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LETTER

Improved confinement produced by ion Bernstein waves in hydrogen and deuterium plasmas of FTU

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Abstract
New experiments with the ion Bernstein waves (IBWs) have been performed in the Frascati Tokamak Upgrade (FTU) both in hydrogen and deuterium plasmas at higher power level, operation at higher density, higher plasma current and lower effective ion charge values than in the previous campaign. Improved confinement in a region with larger radius is obtained when operating in deuterium. Transport analysis shows a uniform decrease of the electron thermal conductivity by 40% over the radial region bounded by the absorption layer.

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1. Introduction

The previous experiments performed in the Frascati Tokamak Upgrade (FTU) [1], utilizing a waveguide antenna for coupling ion Bernstein waves (IBWs) to a Tokamak plasma [2, 3], obtained improved confinement regimes in hydrogen plasmas, accompanied by a simultaneous increase of the electron density and temperature with profile peaking. Improved confinement can be achieved by IBW-induced $E \times B$ sheared plasma flows [4, 5]. Some support for improving confinement by IBWs was obtained from the IBW experiment in the HT-7 Tokamak [6].

In this letter, the results of the recent campaign in the FTU that aimed to continue the investigation of IBW-induced improved confinement regimes are presented. These experiments operate at a toroidal field of 7.9 T and a frequency of 433 MHz, as in the previous campaign, but with higher IBW power level, higher density, higher plasma current and lower effective ion charge values. It utilized both pure hydrogen (H) and deuterium (D)-majority plasma (with 20% H minority). The full IBW power is absorbed at the first pass outside the ion-cyclotron harmonic resonant layer, in the low field side [7, 8]. Indeed, the IBWs are electrostatic plasma waves, which are strongly damped on plasma ions and electrons via ion-cyclotron harmonic damping and electron Landau damping, respectively. For the operating magnetic field and IBW frequency, the resonant layer corresponds to the fourth ion-cyclotron harmonic in H plasma ($r_{abs}/a \approx 0.3$) and to the ninth harmonic for deuterium ($r_{abs}/a \approx 0.65$), where a indicates the minor radius of the plasma. The calculation of the $E \times B$ shearing rate produced by the IBW power has been performed utilizing the compressible fluid model [5]. For the IBW experiment performed in the FTU [7], sheared plasma flows occur at a radial position close to the resonant layer (within a layer with radial width of the order of 1 cm). Both in H and D plasmas the shearing rate (5–8 MHz) exceeds the threshold for turbulence suppression

(≈1–2 MHz) (the uncertainty is due to the error bar of the kinetic input profiles). This result has been obtained considering 0.4 MW of IBW power and a line averaged plasma density of $0.5 \times 10^{20}\,\mathrm{m}^{-3}$. The IBW power coupled in the experiments in the FTU was estimated to be sufficient for producing turbulence suppression and, in turn, improved confinement both in H and D plasmas.

With respect to the previous campaign, this experiment takes advantage by the boronization of the FTU vacuum chamber, which reduces the impurity influx during the IBW power injection. Moreover, the IBW power has been increased adding a new waveguide antenna to the one utilized in the previous campaign.

2. Experimental results and transport analysis

At the present time the coupled routine power of the two IBW launchers is about 0.4 MW. It corresponds to 30% more than in the previous FTU experiments, which utilized only one launcher. Operating at a higher power than in the previous campaign, no significant parasitic effect occurring at the edge seems to prevent both the antenna coupling and the IBW propagation into the plasma core as was the case in other unsuccessful IBW experiments [9, 10]. This method confirms the advantage of operating at a high frequency and with waveguide antennas [7, 8].

The influx of impurity during the injection of high IBW power is negligible. The concentration of oxygen (the main light impurity) does not change. The concentration of heavy impurities shows the following behaviour: iron has a small increase (10%), nickel does not change and molybdenum decreases (30%). Moreover, the experiments are performed with the plasma column leaning on the inner toroidal limiter, which is the standard mode of operation in the FTU. Operation with the column leaning on the poloidal limiter was necessary in the previous campaign to reduce the influx of impurity during IBW injection. The better behaviour of impurities, observed during the new campaign, is due to the recent boronization of the FTU vacuum chamber.

Experiments in both H and D plasmas have been performed with the aim of verifying the dependence on the location of the resonant layer of the pressure profile shape and of the radial width of the improved confinement region, which was obtained in the previous campaign while operating in H plasma only. The operating toroidal magnetic field of 7.9 T, plasma current of 0.4 MA and averaged plasma density of $0.3 \times 10^{20}\,\mathrm{m}^{-3}$, the same as in the previous campaign, have been maintained in both H and D plasmas. The electron pressure profiles obtained by kinetic measures during the Ohmic and the IBW phases are compared in figure 1. A radially broader pressure profile is observed when operating in deuterium. As the operating conditions are the same, the broader profile in D can be related to the radial position of the absorption layer that occurs in the outer half of plasma in deuterium (and in the inner half in hydrogen).

Transport analysis is made using the JETTO code [11] supplemented with the IBW deposition model. The following parameters, obtained by experimental measures, have been utilized as input data: the profiles of plasma density, electron temperature, radiation, effective ion charge and the magnetic

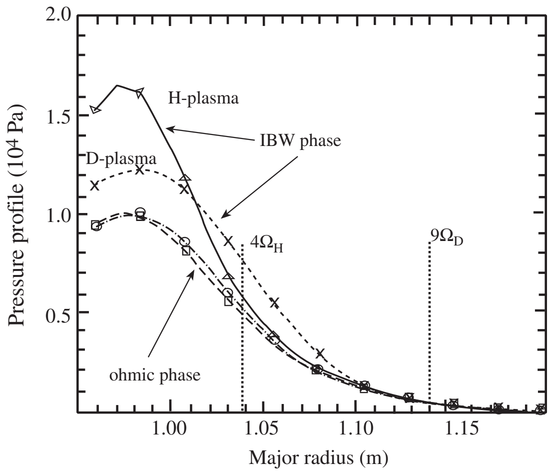

Figure 1. Electron pressure profile during the Ohmic and the IBW phases of discharges performed with same parameters, but with hydrogen and deuterium majorities. Both experiments are performed with toroidal magnetic field of 7.9 T, plasma current of 0.4 MA, and line averaged density of $0.3 \times 10^{20}\,\mathrm{m}^{-3}$.

reconstructed equilibrium. The experimental loop voltage behaviour is well reproduced, assuming a neoclassical plasma resistivity, consistent with the measured radially averaged effective ion charge: $Z_{\mathrm{eff}} = 3.0 \pm 0.5$. As a general trend, during IBW injection the Z_{eff} decreases by about 25%. In D plasmas, where the measure of neutron yields is available, the ion transport has been estimated to be about 2.7 times the neoclassical. The same ion anomaly is also retained for modelling the H plasma (conversely an ion anomaly of 1 was considered for the analysis in the previous campaign [1]). However, during the IBW phase, a reduction of at least a factor 2 of the electron thermal diffusivity, χ_e, occurs inside the region bounded by the absorption layer, where a break in the slope of the pressure profile is observed. It confirms the previous results obtained in [1]. The weak dependence of the χ_e on the ion anomaly is due to the small ion–electron thermal exchange at the considered low operating densities ($n_{e0} \approx 0.5 \times 10^{20}\,\mathrm{m}^{-3}$, $T_{e0} \approx 2.5\,\mathrm{keV}$, $T_{e0}/T_{i0} \approx 2$–3). In deuterium, a lower reduction of χ_e, which is within the uncertainties of transport analysis, is observed over a wider radial region.

In experiments at higher plasma current the effect of IBW in producing improved confinement in D plasmas is very evident. It is shown by FTU discharges operating at $I_p = 0.8$ MA. The time traces of the main plasma parameters of a D-majority are shown in figure 2. During IBW power injection, the line averaged density increases by 30% (accompanied by a profile peaking of 20%). The electron temperature does not change significantly. Consequently, the electron pressure profile peaks by a factor 1.2. The effective ion charge decreases from 2.2 to 1.9. The Dα emission from the toroidal (internal) limiter during the IBW phase decreases (≈50%). Some enhancement of the Dα emission (promptly correlated in time to the IBW pulse) is only observed by the line of sight looking at the outer wall region close to the mouth of the antenna.

The Ohmic power density profile does not change significantly during the IBW phase (decreases at the centre by about 10%). Details of the shape of the IBW deposition and of the effective ion charge profiles do not affect the transport analysis results appreciably. According to ray-tracing calculations, the RF power is deposited with Gaussian profiles on plasma ions and electrons at plasma radii $r/a \geqslant 0.31$ for H and $r/a \geqslant 0.65$ for D plasmas. The Ohmic power is the dominant heating source in the experiments.

In such discharges, operating with higher Ohmic input, the transport analysis shows a uniform decrease of the electron thermal conductivity by 40% over the region inside the absorption radius (see figure 3).

A useful function for characterizing the behaviour of an improved confinement regime is the energy confinement time, defined as

$$\tau_E(R) = \frac{W_{\mathrm{th}}(R)}{P_{\mathrm{tot}}(R) - \mathrm{d}W_{\mathrm{th}}(R)/\mathrm{d}t} \qquad (1)$$

where $W_{\mathrm{th}}(R)$ is the total thermal energy and $P_{\mathrm{tot}}(R)$ the total input power deposited inside the plasma column bounded by the magnetic flux surface labelled by the major radius coordinate R. This function is a general and direct indicator of a transport improvement, which does not depend on the particular transport mechanism. The comparison of $\tau_E(R)$ during the Ohmic and the IBW phases is shown in figure 4. During the IBW phase, the energy confinement time increases by about 30% inside the resonant layer. An analogous behaviour is also obtained in the H discharges.

The global energy confinement time has been compared with the ITER-97 scaling. In the Ohmic phase, τ_E is about 36 ms (corresponding to about $0.9\tau_{E\text{-ITER-97}}$). The IBW injection produces an increase of $\tau_E/\tau_{E\text{-ITER-97}}$ up to 1.0, which persists after the IBW power switch off for at least two confinement times up to the end of the plasma current plateau (see figure 2(f)). τ_E is about 42 ms at the end of the IBW pulse.

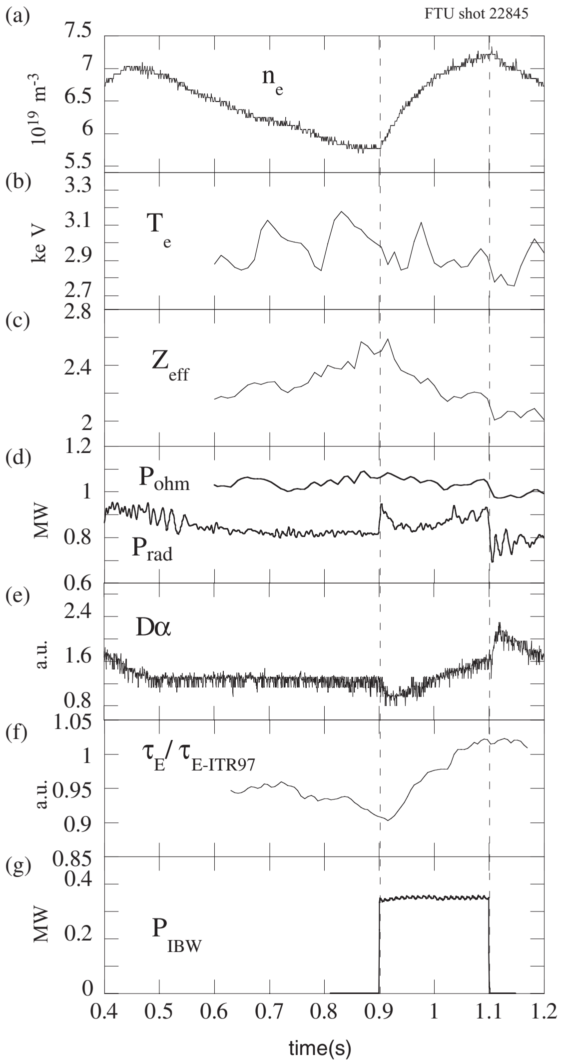

Figure 2. Time traces of the main plasma parameters during injection of IBW power (0.35 MW) at an operating magnetic field of 7.9 T and a plasma current 0.8 MA. Deuterium is the majority plasma, with 20% of hydrogen minority. Line averaged plasma density (a), central electron temperature from ECE (b), effective ion charge (c), radiated power (d), Dα emission from the outer plasma edge (e), ratio of the energy confinement and the ITER-97 scaling (f), IBW power (g).

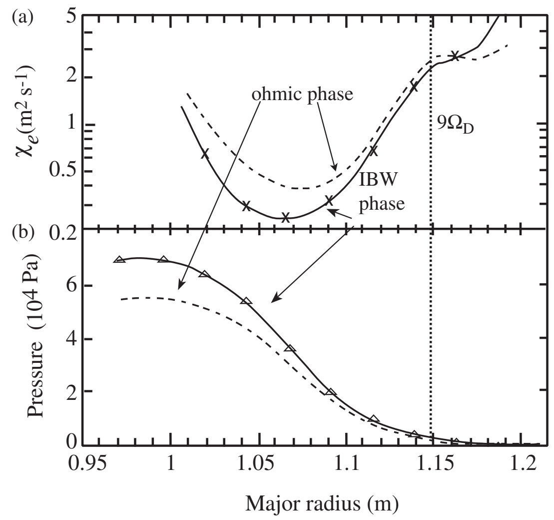

Figure 3. Profiles of the electron thermal conductivity (a) and of the electron pressure (b) during the Ohmic and the IBW phases. The same plasma discharge of figure 2 is considered.

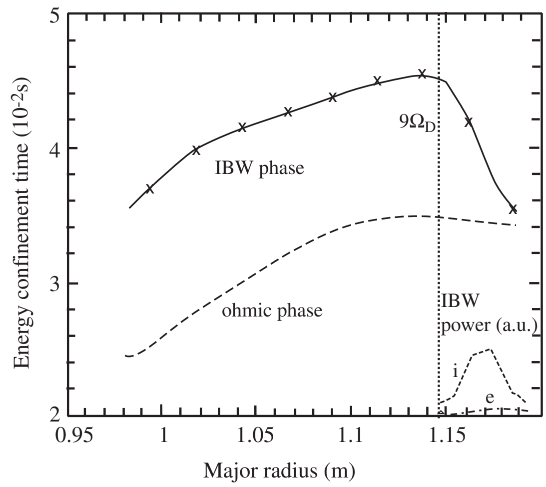

Figure 4. Profile of the energy confinement time calculated inside the plasma volume bounded by the magnetic flux surface with major radius label R. The IBW power deposition profiles of both the ions (i) and the electrons (e) are shown. The same plasma discharge of figure 2 is considered.

The density increase with profile peaking can be attributed to an increase of the particle confinement, which is related to the decrease of the Dα emission from the toroidal limiter. It is worth nothing that some gas desorbtion from the wall close to the antenna mouth produced by RF sheaths [12] (consistent with the aforementioned Dα emission increase in the outer wall) can also contribute to the density rise. However, experiments have been performed in the FTU under the same conditions of the considered IBW experiments but with gas puffing instead of injecting RF power, with the aim of reproducing the same rise of the plasma density obtained with IBWs. As a result, the Dα emission increases during the extra-gas puffing; conversely, it is lower during the IBW phase.

3. Conclusions

The recent campaign performed with about 0.4 MW of coupled IBW power in deuterium plasma at $I_p = 0.8$ MA, $n_e = 0.5 \times 10^{20}$ m^{-3} and $B_T = 7.9$ T shows a peaking of the electron pressure profile (20%). It is accompanied by some reduction (10%) of the central Ohmic power density, which provides the main power input in the experiments. Transport analysis shows a uniform decrease of the electron thermal conductivity by 40% over the region inside the absorption radius. The radial foot point of the improved confinement region obtained in the D plasma occurs in the outer half of plasma rather than in the inner half as in the H plasma. These results are consistent with the models of IBW deposition and local generation of plasma flows, useful for confinement improvement.

The recent results of the IBW experiment in the FTU supports the IBW scheme for producing improved confinement regimes, as required by advanced Tokamaks. For further testing the IBW scheme, experiments will be performed in the FTU in order to search for differences in the improvement confinement behaviour produced by IBW power or by extra-gas puffing, in plasma targets operating with low recycling and in the linear Ohmic confinement regime.

References

[1] Cesario R. *et al* 2001 *Phys. Plasmas* **8** 4721
[2] Ono M. 1993 *Phys. Fluids* B **2** 241
[3] Ono M. *et al* 1988 *Phys. Rev. Lett.* **60** 294
[4] Le Blanc B. *et al* 1999 *Phys. Rev. Lett.* **82** 331
[5] Jaeger E.F., Berry L.A. and Batchelor D.B. 1999 *Phys. Rev. Lett.* **82** 1871
[6] Baonian Wan *et al* 2003 *Phys. Plasmas* **10** 3703
[7] Cardinali A., Castaldo C., Cesario R., de Marco F. and Paoletti F. 2002 *Nucl. Fusion* **42** 427
[8] Cesario R. *et al* 2003 *Proc. 15th RF Conf. (Moran, Whyoming USA, May 2003)* ed C. Forest (New York: American Institute of Physics) at press
[9] Pinsker R. *et al* 1993 *Nucl. Fusion* **33** 777
[10] Rogers J.C. *et al* 1997 *Proc. 12th Top. Conf. on RF Power in Plasmas (Savannah, 1997)* vol 403 (New York: American Institute of Physics) p 13
[11] Cenacchi G. and Taroni A. 1986 *8th Conf. on Computational Physics Computing in Plasma Physics (Eibsee, Germany, May 1986)* vol 10D (*Europhysics Conference Abstracts*) (Geneve: European Physical Society) p 57
[12] Cesario R. *et al* 1994 *Nucl. Fusion* **34** 1527