Improved Plasma Confinement by Ion Bernstein Waves (IBWs) Interacting with Ions in JET (Joint European Torus)

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Abstract. A new coupling scheme of ion Bernstein waves (IBW) to plasma ions, by mode conversion of fast waves, has been tested in D-^{3}He plasma of the JET tokamak. Injecting 4.8 MW ion cyclotron radio frequency power, 1.8 MW IBW power absorption on deuterons occurs at the fundamental cyclotron resonant layer, which is located in the high field side near the plasma edge (R = 2.1 m). Plasma sheared flows, ponderomotively induced by IBW, are observed near the edge, producing an E×B shearing rate of 5 MHz, higher than the threshold expected for turbulence suppression. Transport analysis shows a 70% reduction of the thermal diffusivity of both electrons and ions in the edge plasma region where the sheared flows are observed.

1. Introduction.

A new scheme for excitation of ion Bernstein waves (IBW) by mode conversion (MC) of externally launched electromagnetic fast waves (FW) has been tested in D-^{3}He plasma of the JET tokamak. Rather than aiming at localised electron heating close to the mode conversion layer as in standard mode conversion heating experiments [1], the present scheme aims at IBW power absorption by deuterons at the fundamental cyclotron resonant layer, located on the high field side near the plasma edge (see Fig. 1). This scheme allows to avoid, in principle, the non-linear interactions of the RF power with the plasma edge, typically present in the standard IBW coupling experiments by MC of externally launched slow electrostatic plasma waves [2]. The main goal of the experiment is to obtain an internal transport barrier, due to local IBW-induced E×B sheared plasma flows that, in turn, can suppress the ambient turbulence [3], [4].

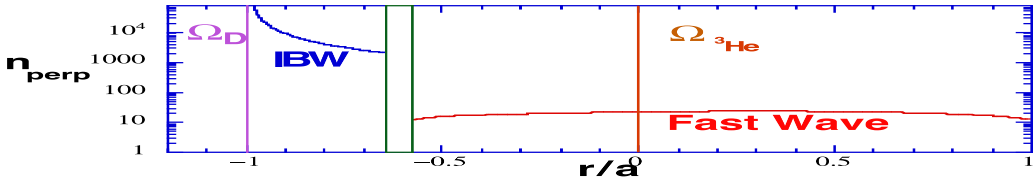

FIG.1. Solution of the full dispersion relation of the waves involved in the FW-IBW mode conversion scheme based on the plasma parameters similar to the experimental values. The FW launched in low field side by ICRF antennas is mode converted at the ion-ion hybrid resonant layer. The IBW propagates towards the fundamental cyclotron resonant layer of deuterium. The low electron temperatures occurring in the outer half of plasma inhibit full electron Landau damping, allowing IBW power propagation and absorption by deuterons.

2. Overview of modelling results

According to modelling result [5], 1-2 MW IBW power can be available for damping on deuterons by injecting 5 MW FW power. The IBW-induced E×B sheared flow has been calculated in the framework of a compressible fluid model [3]. The calculation is based on the operating parameters of the present experiment. Full-wave analysis is used to evaluate the IBW mode-converted power, which is 80% of the FW power. The IBW power absorption by the electrons is about 30% of the mode-converted power by ray tracing analysis (2-D in velocity space, relativistic Fokker-Planck code). The gradient of the IBW-induced poloidal velocity provides the main contribution to the calculated E×B shearing rate (Fig. 2). The threshold value of the shearing rate for turbulence suppression (about 0.6 MHz) has been evaluated by the electron diamagnetic frequency. As a result, 0.3 MW IBW power is sufficient to suppress the ambient turbulence in a plasma region of 1.5 cm radial width. For comparing with the experiment, a reduction of the expected shearing rate by a factor 4 must be considered, and the radial width of the region interested by the sheared flow is expected to be larger by a factor 4. The 4 ICRH antennas operated indeed with relative shift in frequency higher than the frequency width of resonance. Following the quoted model, a linear increase of the poloidal velocity with IBW power should be observed. However, a single particle analysis suggests that a nonlinear saturation can occur [6], further reducing the shearing rate obtainable.

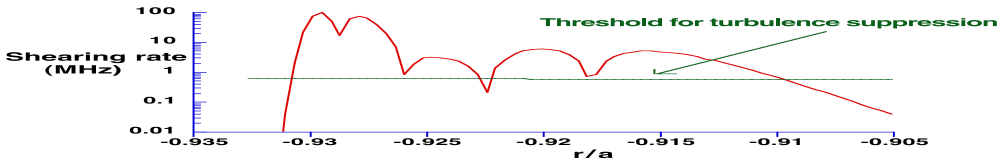

FIG.2. E×B shearing rate vs. the normalised minor radius (the negative sign indicates that the resonance is located in the high field side) calculated by fluid model retaining the compressible term. The calculation is based on the operating parameters of the present experiment.

3. Experimental results

The effect of the present FW-IBW mode-conversion scheme can be usefully studied by comparing two plasma discharges, shot 55708 and shot 55700. These shots are performed in similar conditions, but with different antenna phasing and operating frequency. Shot 55700 is performed in ordinary FW-MC regime aimed to maximise the power absorption by the electrons near the plasma centre operating with B_T= 3.4T, f_1=34 MHz with -π/2 phasing, injecting 3 MW of ion cyclotron radio frequency (ICRF) power. In shot 55708 the new FW-IBW MC scheme was explored, operating at f_0=37 MHz with 00ππ phasing, injecting 4.8 MW of ICRF power. The shots compared have the same input total power (≈4.5 MW) inside the plasma volume ρ≤0.9 (ρ is the square root of the normalised toroidal flux), taking into account also the neutral beam and the ohmic power (in total about 1.5 MW). The confinement time calculated inside this plasma volume is about 0.2 s before the ICRF power pulse in both plasma discharges. During the ICRF power pulse, it increases by about 50% in shot 55708, and it is constant or decreases in shot 55700. The direct electron RF power deposition was obtained by the break-in-slope analysis of fast spatially resolved ECE (electron cyclotron emission diagnostics) electron temperature data during ICRF power modulation. As a result, the ICRF power fraction absorbed by the electrons is about 85% in shot 55700, and about 50% in shot 55708. The ICRF power balance in the discharge 55708 is obtained taking into account that about 1.8 MW of IBW power is deposited on ions for ρ≥0.9, according to modelling result and to indication of ion flux by neutral particle analyser (NPA) diagnostics. Therefore, such IBW power was not considered for calculating the confinement time in the plasma volume ρ≤0.9. A direct evidence of IBW interaction with deuterons in shot 55708 is found by the NPA diagnostics. The distribution function of deuterons is typically distorted by IBW power coupling to the thermal ions near an ion cyclotron harmonic resonant layer [7]. Comparing the deuterium flux vs. energy from NPA for discharge 55700 and discharge 55708 shows the effect of the IBW interaction with deuterons (Fig. 3).

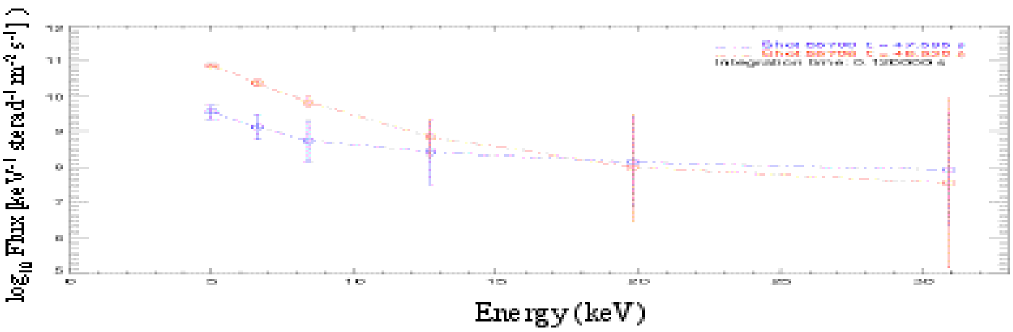

FIG.3. Deuterium flux vs. energy from Neutral Particle Analyser (NPA) for discharge 55700 (standard FW-MC scheme, blue curve) and discharge 55708 (new IBW scheme, red curve). The logarithm of the experimental flux decay linearly with the energy up to the value E_L ≈ 7.5 keV. Theoretical model [7] predicts such a linear decay up to the energy E_L ≈ 14.8 T_{eres}, where T_{eres} is the electron temperature at the ion cyclotron resonant layer. Therefore the electron temperature at the resonant layer can be evaluated by NPA data as T_{eres} ≈ 0.5 keV. This value corresponds to the electron temperature at ρ ≈ 0.9, which is the location of the region of IBW interaction with deuterons expected by the theory (see Fig. 2). The slope of the linear decay allows an evaluation of the electric field amplitude, which is consistent with 1.8 MW of IBW power absorbed on deuterons.

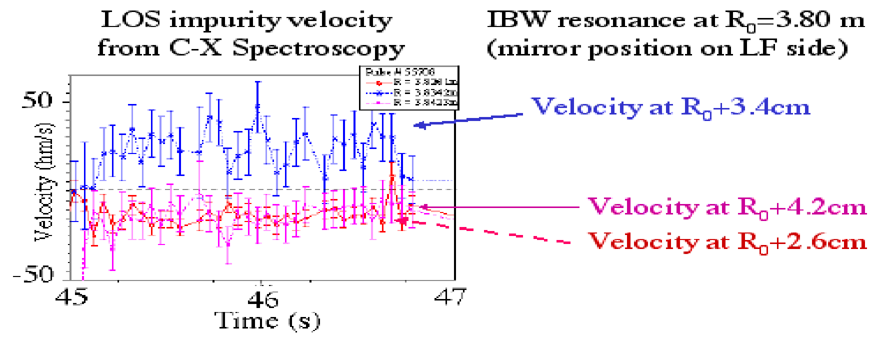

FIG.4. Time evolution of the line of sight (LOS) impurity velocity measured by charge-exchange spectroscopy (CXS) diagnostic in shot 55708. The velocity increases after the ICRF power switch-on (45.0 s). Saturation occurs during the ICRF power linear ramp-up (45.0s – 46.0 s) at a power level of about 2.5 MW.

The deuterium flux observed in shot 55708 is about one order of magnitude higher in the range of energy where deuterons acceleration by IBW is expected. The measured flux in shot 55708 is consistent with 1.8 MW IBW power absorption at ρ≈0.9. In this region an increase of the plasma flow along the lines of sight of the charge-exchange diagnostic is observed during the ICRF power ramp-up (Fig. 4). A velocity of 35±14 km/s is observed at the radial location R=3.834 m (ρ=0.94). Along the adjacent chords, at R=3.826 m and R=3.842 m, the velocity direction is opposite (16±5 km/s). The resulting velocity derivative of 5 MHz, providing the main contribution to the shearing rate, exceeds the threshold for turbulence suppression (0.6 MHz). Transport analysis shows a reduction of the electron thermal diffusivity in the plasma region where IBW damping on deuterons occurs and sheared plasma flows are observed (Fig. 5a). The plasma electron pressure increases in a wide plasma volume (ρ≤0.9).

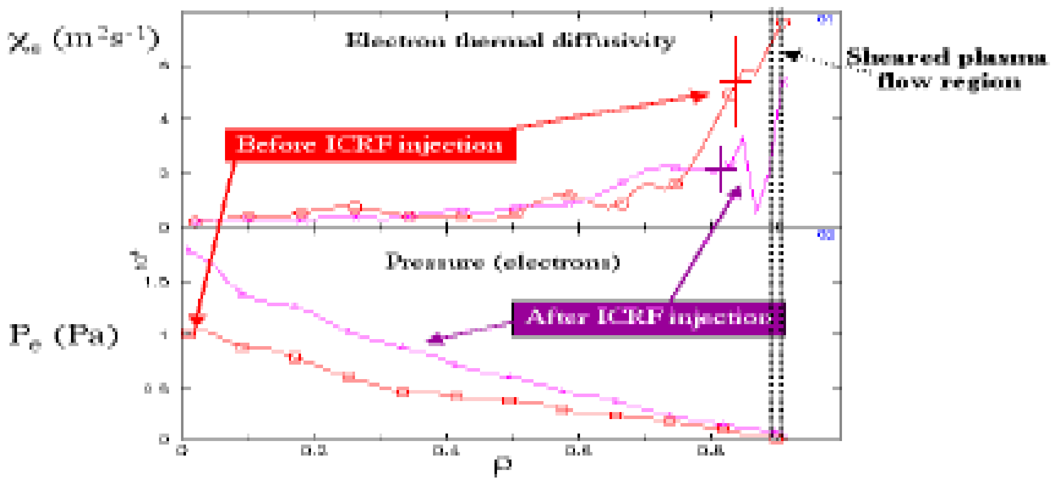

Fig. 5. In the IBW scheme, the electron thermal diffusivity decreases by a factor about 3 in a radial region close to the region of the observed sheared flow. The electron plasma pressure increases in a wide plasma volume (ρ≤0.9) bounded by the region of transport reduction.

4. Comment and conclusions

A new scheme of IBW power coupling to plasma ions was tested in JET. Injecting 5 MW of electromagnetic FW power (ICRH) in a D-^{3}He plasma, 1.8 MW of mode-converted IBW power was available for damping on ions at the fundamental ion cyclotron resonant layer. Sheared plasma flow was observed in the plasma region of IBW interaction with deuterons at $\rho \approx 0.9$, producing 5 MHz E×B shearing rate. Such shearing rate exceeded the expected threshold for turbulence suppression (0.6 MHz). The electron thermal diffusivity decreased by 70% in a plasma region close to $\rho \approx 0.9$. The plasma pressure increased in a wide plasma volume ($\rho \leq 0.9$) bounded by the region of transport reduction. An analogous behaviour is observed for the ion species and suggests an improvement of the confinement similar to that observed in other regimes like internal transport barrier (ITB). The energy confinement time calculated in this plasma volume, covering about 80% of the overall plasma volume, increased by 50% (the IBW power absorbed on ions was not considered for calculating the related confinement time, as such power is deposited at $\rho \geq 0.9$). Such parameter is important for evaluating the effect on the confinement of power absorbed in a wide radial region relevant for fusion applications. The improved confinement regime persists during the whole FW power pulse (6s). The robustness of the improved confinement regime was tested in all the discharges obtained in the present new IBW launching scheme, in different conditions of plasma density. However, further analysis and experimental tests are necessary for verifying the turbulence behaviour.

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