

On the influence of ECRH on neoclassical and anomalous mechanisms using a dual Heavy Ion Beam Probe diagnostic in the TJ-II stellarator

C. Hidalgo¹, A. Chmyga², J. Chercoles¹, G.N. Deshko², L.G. Eliseev³, P. O. Khabanov³, S.M. Khrebtov², A.D. Komarov², A.S. Kozachek², L.I. Krupnik², B. Liu¹, J. Lopez¹, U. Losada¹, G. Martin¹, A.V. Melnikov^{3,4}, B. van Milligen¹, A. Molinero¹, J.L. de Pablos¹, E. Sánchez¹, M.V. Ufimtsev⁵, V.N. Zenin³, A.I. Zhezhera² and TJ-II team¹

¹Fusion National Laboratory, CIEMAT, 28040, Madrid, Spain

²Institute of Plasma Physics, NSC KIPT, 310108, Kharkov, Ukraine

³National Research Centre ‘Kurchatov Institute’, 123182, Moscow, Russia

⁴National Research Nuclear University MEPhI, 115409, Moscow, Russia

⁵Moscow State University, 119991, Moscow, Russia

E-mail contact of main author: carlos.hidalgo@ciemat.es

Abstract. The unique capabilities of the dual HIBP system allows the investigation of multi-scale mechanisms to be expanded from the plasma edge to the plasma core in the TJ-II stellarator. Experiments with combined NBI and ECR heating have shown direct experimental evidence of the influence of ECRH on turbulent mechanisms, increasing the level of fluctuation, on the amplitude of Long-Range-Correlations (LRC) as proxy of ZFs for potential fluctuations but not for density and poloidal magnetic fluctuations and on neoclassical radial electric fields. Whereas ECRH influences the level of fluctuations in a wide range of plasma densities, ECRH induced reversal of the neoclassical radial electric field has been observed only in low-density plasmas. The TJ-II unique experimental capabilities would allow validation of nonlinear saturation of turbulence simulations (e.g. TEM), including quantitative assessments of discrepancies (e.g. level of fluctuations, correlation lengths and interplay with Zonal Flows) between theoretical and experimental results.

1. Introduction

Particle and impurity transport are usually described empirically in terms of diffusive and convective terms driven by neoclassical and turbulence mechanisms. In the framework of neoclassical mechanisms in tokamaks, the main ion density gradient (inwards) and the ion temperature gradient (outwards at low collisionality, otherwise known as temperature screening) are responsible for opposite convective fluxes. In non-axisymmetric devices the sign of the radial electric field is expected to play a dominant role in the convection of impurities. Thus, by standard neoclassical theory, high inward radial electric fields are foreseen to enhance inward impurity convection in stellarators. As a consequence high density (ion root operation) shows a tendency for impurity accumulation [1]. Interestingly, efficient impurity control has been achieved in non-axisymmetric plasma regimes with radially inwards radial electric field in high-density H-mode plasmas in the W7-AS stellarator [2] and in the so call impurity hole regime in the LHD helical device [3]. In both cases the underlying mechanisms remain unknown. Those results show that, indeed it is possible the simultaneous achievement of improved energy confinement with low impurity accumulation which is a necessary condition for the development of fusion reactor relevant scenarios.

Electron Cyclotron Resonance Heating (ECRH) is known as a powerful tool for the radially

localized heating of the plasma electrons. Significant progress has been reported regarding the physics understanding of empirical actuators like ECRH / ICRH core heating to avoid impurity accumulation as potential showstopper for the development of fusion energy, including the following mechanisms:

- A reduction of the background density gradient, leading to a reduction of the inward (neoclassical) convection of impurities in tokamaks [4].
- An increase of turbulent level both tokamaks [5] and stellarators.
- The amplification of core temperature screening, which would be relevant in core α -heating regimes in tokamaks.
- Modification in the neoclassical radial electric fields in stellarators.
- The development of core plasma potential flux surface asymmetries which due to its 3-D structure is expected to be stronger in stellarators [6] than in tokamaks. Direct experimental observations of electrostatic potential variations within the same magnetic flux surfaces have been reported both in electron and ion root regimes in the TJ-II stellarator [7].

In the present paper we have investigated the influence of ECRH on neoclassical (radial electric fields) and anomalous (fluctuation levels) and zonal flows mechanisms in the TJ-II stellarator.

2. Experimental set-up

TJ-II is a four-period flexible Helic with low magnetic shear with major radius 1.5 m, minor radius of about 0.22 m and magnetic field 1 T. TJ-II plasmas studied here were heated by Electron Cyclotron Resonance Heating (ECRH) (2 x 300 kW gyrotrons, at 53.2 GHz, 2nd harmonic, X-mode polarisation) and Neutral Beam Injection (NBI) (2 x 500 kW, port-through power at 33 kV). Central electron temperature and plasma density up to 1 keV and $1.7 \times 10^{19} \text{ m}^{-3}$ are achieved in ECRH plasmas whereas in NBI sustained regimes core plasma densities and electron temperatures in the range $(0.5 - 2) \times 10^{19} \text{ m}^{-3}$ and 400 eV respectively were

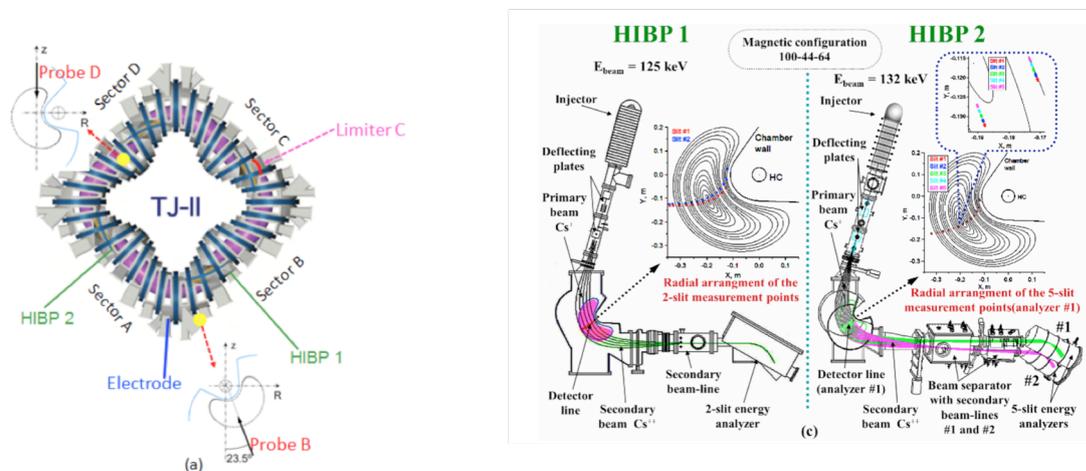


Figure 1. Experimental set-up: (a) Schematic view of TJ-II showing the locations of dual HIBP and Langmuir probe systems. (b) The dual HIBP system.

investigated.

The TJ-II vacuum vessel is divided into four sectors that are marked in figure 1(a) as Sector A, B, C and D, corresponding to its four-fold toroidal symmetry. Each Sector is divided into 8 regions. Results reported in the paper were obtained using a unique experimental set-up in operation in the TJ-II stellarator that includes two Langmuir probe arrays and two Heavy Ion Beam Probe (HIBP) systems [Fig. 1]. The dual HIBP system was used to study the temporal and spatial evolution of density and plasma potential profiles, fluctuation levels and Long-Range-Correlations (LRC) as proxy of zonal flows (ZFs) in the whole plasma cross-section [8]. A 20-channel stainless steel split plate is used as ion beam detector in HIBP-2, while 8-channel detector is in operation in HIBP-1 at the moment. Two Langmuir probe arrays are installed at reciprocating systems in Sectors D4 and Sector B2 from which we named the probes: ‘Probe D’ and ‘Probe B’.

The unique possibilities of the dual HIBP system allow us to expand the investigation of multi-scale mechanisms from the plasma edge, using the dual Langmuir probe system, to the plasma core.

3. Experimental results

3.1. Influence of ECRH on radial electric fields and plasma profiles

Fig. 2 shows the time evolution of plasma parameters in on-axis ECRH / NBI heated plasmas and the corresponding radial profile of plasma potential. In low density plasmas ($n \approx 0.6 \times 10^{19} \text{ m}^{-3}$) there is a transition from negative (ion root of the ambipolarity equation) to positive (electron root) radial electric field (E_r) once ECRH is turn-on in agreement with neoclassical predictions [9]. So far the reversal in E_r induced by ECRH has been observed at low density plasmas (Fig. 2 left) but not in high density $> 1 \times 10^{19} \text{ m}^{-3}$ regimes (Fig. 2 right).

As ECRH is added to the discharge at plasma densities below the ECRH density cut-off ($\approx 1.7 \times 10^{19} \text{ m}^{-3}$) a pronounce increase of electron temperature can be observed with central electron temperature reaching values up to 1 keV [see fig.2 and fig.3].

It should be noted that the influence of long-scale length (neoclassical) radial electric field components on zonal flow-like structures has been recently reported in the TJ-II stellarator [10].

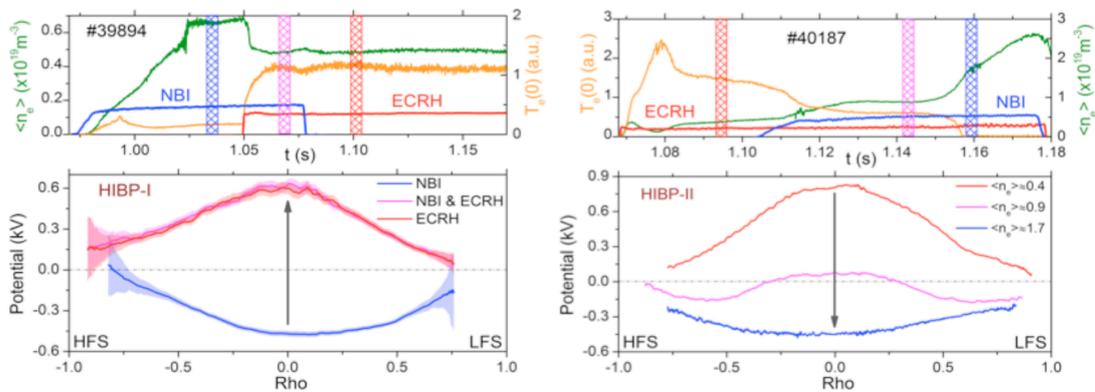


Fig. 2 Time evolution of plasma density and electron temperatures with combined ECRH / NBI regimes and corresponding plasma potential profiles in the TJ-II stellarator. The plasma potential reverses from negative values to positive values in low density plasma (left) but not at high density (right) regimes with combined ECRH and NBI heating. ECRH was on axis for shot #39894 (left) and off-axis for shot #40187 (right).

The $E_r \times B$ shearing rate corresponding to the short scale length structures of the radial electric field may be sufficient to regulate turbulence. Interestingly, direct observation of fine scale structures in radial electric fields have been also reported in the JET tokamak consistent with stationary zonal flows [11].

3.2. Influence of ECRH on fluctuation levels

The influence of ECRH heating on the profile of total current fluctuation levels is illustrated in Fig. 3. In these studies the HIBP-1 system was in the radial scanning mode covering the whole TJ-II plasma cross-section (from the low to the high field side region). The level of density plasma fluctuations is significantly increased from the deep core ($\rho \approx 0$) up to edge ($\rho \approx 0.8$) in the ECRH phase.

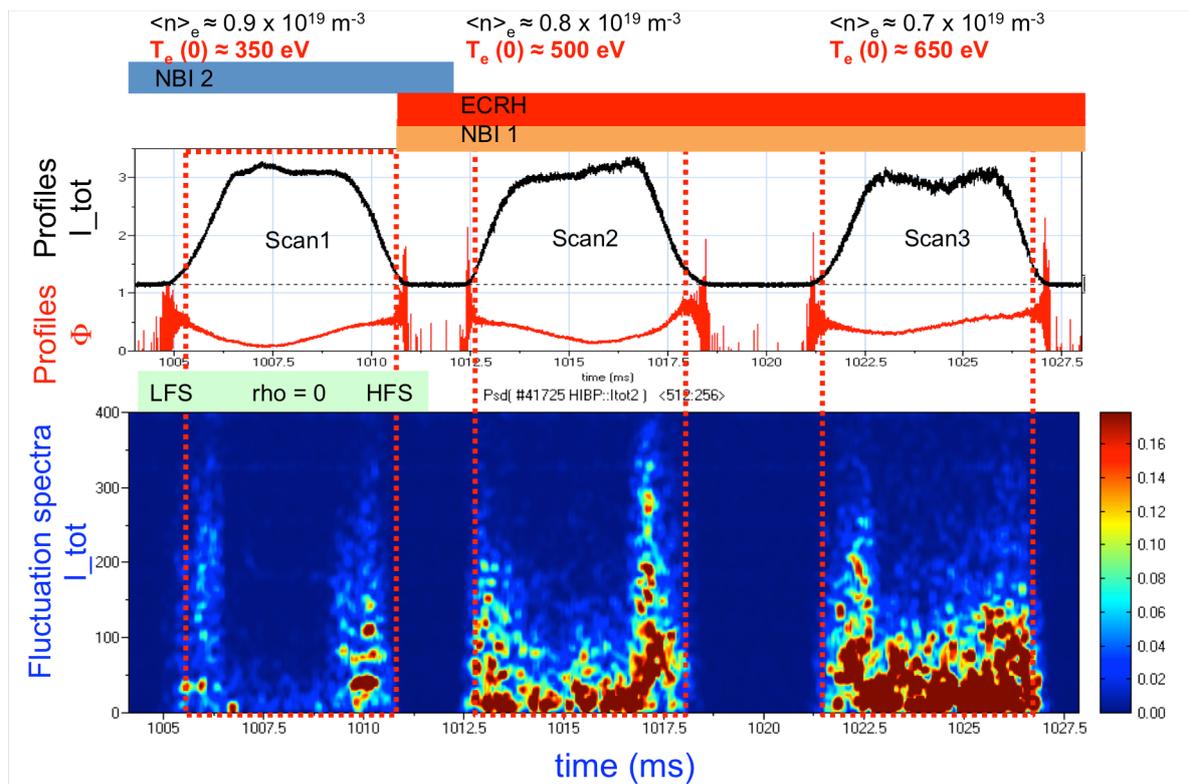


Fig. 3 Influence of ECRH on density fluctuation profiles (shot 41725) measured with the HIBP-I system in the scanning mode.

The increasing in the level of fluctuations is due to the amplification of broad-band fluctuations in the range 1 – 300 kHz and is empirically correlated with the peaking in the electron temperature profile while keeping plasma density roughly constant in the ion root (negative radial electric field) regime. Thus, electron temperature driven instabilities (e.g. TEM) as well as ECRH induced kinetic effects are candidates to explain the observed influence of ECRH on TJ-II fluctuation levels.

It is interesting to note that previous experiments in the AUG tokamak [5] have shown that the influence of ECRH power on the turbulence level is only observed close to the ECRH deposition location, whereas in the TJ-II stellarator the influence of ECRH on the level of fluctuations is observed in the whole plasma cross-section as shown in Fig. 3.

3.3. Influence of ECRH on LRC

The amplitude of Long-Range-Correlations (LRC) increases for potential fluctuations but not for density and poloidal magnetic fluctuations as shown in Fig. 4. Furthermore, LRC in plasma potential are dominated by low frequencies (< 20 kHz) with cross-phase consistent with zero value in agreement with previous LRC studies using edge probes [12]. These results are consistent with the development of ZF structures that are amplified by ECRH.

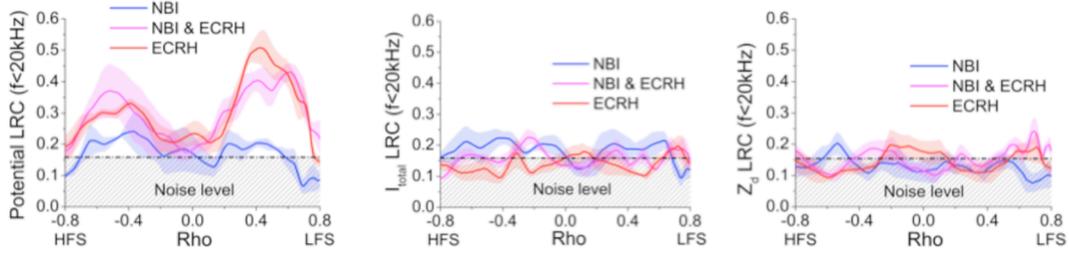


Fig. 4 Long-Range-Correlations at $f < 20$ kHz measured with HIBP-I in the scanning mode and HIBP-II at point $\rho = -0.63$ (shot 39894) for plasma plasma potential, secondary ions (density) and toroidal shift (poloidal magnetic fluctuations).

It should be noted that previous experiments in the TJ-II plasma edge region have shown that as plasma density increases, and ECRH-heated plasmas ($n < 10^{19} \text{ m}^{-3}$) give way to pure NBI-heated plasmas ($n > 10^{19} \text{ m}^{-3}$), the amplitude of LRC (characterized by the dual Langmuir probe system) increases. An experimental programme is in progress to compare the influence of ECRH on fluctuation level and LRC characterized by the dual HIBP (core and edge regions) and Langmuir probe (edge region) systems in the TJ-II stellarator.

4. Conclusions

Experiments in plasmas with combined NBI and ECR heating in the TJ-II stellarator have shown direct experimental evidence of the influence of ECRH on turbulent mechanisms, increasing the level of broadband fluctuations, on the amplitude of LRC (as proxy of Zonal Flows) and neoclassical radial electric fields. The increasing in the level of fluctuations is due to the amplification of broad-band plasma fluctuations in the range $1 - 300$ kHz and is empirically correlated with the peaking in the electron temperature profile. Thus, electron temperature driven instabilities (e.g. TEM) as well as ECRH induced kinetic effects are candidates to explain the observed influence of ECRH on TJ-II fluctuation levels. These findings show that multi-scale interactions are a crucial ingredient for understanding the influence of ECRH on anomalous transport mechanisms.

Whereas the influence of ECRH on the level of fluctuations takes place in a wide range of plasma densities, ECRH induced reversal of the neoclassical radial electric field has been observed only in low-density plasmas ($n < 1 \times 10^{19} \text{ m}^{-3}$).

Trapped electron modes (TEMs) are important micro-instabilities to understand transport in fusion plasmas that are sensitive to the overlap of regions of trapped electrons and bad curvature. Due to the method in which different stellarators have been optimized, the overlapping between trapped electron and bad curvature regions is minimized in W7-X to

stabilize TEMs but not in TJ-II or HSX stellarators. Indeed, gyrokinetic calculations indicate lower growth rates in W7-X than in HSX [13,14]. However, nonlinear calculations show that the turbulent heat flux levels are only slightly reduced in TEM optimised configurations compared to non-optimized ones [13], possibly hinting at the critical role of zonal flows in the saturation mechanism. The TJ-II unique experimental capabilities would allow validation of nonlinear saturation of turbulence simulations (e.g. TEM), including quantitative assessments of discrepancies (e.g. level of fluctuations, correlation lengths and interplay with Zonal Flows) between theoretical and experimental results.

5. Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work has been partially funded by the Spanish Ministerio de Economía y Competitividad under contract number ENE2015-68206-P.

References

- [1] BURHENN, R., et al., Nuclear Fusion 49 (2009) 065005
- [2] MCCORMICK, K., et al Phys. Rev. Lett. 89 (2002) 015001
- [3] YOSHINUMA, M., et al., Nuclear Fusion 49 (2009) 062002
- [4] CASSON, F. J., et al., Plasma Phys. Control. Fusion 57 (2015) 014031
- [5] HAPPEL, T., et al., Physics of Plasmas 22, 032503 (2015)
- [6] GARCÍA-REGAÑA, J. M. et al. Plasma Phys. Control. Fusion 55 (2013) 074008
- [7] PEDROSA, M. A., et al., Nuclear Fusion 55 (2015) 052001
- [8] MELNIKOV, A. V., et al, Fusion Engineering and Design 96-97 (2015) 724
- [9] VELASCO, J. L., et al., Phys. Rev. Lett. 109 (2012) 135003
- [10] LOSADA, U., et al., Plasma Phys. Control. Fusion 58 (2016) 084005.
- [11] HILLESHEIM, J. C., et al., Phys. Rev. Lett. 116 (2016) 065002
- [12] HIDALGO, C., et al., EPL 87 (2009) 55002
- [13] PROLL, J.H.E., et al., Plasma Phys. Control. Fusion 58 (2016) 014006.
- [14] HELANDER, P., et al., Nuclear Fusion 55 (2015) 053030