Heavy Ion Beam Probe investigations of plasma potential in ECRH and NBI in the TJ-II stellarator

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Abstract. The investigation of plasma potential profiles reveals a direct link between electric fields, density and plasma confinement in the TJ-II stellarator. The smooth change from positive to negative electric field observed in the core region as density is raised is correlated with global and local transport results, showing a confinement time improvement. Core plasma potential is also linked to kinetic effects (suprathermal electrons). Quasicoherent modes have been observed in TJ-II plasma under specific conditions when plasma density and heating power exceed some threshold values. This suggests the role of low order rationals and of threshold gradients in the triggering of the quasicoherent modes.

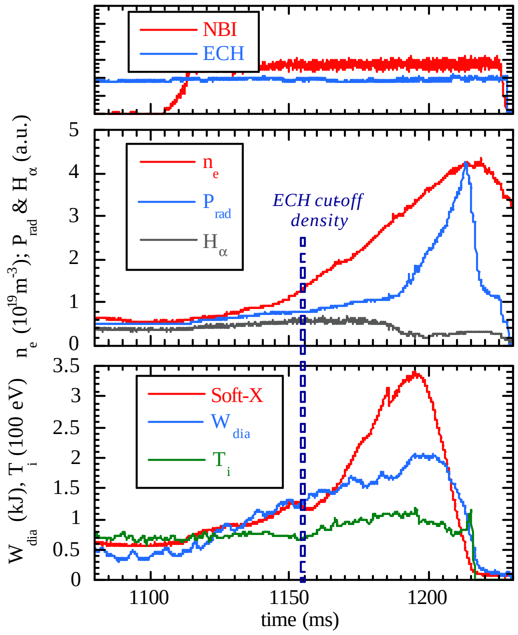
1. Introduction

Direct measurements of electric potential and its fluctuations are of a primary importance in magnetic confinement systems [1]. The Heavy Ion Beam Probe (HIBP) diagnostic is used in TJ-II stellarator with helical axis ($\langle R \rangle$ = 1.5 m, $\langle a \rangle$ = 0.22 m, B_0 = 1.0 T) to study directly plasma electric potential profiles with spatial (up to 1cm) and temporal (up to 10 μs) resolution. The singly charged heavy ions Cs^+ with energies up to 125 keV are used to probe the plasma column from the edge to the core [2, 3]. Both ECRH and NBI heated plasmas (P_{ECRH}= 200 - 400kW, P_{NBI} = 200 - 400kW, E_{NBI} = 28 kV) were studied.

The significant improvement in the HIBP beam control system and the acquisition electronics leads us to increase the capabilities of the diagnostic. The most crucial one is the extension of the signal dynamic range, which allows us to have reliable profiles from the plasma center to the plasma edge both in the high and low field side regions. The NB were injected on target ECRH plasmas whose typical parameters were: T_e (0) ~1 keV, T_i ~80 eV, $\overline{n}_e \sim (0.5 - 1)\times10^{19}$ m^{-3} and energy confinement time τ_E ~ 3 - 4 ms.

2. Plasma potential in ECRH and NBI plasmas

Different combinations of gas puffing, ECRH heating and wall conditioning strategies have been investigated with the aim of optimizing power coupling and density control in NBI plasmas. Density control in NBI discharges has so far proven to be difficult. Figure 1 shows the temporal evolution of the plasma density, edge radiated power, ion temperature, stored



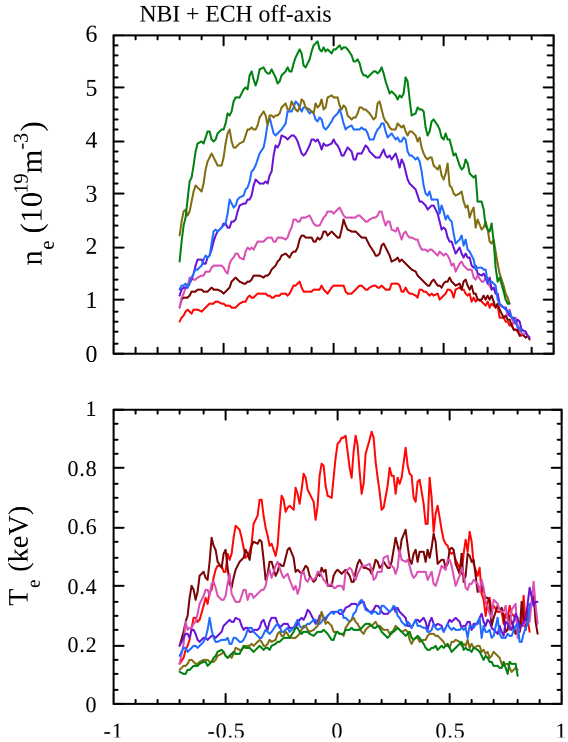


Fig 1. The temporal evolution of a non-steady state ECRH plus NBI discharge where the density increases up to radiation collapse. The signals shown are: ECRH and NBI monitors, line-averaged electron density $\overline{n}_e$, edge radiation P_{rad}, H_α emission, stored energy W_{dia}, soft X-ray and central ion temperature T_i.

Fig 2. Electron density and temperature profiles evolution in a non-steady state off-axis ECRH plus NBI plasmas. Data obtained by the Thomson scattering diagnostic for a set of reproducible shots. Corresponding curves are shown with the same colors. Measurements were taken in standard TJ-II magnetic configuration (100_44_64) with $\iota(a)/2\pi \sim 1.62$.

energy, H_α monitor and soft-X rays in such discharges. The density increases monotonically along with temperature decay (Fig. 2) until a radiation collapse occurs. Note that ECRH cut-off takes place at the local density n_e = 1.7×10^{19} m^{-3}. Plasmas created by off-axis ECH and with ECH maintained during the NBI phase, together with wall conditioning techniques, are promising. In this way NBI plasma discharges with density control (up to 130 ms) have been obtained.

Low density ECRH (n = 0.5-1.1×10^{19} m^{-3}) plasmas in TJ-II are characterised by core positive plasma potential of order of 500 – 1000 V and positive electric fields up to 50 V/cm. Fig. 3 shows the temporal evolution of electron density while Fig. 4 shows the plasma potential profile for the time instants marked in figure 3. Edge radial electric fields remain positive at low densities and become negative at the threshold density that depends on plasma configuration.

NBI plasmas are characterized by negative electric potential in the full plasma column and negative radial electric fields in the range of 10 – 40 V/cm, (Fig 4). The density rise during the NBI phase is accompanied by the decay of core plasma potential. When density is getting the level of n ~ 2.0 ×10^{19} m^{-3}, the potential remains almost constant (Fig. 5). The evolution of plasma potential in one shot shows the clear link between plasma potential and density, but not with the heating method, ECRH or NBI (Fig. 6).

It is important to note that potential profile evolves smoothly from positive to negative values passing through the zero average potential (Fig. 7). It should be noted that global energy confinement time of TJ-II follows the new ISS04 scaling which is based on data from nine major stellarators, and shows robust dependencies on density and heating power [4].

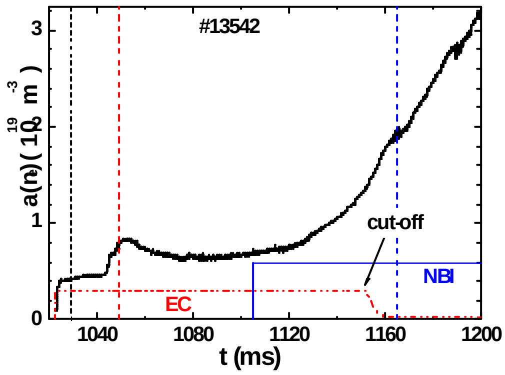


Fig 3. Temporal evolution of the density in a non-steady ECRH and NBI shot. The vertical lines show the time instants of potential profiles measurements.

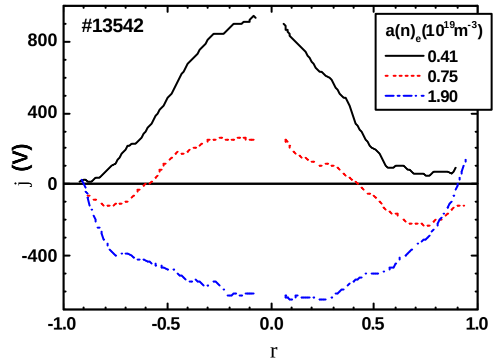


Fig 4. Temporal evolution of the potential profile. In the ECRH phase the potential is positive, in NBI phase the potential is negative.

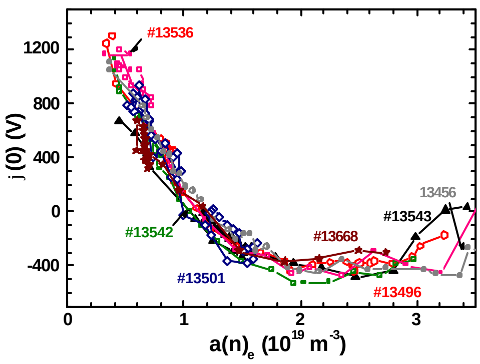


Fig 5. Dependence of the central potential on the line-averaged electron density for several ECRH/NBI discharges.

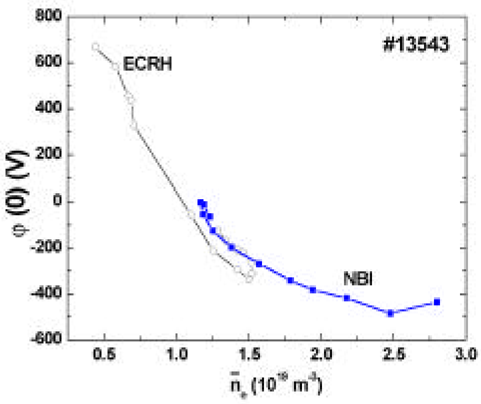


Fig 6. Dependence of the central potential on the line-averaged electron density for a single ECRH/NBI discharge. The potential is unambiguously linked with density.

3. Edge electric fields and influence of plasma density

It was reported that the existence of edge sheared flows in TJ-II requires a minimum plasma density in ECRH plasmas. Near (below) this threshold density, the level of edge turbulent transport, as well as the turbulent kinetic energy, increases significantly at the plasma edge. Langmuir probe measurements in ECRH plasmas revealed the negative E_r formation at the plasma edge (0.85 < ρ <1) when $\bar{n}_e > 0.5\times10^{19}$ m^{-3} [5]. The upgrading of the HIBP signal dynamic range allows reliable radial profiles to be obtained from the plasma center to close to the edge (0.1< ρ <0.9), where they can be overlapped with Langmuir probes data. Figure 8 shows an example of the potential profile evolution obtained in a single shot. These data show that the origin of the negative potential is at the plasma edge; the negative well then spreads across the whole plasma radius as the density increases. Note that both diagnostics, *i.e.* the HIBP and edge probes (Fig. 8), show the same threshold density for the negative potential formation, n_{cr} ~ 0.5×10^{19} m^{-3}.

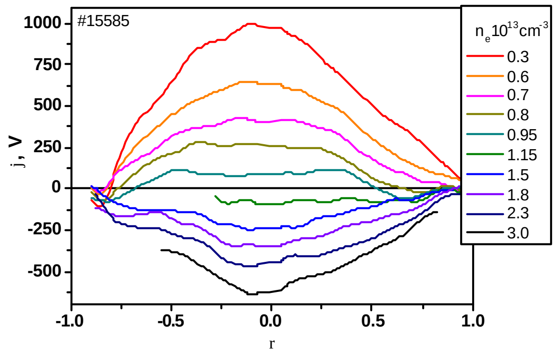


Fig 7. Potential profile evolves smoothly from positive to negative values passing through the zero average potential.

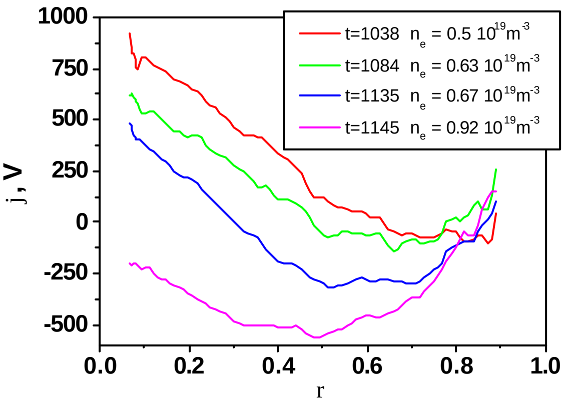


Fig 8. Evolution of the potential profile, with density in an ECRH plasma. When the density exceeds n_{cr} = 0.5×10^{19} m^{-3}, a negative electric field is formed near the edge.

4. Plasma potential and kinetic effects

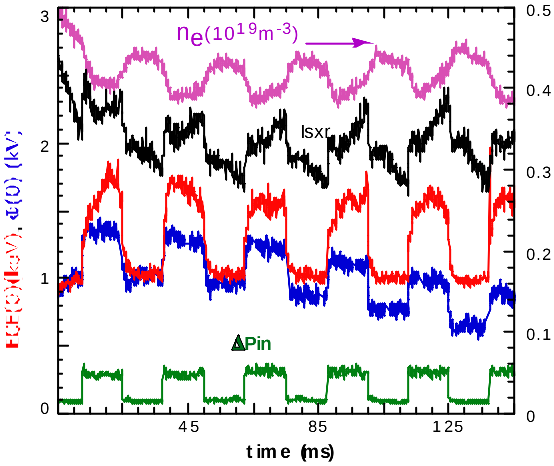
Low frequency ECR input power modulation experiments have shown that at the times of switching on/off one of the gyrotrons (i.e. during fast changes in absorbed power density) there is a sudden increase/decrease of core plasma central potential. At the same time, as shown in Fig. 9 rhs, there is a change of the characteristic energy of the suprathermal electron tail, evaluated from soft-x ray energy spectra (in the range of 4 to 10 keV). The associated increase/decrease of electron pump-out can be seen even in the line-averaged density. The rapid modification of the radial profile of the electric field affects the trapped particle transport so strongly that the spatial distribution of plasma emissivity can be rather distorted [6].

5. Quasi-coherent oscillations

Quasi-coherent oscillations have been observed in TJ-II plasma with different diagnostics. The recent improvement in the signal to noise ratio of the Heavy Ion Beam Probe (HIBP) diagnostic has allowed us to observe the radial structure of these oscillations from the edge to the plasma core region.

Edge quasi-coherent fluctuations (with frequencies in the order of 10 - 20 kHz) have been observed in some configuration windows when plasma density/heating power are above a threshold in ECRH heated plasmas [7]. HIBP measurements suggest that the amplitude of those modes tends to be larger in the low field side region. HIBP signals are strongly correlated with probe (Langmuir and Mirnov) signals. The appearance of those modes in specific configuration windows suggests the role of low order rationals in the plasma edge. The existence of threshold densities and heating power points out the role of threshold gradients to trigger quasi-coherent modes. Finally, the mode frequency slightly increases with plasma density; this result can be explained on the basis of (ExB) shift effects due to the link between perpendicular velocity and plasma density.

When rationals move towards the plasma core (ρ~ 0.3), the modes are clearly seen in ECE emission and in HIBP secondary current and potential signals. These quasi-coherent



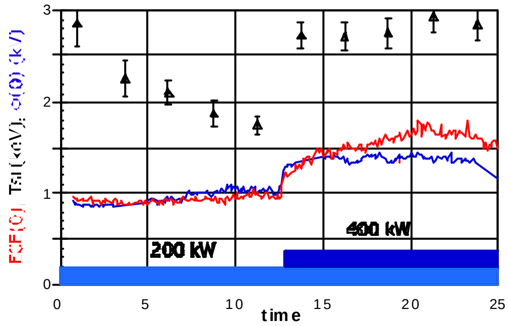


Fig. 9. Lhs) Plasma response to low-frequency input power modulation. rhs). Evolution of the mean energy of the electron suprathermal tail during the first cycle.

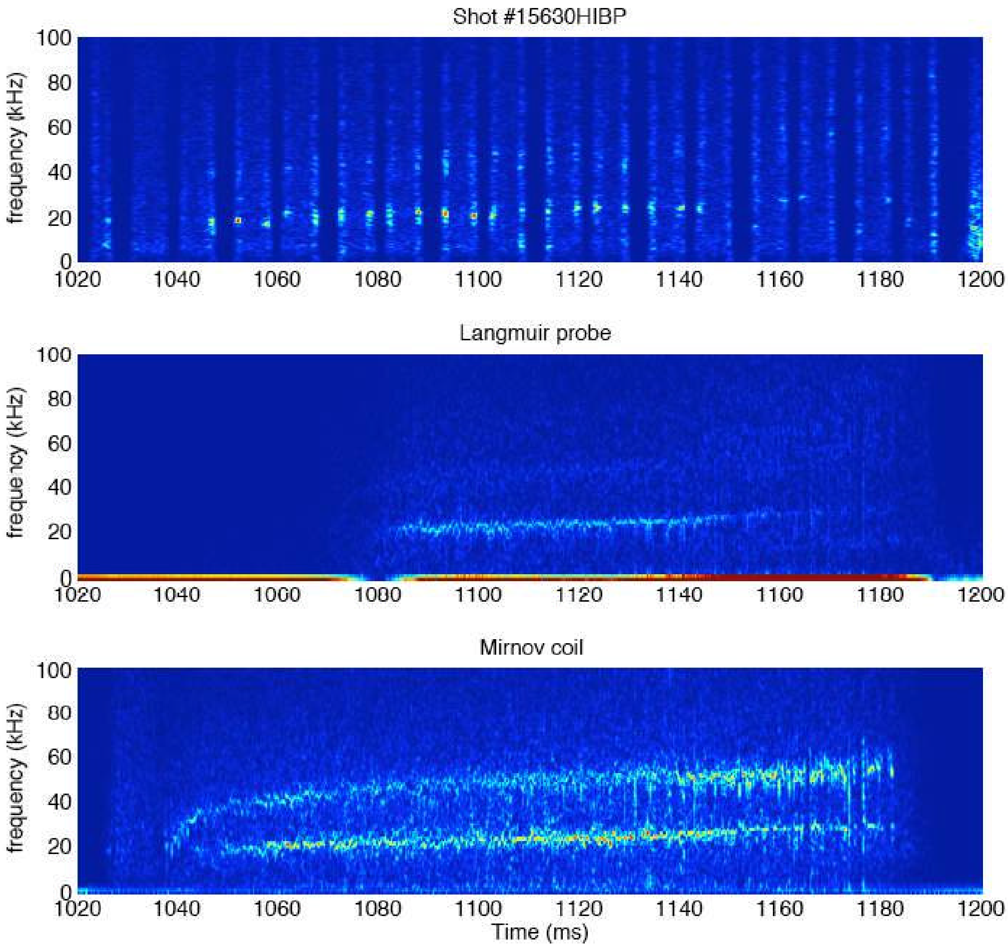


Fig. 10 Quasicoherent modes have been observed in TJ-II plasma under specific condition:

oscillations (in range 20 kHz) have been connected with the development of electron internal transport barriers. Recent results show a decreasing in the mode amplitude as e-ITBs are fully developed [8].

5. Conclusions

The recent study of ECE&NBI regimes in TJ-II shows:

- The evidence of the electron root features with positive electric potential up to + 1300 V in low density target ECRH plasma.
- The evidence of the ion root features with negative electric potential up to – 600 V in the whole NBI heated plasma column.
- A link between plasma density, potential and electric fields. The smooth change from positive to negative electric field observed in the core region as density is raised is correlated with global and local transport results, showing a confinement time improvement. Core plasma potential is also linked to kinetic effects (suprathermal electron transport).
- Quasicoherent modes have been observed in TJ-II plasma under specific conditions when plasma density and heating power exceed some minimal values in plasma configuration. This suggests the role of low order rationals and of threshold gradients in the triggering of the quasicoherent modes.

Acknowledgments

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