Plasma potential profiles and oscillations in ECRH and NBI plasmas in the TJ-II stellarator

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The direct measurements of an electric potential and its fluctuations in a core plasma are of a primary importance for the understanding the confinement improvement mechanisms and the role of electric field E_r in toroidal plasma confinement. Heavy Ion Beam Probe (HIBP) diagnostics is used in TJ-II (four-period flexible heliac, $B_0 = 1$ T, $R = 1.5$ m, $a = 0.22$ m) to study directly the plasma potential φ with fine spatial (< 1 cm) and temporal (1 μs) resolution. Cs^+ ions with energies up to 150 keV are used to probe ECRH and NBI heated plasmas ($P_{ECRH} \leq 600$ kW, $P_{NBI} \leq 900$ kW (port through), $E_{NBI} = 30$ kV) from the edge to the core. Poloidally resolved potential measurements provide poloidal electric field E_{pol} = $(\varphi_1-\varphi_2)/x$, x~1 cm, so the turbulent particle flux: $\Gamma_r = \Gamma_{E pol\times Btor} = \langle n_e^{\sim} v_r^{\sim}\rangle$ [1].

Low density ECRH plasmas ($n_e = 0.25$ - 0.7×10^{19} m^{-3}) are characterised by positive plasma potential up to $\varphi(0) = +1200$ V at the centre, obtained at the lowest density and maximum $P_{ECRH} = 600$ kW. The minor area of the negative electric potential may appear at the edge depending on the plasma density. Figure 1 shows that the density rise is accompanied by the decrease in the plasma potential, which evolves to the smaller absolute values becoming fully negative for the densities $n_e > 1.5\times10^{19}$ m^{-3}, obtained in the NBI sustained plasma [2]. During the further density rise, potential and E_r dives lower, getting a kind of saturation at $\varphi(0) = -600$ V, when the line-averaged density approaches $n_e = 1.0$-1.5×10^{19} m^{-3}, as presented in Fig. 2. The density, at which the potential obtains saturation, depends on the plasma conditions and P_{ECRH}. Contrary, the rise of T_e due to the increase of P_{ECRH} leads to the increase of the plasma potential, as presented in Fig. 3. This P_{ECRH} scan was performed at the constant density (n_e = 0.65×10^{19} m^{-3}). In this experiment, ECRH plasmas shows the linear dependence of the central potential φ_0 on the energy confinement time τ_E, estimated by diamagnetic signal, as presented in Fig. 4. The central potential and so the mean radial electric field E_r are decreasing (evolving towards more negative values), when the plasma confinement increases. Similar trend has been observed in tokamaks [3, 4].

In addition, potential and density oscillations caused by Alfvén Eigenmodes (AE) have been studied in NBI plasma. NBI induced AEs are pronounced in both plasma potential and density measured by HIBP in the frequency band $50 < f_{AE} < 350$ kHz. AEs are also visible in HIBP beam toroidal shift, representing B poloidal, in Mirnov signal and other diagnostics. Plasma density is increasing during NBI pulse, AE frequencies are changing in accordance with the Alfvénic scaling $f_{AE} \sim n_e^{-1/2}$. The oscillating core poloidal electric field due to AEs was found to have a range E_{pol}~10 V/cm [1]. The AE contribution into the bulk plasma turbulent particle flux was studied in details. Figure 5 presents the frequently resolved turbulent particle flux in the NBI sustained discharge. The flux related to the broadband turbulence has an intermittent character. It consists of stochastic sequence of spikes, mostly directed outward. AEs present quite pronounced quasi-coherent peaks in flux spectrograms Figure 5 shows AE may contribute to both outward and inward flux, and also produce no flux, depending on the phase relations between E_{pol} and density oscillations.

A new type of the modes was found in ECRH plasma with extremely low density (n_e = 0.2 - 0.3×10^{19} m^{-3}, P_{ECRH} = 600 kW), apparently associated with the presence of suprathermal electrons. These modes are seen both on the bolometer signal and on the plasma potential and density measured by HIBP, as a set of 2-4 of peaks with typical frequencies f = 30-60 kHz,- with a constant shift one to another. Figure 6(a) present the typical mode radial/frequency structure in HIBP density spectrogram obtained by radial scan. Contrary to the NBI induced AEs, these modes are not visible in the HIBP beam toroidal shift and in Mirnov signal. These modes do not produce any visible contribution to the turbulent particle flux. The radial distribution of the frequently resolved turbulent particle flux is presented in Fig. 6(c). It shows no contribution of the modes to Γ_r, due to due to the phase shift between E_{pol} and density oscillations, which was found to be $-\pi/2$ for all mode branches.

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References

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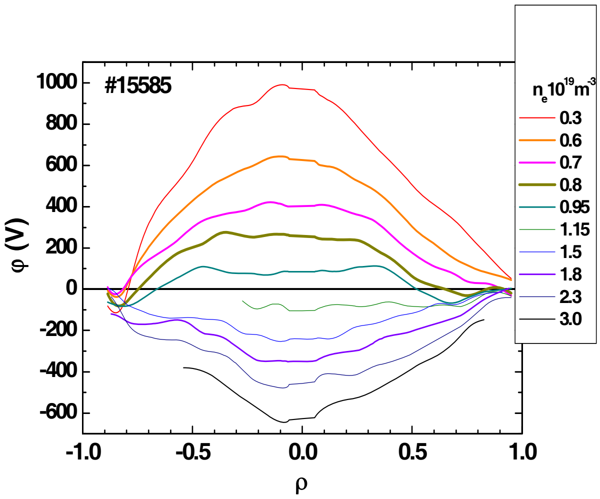

Fig. 1. Plasma potential profile evolution, associated with the density increase in the combined ECRH and NBI heated discharge. Upper set of the profiles is ECRH phase. Lower set of the profiles - NBI phase. Various densities marked with different colours.

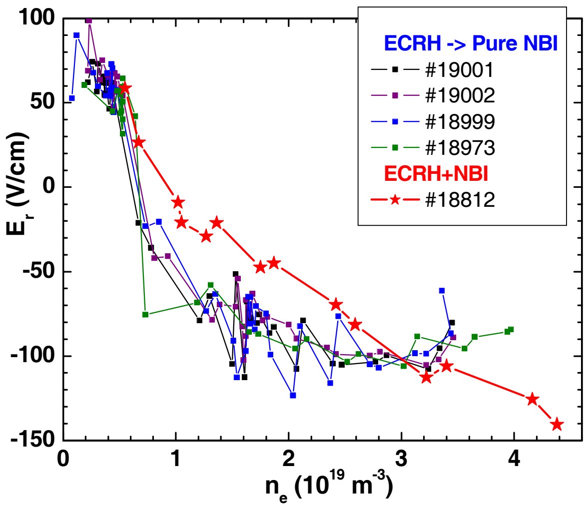

Fig. 2. Evolution of the radial electric field at ρ = 0.7 with line averaged density in series of shots with ECRH followed by NBI in dark colours, combined ECRH & NBI are in red.

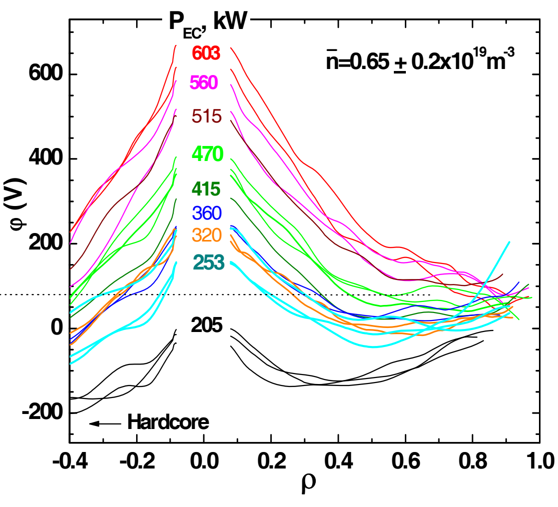

Fig. 3. Plasma potential profiles for the P_{ECRH} scan. Profiles in different colours correspond to various P_{ECRH}.

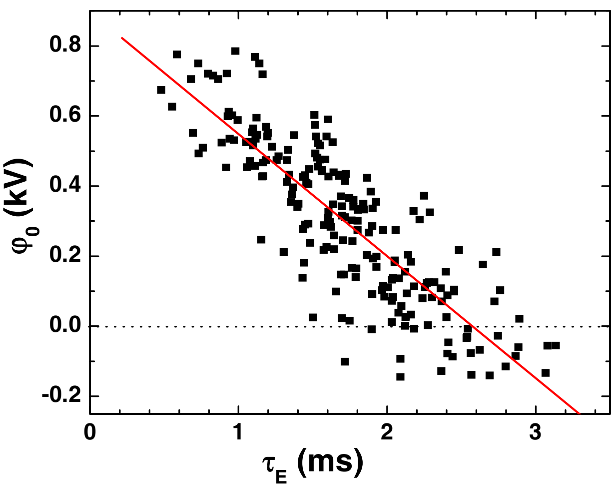

Fig. 4. The central potential versus the energy confinement time for the ECRH power scan with $n_e = 0.65\times10^{19}$ m^{-3}.

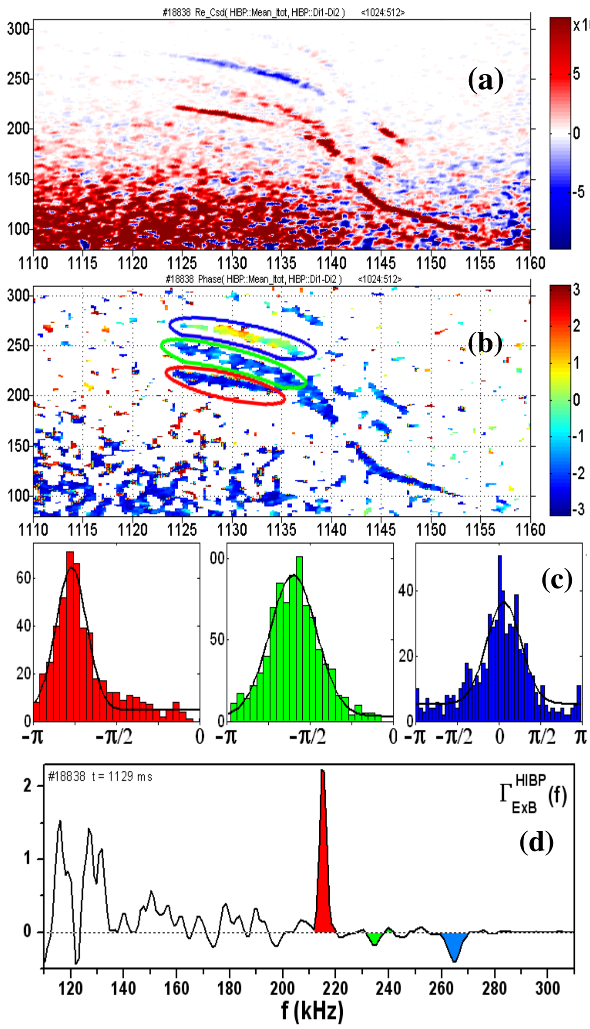

Fig. 5. a) Frequently resolved turbulent particle flux (in arb. units) in the NBI sustained discharge. Red color means outward flux, blue – inward flux. The Alfvén Eigenmodes are quite visible in the spectrogram, indicating the AE contribution in the total turbulent flux is significant.

b) Cross-phase between E_{pol} and n_e oscillations. Colour bar is in radians. Three branches of the AE are marked by coloured ovals.

c) The histograms of the cross-phase for each marked branches with corresponding colorus. Left box – -3/4π phase, corresponding to the outward flux, central box – -π/2 phase, corresponding to zero flux, right box ~ 0 phase, corresponding to inward flux.

d) An example of the frequency spectrum of the turbulent particle flux, taken at some time instant, averaged over 1 ms. Three frequency peaks for the discussed branches of the AE are marked by corresponding colours.

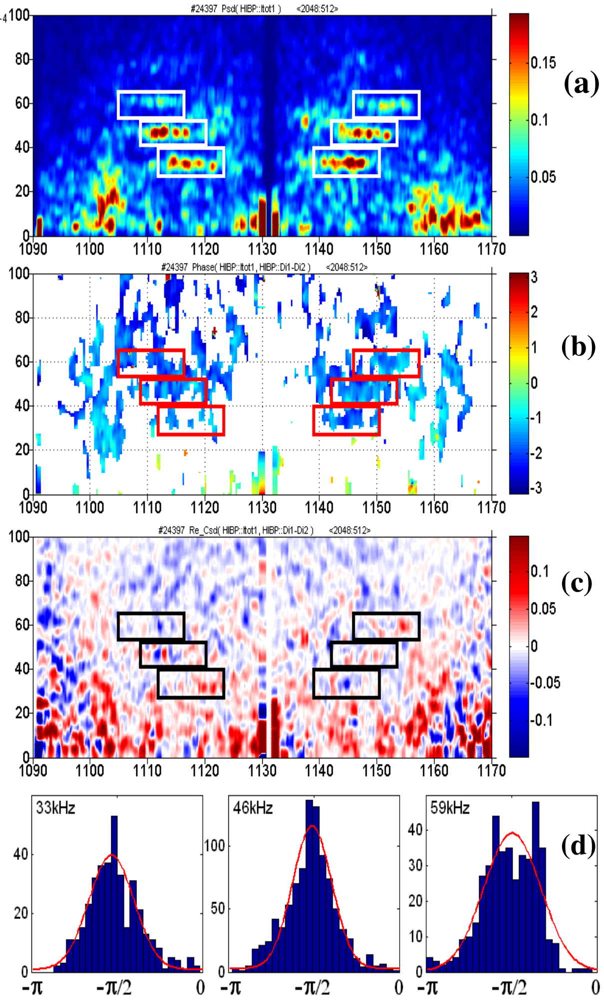

Fig. 6. a) Radial distribution of plasma density PSD, obtained during scan from ρ=0.8 at *t*=1090 to ρ=0.2 at *t*=1130 and back to ρ =0.8 at *t*=1170 ms. Three quasi-monochromatic modes are clearly pronounced.

b) Cross-phase between E_{pol} and n_e oscillations. Three branches of the modes are highlighted by red rectangles. Colour bar is in radians.

c) Radial distribution of the frequently resolved turbulent particle flux (in arb.units). Red color means outward flux, blue – inward flux. The modes are invisible in the spectrogram, indicating the mode contribution in the total turbulent flux is negligibly small compared to the broadband turbulence.

d) The histograms of the cross-phase for each marked branches. All three branches presents phase -π/2, corresponding to zero flux.