diffusivity close to the neoclassical value, $\chi_i \cong (1-5)\chi_i^{neo}$. An assumption of higher χ_i values leads to a discrepancy (more than 15%) between the calculated W_{tot} value and the experimentally measured values of β_{dia} and $\beta+l_i/2$ (*FIG. 5,b*). Thus the confinement saturation discussed here is the result of the predominant influence of an additional energy loss in the electron channel. The possible development of ion modes of turbulence has no significant effect on saturation of plasma confinement at high densities ($\bar{n}_e \geq 0.6n_{Gw}$). Moreover, as is shown in [6], ITG development leads to the broadening of the plasma density profile. However, interferometer measurements show that in the regimes discussed here, no density profile broadening was observed with the density increase (*FIG. 5,c*). On the contrary, $n_e(r)$ becomes more peaked and the narrowest profile is observed before a disruption. A broad $n_e(r)$ profile, which could be a result of ITG mode development, is observed only during strong gas puffing (*FIG.1*) at the first 50 ms after EC pulse and gas puffing switch-on, Δt_{st}. This leads to the decrease of the energy confinement time at ~15%. The τ_E value recovers after the decrease of $d\bar{n}_e/dt$ (at the quasi-plateau).

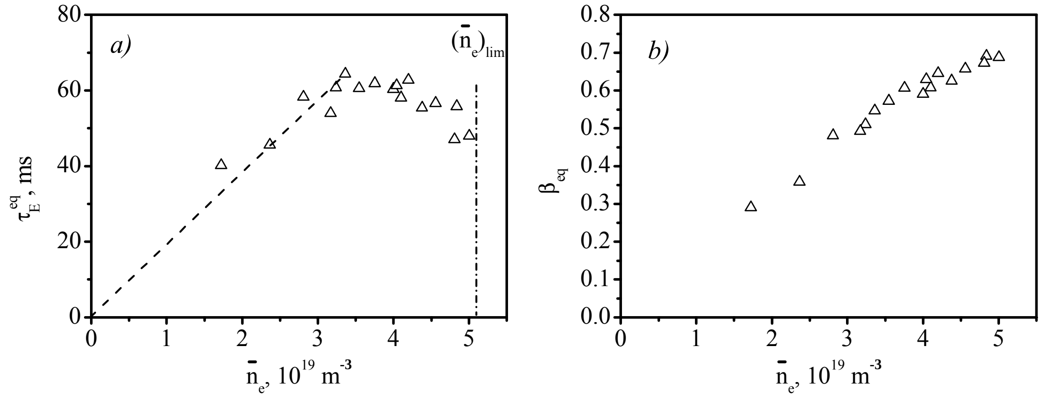

FIG. 3. Dependences of τ_E (a) and β measured from equilibrium (b) in the ohmic discharges.

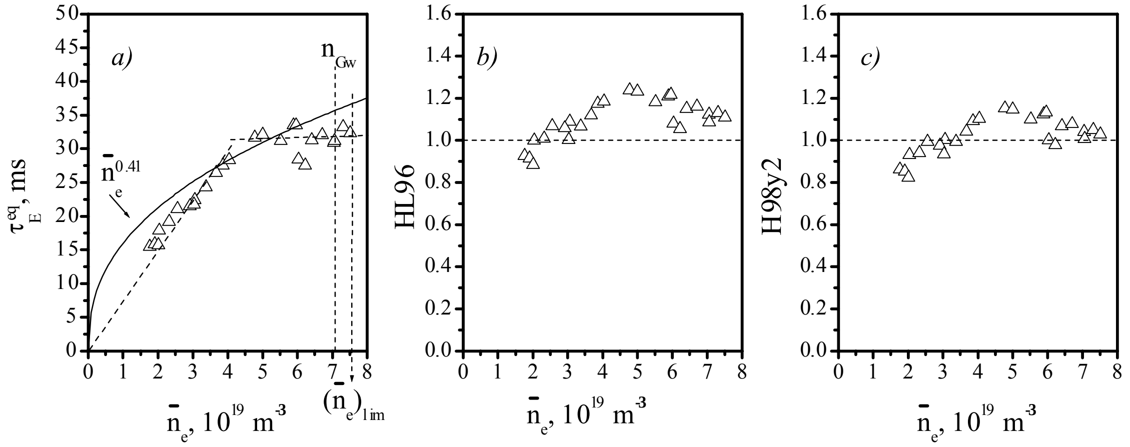

FIG. 4. (a) Dependence of the energy confinement time on the plasma density under ECRH; (b),(c) enhancement factor in comparison with the ITER L- and H-mode scalings.

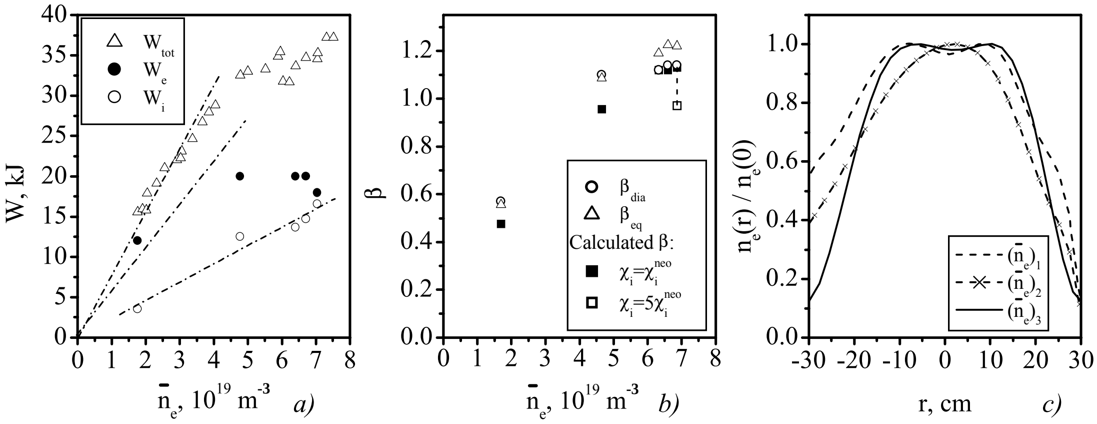

FIG. 5. (a) Experimental values of W_{tot}, W_e, W_i; (b) comparison of the experimental β with the results of estimation with assumption of $\chi_i \cong \chi_i^{neo}$ and $\chi_i \cong 5\chi_i^{neo}$; (c) changes of the density profile with $\bar{n}_e$ increase: $(\bar{n}_e)_1 \cong 1.8\times10^{19}$ m^{-3}, $(\bar{n}_e)_2 \cong 4.9\times10^{19}$ m^{-3}, $(\bar{n}_e)_3 \cong 7.3\times10^{19}$ m^{-3}.

Analysis of the plasma turbulence was carried out by correlation reflectometry [7]. These data demonstrate that ECRH switch-on with $P_{ab} \cong 1$ MW leads to an increase of the turbulence level by a factor of 1.7 with respect to the OH discharge [7]. This seems to be in agreement with changes of τ_E values. The level of the relative density fluctuations typically does not depend on the plasma density. The turbulence frequency spectra are relatively narrow with pronounced low frequency (f~100 kHz) quasi-coherent (QC) perturbations in both OH and ECRH regimes at low $\bar{n}_e$. A density rise leads to the appearance of high frequency (f~200 kHz) QC perturbations, which is interpreted in [7] as DTE mode, and to broadening of the turbulence frequency spectra.

4. Conclusions

The results of the T-10 experiments under gas puffing and ECRH demonstrate that:

- In T-10 conditions the Greenwald limit can be exceeded by a factor of 1-1.8 depending on plasma current;
- Energy confinement time increases with plasma density up to $\bar{n}_e \cong 0.6 n_{Gw}$ and saturates at higher densities, remaining above the ITER L-mode scaling predictions (and close to the H-mode scaling) up to the limit density;
- Saturation of the $\tau_E(\bar{n}_e)$ dependence at high densities seems to be a result of the electron instability (but not ITG) development.

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