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Evolution of the electric potential and turbulence in OH and ECRH low-density plasmas in the T-10 tokamak

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Positive plasma potential was observed for the first time in a core tokamak plasmas, conventionally characterized by negative potential. Direct measurement of the electric potential in the core plasma is of paramount importance for the understanding of the role of radial electric field E_r in the mechanisms regulating the toroidal plasma confinement. New experimental observations and theoretical description of the E_r formation based on neoclassical (NC) models in the core and turbulent dynamics in the edge of the T-10 tokamak are the goals of this paper. A Heavy Ion Beam Probe (HIBP) diagnostic was developed for T-10 (circular tokamak, B_0=1.7-2.42 T, R=1.5 m, a=0.3 m) to study the plasma potential with high spatial (<1 cm) and temporal (1 μs) resolution. Tl+ ions with energies E_{beam} up to 330 keV were used to probe the plasma from the edge to the core {1}. Low-density OH deuterium plasmas (n_e=1.0x10^19 m^−3,T_e<1.3 keV, T_i<0.6 keV) in T-10 are characterized by a negative potential up to φ= 1500 V near the centre (ρ=r/a=0.3), Fig. 1. The potential profile monotonically increases towards the periphery, forming the radially averaged electric field E_r = -75 V/cm. At the edge (ρ=1), HIBP data agrees with Langmuir Probe measurements (star in Fig. 1). The density rise due to gas puff is accompanied by an increase of negative potential. This is valid both for the steady-state phase of the discharge, and for the initial phase of the plasma current and density ramp-up. Powerful off-axis (ρ_{EC}=0.5) second harmonic X-mode ECRH with P_{EC_off}<1.7 MW (f_{EC_off}=144 GHz, gyrotrons A and C) leads to an increase of T_e up to 2 keV in the centre, as measured by ECE and shown in Fig. 2. It also causes a dramatic raise of the core plasma potential towards the positive values over the whole observation area, with the local potential increase $\Delta\varphi$=1000 V near the centre and E_r= - 20 V/cm. Potential profile has a sort of a plateau near the edge (ρ=0.8-1). An extra nearly on-axis (ρ=0.2) ECRH with P_{EC_on}<0.5 MW (f_{ECon}=129 GHz, gyrotron B) leads to a further increase of T_e up to 3.3 keV at the centre and a potential raise in the core plasma forming an extended area of positive E_r = 20 V/cm, from the core to the edge as presented in Fig. 1. Remarkably, the plasma potential in the TJ-II stellarator with similar size and plasma parameters shows positive electric potential for low-density plasmas with powerful second harmonic X-mode ECRH {2}.
Geodesic Acoustic Modes (GAMs) and broadband (f<400 kHz) turbulence of the plasma potential and density have been directly studied by HIBP from the plasma core to the edge and by Langmuir probe at the edge. GAMs altogether with higher frequency satellite are dominating in potential power spectra in OH plasma, GAM amplitude increases during ECRH. Both GAM and satellite have uniform structure with constant frequencies over a wide radial extension, exhibiting the features of global eigenmodes of plasma oscillations, as shown in Figs. 3 and 4, where f_{GAM}=18-22 kHz, and f_{sat}=23-25 kHz.
The main GAM peak has wider outer bound at the plasma edge than the satellite; f_{GAM} follows the theoretical scaling f_{GAM}~sqrt(T/m_i)/R (for T_e at ρ=0.7) for both OH and ECRH regimes in a wide temperature range, covering the whole operational limits of T-10. In addition to GAM, quasicoherent (QC) electrostatic mode with frequency 50-120 kHz takes place. In contrast to GAM, dominating in potential power spectra, QC-mode dominates in density power spectra. A Stochastic Low Frequency (SLF) mode with frequency <50 kHz is also seen in the plasma density and potential power spectra, density poloidal coherence and cross-phase. Bicoherence analysis has shown three-wave coupling between GAM and broadband turbulence, predominantly with QC. NC modeling was performed with various codes from the simple analytical approach {1} to the NC orbit code VENUS+δf {4}. Core radial profiles and the main tendencies like potential decrease with density raise and potential raise with T_e increase due to ECRH were explained by NC models within the experimental and modeling accuracy. Direct numerical calculation of the turbulent dynamics in the edge plasma by the 4-field {ρ, n, p_e, p_i} nonlinear two-fluid MHD Braginskii model based on {4} explains the E_r dynamics due to the influence of the Reynolds stress, in turn caused by potential phase relations, and the Winsor force. In summary, the results indicate the important features of φ and E_r profiles and electrostatic turbulence: the negative potential growth with density (confinement time), change of potential sign to positive, and positive potential growth with ECRH (decrease of confinement time) may shed a light to the properties of plasma energy confinement.
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