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STUDIES OF ELECTROSTATIC AND MAGNETIC FLUCTUATIONS IN CASTOR TOKAMAK

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Abstract

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The electrostatic and magnetic edge turbulence of the CASTOR plasma was investigated with poloidal resolution. The effect of fluctuation suppression in the presence of a lower hybrid wave was studied. A theoretical model is presented as an attempt to understand the microscopic processes occurring in the CASTOR plasma.

1. INTRODUCTION

The improvement of global particle confinement during combined inductive/lower hybrid (LH) current drive was routinely observed in the CASTOR tokamak (R = 0.4 m, a = 0.085 m, B = 1 T, I = 12 kA) [1]. For a better understanding of this interesting effect, the experimental effort was focused on determining the poloidal dependence of both electrostatic and magnetic fluctuations and on studying this effect near the density limit for the LH current drive (Sections 2 and 3).

The aim of the theoretical studies was to explain the particle confinement in this tokamak (the density decay appearing in Ohmic discharges) and the effect of the LH wave on the electrostatic fluctuations (Section 4).

2. EXPERIMENTAL ARRANGEMENT

The experiments were performed in the CASTOR tokamak in standard Ohmic heating discharges (OH) and in regimes with combined inductive and lower hybrid current drive (OH/LHCD). In the latter case, a lower hybrid wave (f = 1.25 GHz,

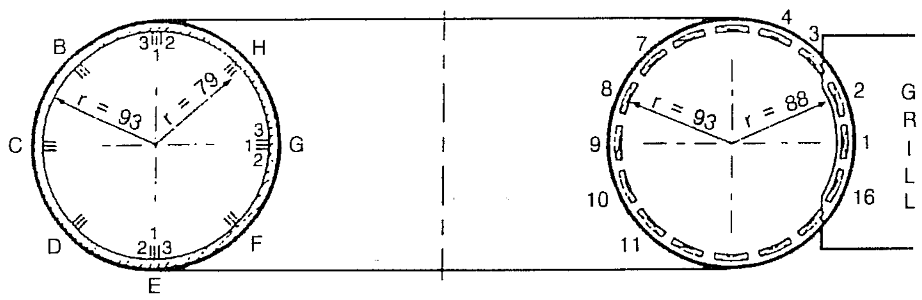

FIG. 1. Experimental arrangement of triple probes and Mirnov coil poloidal arrays in CASTOR.

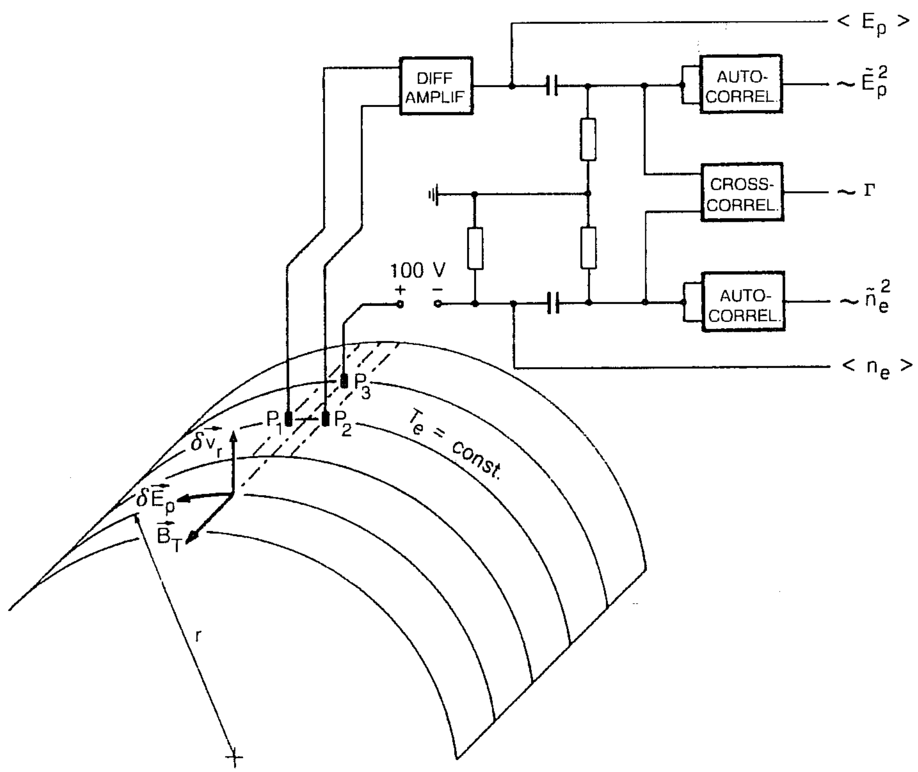

FIG. 2. Arrangement of three-channel analogue correlator for determining cross-field drift induced transport parameters.

$P \leq 40$ kW) was launched into an OH plasma by a multijunction waveguide grill with a broad power spectrum ($N_{\parallel} = 1$–4) and rather low directivity. The position of the plasma column inside the liner was feedback controlled.

The MHD activity was monitored by a set of Mirnov coils uniformly distributed inside the liner (Fig. 1). The signals from the coil were digitized by seven A/D converters in the 0.1–300 kHz frequency band.

The edge electrostatic turbulence was investigated by a poloidal array of triple probes (Fig. 2). The tips of each probe were arranged in a triangular shape (d = 3 mm). The two poloidally separated floating tips are used to determine the poloidal electric field fluctuations. The third, negatively biased tip is used to monitor the density fluctuations. The triple probe is connected to a three-channel analogue correlator (Fig. 2), which gives the temporal evolution of the RMS values of density and E_p fluctuations, together with their cross-correlation. The cross-correlation represents the turbulent particle flux $\langle \delta v_r \cdot \delta n_e \rangle$, where the radial velocity is given by the cross-field drift $v_r = \vec{E}_p \times \vec{B}/B^2$. Moreover, the quasi-stationary values of $\langle n_e \rangle$ and $\langle E_p \rangle$ were monitored. Consequently, the quasi-stationary particle flux $\langle \Gamma \rangle = \langle n_e \rangle \langle E_p \rangle / B$ can be simply derived for different poloidal angles.

3. EXPERIMENTAL RESULTS

3.1. The quasi-stationary cross-field drift induced transport in the OH regime

Figure 3 presents an example for the poloidal variation of three quantities measured by the triple probe array. We see that the poloidal dependence of the edge density (and edge electron temperature) is approximately uniform. The poloidal dependence of the quasi-stationary poloidal electric field (and also the floating potential), however, exhibits a very pronounced maximum and even changes the direction. The negative sign of E_p, in our case, corresponds to the inward direction of the quasi-stationary flux $\langle \Gamma \rangle$. A similar asymmetry is observed for the turbulent component of this flux. Nevertheless, a poloidal averaged value of $\langle E_p \rangle = 500$ V/m seems to yield an outward flux of an order comparable to the measured turbulent flux and the particle flux determined from global particle balance. It indicates that the quasi-stationary value of the cross-field drift induced transport should be taken into account. However, it should be noted that $\langle E_p \rangle$, determined here as a difference of potentials of two floating tips, is a correct value of the poloidal electric field only in the case where the tips are on magnetic surfaces which are so close that $T_e^1 - T_e^2 \ll (V_f^1 - V_f^2)e$, for a hydrogen plasma. This condition may be even more severe for non-Maxwellian plasmas.

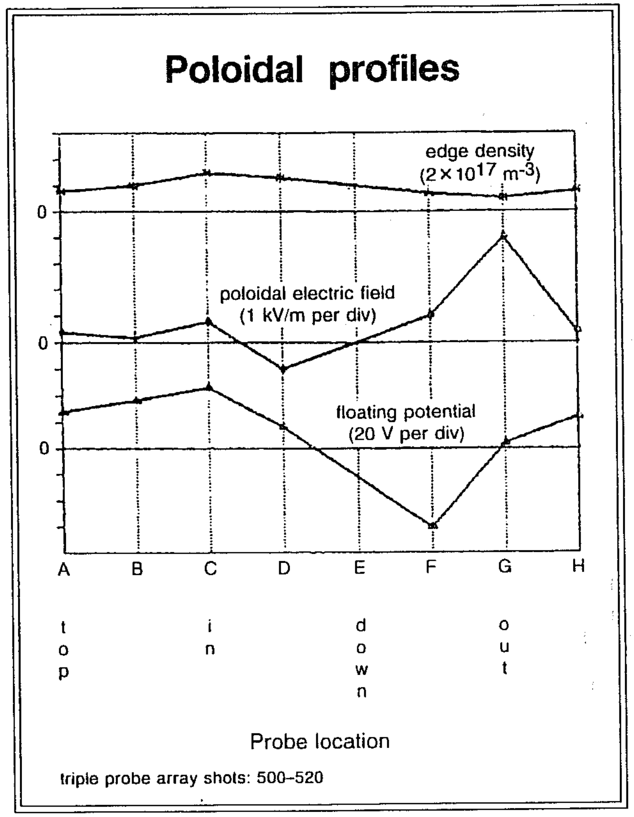

FIG. 3. Poloidal variation of edge parameters for determining quasi-stationary flux.

3.2. Electrostatic and magnetic fluctuations during the OH/LHCD regime

It has been shown that the level of electrostatic turbulence drops substantially during the OH/LHCD period of CASTOR discharges (Fig. 4) [1]. Simultaneously, an enhancement of global particle confinement is observed. Here, it is documented by a slowing-down of the line average density decay during OH/LHCD [2].

Figure 4(b) demonstrates that both effects are still well pronounced near the density limit of the LH current drive, when a relatively small number of superthermal, current carrying electrons is present in the plasma column.

The MHD turbulence is similarly affected during the OH/LHCD part of the discharge, as is shown in Fig. 5. It is seen that, despite a poloidal variation of the fluctuation levels, the relative suppression of the MHD turbulence is constant and equals 0.4. The fast Fourier transform spectra of the coil signals are shown in

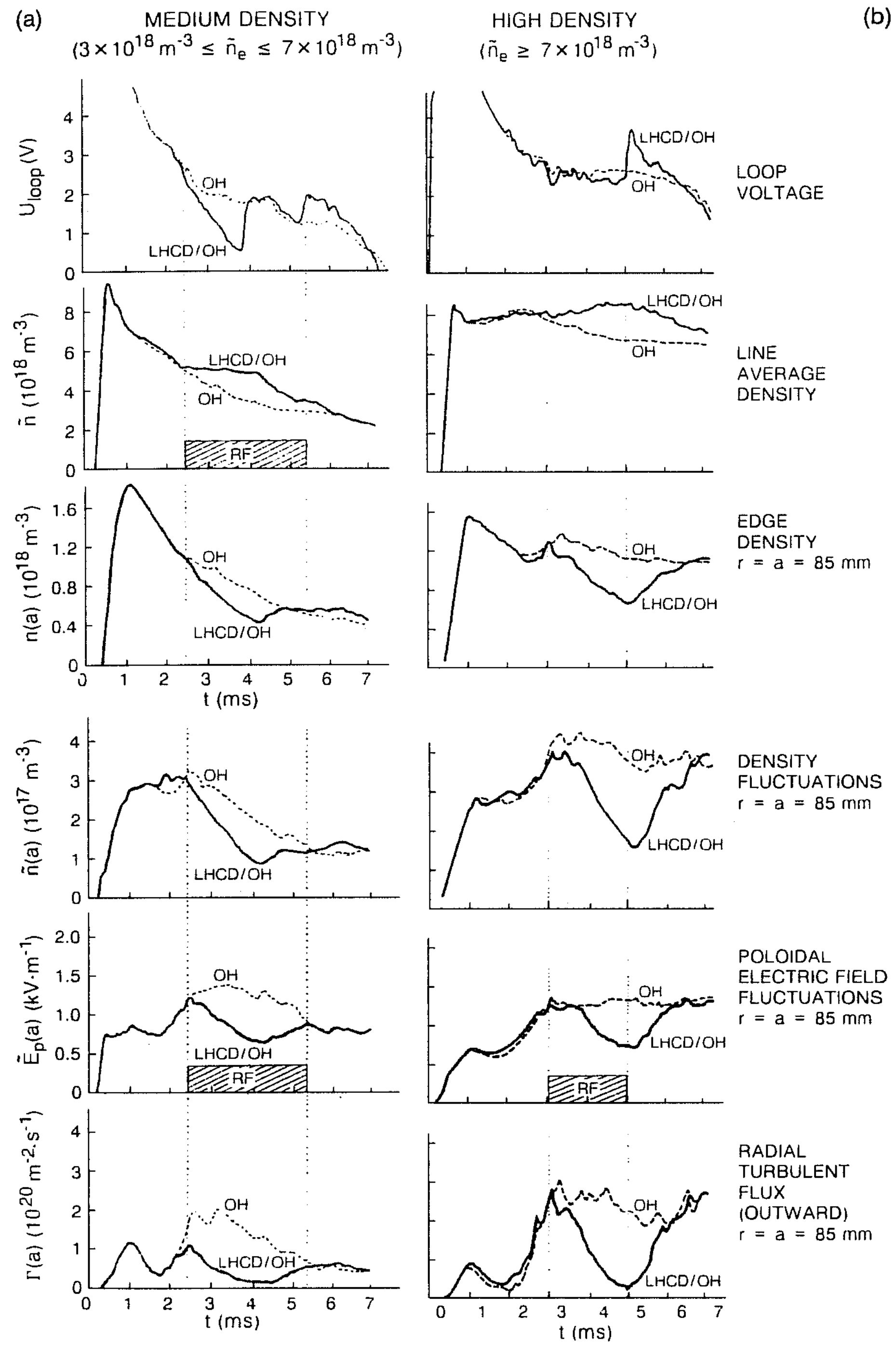

FIG. 4. Temporal evolution of plasma parameters for a medium density discharge (a) and for a high density discharge, near the density limit of LHCD (b).

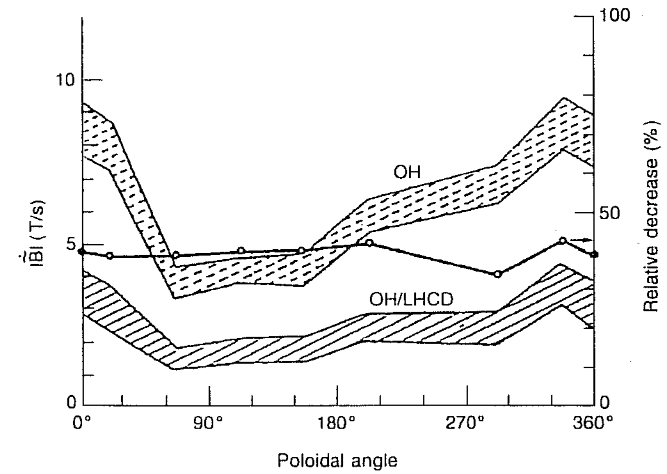

FIG. 5. Levels of MHD turbulence for OH and OH/LHCD regimes.

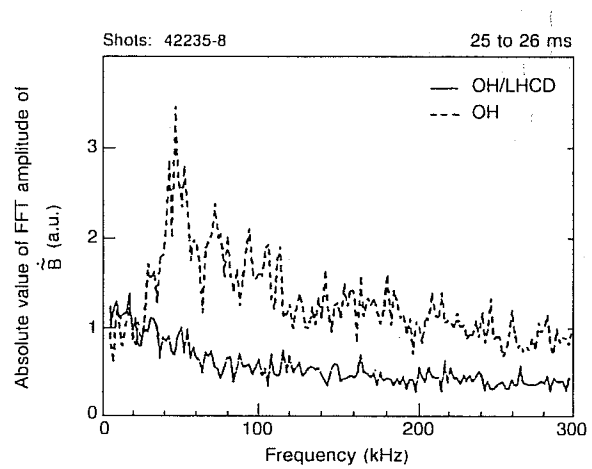

FIG. 6. Frequency spectra of magnetic fluctuations.

Fig. 6. The suppression takes place in a broad spectral range. Therefore, it seems that this effect differs from the suppression of the coherent m = 2 mode observed during LHCD on Petula [3].

4. THEORETICAL MODEL

The results of the measurements performed in the OH regime of CASTOR have previously been used to solve the inverse problem of the plasma transport.

This consists in determining the transport coefficients from the available experimental data using numerical simulations. The specially elaborated method [4] permitted the thermal conductivity coefficient to be determined and also a realistic picture of the evolution of the plasma parameters in CASTOR to be obtained.

Because of the steep density gradient developing from the start, the theoretical explanation of these experimental and numerical results must invoke the low frequency electrostatic drift instability. The high collisionality of CASTOR discharges drives the dissipative branch unstable which is saturated by magnetic shear and ion damping. A specific feature of the low density CASTOR discharges is the fast decay of the average density, after reaching a maximum (1 ms) (Fig. 4(a)). It appears in conditions in which no fully developed turbulence is expected. This enhanced diffusion has a rather sudden onset and is too effective for the expected low level of turbulence, at that time. Indeed, estimating the linear growth rate and the level of non-linearity [5], we obtain $(k_\parallel v_T)^2/(\omega_{*e}\nu_{ei}) \cong 20 > 1$, which shows an almost adiabatic response of the electrons and a low level of non-linear coupling. Then, the modes can have a quasi-coherent structure which is slightly perturbed by non-linearity. It is then important to investigate the contribution of non-conventional transport mechanisms which are related to the existence of large scale coherent potential structures.

We consider the potential structure of a single drift mode which, ideally, shows two-dimensional periodicity in a finite radial region. The separatrices are perturbed non-linearly and the particle motion in this finite width zone is not integrable. The particles perform $\vec{E} \times \vec{B}$ oscillations in the potential cells, but those which are close to the stochasticized separatrices can be scattered by collisions and perform jumps to the neighbouring cells. A combination of such jumps allows the particles to make significant radial excursions. The transfer of particles (i.e. a flux) from one side to the other of such periodic structures is possible when the probability of the elementary process of scattering is greater than a critical value [6]. This particle loss mechanism has important peculiarities: (1) is not directly connected to the density gradient; (2) it has a threshold; (3) it is non-local as is the basic potential 2-D structure; (4) it is not accompanied by heat conduction (the proportionality between D and κ is not maintained).

A similar percolation process can be identified in a regime of higher turbulence provided that the correlation time is still longer than the characteristic time of electron drift motion. In this situation, long range potential structures can randomly occur in the 2-D stochastic geometry of a superposition of electrostatic modes. These structures, having large extensions in the radial direction, provide, via the particle drift, an efficient contribution to the anomalous transport. The diffusion arising from this additional mechanism when a sufficiently high radial electric field is present (as in the CASTOR case) is [7]:

$$D_p = \lambda^2 \omega k_\perp \tilde{\Phi}/E_r \quad \text{for} \quad E_r/(k_\perp \tilde{\Phi}) > (v_{ph\perp}/v_d)^{(\nu+1)/(\nu+2)}$$

where $\nu = 4/3$ is the correlation length exponent in the 2-D percolation theory,

$v_d = k_\perp \tilde{\Phi}/B$, $\lambda = 2\pi/k_\perp$ and $v_{ph\perp}$ is the phase velocity of the mode. In our case, the resulting diffusion is of the order of 1 m^2/s. This value is comparable with the empirical result obtained from numerical simulations.

The particles which traverse the zone with potential cells determine a modification of the density profile by increasing the density gradient in the marginal region. Such a steep boundary profile was experimentally observed in the first milliseconds of the CASTOR discharges.

As the turbulence increases, the dominant contribution to the diffusion arises from the fluid like response of the electrons. The non-adiabatic contribution of the electron density response was estimated from the theory of collisional drift instability:

$$\mathrm{Im}\left[\left(\frac{\tilde{n}}{n}\right)\Big/\left(\frac{e\tilde{\Phi}}{T_e}\right)\right] \approx 0.6$$

The calculated levels of fluctuations (3% at the centre and 40% at the border) are close to the experimental observations [1]. This turbulent phase of the drift instability provides a satisfactory model for the plasma evolution after the fast density decay when the density continues to decrease, but at a slower rate. The drift turbulence affects the major part of the plasma cross-section.

The fact that particle losses are due to different mechanisms can be observed in the experimental determination of edge particle flux. A separated peak appears at

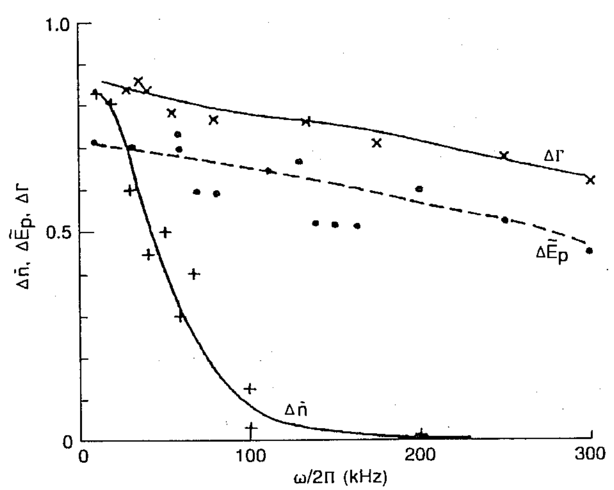

FIG. 7. Relative drop of density and poloidal electric field fluctuations and of turbulent flux as functions of frequency.

the time of maximum density decay which, according to our model, is determined by percolations; after this the turbulent flux develops (Fig. 4).

The marginal zone of the plasma is affected by the existence of a quasi-stationary radial electric field [1] which determines a sheared poloidal flow of the plasma providing a free energy source through the relaxation of the vorticity gradient. This determines a shift of the frequencies from the diamagnetic values ($\omega_{*e} \approx$ 90 kHz) to $\omega_E = E_r k_\perp / B \approx$ 320 kHz and explains some other observed features of the edge turbulence: the reversion of the sign of the fluctuation phase velocity near the limiter and the presence of a minimum in the fluctuation level in this region.

A very important feature revealed by the measurements performed in the OH/LHCD regime is the partial suppression for the low frequency part (< 100 kHz) of the edge turbulent density fluctuations (Figs 4 and 7). Since the high frequency part, which is related to the radial electric field drive is non-perturbed, the LH wave acts on the dissipative drift wave turbulence. We have considered the direct effect of the LH wave on the linear drift mode evolution. The result was that the linear growth of the mode is inhibited only for values of the LH wave electric field which are much higher than in CASTOR experiments. It may be deduced that the LH wave acts on the non-adiabatic part of the electron response, e.g. reducing the lifetime of the small scale correlations. This is also supported by the experimental observation that the poloidal field fluctuations are much less affected than the density fluctuations.

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