ELECTRIC FIELD STUDY WITH HIBP IN OH AND ECRH PLASMAS ON THE T-10 TOKAMAK

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The plasma potential φ and radial electric field E_r were studied on T-10 in a wide range of ohmic and ECRH regimes. At densities $n_e > 10^{19}$ m^{-3}, the potential has negative sign over the whole plasma cross section. At lower densities, the outer zone with positive φ and E_r is formed. The absolute value of potential at mid-radius grows with density up to $n_e \approx 3\times10^{19}$ m^{-3} and then saturates. In regimes with ECR heating, $|\varphi|$ decreases owing to the density pump-out and the electron temperature increase. Measurements of E_r are compared with numerical simulations with several codes including nonambipolar fluxes due to the toroidal field ripple. The change of radially averaged $\overline{E}_r$ with density and temperature qualitatively agrees with neoclassical expectations.

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INTRODUCTION

The measurements of the electric potential φ in the core plasma are very important for understanding of the role of the radial electric field E_r in the confinement. The new observations of the potential evolution were performed in the T-10 tokamak (B=1.5…2.5 T, I_p=150…250 kA, R=1.5 m, a=0.3 m) in wider range of densities $\overline{n}_e$= (0.6…4.7)×10^{19} m^{-3} than previously [1]. We used the Heavy Ion Beam Probing (HIBP) with high spatial (< 1 cm) and temporal (1 μs) resolution. Tl^{+} ions with energies up to 300 keV allow us to probe almost the whole plasma cross section. Also we used the standard set of diagnostics: soft X-rays (SXR), electron cyclotron emission (ECE), diamagnetic loops, interferometers, neutral particles analyzer, Langmuir probes and other. Experimental data were compared with numerical simulations.

1. POTENTIAL MEASUREMENTS

Ohmic (OH) D_2 plasmas in T-10 (T_e<1.3 keV, T_i<0.7 keV) are characterized by a negative potential up to φ(0) = -1400 V at the centre, monotonically increasing towards the edge. The density rise due to gas puffing is accompanied by an increasing the absolute value of the negative potential (Fig. 1). Correspondingly, the radially averaged $\overline{E}_r$ value changes from 0 to -60 V/cm. This is valid both for the steady-state plasmas as well as for the initial stage with ramped plasma current I_p and density. At the very low densities, $\overline{n}_e$=(0.4…0.8)×10^{19} m^{-3}, the potential is positive and the edge E_r is about zero (Fig. 2).

When the density approaches to a certain value $\overline{n}_e$=(2.5…3.5)×10^{19} m^{-3}, the growth of potential saturates (Fig. 3), while the plasma stored energy W and energy confinement time τ_E are still growing with density (see Fig. 1). Powerful electron cyclotron heating (ECRH, P_{EC} < 3 MW) leads to the increase of $T_e(0)$ up to 3 keV, strong deformation the density profile with diminishing the central line-averaged density ("pump-out") up to $\Delta n_e/n_e$<20%. The mid-radius potential jumps by Δφ=200…400 V during on-axis ECRH, and then recovers up to the initial value after the ECRH switch-off.

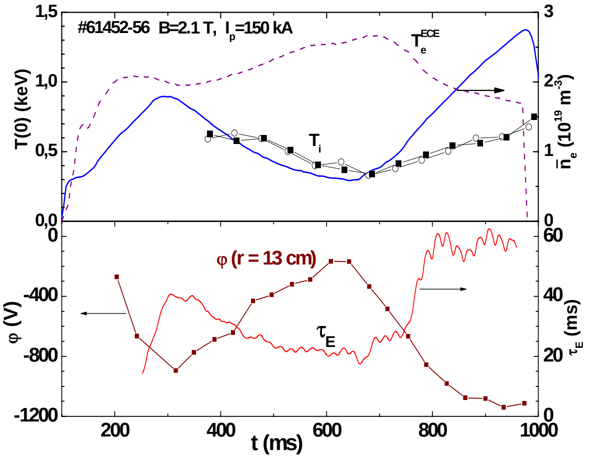

Fig. 1. Evolution of density, potential, electron and Ion temperatures and energy confinement time in shot with gas puffing

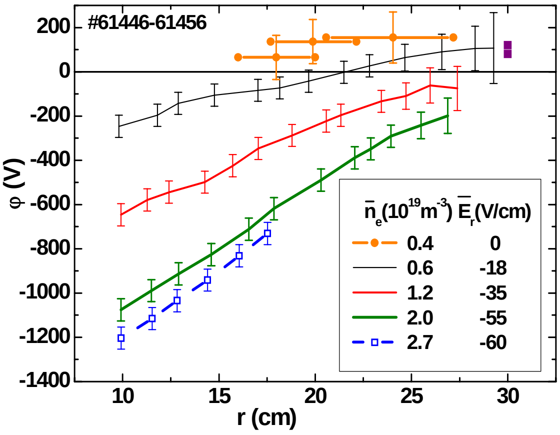

Fig. 2. The profiles of potential in shots with varying density measured by HIBP (lines) and Langmuir probe (squares)

Note that Δφ is nearly the same, ~400 V, independently on the density up to $\overline{n}_e$≤2.5×10^{19} m^{-3}.

When the density raises further, Δφ decreases and at the $\bar{n}_e$ ~5×10^{19} m^{-3}, it is about 200 V (Fig. 4). At the low-density ECRH, n_e=1.5×10^{19} m^{-3}, the edge potential is positive (Fig. 5) and the edge E_r is about zero.

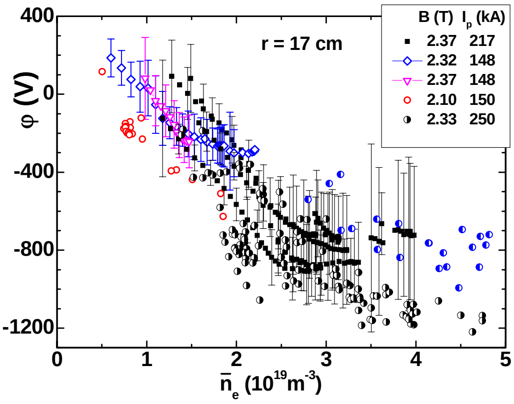

Fig. 3. The mid-radius potential evolution in the wide density range both for initial and steady states for different shots

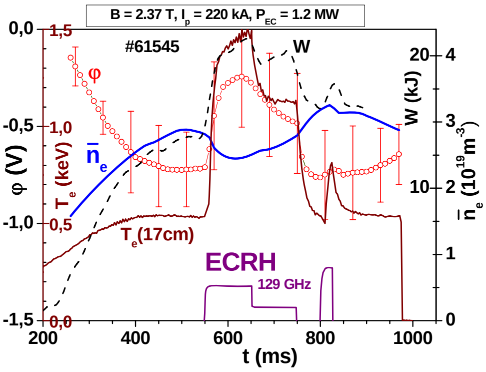

Fig. 4. Temporal evolution of density n_e, stored energy W, electron temperature T_e and potential φ (r=17 cm) in shot with ECR heating

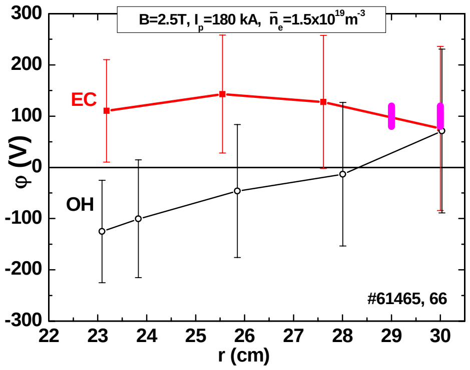

Fig. 5. Comparison of the edge potential profiles in shots with Ohmic and ECR heating at low density regime

2. NUMERICAL SIMULATION

The steady state electric field E_r can be obtained from ambipolarity of radial particle fluxes:

$$\Gamma_e(E_r) = \Gamma_i(E_r). \qquad (1)$$

Breaking of the toroidal symmetry in a tokamak leads to nonambipolarity of the radial particle fluxes (intrinsic ambipolarity violation). One of reasons for that is local magnetic field ripples due to the discrete toroidal coils. The T-10 tokamak with N=16 coils has a rather large ripple of toroidal field, δ~ 3% at the edge, that leads to formation of special population of locally trapped particles.

At low frequencies, $\nu^*<qN\delta^{3/2}$, where $\nu^*=\nu/(V_t/qR)$, V_t is a thermal velocity and q is safety factor, the radial transport of such particles is similar to 1/ν – regime of superbanana diffusion in stellarators, where particle fluxes are expressed as:

$$\Gamma_j \propto A_j\delta^{3/2}\left(\frac{T_j}{BR}\right)^2 \frac{1}{\nu_j}\left[\frac{n'}{n}+\frac{q_jE_r}{T_j}+\gamma_j^{rp}\frac{T_j'}{T_j}\right], \qquad (2)$$

where $j=e$, i, $A_i/A_e\approx2$, charge $q_j=\pm e$, $\gamma_{i,e}^{rp}$=3.37 or 3.45 for ions and electrons respectively, $\nu_j=\nu_{ii}$ or ν_{ei} [3]. In (2) fluxes strongly depend on the temperatures. Estimations predict that in regimes with $T_e/T_{i,}\geq4$, the electron and ion fluxes are comparable, and the electric field can change the sign to positive one. So, approaching of the measured potential to zero in regimes with low density and high $T_e/T_{i,}$, shown in Fig. 2, in general, does not contradict to neoclassical theory. However, at the middle and edge regions of plasma, $T_e/T_{i,}$ is somewhat less than 4, so the observed φ>0 at the edge can be explained by suprathermal electrons existence (increasing of the effective T_e and γ_e^{rp} value).

In regimes with higher densities and, as consequence, with higher collisionality and the ion temperature, the ion neoclassical flux is dominant. In this case, the ambipolar electric field can be estimated from the condition Γ_i=0:

$$E_r = T_i\,(n_i'/n_i + \gamma\ \ T_i'/T_i), \qquad (3)$$

which leads to E_r<0. The theory gives γ=1.5 for the "plateau" regime.

Numerical simulation of shots with measured profiles of electron and ion temperatures and density [1, 4], shown in Fig. 6, was performed with DKES and VENUS+δf codes [5]. Figure 7 shows comparison of calculation by different codes with experiment (shot #57412 with $\bar{n}_e$=2.0×10^{19} m^{-3}). Also, the analytical neoclassical estimations by Eq. (3) are presented with theoretical value γ = 1.5 and with best fit to experiment, γ = 2.5. The theoretical absolute values of the electric field are substantially lower than experimental ones, but the sign of field and its dependence on the temperature and density for several shots are within the neoclassical framework. Possible reasons of discrepancy may be the suprathermal particles or underestimation of plasma rotation.

In summary, these results present the important features of φ and its complicate link with confinement. Main tendencies of the electric field change with density and temperature agree with neoclassical expectations.

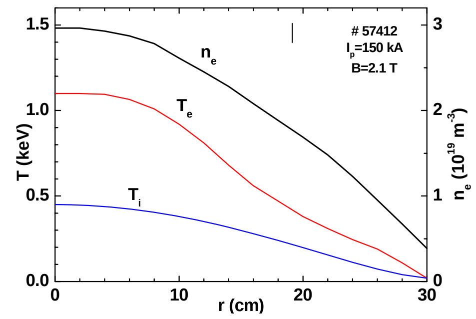

Fig. 6. Profiles of temperatures and densities used for simulation

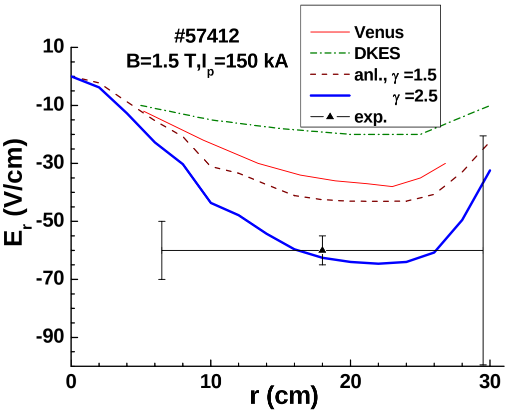

Fig. 7. Radial electric field computed by the DKES and VENUS codes, analytically (Eq. 3) with γ = 1.5 and best experimental fit, γ = 2.5 vs averaged field $\bar{E}_r$ from HIBP experiment (triangle)

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ИССЛЕДОВАНИЕ ЭЛЕКТРИЧЕСКОГО ПОЛЯ С ПОМОЩЬЮ HIBP ПРИ ОМИЧЕСКОМ И ЭЦР-НАГРЕВЕ НА ТОКАМАКЕ Т-10

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Потенциал плазмы φ и радиальное электрическое поле E_r исследовались на токамаке Т-10 в широком диапазоне омических и ЭЦР-режимов. При плотностях $n_e > 10^{19}$ м$^{-3}$ потенциал имеет положительный знак во всем сечении плазмы. При меньших плотностях во внешней зоне потенциал и E_r меняют знак. Абсолютное значение потенциала на середине радиуса растет с плотностью вплоть до $n_e \approx 3\times10^{19}$ м$^{-3}$, а затем насыщается. В режимах с ЭЦР-нагревом абсолютная величина $|\varphi|$ уменьшается за счет откачки плотности и роста электронной температуры. Измерения E_r сравнивались с численными расчетами по нескольким кодам, учитывающим неамбиполярные потоки за счет гофрировки тороидального поля. Изменение среднего поля $\bar{E}_r$ с плотностью и температурой не противоречит неоклассическим ожиданиям.

ДОСЛІДЖЕННЯ ЕЛЕКТРИЧНОГО ПОЛЯ ЗА ДОПОМОГОЮ ЗППВІ ПРИ ОМІЧНОМУ ТА ЕЦР-НАГРІВІ У ТОКАМАЦІ Т-10

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Потенціал плазми φ та радіальне електричне поле E_r було досліджено на токамаці Т-10 у широкому діапазоні омічних та ЕЦР-режимів. При щільностях $n_e > 10^{19}$ м$^{-3}$ потенціал має позитивний знак в усьому перетині плазми. При менших щільностях у зовнішній зоні потенціал та E_r змінюють знак. Абсолютне значення потенціалу на середині радіуса росте зі щільністю майже до $n_e \approx 3\times10^{19}$ м$^{-3}$, а потім насичується. У режимах з ЕЦР-нагрівом абсолютна величина $|\varphi|$ зменшується за рахунок відкачки щільності та росту електронної температури. Вимірювання E_r порівнювалися з числовими розрахунками за декількома кодами, які враховують неамбіполярні потоки за рахунок гофрировки тороїдального поля. Зміна середнього поля $\bar{E}_r$ з щільністю та температурою не протирічить неокласичним сподіванням.