Journal of the Physical Society of Japan
Vol. 66, No. 11, November, 1997, pp. 3453-3460

Correlation between Plasma Edge Electrostatic and Magnetic Oscillations in the Brazilian Tokamak TBR

Maria V. A. P. HELLER, Raul M. CASTRO, Ibere L. CALDAS, Zoezer A. BRASÍLIO, Ruy P. da SILVA and Ivan C. NASCIMENTO

Institute of Physics, University of São Paulo, C. P. 66318, 05315-970, São Paulo, SP, Brazil

(Received March 17, 1997)

Measurements of poloidal and radial magnetic field, density, potential, and temperature fluctuations were simultaneously performed at the plasma edge of the TBR tokamak using a especially constructed probe system. Direct cross spectral and bispectral analyses of these fluctuations showed evidences of both linear and nonlinear coupling between electrostatic and magnetic oscillations. Resonances created by external perturbing magnetic fields slightly reduced the linear coupling and almost entirely suppressed the quadratic coupling.

KEYWORDS: turbulence, transport plasma, tokamak

§1. Introduction

It is generally believed that plasma edge fluctuations are critical for tokamak performance and could cause strong transport and poor magnetic energy confinement.[1,2] However, despite the known experimental results, the sources of these turbulent oscillations have not been completely identified yet.

Although in some devices both electrostatic and magnetic fluctuations directly contribute to the edge transport,[3,4] in tokamaks this effect seems to be determined by the electrostatic fluctuations only. Nevertheless, a possible correlation between electrostatic fluctuations and magnetic field oscillations in plasma edge has been studied in tokamaks.[1,4-7] Coupling between these oscillations could affect the electrostatic fluctuations and, consequently, modify the transport.

It is known that the electrostatic turbulence can be modulated by a dominant magnetohydrodynamic mode[8] and that there is some correlation between electrostatic and magnetic oscillations.[6,7,9,10] Other than these observations, there is no general understandings on the influence of the magnetic oscillations on microturbulence in tokamaks. Thus, determining the precise correlation between these two kinds of fluctuations is important to improve the description of turbulence.

The correlation between plasma edge electrostatic and magnetic oscillations was studied in the Brazilian tokamak TBR. A feature of this device is a partial superposition of the magnetic and electrostatic power spectra which may enhance the correlation[11] and create favorable conditions for observing this effect.

In order to study this correlation, data were collected with a system of Langmuir probes and two sets of magnetic coils and then subjected to linear spectral and bispectral analyses.[12,13] Cross spectra of fluctuations at every radial location were calculated to determine a possible relation between these oscillations. Temperature fluctuations had significant correlation with magnetic field fluctuations (both, poloidal and radial magnetic components).

Bispectral analysis, that uses the lowest-order coupling of three waves as the dominant nonlinear wave-wave interaction,[10,12-16] was applied to our experimental data. We also estimated linear and quadratic transfer functions[12,13] for fluctuations monitored at two points in space[12,13] in order to determine coupling coefficients, energy transfer, and thus, the energy cascading through the main frequency components.

Although conditions for the existence of intermittence in the measured signals were studied here, no conclusive proof of its existence in the plasma edge turbulence was obtained.

Section 2 of this paper gives a brief description of the experimental set up. Section 3 describes the spectral characteristics of the magnetic and electrostatic fluctuation fields, with or without the external resonant perturbation. Section 4 discusses the coupling between electrostatic and magnetic oscillations, and §5 presents the conclusions of this work.

§2. Experimental Set-Up

The experiment was carried out using the Ohmically heated TBR tokamak (major radius R_0=0.30 m, minor radius a=0.08 m, toroidal magnetic field B_ϕ=0.4 T, plasma current I_p=10 kA, chord average density n_0=7×10^{18} m^{-3}, and pulse length of 10 ms) with a circular cross-section, a full poloidal limiter, and using hydrogen as working gas.

We constructed and installed at TBR a complex system of probes to measure simultaneously the electrostatic and magnetic fluctuations and some of the plasma parameters. Fig. 1(a) shows this probe system scheme. This system consisted of a set with four tips, a modified triple probe (with a four-tip probe array), and a single probe tip. More details of the experiment can be found in references.[17,18] We used a modified triple probe technique with four tips to consider the phase delay error corrections,[19,20] and to determine the following quantities: the mean electron temperature and ion saturation

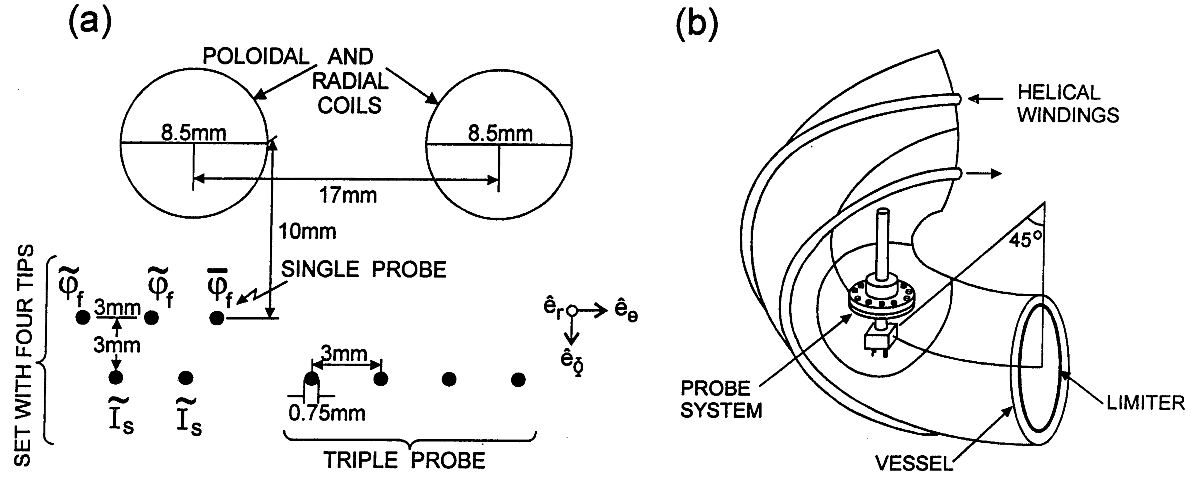

Fig. 1. Scheme of probe assembling (a), section of the tokamak ilustrating measurement position (b).

current and their corresponding fluctuations. Two of the four-tip configuration measured floating potential fluctuations, and the other two, the ion saturation current fluctuations. The single tip measured the mean value of floating potential.

The fluctuating plasma density, $\tilde{n}$, was obtained from the fluctuating ion saturation current, $\tilde{I}_s$, by using $\tilde{n} \simeq \tilde{I}_s/T_e^{1/2}$. The plasma potential fluctuation, $\tilde{\varphi}_p$, was obtained from the floating potential fluctuation, $\tilde{\varphi}_f$, considering the approximation $\tilde{\varphi}_p \simeq \tilde{\varphi}_f$.

Temperature fluctuations should not be neglected to estimate some relevant turbulence characteristics in tokamaks, as turbulence induced energy and particle transport.[17,19] However, these corrections difficult to calculate properly the correlations between the fluctuations studied in this work. In fact, estimations of these corrections (see ref. 17) show that they obscure the investigated correlations. Therefore, we used the measured electrostatic signals ($\tilde{I}_s$ and $\tilde{\varphi}_f$) to calculate the correlations concerning density and plasma potential fluctuations.

Two pairs of magnetic coils were mounted in the same system to measure the poloidal and the radial components of the magnetic field fluctuations. The probe system was mounted on a single axially movable shaft (Fig. 1(b)) allowing radial profile measurements and two-point estimates of poloidal wave numbers.

The data sampling frequency (1 MHz) used was sufficient to study edge electrostatic and magnetic fluctuations with frequencies up to 500 kHz. Time series measurements of approximately 4 ms, during the flat top phase of plasma current, were averaged and recorded over seven consecutive shots. These series were studied using a statistical criterion in order to eliminate spurious points that would otherwise have overestimated the fluctuations. The statistical properties were obtained averaging over 105 realizations of 256 point intervals.

The magnetic field perturbation was created by an electric current (I_h=280 A) through resonant helical windings (RHW) externally located around the torus[11,18] (Fig. 1(b)). Figure 2 shows both the time evolution of plasma current with or without the application of RHW current, and the time when the resonat perturbation was applied. The application of RHW does not alter the global discharge conditions. The RHW coils produced a perturbation field $\boldsymbol{b}$ with dominant helicity m=4/n=1, and an average radial amplitude $\langle|b_r(a)/B_\phi|\rangle \simeq$0.4% at the limiter radius. Such perturbation was resonant at the region with safety factor $q \approx 4$. In this experiment the RHW created a field line configuration similar to those obtained with ergodic divertors in TEXT[21] and TORE SUPRA[22] tokamaks.

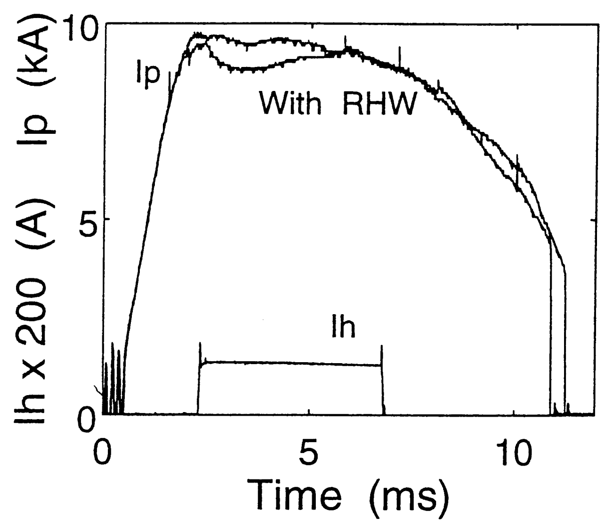

Fig. 2. Time evolution of plasma current (I_p) with or without RHW current (I_h).

§3. Spectral Characteristics of Field Fluctuations

As previously reported,[11] the main frequencies observed in the spectra of electrostatic fluctuations in TBR are lower than the Mirnov frequencies. Nevertheless, there is a marked partial superposition of the magnetic and the electrostatic spectra. This instrumental peculiarity made possible for us to study linear and quadratic correlations between electrostatic and magnetic spectral components. Figure 3 shows this peculiar partial su-

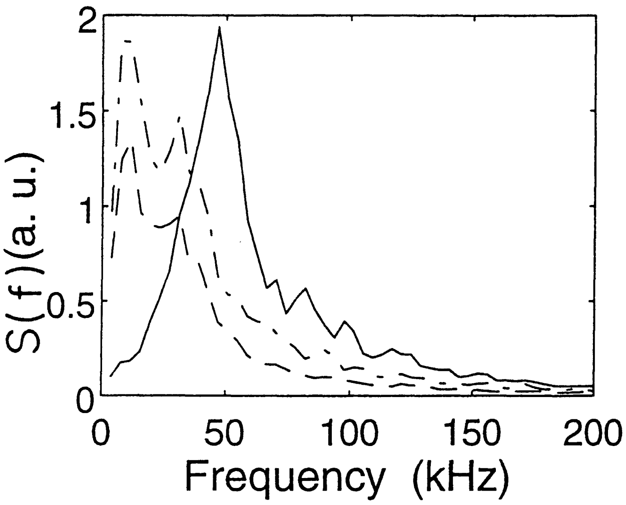

Fig. 3. $S(f)$ spectra of fluctuating density (- · - · -, plasma potential (- - -) at r/a=0.85, and poloidal magnetic field (——) at r/a=1.07.

perposition of density, plasma potential, and magnetic poloidal fluctuation spectra measured at r/a=0.85 (for electrostatic fluctuations) and at r/a=1.07 (for poloidal magnetic fluctuations).

In TBR not only the magnetic oscillations were strongly reduced (their amplitudes decreased to less than one third of the umperturbed values), as in other tokamaks,[23-25] but also the electrostatic oscillations were slightly modified by the RHW.[18] Furthermore, some equilibrium parameters could have also been changed had the plasma been properly perturbed by these resonant fields.[18]

Predominant magnetic fluctuations occurred in a broad frequency range centered at $f \simeq 50$ kHz with amplitudes $B_\theta^{\rm rms}/B_\theta(a) \simeq 1.2 \times 10^{-3}$, where $B_\theta^{\rm rms}$ is the root mean square of the poloidal magnetic fluctuation B_θ. The correlation analysis showed magnetic fluctuations, detected by two poloidal or radial oriented coils, to be highly correlated. In fact, the coherence was higher than 0.9 for the most relevant frequency regions. Phase angles between fluctuations obtained from two poloidal or radial coils (separated poloidally by 0.2 rad) were approximately equal to $\pi/6$. Furthermore, the phase angle between poloidal and radial fluctuations, measured with coils at the same poloidal position, was approximately equal to $\pi/2$, as expected from the magneto hydrodynamic (MHD) theory.[26] The RHW kept constant these phase angles.

Figures 4(a) and 4(b) show the influence of the RHW on the $S(k, f)$ spectra of potential fluctuations measured at r/a=0.89; and Figs. 4(c) and 4(d) show the same for poloidal magnetic field fluctuations measured at r/a=1.07. The perturbed spectral density expanded the frequency distribution and lowered the wave number values.

Since we performed simultaneous two-point measurements of electrostatic and magnetic fluctuating quantities, we were able to compare their propagation characteristics. Behind the limiter, some propagation characteristics for $\dot{\tilde{B}}_r$ and $\dot{\tilde{B}}_\theta$ are similar to those of electrostatic fluctuations. In fact, both average dispersions were linear (i.e., the average wave vectors, $\bar{k}$, are proportional to the frequencies, f in the region of high spectral power density and $\sigma_k/\bar{k}$ (wave vector spectral width) >1. In addition, the phase velocities diminished in the outside rarefied plasma region. However, the propagation velocities for magnetic fluctuations were always in the electron drift direction, while the electrostatic fluctuation velocities were in the ion diamagnetic drift direction. Furthermore, as in other tokamaks,[27] the magnetic phase velocities were much higher than those of electrostatic fluctuations.

The RHW raised the value of phase velocity for the electrostatic fluctuations, although for magnetic fluctuations this effect was observed only near the limiter. For the measured poloidal magnetic oscillations at these positions, the phase velocity was $v_{B_\theta} \simeq -9.0 \times 10^3$ m/s for the discharges without RHW, and $v_{B_\theta} \simeq -13.0 \times 10^3$ m/s with RHW. As seen in Fig. 4, the high power magnetic fluctuations with k values smaller than those of the electrostatic fluctuations are responsible for these results.

Figures 5(a) and 5(b) show phase velocity radial profiles of electrostatic and magnetic poloidal fluctuations with or without an external perturbation. The average phase velocities of the electrostatic fluctuations, shown in Fig. 5(a), were calculated by using the spectra $S(k, f)$ obtained from two single probes indicated in Fig. 1. As we can see in Figs. 5(a) and 5(b), the phase velocities of the electrostatic fluctuations are one order of magnitude lower than those for magnetic oscillations.

Fluctuation levels and wave vectors predicted for the drift wave and rippling modes[28-30] were compared with those values obtained in our experiment. Despite some discrepancies, which were also observed in other tokamaks,[1] the rippling mode gives a better description of our experimental electrostatic fluctuation levels than the drift wave theory. Nevertheless, none of these models, even in their present versions, adequately describe our measured temperature fluctuations.[31]

§4. Coupling Between Electrostatic and Magnetic Fields

Data were treated with spectral and bispectral estimation methods[12-15] in order to determine linear and quadratic couplings between measured electrostatic and magnetic fluctuations.

These fluctuations were measured with different probes separated by 1.8×10^{-2} m in radial direction. Even so, in this work the correlation estimations are realiable, once correlation between magnetic and electrostatic oscillations extends to beyond the radial correlation length of electrostatic fluctuations.[6] In fact, our correlation lengths are 3.0×10^{-2} m for magnetic and 0.6×10^{-2} m for electrostatic oscillations. However, due probe separation, the correlations were not sensitive to eventual small localized structures, as that suggested by the sudden change of phase velocity at r/a=0.85 (Fig. 5(a)).

We studied linear correlations between magnetic (poloidal or radial field) fluctuations and electrostatic (density, temperature, or plasma potential) fluctuations,

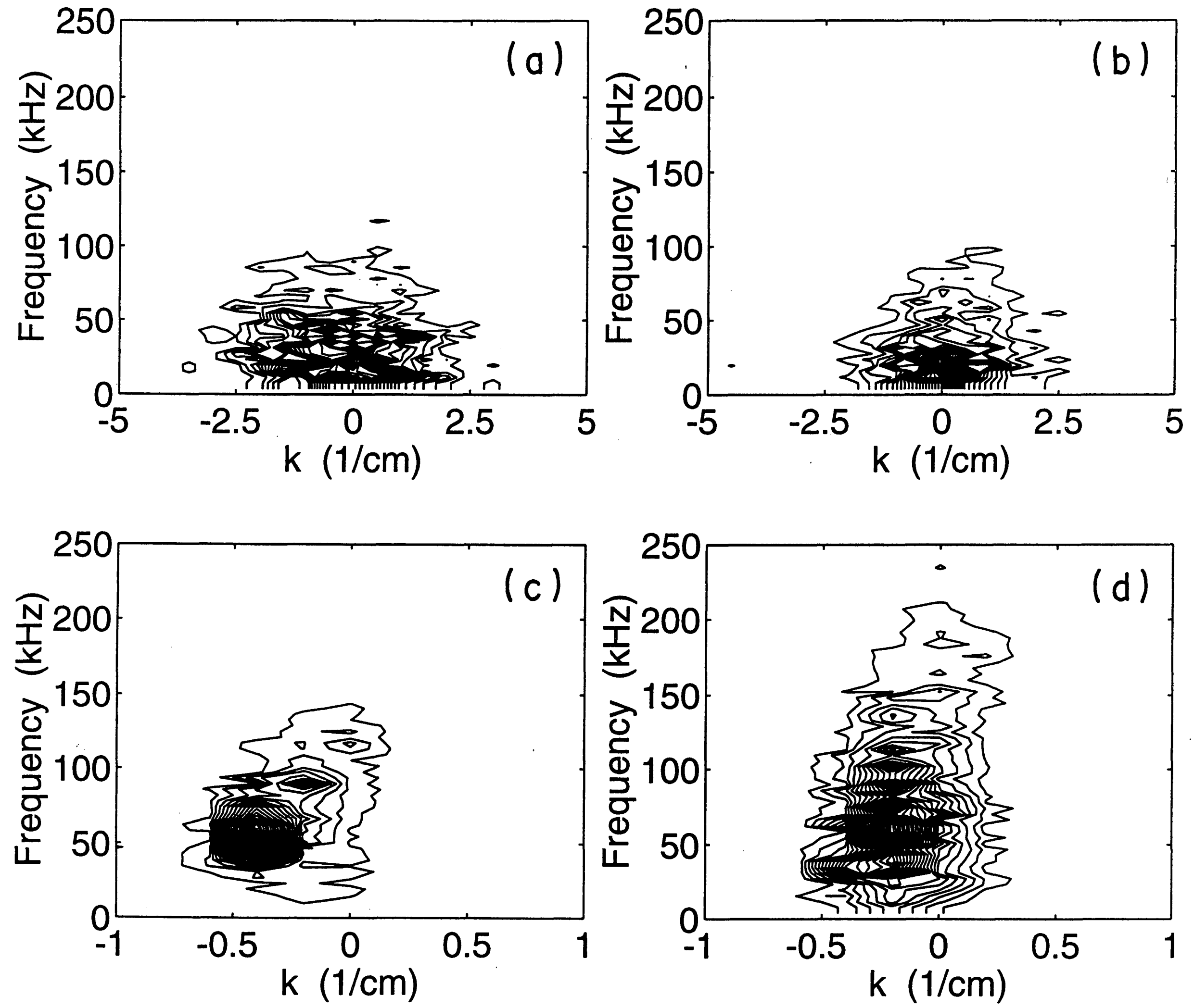

Fig. 4. Contour plot of $S(k, f)$ spectrum of plasma potential fluctuations without (a) and with (b) the RHW, measurements at r/a=0.89; the same for poloidal magnetic fluctuations without (c) and with (d) the RHW, measurements at r/a=1.03. The safety factor at the plasma edge was $q(a) \cong 5.0$.

with or without a resonant external perturbation. Figure 6 shows the linear coherence between the magnetic poloidal fluctuations and temperature or density fluctuations, without resonant external perturbations. For the spectral region of high-power density, the highest values of the coherence are given by $\gamma \simeq 0.4$. This highest coherence occurs in the range of frequencies that accounts for most of the transport associated with electrostatic turbulence.[18] Our results obtained for the parameter γ suggest that electrostatic fluctuations are correlated with a perturbing plasma current, as pointed out in ref. 6. This is so because the measured magnetic fluctuation is usually interpreted as created by a fluctuating current density, flowing on rational flux surfaces.[6, 26]

A radial scan of coherence showed no substantial variation in the reported coherence values. The perturbation caused by the RHW produced a small reduction of these values, without any considerable change of their radial profiles.

There were no significant variation in the linear correlation between magnetic and electrostatic fluctuations (potential and density) for a scan of the safety factor $q(a) = (aB_\phi)/(RB_\theta)$ at the plasma edge ($r = a$), ($6.5 > q(a) > 4.5$) obtained at a fixed radial position in the plasma edge. We noted, however, a pronounced dependence on $q(a)$ for the correlation between temperature and magnetic fluctuations. Indeed, this correlation decreased from $\gamma \simeq 0.50$ to $\gamma \simeq 0.25$ for increasing values of $q(a)$.

Using the model suggested in ref. 27, to link the computed coherence with the fraction of magnetic fluctuation power $B(f)$ attributed to the electrostatic turbulence, the magnetic fluctuation signal becomes:

$$B(f) = S_{EL}(f) + N(f) \tag{1}$$

where S_{EL} is the magnetic signal due to the local electrostatic fluctuation, and $N(f)$ is the magnetic noise element. From ref. 27, we can establish an equation for the coherence between the magnetic and electrostatic fluctuations and the ratio S_{EL}/N, as follows:

$$\gamma(f) = (1 + (S_{EL}/N)^{-2})^{-1/2}. \tag{2}$$

Then a maximum of $\gamma \simeq 0.4$ corresponds to $(S_{EL}/N)^2 \simeq 0.2$. Consequently, in our case a small fraction ($\simeq$20%)

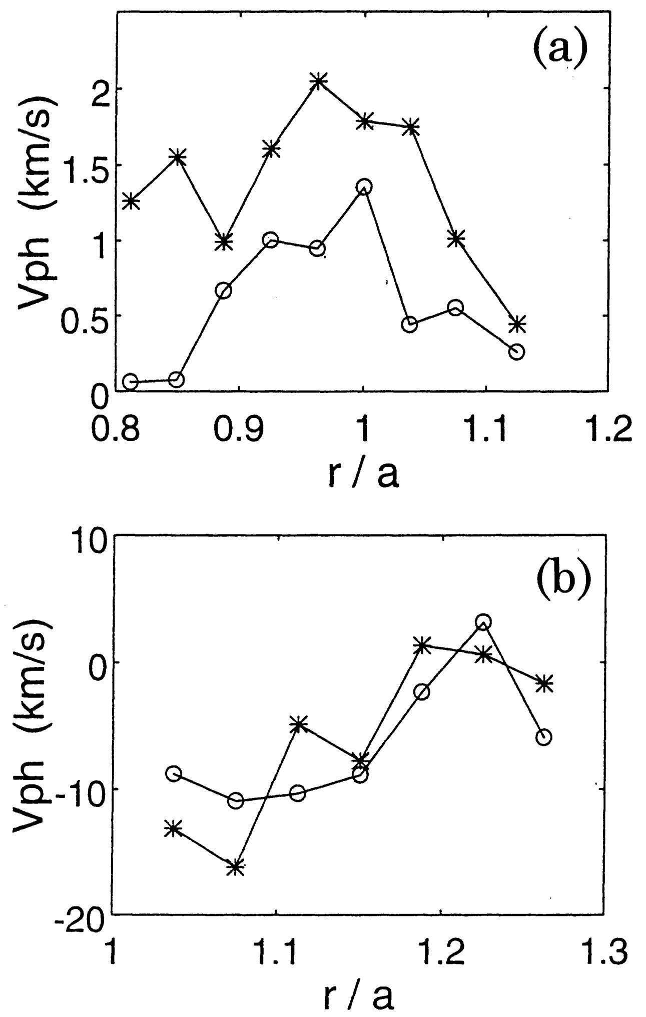

Fig. 5. Phase velocity profiles for potential fluctuations with (∗) and without (◯) RHW, (a) the same for poloidal magnetic fluctuations (b). The safety factor at the plasma edge was $q(a) \cong 5.0$.

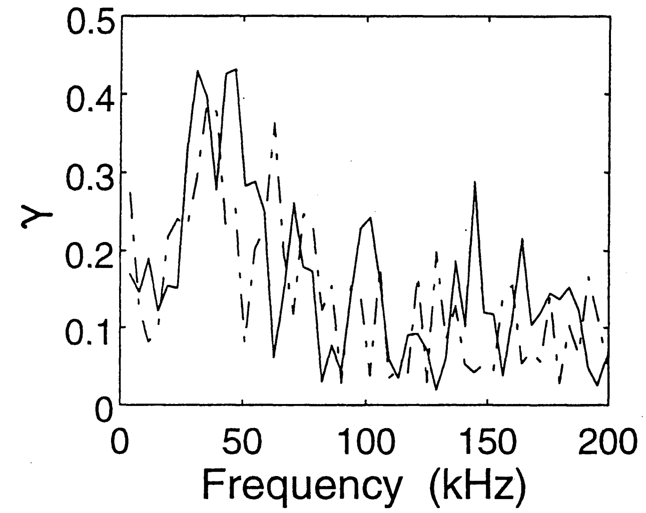

Fig. 6. Linear coherence between poloidal magnetic field and temperature and density fluctuations, respectively (——) and (– · – · –). Electrostatic fluctuations at r/a=0.85 and magnetic fluctuations at r/a=1.07.

of magnetic fluctuation power is due to the local electrostatic fluctuation.

Inspection of the autobicoherence of poloidal and radial magnetic fluctuations using the bispectral analysis showed that the nonlinear interaction is concentrated mainly in the frequency intervals $10 \simeq< f_1 \simeq< 60$ kHz and $10 \simeq< f_2 \simeq< 50$ kHz. Furthermore, this interaction was significantly above the statistical uncertainty.

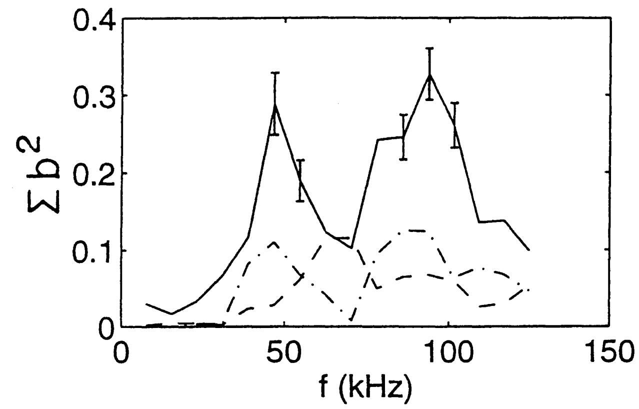

Fig. 7. Integrated bicoherence for poloidal magnetic fluctuations (——) at r/a=1.07, density (–·–·–) potential fluctuations (– – –) at r/a=0.85.

Figure 7 shows the integrated bicoherence of poloidal magnetic fluctuations at r/a=1.07, and density and potential fluctuations at r/a=0.85. We observed the highest bicoherence values for the 50 and 100 kHz components of the magnetic and density oscillations. This power distribution, however, was not the same for the potential fluctuations. For these fluctuations, the integrated bicoherence for magnetic fluctuations is higher than for electrostatic fluctuations. The bicoherence did not show contributions from modes of the high frequency band for any of the two frequency components that satisfy the resonant condition $f = f_1 + f_2$. Although the effect of external perturbations were reduced for all the calculated bicoherences, the general features mentioned above remained unchanged.

The crossbicoherence between poloidal or radial magnetic fluctuations measured by two different coils was more significant without than with the RHW perturbation. Figure 8 shows the crossbicoherence between data from the coils at r/a=1.07. The highest values of the nonlinear coupling appear between components at $f_1 = 100$ kHz and $f_1 - f_2 \simeq 50$ kHz, and $f_1 \simeq 50$ kHz and $f_1 + f_2 \simeq 100$ kHz; the modes were coupled in both sum and difference regions.

The crossbicoherence between electrostatic fluctuations and poloidal or radial magnetic field fluctuation was significative for temperature and density fluctuations, but not for the potential. Figures 9(a) and 9(b) show the squared crossbicoherence spectrum of density fluctuations at r/a=0.85 and poloidal magnetic fluctuations at r/a=1.07; Fig. 9(a) shows a surface plot while Fig. 9(b) shows a contour plot, both with a maximum level of 0.19. For the analyzed data the statistical uncertainty in the crossbicoherence is less than 0.02. In this figure the highest values appear in the same frequency region of the maximum crossbicoherence between two poloidal magnetic coils (Fig. 8). The crossbicoherence levels between magnetic field and potential oscillations

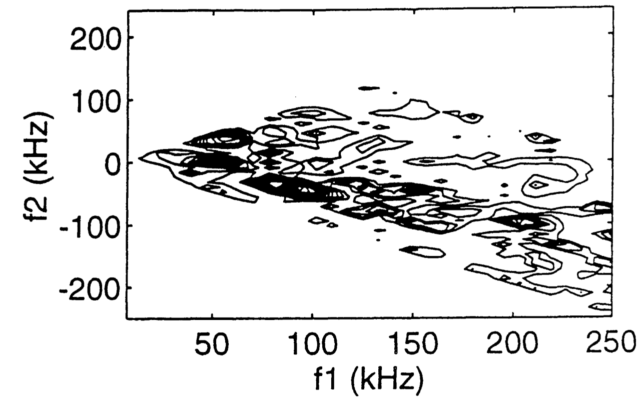

Fig. 8. Crossbicoherence between poloidal magnetic fluctuations at r/a=1.07 (maximum level b_c^2=0.34).

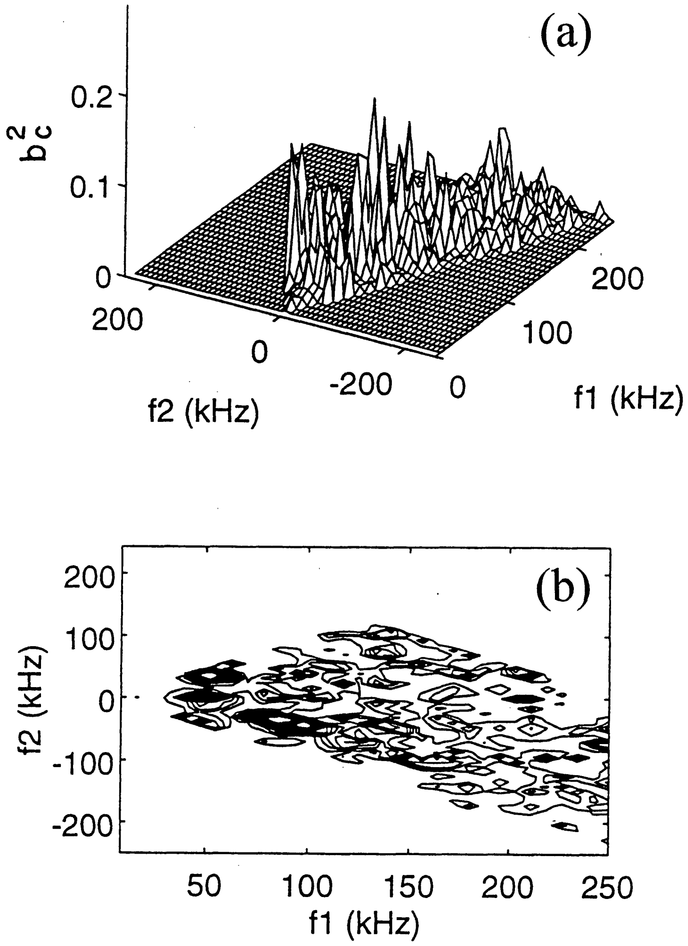

Fig. 9. Squared crossbicoherence spectrum for density and poloidal magnetic fluctuations, at r/a=0.85 and r/a=1.07 respectively. Surface plot (a), and contour plot (b) (maximum level b_c^2=0.19).

were not appreciable. The effect of RHW perturbation had almost entirely supressed any crossbicoherence between the measured parameters.

The observed level of the nonlinear interactions (higher than the statistical uncertainties) shows that a nonlinear coupling exists between the electrostatic and magnetic field fluctuations at tokamak plasma edge.

We used the methods proposed in refs. 12 and 13 to evaluate the nonlinear coupling coefficient and the amount of energy cascading between waves. We calculated the power transfer between three spectral components with frequencies f_1, f_2, and $f = f_1 + f_2$, in terms of the quadratic coupling coefficient. The coupling coefficient is a complex quantity and gives the change in amplitude, as well as changes in the phase of the spectrum, due to three wave interactions. Due to symmetry properties the coupling coefficient does not need to be computed over the entire (f_1, f_2) plane. The region where f_1, $f_2 > 0$ denotes sum frequency $f = f_1 + f_2$ interactions, and regions where $f_1 > 0$, $f_2 < 0$ denotes difference frequency interactions $f = f_1 - f_2$. In this paper a positive energy transfer corresponds to a power transference from low to high frequency modes.

The resulting coupling coefficients for both electrostatic and magnetic fields were small. Power transfer functions for the potential fluctuations showed that the difference frequency interaction region was dominated by negative transfer rates. Conversely, for the density, the power transfer function was lower and presented no preferential direction.

For magnetic fluctuations the amplitude of the quadratic coupling coefficient without magnetic perturbations was high. The most efficient coupling was observed for the sum interacting modes $f_1 + f_2 \simeq 80\,\mathrm{kHz}$ and involves spectral components with frequencies $f_1 \simeq 50\,\mathrm{kHz}$ and $f_2 \simeq< 30\,\mathrm{kHz}$. The power transfer function presented positive transfer rates only in the difference interaction region. The external perturbation reduced to negligible values both the quadratic coupling coefficient and the power transfer function.

Finally, in order to study the oscillation distribution function, we calculated the correlation time τ for magnetic and electrostatic fluctuations. This quantity was computed from the e-folding time of the auto-correlation functions, R, according to the equation $R(r, \tau) = \langle X(r, t)X(r, t + \tau)\rangle$, where $\langle ...\rangle$ represents the ensemble average over a temporal interval and $X(r, t)$ is a measured time series. The calculated correlation time, $\tau \simeq 4\mu s$, was approximately the same for all fluctuations, a small value when compared to the time scale of the experiment or even to the fluctuation time scale. This result might suggest Gaussian distributions for our data. However, this was not confirmed by more precise tests as described in the next paragraph.

The results of the analysis of high order momenta, such as skewness and kurtosis,[32] did not produce a clear evidence of a Gaussian distribution for electrostatic fluctuations with or without magnetic perturbations. On the other hand, for magnetic fluctuations the mean skewness was zero but the mean kurtosis was high. The RHW perturbation enhanced the value for the kurtosis.

§5. Conclusions

We used especially designed probes and advanced statistical techniques to study the correlation between electrostatic and magnetic oscillations in the TBR tokamak.

This work was motivated by the marked partial superposition between magnetic and electrostatic spectra in this tokamak, which made feasible measurements of the correlation. However, as in other experiments with tokamaks,[33] we faced a serious experimental limitation when measuring magnetic turbulences, because the coils were placed behind the limiter. Thus, the components of the low-power region of the magnetic spectrum were hardly detectable because magnetic oscillations decreased very rapidly from the plasma surface. Despite this limitation, we found statistically significant correlation between the magnetic and electrostatic turbulence that we could analyze.

Our results showed some similarities on dispersion relations between magnetic and electrostatic oscillations. Such similarities are compatible with a partial common driving process for these waves.[7] These observations were expected if magnetic fluctuations in the plasma edge were due to the currents driven by electrostatic turbulences.[27]

The driven mechanisms mentioned above are supported by (statistically significant) a linear correlation between edge electrostatic fluctuations and floating magnetic fields. That is, the linear coherence between these two kinds of fluctuations showed its highest values between temperature and magnetic field fluctuations. In addition, we used a model suggested in ref. 27 (which estimates a maximum values of 20% for the magnetic fluctuation power associated to the electrostatic fluctuation) to evaluate the relevance of these correlations.

For all of our recorded time series, the nonlinear coupling between the various frequency fluctuation components was higher than the estimated maximum level (10%) of the statistical uncertainties. The nonlinear coupling was generally more significant for magnetic than for electrostatic fluctuations.

We found evidence of quadratic correlation between edge electrostatic fluctuations and fluctuating magnetic fields. In fact, the crossbicoherence between temperature (or density) and magnetic fluctuations was appreciable. Moreover, the highest calculated values occurred in the same frequency region of the maximun crossbicoherence calculated from two poloidal magnetic coil data.

The energy transfer between different frequency components of the electrostatic power spectra was negligible in this work. On the other hand, for the magnetic fluctuations energy transfers were significant and presented positive transfer rates (from low to high frequency components) only in the difference frequency interaction region, i.e., from waves with frequencies f_1 and f_2 to waves with frequencies $f_1 - f_2$. Furthermore, the existence of these linear and quadratic couplings (although small) in the power spectra could be important for energy transmission between electrostatic and magnetic frequency components. This effect had been predicted by a basic turbulence theory for the wave-vector power spectra.[34]

We also studied the response of linear and nonlinear coupling between the magnetic and the electrostatic fluctuations to the applied magnetic perturbation created by the resonant helical windings. These resonant perturbations globally decreased the turbulence level at the plasma edge and somewhat modified the experimental dispersion relations.

The main effects induced by the RHW were mostly a small reduction of the linear coherence and a suppression of the crossbicoherence between all measured parameters. This external perturbation also reduced to negligible values the power transfer function. The supression of the quadratic coupling between the magnetic and the electrostatic fluctuations showed its effect on the amplitude of the magnetic fluctuations, which were also reduced by the perturbation.

We did not find a model that adequately described most of the measured characteristics of edge turbulence, in particular, the correlation between electrostatic and magnetic fluctuating fields presented in this work. Our data, however, may contribute to identify the basic mechanisms that determined edge turbulences.

As with other tokamaks,[1,2] plasma edge transport in the TBR is driven by electrostatic fluctuations.[18] Although the relation of magnetic and electrostatic fluctuations found in our work did not change the transport framework, it confirmed that the magnetic fluctuations are somewhat linked to the electrostatic fluctuations. Consequently, this linking may have an indirect influence on transport, as discussed in some review articles.[1,35] Recent numerical results obtained from a drift-wave model confirm that the transport is predominantly electrostatic.[31] Magnetic fluctuations, however, may have an important influence on the relation between density and potential fluctuations, enhancing the nonadiabatic character of electrons.[34]

Acknowledgements

The authors would like to thank Dr. F. Karger (Max-Planck Institut für Plasmaphysik) and Dr. S. J. Camargo (State of São Paulo University) for discussions, and Dr. E. Browne (Lawrence Berkeley Laboratory) for revising the manuscript. This work was partially supported by the Brazilian Governamental Agencies FAPESP and CNPq.

1) A. J. Wootton, B. A. Carreras, H. Matsumoto, K. McGuire, W. A. Peebles, Ch. P. Ritz, P. W. Terry and S. J. Zweben: Phys. Fluids **2** (1990) 2879.
2) F. Wagner and V. Stroh: Plasma Phys. Control. Fusion **35** (1993) 1321.
3) G. Li, J. R. Drake, H. Bergsaker, J. H. Brzozowski, G. Hellblom, S. Mazur, A. Moller and P. Nordlund: Phys. Plasmas **2** (1995) 2615.
4) P. R. Brunsell, Y. Mayima, Y. Yagi, Y. Hirano and T. Shimada: Phys. Plasmas **1** (1994) 2297.
5) T. D. Rempel, C. W. Spragins, S. C. Prager, S. Assadi, D. J. Denhartog and S. Hokin: Phys. Rev. Lett. **67** (1991) 1438.
6) Y. J. Kim, K. W. Gentle, Ch. P. Ritz, T. L. Rhodes and R. D. Bengtson: Nucl. Fusion **29** (1989) 99.
7) Y. J. Kim, K. W. Gentle, Ch. P. Ritz, T. L. Rhodes and R. D. Bengtson: Phys. Fluids B **3** (1991) 674.
8) H. Lin: Ph.D. Thesis FRCR #401, University of Texas, Fusion Research Center, Austin, TX, 1991.
9) N. Ohyabu, G. L. Jahns, R. D. Slambaugh and E. Strait: Phys. Rev. Lett. **58** (1987) 120.
10) H. Y. Tsui, K. Rypdal, Ch. P. Ritz and A. J. Wootton: Phys. Rev. Lett. **70** (1993) 2565.
11) M. V. A. P. Heller, R. M. Castro, Z. A. Brasilio, I. L. Caldas and R. P. da Silva: Nucl. Fusion **35** (1995) 59.
12) Ch. P. Ritz and E. J. Powers: Physica **1D20** (1986) 320.
13) Ch. P. Ritz, E. J. Powers and R. D. Bengston: Phys. Fluids B **1** (1989) 153.

14) Y. J. Kim and E. J. Powers: IEEE Trans. Plasma Sci. **PS-7** (1979) 12.
15) K. Rypdal and F. Øines: Phys. Lett. A **184** (1993) 114.
16) T. Estrada, E. Sanches, C. Hidalgo, B. Brañas and CH. P. Ritz: *Proc. 20th EPS Conference on Controlled Fusion and Plasma Physics, Lisbon, 1993*, Europhysics Conference Abstracts **17C** (1993) 373.
17) R. M. Castro, M. V. A. P. Heller, I. L. Caldas, Z. A. Brasilio, R. P. da Silva and I. C. Nascimento: Phys. Plasmas **3** (1996) 971.
18) R. M. Castro, M. V. A. P. Heller, I. L. Caldas, Z. A. Brasilio, R. P. da Silva and I. C. Nascimento: Phys. Plasmas **4** (1997) 329.
19) H. Ji, H. Toyama, K. Yamagishi, S. Shinohara, A. Fujisawa and K. Miyamoto: Rev. Sci. Instrum. **62** (1991) 2326.
20) H. Y. Tsui, R. D. Bengston, G. X. Li, H. Lin, M. Meier, Ch. P. Ritz and A. J. Wootton: Rev. Sci. Instrum. **63** (1992) 4608.
21) S. C. McCool, A. J. Wootton, A. Y. Aydemir, R. D. Bengtson, J. A. Oedo, R. V. Bravenec, D. L. Brower, J. S. DeGrassie, T. E. Evans, S. P. Fan, J. C. Forster, M. S. Foster, K. W. Gentle, M. Kotschenrenther, N. C. Luhmann, Jr., W. H. Miner, Jr., T. L. Rhodes, B. Richards, Ch. P. Ritz, D. W. Ross, W. L. Rowan, P. M. Schoch, B. O. Smith, J. C. Wiley, X. H. Yu and S. B. Zheng: Nucl. Fusion **29** (1989) 547.
22) A. Grosman, P. Gendrih, C. DeMichelis, P. Mourier-Garbet, J. C. Vallet, H. Capes, M. Chantelier, T. E. Evans, A. Geraud, M. Góniche, C. Grisolia, D. Guilhem, G. Harris, W. Hess, F. Nguyen, L. Poutchy and A. Samain: J. Nucl. Mater. **196** (1992) 59.
23) A. Vannucci, O. W. Bender, I. L. Caldas, I. H. Tan and I. C. Nascimento and E. K. Sanada: Il Nuovo Cimento **10D** (1989) 1193.
24) Pulsator Team: Nucl. Fusion **25** (1985) 1059.
25) C. Robinson: Nucl. Fusion **25** (1985) 1101.
26) J. M. Finn: Nucl. Fusion **19** (1975) 845.
27) G. Vayakis: Nucl. Fusion **33** (1993) 547.
28) P. W. Terry and P. H. Diamond: Phys. Fluids **28** (1985) 1419.
29) L. Garcia, P. H. Diamond, B. A. Carreras and J. D. Callen: Phys. Fluids **28** (1985) 2147.
30) T. S. Hahm, P. H. Diamond, P. W. Terry, L. Garcia and B. A. Carreras: Phys. Fluids **30** (1987) 1452.
31) B. D. Scott: Phys. Rev. Lett. **65** (1990) 3289; Phys. Fluids B **4** (1992) 2468.
32) J. S. Bendat and A. G. Piersol: *Random Data: Analysis and Measurement Procedures* (Wiley, New York, 1996) 2nd ed.
33) I. H. Tan and S. C. Prager: Phys. Fluids **28** (1995) 1419.
34) S. J. Camargo, B. D. Scott and D. Biskamp: Phys. Plasmas **3** (1996) 3912.
35) Ph. Ghendrih, A. Grosman and H. Capes: Plasma Phys. Control. Fusion **38** (1996) 1653.