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Plasma turbulence in tokamaks

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Abstract

We present results from experiments on electrostatic and magnetic fluctuations in TBR Brazilian tokamak. The observed electrostatic turbulence induces anomalous particle transport that deteriorates the plasma confinement. We describe how to control this effect, by decreasing plasma turbulence, with resonant magnetic perturbations that creates a Lagrangian diffusion of the chaotic magnetic field lines. © 1998 Elsevier Science B.V. All rights reserved.

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Control of anomalous plasma-edge transport, induced by electrostatic turbulence, improves plasma confinement in tokamaks [1,2].

In TBR tokamak, we control plasma edge turbulence with electrical currents on resonant helical windings [3]. The external magnetic perturbations created by these resonant currents were used to create a chaotic magnetic field lines to control particle and heat diffusion and, consequently, to improve the plasma confinement.

The experiment was carried out on the Ohmically heated TBR tokamak, with major radius $R_0 = 0.30\,\mathrm{m}$, minor radius $a = 0.08\,\mathrm{m}$, toroidal magnetic field $B_\varphi = 0.4\,\mathrm{T}$, plasma current $I_\mathrm{p} \cong 10\,\mathrm{kA}$, average particle density $n_0 \cong 7 \times 10^{18}\,\mathrm{m}^{-3}$, and pulse length of 10 ms [4]. The plasma had a circular cross section.

To estimate particle transport in this turbulent plasma, we measured density and potential fluctuations, and the phases and correlations between these fluctuating quantities [5,6]. For that, we used a complex system of probes, which measures simultaneously electrostatic and magnetic fluctuations and some plasma mean parameters (Fig. 1) [7].

Data were collected from a multipin Langmuir probe (Fig. 1) inserted into the plasma through a diagnostic port at the top of the tokamak. Probe measurements were done during the flat top phase of the plasma current, in time intervals of approximately 4 ms and averaged throughout seven consecutive shots. Time-series measurements were

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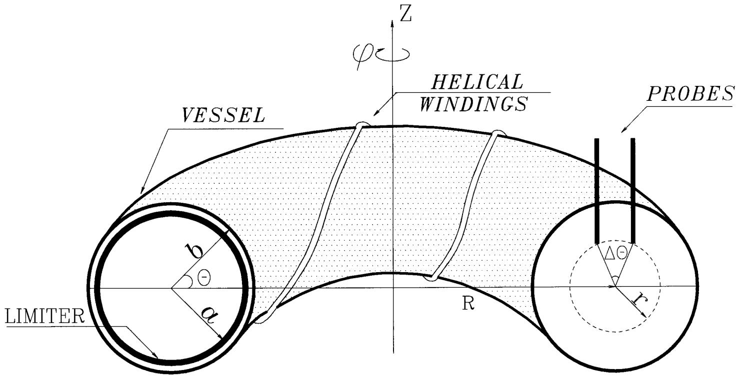

Fig. 1. Scheme of the tokamak, resonant helical windings, and probe assembly.

recorded using 8 bit digitizers, with a maximum sampling rate of 1 Mhz. The length of the used data consisted of 105 samples of 256 points.

Spectral analyses show that these electrostatic fluctuations are turbulent with broad spectra of wave vectors and broad spectra of frequencies at each wave vector [8,4].

The external magnetic field perturbation was created by electric currents circulating in a set of helical windings placed externally around the torus [7]. These coils produced a dominant radial perturbation field $b_{\mathrm{r}} \cos(4\theta - \varphi)$ with average radial amplitude $\langle |b_{\mathrm{r}}(a)|/B\varphi \rangle \cong 0.4\%$ at $r = a$. This perturbation was resonant for the field lines on the rational magnetic surface with a rotational transform

$$\iota \equiv (2\pi R B_{\varphi})/(r B_{\theta}) = 2\pi/4 = \pi/2 \,. \tag{1}$$

The currents circulating in these coils were adjusted to $I_{\mathrm{h}} = 285\,\mathrm{A}$ and they were switched on after the plasma current had reached steady values.

These coils created both primary magnetic islands on the rational surface with $\iota = \pi/2$ and chaotic regions near this surface. Chaos is due to the overlapping of these primary islands with neighbor secondary islands that appear in the perturbed non-integrable field, as shown on the Poincaré map of Fig. 2. This perturbation destroyed the magnetic surfaces in a chaotic layer of about $1.2 \times 10^{-2}\,\mathrm{m}$ radial width at the plasma edge.

The resonant magnetic perturbation changed remarkably the equilibrium parameters and fluctuating quantities at the plasma edge. A sharp density gradient exists without the magnetic perturbation (Fig. 3). With the perturbation this radial profile became flat. This behavior is attributed to the different connection to the walls, along the chaotic field lines, created by the perturbation resulting in a larger area seen by the plasma. Similar alterations were also induced by a chaotic divertor in the Tore Supra tokamak [9,10].

To study the effect of the resonant perturbation on particle transport we investigated the changes in the plasma edge parameters that are commonly associated with that transport. Thus, digital spectral analysis is used to compute the spectral power density distribution function $S(k,f)$ [8], for density and fluctuating potential time series. As

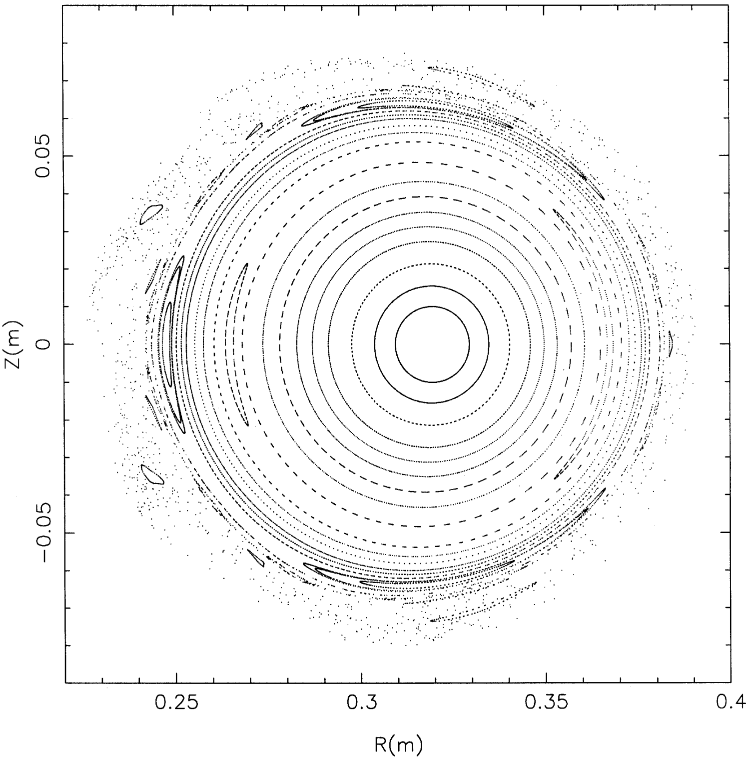

Fig. 2. Poincaré map (at a plane Z×R, see Fig. 1) showing the magnetic field line configuration with perturbation created by currents ($I_h = 285$ A) on the resonant helical windings.

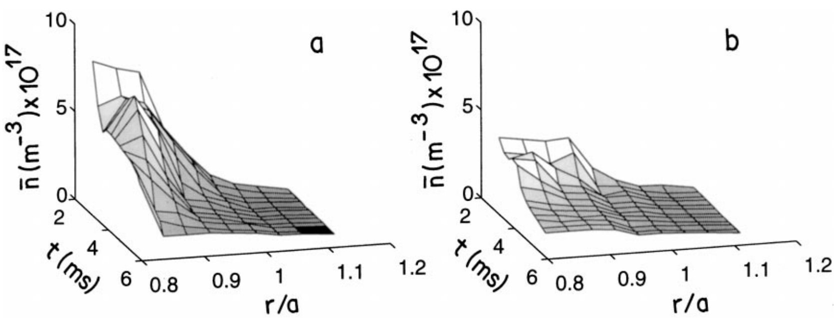

Fig. 3. Time and radial profiles of density, at plasma edge, for plasma discharges without (a) and with (b) resonant helical windings.

shown in Fig. 4, density fluctuations are strongly reduced by the resonant perturbation. Although not so marked, the same kind of alteration was also produced on the plasma potential, ϕ, spectra.

In this work, the driven particle flux, Γ is calculated by [11]

$$\Gamma = 2k_\theta |P_{n_\phi}| \sin(\theta_{n_\phi})/B_\varphi \,, \qquad (2)$$

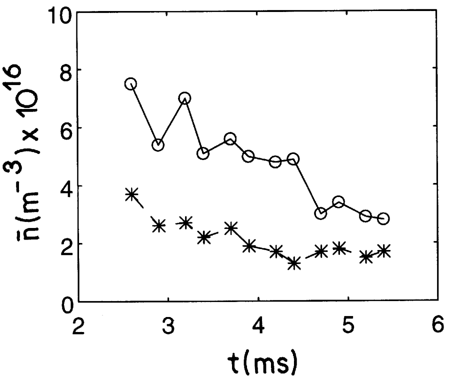

Fig. 4. Time profiles of fluctuating density, at the radial position $r/a = 0.89$, with (∗) and without (∘) resonant helical windings.

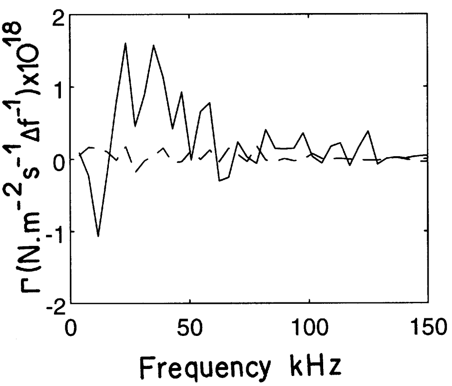

Fig. 5. Induced particle flux frequency-spectra, at the radial position $r/a = 0.89$, without (—) and with (- - -) resonant helical windings.

where k_θ is the wave number of the fluctuating plasma potential, P_{n_ϕ} and θ_{n_ϕ} are, respectively, the crosspower spectrum and the phase angle between the plasma potential, ϕ, and density, n, fluctuations.

Fig. 5 shows the particle flux profiles for plasma discharges with and without the resonant perturbation. An appreciable alteration was produced in the plasma edge transport by the resonant perturbation. The results show not only a reduction of the particle flux in the whole spectrum but even, for some low-frequency intervals, an inversion in its radial direction.

From the radial distribution of electron density at the plasma edge (Fig. 3) we can roughly estimate the radial diffusion coefficient across the main magnetic field under the effect of the applied perturbation. The diffusion coefficient, D, is given by

$$D = -\Gamma/\nabla n \,, \tag{3}$$

where Γ is the particle flux. Results obtained near the limiter ($r/a \approx 1$) give $D \approx 0.3\,\mathrm{m}^2/\mathrm{s}$. We compare this diffusion coefficient with that theoretically predicted under the conditions of the described experience. Thus, in the collisionless plasma limit with a chaotic magnetic field, the following expression can be used to estimate the diffusion coefficient, D^{C} [12]:

$$D^{C} = \langle D_{m} \rangle \, v_{thi} , \tag{4}$$

where D_{m} is the magnetic diffusion coefficient of the chaotic field lines given by

$$D_{m} = \pi R \left\langle |B_{r}/B_{\varphi}|^{2} \right\rangle . \tag{5}$$

The ion thermal velocity, v_{thi}, is estimated by considering the average values of the plasma edge temperatures, near the limiter, $T_{i} \cong T_{e} \cong 15\,\mathrm{eV}$, as usually. Thus, we obtain $D^{C} \approx 0.27\,\mathrm{m^{2}/s}$, as the average radial diffusion coefficient in this region. This value is in good agreement with the experimental diffusion coefficient D.

Magnetic fluctuations were detected by pick-up coils outside the plasma. Comparing the amplitude and phase of these fluctuations with the electrostatic parameters, we detected small correlation between these two kinds of oscillations and, consequently, between the magnetic oscillations and the anomalous transport during the tokamak discharges [13].

In TBR not only the magnetic oscillations were strongly reduced, as in other experiments [14], but also the electrostatic oscillations were slightly modified by the resonant helical windings used to perturb the magnetic field. This could be associated to the uncommon (for tokamaks) partial superposition of the frequency spectra obtained for these two kinds of oscillations [4].

In conclusion, relevant alterations on the turbulent spectra of these oscillations and on the electrostatic driven transport were observed after the edge magnetic structure, perturbed by the external resonant helical fields, became predominantly chaotic.

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